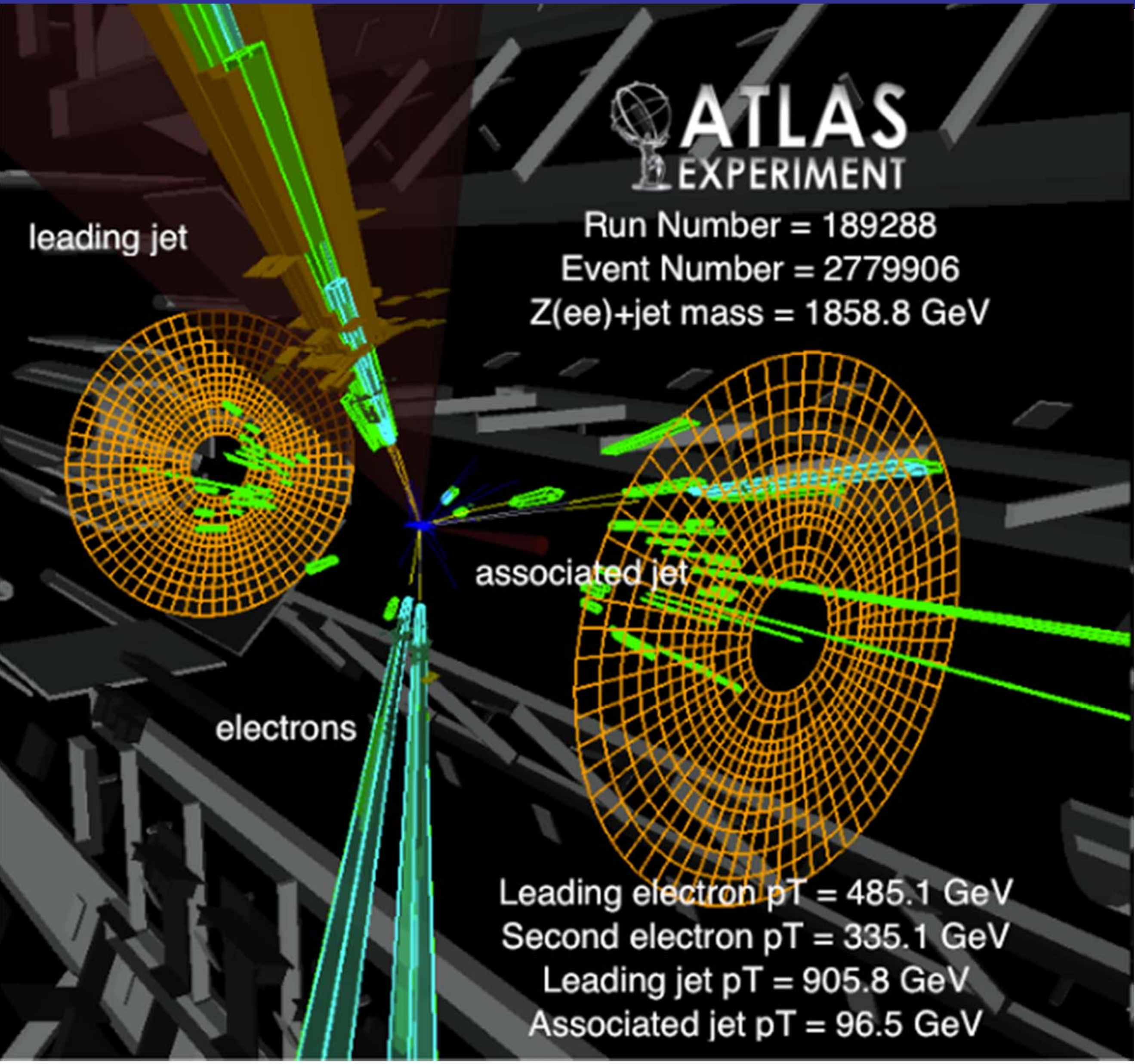
Exotics Searches at LHC



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Acknowledgement

- Hitoshi Murayama,http://arxiv.org/abs/0704.2276v1
- Lykken, http://arxiv.org/pdf/1005.1676.pdf
- CERN 2012 summer school

Discussions with

- Henri Bachacou
- Bryan Lynn
- Christophe Grojean
- Glenn Starkman
- Steven Worm

Outline....

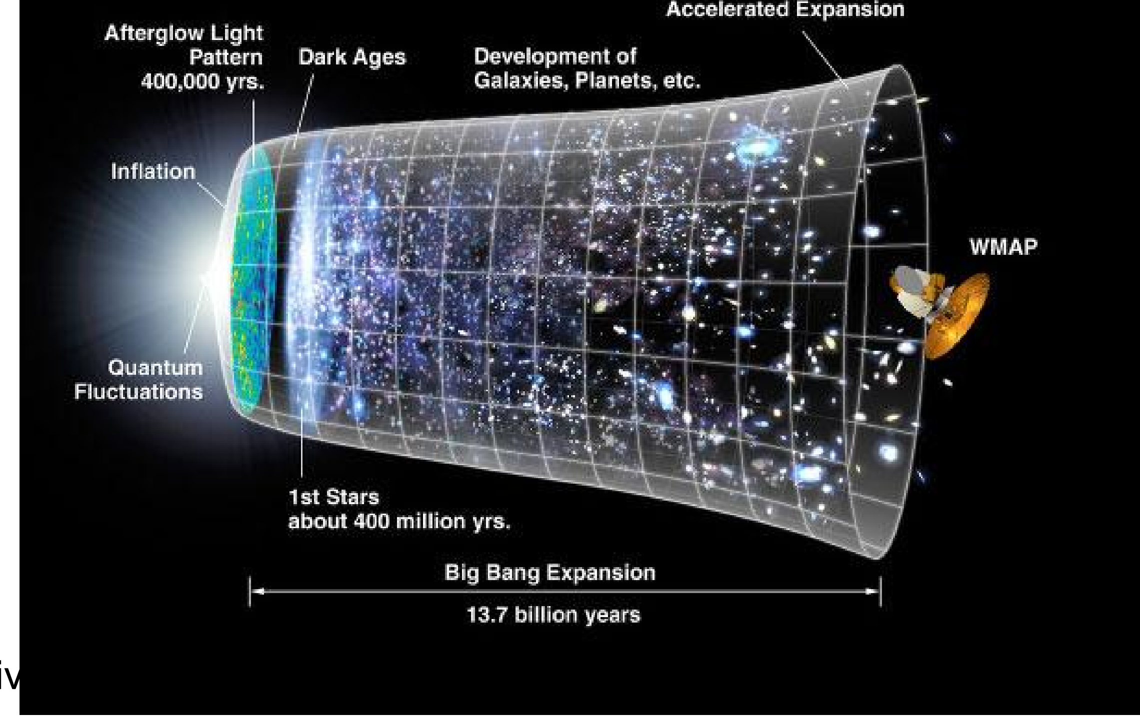
- Why search for new physics?
- What are Exotics Searches?
- Examples of Searches

Why search for new physics?

- We are **reSEARCHers**
- We strive for **new understandings**
- Our goal is to increase our **KNOWLEDGE**
- Inspiring, humbling,

  exciting,

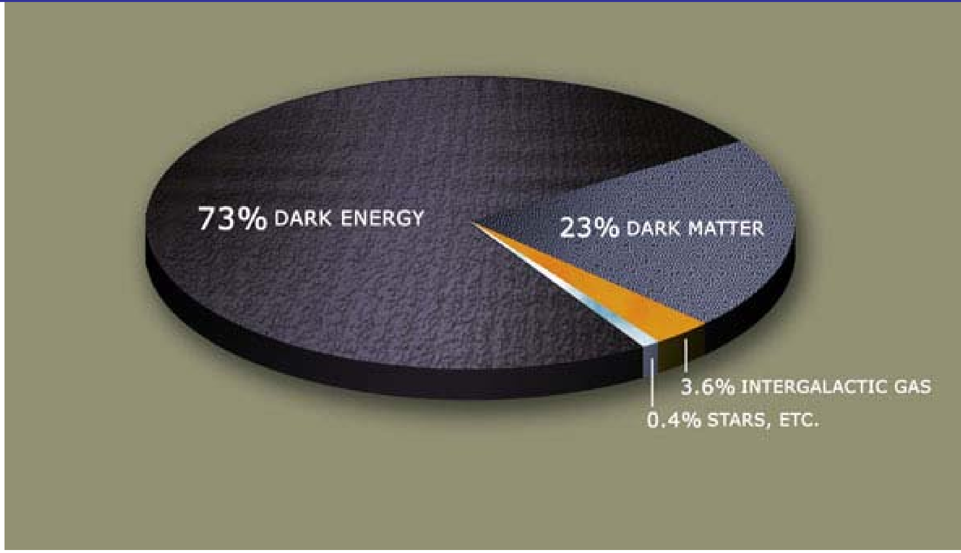
  FUN

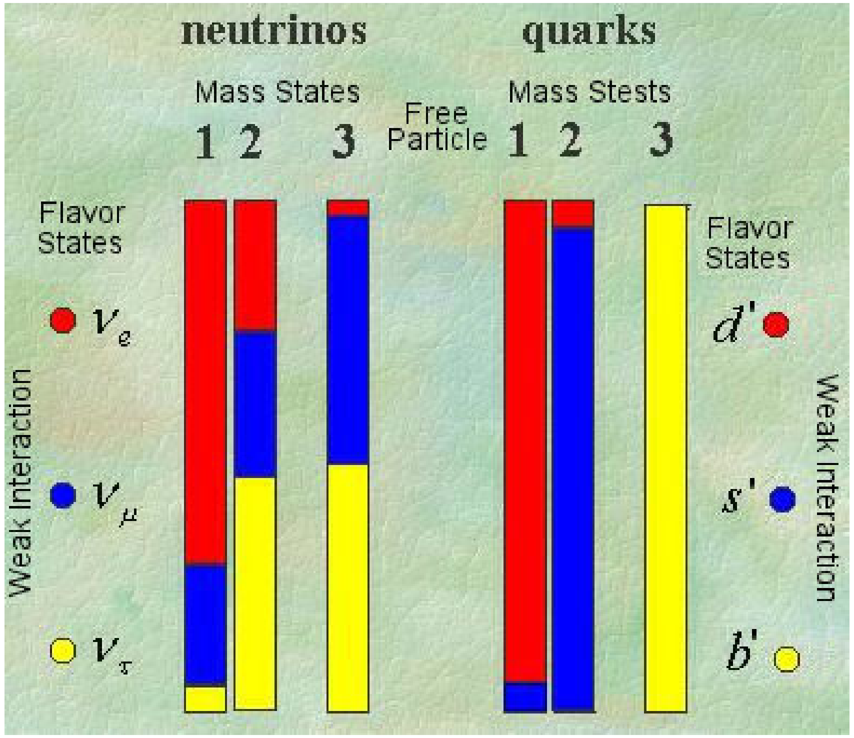


and a LOT of work.....

Why look beyond the Standard Model?

- Experimental Evidence
  - **Non-baryonic dark matter (~23%)**
    - Inferred from gravitational effects
    - Rotational speed of galaxies
    - Orbital velocities of galaxies in clusters
    - Gravitational lensing
    - …..
  - **Dark Energy (~73%)**
    - Accelerated Expansion of the Universe
  - **Neutrinos have mass and mix**
  - **Baryon asymmetry**
  - **Acausal density perturbations**





Standard Model Lagrangian

$$\mathcal{L}_{SM} = -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{2g^2} \mathrm{Tr}(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2g_s^2} \mathrm{Tr}(G_{\mu\nu} G^{\mu\nu})$$
$$+\bar{Q}_i i \not{D} Q_i + \bar{L}_i i \not{D} L_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{e}_i i \not{D} e_i$$

Above: Describes gauge fields and interactions

$\not{D}$ determined by **gauge quantum numbers**

strange

Gravity is not included!!

	$SU(3)$	$SU(2)$	$U(1)$	chirality
Q	3	2	$+1/6$	left
U	3	1	$+2/3$	right
D	3	1	$-1/3$	right
L	1	2	$-1/2$	left
E	1	1	-1	right

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$$+(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + \mathrm{h.c.})$$

- Responsible for mass and mixing of quark masses
- Responsible for charged lepton masses
- Generation index: i, j = 1,2,3
- Why 3 families?
- No neutrino masses or mixing included

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θ term in QCD

Periodic: 0 - 2π

Violates T and CP

Strong CP Problem in SM

- Why is $\theta < 1.2 \times 10^{-10}$???
- Natural value ~ 1

Standard Model Lagrangian

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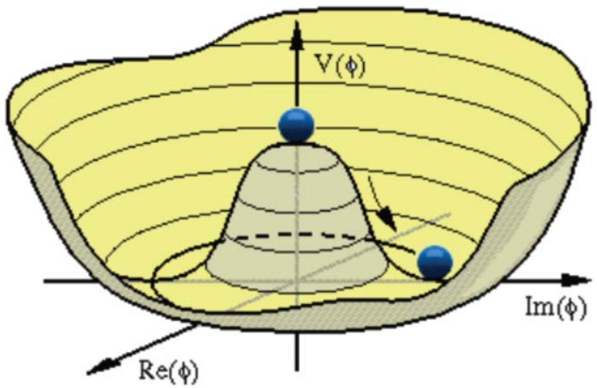
Higgs field

$$m_H = \sqrt{\lambda/2}vev$$

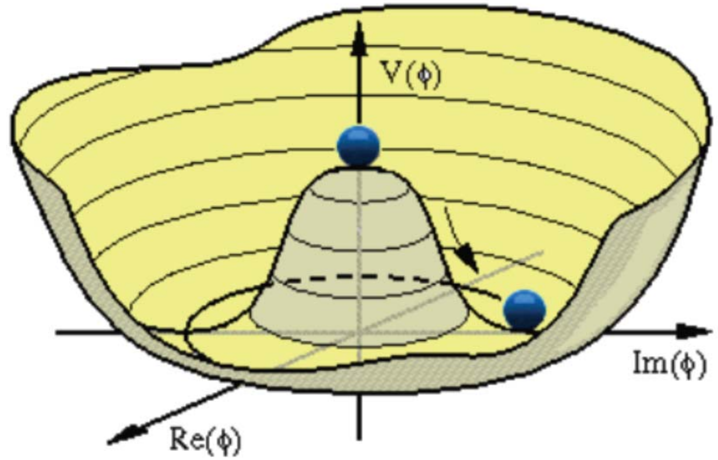


λ self coupling constant

vev = vacuum expectation value

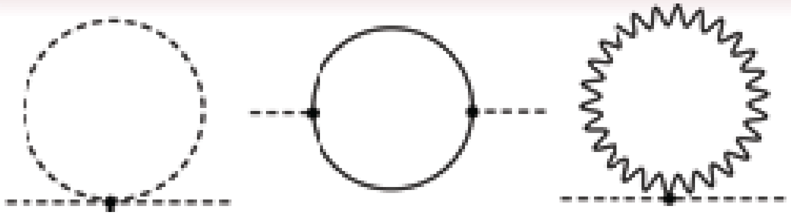
The Higgs is an EXOTIC particle

- ONLY spin 0 elementary particle
- Couplings are NOT dictated by gauge symmetry
  - Hmm….
- Symmetry breaking
  - Underlying reason?
  - Unable to explain dynamical



- Small mass possible if protected by
  - Symmetry
  - Not elementary particle

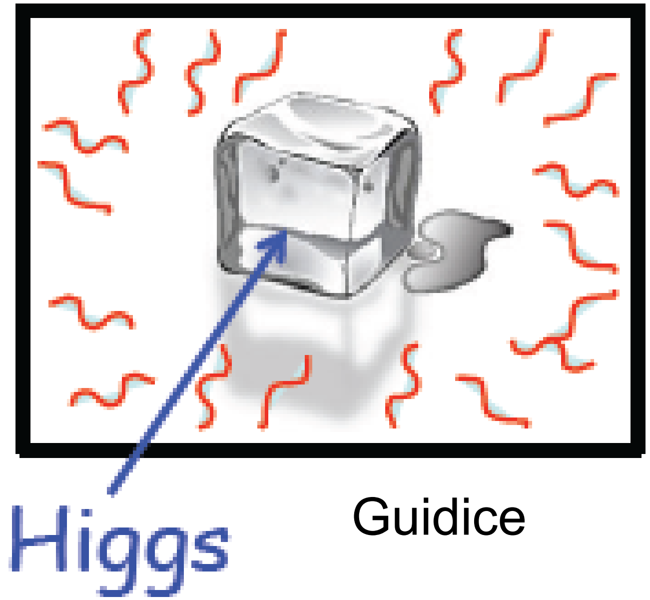
Comment to Fine Tuning….



G. Servant $\Rightarrow \delta M_H^2 \propto \Lambda^2$

4 ways to solve it

- Supersymmetry
  - Sparticles cancel particle contributions
- Extra Dimensions
  - Higgs is a vector in 5D
- Higgs is composite
  - Strongly coupled new physics
- There is no fine tuning problem in SM
  - *Not everybody thinks SM has a fine tuning problem*
    http://arxiv.org/pdf/1306.5647.pdf



Guidice

Higgs sector looks like a provisional structure

Courtesy of C. Grojean & A. Weiler, 7

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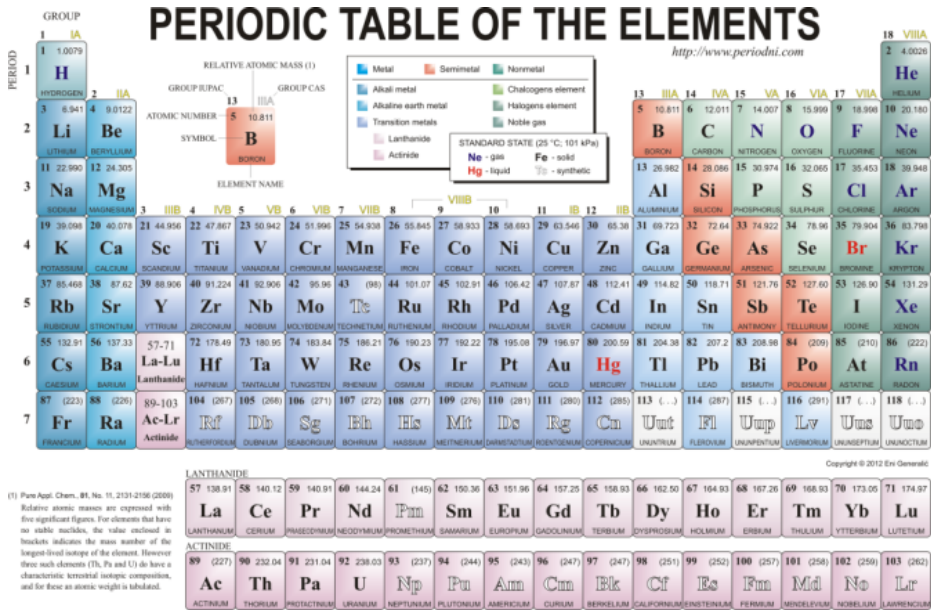
Only term in L_{SM} with a dimensionful parameter

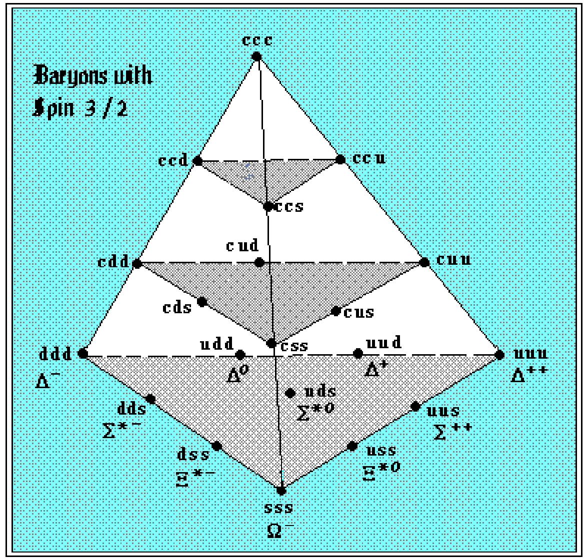
Sets the energy scale for the SM: VEV ~ 246 GeV

History suggests…..

- Fundamental theory at <u>shorter distances </u>than distance scale of the problem.
- **~1900** reached atomic scale
  - 10^{-8} cm $\approx \hbar^2/e^2 m_e$
  - Quantum Mechanics
  - Quantum Electrodynamics



- **~1950** reached strong interaction scale
  - **10^{-13} cm $\approx M e^{-8\pi^2/g_s^2(M) b_0}$**
  - **QCD**
  - **Quarks, Gluons**



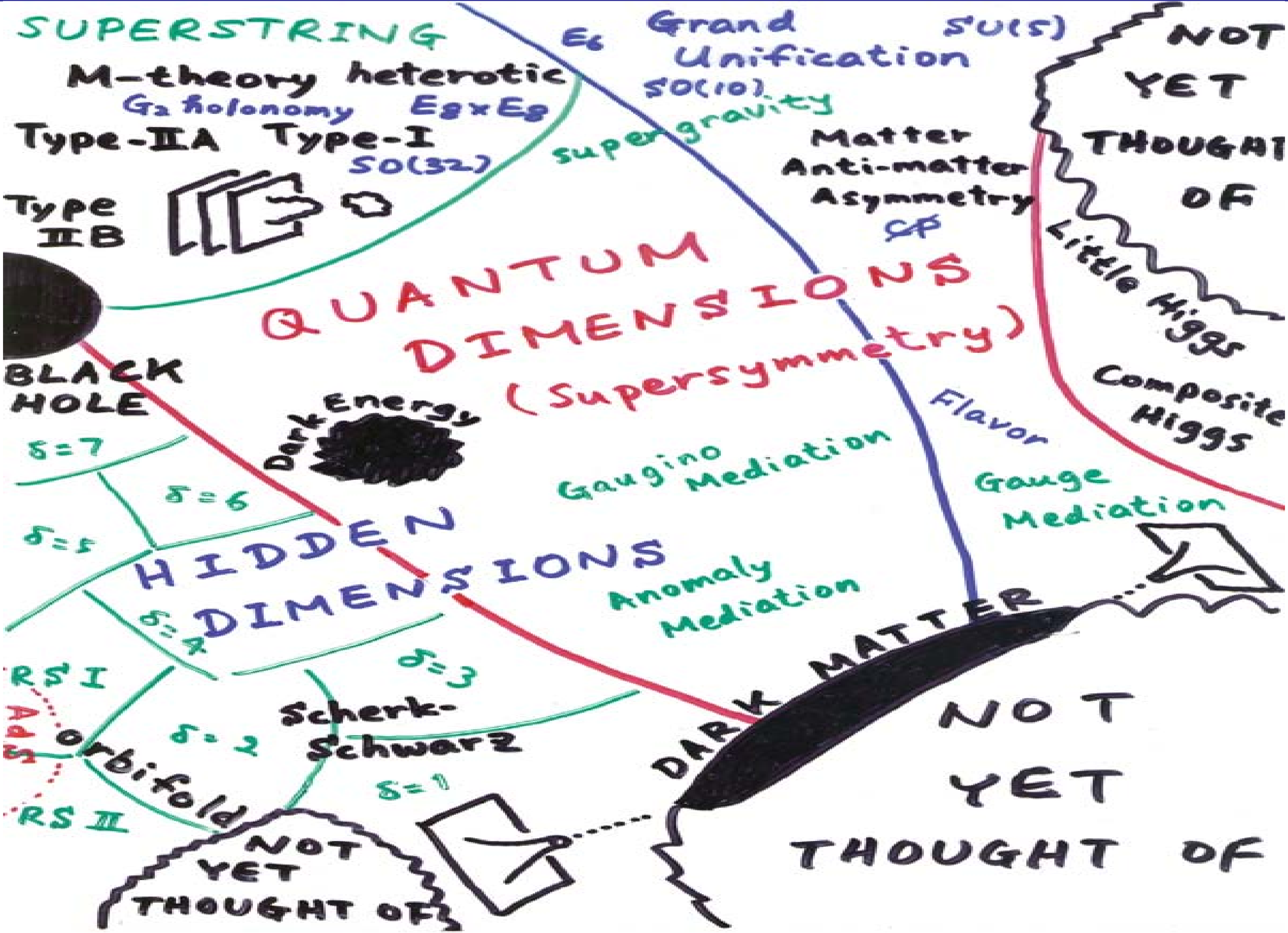
Today….Very Special Times

- LHC goes beyond EWK scale: $TeV^{-1} \sim 10^{-17}$ cm
- EWK scale: phase transition is happening
  - W,Z,electron…etc. acquire mass
- $v = (\sqrt{2}G_F)^{-1/2} \sim 246\ GeV$ ← Higgs VEV
  - <u>This is the scale of SM!</u>
  - Beyond this we will find **NEW INSIGHTS!!!!**

Why look beyond the Standard Model???

- Aesthetic/Theoretical Reasons
  - Hierarchy Problem:
    - why is $G_F \sim 10^{-5}$ GeV^{-2} << $G_N \sim 10^{-38}$ GeV^{-2}
  - Quantum gravitational description of Gravity?
    - Gravity is not included in SM
  - Higgs
  - ….
- Experimental Reasons
  - Dark Matter/Energy
  - Neutrino masses
  - Baryon Asymmetry
  - …..

Models



Murayama Hitoshi

What else is there beside SUSY framework?

- SUSY is NOT a model
  - "Symmetry principle characterizing a BSM framework with an infinite number of models"….Lykken
- SUSY is only one possible way…..
  - Many more ways to solve problems with Standard Model
  - What if nature has not chosen SUSY?
  - Make sure to cover every feasible corner…
- SUSY mass limits pushed to 1 TeV
  - SUSY becoming more "Exotic" the higher the mass limits get.

Models try to answer questions

- Hierarchy Problem
  - EWK force ~ 10^{32} X Gravity?

  → Extra dimension models
- Fine Tuning Problem

  → SUSY

  → Composite Higgs

  → Extra dimension models
- What is Dark Matter?

  → SUSY

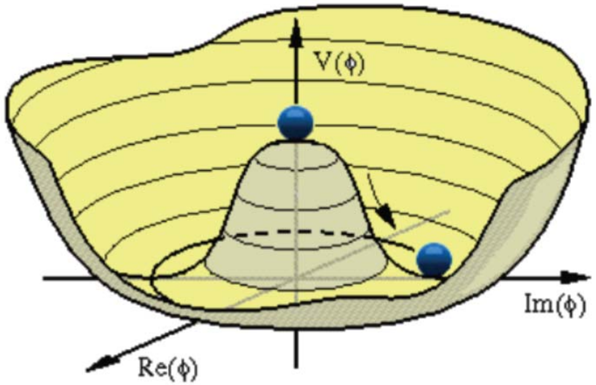
  → Extra dimensions….
- Family structure in SM?
- Running coupling constants?

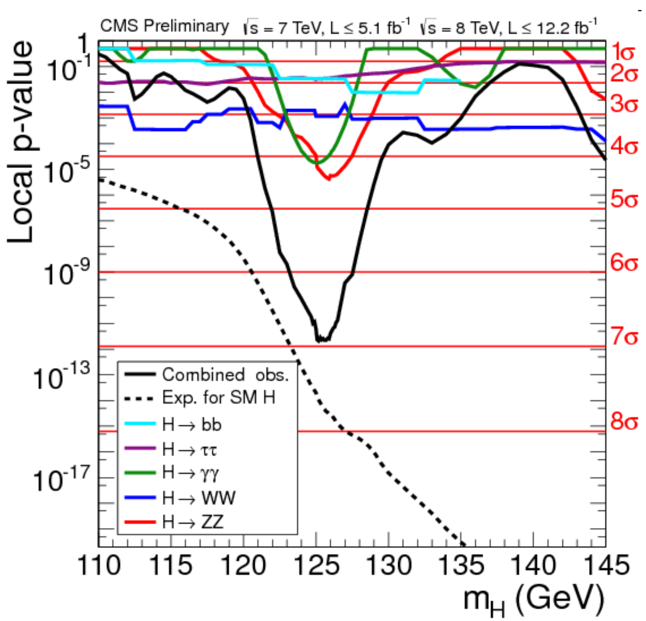
  → GUT
- Have elementary particles a sub-structure?
- …..

Not all questions may be sensible..

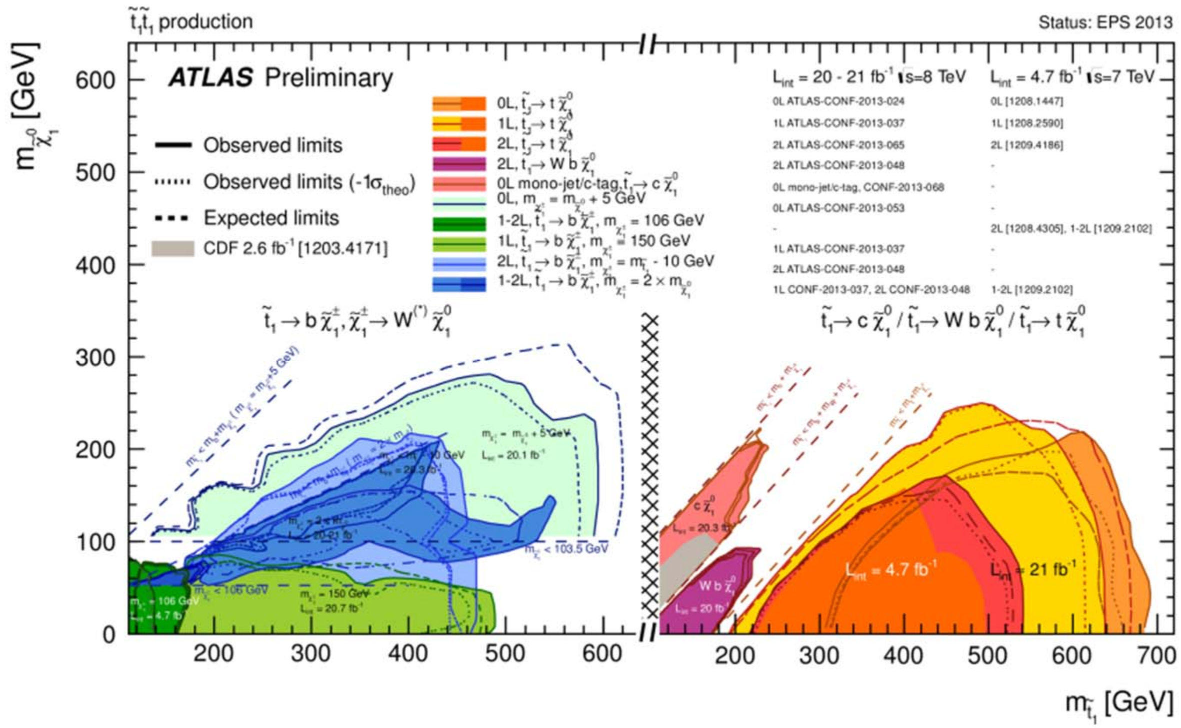
What Characterizes Exotics Searches?

- No specific Model to guide us.

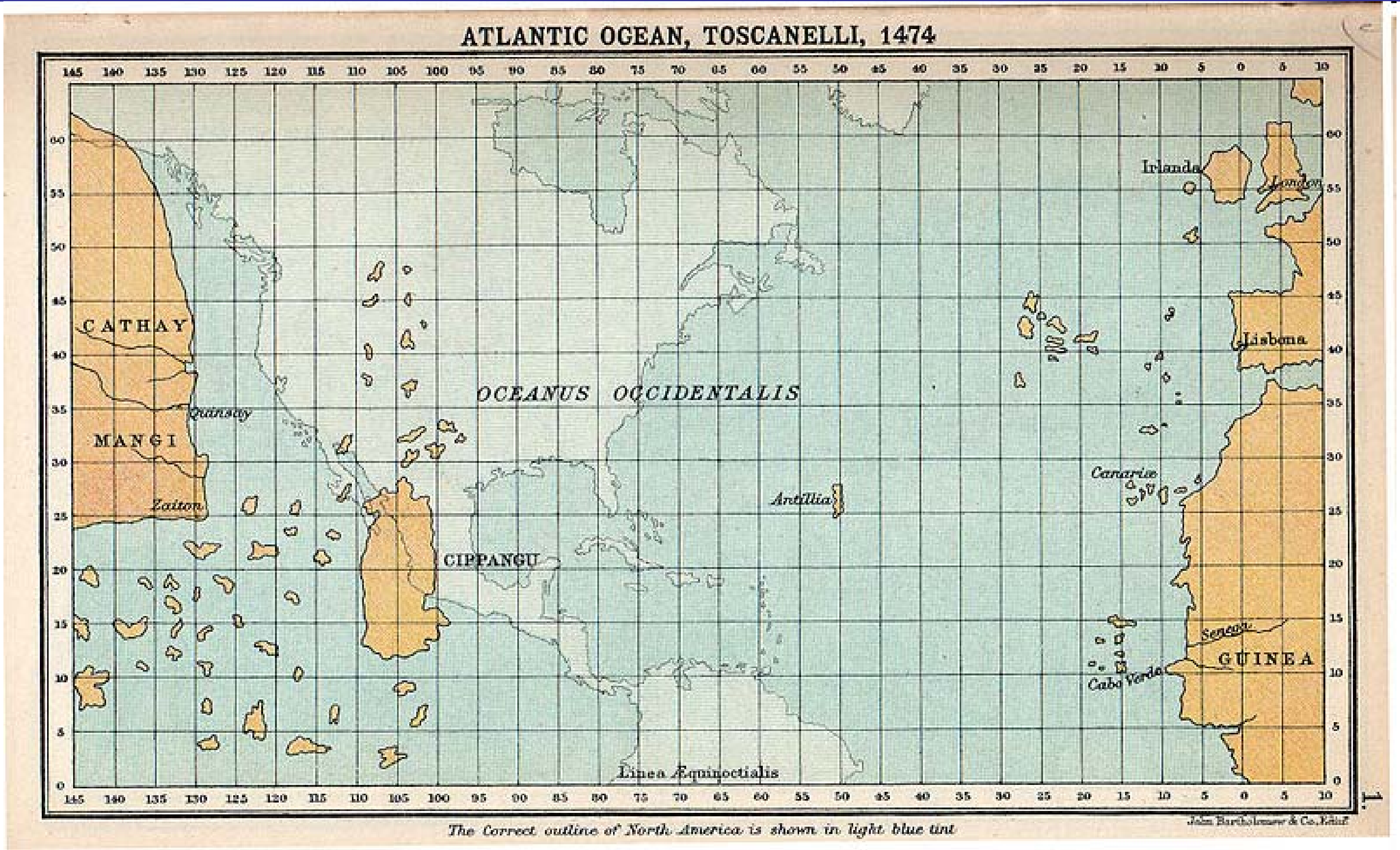




- No unified parameter phase space to map results

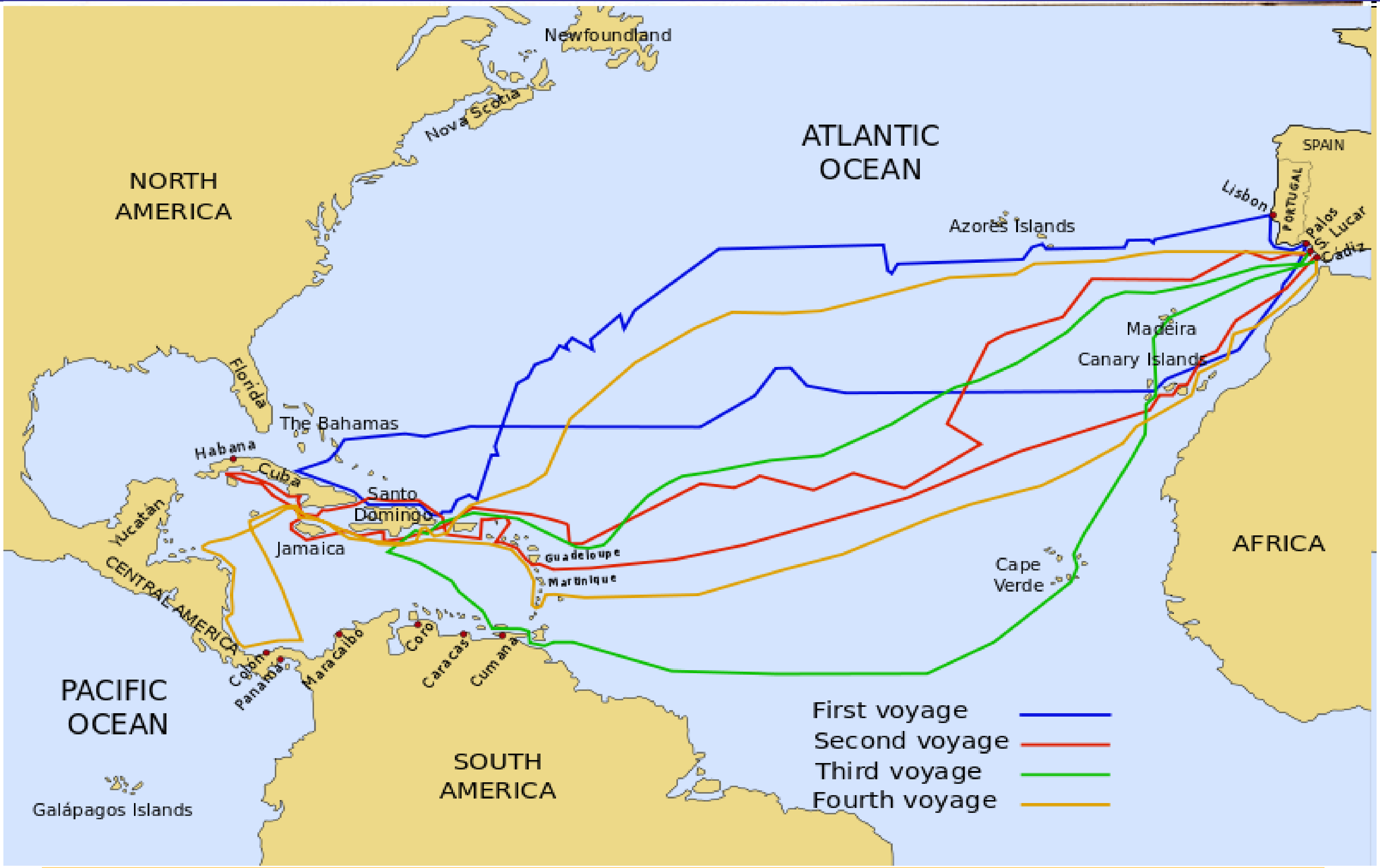


The Role of Models in “most” Exotics Searches



Toscanelli's model of the geography of the Atlantic Ocean, which directly influenced Columbus's plans

The Role of Models in “most” Exotics Searches



Columbus’ Voyages

The Role of Models in "most" Exotics Searches

- Models used to quantify our reach.
  - How far did we get?
  - How do we compare to previous searches?

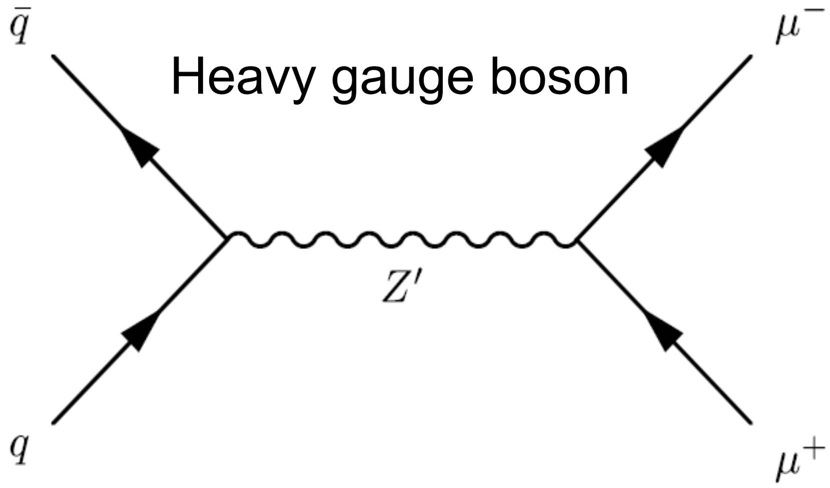
- We use so called Bench Mark Models
  - Used before by other experiments

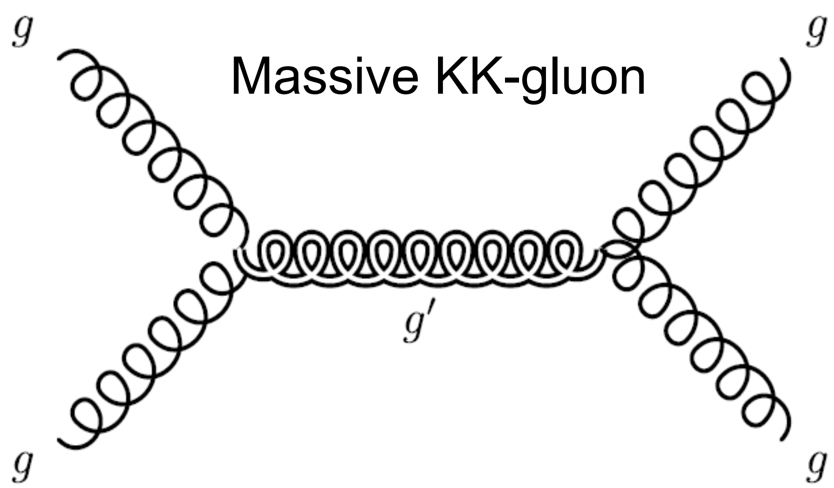
- Simplified Models or generic resonances

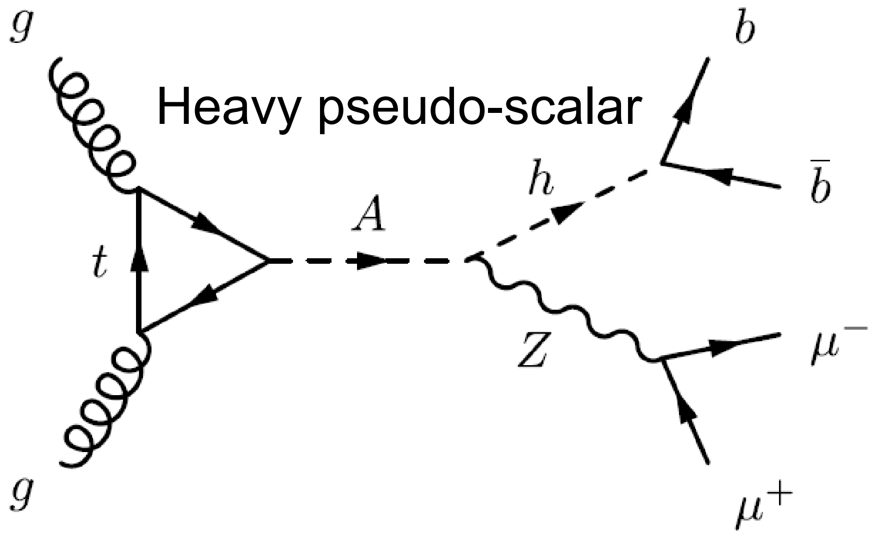
Exotics Search Signatures

Lykken, http://arxiv.org/pdf/1005.1676.pdf

- s-channel production



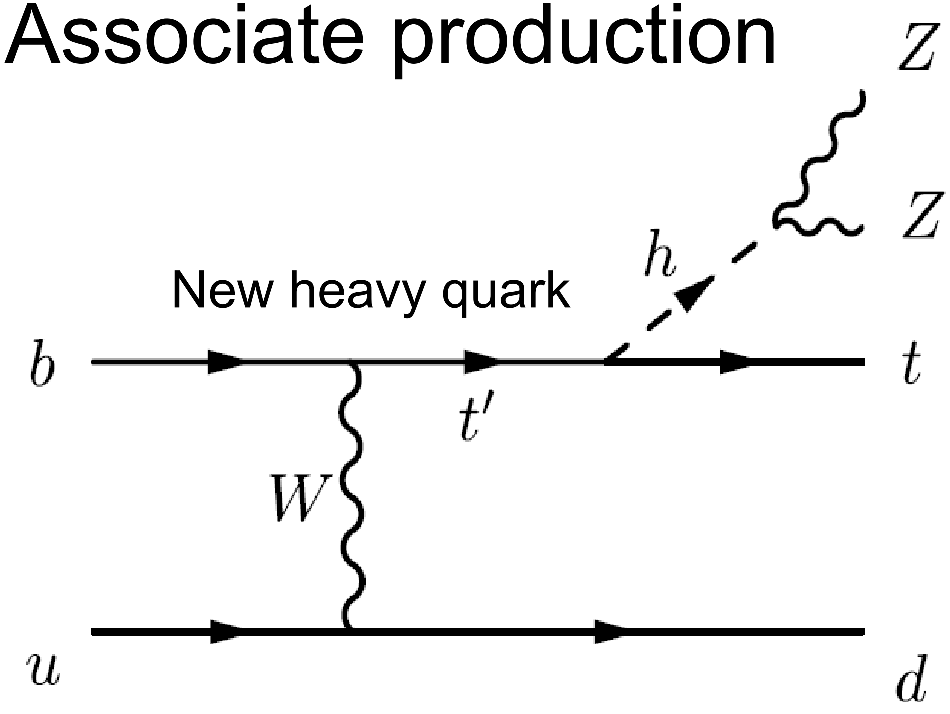




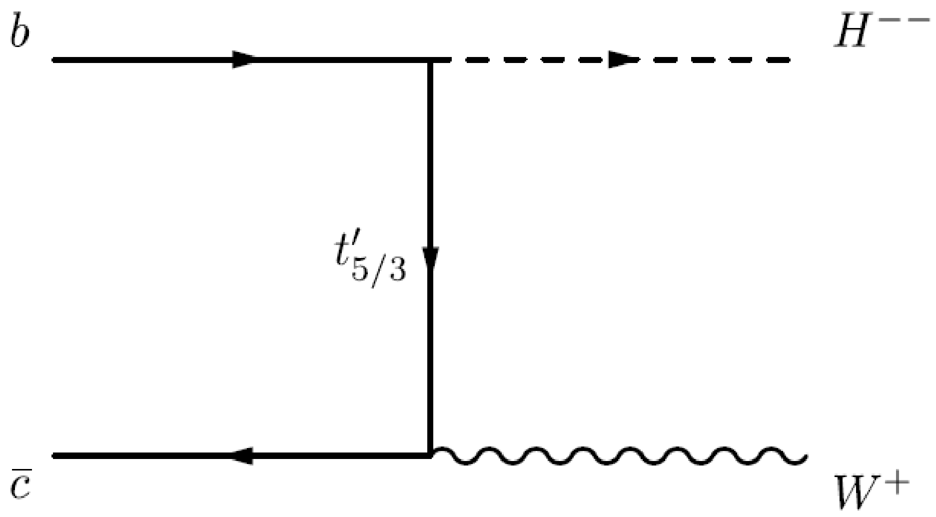
Exotics Search Signatures

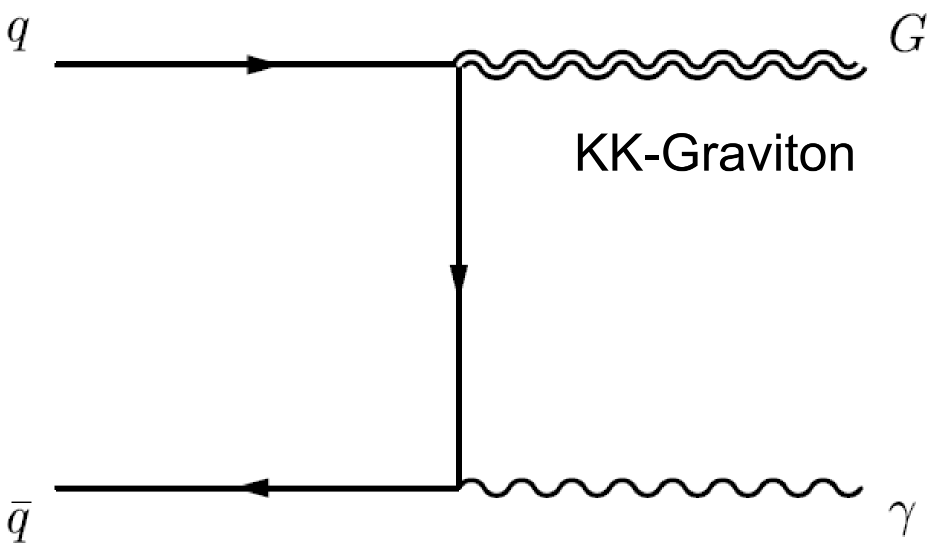
- Associate production

Lykken, http://arxiv.org/pdf/1005.1676.pdf



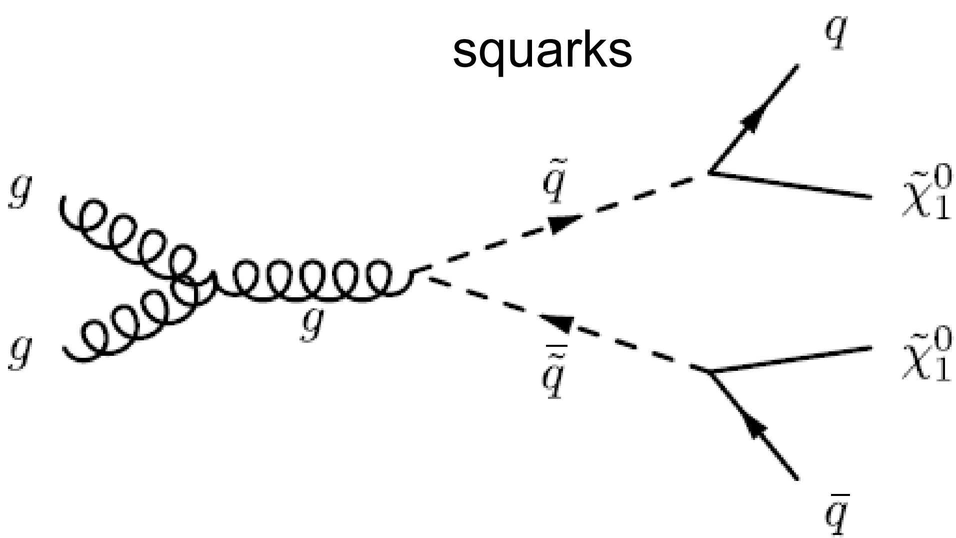
Doubly charged Higgs

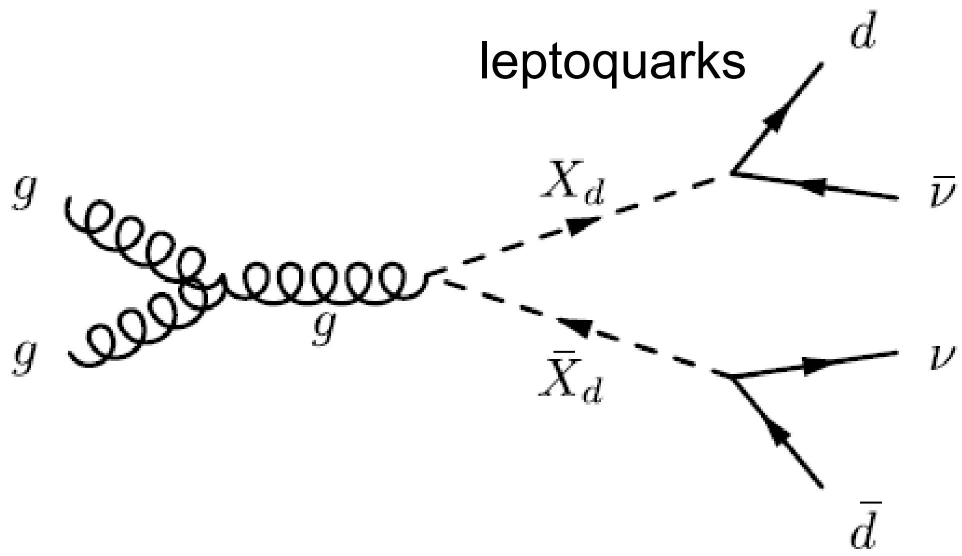




Lykken, http://arxiv.org/pdf/1005.1676.pdf

- Pair production

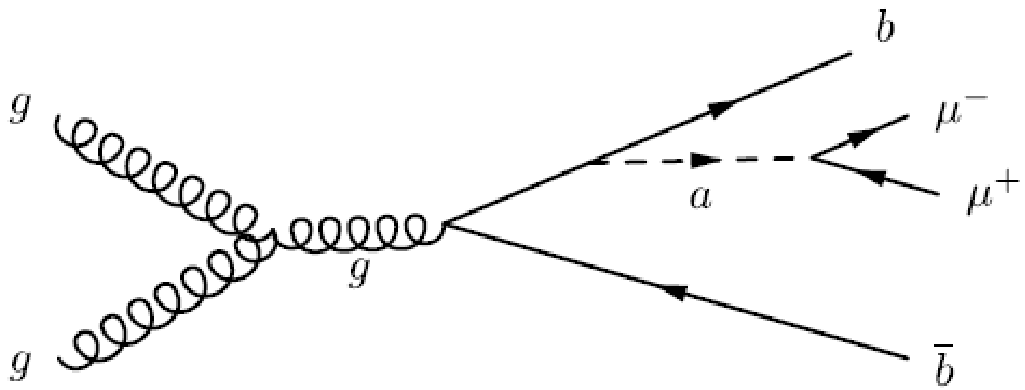


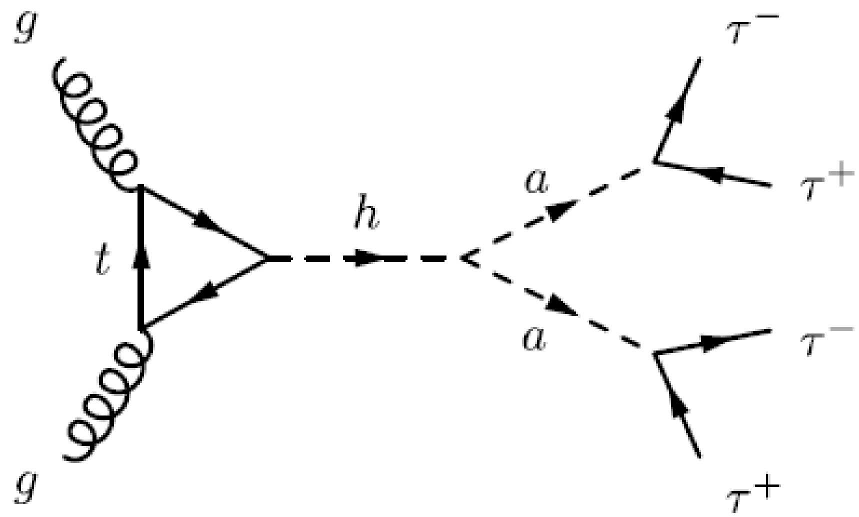


Exotics Search Signatures

Lykken, http://arxiv.org/pdf/1005.1676.pdf

- BSMstrahlung





Pseudo-scalar

Models-Signature Mapping and vice versa.

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- What else?

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- What else?

H. Bachacou

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A complex 2D problem

Experimentally, a signature standpoint makes a lot of sense:

→ Practical

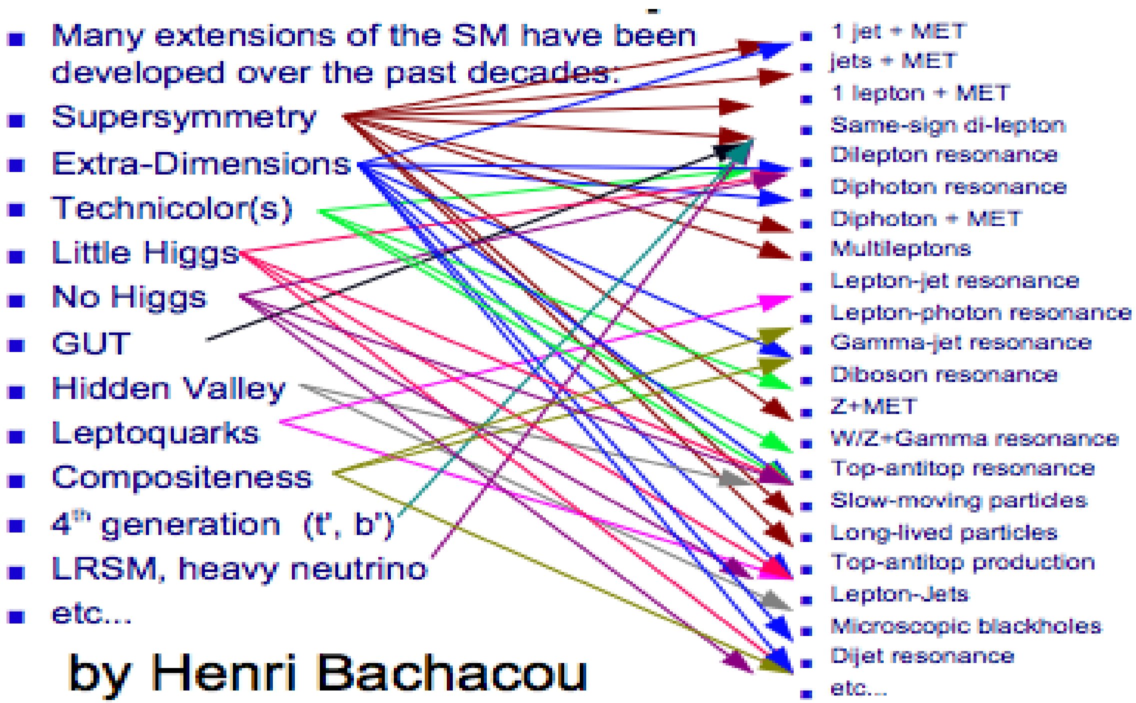
→ Less model-dependent

→ Important to cover every possible signature

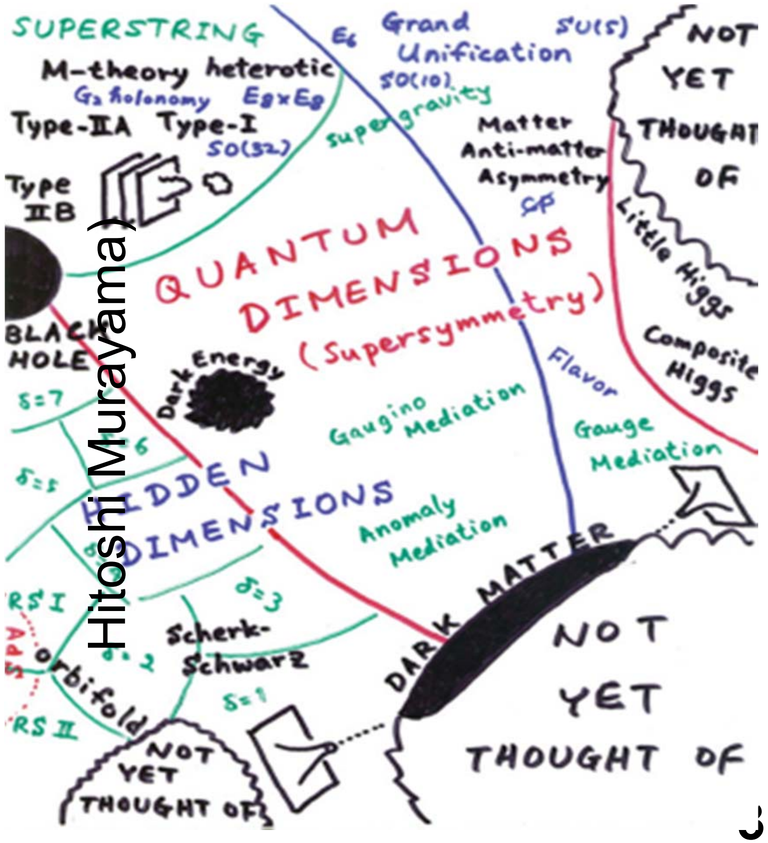
H. Bachacou

What Characterizes Exotics Searches?

- Exotics Search Strategy
  - Cover wide range of final states
  - Largely Model independent
    - Look for resonances
    - Look for any disagreement from expectations
  - Cover interesting new BSM models



by Henri Bachacou



Hitoshi Murayama)

How do you search for the UNKNOWN?

You look everywhere for any deviation…

Basic Principles of Exotics Searches

- Identify your discriminant!

- Most important: Robust background estimation!

- Biases ?
  - Blind analysis ← not appropriate at LHC
  - Control regions

- Trade-off between Signal and Background
  - Do NOT optimize towards a specific model
  - Selection cuts defined by triggers and background reduction.

Basic Principles of a Search

- You have a background estimate…what now?
- Check if data agrees with this expectation.
- If it does not agree…
  - Is the significance increasing with more data?
  - Look at time dependences...
  - Cross checks….
  - Discovery if significance is greater than 5 sigma.

- If it does agree….
  - How far did we explore the new physics phase?
  - Use models to quantify the search reach.
  - Useable for others (publish acceptance and efficiencies)

.

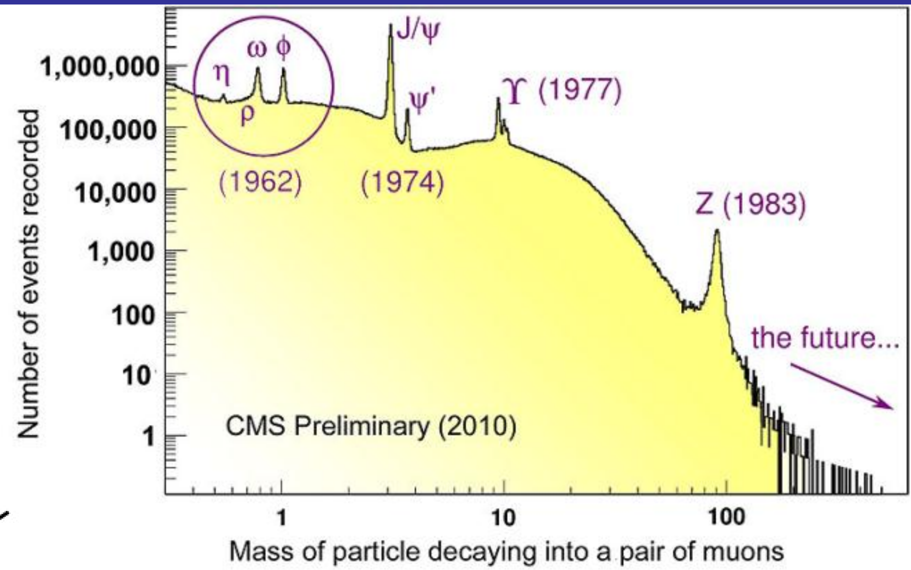
Show some typical search examples

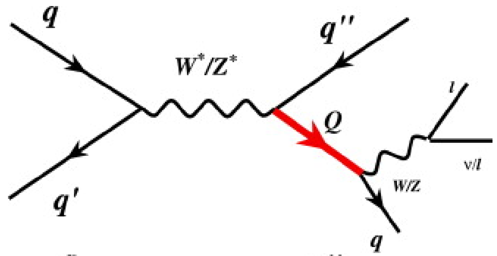
“What is the impact of the newly discovered boson on Exotics searches at the LHC?”

8 TeV Results

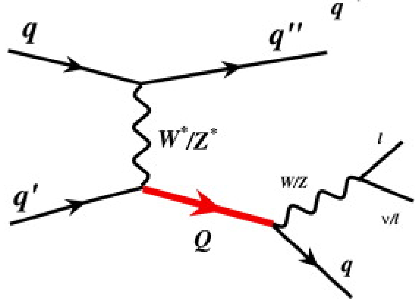
Exotics Searches

- **Heavy resonances**
  - **Dileptons**
  - **Dijets**
  - **Ttbar**





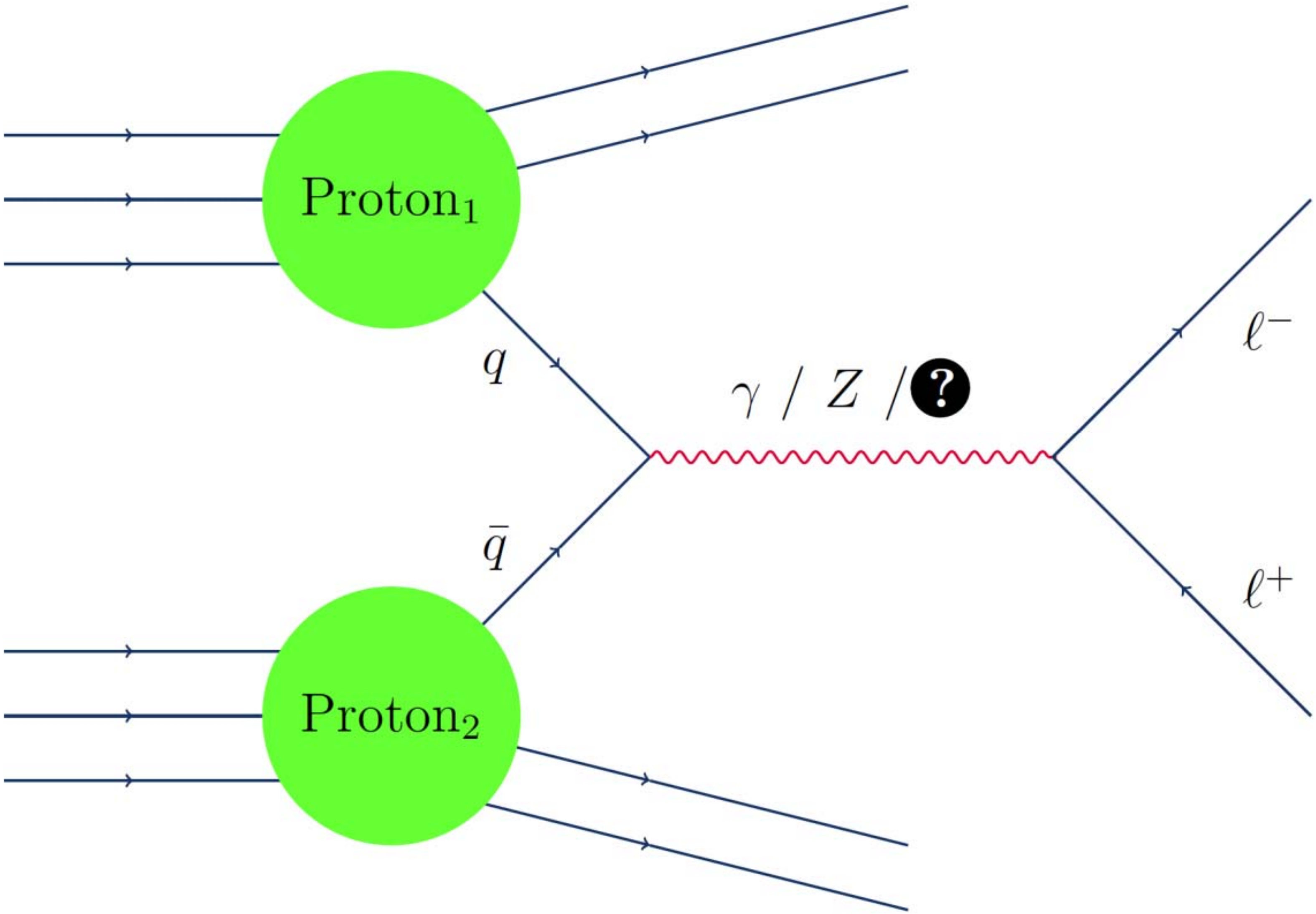
- **Vector-like quarks**



- **Dark matter and extra dimension**

Dilepton Resonance Search

Noam Tal Hod
CERN-THESIS-2012-155

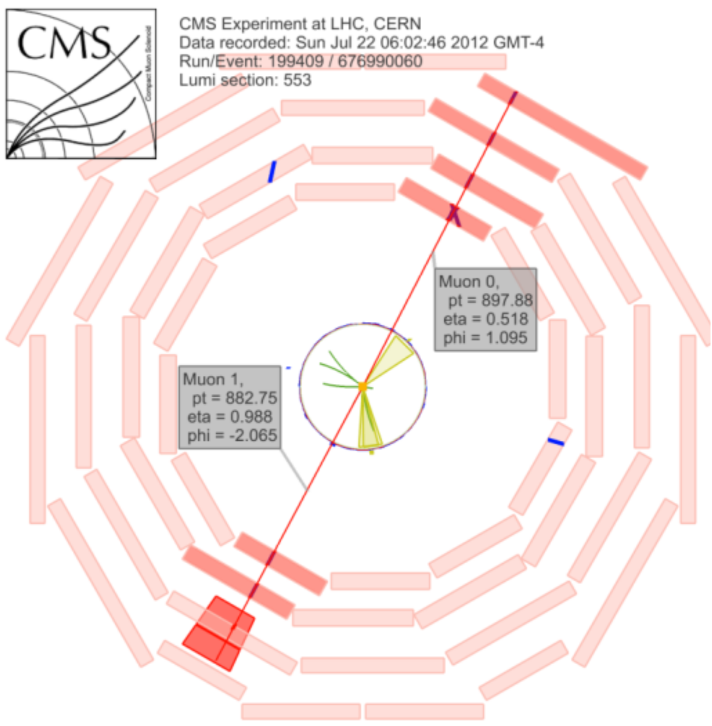


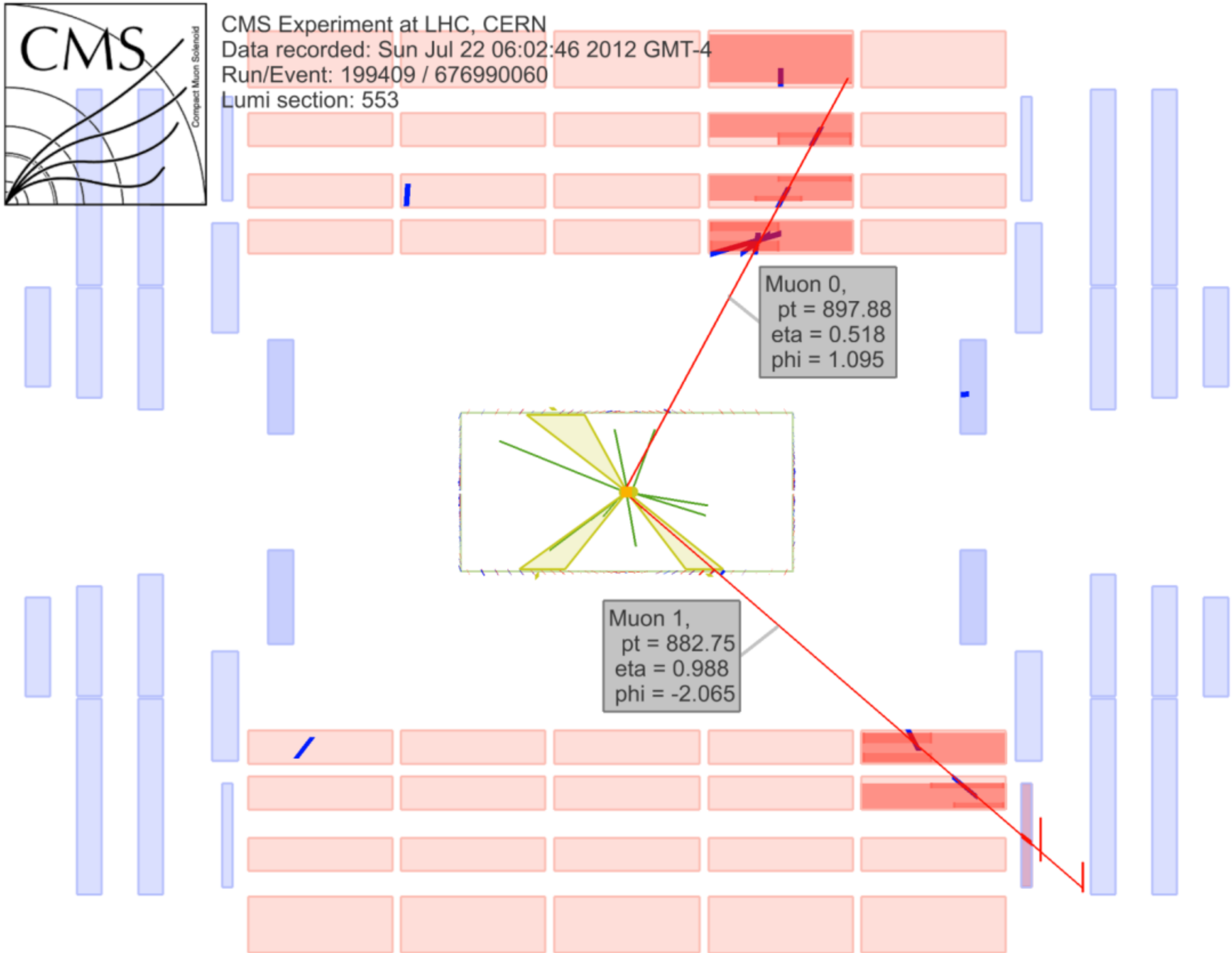
Dilepton Resonance Search

ATLAS-CONF-2013-017
PAS EXO-12-061

- Models:
  - Little Higgs → heavy gauge boson(s) (**Z'**/W')
  - GUT-inspired theories → heavy gauge boson(s) (**Z'**/W')
    - Strong and EWK force merged into one interaction
    - Described by higher symmetry group
      - Popular choices:
        - Left right symmetric models (SO(10))
        - E_6 symmetry models
  - Sequential Standard Model (SSM)
    - Z' carbon copy of Z^0 just heavier
    - Z' decays into any SM lepton-antilepton pair
    - decay into gauge bosons is suppressed by hand
    - not gauge invariant, not very realistic but
    - reference model
  - Randall-Sundrum ED → Kaluza-Klein graviton
  - Technicolor → narrow technihadrons

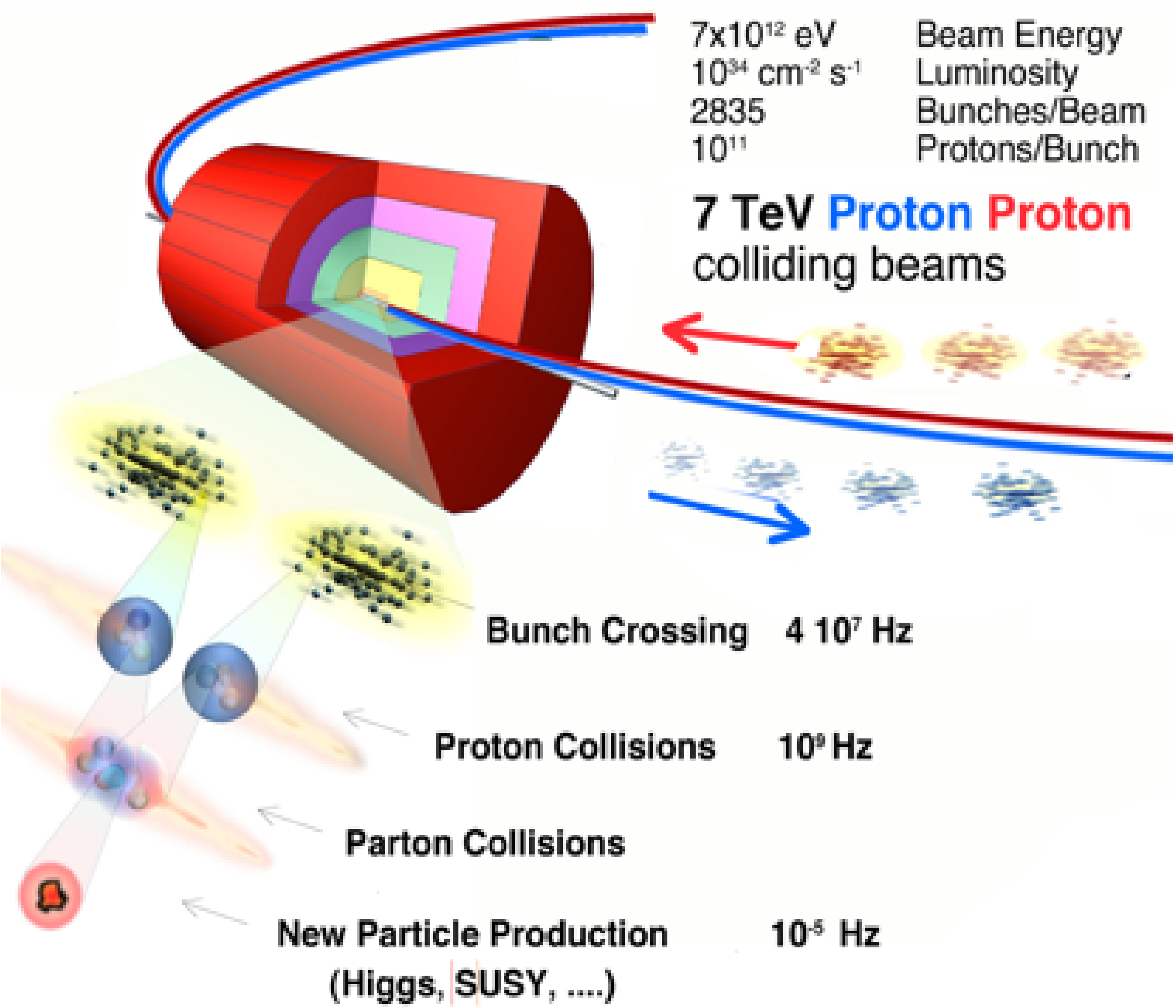
CMS Highest Dimuon Invariant Mass Event; 8 TeV





m_{inv} **= 1824 GeV**

Proton-Proton Collisions



Luminosity

- Single most important quantity
  - Drives ability to observe new rare processes

$$L = \frac{f * n_{bunch} * N_p^2}{4\pi * \sigma_x * \sigma_y}$$

- revolving frequency f = 11245.5/s
- n_{bunch} = 2808
- N_p = 1.15 x 10^{11} Protons/Bunch
- Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

- Rate of physics processes per unit time ~ L

$$N_{Obs} = \int L dt * \varepsilon * \sigma_{process}$$

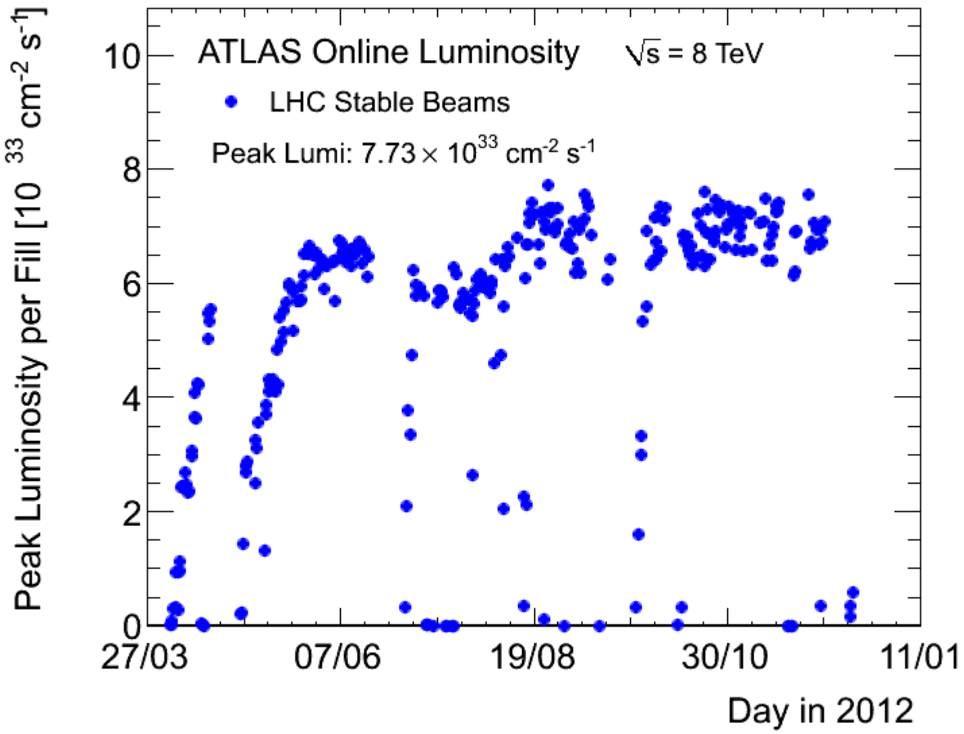
Cross section; given by nature; predicted by theory

Efficiency; optimized by experimentalists

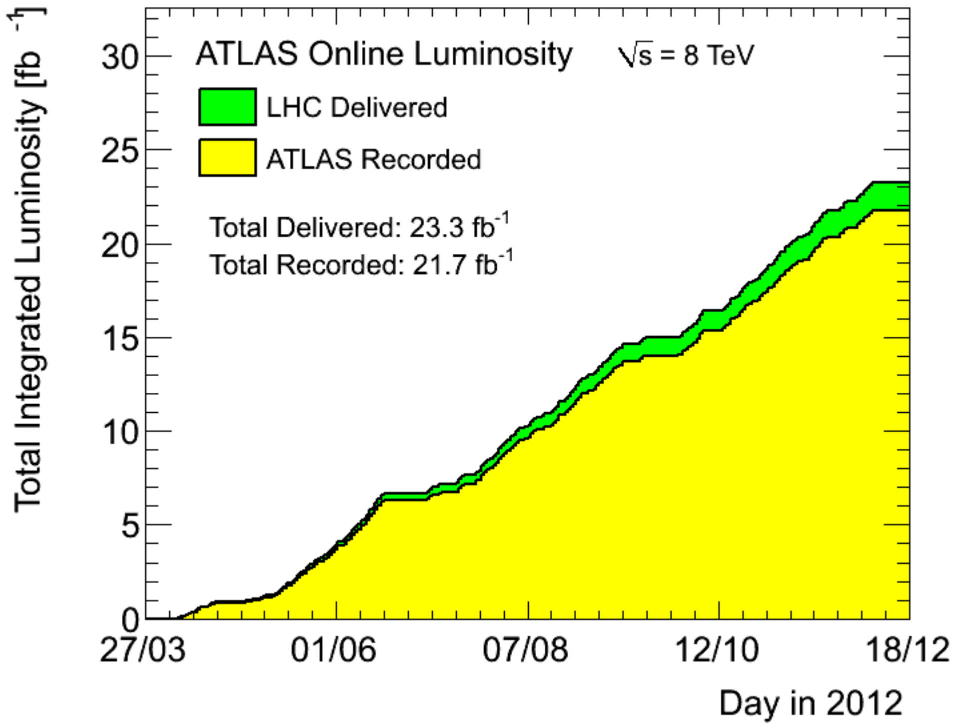
Maximize N_{obs} → max ε and L

Our data sample for 2012

Peak Luminosity in 2012



Integrated Luminosity in 2012



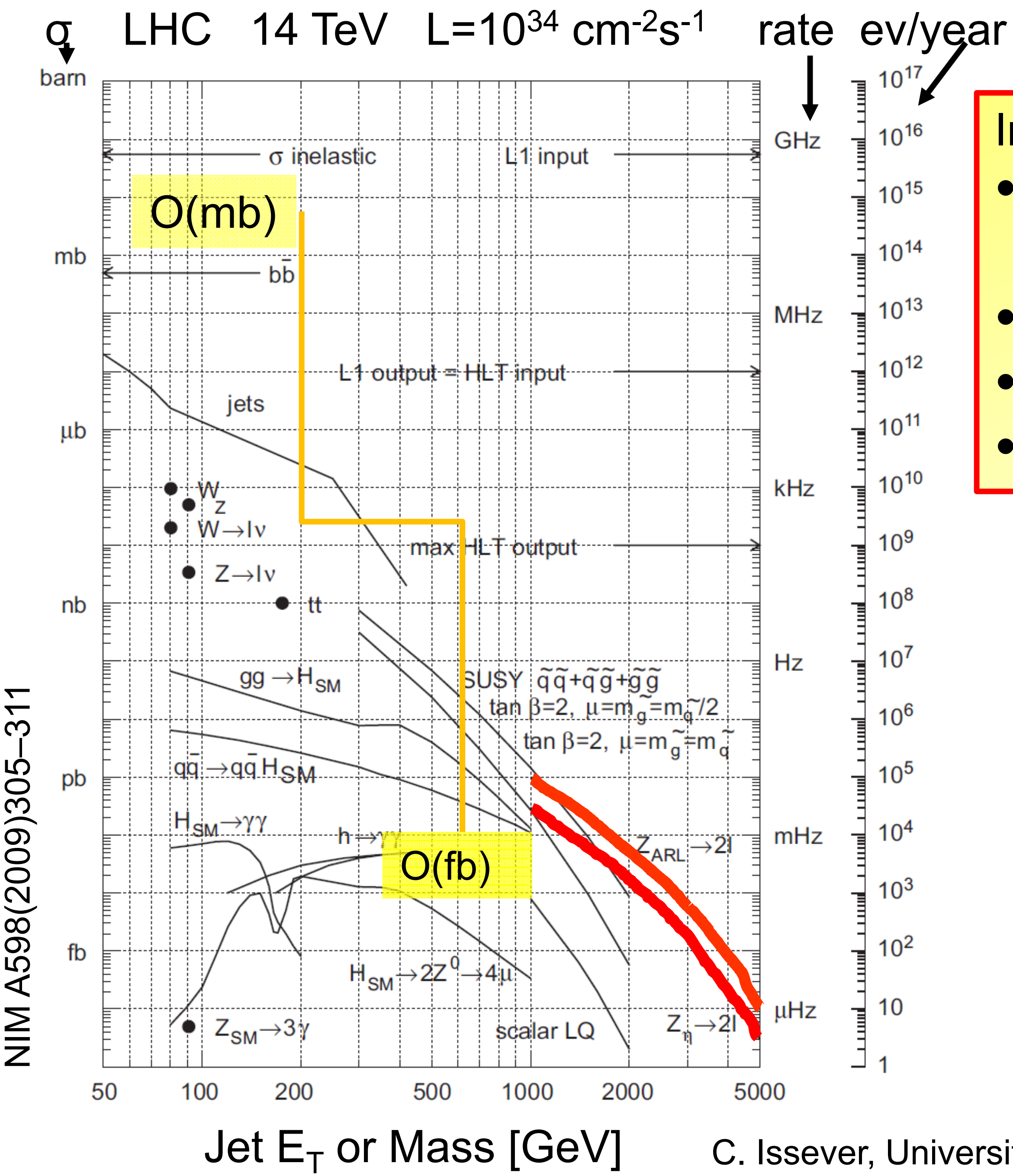
Delivered Integrated L: 23.3 fb^{-1}

Recorded Integrated L: 21.7 fb^{-1}

$1b = 10^{-24}\ cm^2$

$1fb = 10^{-39}\ cm^2$

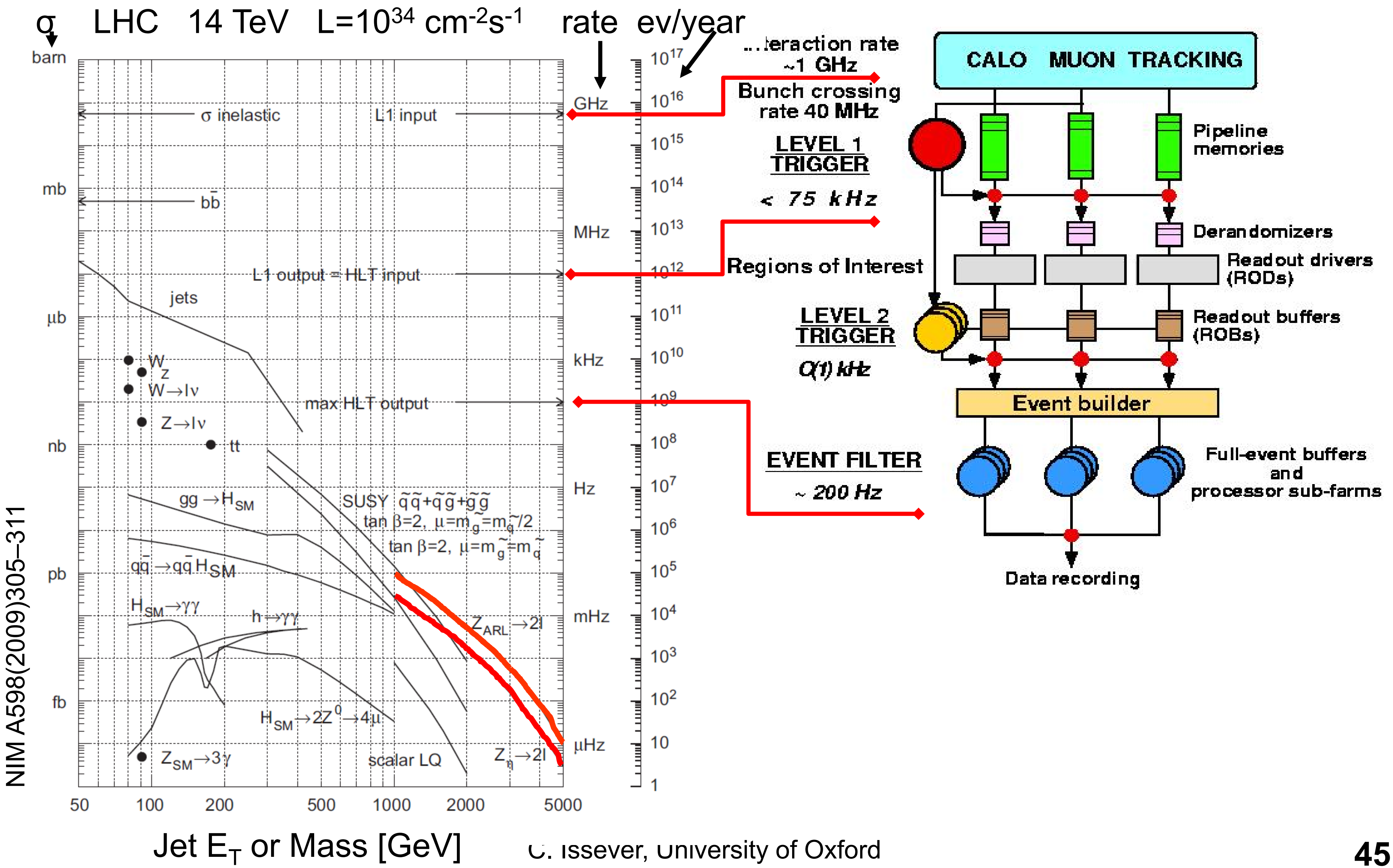
Rates of physics processes @ LHC



Interesting physics swamped by background

- Cross section for new physics:
  - $\sim 10^{12}$ times lower !!
- Need to filter → TRIGGER SYSTEMS
- Carefully decide what to record
- You do not have another chance

Compare this to rates of physics processes



Dilepton Resonance Search: Trigger Strategy

ATLAS

ee channel

- Diphoton trigger
- $E_T > 35$ GeV and $E_T > 25$ GeV

μμ channel

- Single muon triggers
- $E_T > 24$ GeV or $E_T > 36$ GeV

CMS

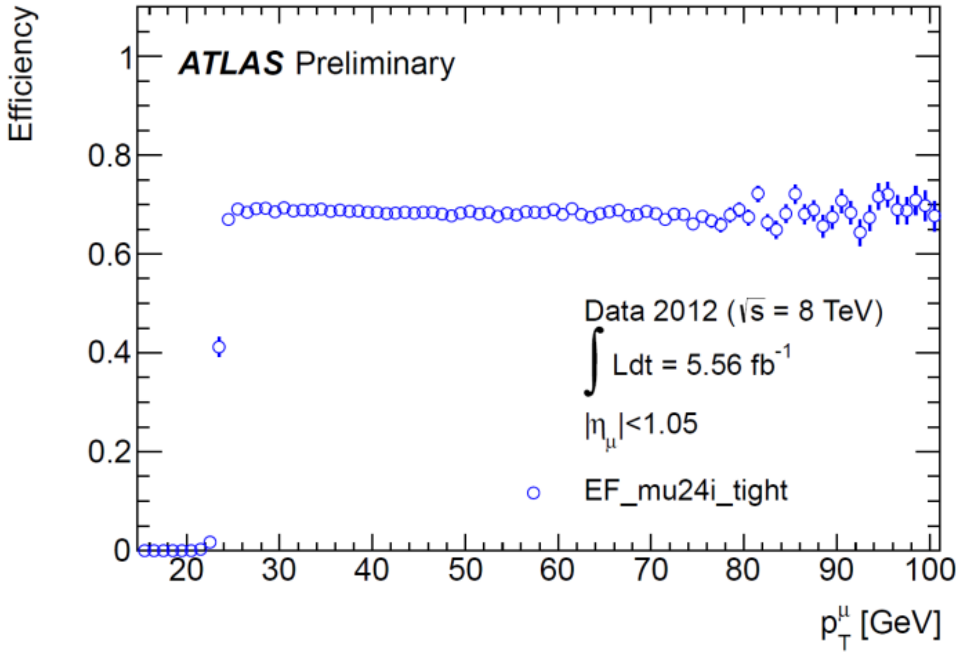
ee channel

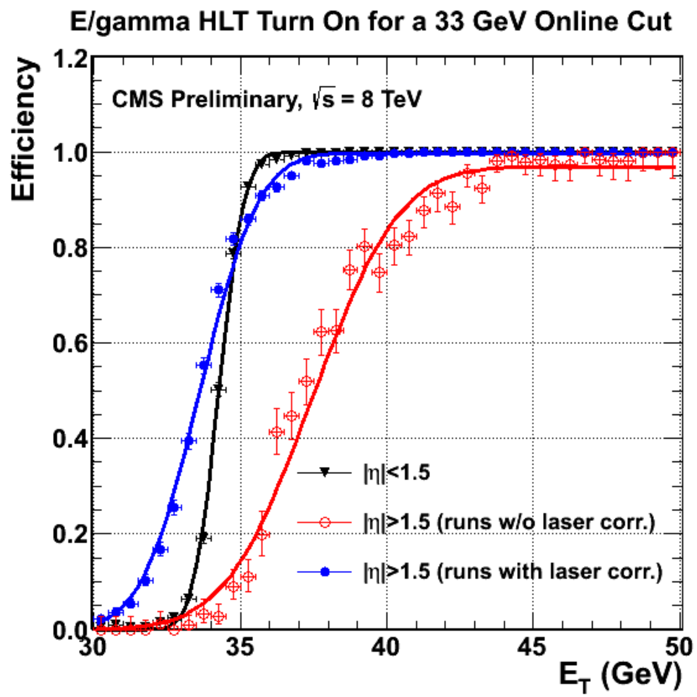
- Dielectron trigger
- Both clusters w $E_T > 33$ GeV

μμ channel

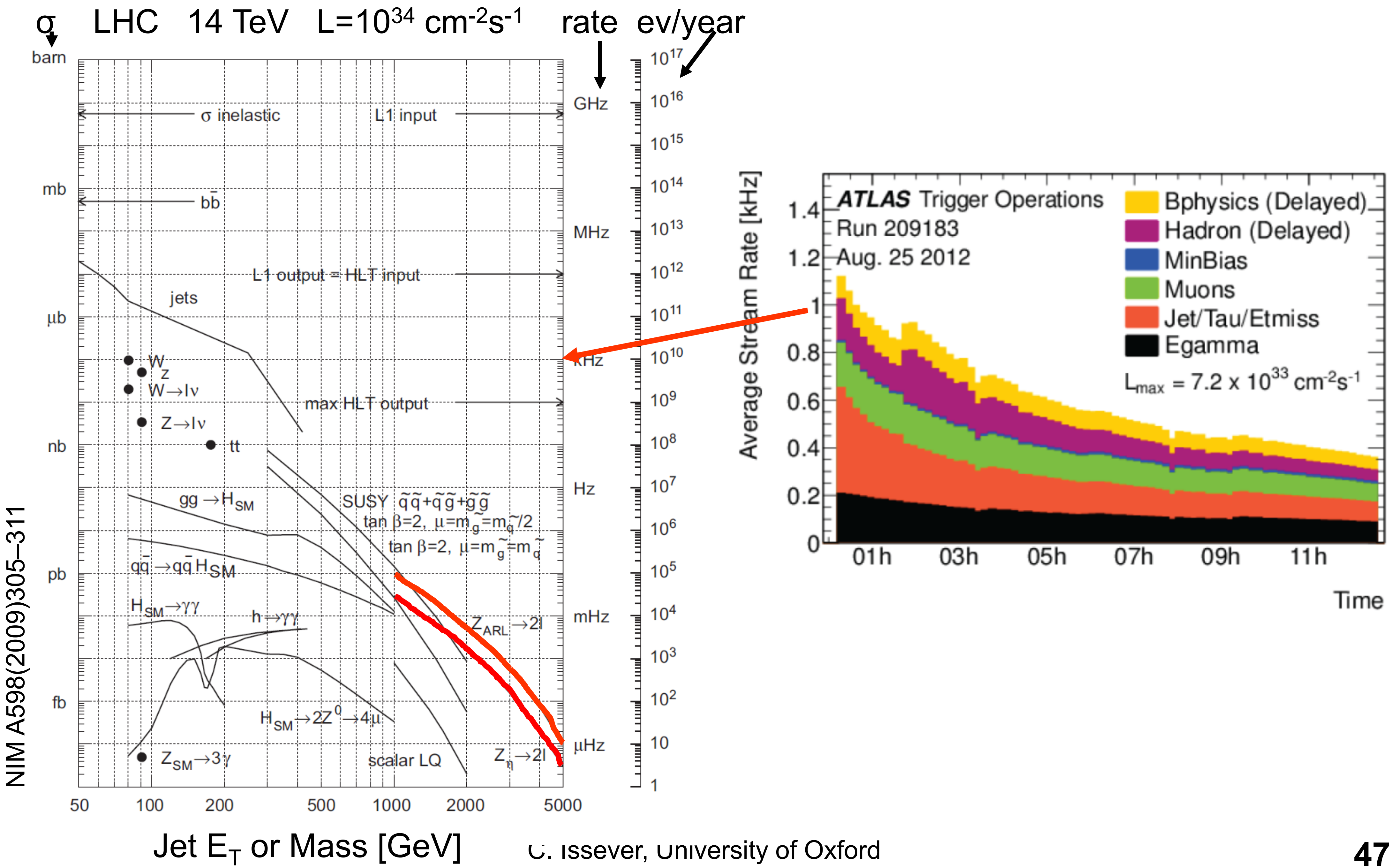
- single muon trigger
- $E_T > 40$ GeV

Takuya Nobe, ATL-DAQ-PROC-2012-067



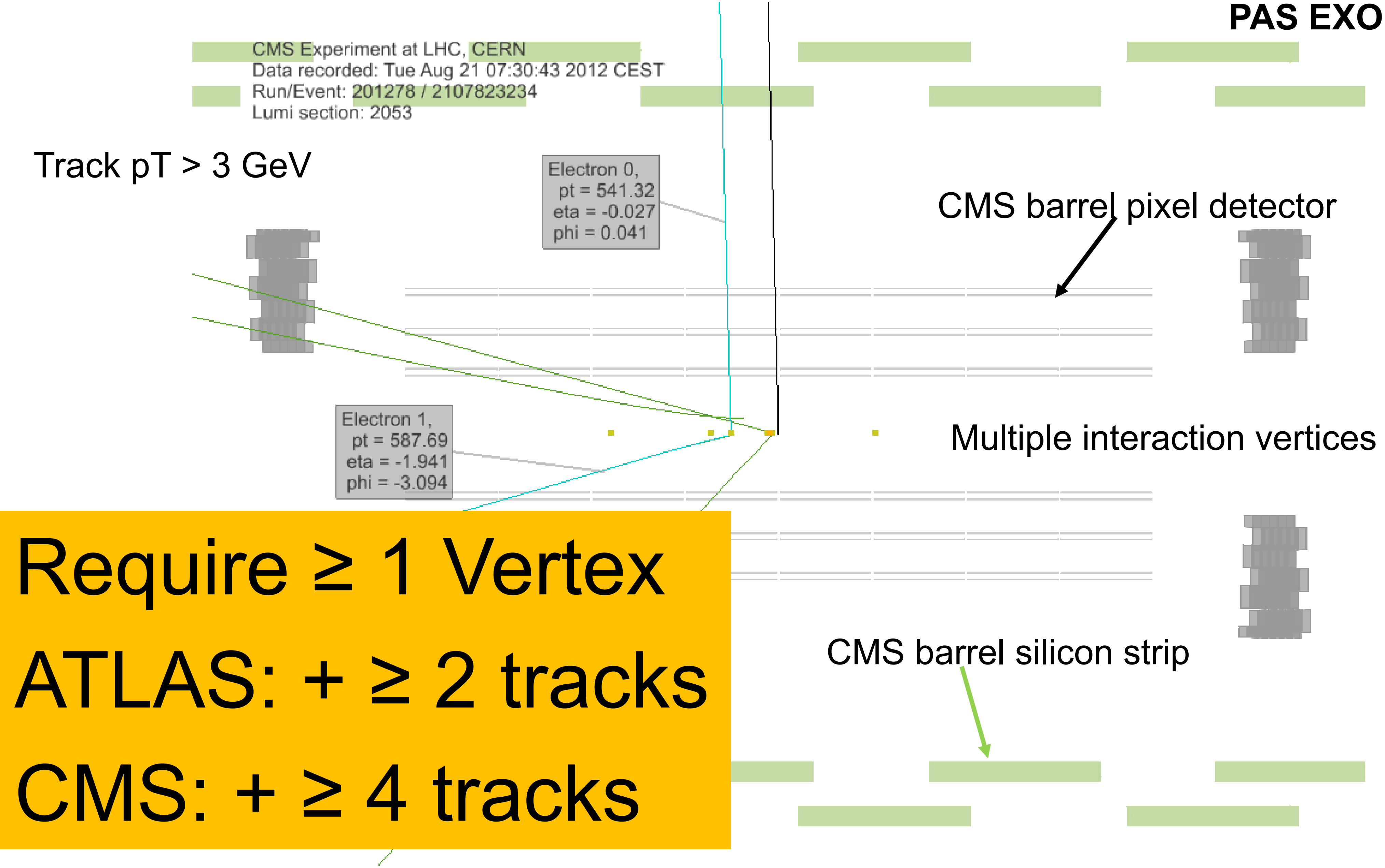


Compare this to rates of physics processes



CMS Di-Electron Event Zoomed into **Inner Detector**

PAS EXO-12-061



Require ≥ 1 Vertex

ATLAS: + ≥ 2 tracks

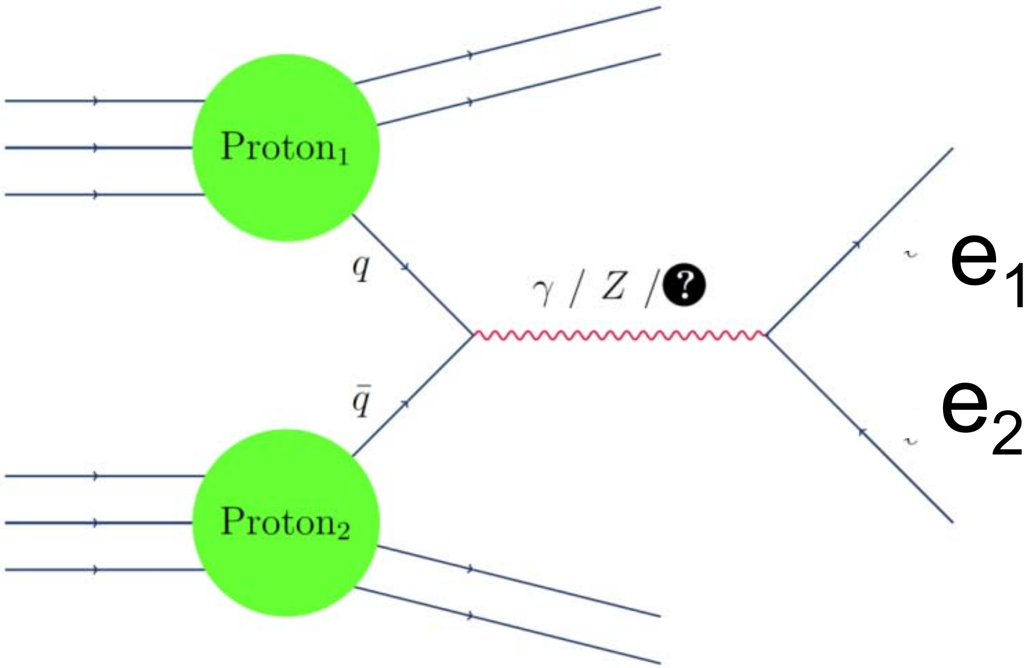
CMS: + ≥ 4 tracks

Di-Electron Channel

ATLAS Barrel Liquid Argon Calorimeter

Accordion Sampling Layers

Selection for Di-Electron Channel

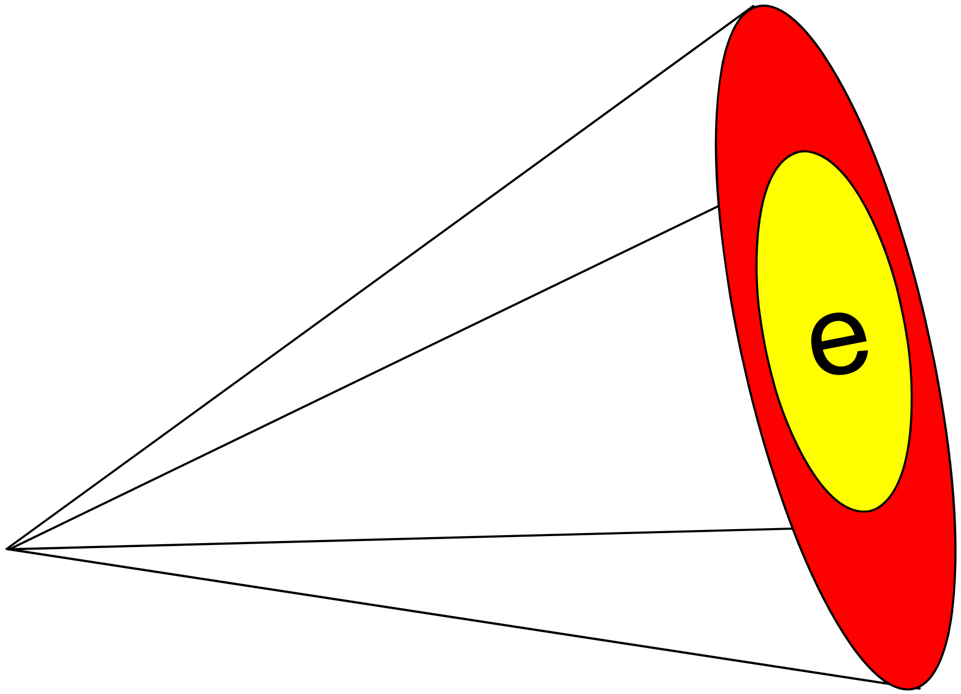


ATLAS	CMS
E_T^1>40GeV	E_T^1>35GeV
E_T^2>30GeV	E_T^2>35GeV

Problem: jets fake electrons

Use isolation to reduce fakes

Electron Isolation $I_{conesize}$



Energy/momentum around lepton

	ATLAS	CMS	
e1	$I^{calo}_{0.2}$<0.7%·E_T + 5 GeV	$I^{tracker}_{0.3}$<5 GeV	$I^{Calo}_{0.3}$<3%·E_T
e2	$I^{calo}_{0.2}$ <2.2%·E_T + 6 GeV		

Acceptance x Efficiency after all Selections

ATLAS

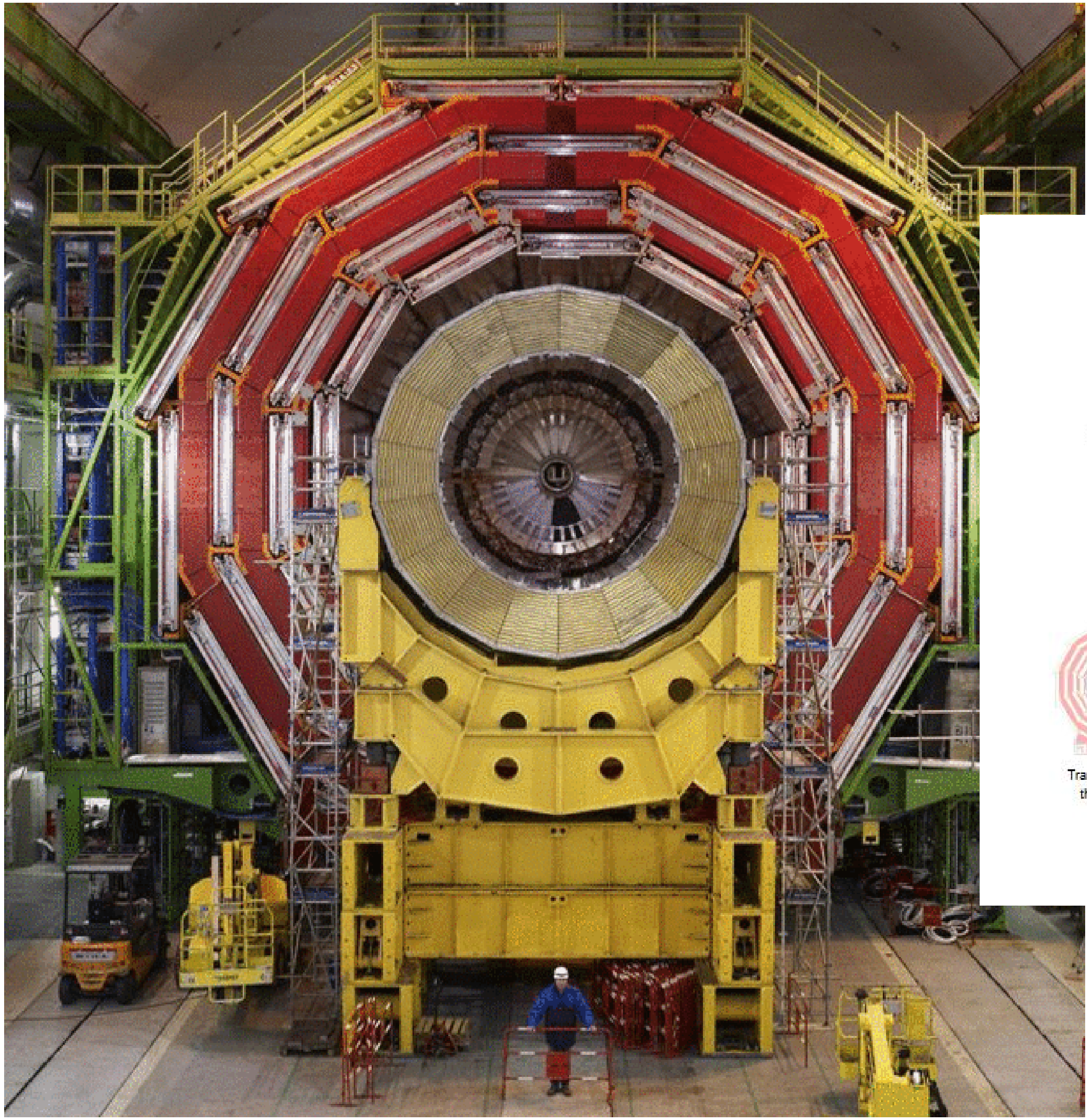
CMS

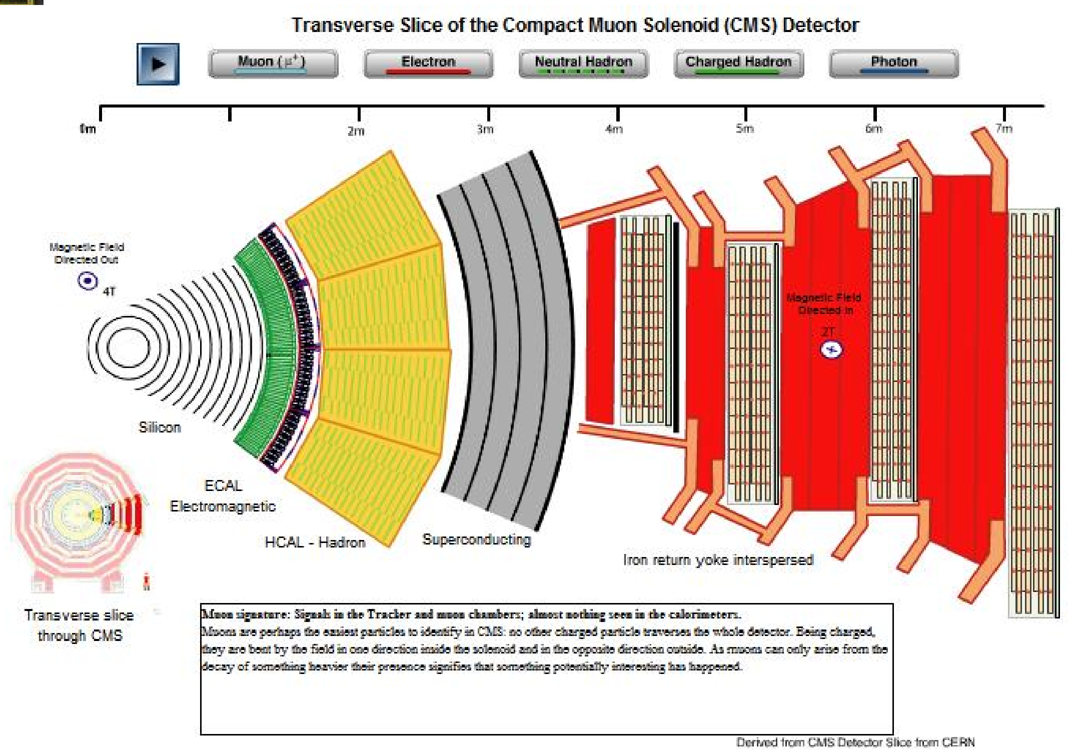
Axε(m = 2 TeV) = **73%**

Axε(m = 2.5 TeV) = **67%**

Similar

Di-Muon Channel





Dilepton Resonance Search:: μμ selections

ATLAS

- Single muon triggers
- $p_T > 25$ GeV
- $|\eta|<2.4$
- Suppress cosmic rays
  - $|d_0| < 0.2$ mm
  - $|z_0\text{-}z(\text{vertex})|<1$ mm
- Suppress jets faking μ's
  - $\sum p_T(\Delta R<0.3) < 5\%\cdot p_T$
- Require opposite charge

CMS

- Single muon trigger
- $p_T > 45$ GeV
- $|\eta|<2.4$
- Suppress cosmic rays

  $|d_0| < 0.2$ mm

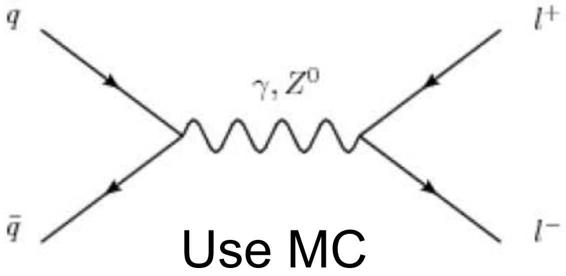
  $|z_0\text{-}z(\text{vertex})|<24$ cm
- Suppress jets faking μ's
  - $\sum p_T(\Delta R<0.3) < 10\%\cdot p_T$
  - $|z_0\text{-}z(\text{vertex})|< 0.2$mm
- Require opposite charge

Very different

$A\times\varepsilon(m = 2\text{ TeV}) = 46\%$ $A\times\varepsilon(m = 2.5\text{ TeV}) = 80\%$

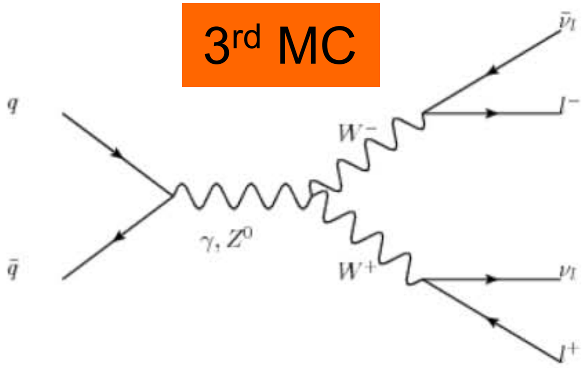
Dilepton Resonance Search: Backgrounds ee

dominant & irreducible



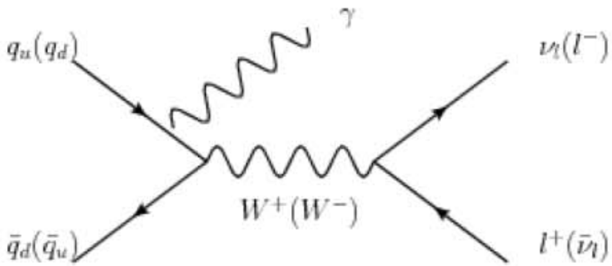
(a) Drell-Yan

3rd MC



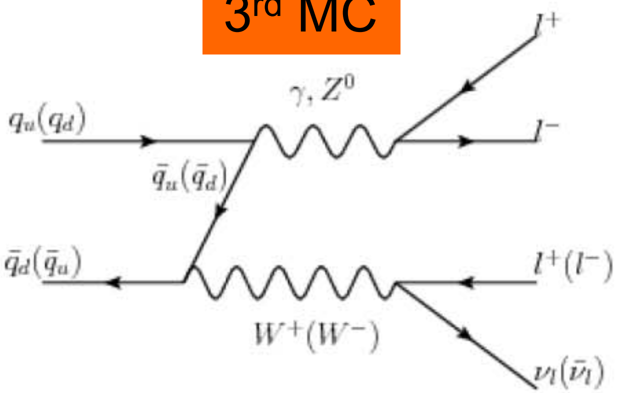
(b) WW

3rd MC



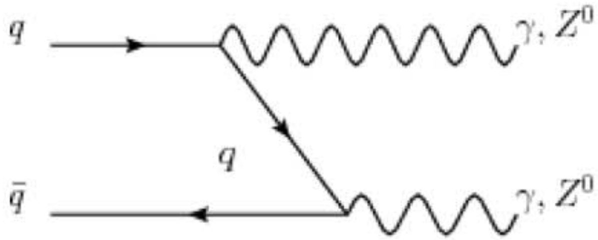
(c) Wγ

3rd MC



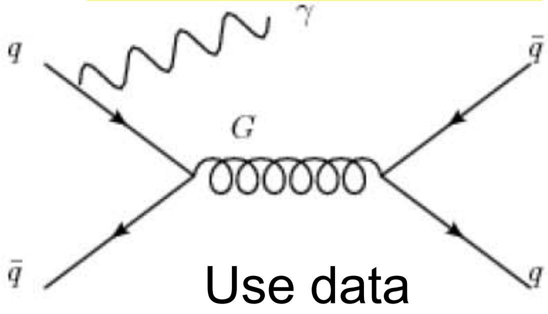
(d) WZ, Wγ

3rd MC



(e) ZZ,Zγ,$\gamma\gamma$

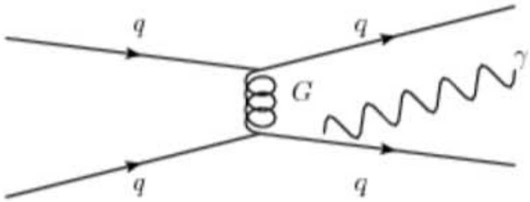
2nd for ee channel



(f) Dijets (without the external photon line),γ+jets

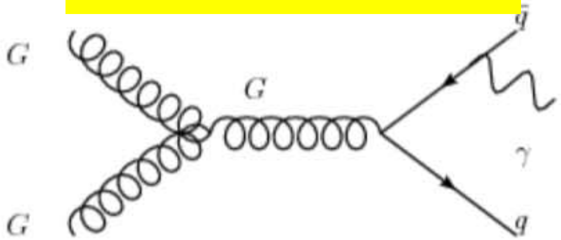
Dilepton Resonance Search: Backgrounds ee

2^{nd} for ee channel data



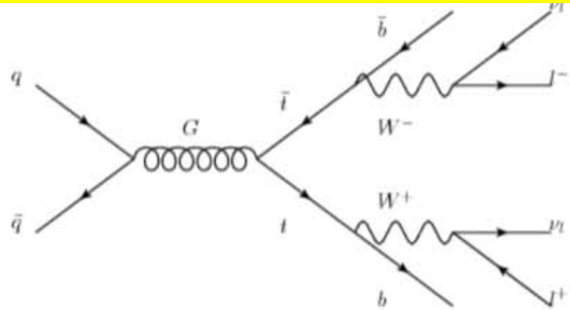
(g) Dijets (without the external photon line), γ+jets

2^{nd} for ee channel data



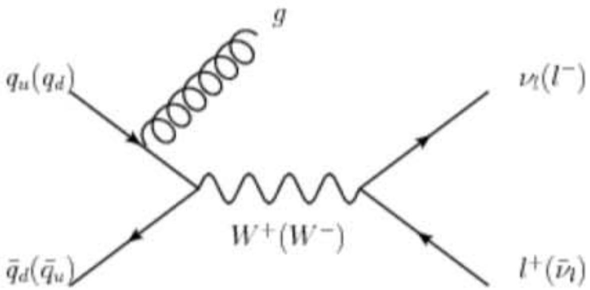
(h) Dijets (without the external photon line), γ+jets

2^{nd} for ee channel semi-leptonic

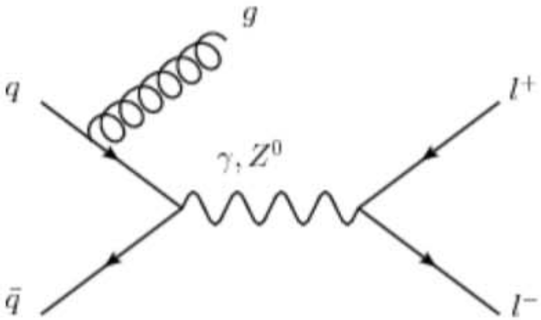


(i) $t\bar{t}$

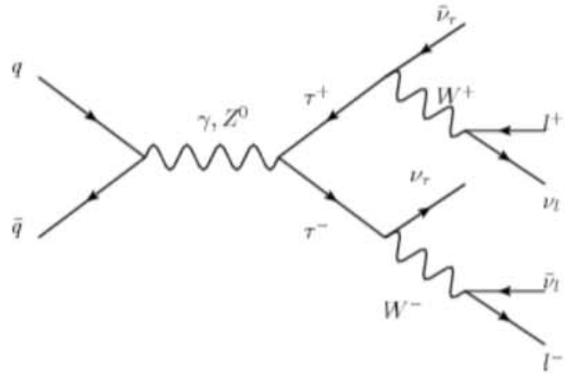
2^{nd} for ee channel data



(j) W+jets



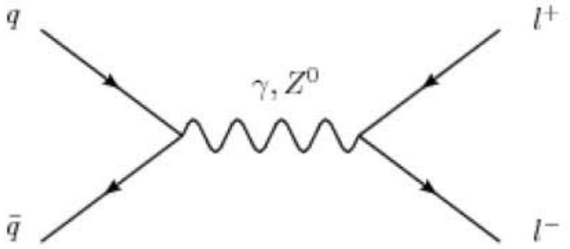
(k) Z+jets



(l) DY to tauons to leptons

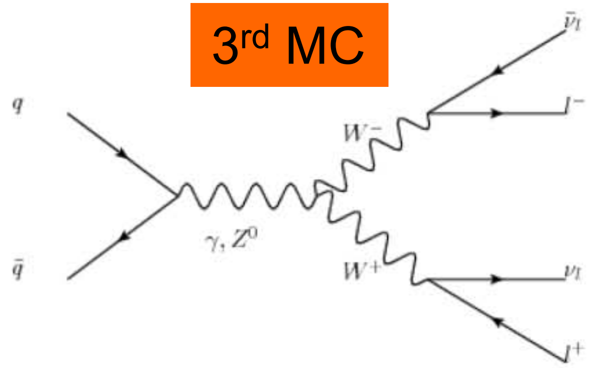
Dilepton Resonance Search: Backgrounds μμ

dominant & irreducible mc



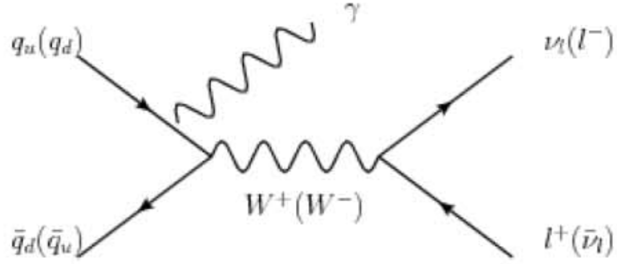
(a) Drell-Yan

3rd MC



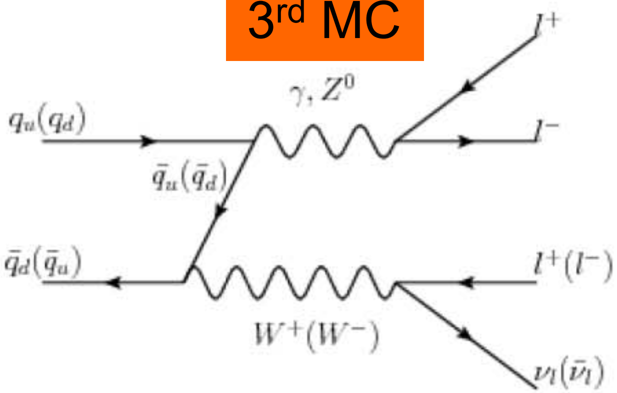
(b) WW

3rd MC



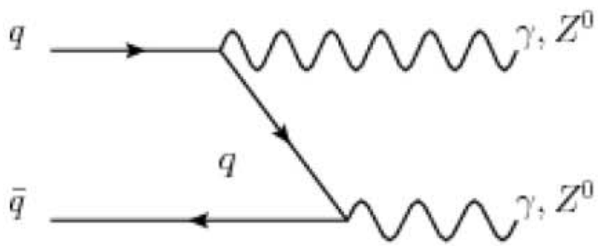
(c) Wγ

3rd MC

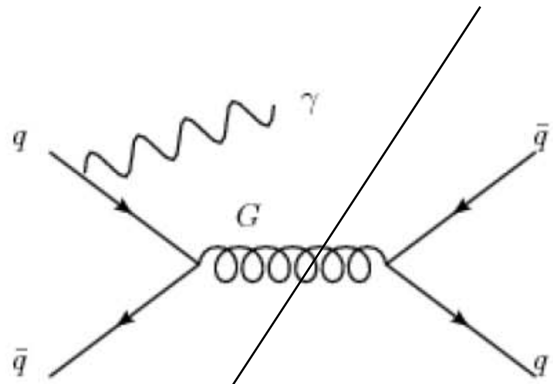


(d) WZ, Wγ

3rd MC



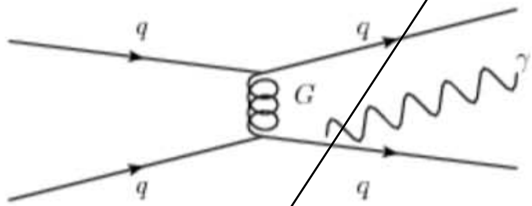
(e) ZZ,Zγ,γγ



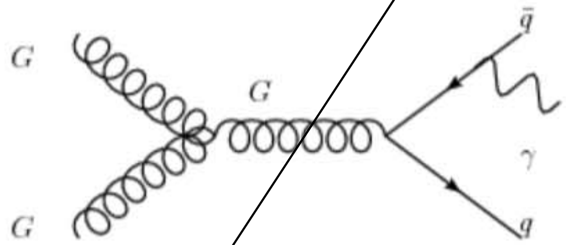
(f) Dijets (without the external photon line),γ+jets

Dilepton Resonance Search: Backgrounds μμ

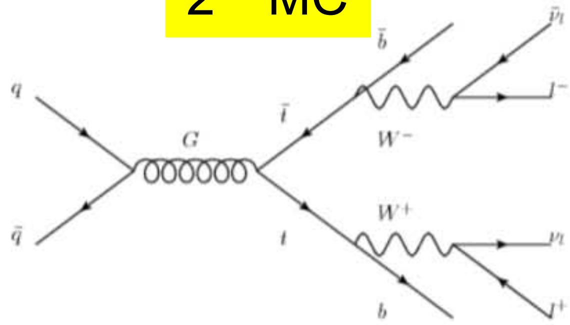
2nd MC



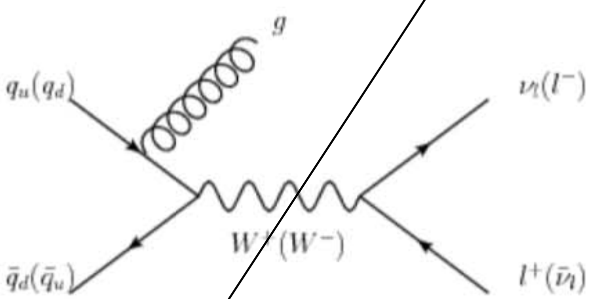
(g) Dijets (without the external photon line),γ+jets



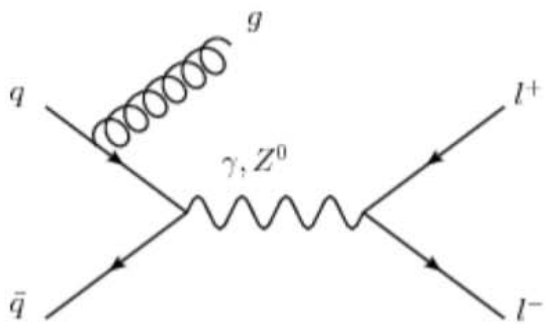
(h) Dijets (without the external photon line),γ+jets



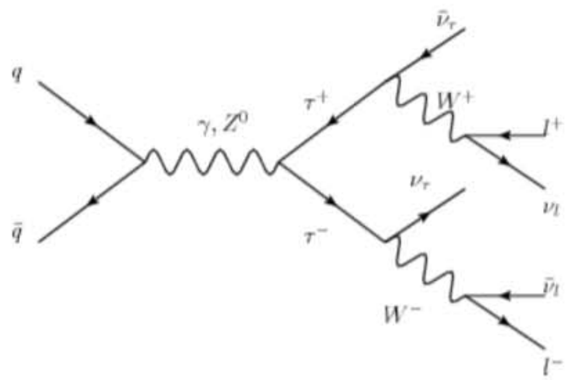
(i) $t\bar{t}$



(j) W+jets



(k) Z+jets



(l) DY to tauons to leptons

Heavy Resonances Search: 8 TeV Dileptons

Backgrounds

- SM Drell-Yan: $\gamma^*/Z \rightarrow l^+l^-$
  - shape taken from Monte Carlo
  - normalisation taken from Z peak in data
- t-tbar:
  - where tt goes to e+e-, mu+mu-
  - est. from MC, cross-checked in data
  - also includes Z->ττ, WW, WZ

ee and μμ

- Jet Background:
  - di-jet, W+jet events where the jets are misidentified as electrons/muons

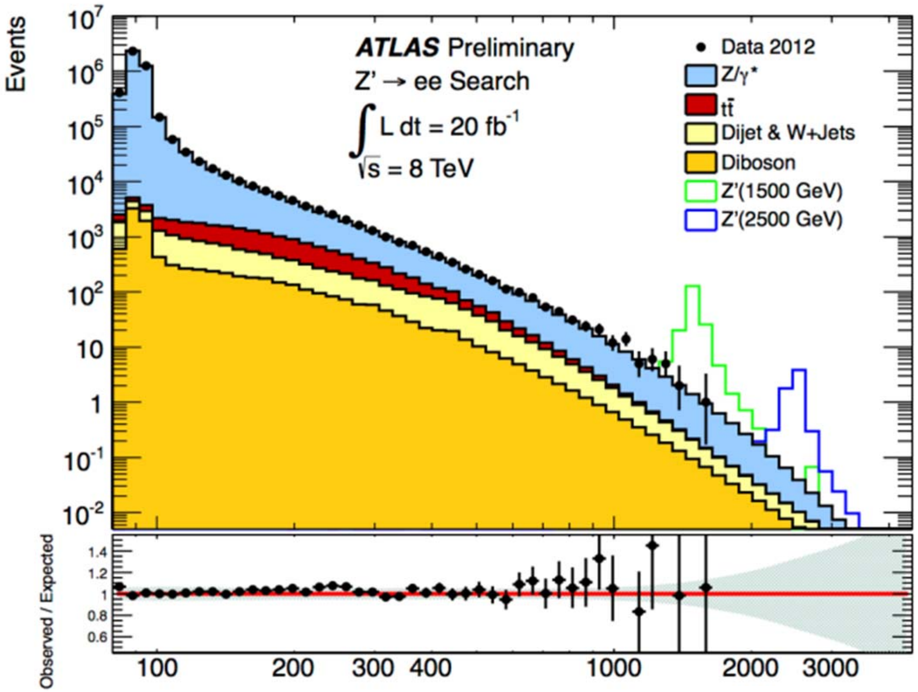
ee

- Cosmic Ray Background:
  - muons from cosmic rays
  - estimated <0.1 event after vertex and angular difference requirements

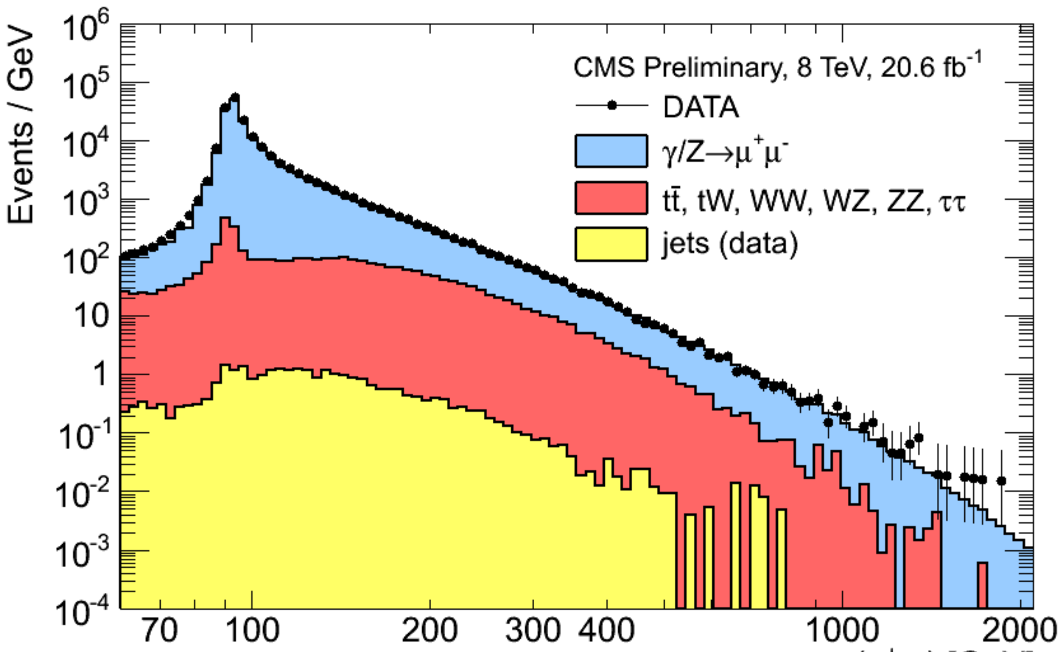
μμ

Dilepton Search: The Discriminant

ATLAS-CONF-2013-017
PAS EXO-12-061



m_{ee} [GeV]



m_{mumu} [GeV]

Invariant mass reach of 1 - 2 TeV

Dilepton Resonance Search: Systematic Uncertainties

ATLAS-CONF-2013-017

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF variation	NA	15%	NA	15%
PDF choice	NA	17%	NA	17%
Scale	NA	-	NA	-
α_s	NA	4%	NA	4%
Electroweak corrections	NA	3%	NA	3%
Photon-induced corrections	NA	4%	NA	4%
Efficiency	-	-	6%	6%
Resolution	-	-	-	3% (7%)
W + jet and multi-jet background	NA	9%	NA	-
Diboson and ttbar extrapolation	NA	5%	NA	4%
Total	5%	26%	8%	25% (26%)

Heavy Resonances Search: 8 TeV Dileptons

m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	119000 ± 8000	13700 ± 900	1290 ± 80	68 ± 4	9.8 ± 1.1	0.008 ± 0.005
$t\bar{t}$	7000 ± 800	2400 ± 400	160 ± 60	2.5 ± 0.6	0.11 ± 0.04	< 0.001
Diboson	1830 ± 210	660 ± 160	93 ± 33	4.8 ± 0.8	0.79 ± 0.26	0.005 ± 0.004
Dijet, W + jet	3900 ± 800	1260 ± 310	230 ± 110	8.6 ± 2.4	0.9 ± 0.6	0.004 ± 0.006
Total	131000 ± 8000	18000 ± 1100	1780 ± 150	84 ± 5	11.6 ± 1.3	0.017 ± 0.009
Data	133131	18570	1827	98	10	0

ATLAS-CONF-2013-017

$m_{\mu\mu}$[GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	111000 ± 8000	11000 ± 1000	1000 ± 100	49 ± 5	7.3 ± 1.3	0.033 ± 0.029
$t\bar{t}$	5900 ± 900	1900 ± 400	140 ± 60	2.7 ± 0.7	0.16 ± 0.08	< 0.001
Diboson	1520 ± 190	520 ± 140	62 ± 26	2.8 ± 1.0	0.38 ± 0.28	0.002 ± 0.003
Total	118000 ± 8000	13300 ± 1100	1160 ± 120	55 ± 5	7.8 ± 1.3	0.035 ± 0.029
Data	118701	13349	1109	48	8	0

What do you do now?

- Observed numbers consistent with background???
- Many ways to do it
- One way e.g.:
  - $P(n \geq n_{obs}) = 1 - f(n; s = 0; b) = 1 - \sum_{n=0}^{n_{obs}-1} \frac{b^n}{n!} e^{-b}$
  - Probability, assuming s = 0, to observe as many events or more for a given expected background amount, b.
- For 800 – 1200 GeV bin in μμ
  - $b = 55$, $n_{obs}=48 \rightarrow P=84\%$

Heavy Resonances Search: 8 TeV Dileptons

ATLAS-CONF-2013-017

m_{ee} [GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	119000 ± 8000	13700 ± 900	1290 ± 80	68 ± 4	9.8 ± 1.1	0.008 ± 0.005
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Dijet, W + jet	3900 ± 800	1260 ± 310	230 ± 110	8.6 ± 2.4	0.9 ± 0.6	0.004 ± 0.006
Total	131000 ± 8000	18000 ± 1100	1780 ± 150	84 ± 5	11.6 ± 1.3	0.017 ± 0.009
Data	133131	18570	1827	98	10	0

Analysis: P(ee) = 18%

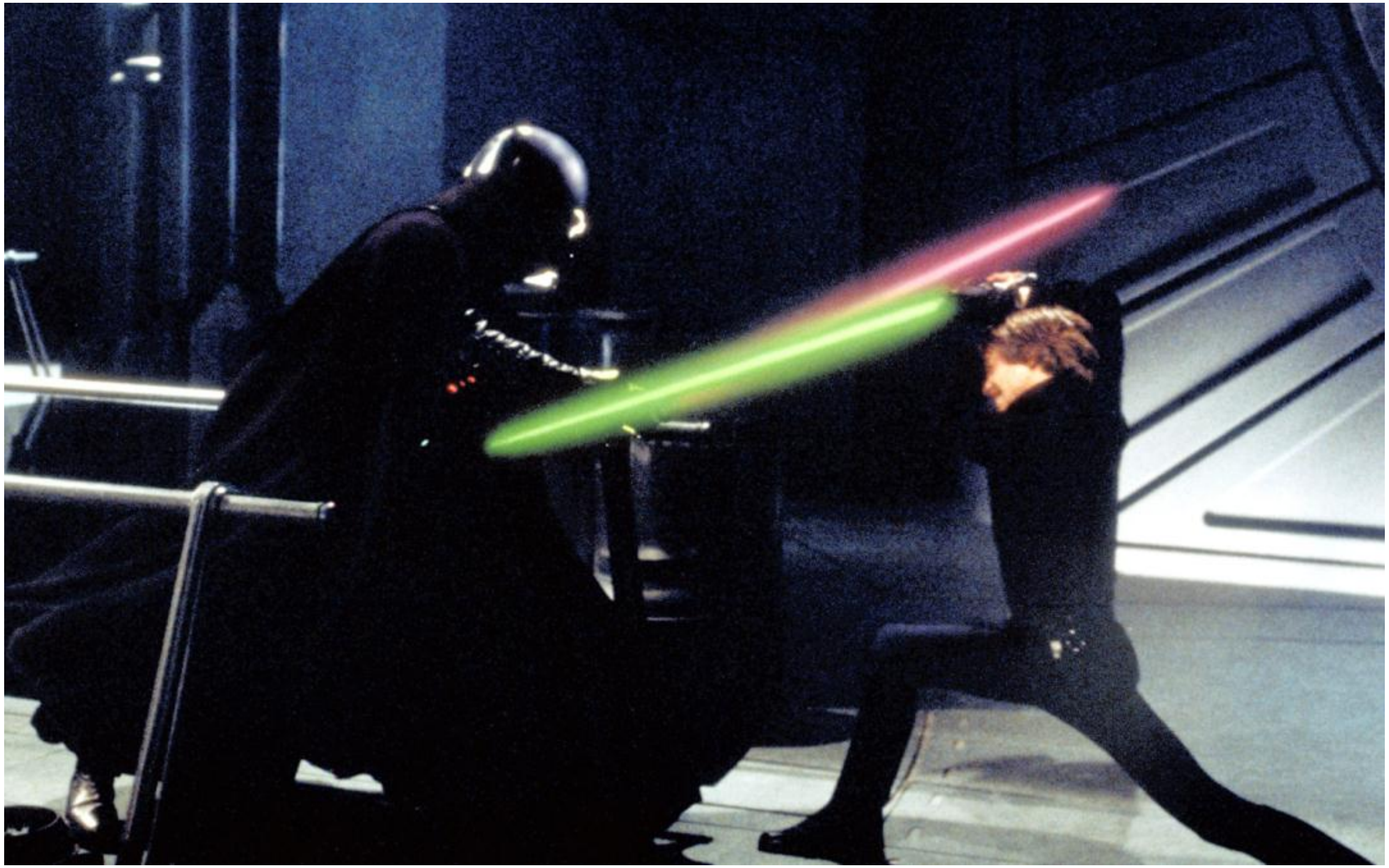
Analysis: P(μμ) = 98%

$m_{\mu\mu}$[GeV]	110 - 200	200 - 400	400 - 800	800 - 1200	1200 - 3000	3000 - 4500
Z/γ^*	111000 ± 8000	11000 ± 1000	1000 ± 100	49 ± 5	7.3 ± 1.3	0.033 ± 0.029
$t\bar{t}$	5900 ± 900	1900 ± 400	140 ± 60	2.7 ± 0.7	0.16 ± 0.08	< 0.001
Diboson	1520 ± 190	520 ± 140	62 ± 26	2.8 ± 1.0	0.38 ± 0.28	0.002 ± 0.003
Total	118000 ± 8000	13300 ± 1100	1160 ± 120	55 ± 5	7.8 ± 1.3	0.035 ± 0.029
Data	118701	13349	1109	48	8	0

No deviation from expectation found.

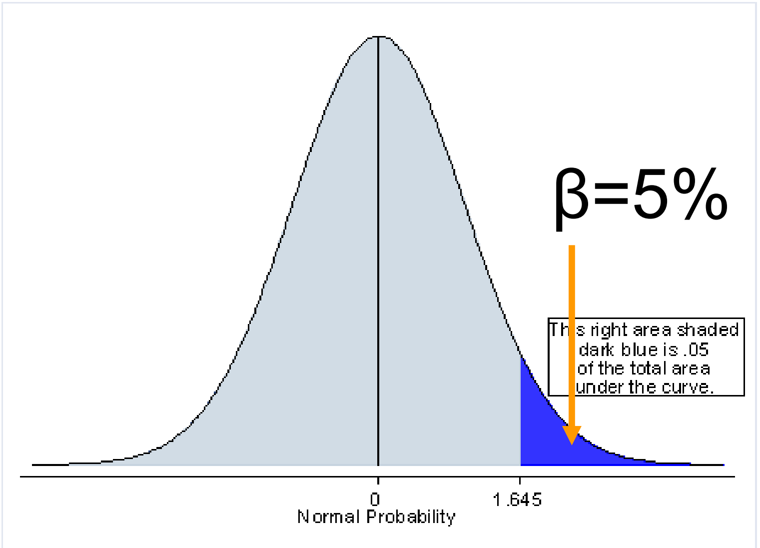
We did not find any deviation…..

- Quantify the sensitivity and reach of our analysis
- Again, many ways to do it….
  - “Religious” wars are being fought about this…..



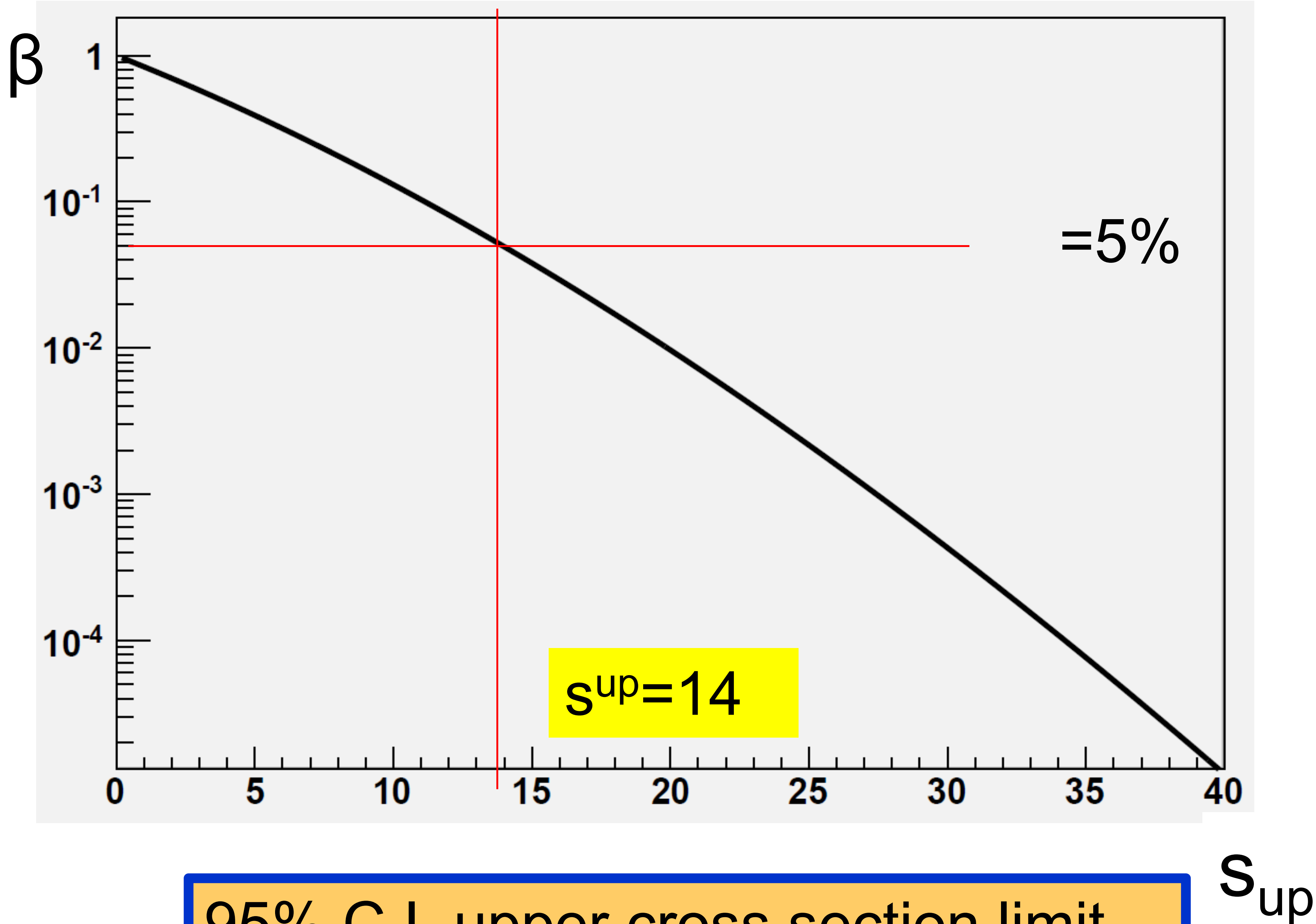
Back of the envelope demonstration…..to get the idea

- $n_{obs} = s + b$
- We want an upper limit (bound on s) given we expect b background events and have observed n_{obs} events.
- Use Bayesian method with uniform prior density
- $\beta = \sum_{n=0}^{n_{obs}} (s^{up})^n e^{-s^{up}} / n!$ solve this numerical
  - $n = s^{up} + b$
- We ignore error on b….
- We ignore systematic errors



- $\beta = \sum_{n=0}^{n_{obs}} (s^{up})^n e^{-s^{up}} / n!$ solve this numerical

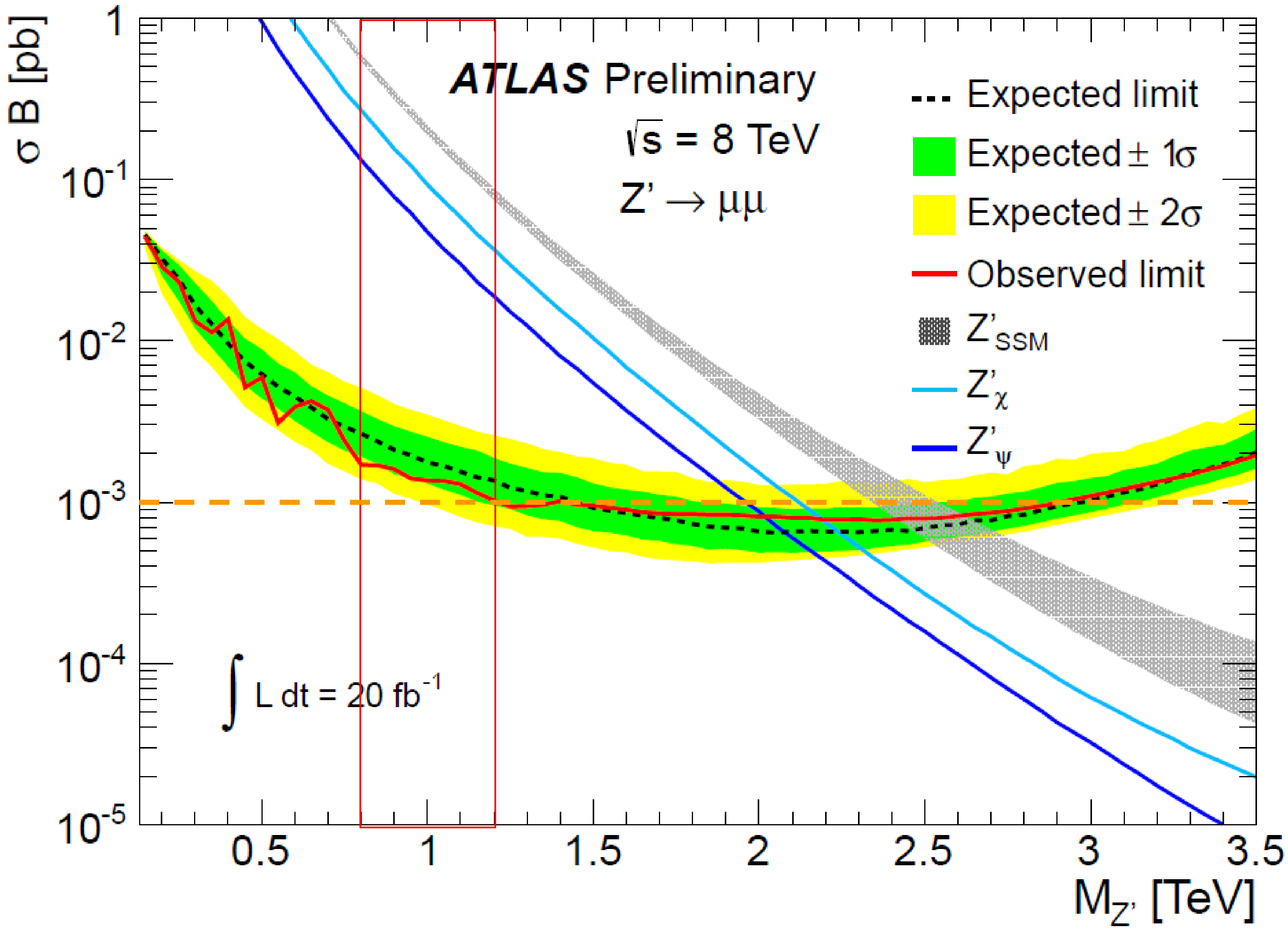
- Back to our example
  - 800 GeV < $m_{\mu\mu}$ < 1200 GeV
  - We have observed n_{obs} = 48 events
  - We expect b=55 background events
  - Our Acceptance x Efficiency ~ 50%
  - We have analysed L = 20 fb-1 of data



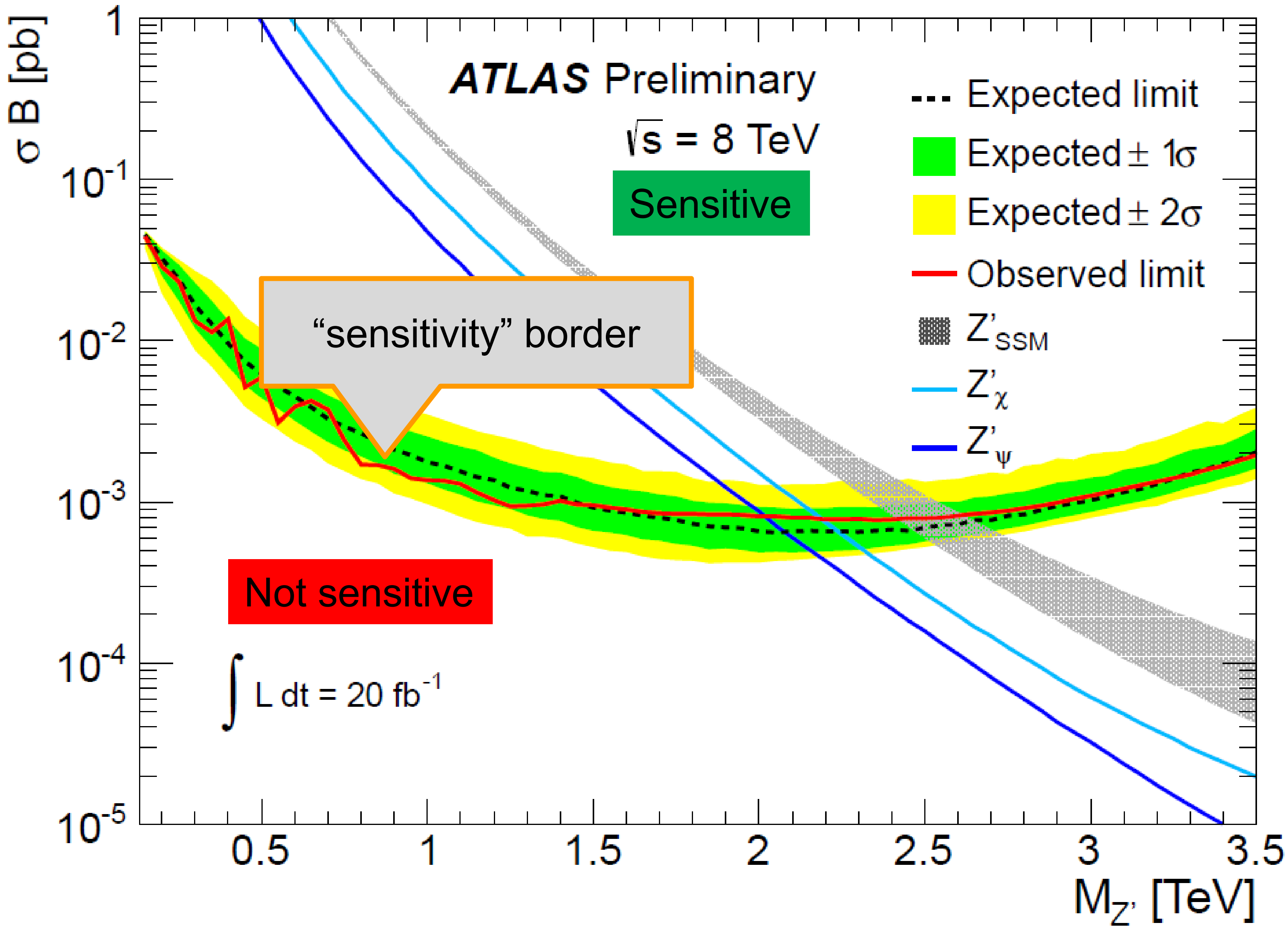
95% C.I. upper cross section limit

14/20fb-1 = 0.7fb ~ 1fb = $\mathbf{10^{-3}}$ **pb**

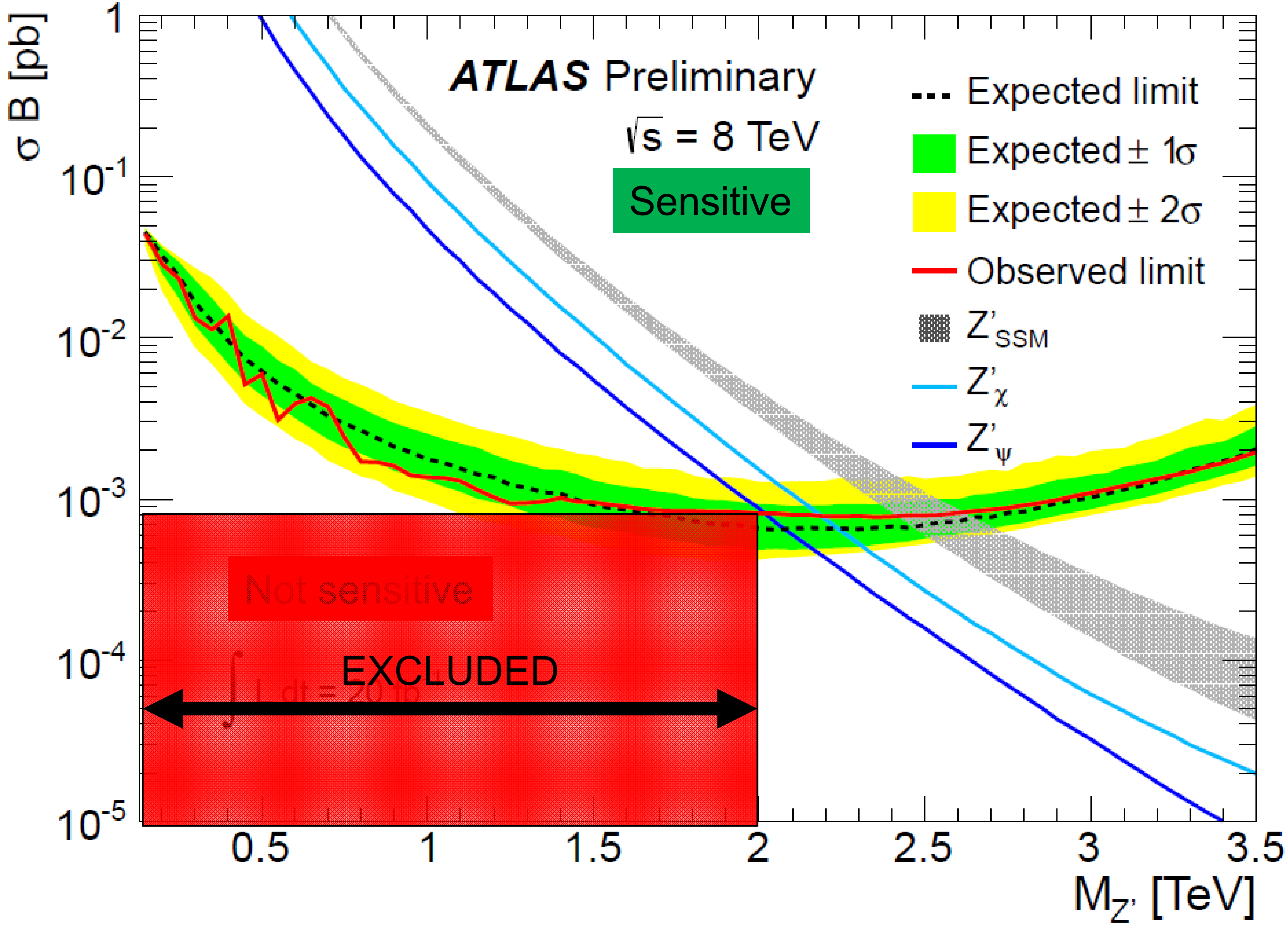
Let us compare with the published limit…



Let us compare with the published limit…

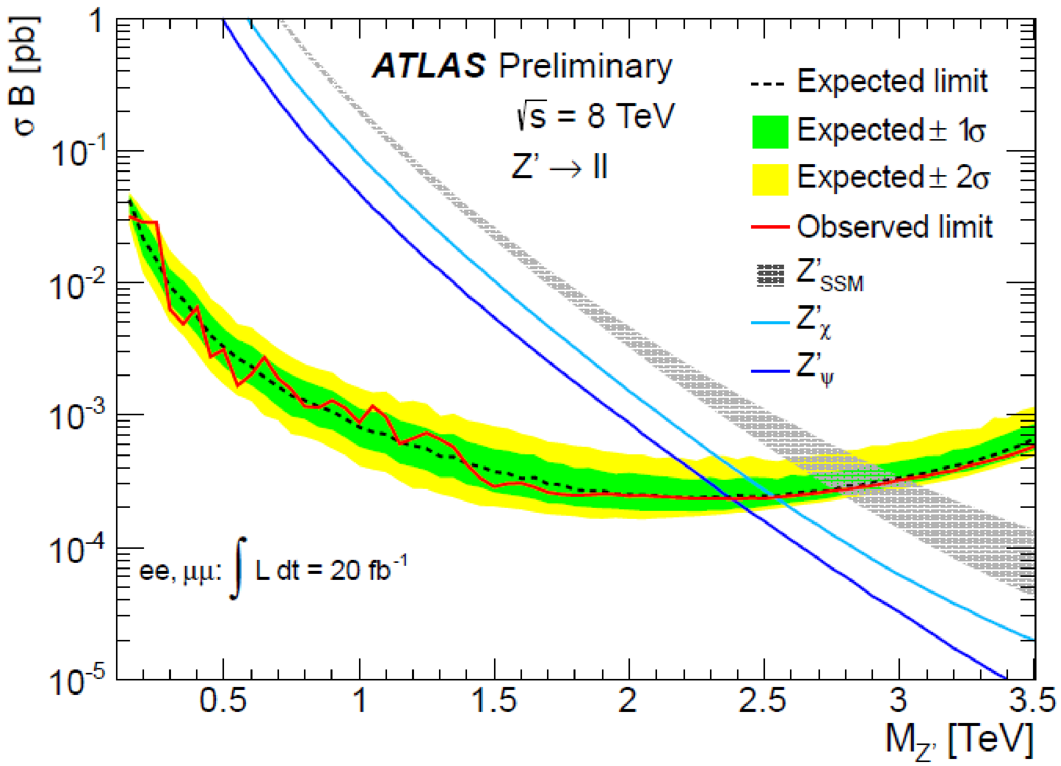


Let us compare with the published limit…

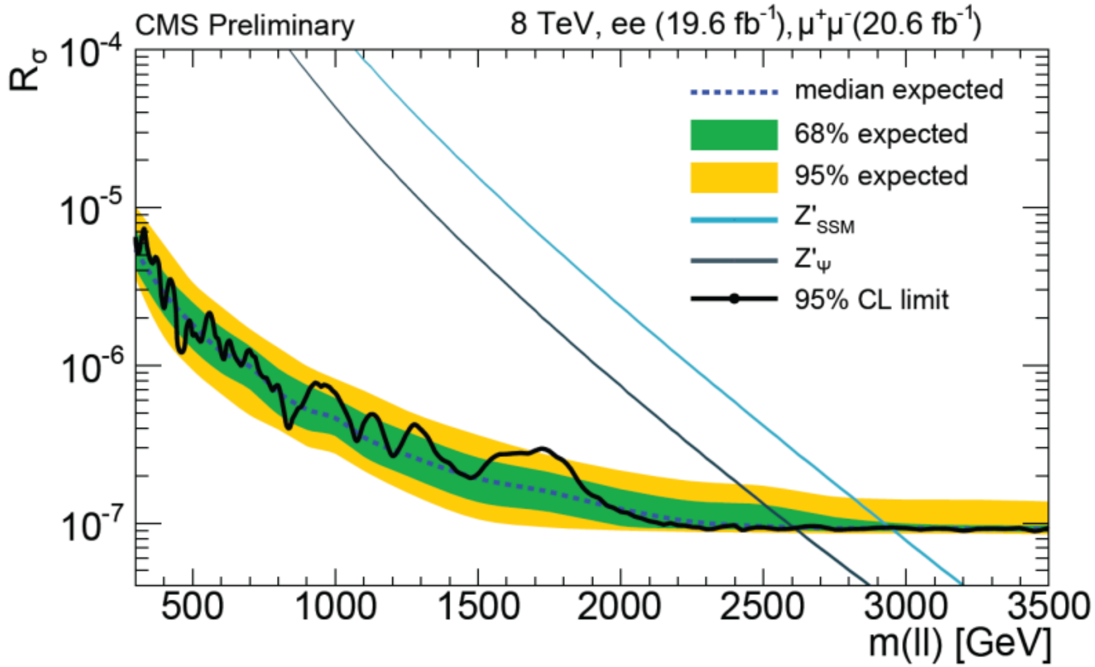


Limits for both channels combined

ATLAS



CMS

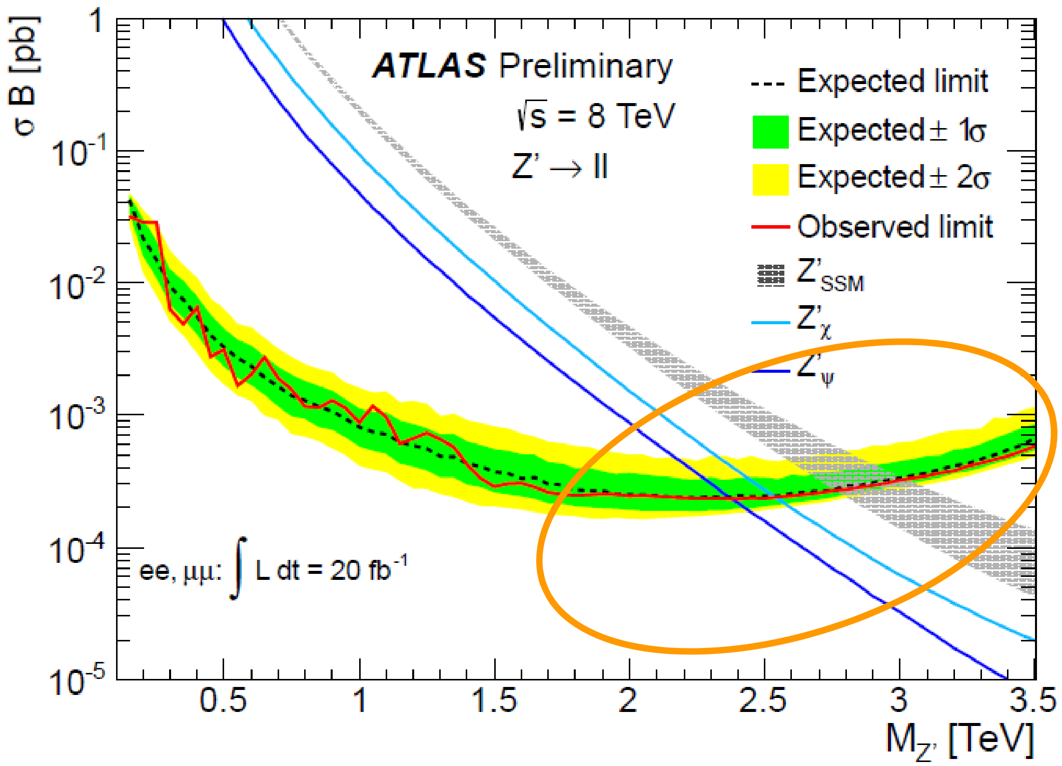


Z'_{SSM} > 2.86 TeV@ 95% C.L.

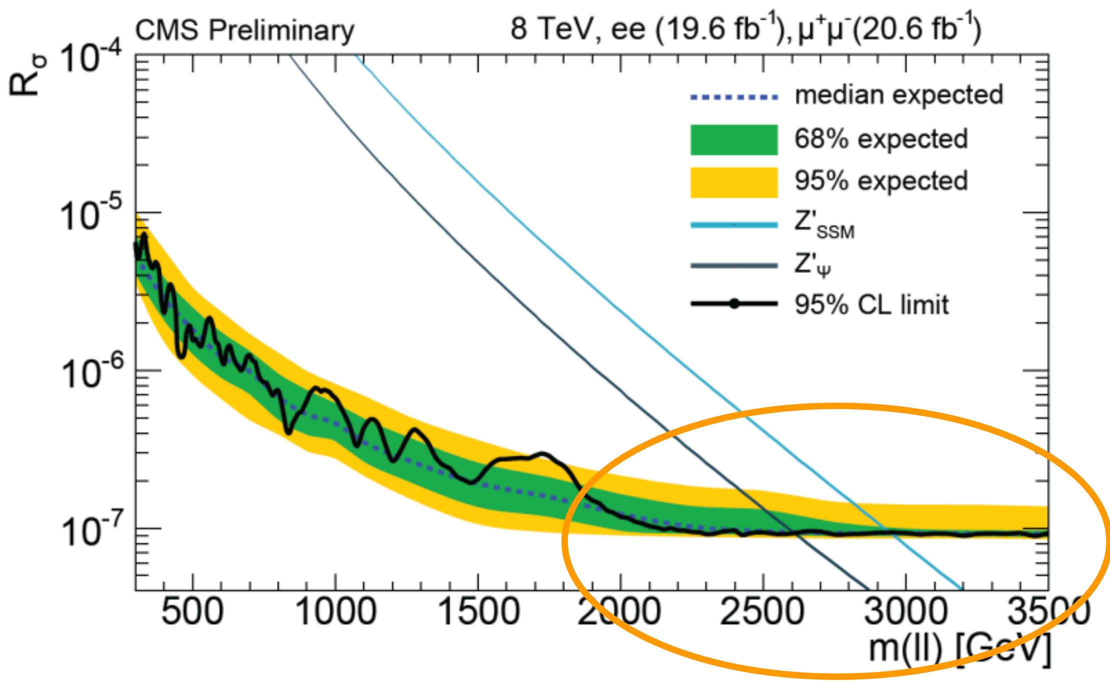
Z'_{SSM} > 2.96 TeV@ 95% C.L.

Let us discuss a bit the difference btw ATLAS/CMS

ATLAS



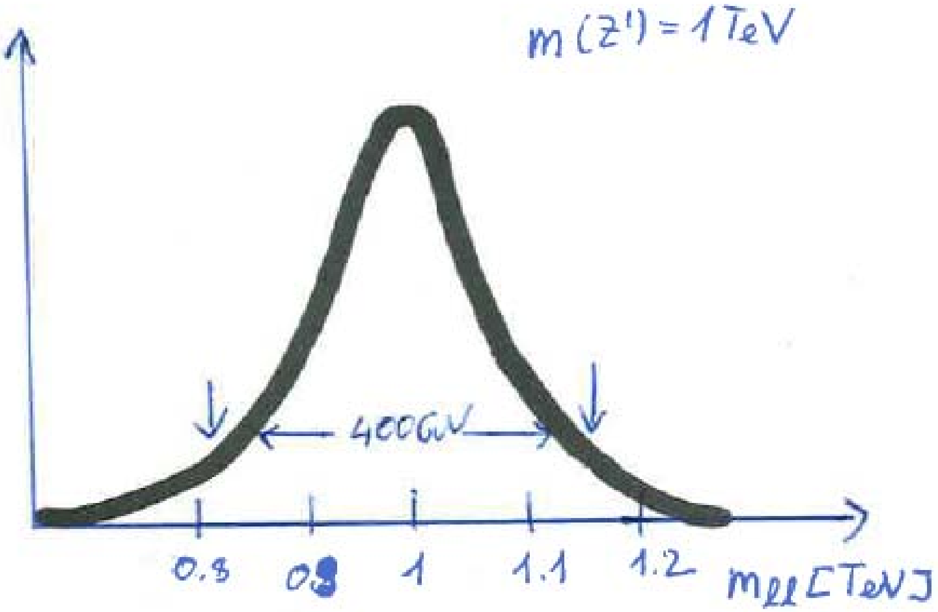
CMS

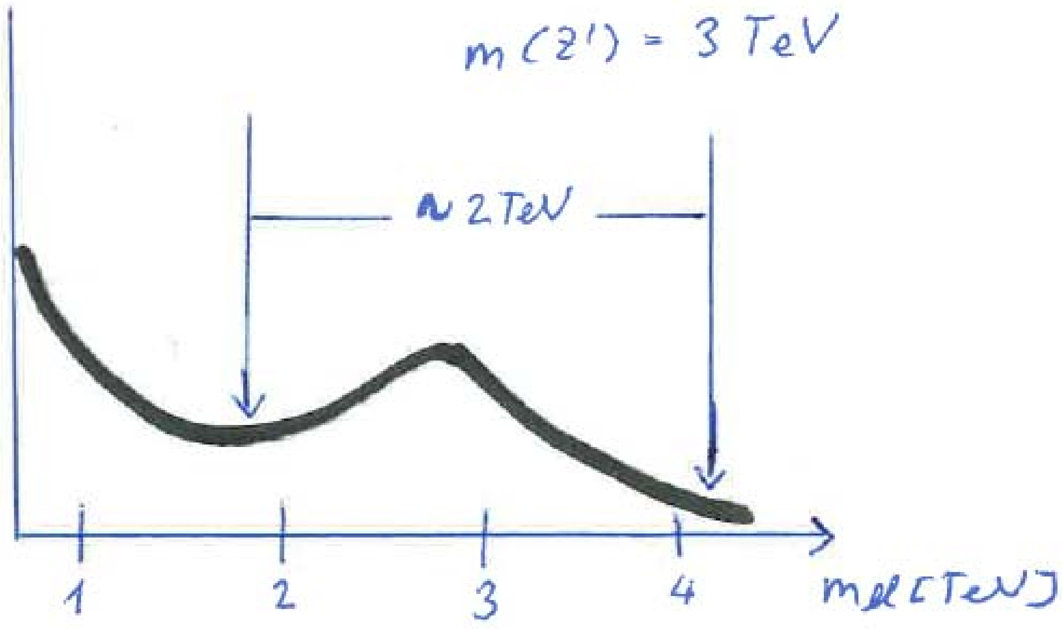


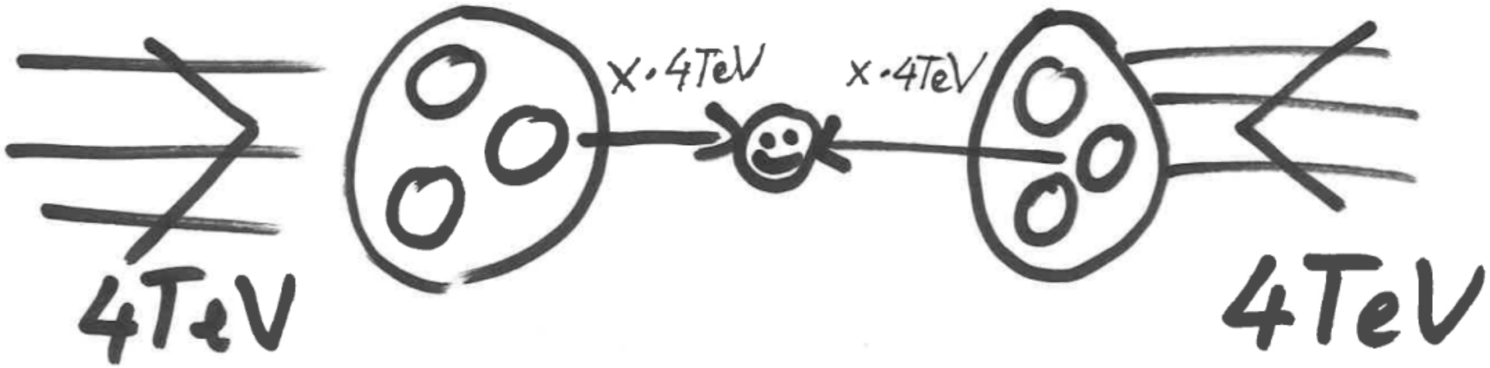
Z'_{SSM} > 2.86 TeV@ 95% C.L.

Z'_{SSM} > 2.96 TeV@ 95% C.L.

Signal Shapes and Parton Luminosities



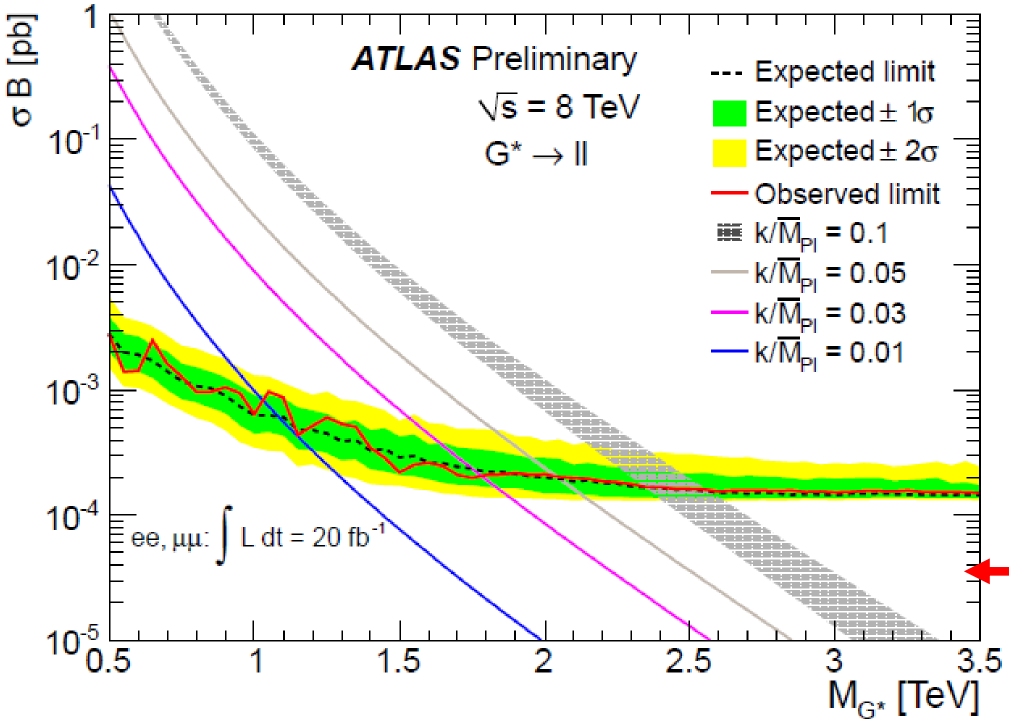




ATLAS CMS Differences in the Limit Setting

ATLAS

- Uses signal templates for limits
- Loss of sensitivity at high masses
  - Parton luminosities
- Upper cross section limits model specific



CMS

- Uses narrow resonance
  - For cross section upper limit
  - Cross section upper limits less model dependent
  - Give outside world description of what was done
- Take signal shapes within +-40% of the mass peak into account to compute theory curves
- Not sensitive to parton luminosities
- generic resonance search

KK Graviton narrow resonance
Obs limit does not go up

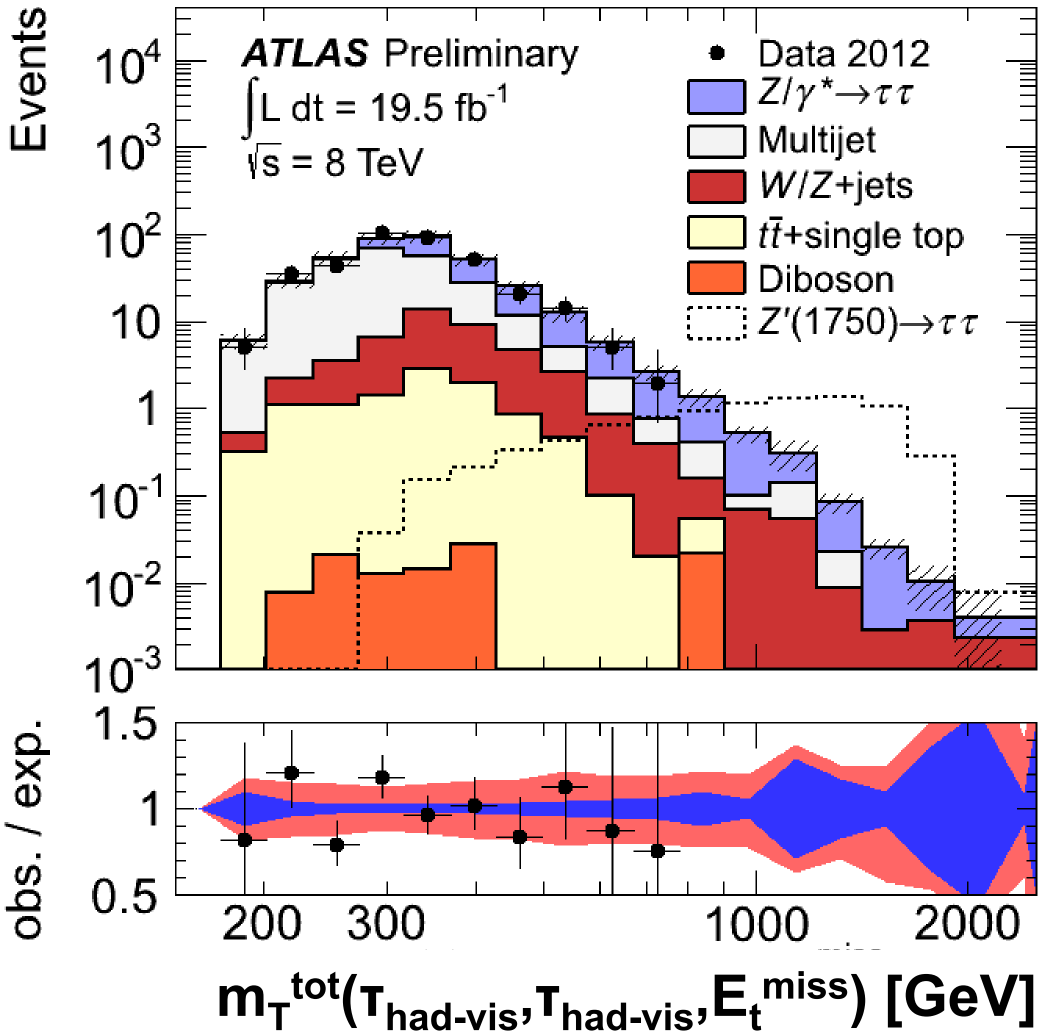
Ditaus (fully hadronic)

- Lepton universality not necessary for these new gauge bosons

→ Essential to search in ALL decay modes

19.5 fb^{-1}

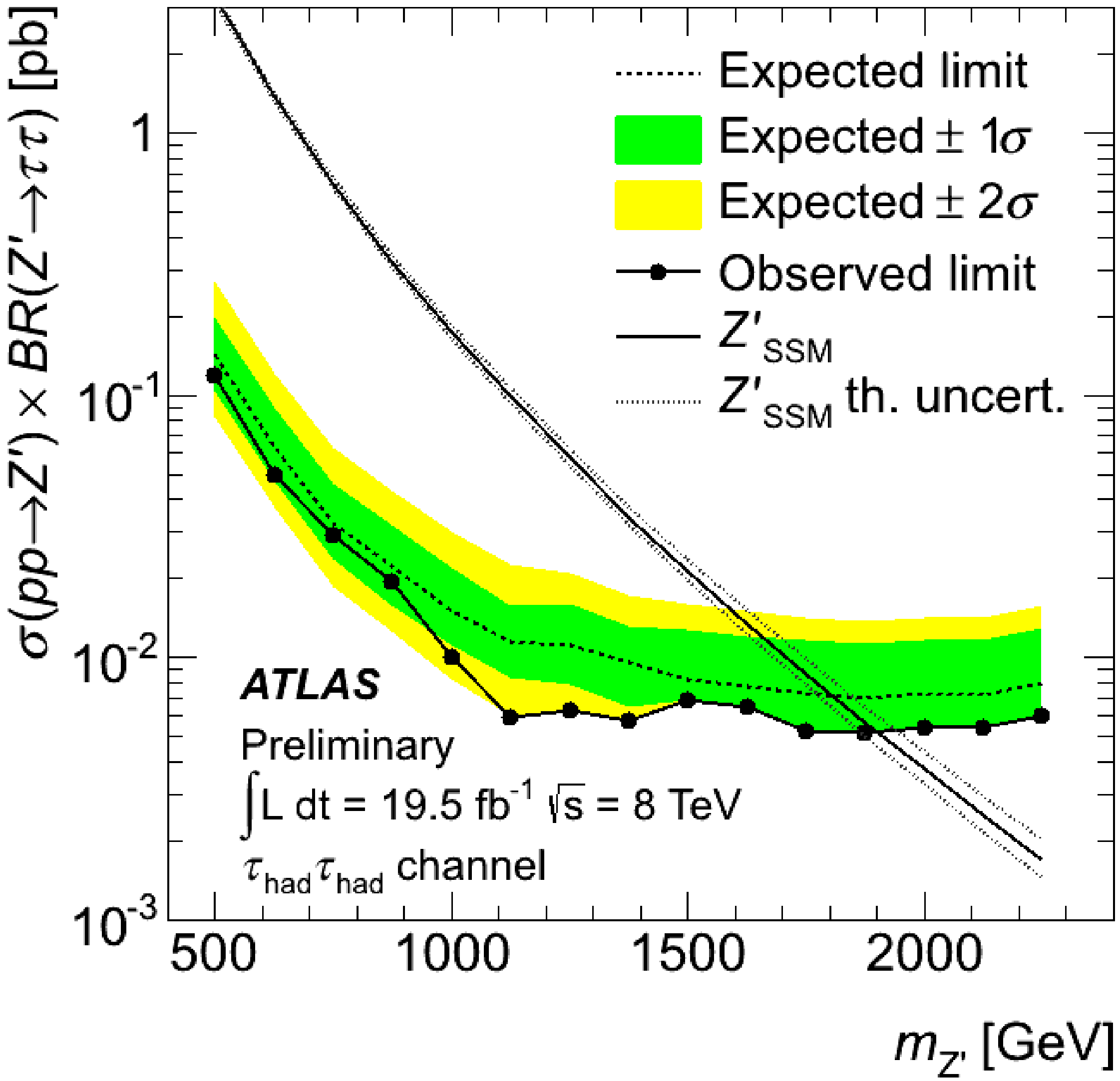
Selections	
≥2 τ candidates	
$p_T(\tau_1)$ > 150 GeV	
Trigger matched	
Opposite charge	
$\Delta\varphi(\tau_1,\tau_2)$>2.7	
Loose BDT ID (60%)	
mass resolution is 30–50% single tau trigger	Axε(mZ'>750) ~ 7-9 % Axε(mZ'=500) ~ 3 %



ATLAS-CONF-2013-066

Ditau 95% Credibility Limits

ATLAS-CONF-2013-066



Model	Obs. Limit
SSM Z'	1.9TeV

Important Systematics @ 1.5 TeV

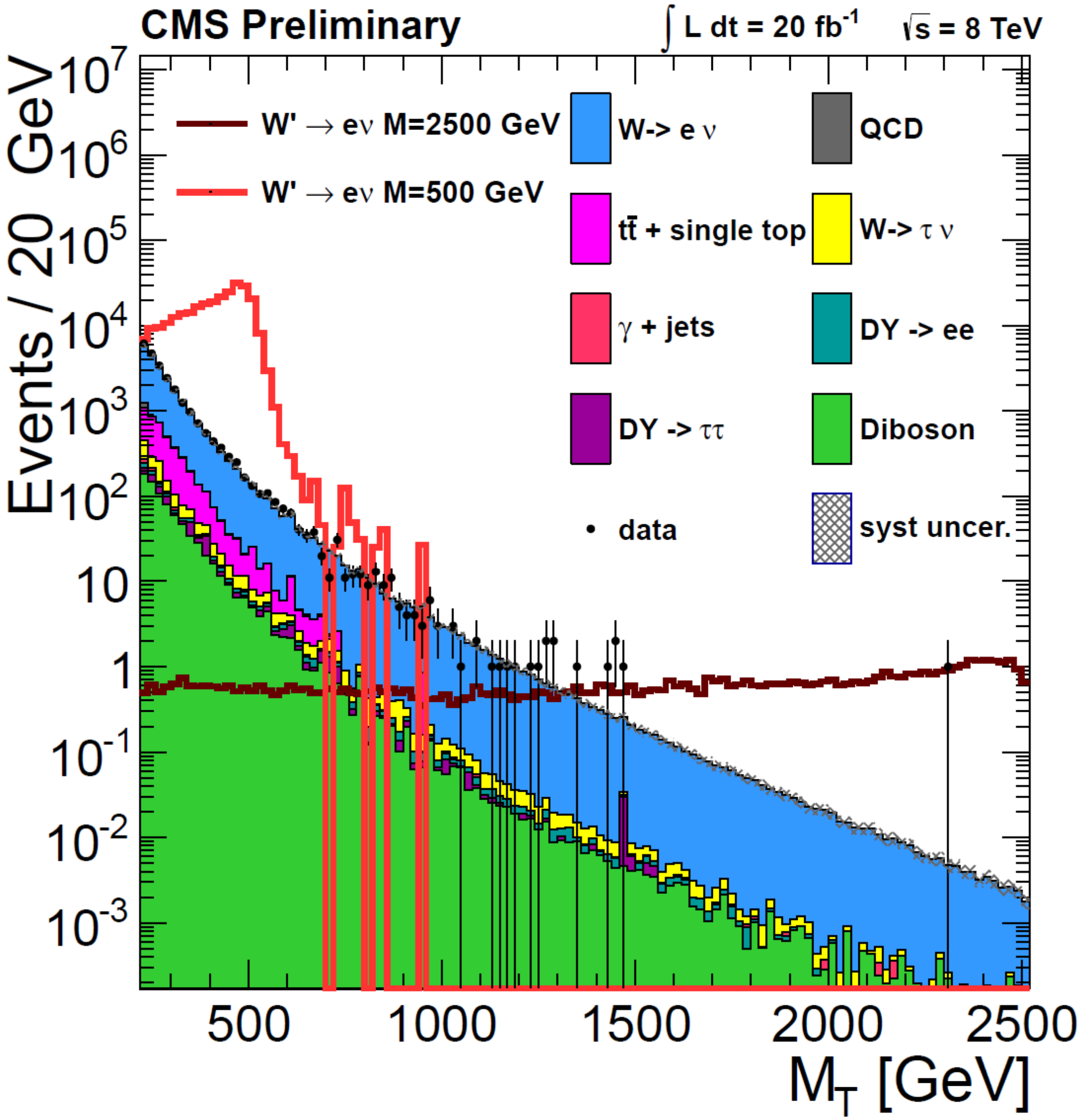
- Jet-to-τ fake rate: 9% on bkg
- Tau energy scale: 9%
- Tau ID : 10%
- Tau trigger: 7 %

Mass Point [GeV]	500	625	750	875	1000	1125	1250–1375	≥1500
m_T^{tot} [GeV]	>400	>450	>500	>550	>600	>700	>750	>850

W' → lν in 8 TeV Data

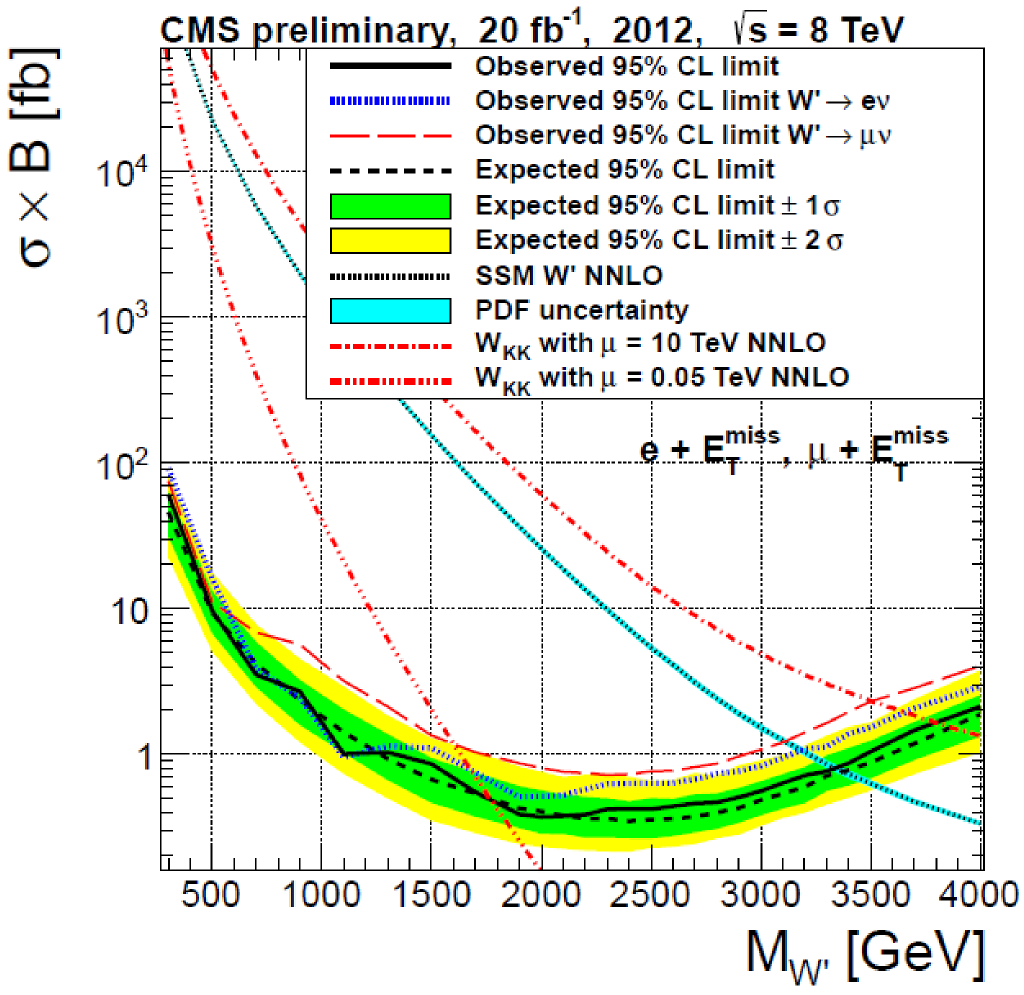
PAS EXO12060

- Many models possible
  - right-handed W' bosons with standard-model couplings
  - left-handed W' bosons including interference
  - Kaluza-Klein W'_{KK}-states in split-UED
  - Excited chiral boson (W*)
- Event Selection and Backgrounds
  - back-to-back isolated lepton and E_T^{miss}
  - Plot transverse mass of lν system
  - backgrounds from W, QCD, tt+single t, DY, VV from data



$$M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

W’ → lν in 8 TeV Data

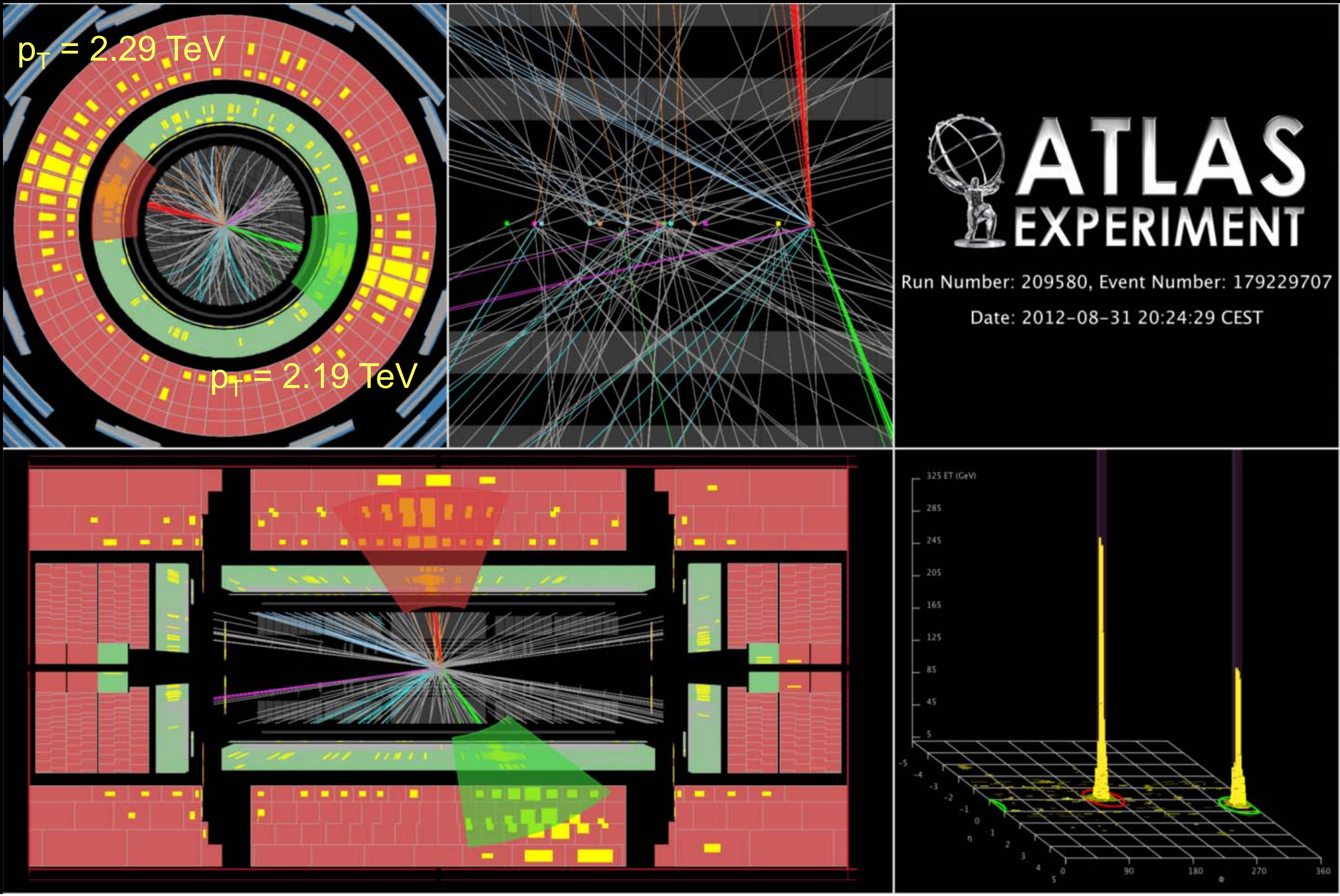


M(W’SSM) 95% CL	Observed
ATLAS e+μ, 2011,4.7fb-1	> 2.55 TeV
CMS e+μ, 2012, 20fb-1	> 3.35 TeV

M(W’SSM) > 3.35 TeV 95% CL

[ATLAS hep-ex 1209.4446]
CMS PAS EXO-12-060

Dijet Event Display with m_{inv} = 4.69 TeV



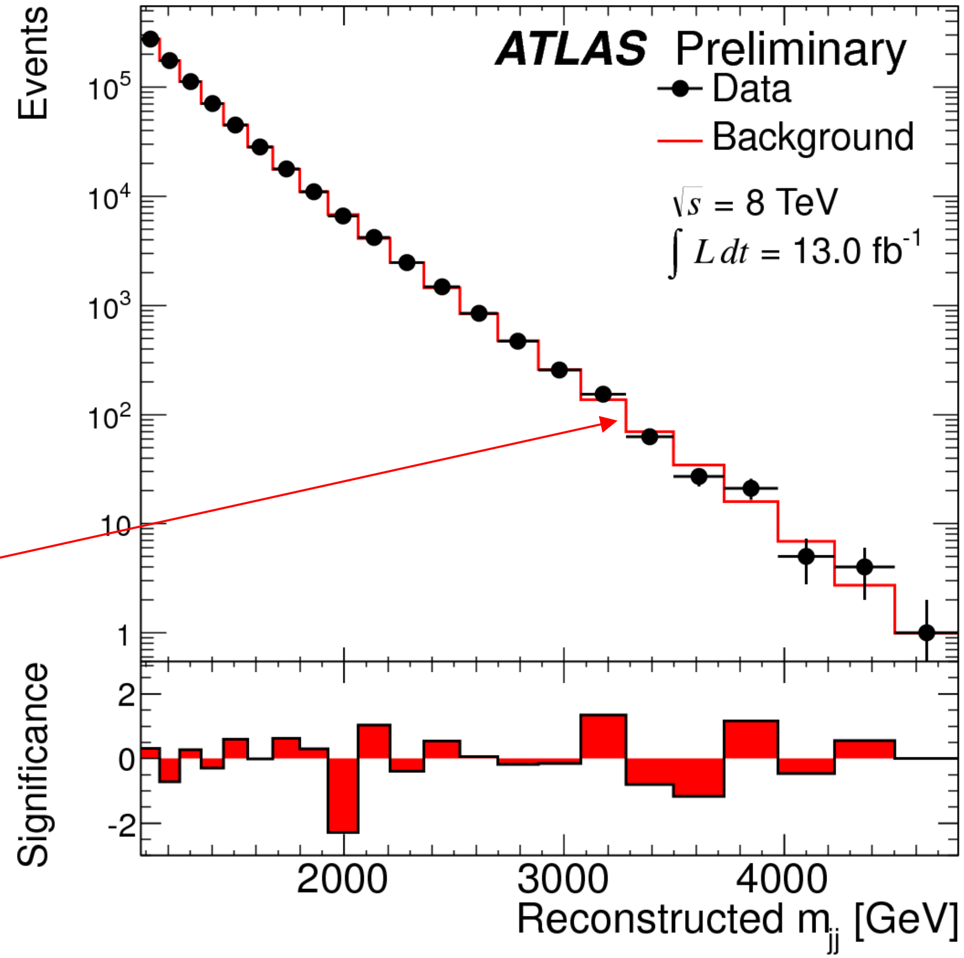
Heavy Resonance Search: 8 TeV Dijets

- Strong gravity, excited quarks
- Selections
  - Two anti-kt 0.6 jets
  - p^{j}_{T}>150 GeV && m_{jj}>1 TeV
  - |y|<2.8 && dijet CM rapidity |y*| < 0.6, $y^{*}=\pm 0.5^{*}(y_1-y_2)$
- Look for resonance above phenomenological fit of data

Probing quark structure ~ 5 TeV

$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x}$$

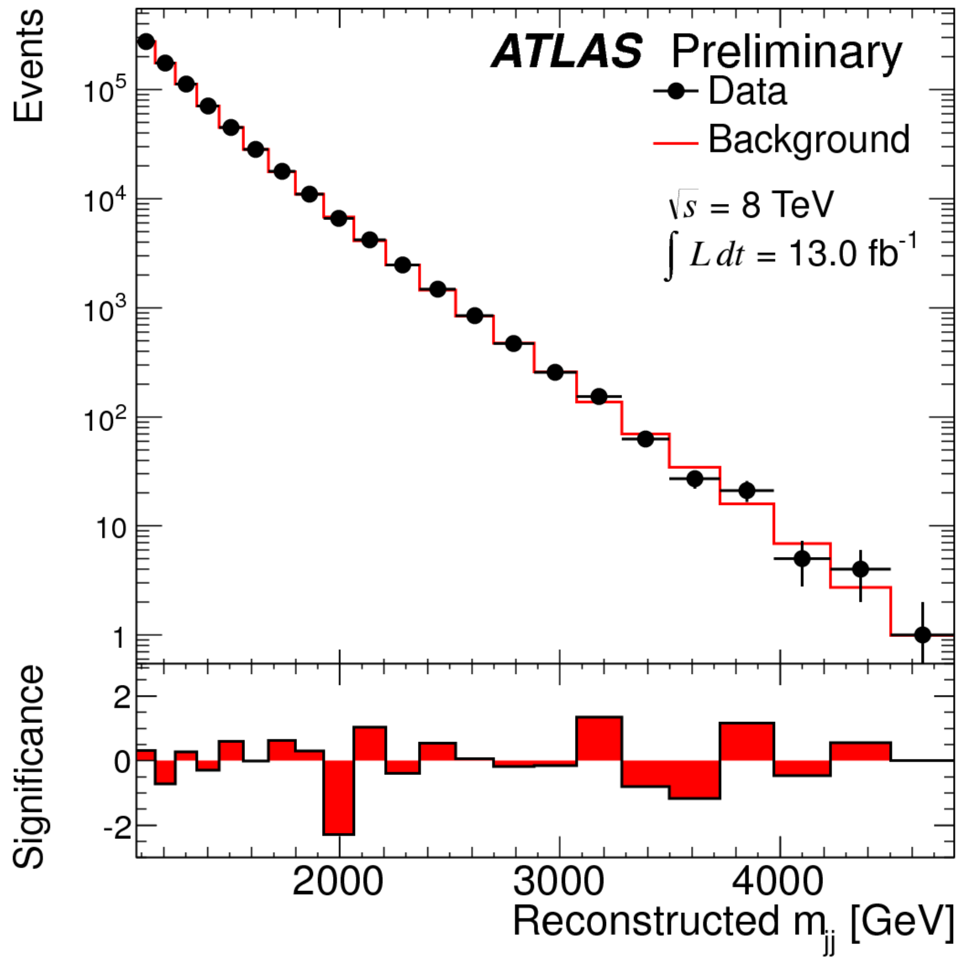
$$x \equiv m_{jj}/\sqrt{s}$$



ATLAS-CONF-2012-148

Heavy Resonance Search: 8 TeV Dijets

- Good agreement btw data and fit.
  - Global χ^2/NDF=15.5/18 = 0.86 → p-value = 0.61
  - good agreement btw data and fit
  - Bump Hunter

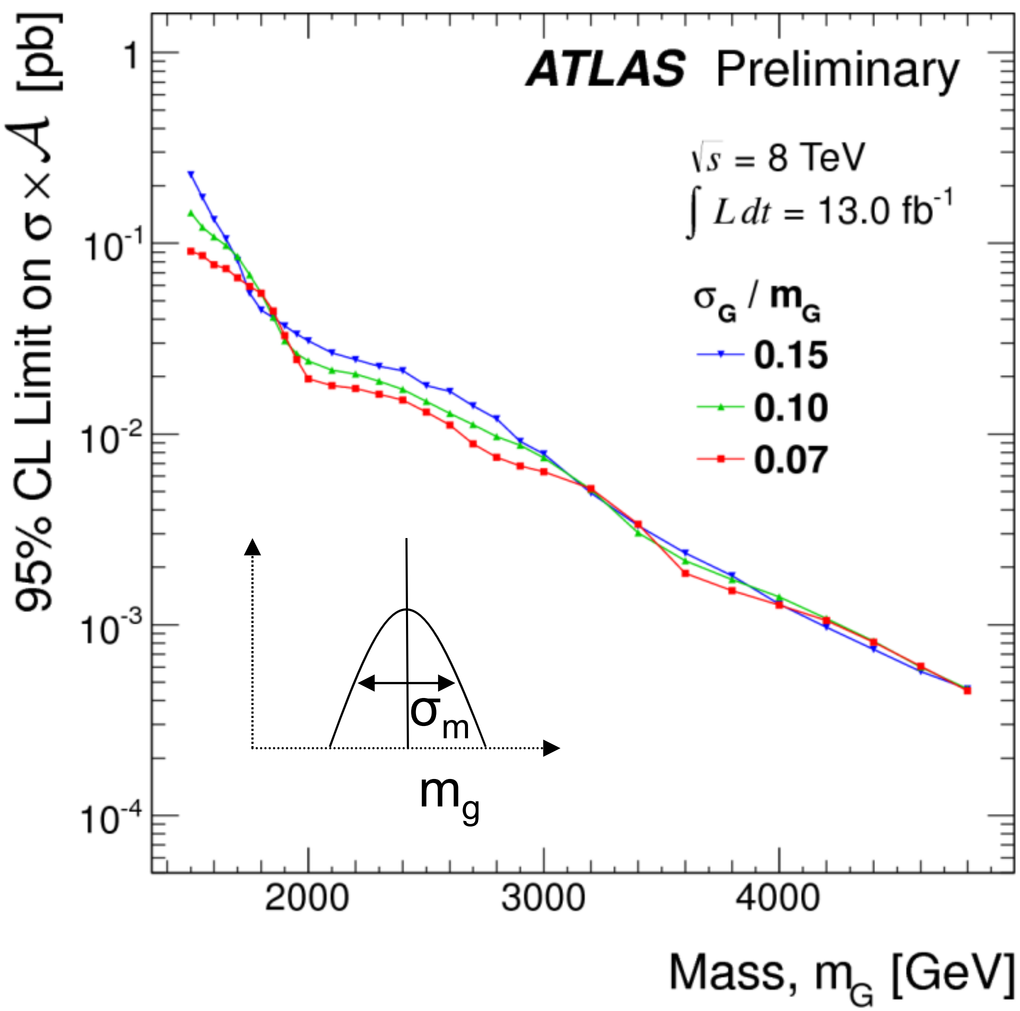


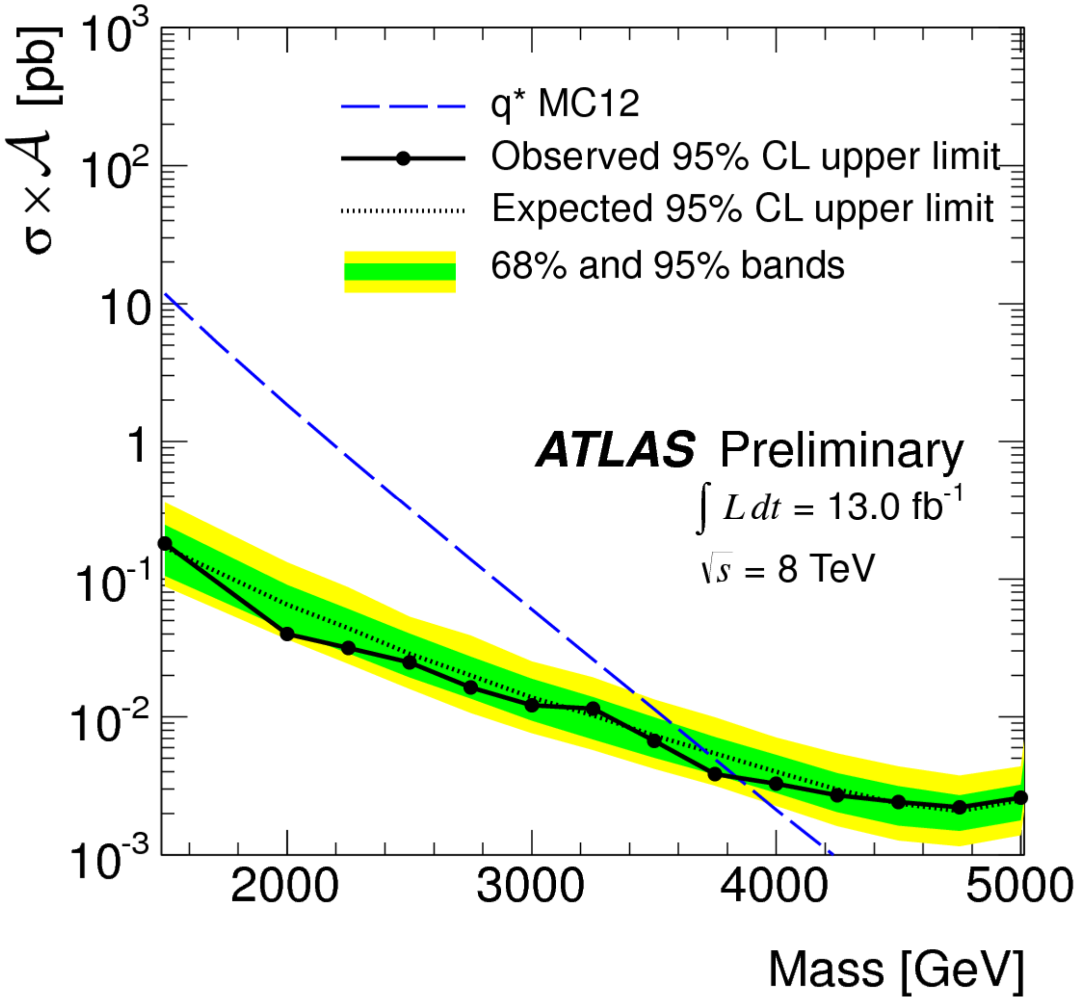
ATLAS-CONF-2012-148

Heavy Resonance Search: 8 TeV Dijets

Gaussian resonance limits: mean mass, $m_{G,}$ and 3 σ_G

Excited quark limit: m > 3.84 TeV at 95% CL

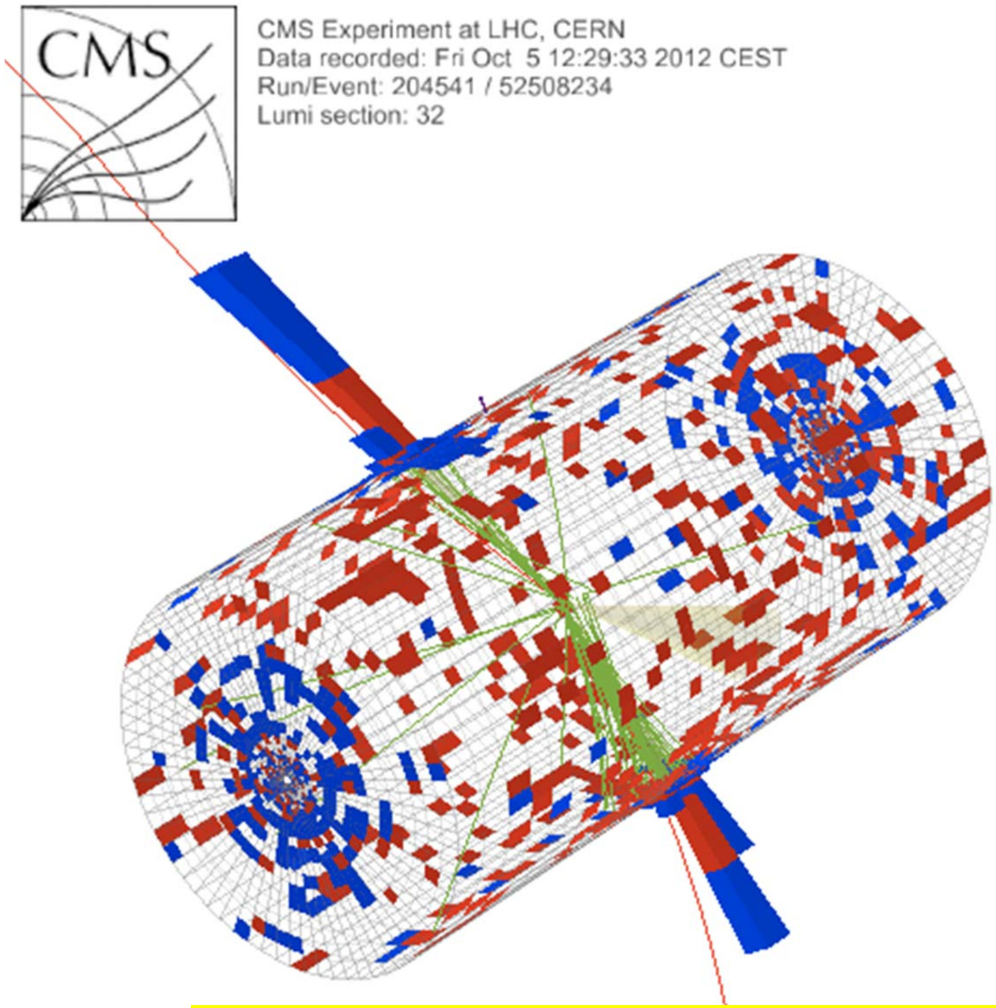




Heavy Resonance Search: 8 TeV Dijets

CMS-PAS-EXO-12-059

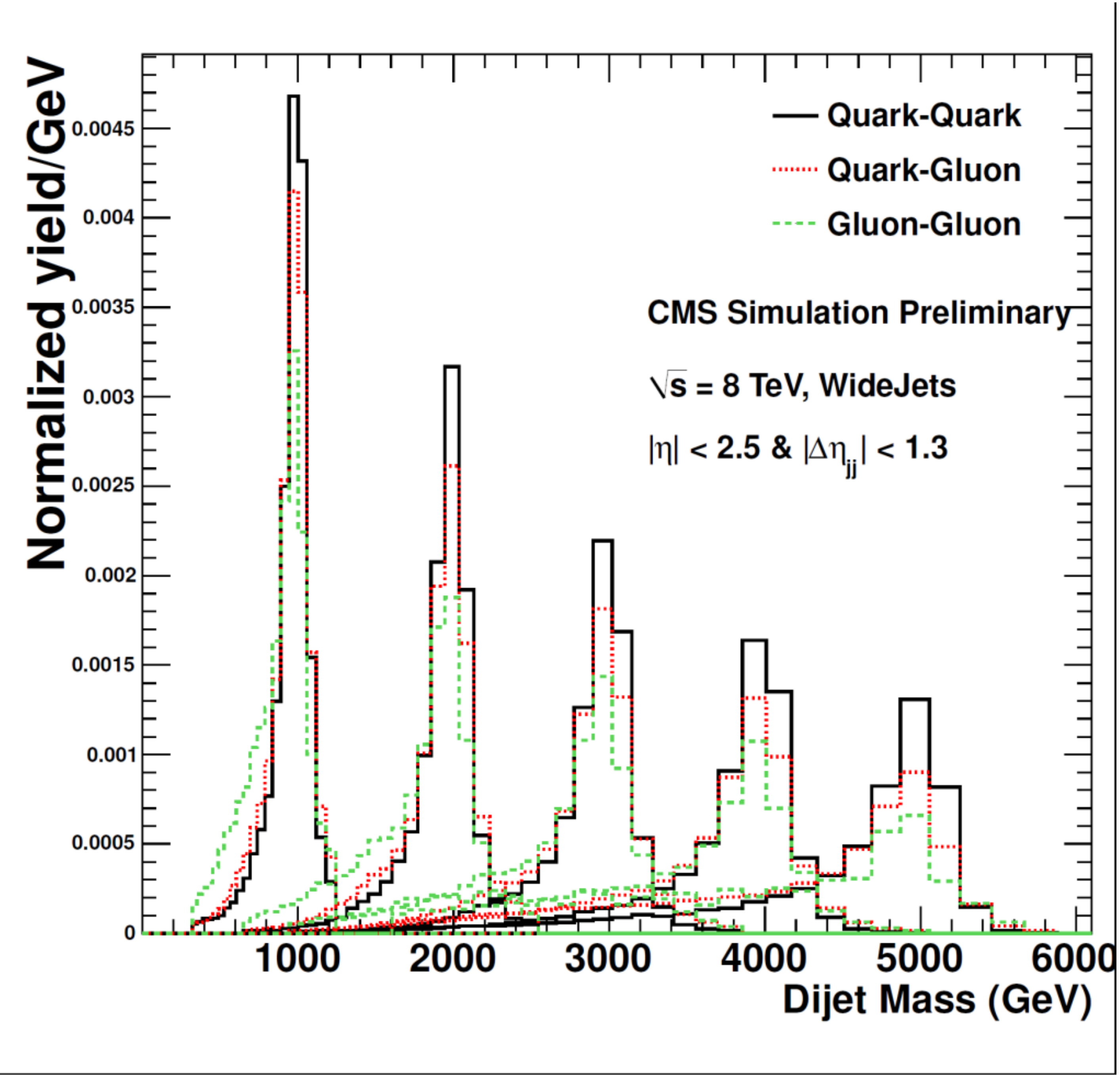
- Trigger:
  - L1: single jet trigger
  - HLT:
    - H_T>650 GeV && m_{jj}>750 GeV
- Jets with R=0.5
- p_T > 30 GeV, |η| < 2.5
- combines 0.5 jets into "wide jets" with R = 1.1
- two wide jets satisfy
  - $|\eta_{jj}|$ < 1.3
  - |η| < 2.5
  - M_{jj}>890 GeV



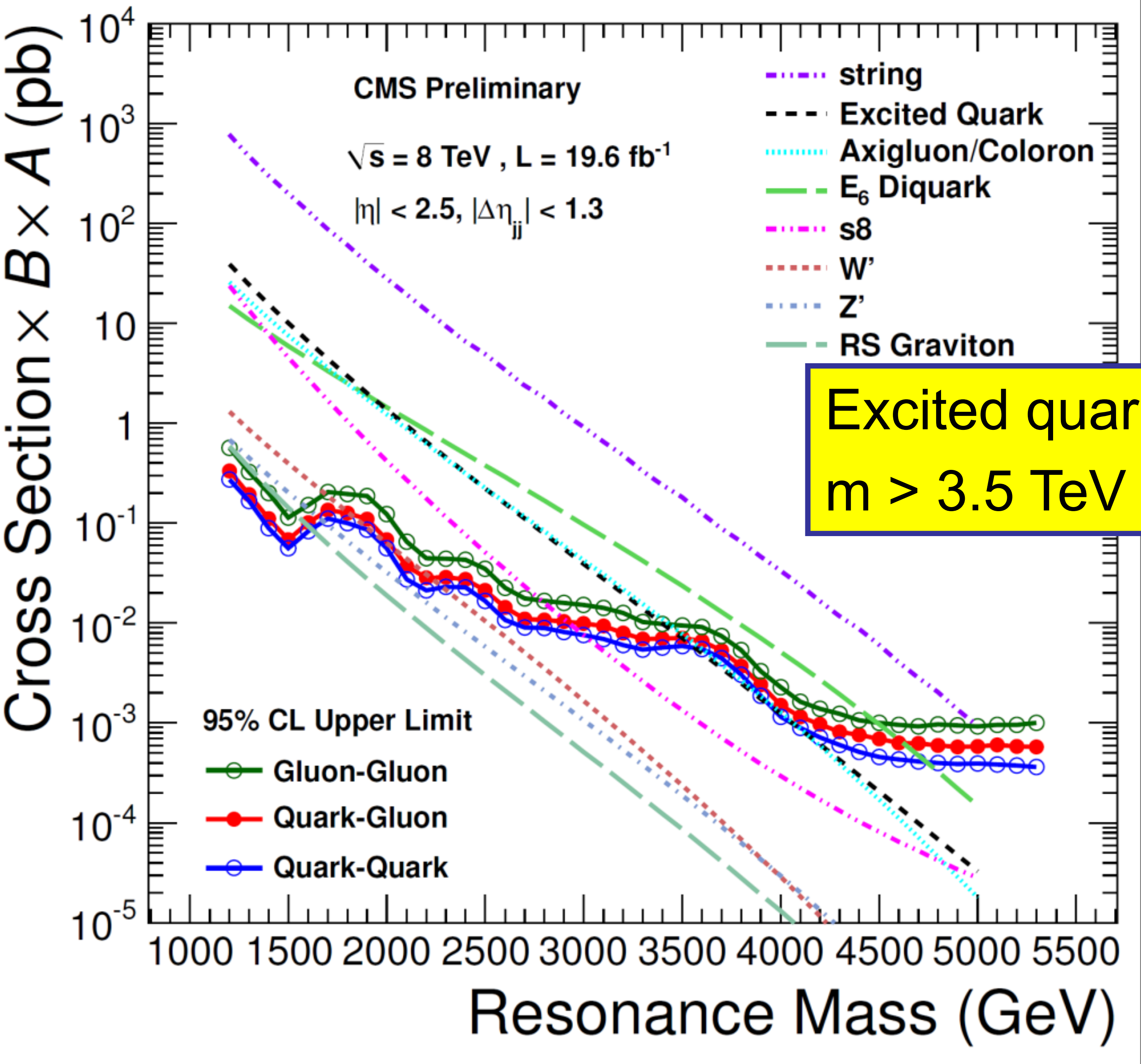
Highest invariant mass dijet event

m_{jj} = 5.15 TeV

Heavy Resonance Search: 8 TeV Dijets



Heavy Resonance Search: 8 TeV Dijets



Excited quark limit:

m > 3.5 TeV at 95% CL

$20.3\ fb^{-1}$

Dijet resonance + W/Z→lν/ll

ATLAS-CONF-2013-074

- Very interesting final state
  - Sensitive to VH
  - Extradimension
  - Technicolor, little Higgs

Selections
$p_T^{l\nu/ll} > 50$ GeV
≥2 jets with $p_T > 30$ GeV
$\lvert\Delta\eta_{jj}\rvert < 1.75$, $\lvert\Delta\varphi_{jj}\rvert > 1.6$

Backgrounds

- Estimated with MC
  - **W/Z+jets dominant**
  - ttbar
  - single-top
  - Diboson
- Multijet – estimate w data

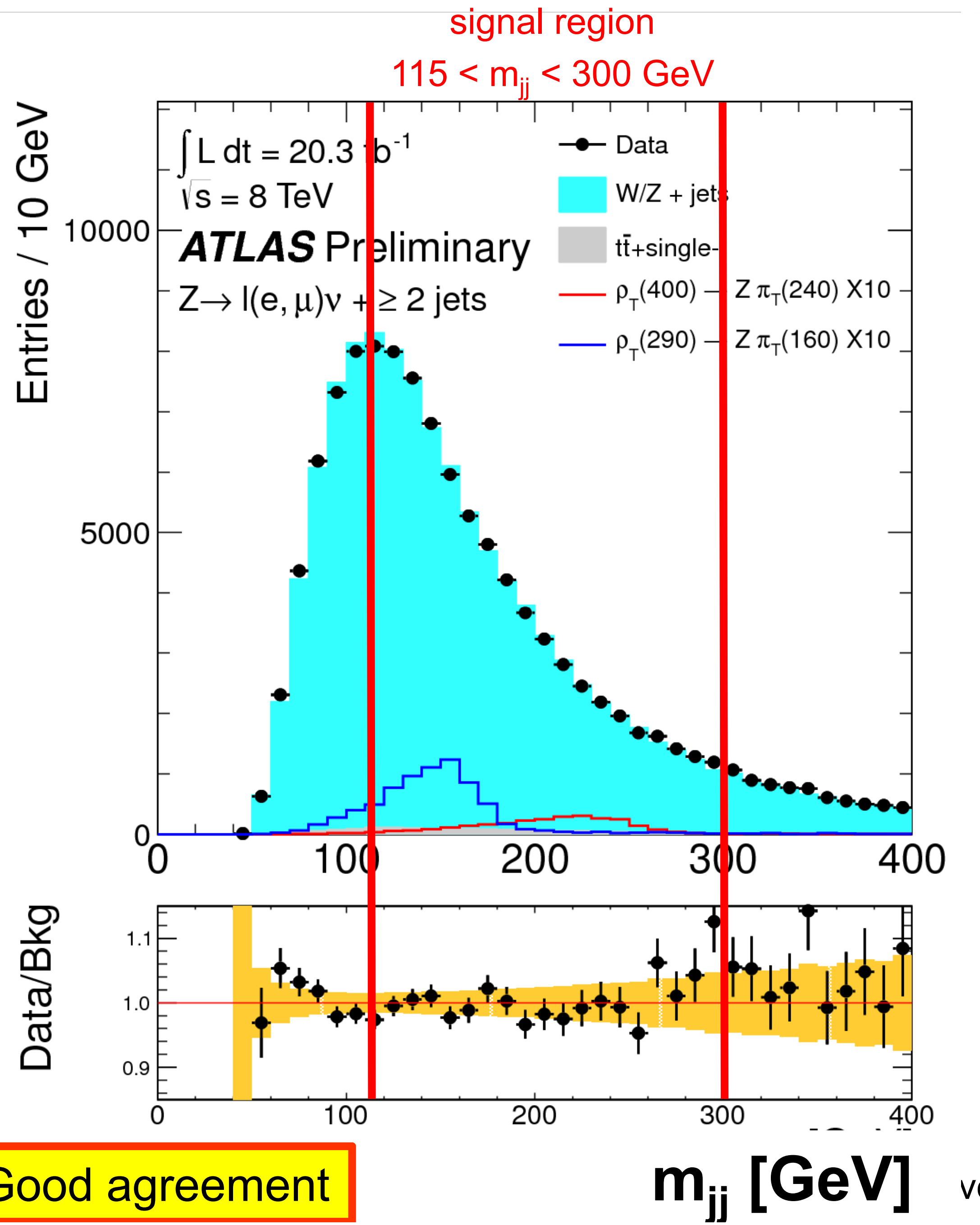
Systematic Uncertainties →

Source	$\Delta\sigma/\sigma$% for Wjj	$\Delta\sigma/\sigma$% for Zjj
W/Z+jets normalization	±5	±16
W/Z jets shape variation	±2	±4
Multijet shape and normalization	±5	N/A
Top normalization	±4	±7
Top Modeling	±3	±4
Jet energy scale (all samples)	±10	±11
Jet energy resolution (all samples)	±2	±3
Lepton reconstruction (all samples)	±1	±3
PDF (signal)	±5	±6
PDF (top)	±6	±3

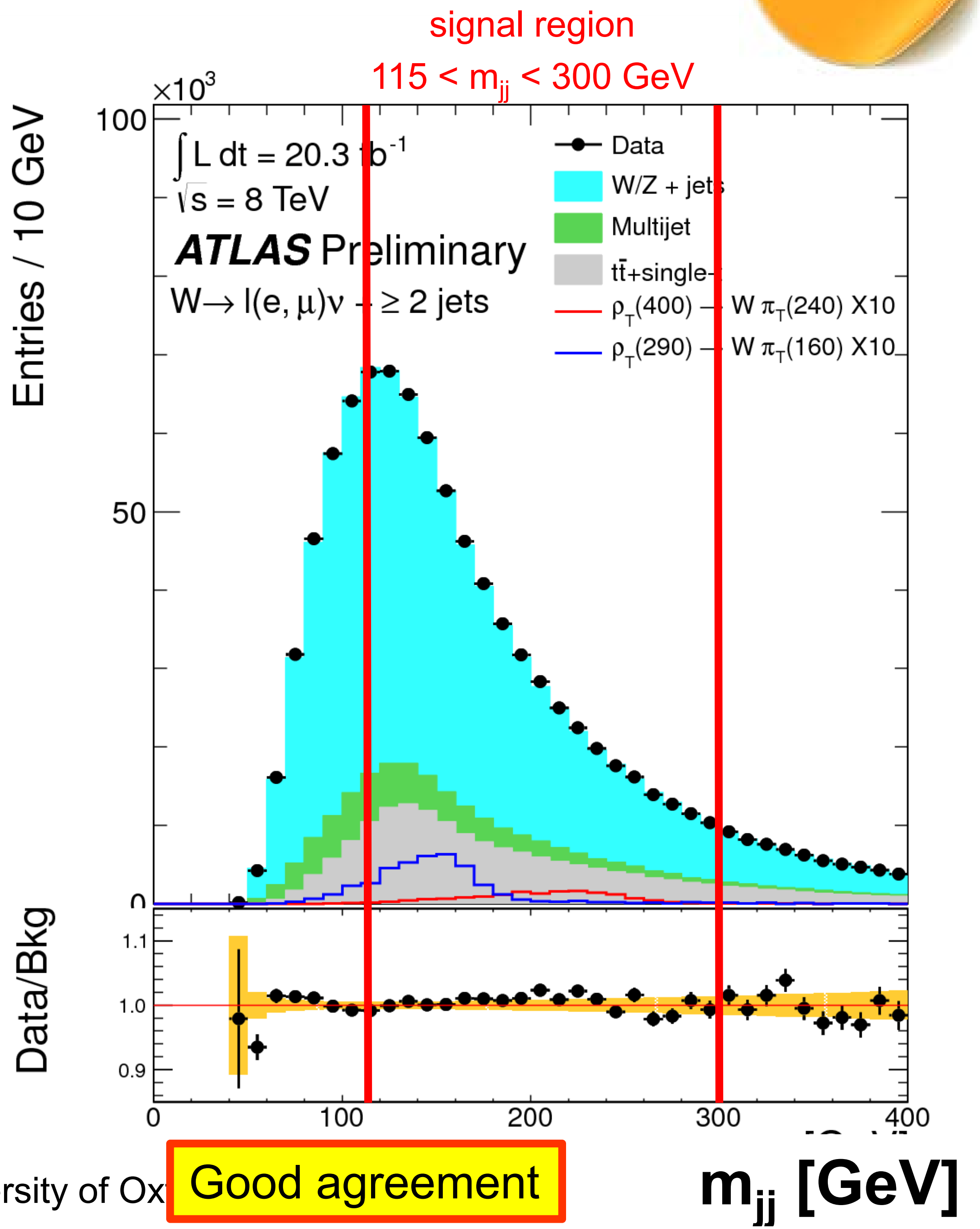
$m(\pi_T) = 180$ GeV

m_{jj} distributions for Z/W+2 jets

new



Good agreement



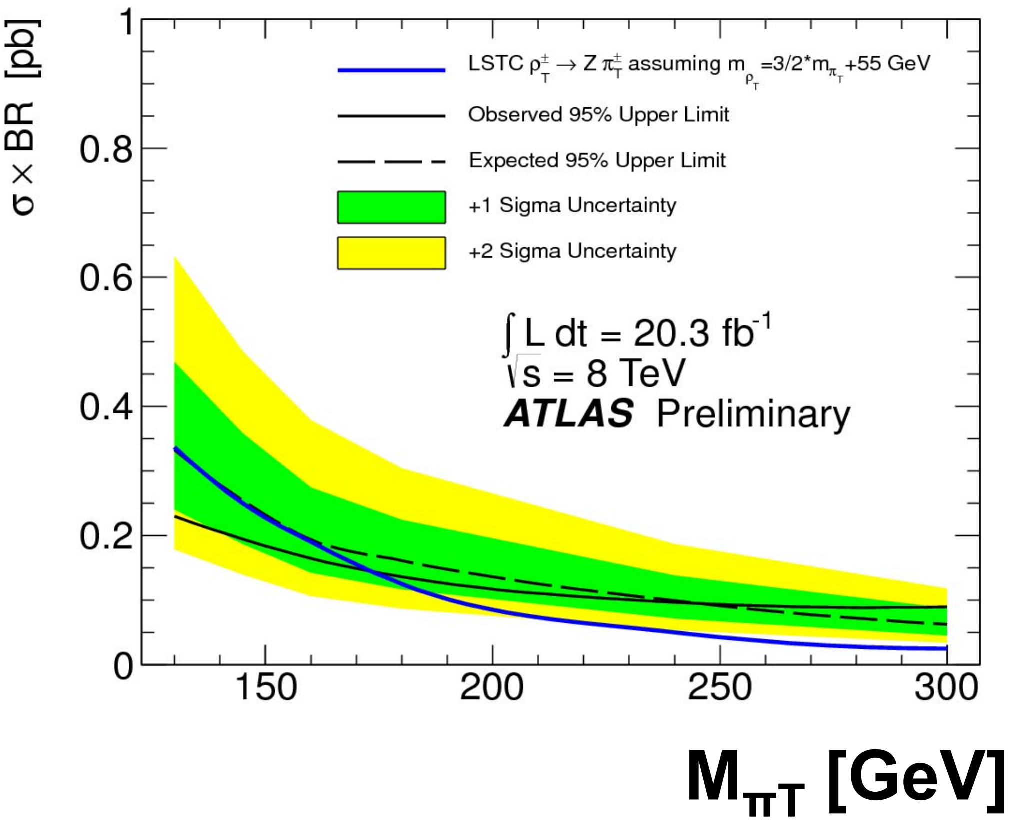
versity of Ox

Good agreement

95% CL upper σXBR on LSTC Technipion + Z/W production

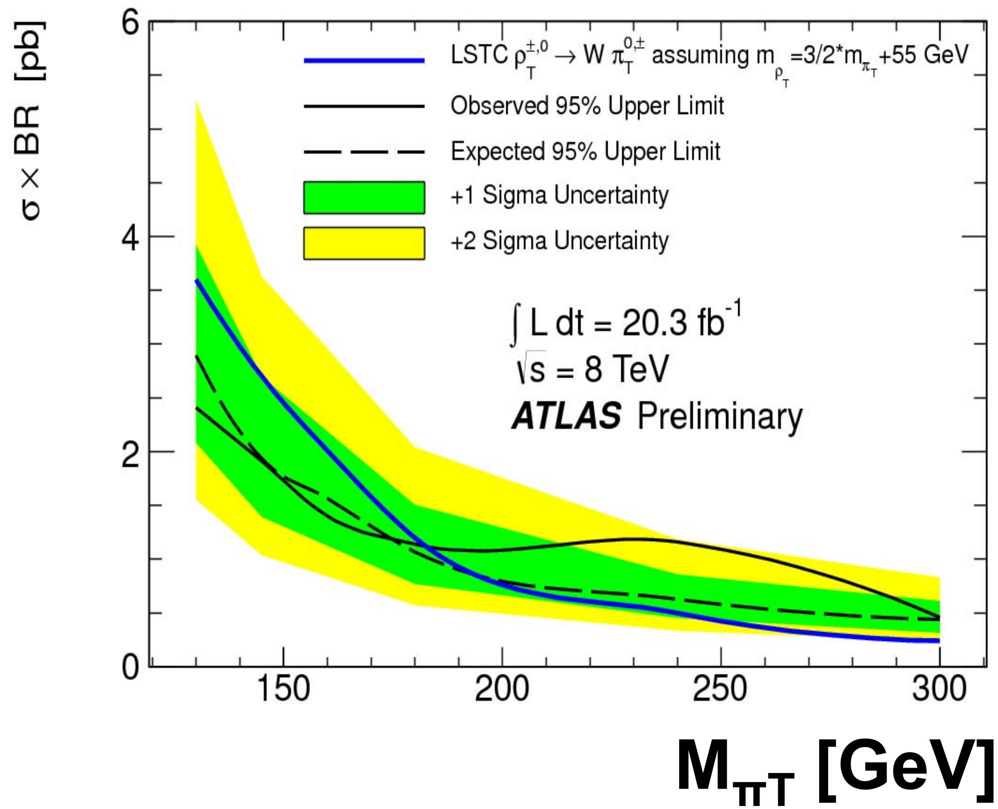
LSTC = Low Scale TechniColor

LSTC $\rho_T{}^{\pm} \rightarrow Z\pi_T{}^{\pm}$



$m_{\pi T} > 170$ GeV

LSTC $\rho_T{}^{\pm,0} \rightarrow W\pi_T{}^{0,\pm}$

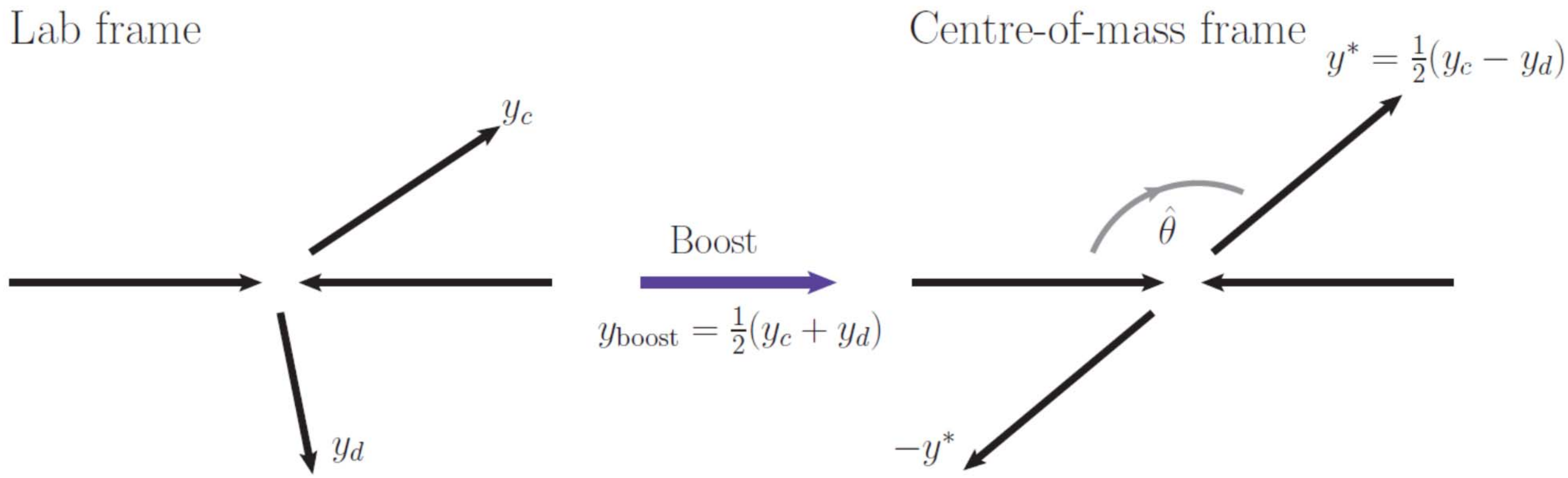


$m_{\pi T} > 180$ GeV

new

$$m_\rho = \frac{3}{2} * m_\pi + 55\ GeV$$

Search for Heavy Resonance: Dijet Angular



$d\hat{\sigma}/d(\cos\hat{\theta}) \propto \sin^{-4}(\hat{\theta}/2)$ t-channel Spin-1 exchange

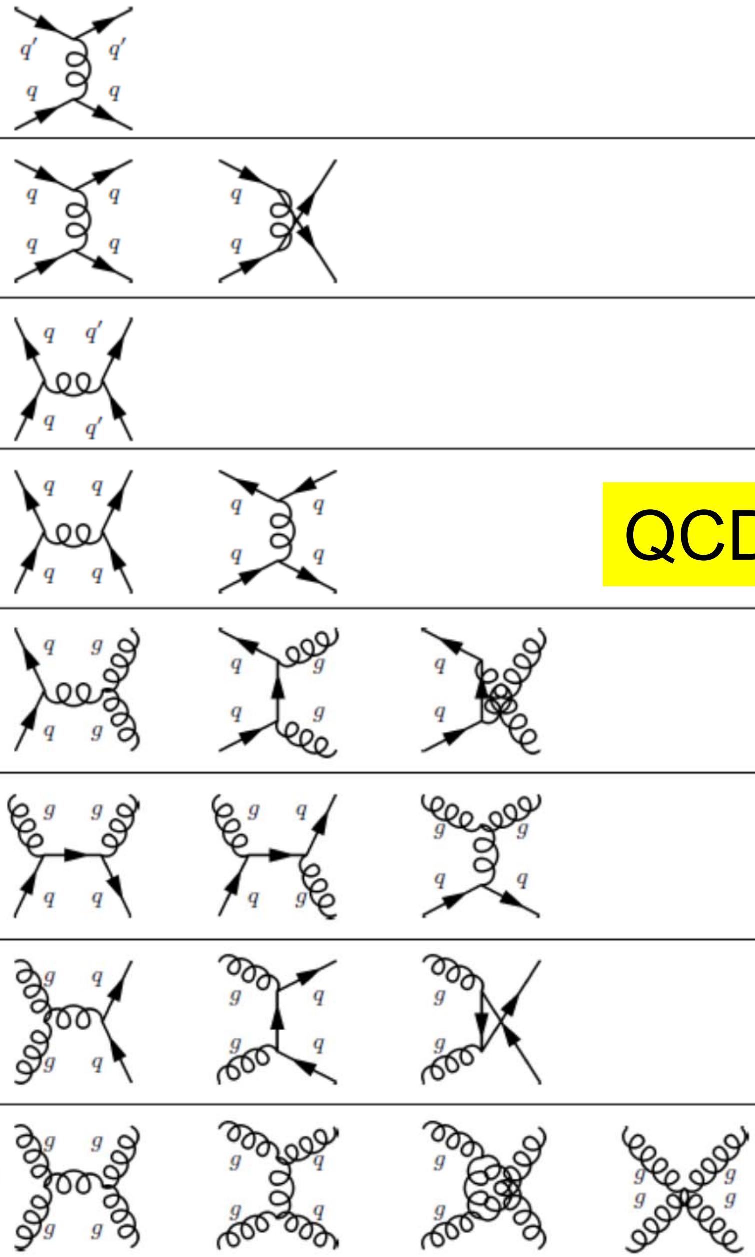
$$\chi = \frac{1 + |\cos\hat{\theta}|}{1 - |\cos\hat{\theta}|} \sim \frac{1}{1 - |\cos\hat{\theta}|} \propto \frac{\hat{s}}{\hat{t}}$$

$$\frac{d\hat{\sigma}}{d\chi} \propto \frac{\alpha_s^2}{\hat{s}} \quad (\hat{s} \text{ fixed}) \quad \hat{s} = m_{jj}$$

Constant in χ for fixed m_{jj}

Search for Heavy Resonance: Dijet Angular

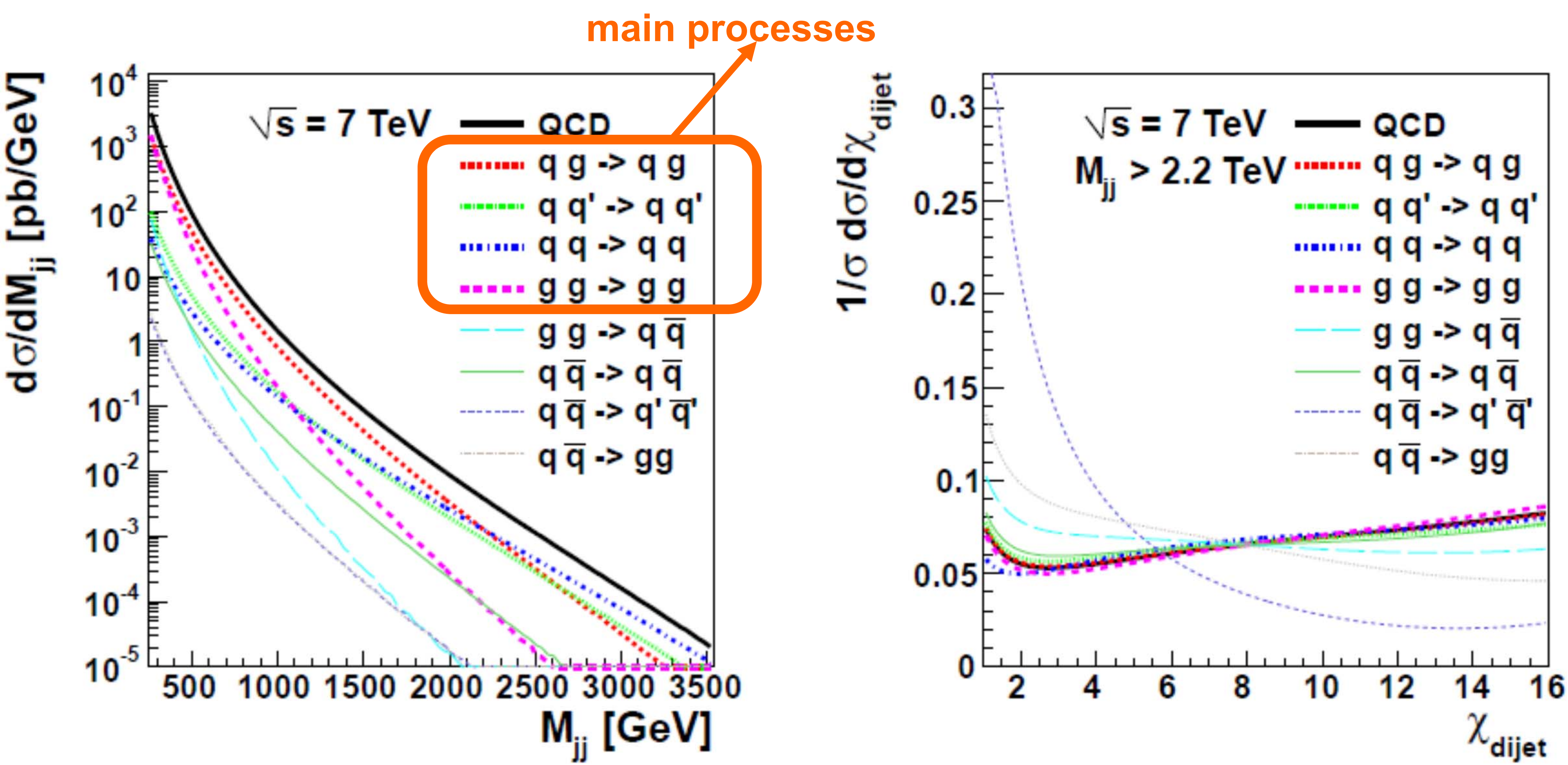
$qq' \to qq' = q\bar{q}' \to q\bar{q}'$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)$
$qq \to qq$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}-\frac{2}{3}\frac{\hat{s}}{\hat{u}\hat{t}}\right)$
$q\bar{q} \to q'\bar{q}'$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)$
$q\bar{q} \to q\bar{q}$	$\frac{64}{9}\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}-\frac{2}{3}\frac{\hat{u}^2}{\hat{s}\hat{t}}\right)$
$q\bar{q} \to gg$	$\frac{128}{3}\alpha_s^2\left(\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
$qg \to qg$	$16\alpha_s^2\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}\right)$
$gg \to q\bar{q}$	$\frac{8}{3}\alpha_s^2\left(\frac{1}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{4}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)$
$gg \to gg$	$72\alpha_s^2\left(3+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}+\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)$



QCD is a bit more complicated…..

Andreas Dominik Hinzmann

Search for Heavy Resonance: Dijet Angular



low M_{jj} gg and qg dominate

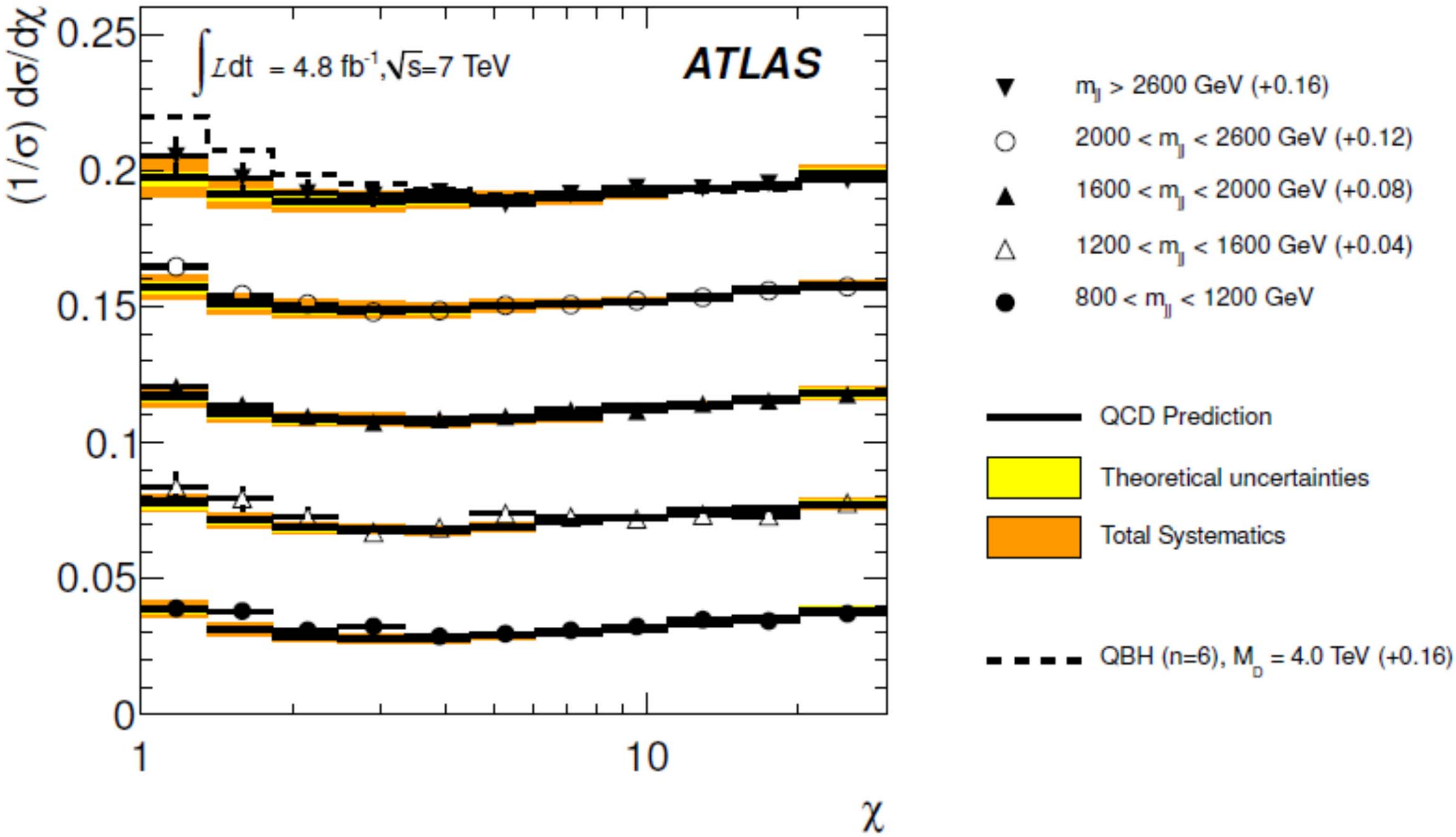
high M_{jj} qq dominate

QCD ~ flat in χ

Andreas Dominik Hinzmann

Search for Heavy Resonance: Dijet Angular

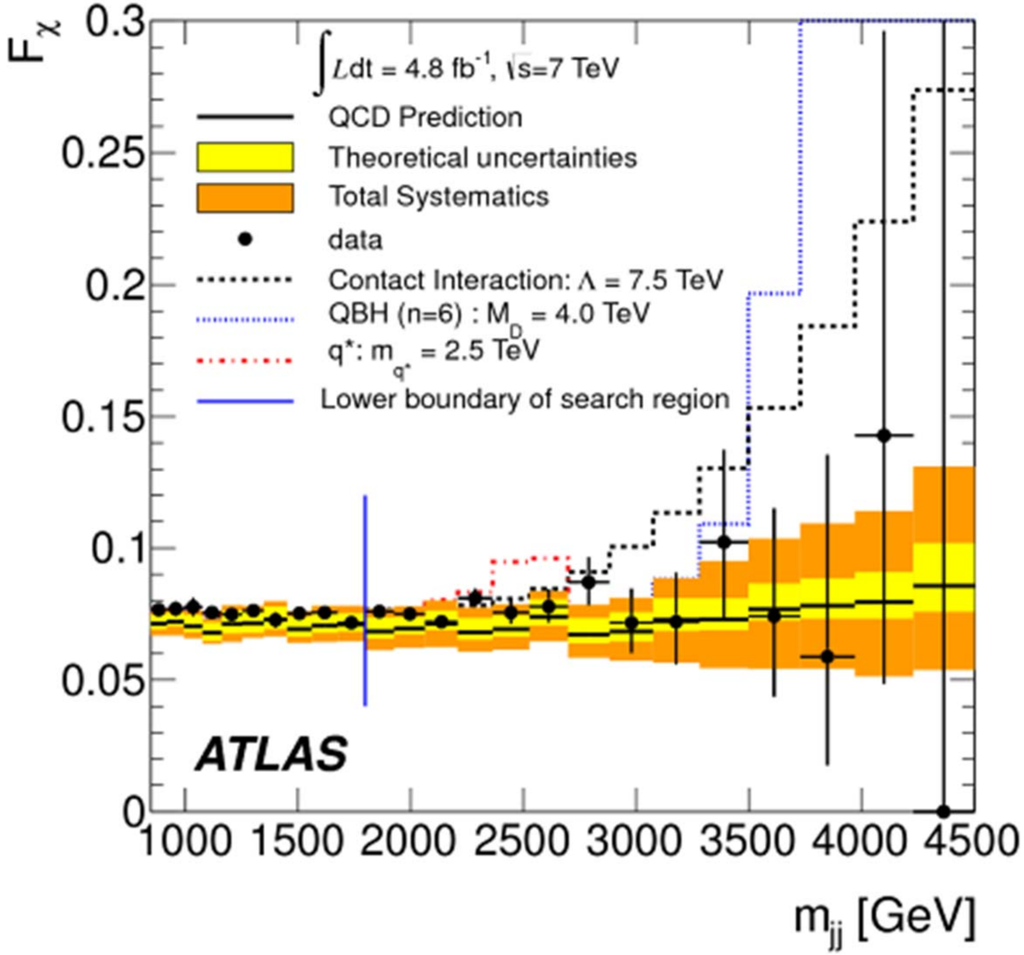
arXiv:1210.1718

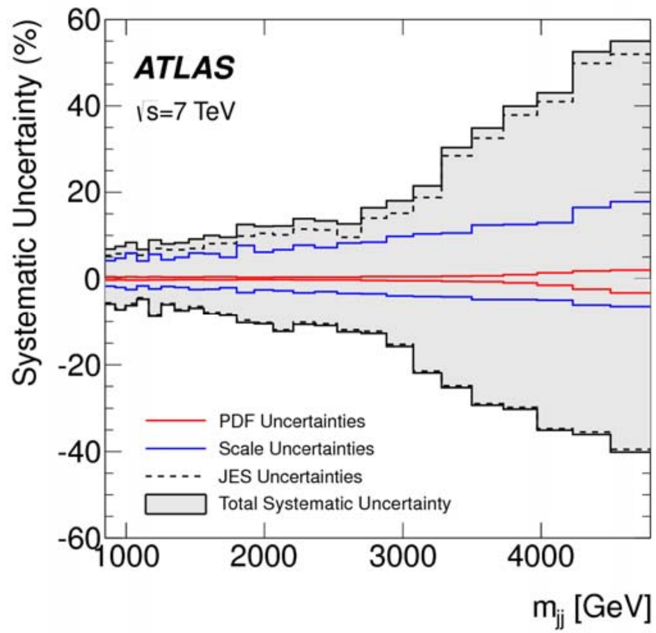


Search for Heavy Resonance: Dijet Angular

arXiv:1210.1718

$$F_\chi(m_{jj}) \equiv \frac{\mathrm{d}N_{\mathrm{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\mathrm{total}}/\mathrm{d}m_{jj}},$$

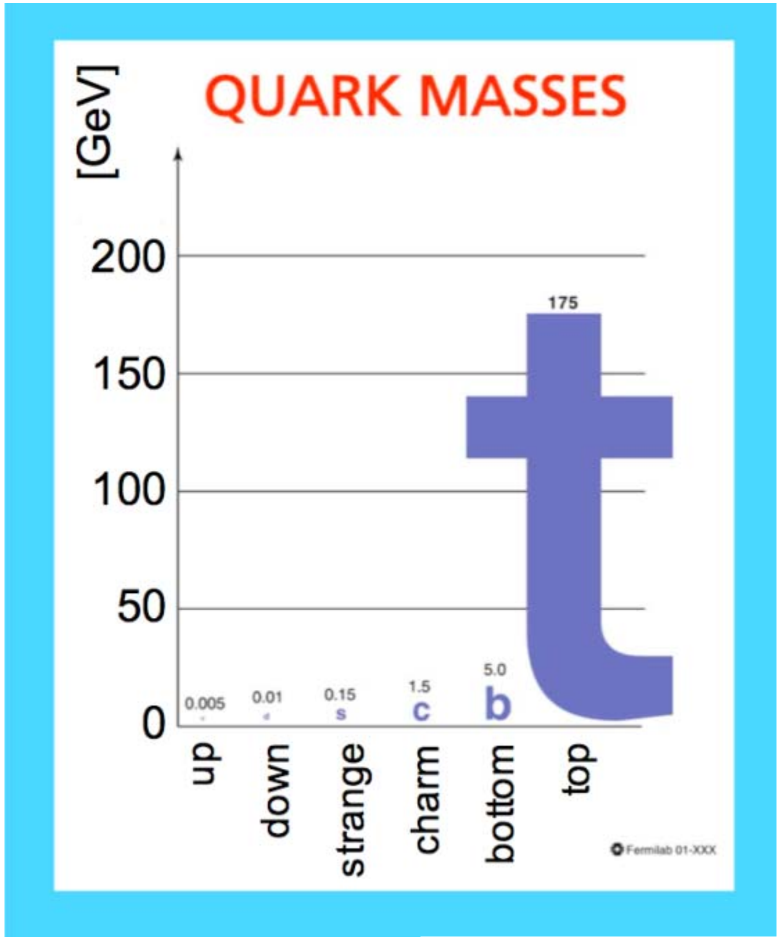




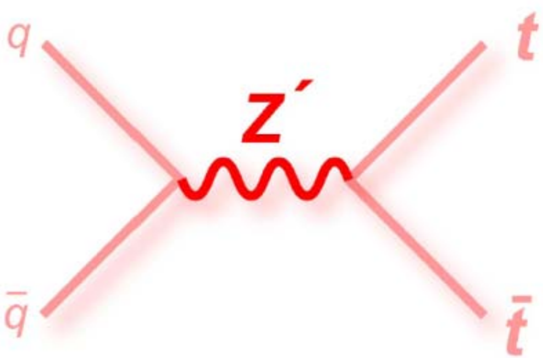
Models and Limits:

- Quark contact interaction (quark compositeness)
  - **Λ>7.6 TeV (7.7 TeV)**
- Quantum Black holes
  - M_D>4.1 TeV (4.2 TeV) n=6

New Physics Searches with high-pt top quarks



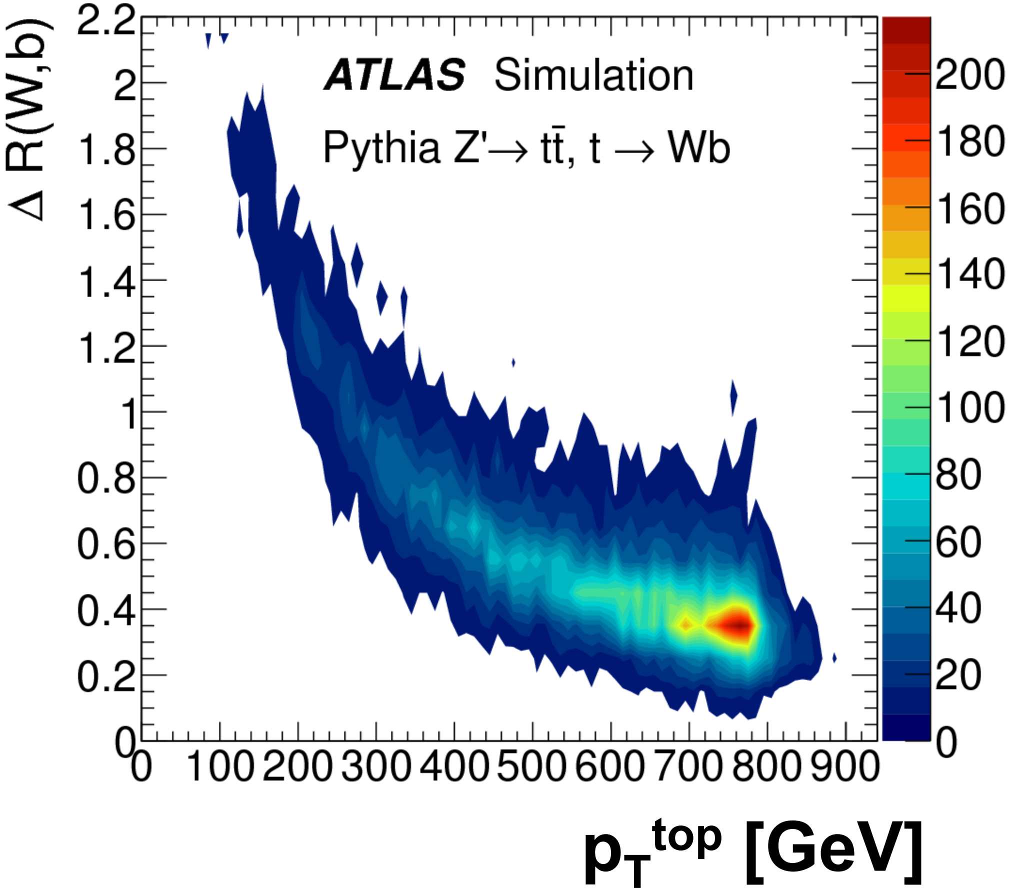
- Top quark properties
  - Highly coupled to EWK symmetry breaking
  - LHC is a top factory
- Huge mass of top
  - Bizarre
  - New physics
- Heavy new particles
  - Couple strongly to top
  - Produce boosted tops
- New techniques for top ID

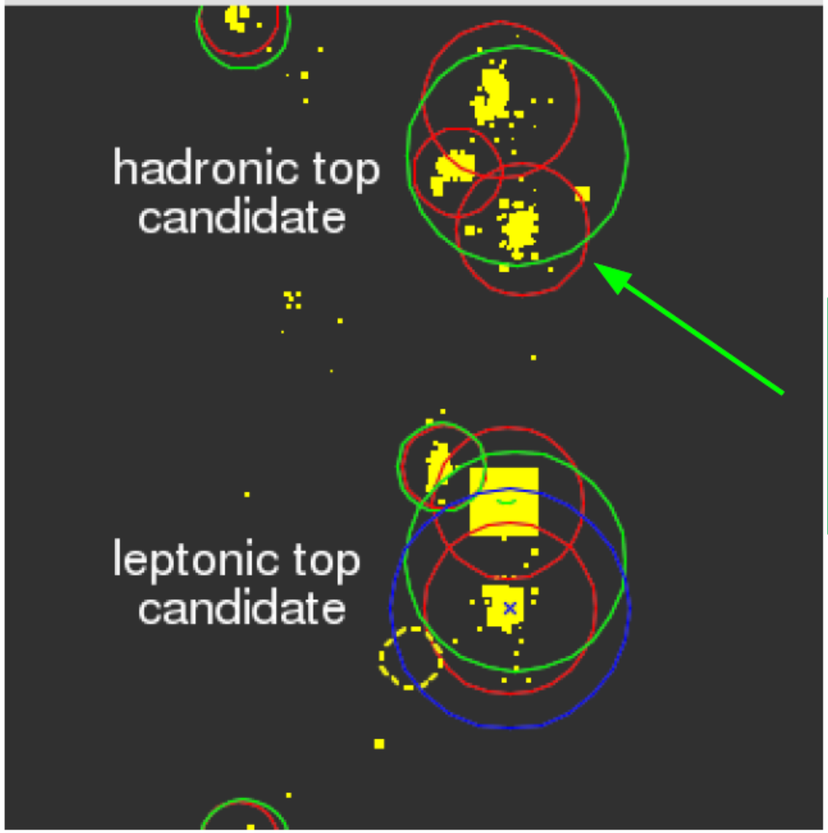


Boosted Regime

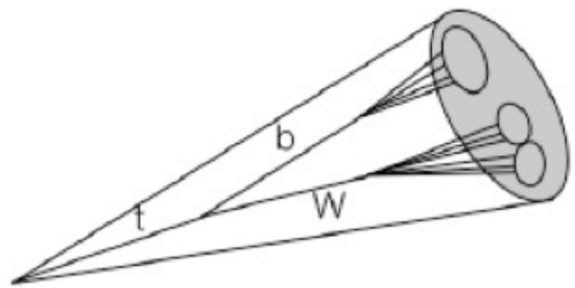
- Rule of thumb: $dR \sim \frac{2m}{p_T}$
- top with p_T > 350 GeV decay products within R~1

CERN-PH-EP-2013-069, arXiv:1306.4945

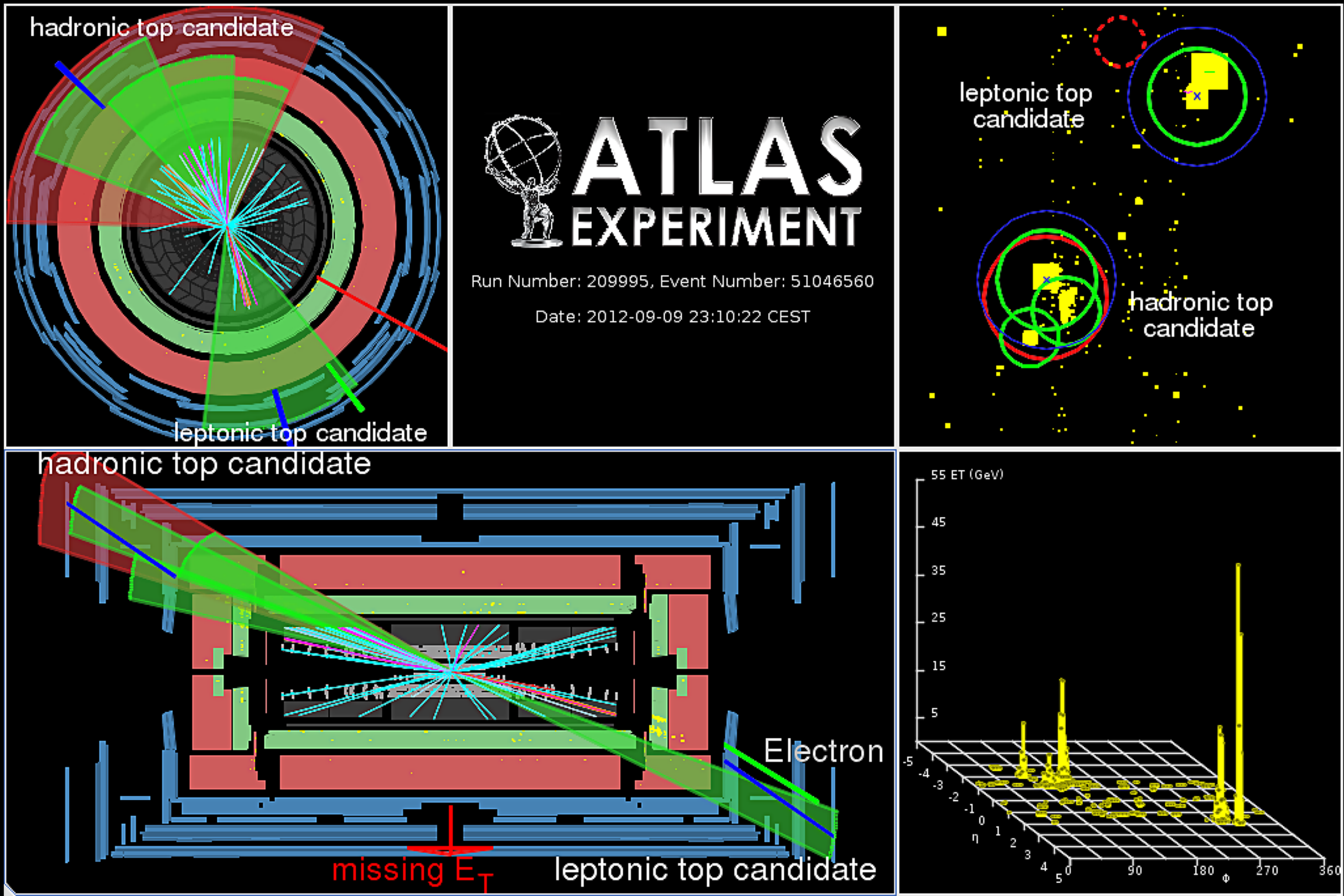




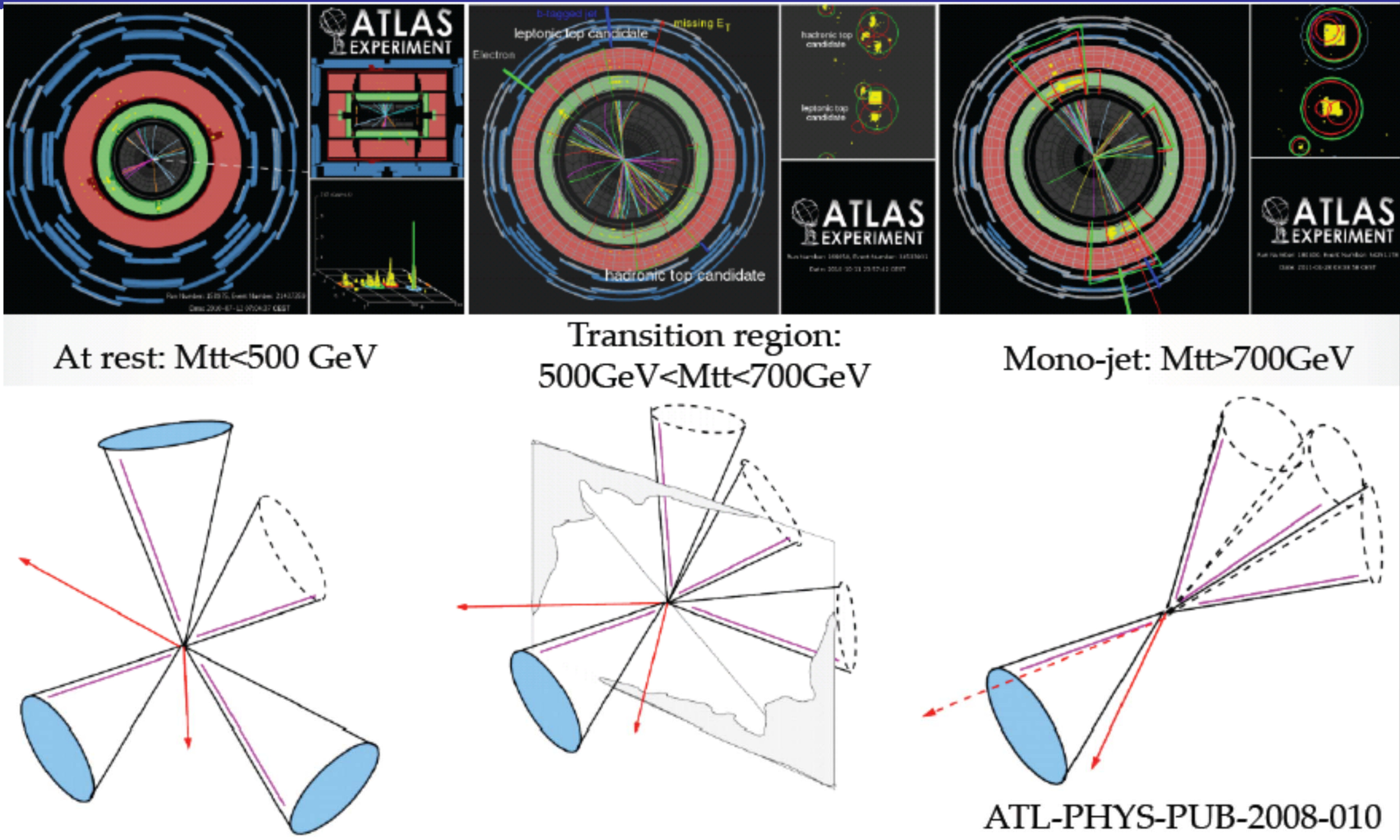
R = 1
m_j=197 GeV
P_T=356 GeV



Boosted Top Event Candidate with m_{ttbar}=2.5 TeV

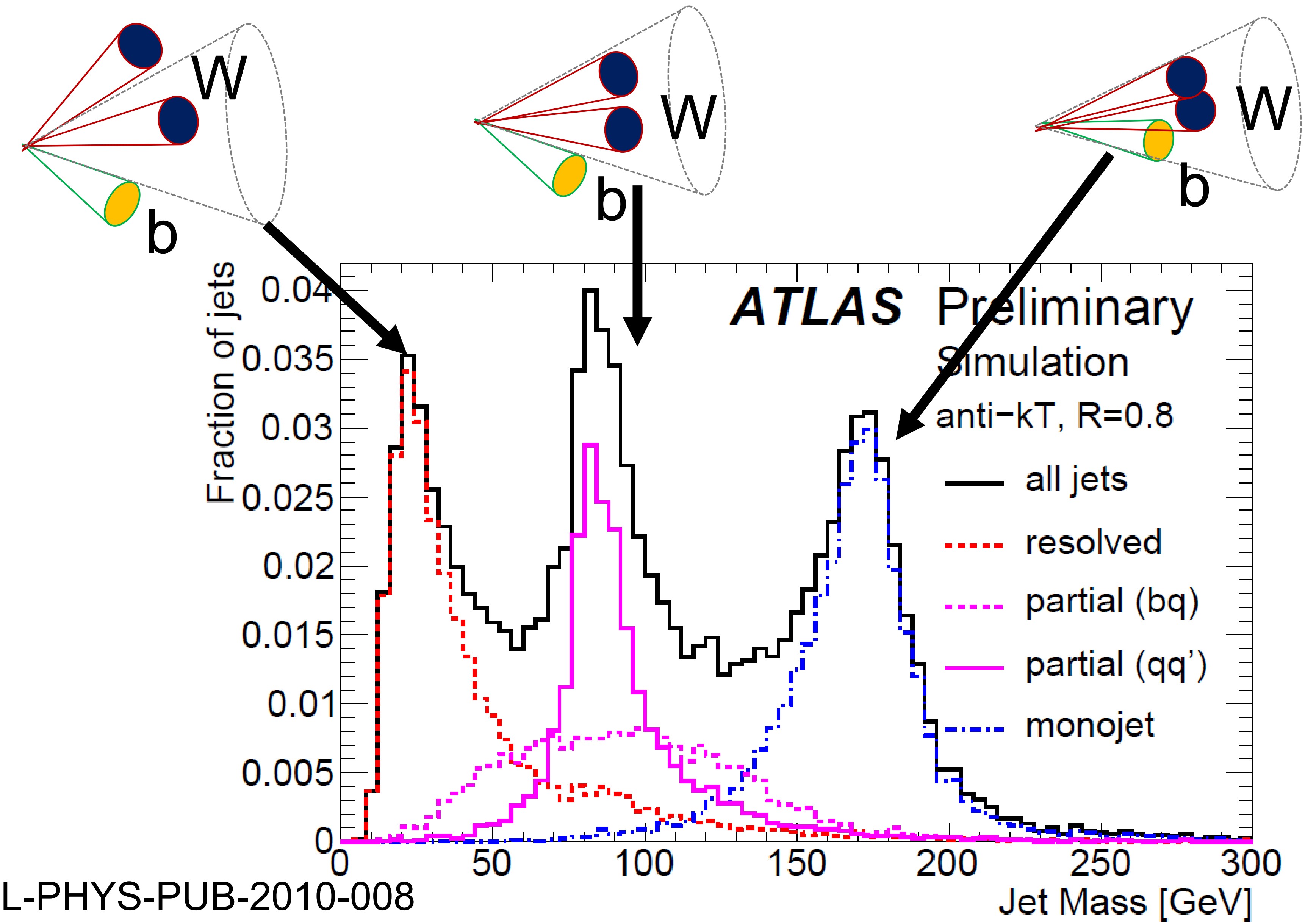


Top Reconstruction @ LHC: 3 Regimes



Jet Substructure: jet mass

- Use jet substructure to “tag” boosted tops



ATL-PHYS-PUB-2010-008

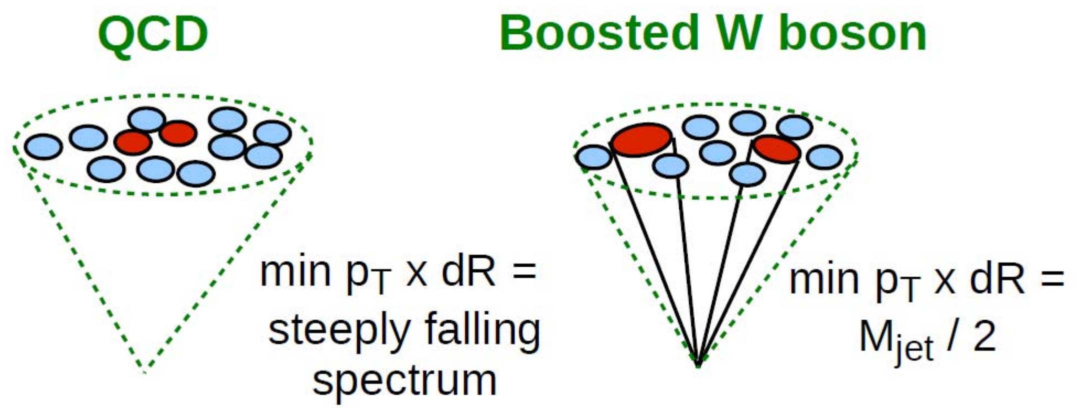
Jet Substructure: Splitting Scales

- e.g k_T-splitting scales

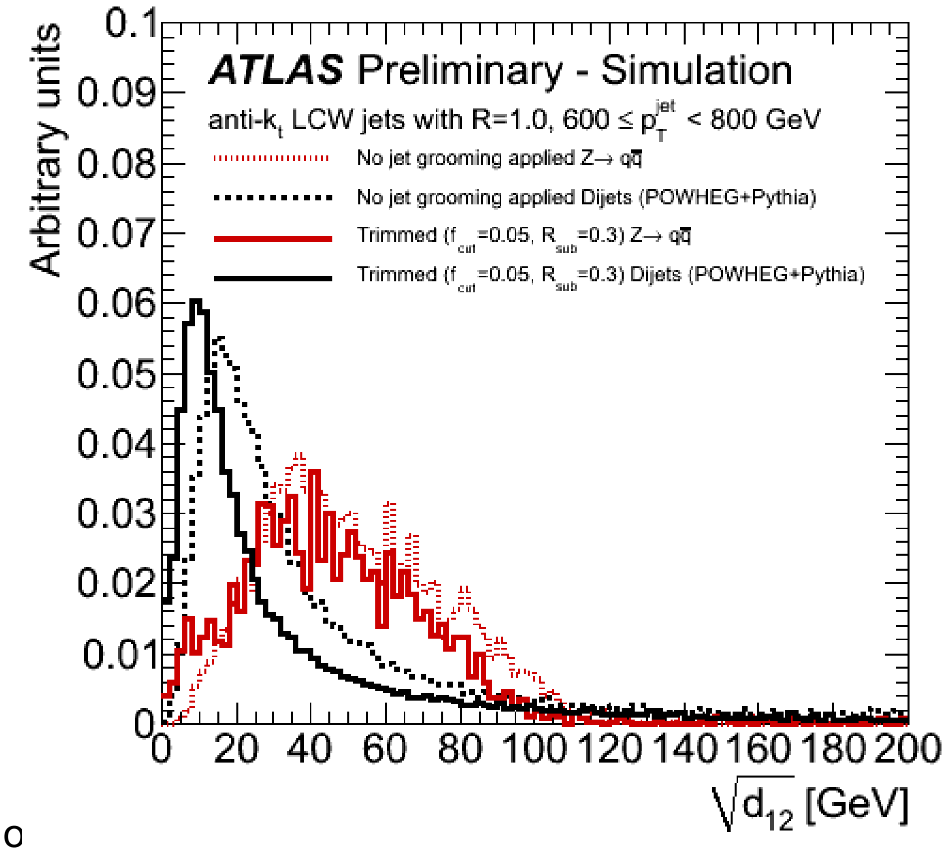
$$d_{ij} = \min({p^2}_{Ti}, {p^2}_{Tj}) \times {\Delta R^2}_{ij}/R^2$$

  - i, j constituents of current jet clustering step
- First: you reconstruct “fat-jet”
- Second: you re-cluster constituents using kt-algorithm

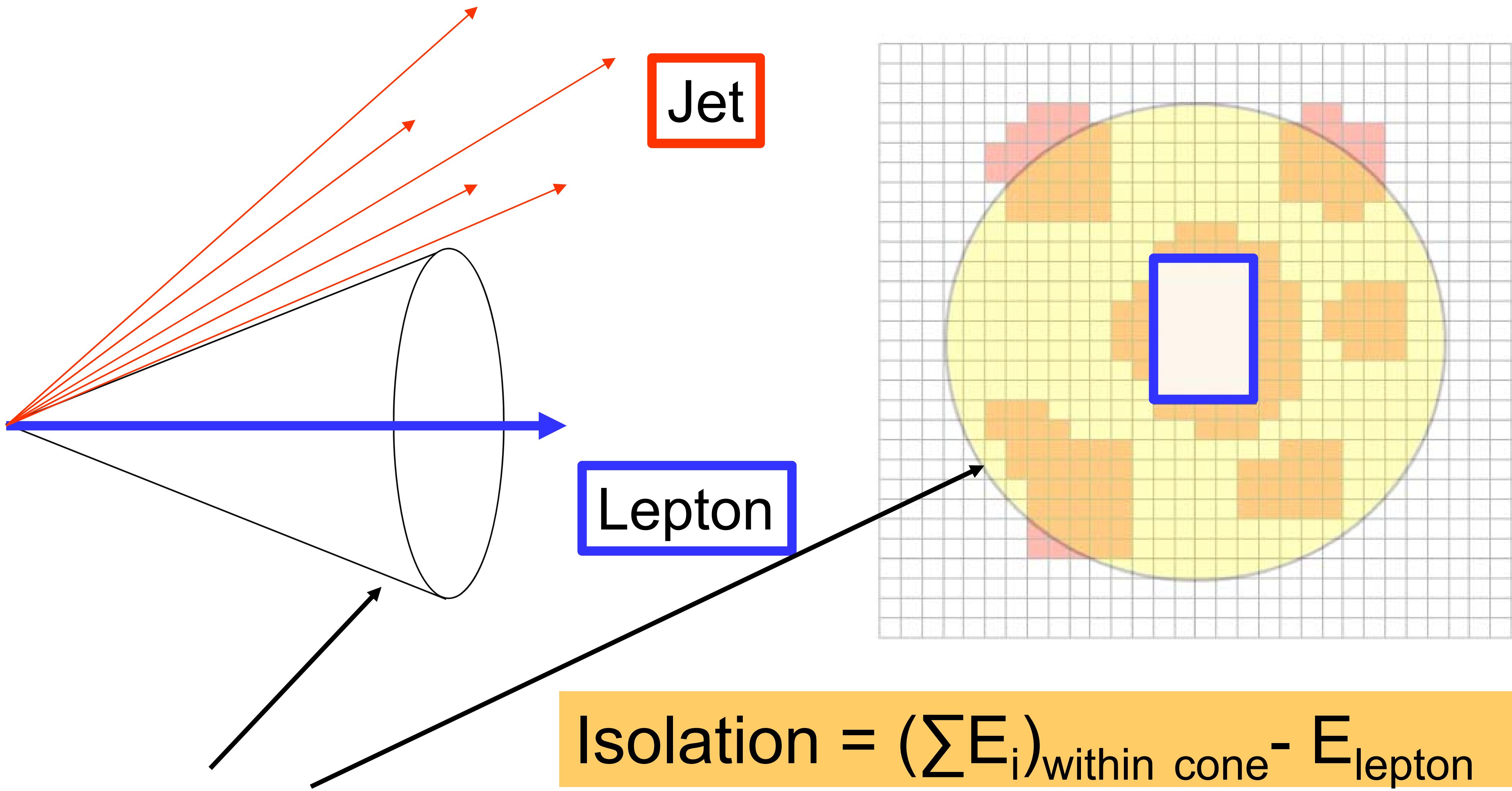
  → highest p_T constituents clustered last



E. Thompson, Jet Substructure and Boosted top-tagging at ATLAS



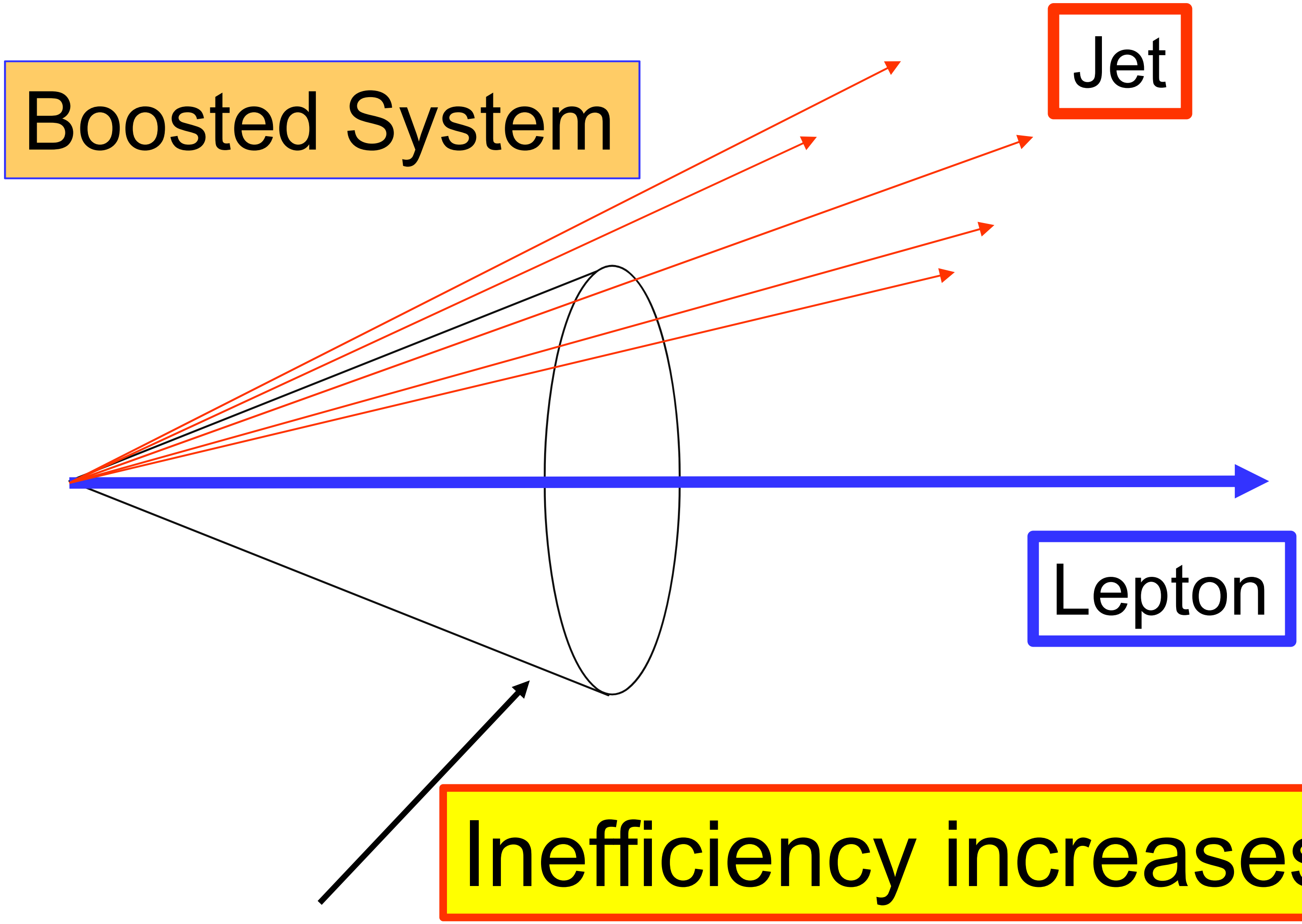
Fixed Cone Size Lepton Isolation



$$\text{Isolation} = (\sum E_i)_{\text{within cone}} - E_{\text{lepton}}$$

"Fixed" Isolation Cone

Fixed Cone Size Isolation



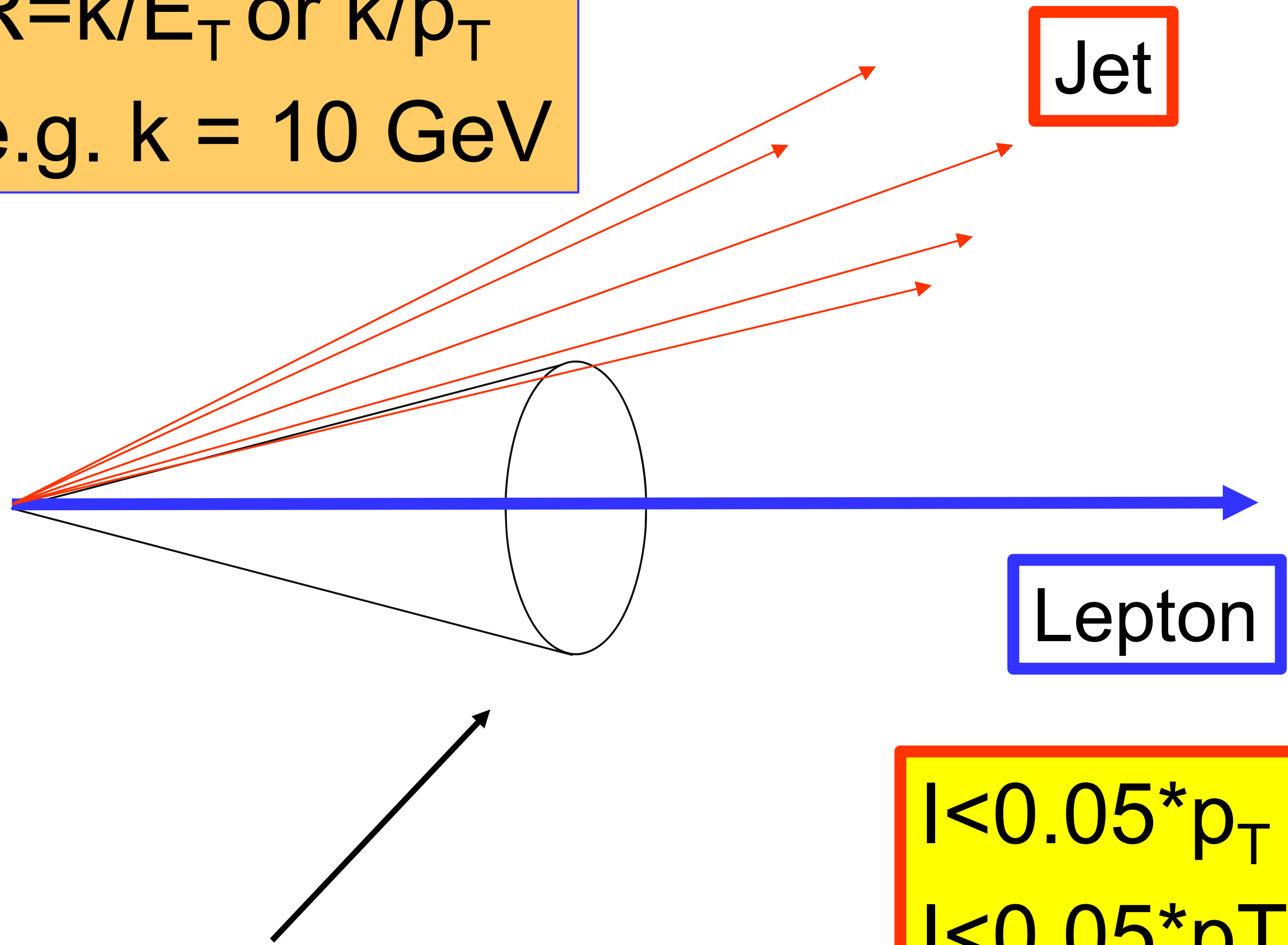
Inefficiency increases with boost !!!

"Fixed" Isolation Cone

Variable Isolation Cone

$R = k/E_T$ or k/p_T

e.g. k = 10 GeV

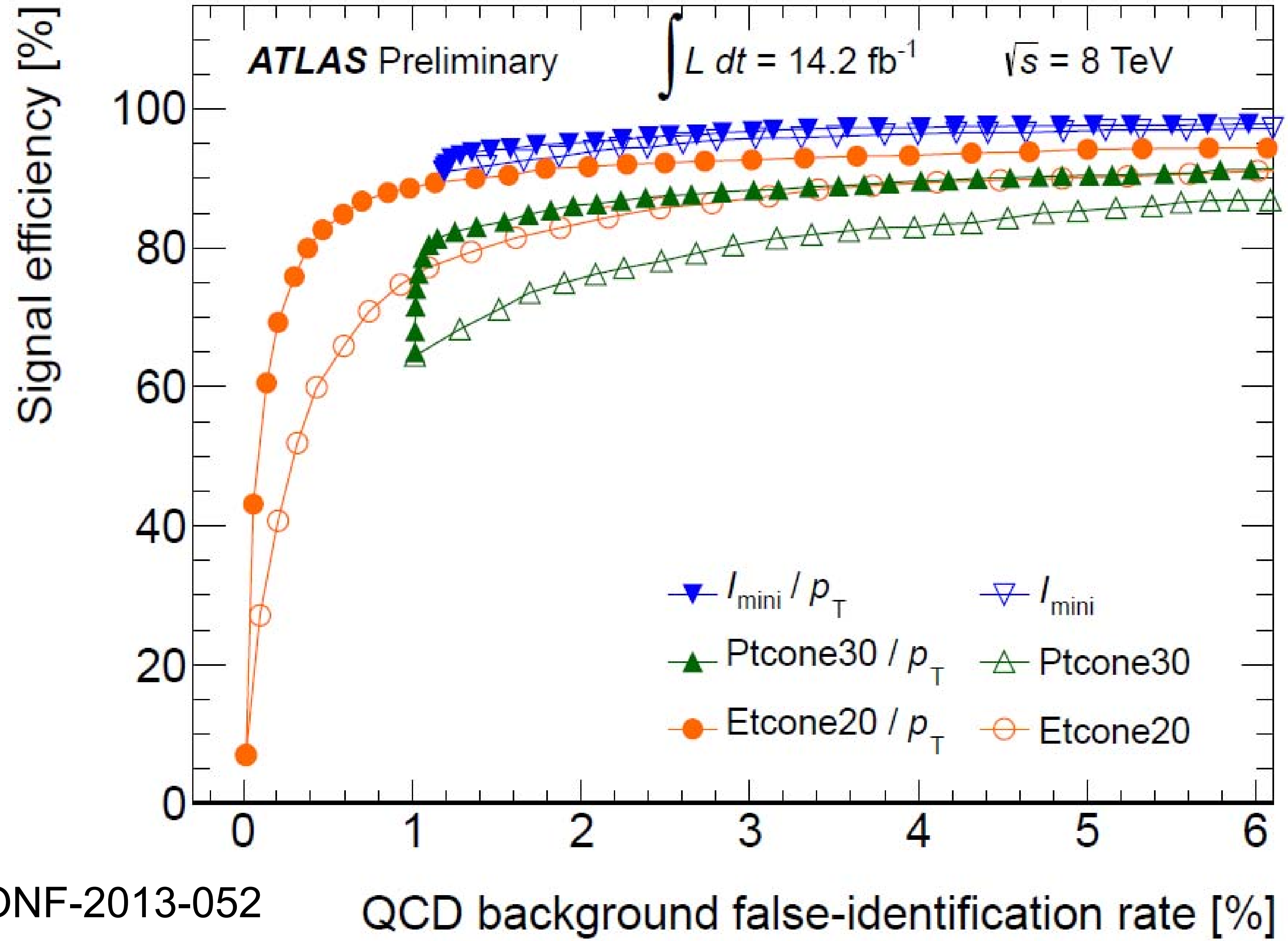


"Variable" Isolation Cone

$I < 0.05 * p_T$ (for electrons)

I<0.05*pT (for muons)

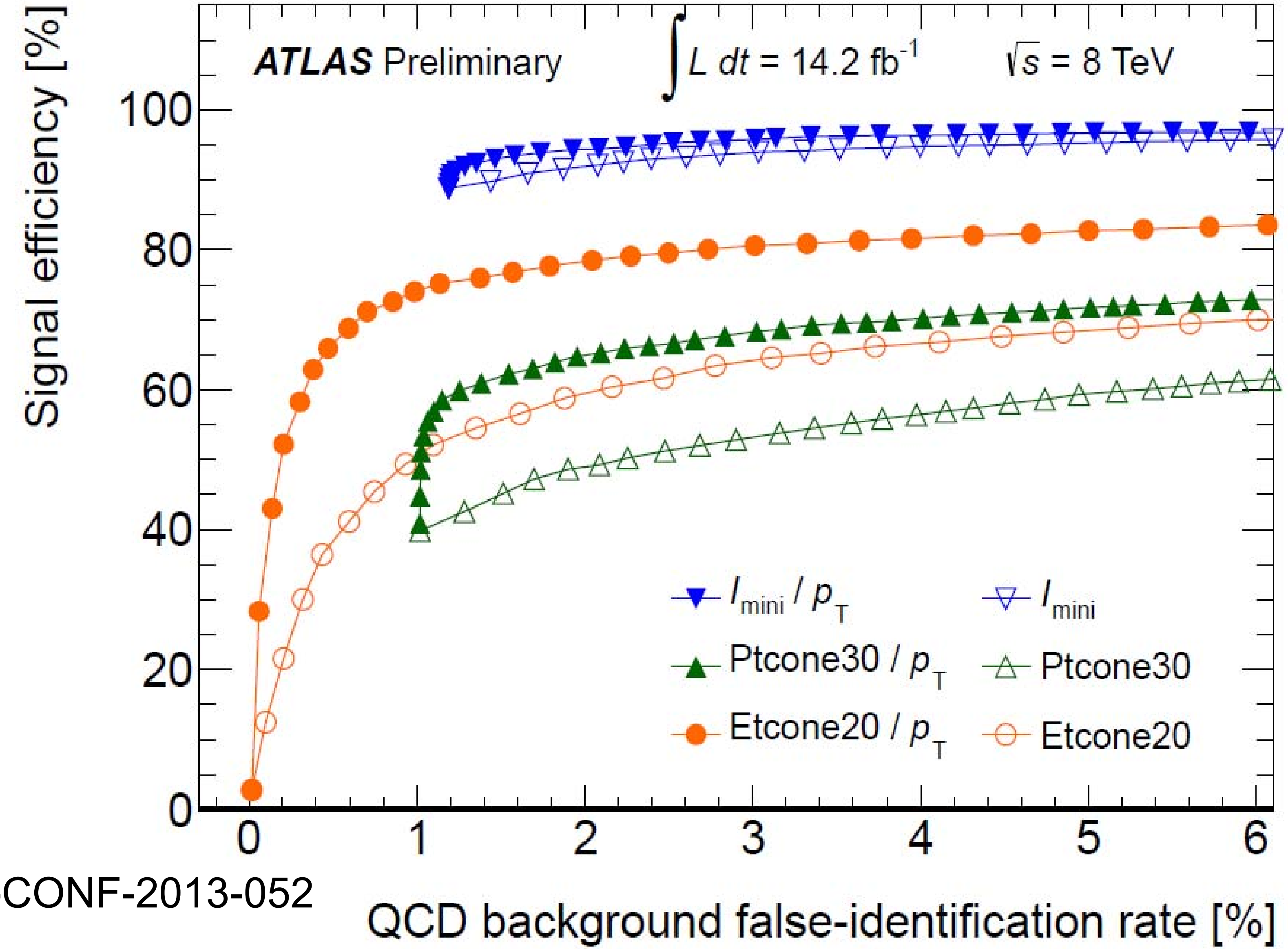
Efficiency Comparisons



ATLAS-CONF-2013-052

(b) 1.0 TeV Z'

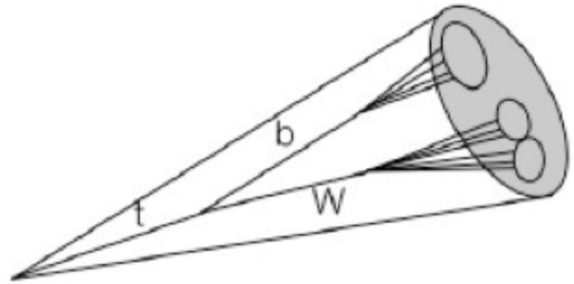
Efficiency Comparisons



ATLAS-CONF-2013-052

(d) 2.0 TeV Z'

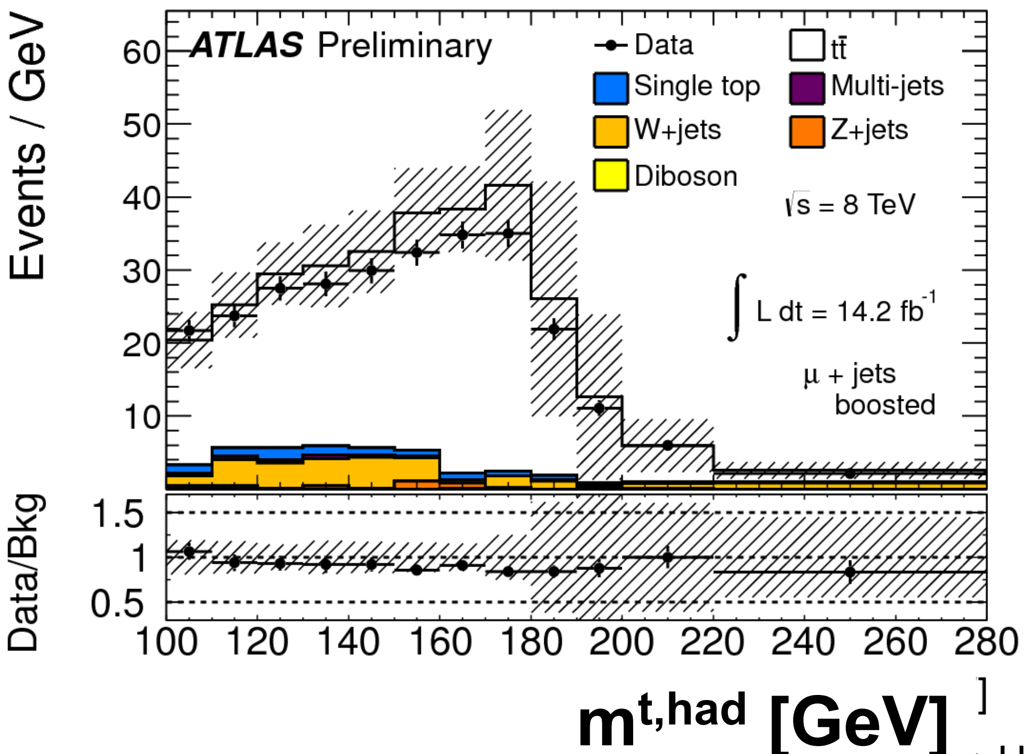
Heavy Resonances Search: ttbar

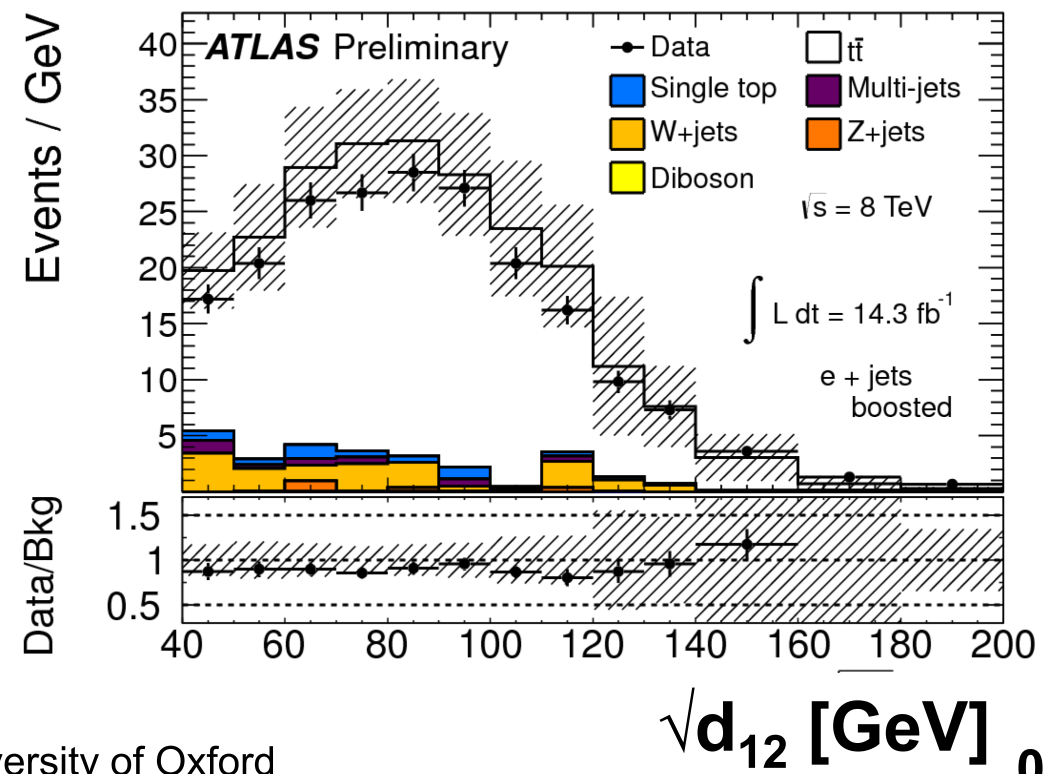


ATLAS-CONF-2013-052

- Lepton+jets channel
- Models: e.g. bulk-RS (esp. KK gluons) and Leptophobic Z'
  - Large Branching Ratio to top-antitop
- Combining **resolved** and **boosted** reconstructions
- Taking full advantage of boosted techniques

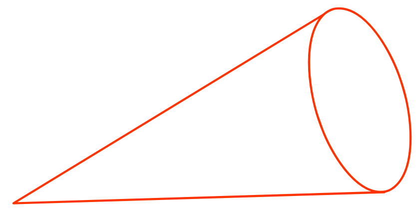
$$d_{ij} = \min({p^2}_{Ti}, {p^2}_{Tj}) \times {\Delta R^2}_{ij}/R^2$$



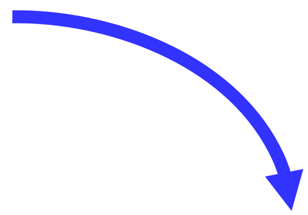


Heavy Resonances Search: Object Selection

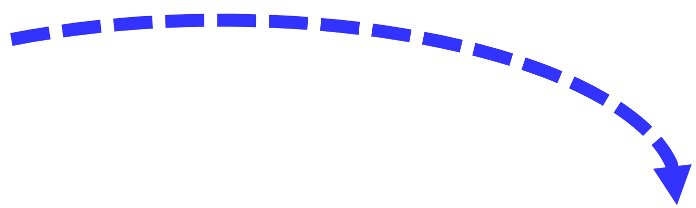
- Jets
  - Small jets: pT > 25 GeV && |η|<2.5
  - Large jets: pT > 300 GeV && |η| < 2.0
  - Require that at least one of the small jets is b-tagged



- Electrons
  - pT > 25 GeV && |η|<1.37, 1.52<|η|<2.47
  - Mini Isolation: $I_{mini} < 0.05\ E_T$
  - z-impact parameter within 2mm of PV



- Muons
  - pT > 25 GeV && |η|<2.5
  - $I_{mini} < 0.05$ pT
  - z-impact parameter within 2mm of PV

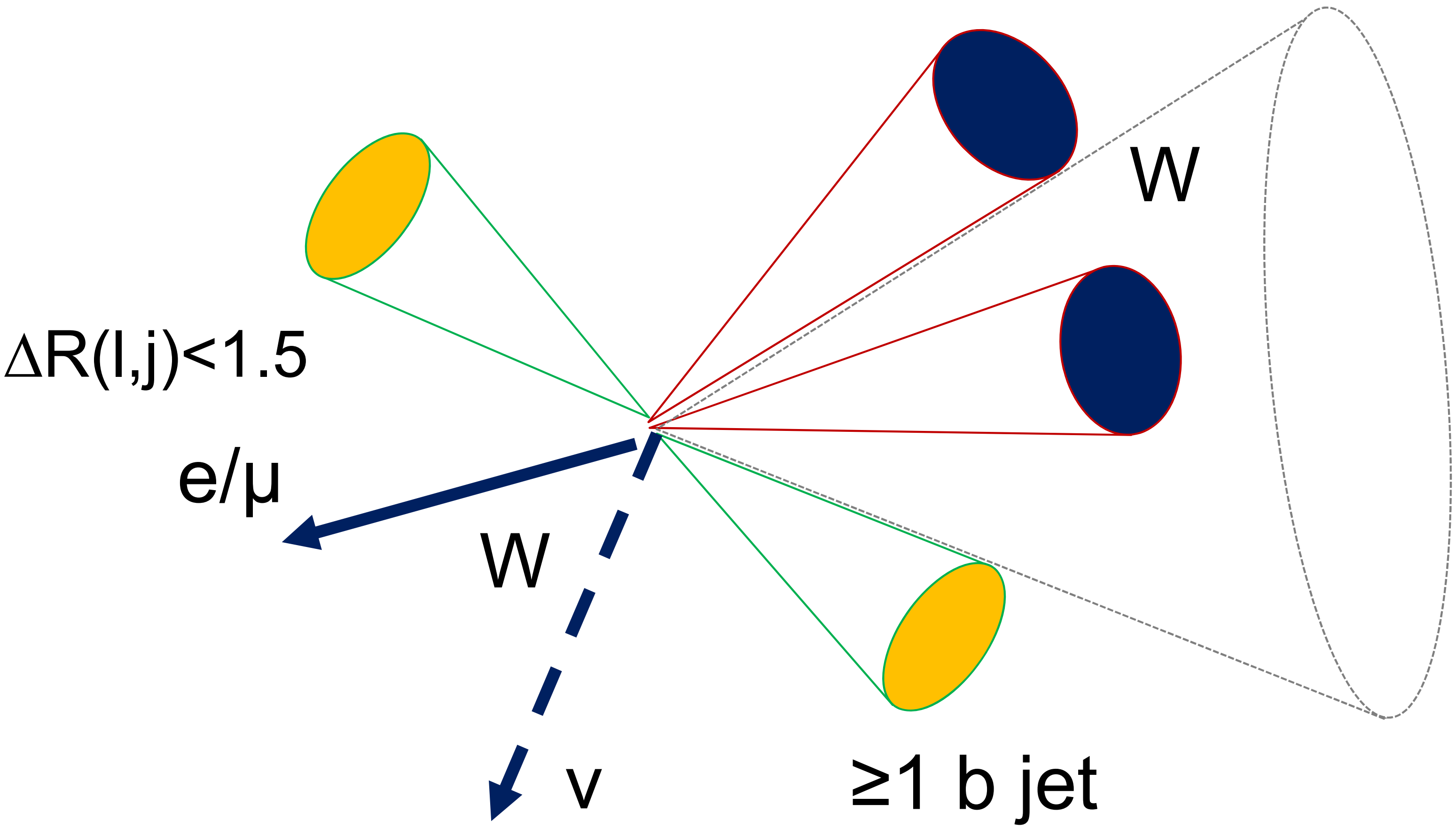


Selections Continued

- Optimized for high-pt tops && reduce ttbar bkg
- High-pt single electron or muon trigger
- >1 primary vertex with ≥ 5 tracks of p_T > 0.4 GeV
- Electron channel
  - ME_T > 30 GeV && $m_T = \sqrt{2 p_T ME_T (1 - cos\Delta\varphi)}$>30 GeV
- Muon channel
  - ME_T > 20 GeV && $ME_T + m_T$ > 60 GeV

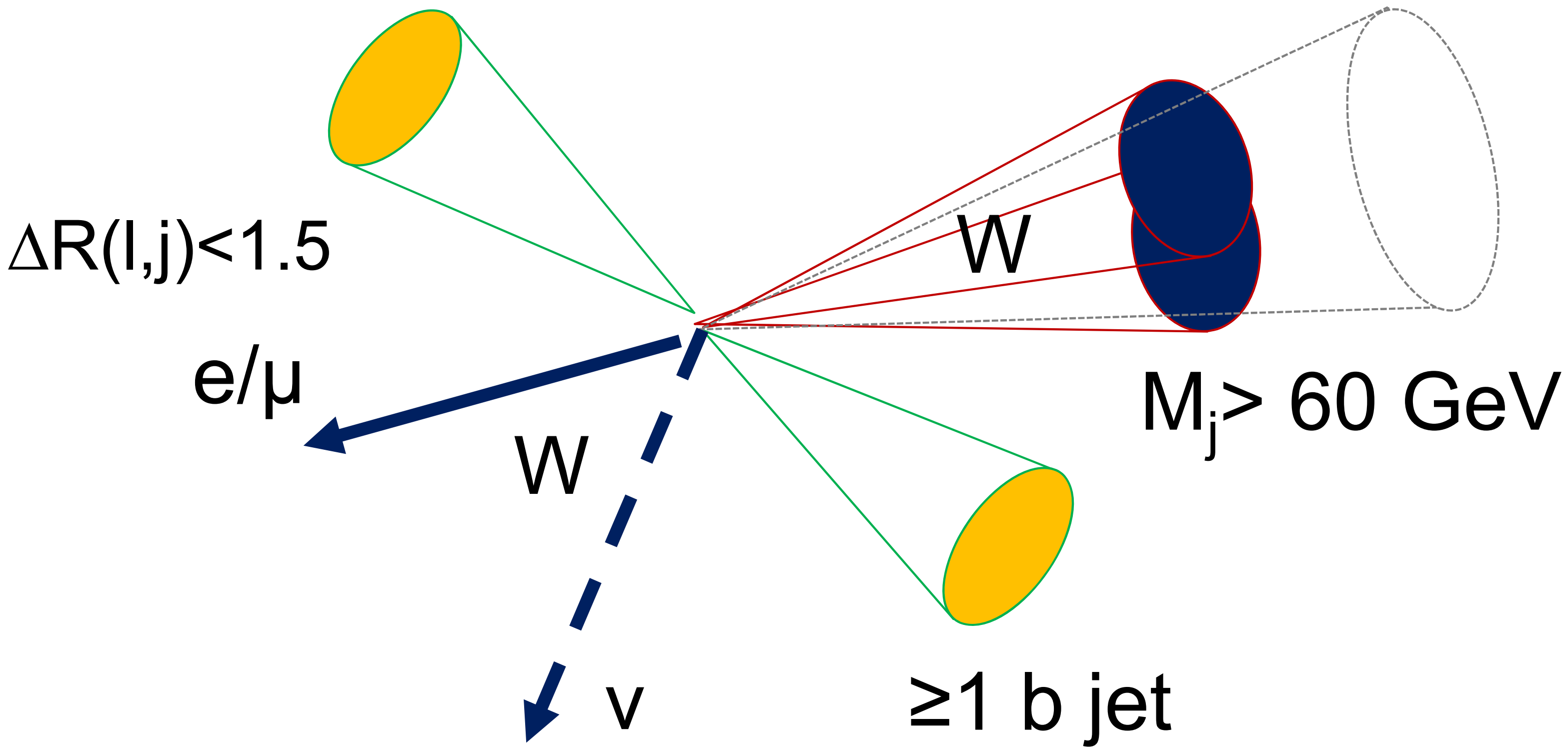
Resolved Selection

≥ 4 small jets, j, with p_T> 25 GeV, |η|<2.5



Merged Selection

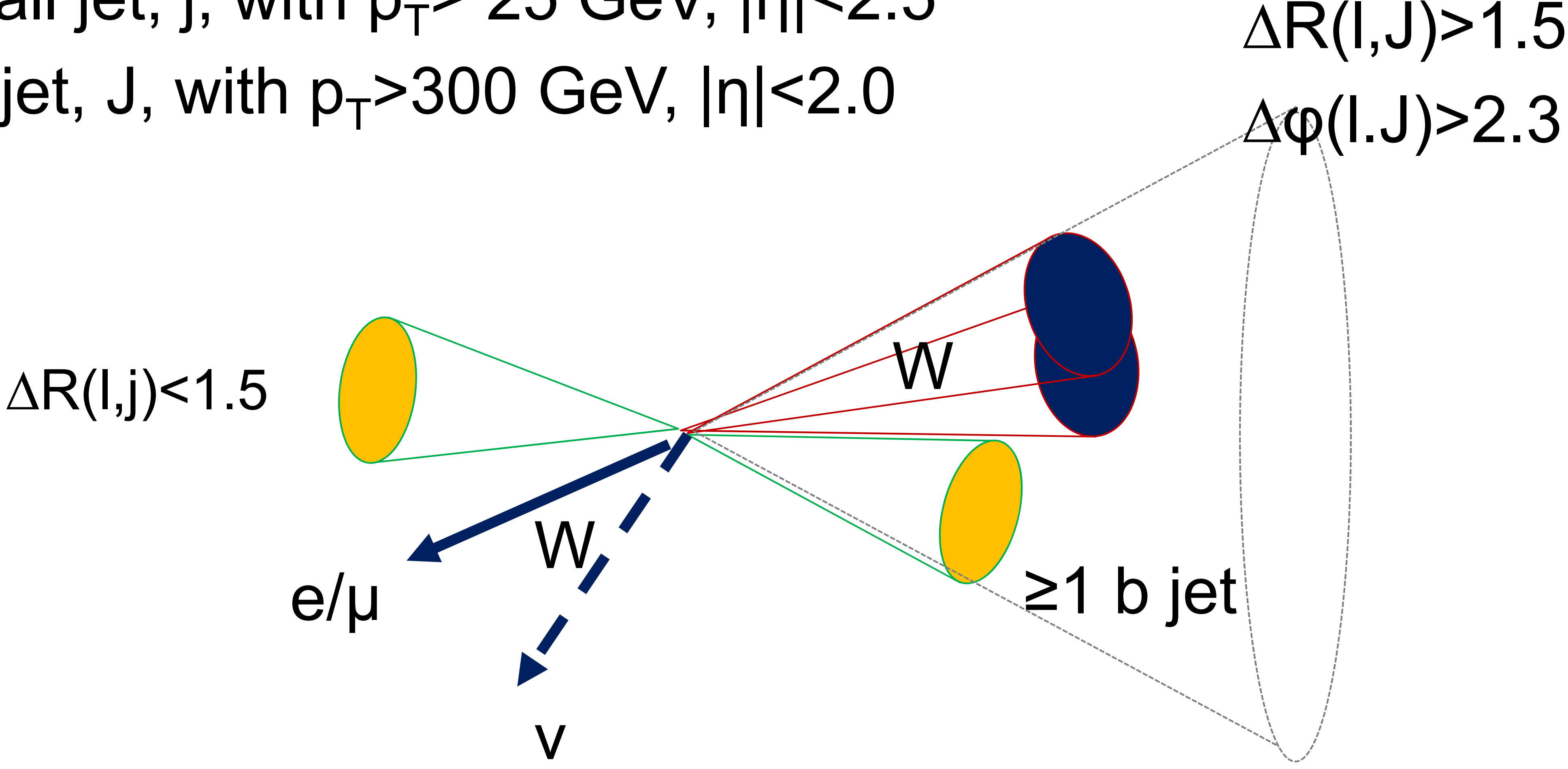
3 small jets, j, with p_T> 25 GeV, |η|<2.5



Boosted Selection

≥1 small jet, j, with p_T> 25 GeV, |η|<2.5

≥1 fat-jet, J, with p_T>300 GeV, |η|<2.0

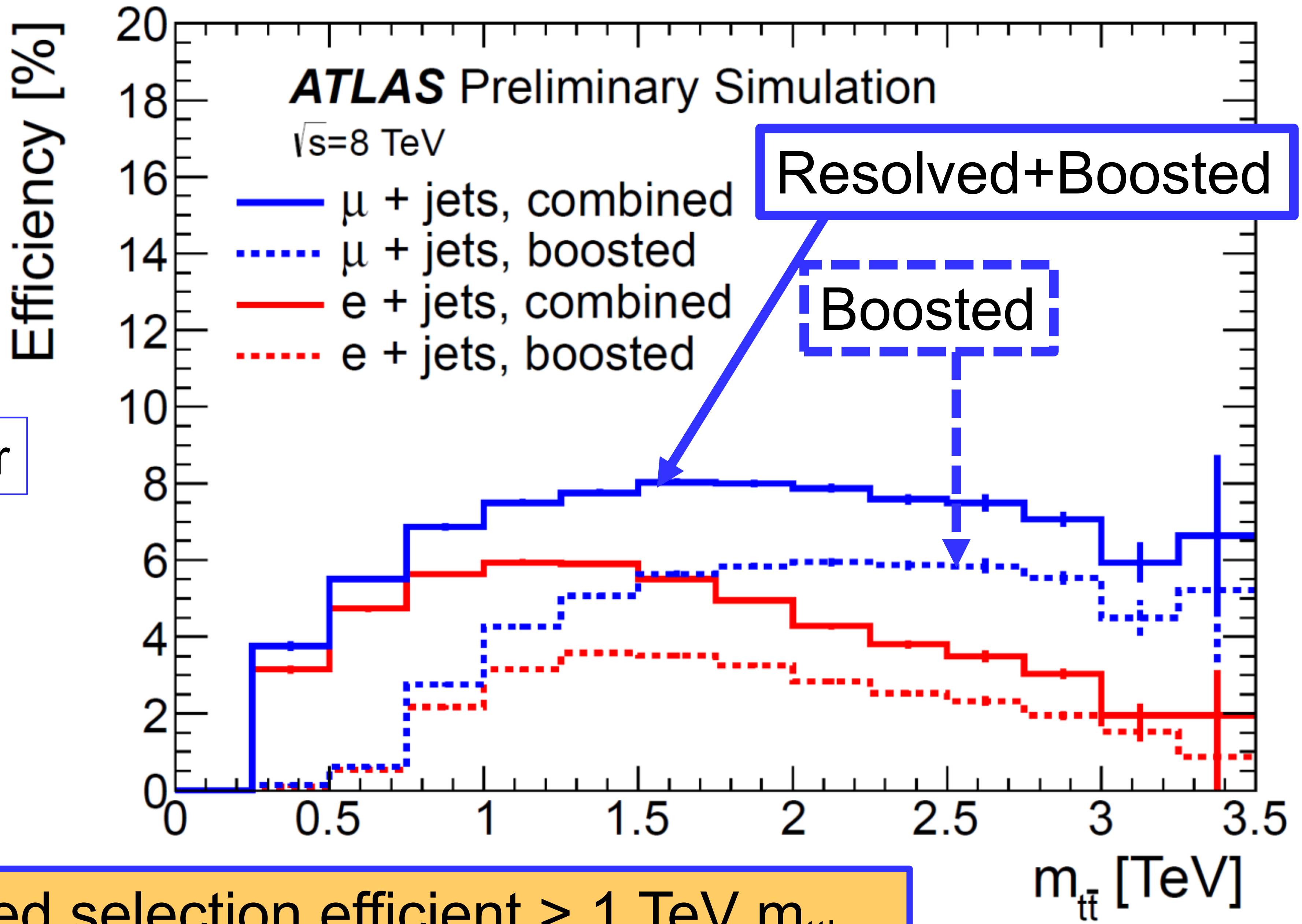


M_J> 100 GeV

$\sqrt{d_{12}} > 40$ GeV

Geometrical Acceptance + Selection Efficiencies

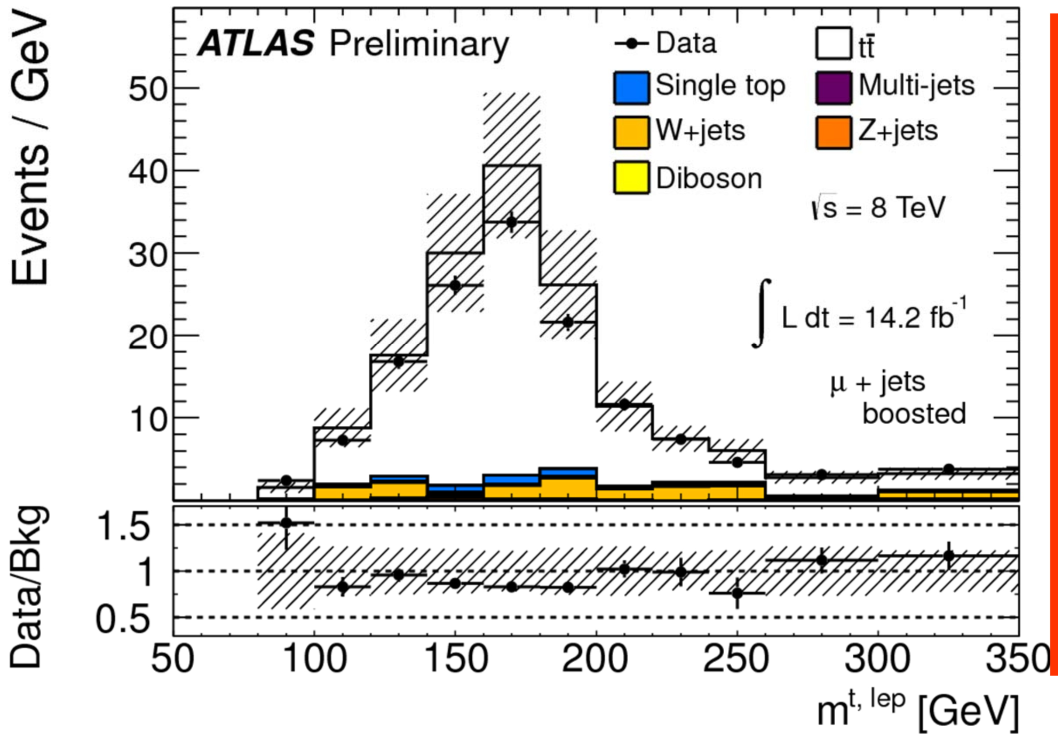
Z'→ttbar



Boosted selection efficient > 1 TeV m_{ttbar}

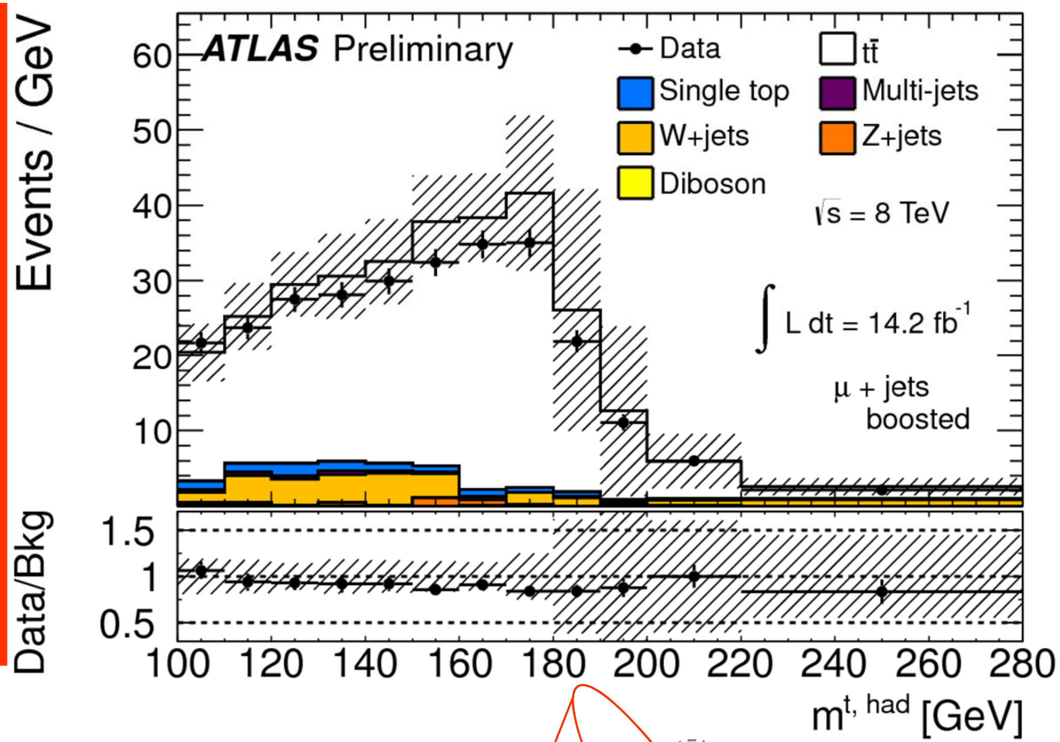
Reconstructed top mass distributions

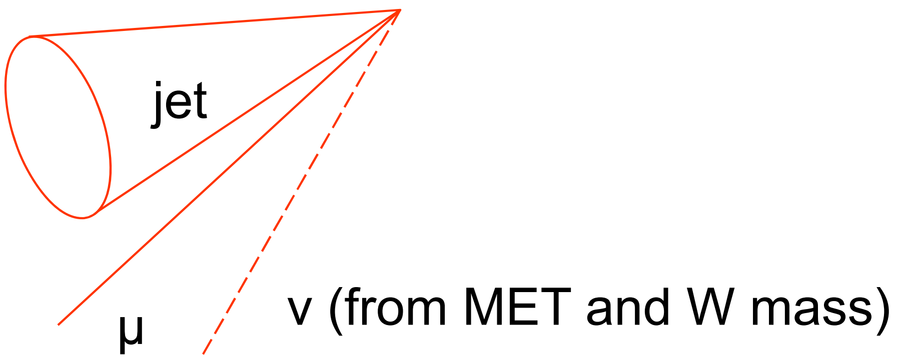
Semi-Leptonically decaying top

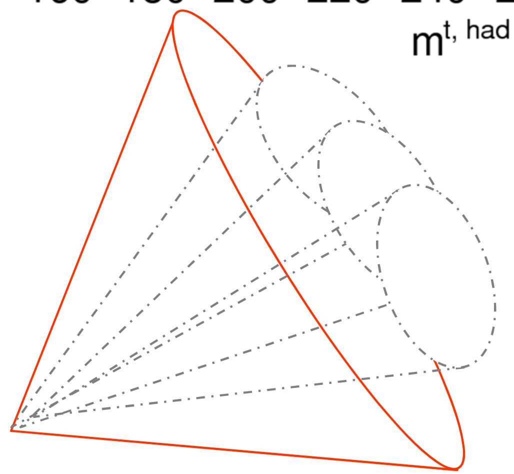


Boosted selection

Hadronically decaying top



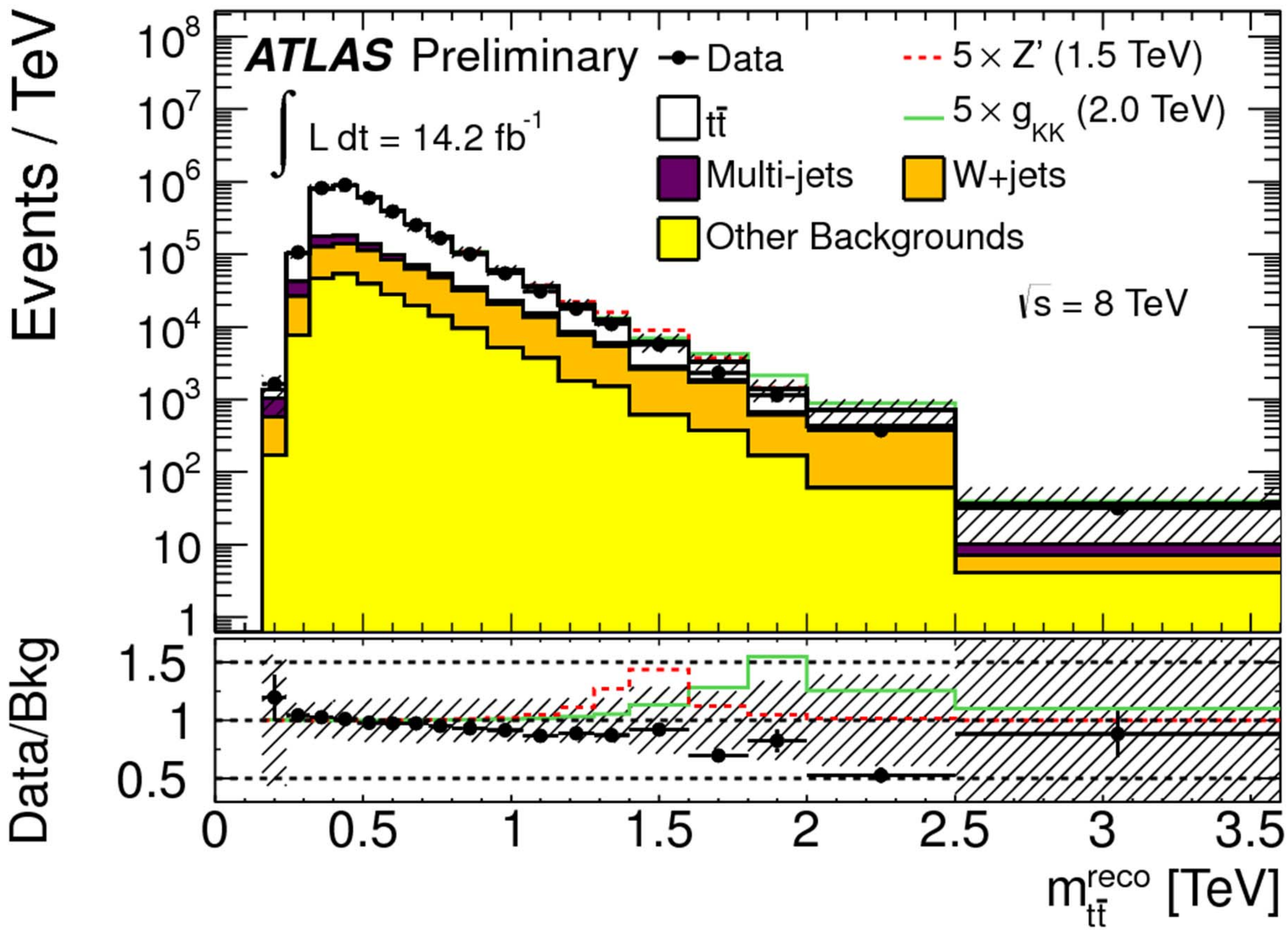




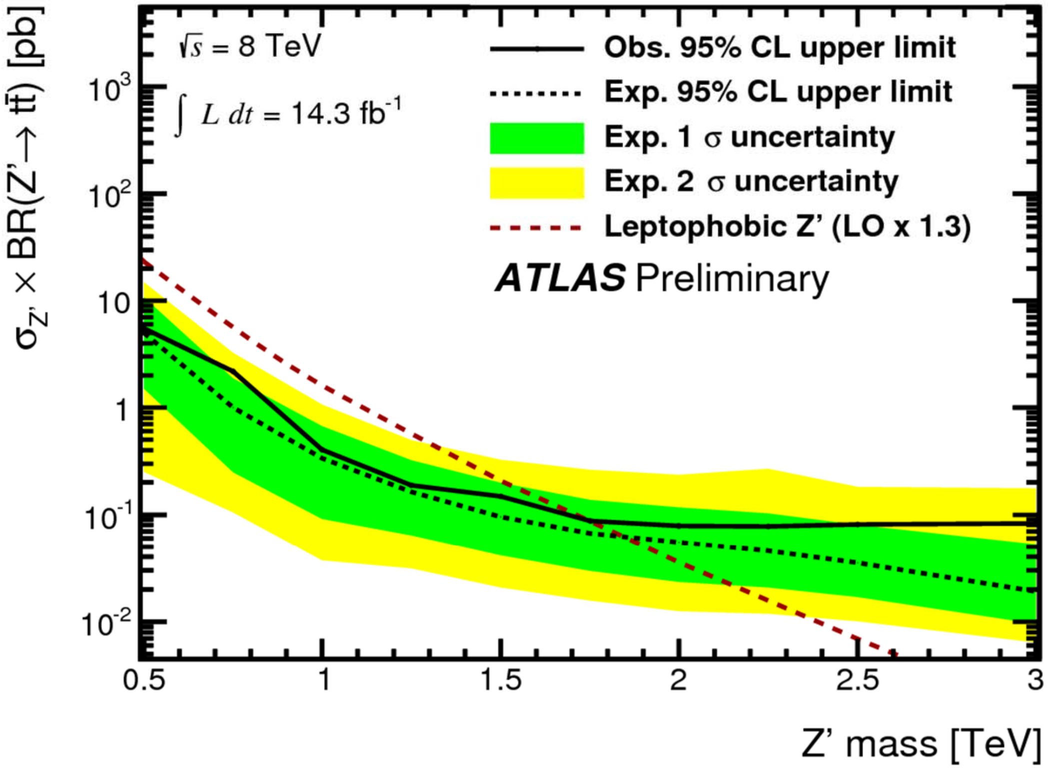
C. Issever, University of Oxford

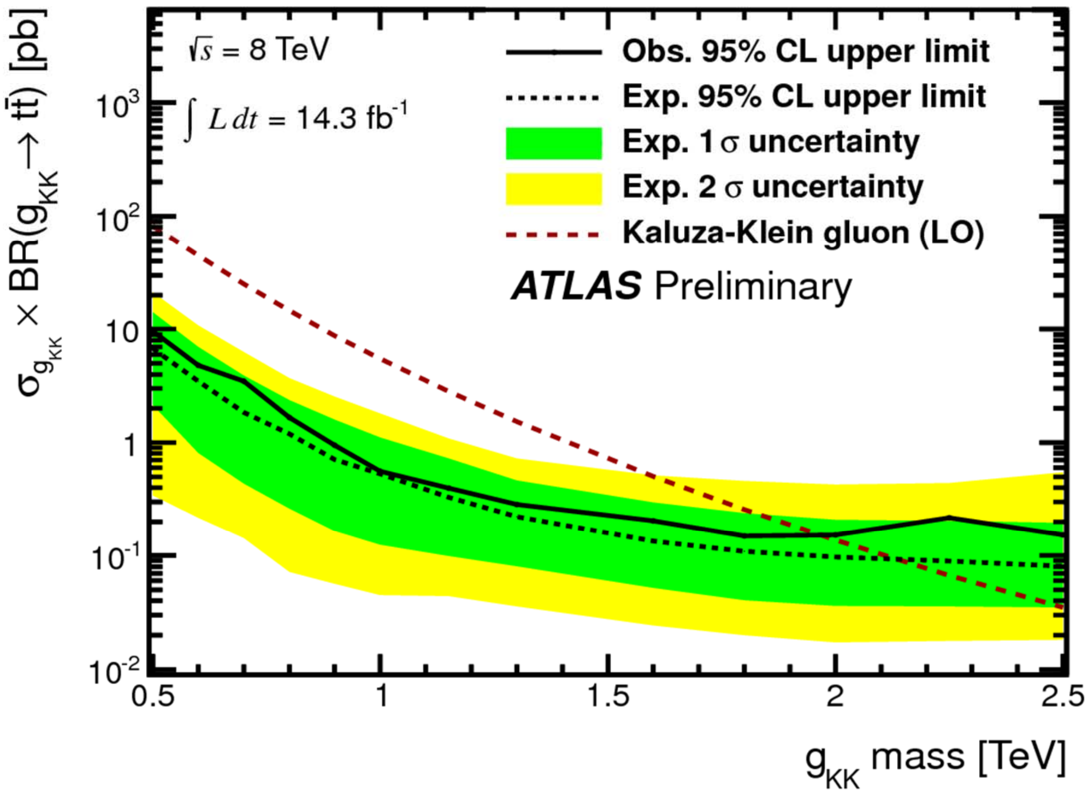
Discriminant distribution m_{ttbar}

- $m_{t\bar{t}}$ resolved + boosted in *e*+jets and *μ*+jets



Heavy Resonances Search: Ttbar





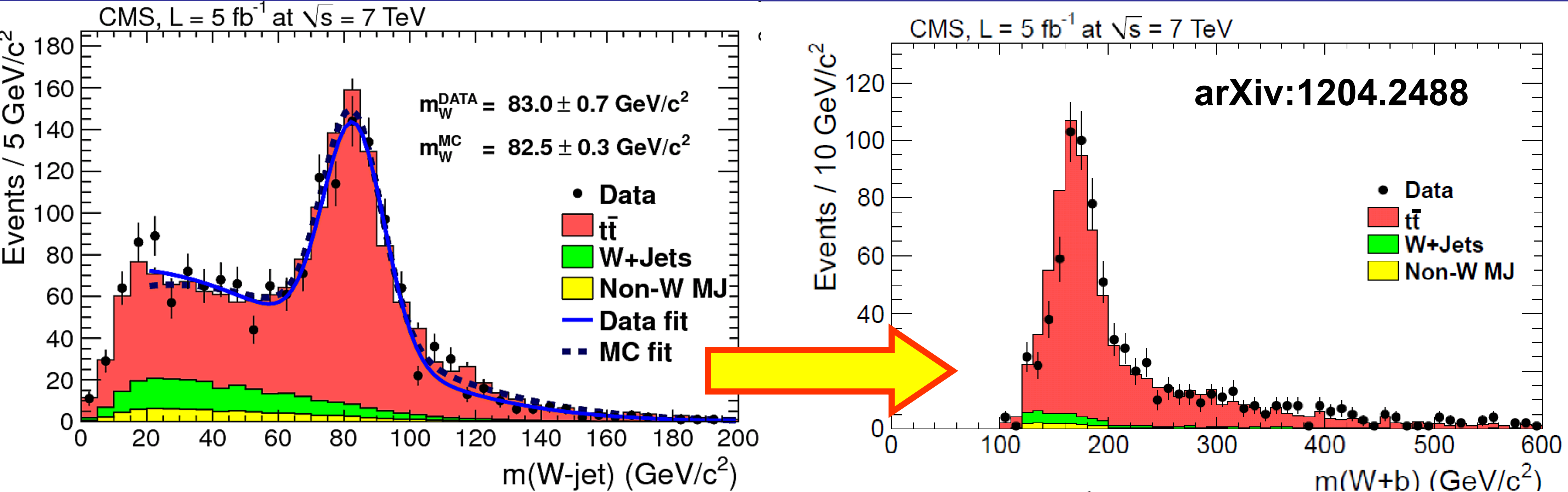
m(Z') > 1.8 TeV @95% Cl

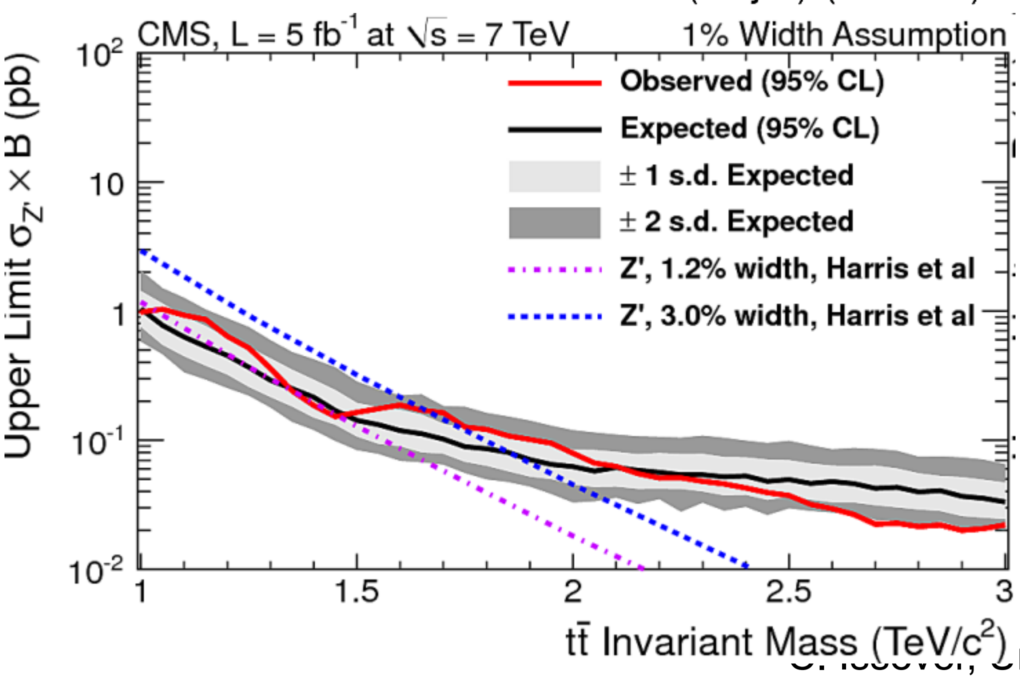
Γ/m(Z') = 1.2%

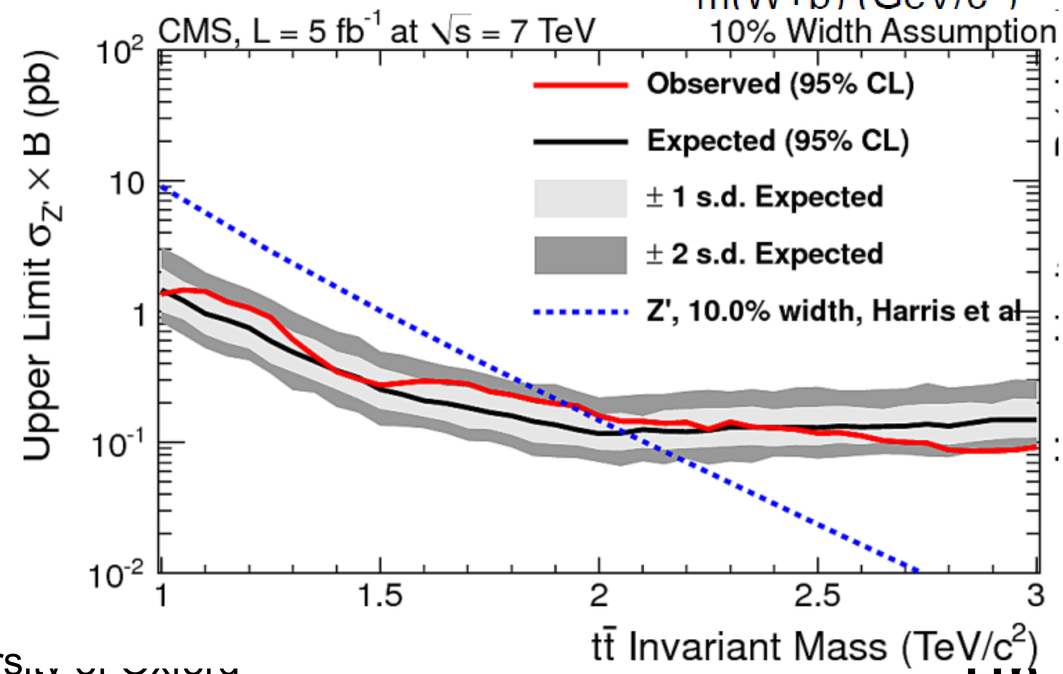
m(g_{KK}) > 2.0 TeV @95% Cl

Γ/m(g_{KK}) = 15%

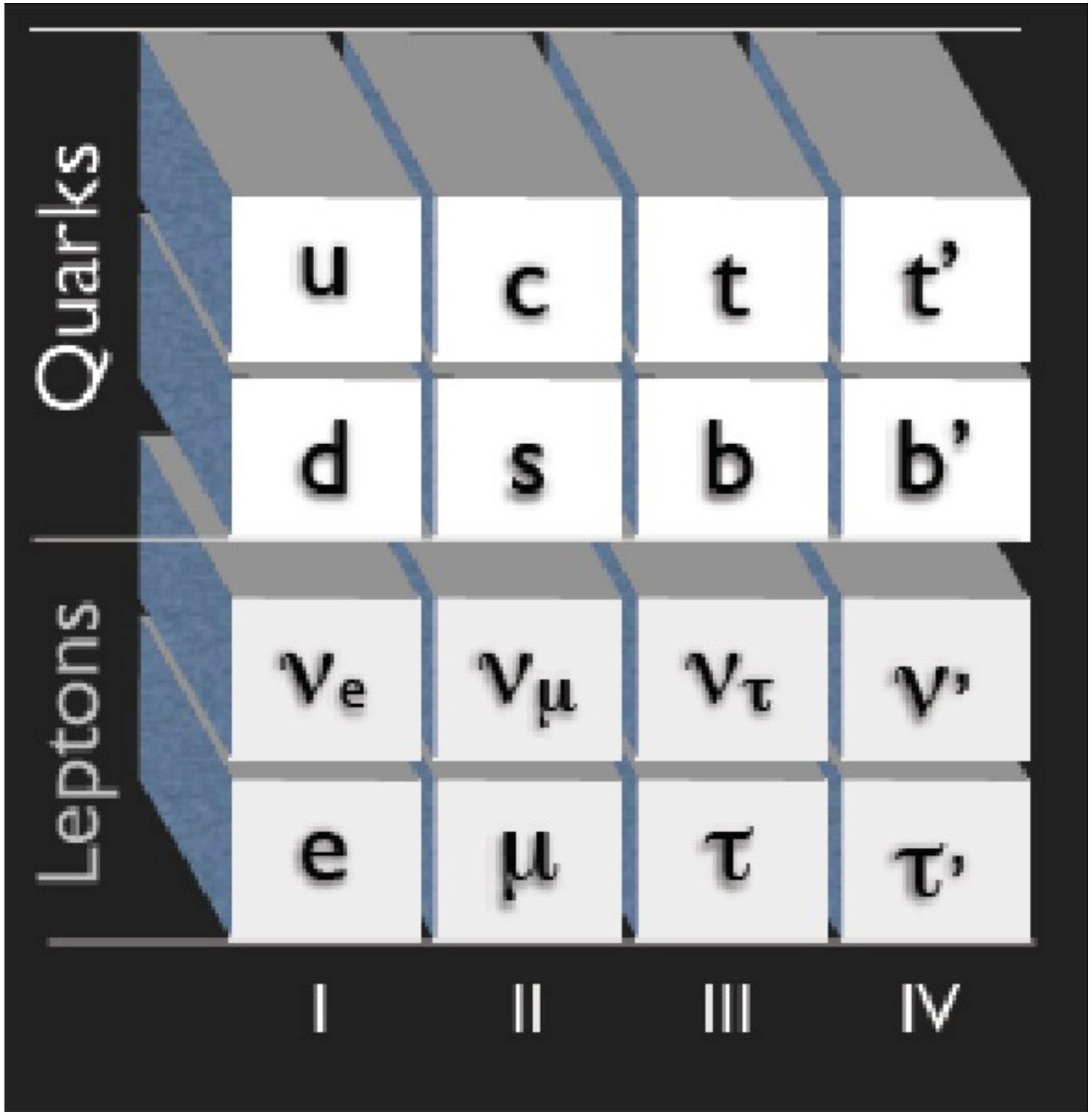
Heavy Resonance Search: ttbar hadronic channel







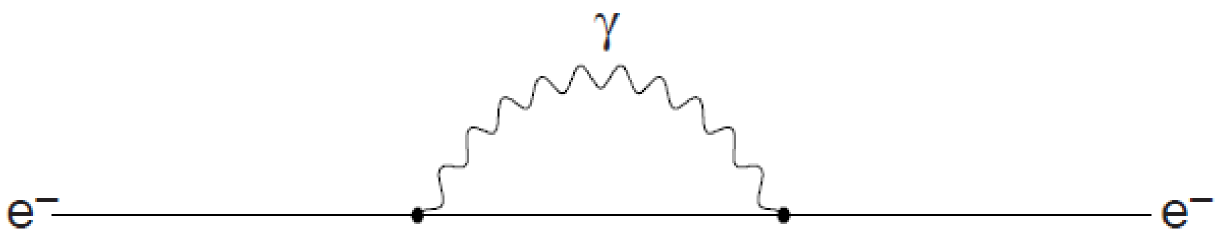
Heavy Quarks



Fine-Tuning Problem in Electromagnetism

$$(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{Coulomb}}$$

Coulomb self-energy



$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e},$$

$$r_e \lesssim 10^{-17}\ \text{cm} \implies \Delta E \gtrsim 10\ \text{GeV}$$

$$0.511 = -9999.489 + 10000.000\ \text{MeV}$$

Fine tuning!

Murayama hep-ph/9410285

Fine-Tuning Problem in Electromagnetism

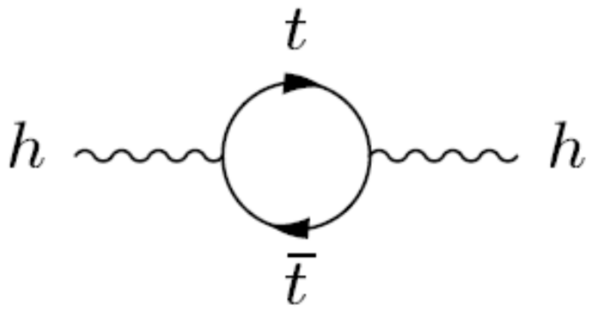
- Picture not complete:
  - Positron cancels $1/r_e$ term
  - New symmetry:
    - particle/anti-particle

$$(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} \left[1 + \frac{3\alpha}{4\pi} \log \frac{\hbar}{m_e c r_e} \right]$$

    - Correction to bare mass becomes small

Supersymmetry

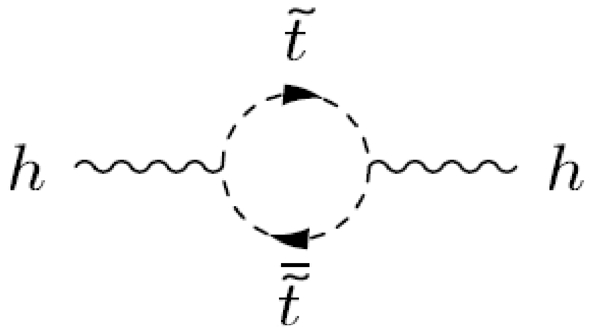
- Same problem with Higgs



$$\Delta\mu^2_{\text{top}} = -6\frac{h_t^2}{4\pi^2}\frac{1}{r_H^2}$$

~ (100 GeV)[2]

125 GeV = (huge number)-(huge number) even more fine tuned!

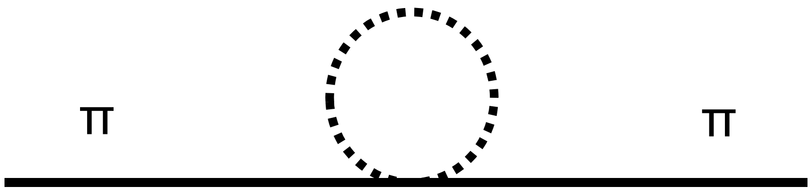


Add new particles (spin symmetry): SUSY

$$\Delta\mu^2_{\text{stop}} + \Delta\mu^2_{\text{top}} = -6\frac{h_t^2}{4\pi^2}(m_{\tilde{t}}^2 - m_t^2)\log\frac{1}{r_H^2 m_{\tilde{t}}^2}.$$

Composite Higgs

- But there is another way….look at QCD

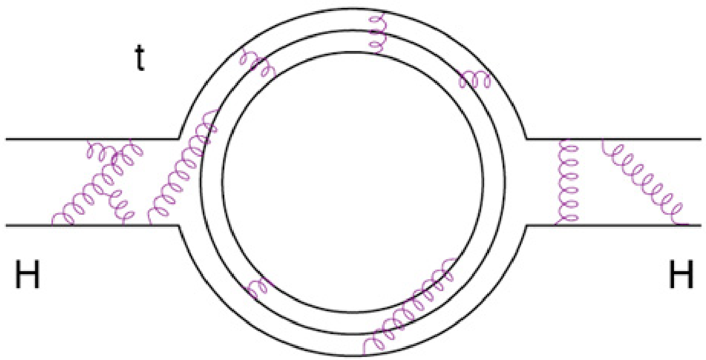


Pion mass is not divergent.

Why?

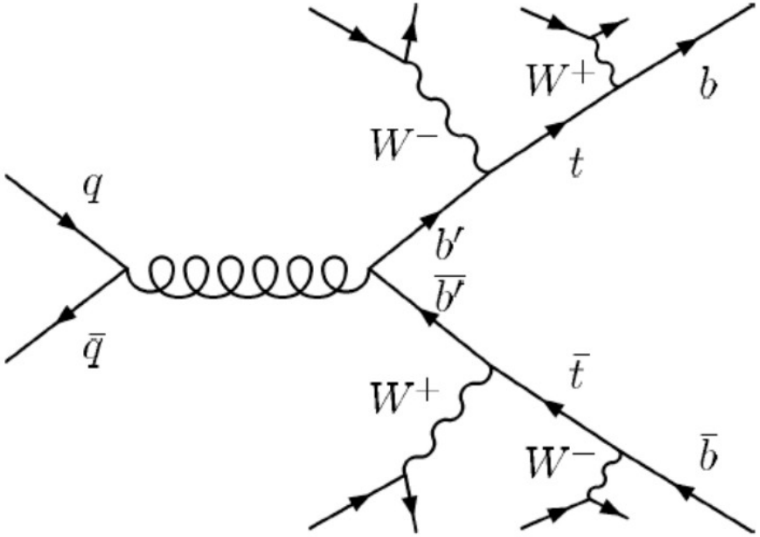
It is a composite particle!

- **Assume Higgs is a composite particle**
  - Changes couplings
  - Introduces new partners to top quarks
  - Vector-like quarks…
    - (both chiralities same under SU(2)xU(1)
  - Solves fine-tuning problem….

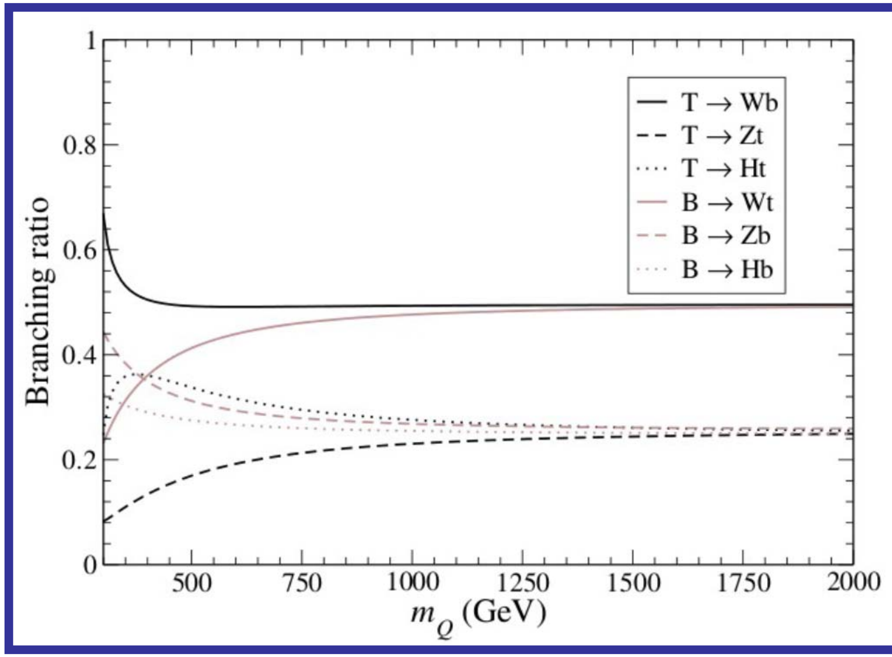


4th Generation and Heavy Quarks

- 4th generation would significantly enhance Higgs production cross section
  - (almost) excluded by observed Higgs cross-section
  - t't' → WbWb (100%): just like t-tbar but heavier
  - b'b' →WtWt (100%): just like ttbar but messier



- Beyond 4th generation: **Vector-Like Quarks** in Composite Higgs theories
  - More diverse phenomenology
  - T': Decays to Wb, Zt, Ht
  - B': Decays to Wt, Zb, Hb
- Loose constraints on CKM4 → decays to light quarks possible!



4th Generation and Heavy Quarks

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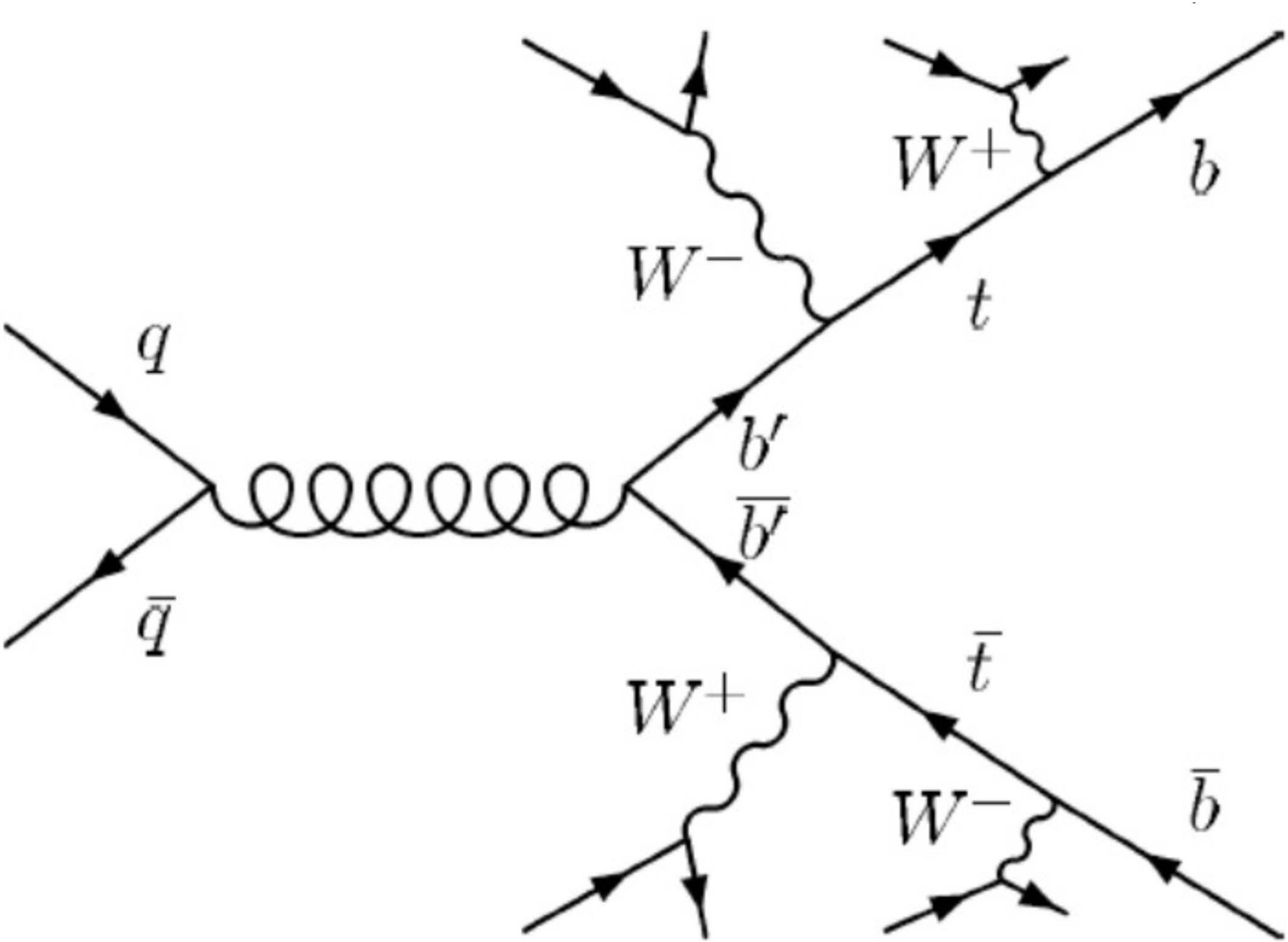

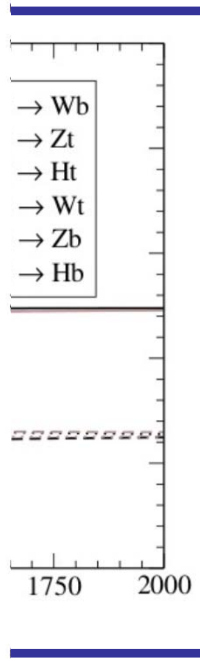

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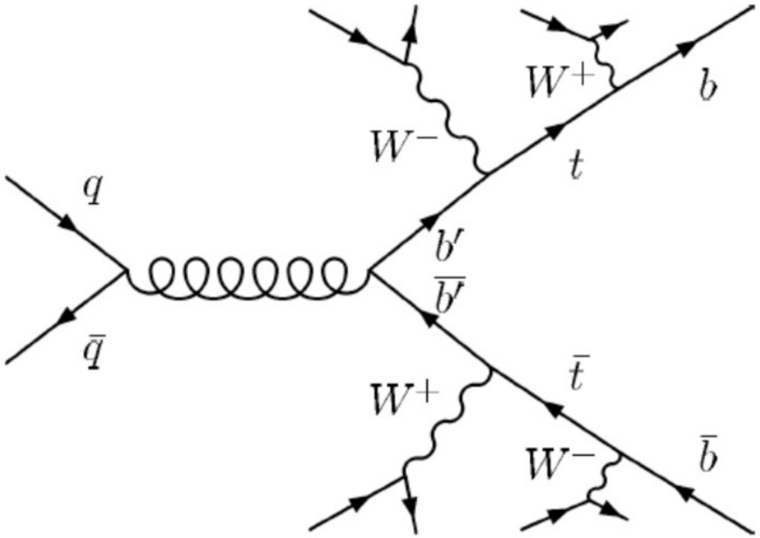

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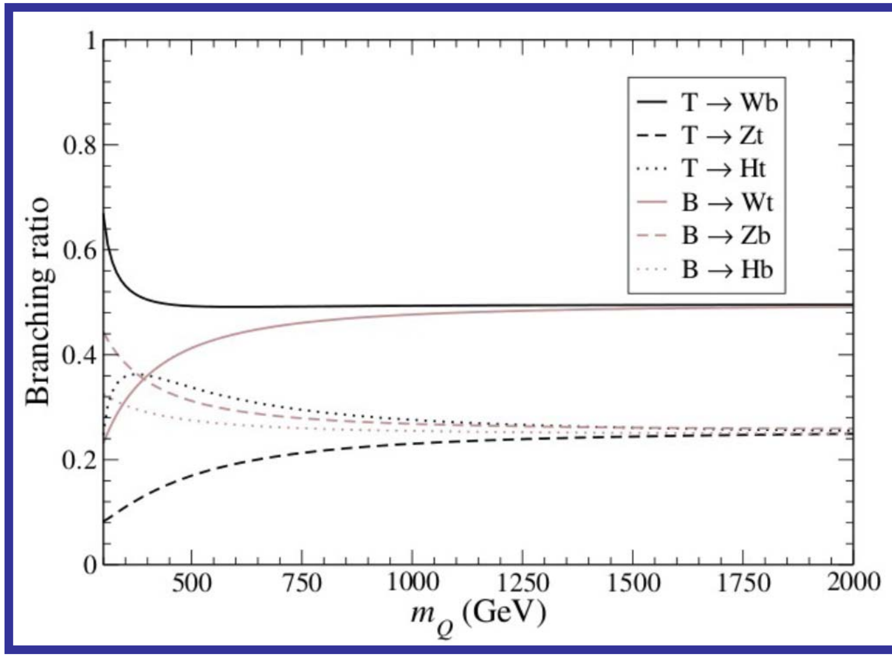

4th Generation and Heavy Quarks

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  - T': I
  - B': I
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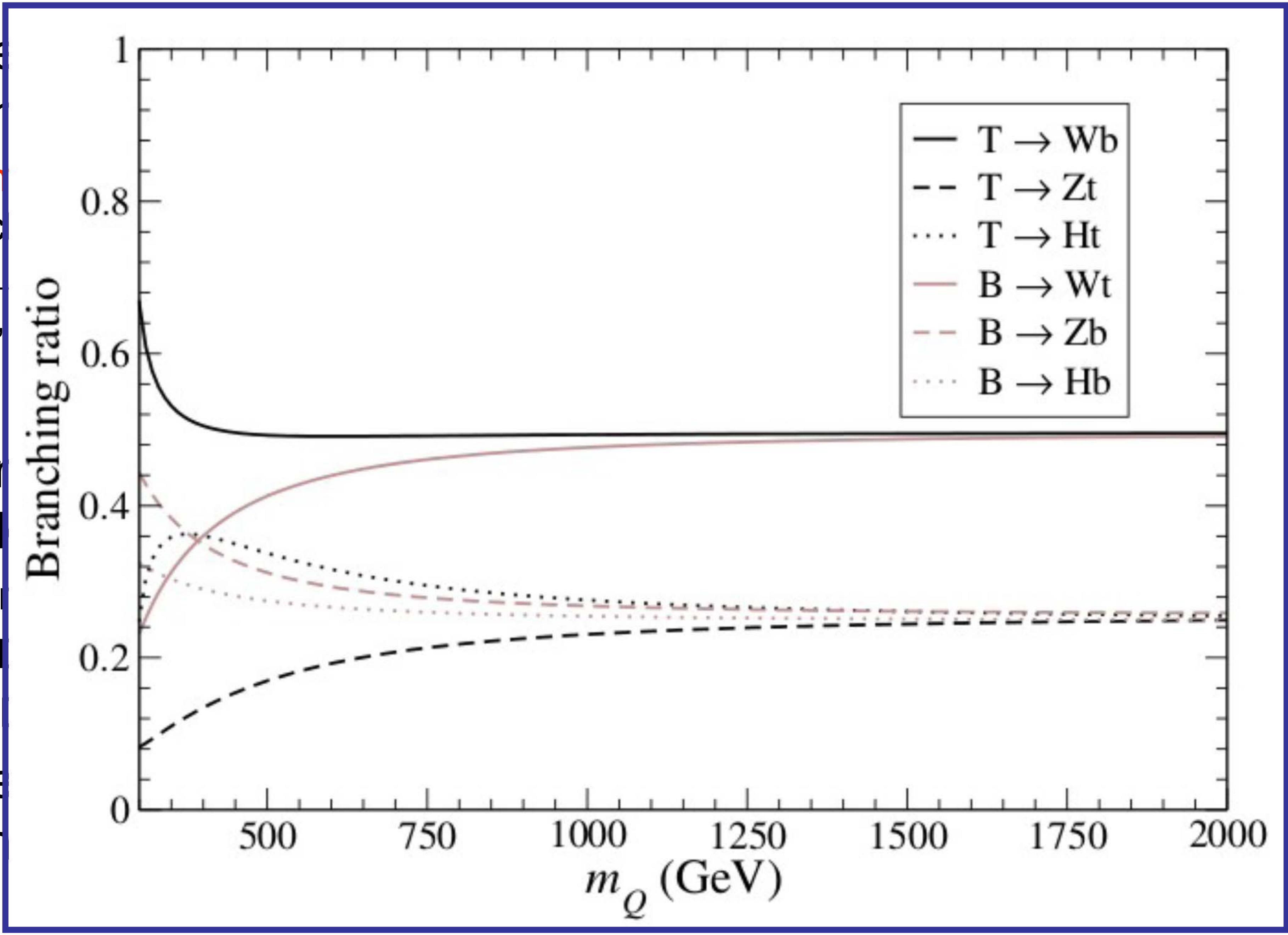
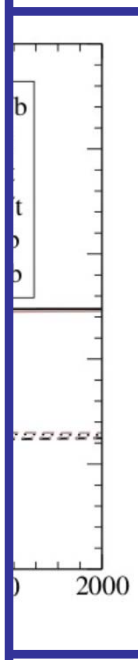
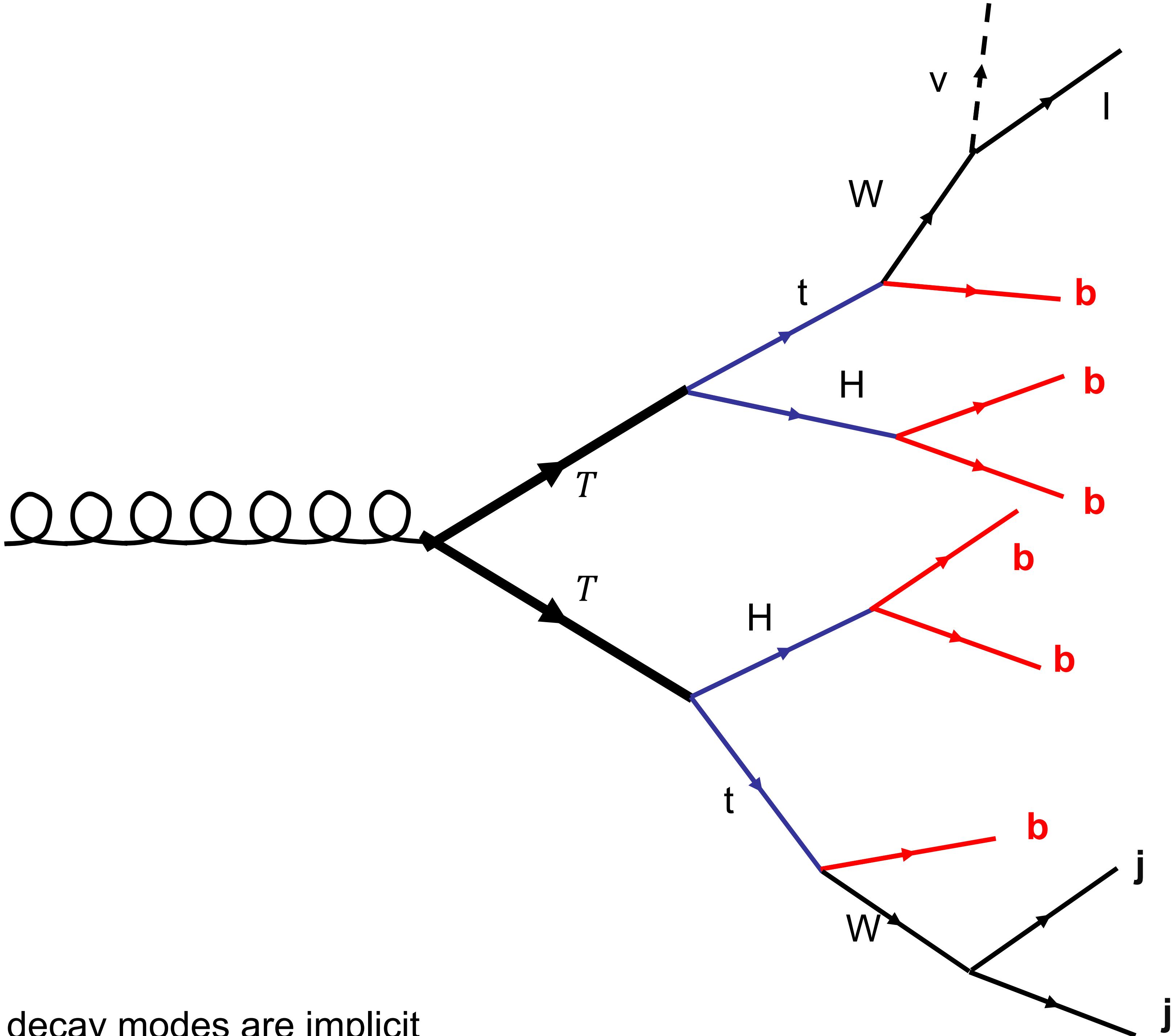


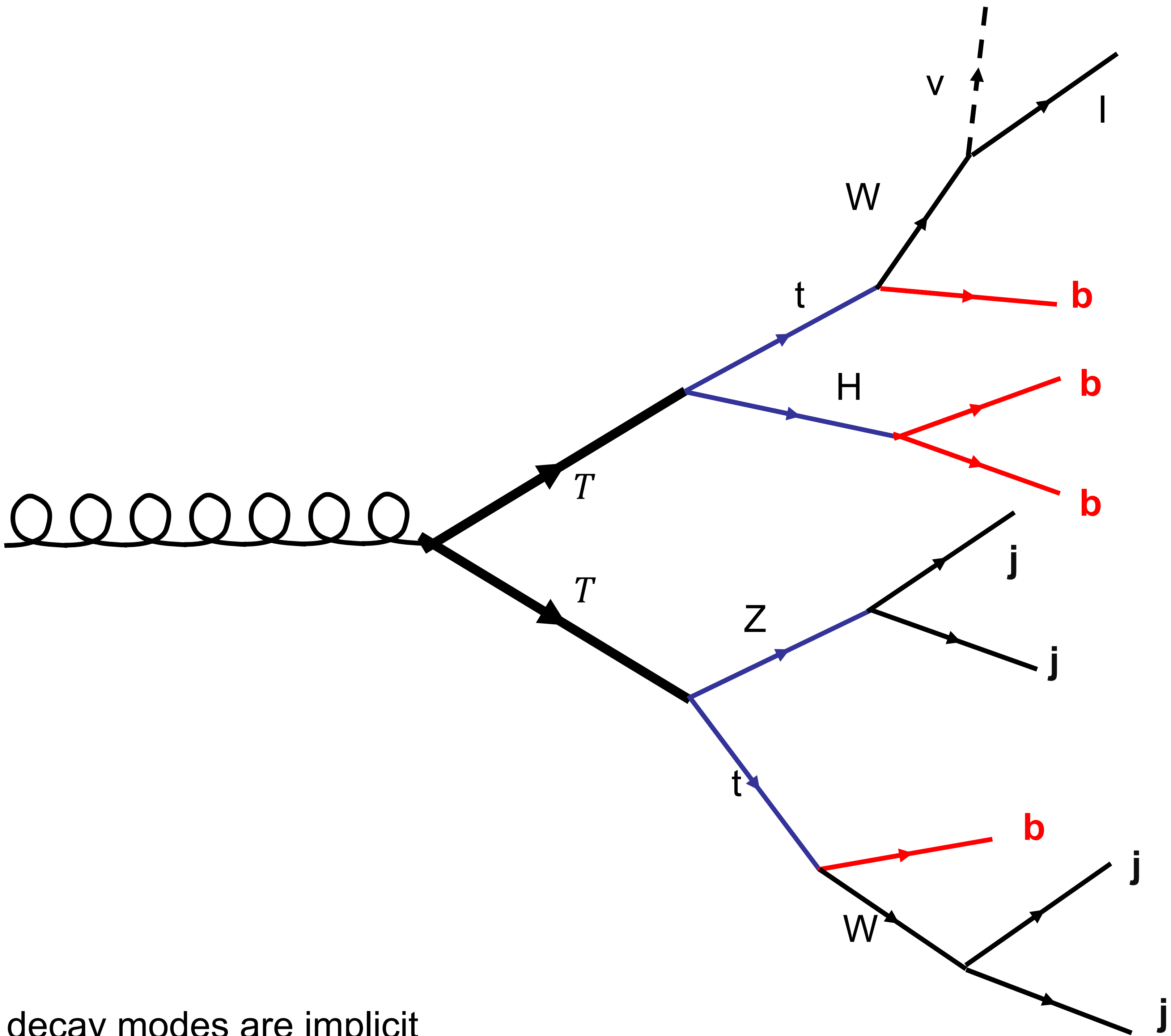


T $\rightarrow$ **H** t

ATLAS-CONF-2013-018

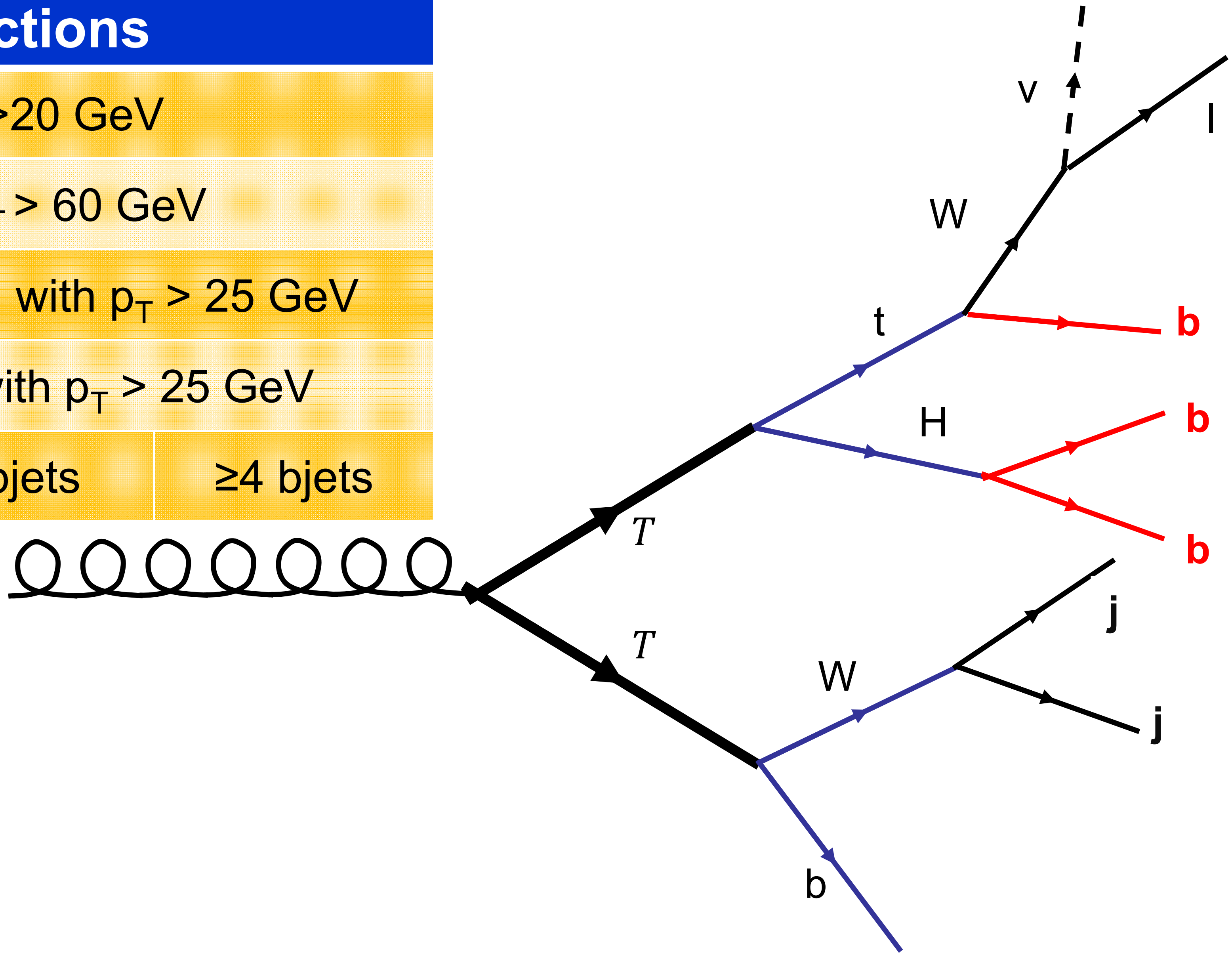


Complex-conjugate decay modes are implicit



Complex-conjugate decay modes are implicit

Selections		
E_T^{miss} >20 GeV		
$E_t^{miss}+m_T$ > 60 GeV		
1 Isolated lepton with p_T > 25 GeV		
≥ 6 akt4 jets with p_T > 25 GeV		
2 bjets	3 bjets	≥4 bjets

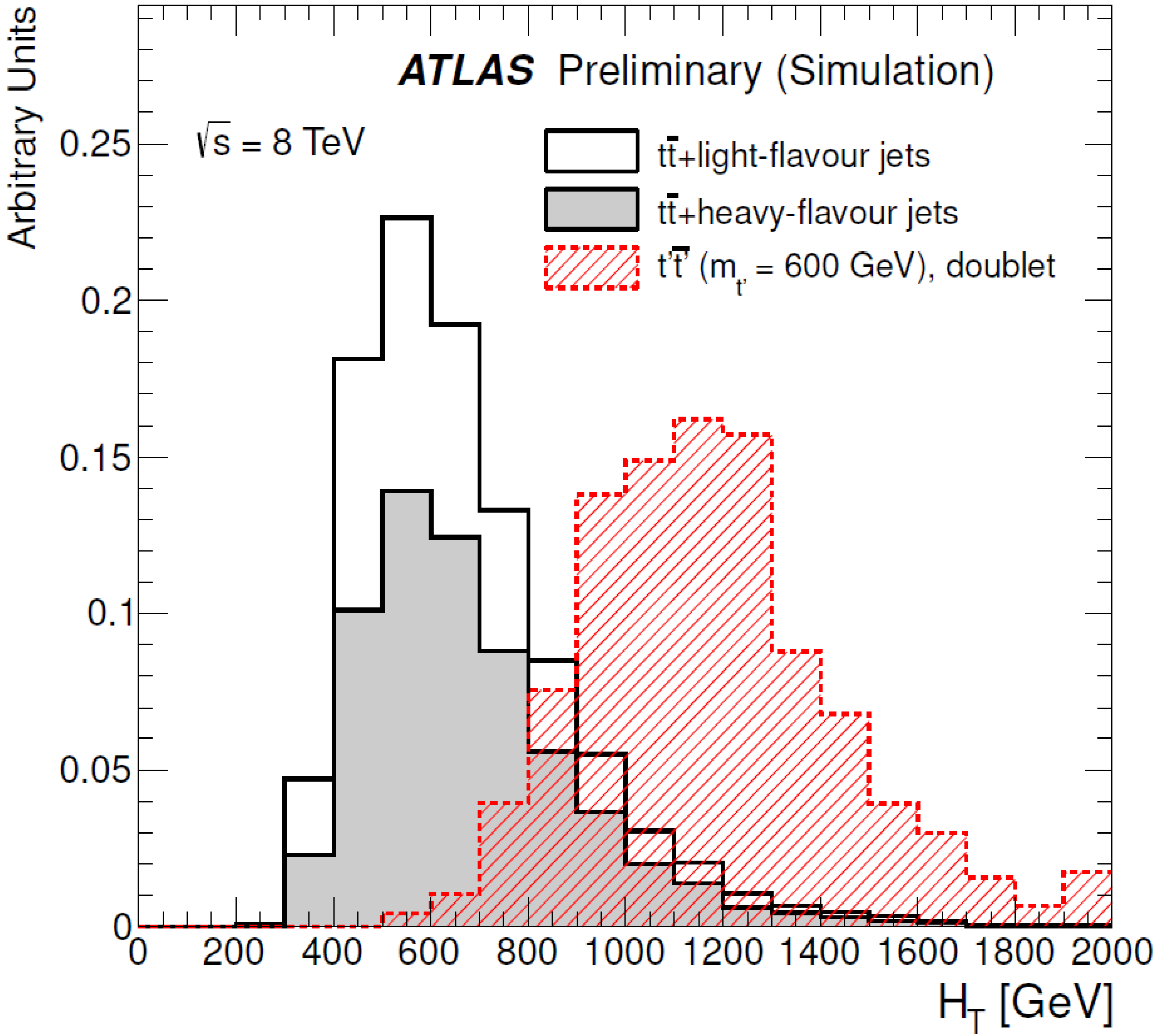


Complex-conjugate decay modes are implicit

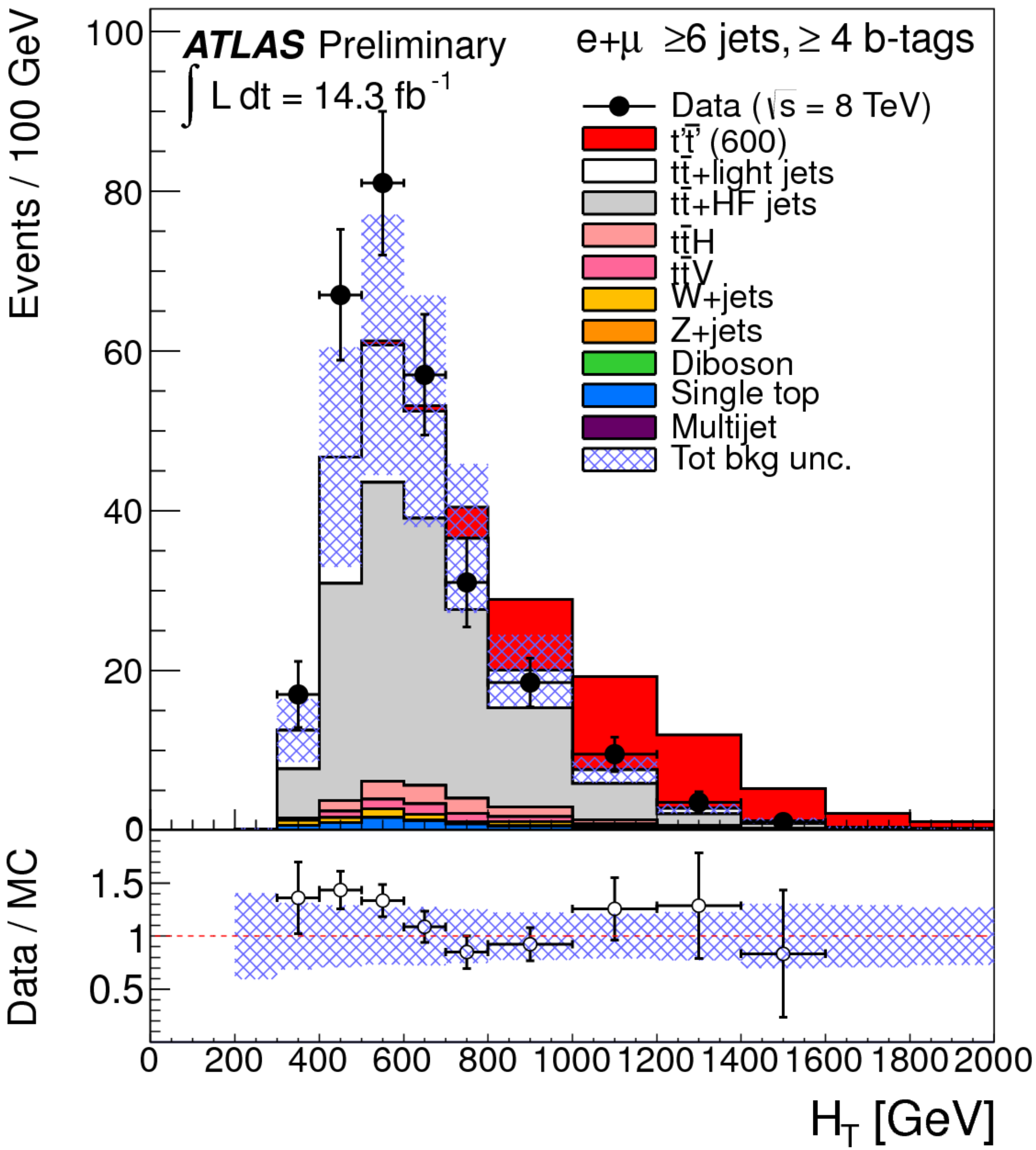
Discriminant Variable H_T

$$H_T = \sum_{Scalar\ Sum} P_{T,lepton} + E_{T,miss} + P_{T,jets}$$

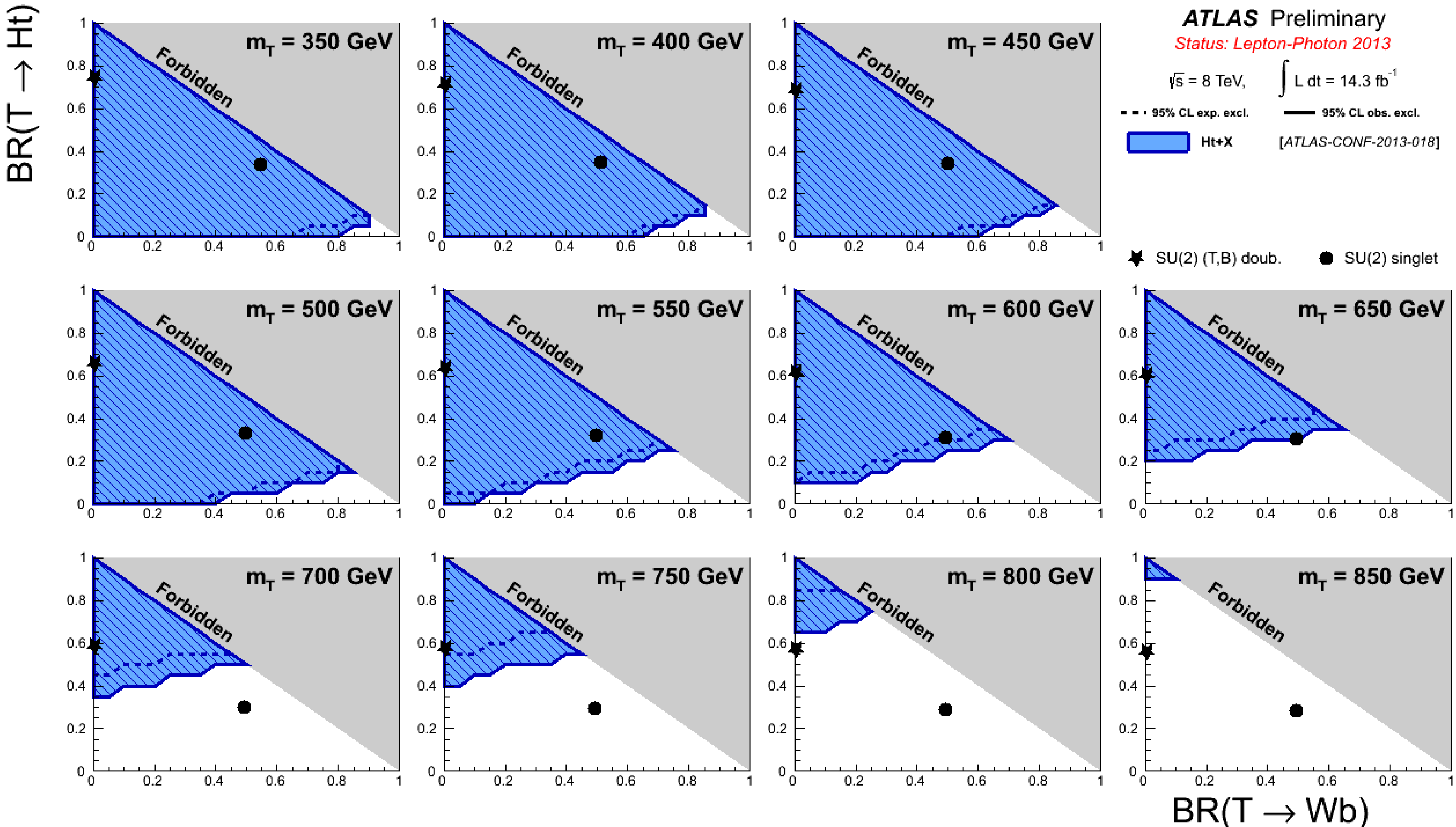
Discriminant Variable H_T



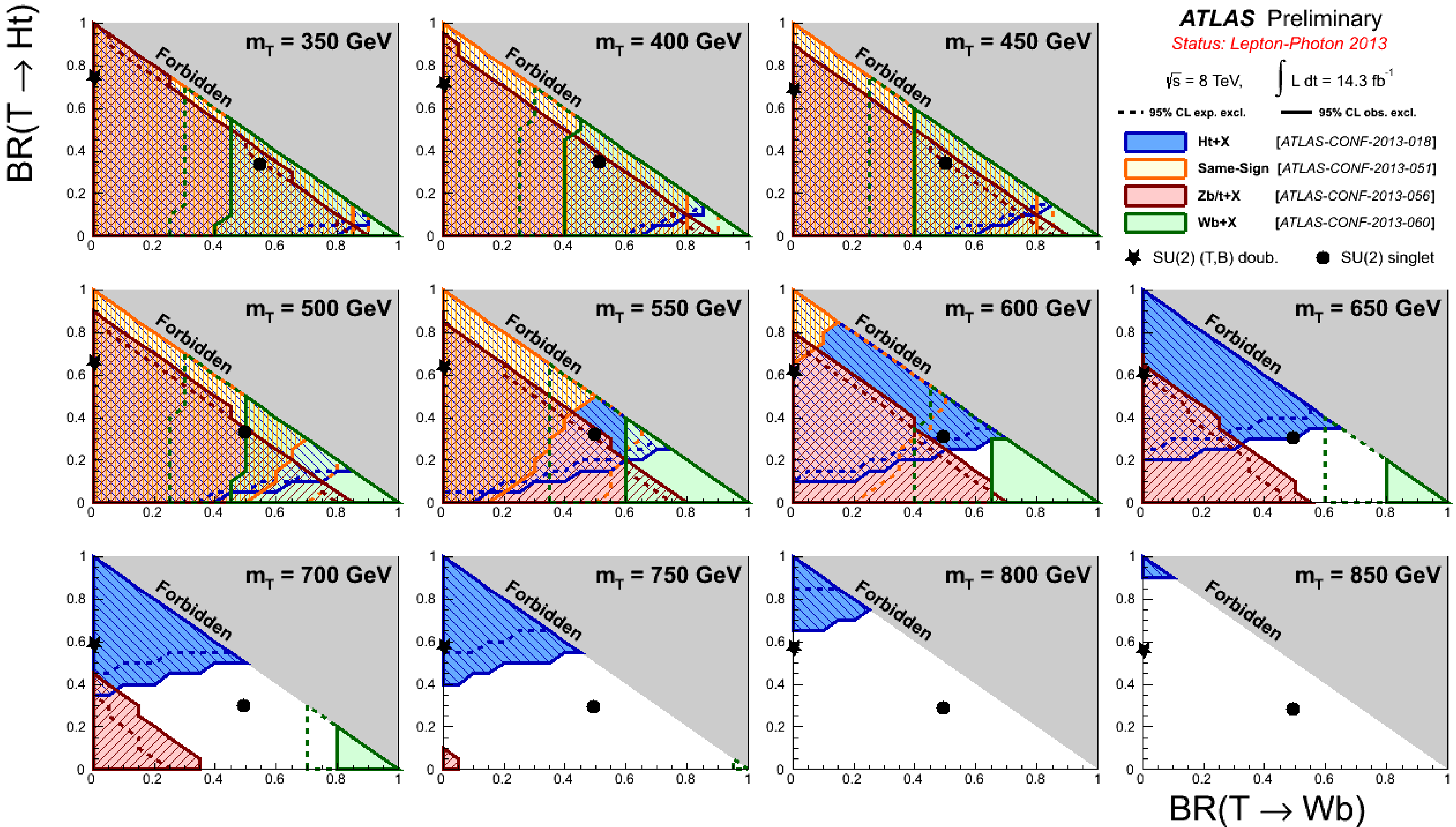
Discriminant Variable H_T



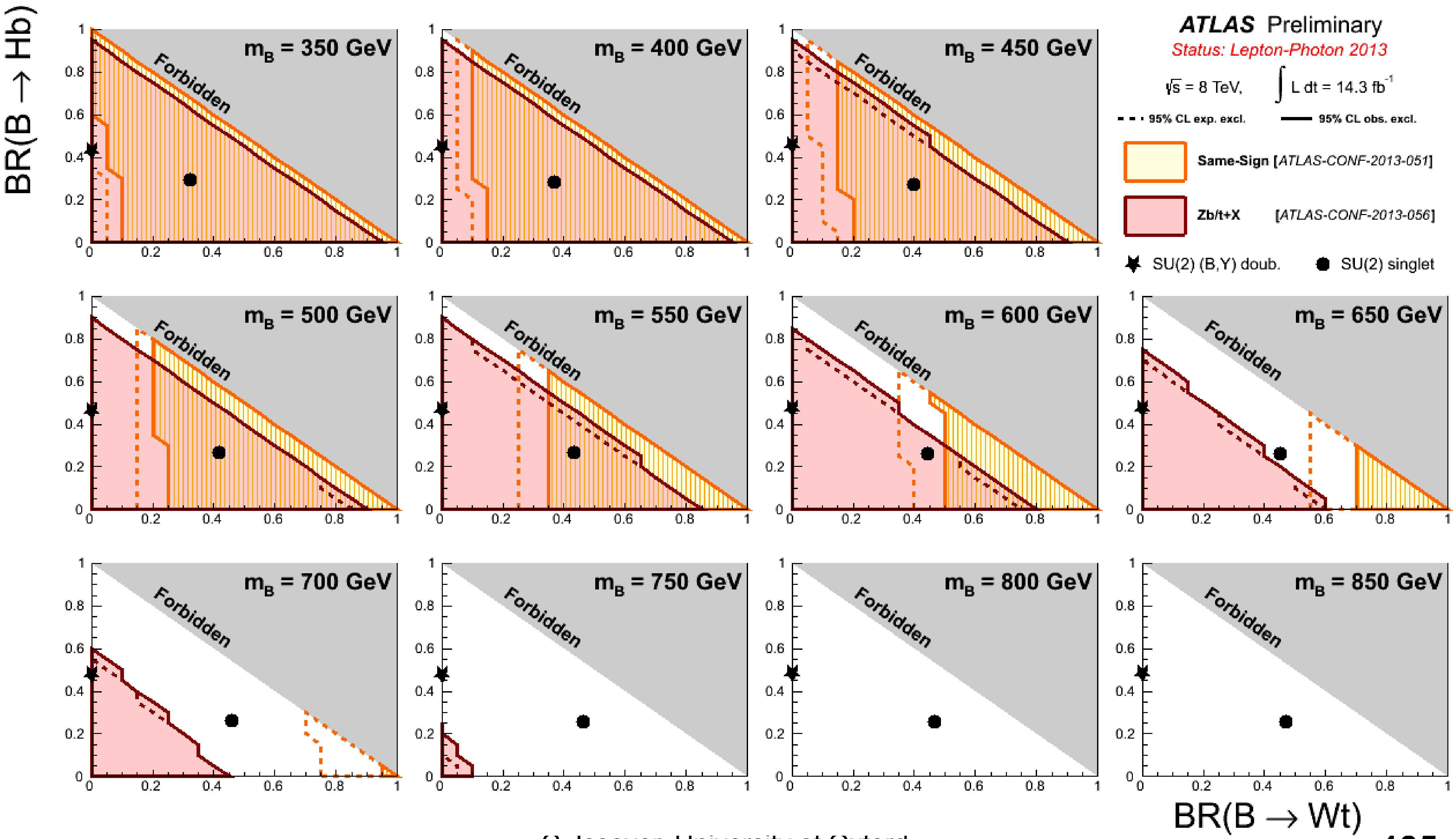
Exlusion Limits for Vector Like T Quark



Exlusion Limits for Vector-Like T Quark



Exlusion Limits for Vector Like B Quark



Inclusive Same-Sign Dilepton Search

1210.4538

- Model independent approach
  - Limit presented in terms of fiducial cross-section limit

$$\sigma_{95}^{\text{fid}} = \frac{N_{95}}{\varepsilon_{\text{fid}} \times \int \mathcal{L} dt}$$

95% CL upper limit on yield (given N_{obs} and N_{bkg})

Reconstruction and Selection efficiency **Within acceptance**

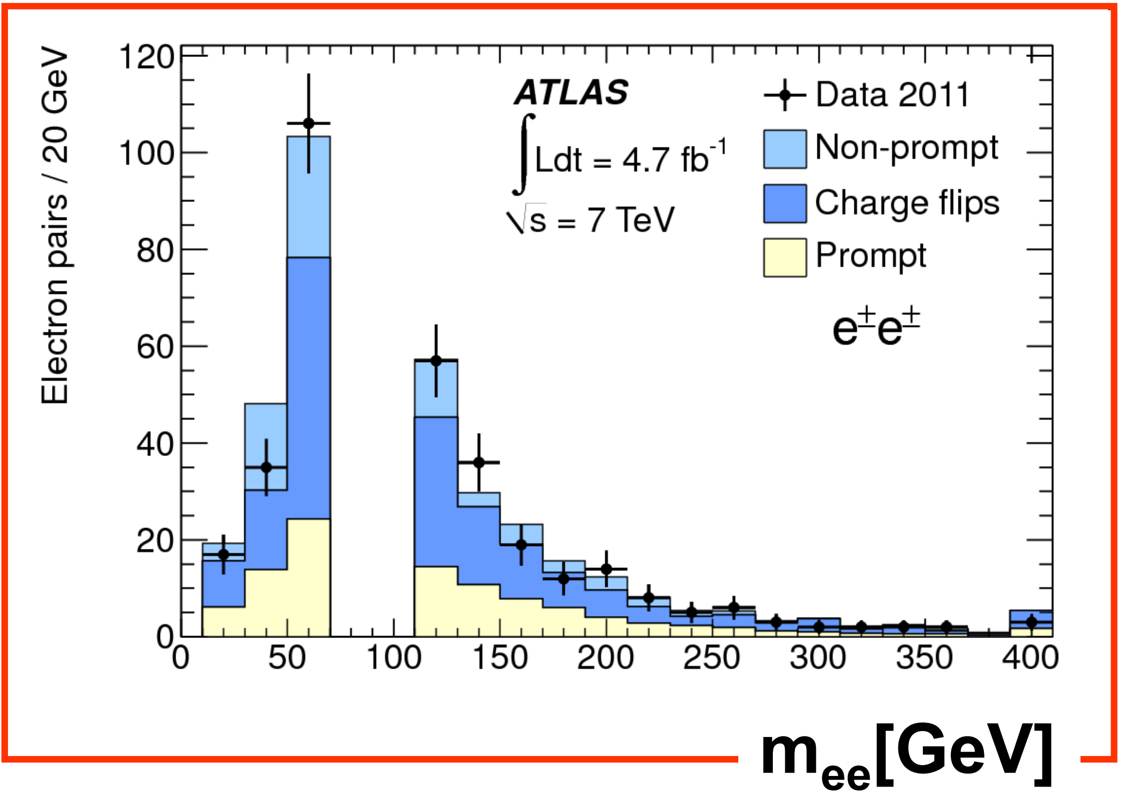
  - σ^{fid} is (almost) model-independent
  - Can turn σ^{fid} into σ^{total} with generator-level information only
  - Caveat: not exactly model-independent → must be conservative

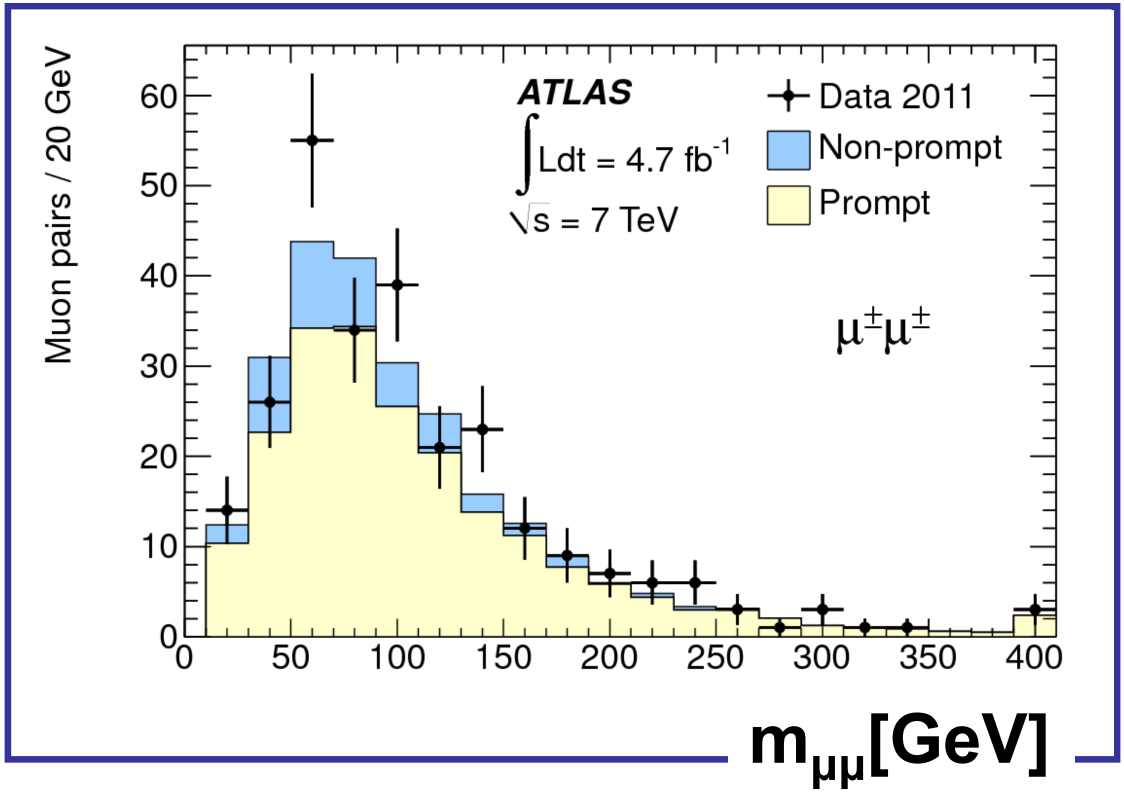
Particle-level definition of acceptance

	Electron requirement	Muon requirement
Leading lepton p_T	$p_T > 25$ GeV	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 20$ GeV	$p_T > 20$ GeV
Lepton η	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.5$
Isolation	$p_T^{cone0.3}/p_T < 0.1$	$p_T^{cone0.4}/p_T < 0.06$ and $p_T^{cone0.4} < 4$ GeV $+ 0.02 \times p_T$

Inclusive Same-Sign Dilepton Search

1210.4538





arXiv:1210.5070

Inclusive Same-Sign Dilepton Search

1210.4538

- 95% upper limits
  - 1.7 fb and 64 fb

Fiducial cross section upper limits

Mass ee eμ μμ
exp obs exp obs exp obs

Mass range	95% C.L. upper limit [fb] expected	observed	expected	observed	expected	observed
	$e^{\pm}e^{\pm}$		$e^{\pm}\mu^{\pm}$		$\mu^{\pm}\mu^{\pm}$	
$m > 15$ GeV	46^{+15}_{-12}	42	56^{+23}_{-15}	64	$24.0^{+8.9}_{-6.0}$	29.8
$m > 100$ GeV	$24.1^{+8.9}_{-6.2}$	23.4	$23.0^{+9.1}_{-6.7}$	31.2	$12.2^{+4.5}_{-3.0}$	15.0
$m > 200$ GeV	$8.8^{+3.4}_{-2.1}$	7.5	$8.4^{+3.4}_{-1.7}$	9.8	$4.3^{+1.8}_{-1.1}$	6.7
$m > 300$ GeV	$4.5^{+1.8}_{-1.3}$	3.9	$4.1^{+1.8}_{-0.9}$	4.6	$2.4^{+0.9}_{-0.7}$	2.6
$m > 400$ GeV	$2.9^{+1.1}_{-0.8}$	2.4	$3.0^{+1.0}_{-0.8}$	3.1	$1.7^{+0.6}_{-0.5}$	1.7
	$e^{+}e^{+}$		$e^{+}\mu^{+}$		$\mu^{+}\mu^{+}$	
$m > 15$ GeV	$29.1^{+10.2}_{-8.6}$	22.8	$34.9^{+12.2}_{-8.6}$	34.1	$15.0^{+6.1}_{-3.3}$	15.2
$m > 100$ GeV	$16.1^{+5.9}_{-4.3}$	12.0	$15.4^{+5.9}_{-4.1}$	18.0	$8.4^{+3.2}_{-2.4}$	7.9
$m > 200$ GeV	$7.0^{+2.9}_{-2.2}$	6.1	$6.6^{+3.5}_{-1.8}$	8.8	$3.5^{+1.6}_{-0.7}$	4.3
$m > 300$ GeV	$3.7^{+1.4}_{-1.0}$	2.9	$3.2^{+1.2}_{-0.9}$	3.2	$2.0^{+0.8}_{-0.5}$	2.1
$m > 400$ GeV	$2.3^{+1.1}_{-0.6}$	1.7	$2.4^{+0.9}_{-0.6}$	2.5	$1.5^{+0.6}_{-0.3}$	1.8
	$e^{-}e^{-}$		$e^{-}\mu^{-}$		$\mu^{-}\mu^{-}$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7	$26.2^{+10.6}_{-7.6}$	34.4	$12.1^{+4.5}_{-3.5}$	18.5
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7	$11.5^{+4.2}_{-3.5}$	16.9	$6.0^{+2.3}_{-1.9}$	10.1
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0	$4.6^{+2.1}_{-1.2}$	4.5	$2.7^{+1.1}_{-0.7}$	4.4
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7	$2.7^{+1.1}_{-0.6}$	3.5	$1.5^{+0.8}_{-0.3}$	1.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3	$2.3^{+0.8}_{-0.5}$	2.5	$1.2^{+0.4}_{-0.0}$	1.2

	$e^{-}e^{-}$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3

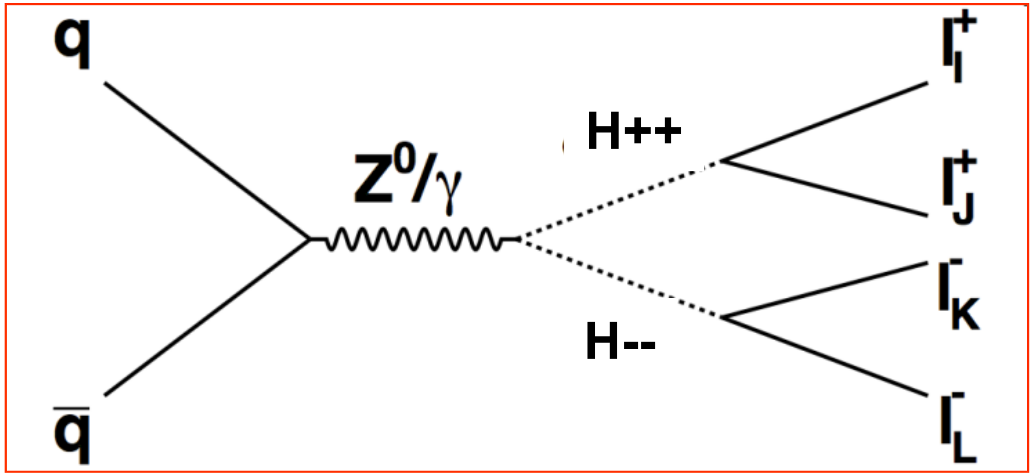
Possible Models

- left-right symmetric models
- Higgs triplet models
- little Higgs model
- fourth-family quarks
- supersymmetry
- universal extra dimensions
- …

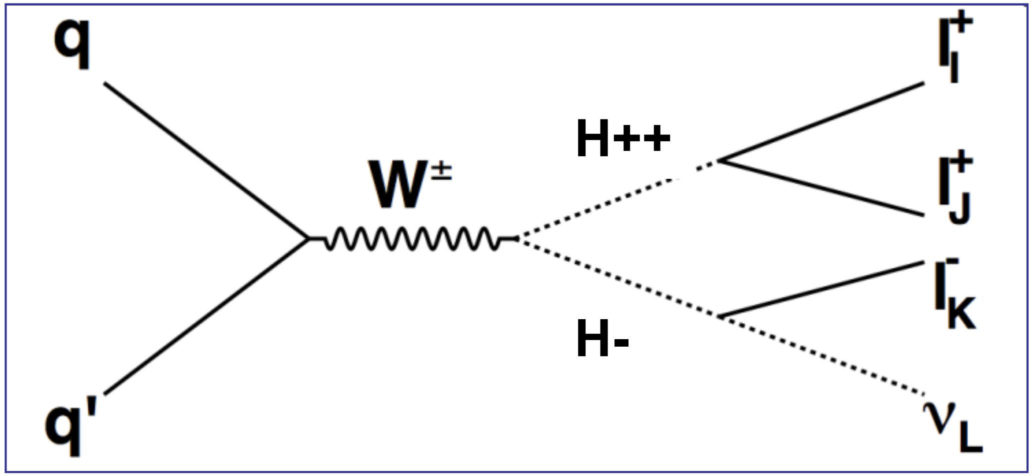
Acceptances: 43% - 65 %

Inclusive Same-Sign Dilepton Search: $H^{++/--}$ Limits

- Models explaining non-zero neutrino masses predict $H^{++/--}$
  - e.g. minimal type II seesaw model
    - additional scalar field
    - triplet (under $SU(2)_L$ with Y=2): $H^{++/--}$, $H^{+/-}$, H^0



pair production

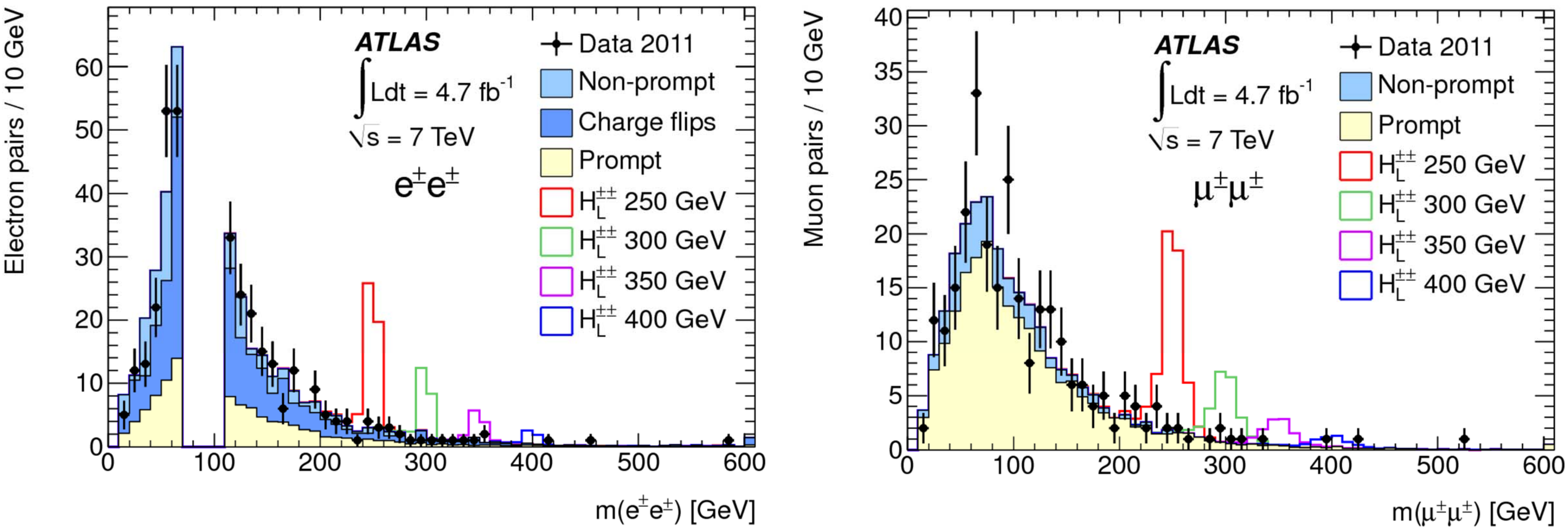


associate production

Signature: same-sign leptons

Inclusive Same-Sign Dilepton Search

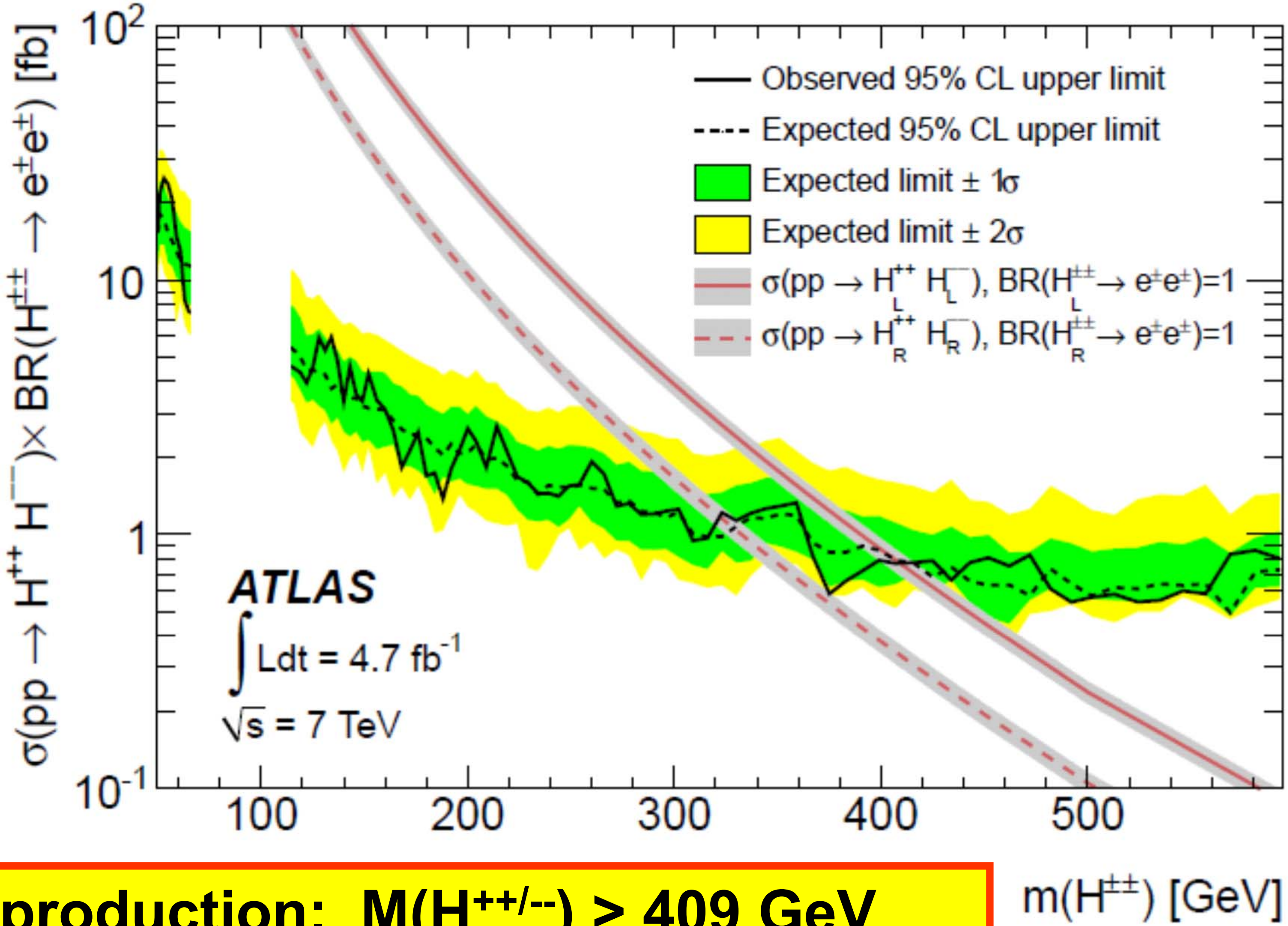
arXiv:1210.5070



Doubly Charged Higgs Limits

arXiv:1210.5070

- Used e.g. limits on doubly charged Higgs

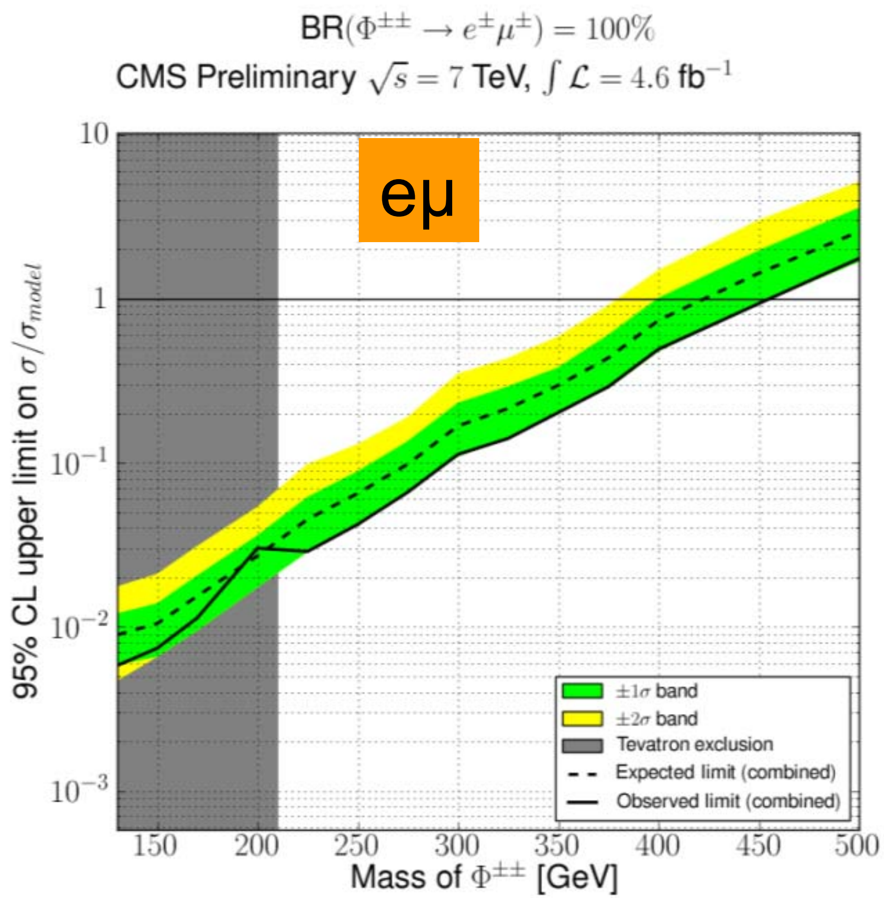


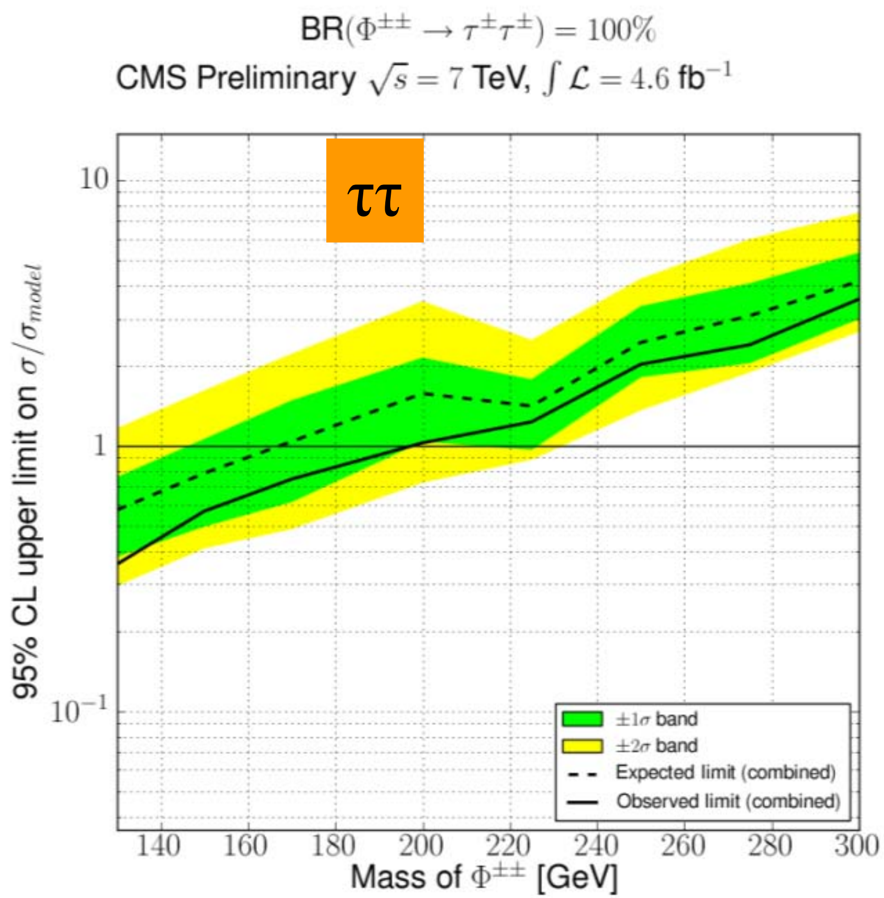
Pair production: $M(H^{++/--}) > 409$ GeV

Doubly Charged Higgs Limits

arXiv:1207.2666

- Example of more optimized search
- Includes also τ-channel and associate production.





Combined eμ: $M(H^{++/--})$ > 455 GeV

Combined ττ: $M(H^{++/--})$ > 198 GeV

General 3 Charged Lepton (e/μ/τ) Search

ATLAS-CONF-2013-070

- complements previous searches – **model independent**
- 4 inclusive signal regions

20.3 fb^{-1}

Flavor Chan.	Z Chan.	Expected			Observed
$\geq 3e/\mu$	off-Z	260 ±	10 ±	40	280
$2e/\mu + \geq 1\tau_{\text{had}}$	off-Z	1200 ±	10 ±	290	1193
$\geq 3e/\mu$	on-Z	3100 ±	40 ±	500	3199
$2e/\mu + \geq 1\tau_{\text{had}}$	on-Z	17000 ±	40 ±	4000	14733

- 100 exclusive signal regions
  - $H_T^{leptons}$, H_T^{jets}
  - Min p_T^l
  - $m_{eff}=|H_t^{jets}| + |E_t^{miss}| + |p_T^l|$
  - for on-Z: m_T^W
  - number of b-jets

Selections

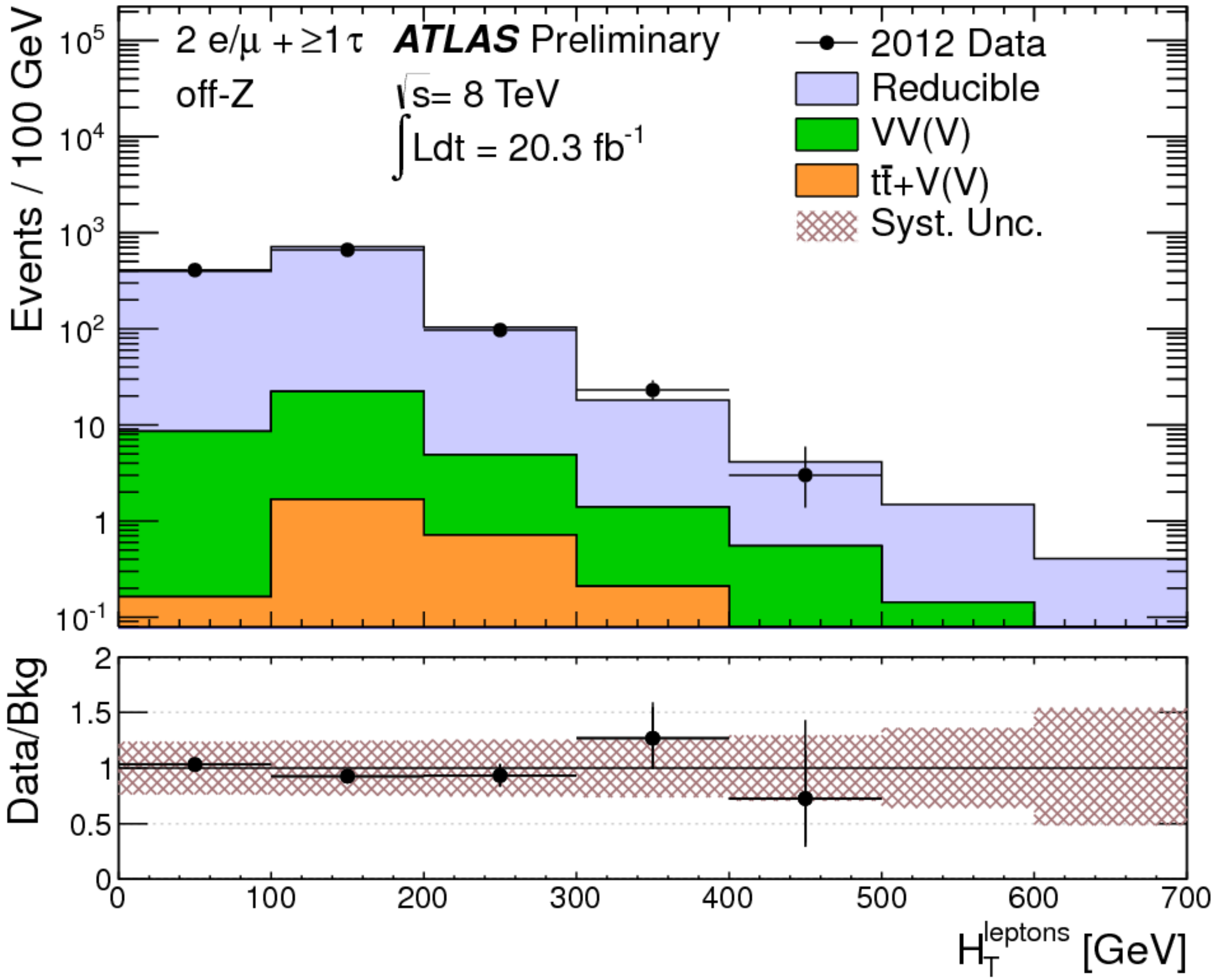
2 isolated electrons or muons,
p_{T1} > 26 GeV, p_{T2}>15 GeV

3rd lepton: e or μ or τ_{had}
$p_T(e,\mu)$>15 GeV, $p_T^{vis}(\tau_{had})$>20 GeV

akt4 jets with p_T > 30 GeV

General 3 Charged Lepton (e/μ/τ) Search

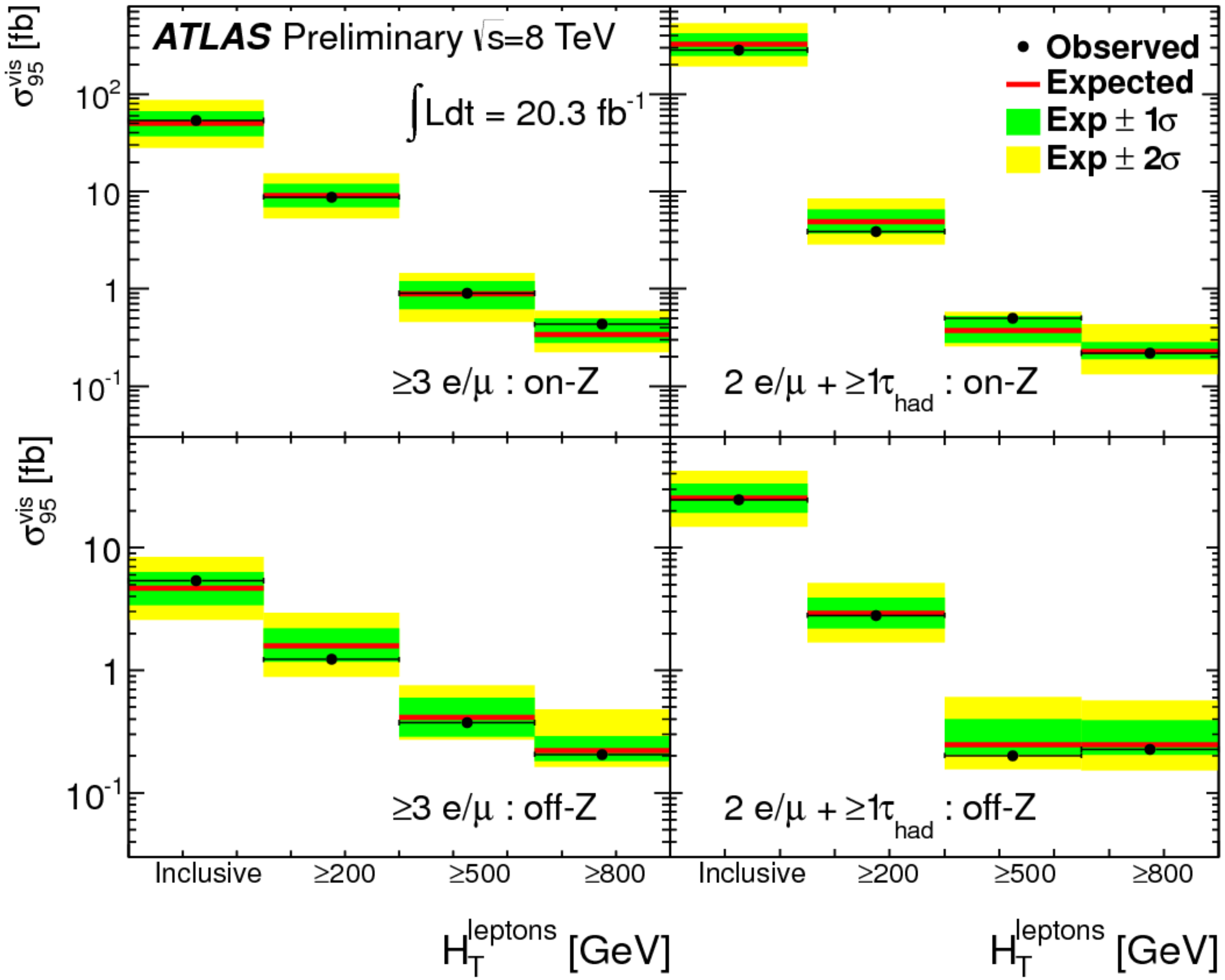
ATLAS-CONF-2013-070



General 3 Charged Lepton (e/μ/τ) Search

ATLAS-CONF-2013-070

95% Confidence Level Limits (using CL_s)



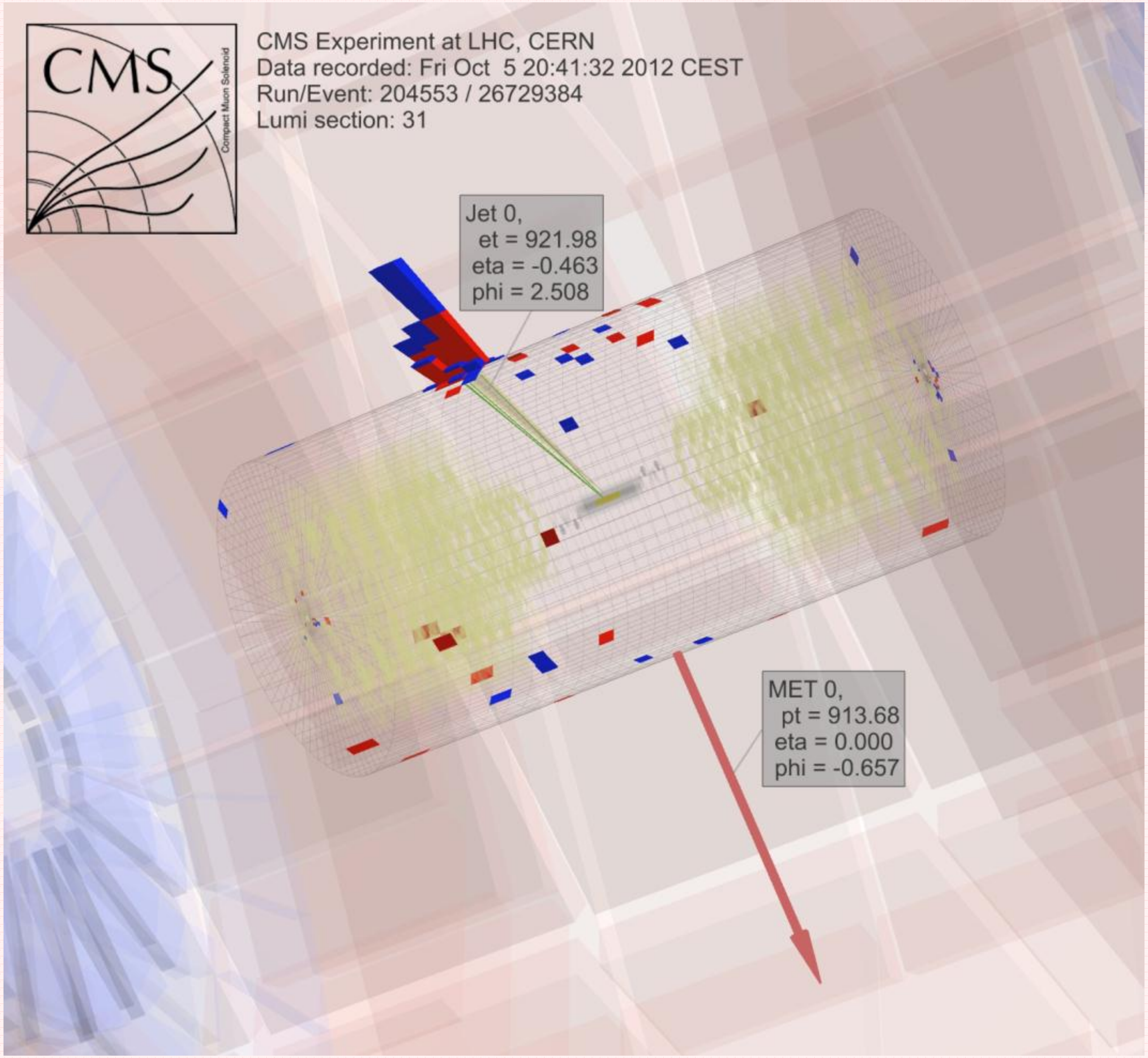
Model Testing with published fiducial lepton efficiencies

p_T [GeV]	Prompt μ $\lvert\eta\rvert > 0.1$	$\lvert\eta\rvert < 0.1$
10–15	0.021±0.001	0.003±0.002
15–20	0.704±0.003	0.37±0.01
20–25	0.808±0.002	0.42±0.01
25–30	0.855±0.002	0.45±0.01
30–40	0.896±0.001	0.498±0.008

...

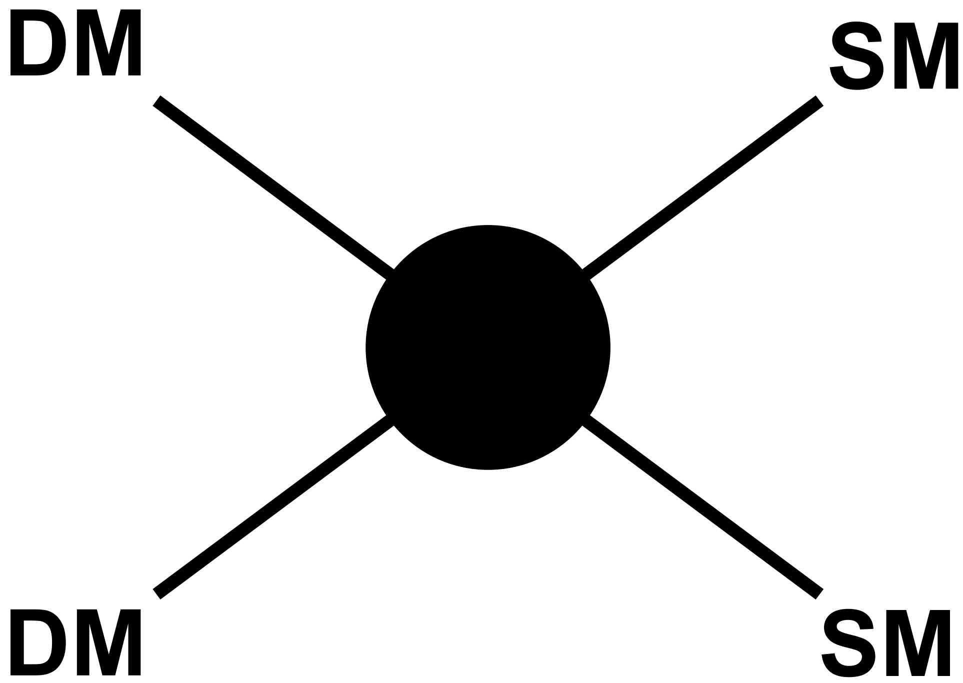
Just one example from note

Mono Jet Event Display



Dark Matter Detection

M. Fedderke



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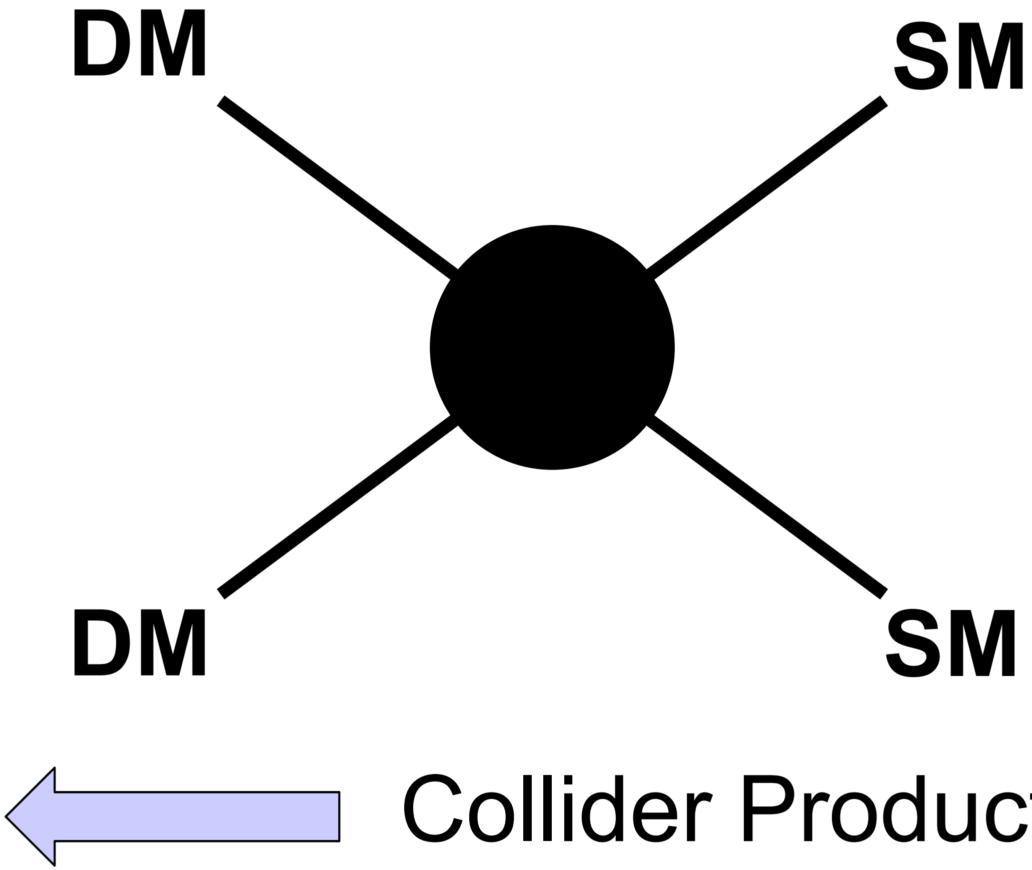
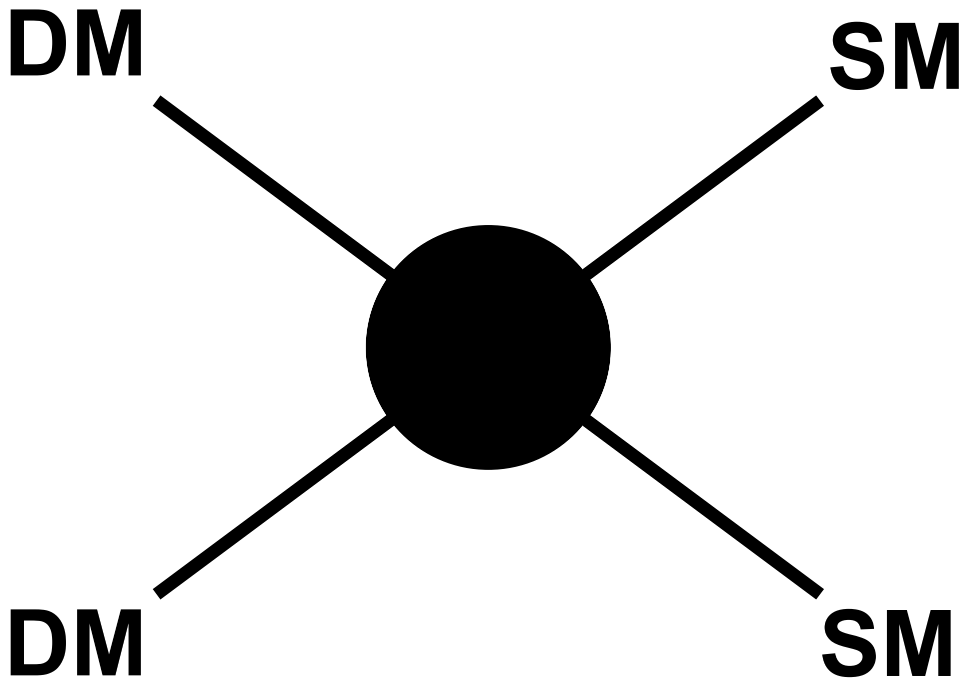
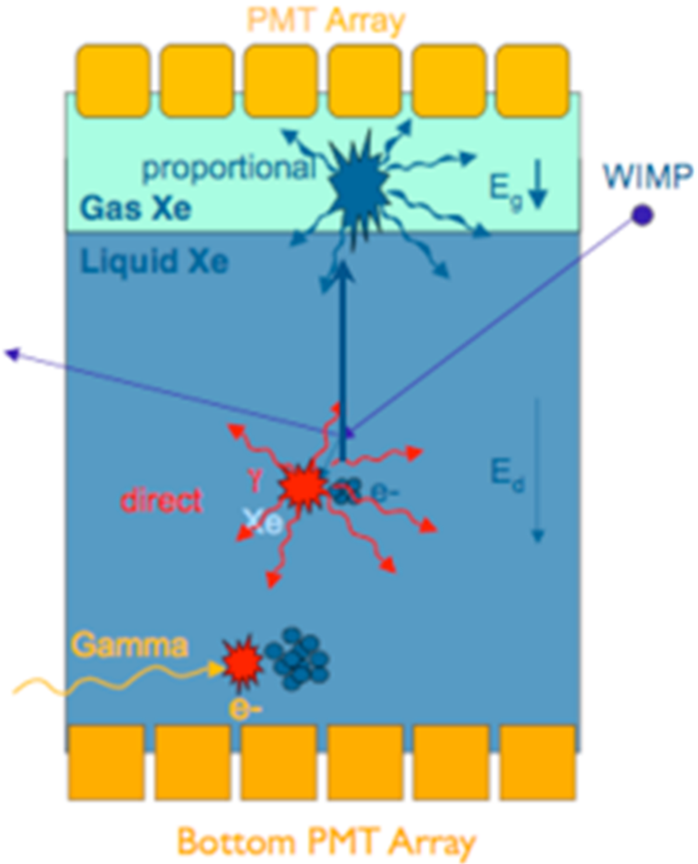


Collider Production

Dark Matter Detection

M. Fedderke



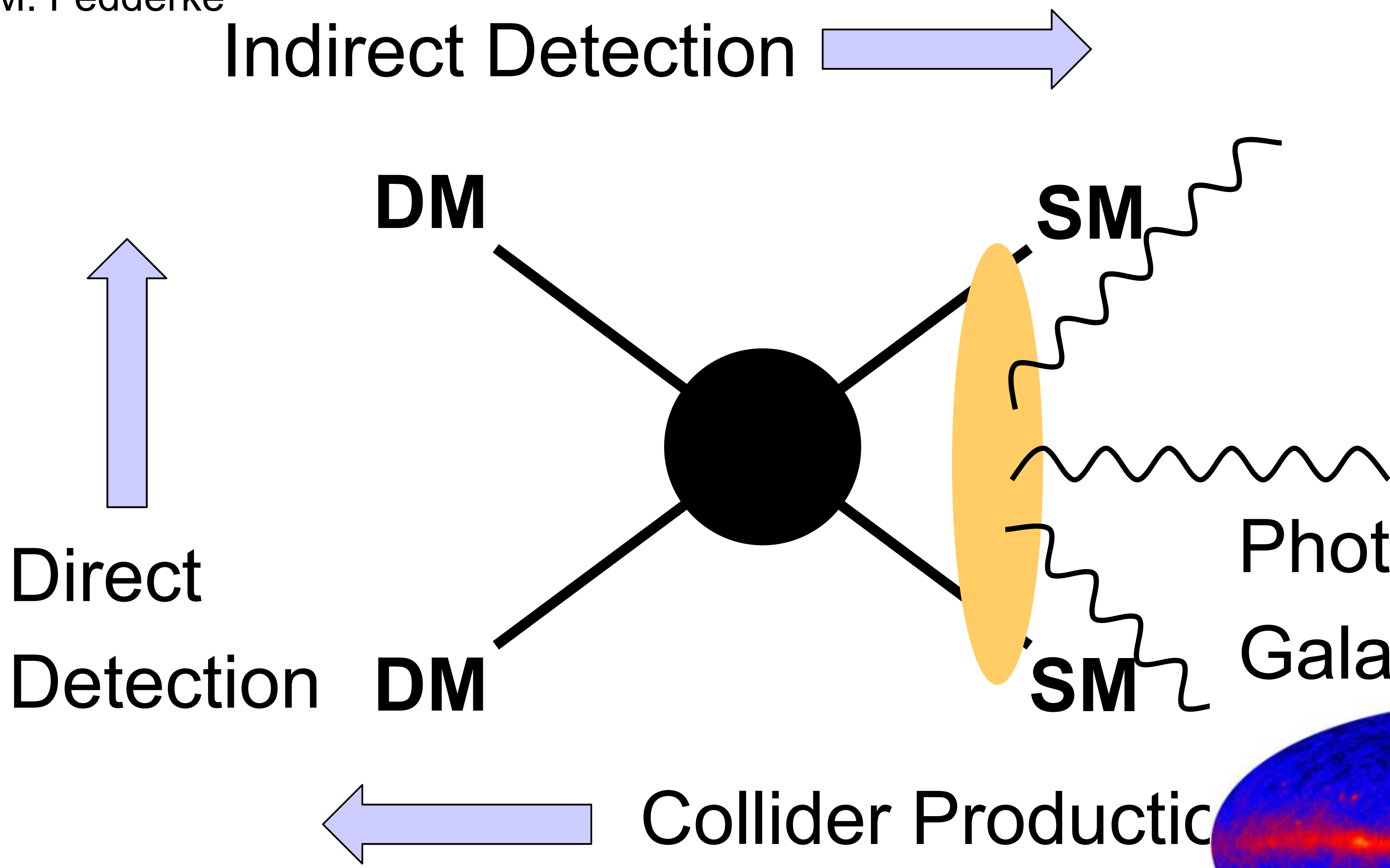


Direct Detection

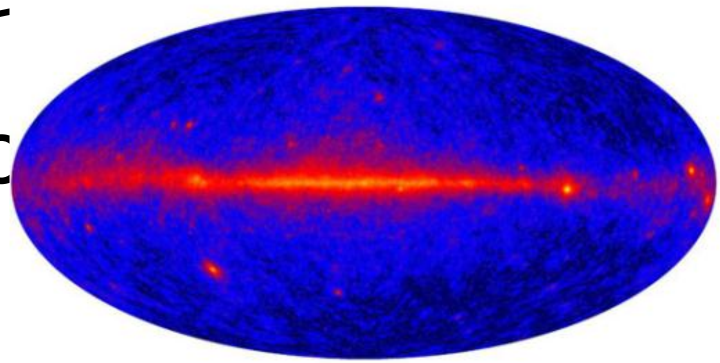
Collider Production

Dark Matter Detection

M. Fedderke



Photons from
Galactic Centre

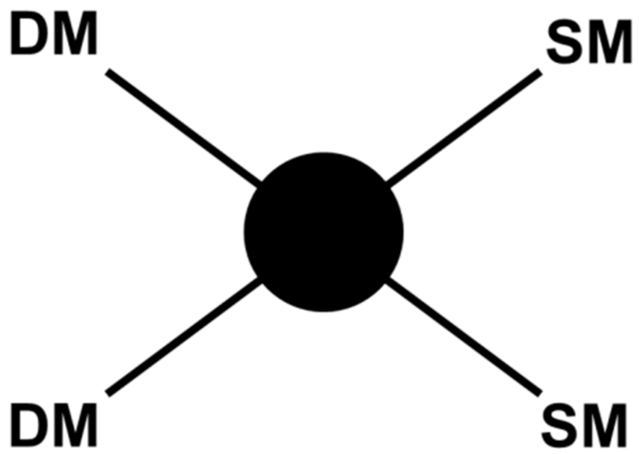


DM Interpretations of Mono-Object Analyses

Johanna Gramling

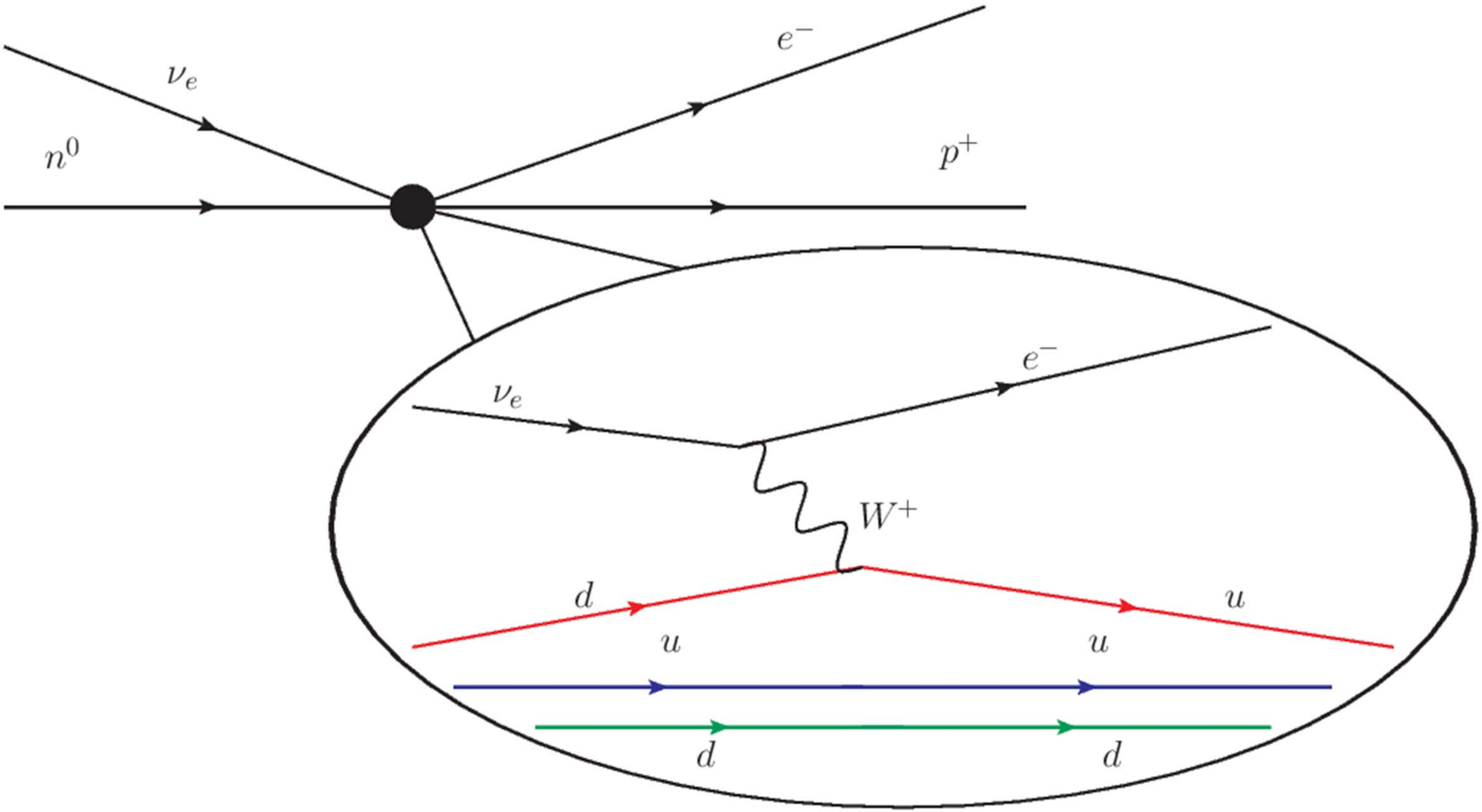
Idea: Effective Theory

- Heavy particle mediating interaction btw DM and SM



- too heavy to be on-shell → can be integrated out
- interaction treated as contact interaction!

Like Fermi's Theory of Beta Decay



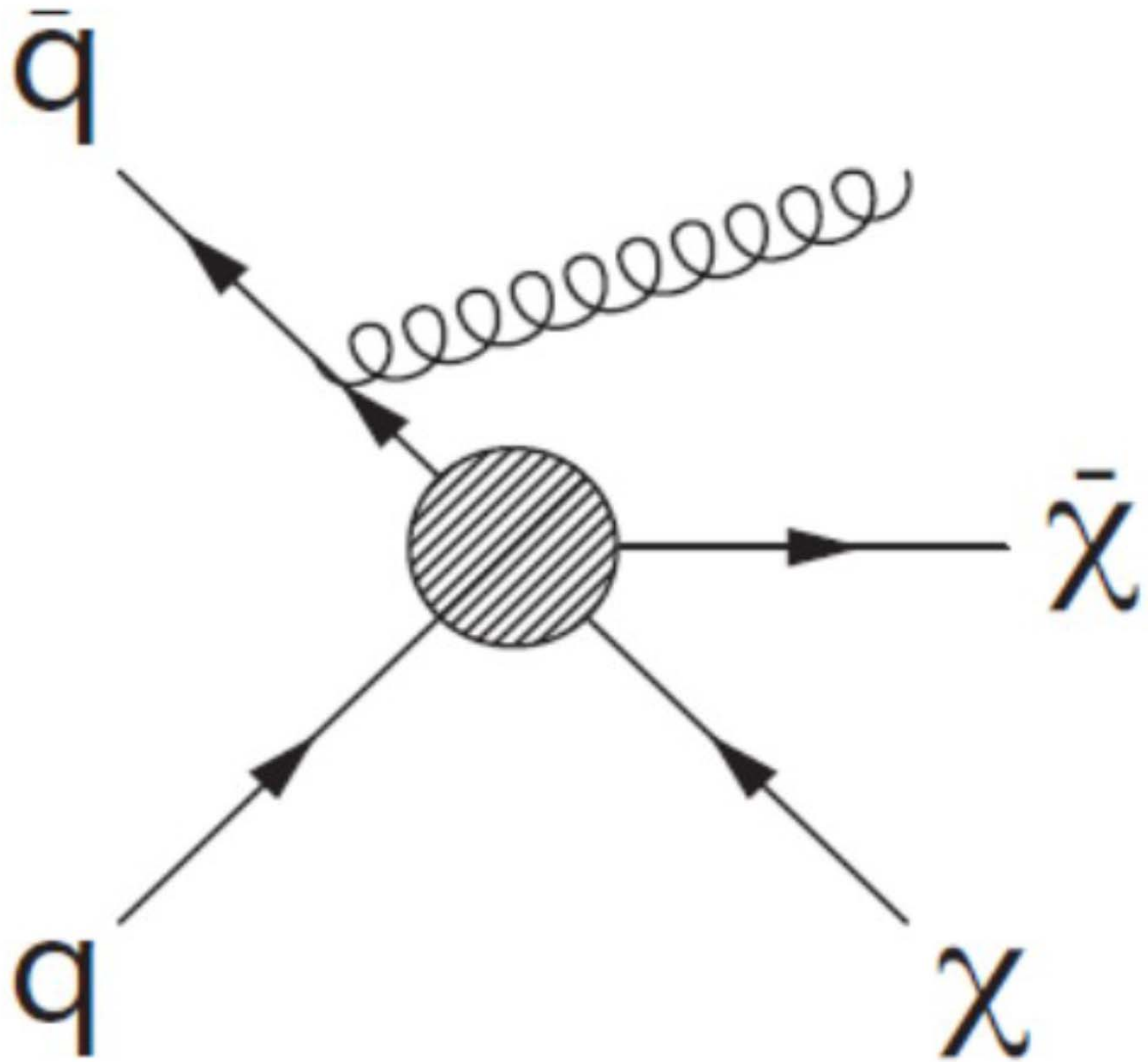
Advantage of Effective Theory

arXiv:1008.1783

- Model depends only on a few parameters
  - dark matter mass, $\mathbf{m_\chi}$
  - cut-off scale **Λ or M$_*$**
  - much easier than e.g. a full SUSY model
- Allows easy comparison to direct or indirect DM detection experiments
- DM
  - Fermion: Dirac or Majorana
  - Scalar: Complex or Real

$$\Lambda = \frac{m_M}{\sqrt{g_q g_\chi}}$$

Dark Matter Production at a Collider



Dark Matter (DM) Production at LHC $pp \rightarrow \chi\chi + X$

Effective interactions coupling DM to SM quarks or gluons

1210.4491v2

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

characteristic set

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[illegible]	[illegible]	[illegible]	[illegible]
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related to spin-independent DM-nucleon interactions

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related to spin dependent DM-nucleon interactions

characteristic set

Conditions of EFT

1. $g_q, g_\chi < 4\pi \rightarrow \frac{m_M}{4\pi} < \Lambda$ (to stay in perturbative regime)
2. $m_M > m_\chi$ (M can not be produced, but χ can)
   - $\Lambda > \frac{m_M}{4\pi} > \frac{m_\chi}{4\pi}$

Johanna Gramling

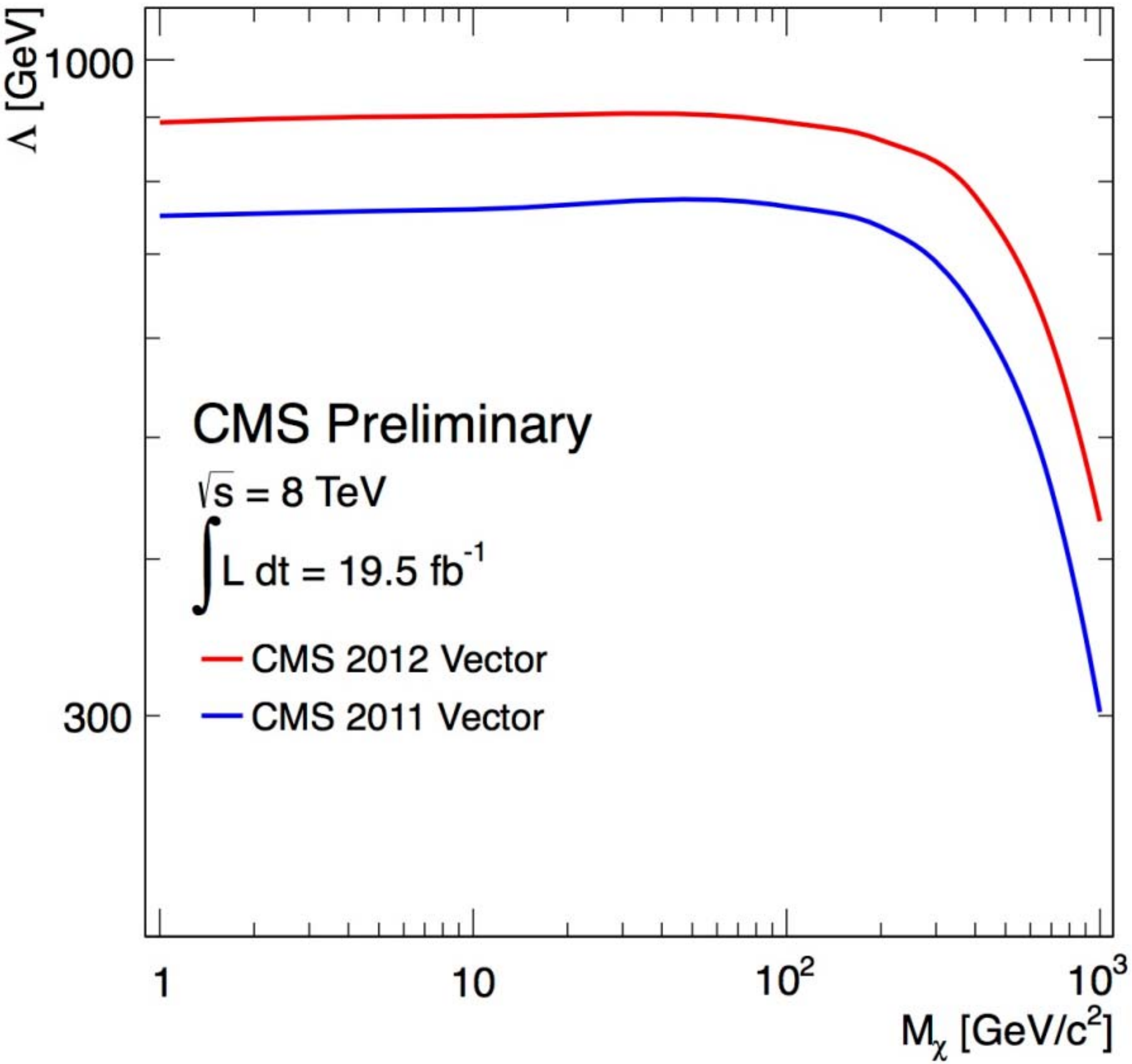
3. $m_M > Q_{TR}$
   - $\Lambda > \frac{m_M}{4\pi} > \frac{Q_{TR}}{4\pi}$
4. $Q_{TR} > 2m_\chi$ (DM pair-produced on-shell)

Combining 3 & 4 gives stronger constraint than 2!

- $\Lambda > \frac{Q_{TR}}{4\pi} > \frac{2m_\chi}{4\pi}$

Spin Independent Limits on Λ

EXO-12-048 PAS



Let say $\sqrt{g_q g_\chi}=1$

- $\Lambda > Q_{TR} > 2m_\chi$
- @LHC
  - $Q_{TR} \sim O(1 TeV)$
- Limits on Λ
  - < 1 TeV
  - Validity of EFT approach questionable

Johanna Gramling

Intensive Discussion about how to interpret Mono-X analyses

- G. Busonia, A. De Simonea, E. Morgantec, A. Riotto
  - "On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC", arXiv:1307.2253v1
  - Derive stronger bounds than currently used by LHC experiments

- New models:
  - A. DiFranzo, K. I. Nagao, A. Rajaraman, T.M.P. Tait,
    - "Simplified Models for Dark Matter Interacting with Quarks", arXiv:1308.2679v1
  - S. Chang, R. Edezhath, J. Hutchinson, and M. Luty,
    - "Effective WIMPs", arXiv:1307.8120v1
  - Yang Bai and Joshua Berger,
    - "Fermion Portal Dark Matter", arXiv:1308.0612v2

Discussion on Validity continued….

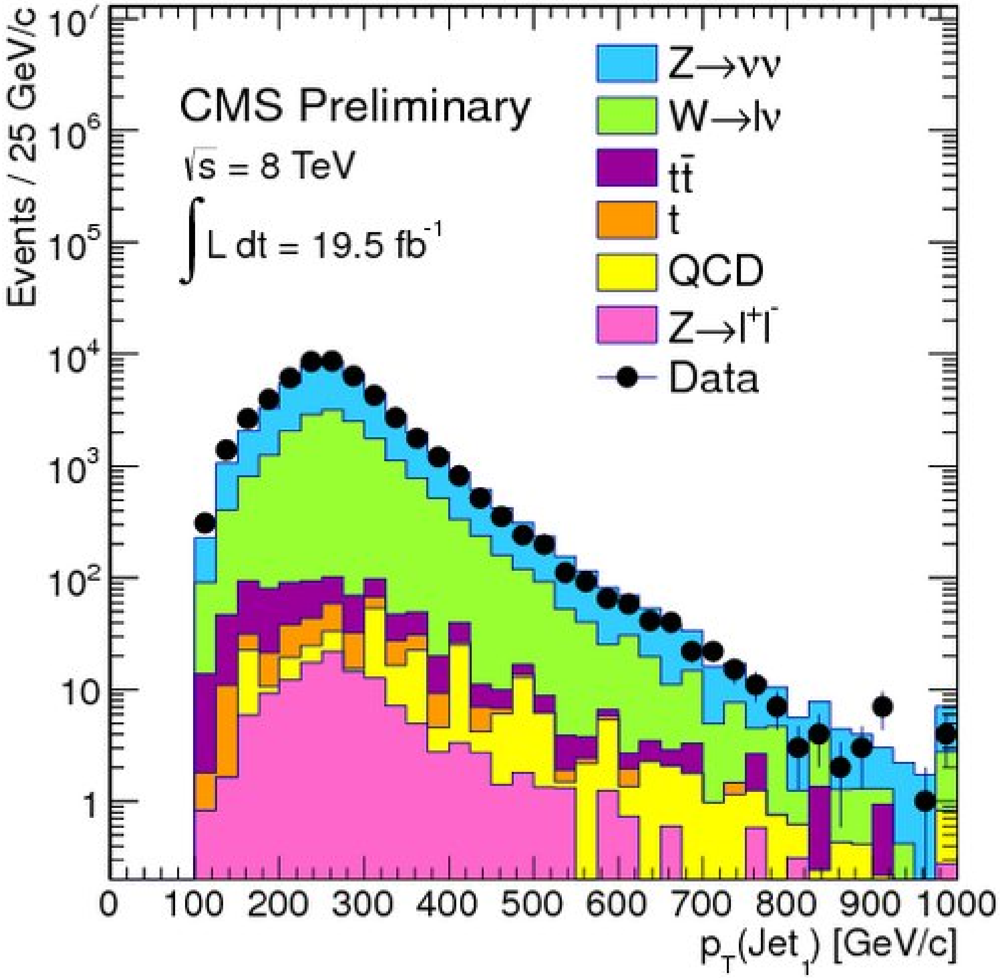
- See recent workshop in Chicago
  - Dark Matter at the LHC, 18.09-21.09.2013
  - ATLAS and CMS mono-object teams met with theorists
  - Expect for Run2 improved presentation of limits

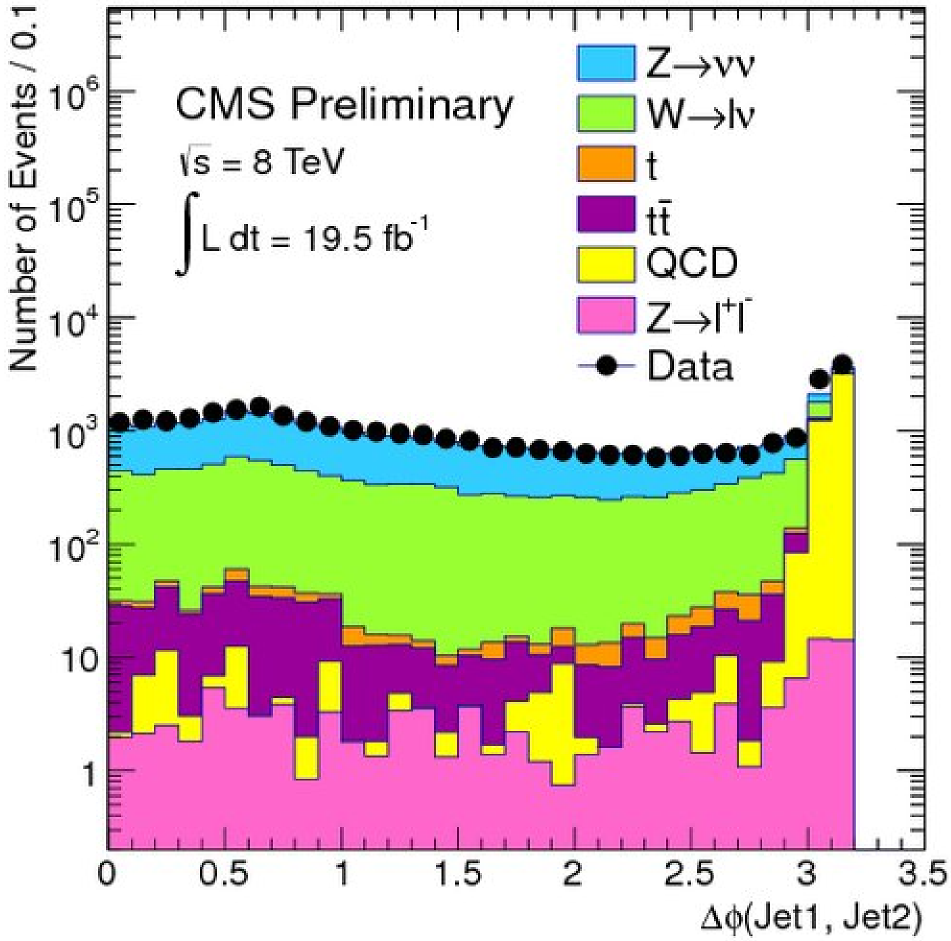
Coming back to CMS Mono-Jet Search

EXO-12-048 PAS

Selections
≥1 good vertex
> 20% E_{jet} from charged hadrons
<70% E_{jet} from neutral hadrons or photons
p_T(jet1) > 110 GeV && $\|\eta_{jet1}\|$ < 2.4
no other jet with p_T>30GeV in $\|\eta\|$ < 4.5 except $\Delta\varphi$(j1,j2) <2.5
no isolated leptons

Selection Variable Distributions

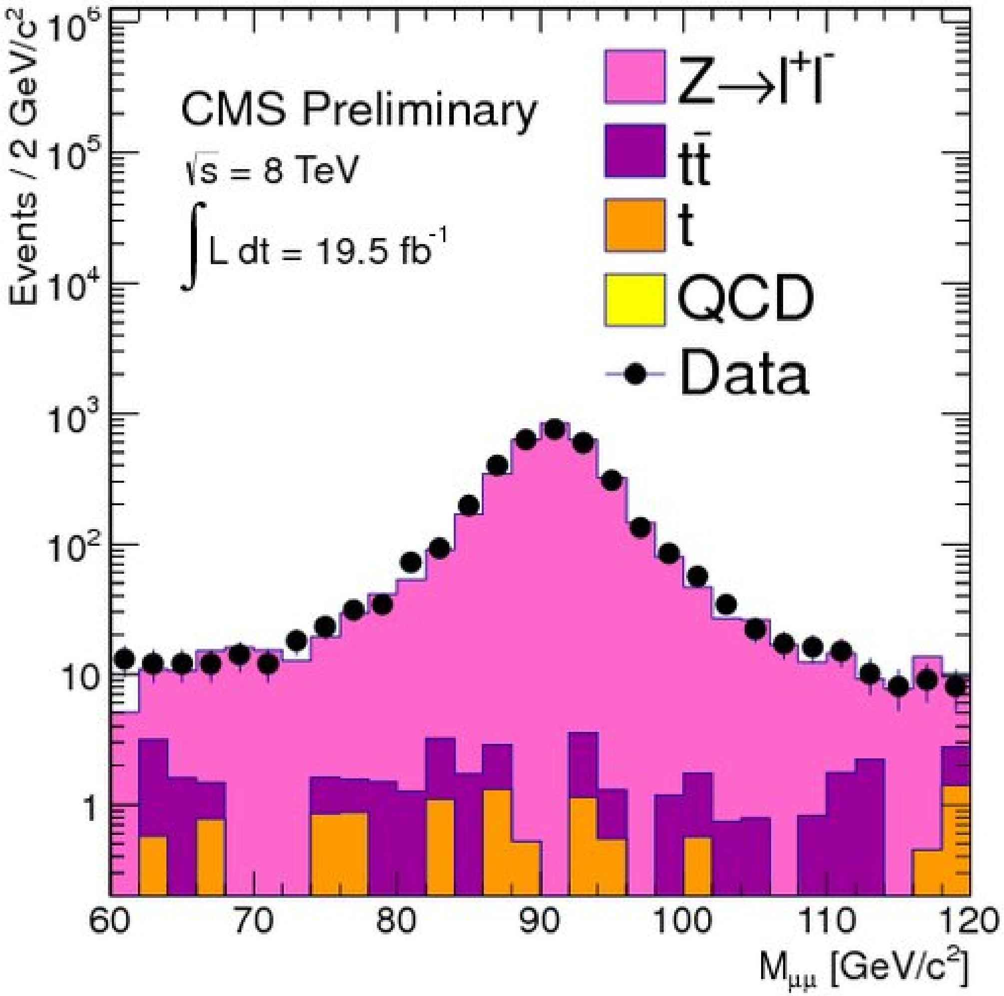


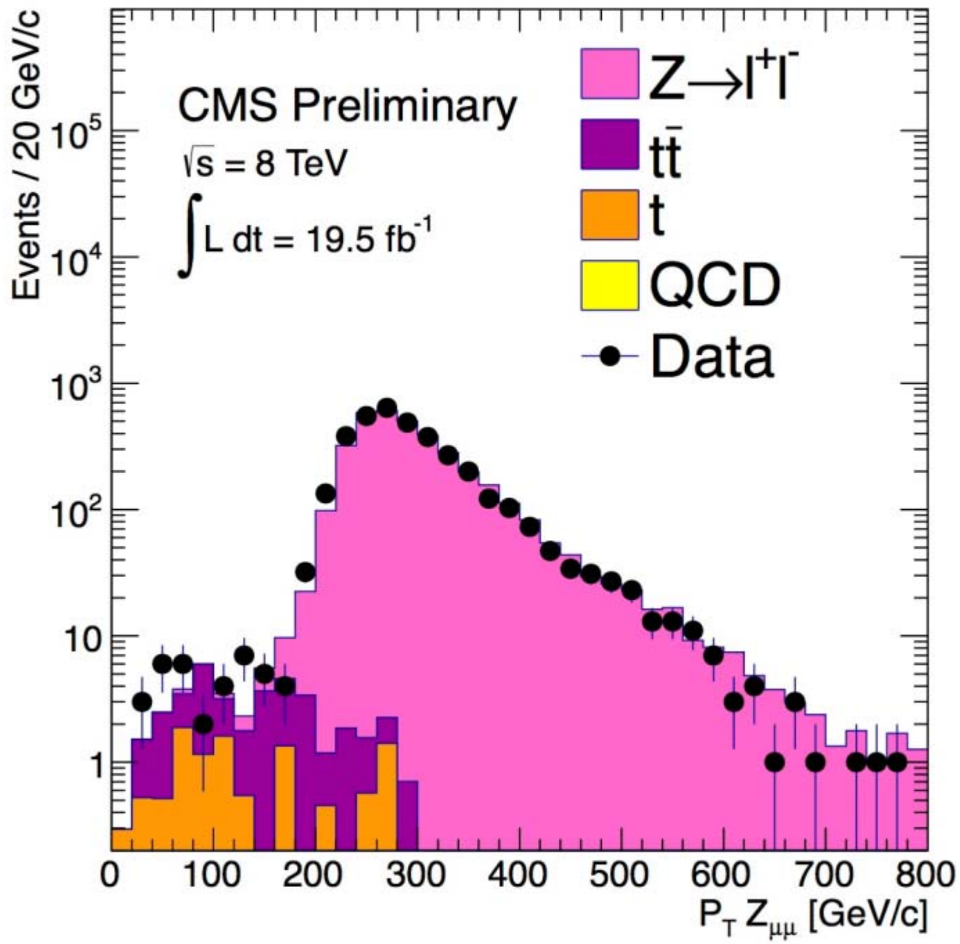


Background: Z(νν)+jet

- Use data to estimate background
- Select Z(μμ)+jet applying all selections BUT lepton veto
- 2 μ with p_T > 20 GeV && $|\eta|<2.1$
- ≥ 1 isolated μ
- 60 GeV < $m_{\mu\mu}$ < 120 GeV

Distribution of Z(μμ) + jet Sample





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- 2 μ with p_T > 20 GeV && |η|<2.1
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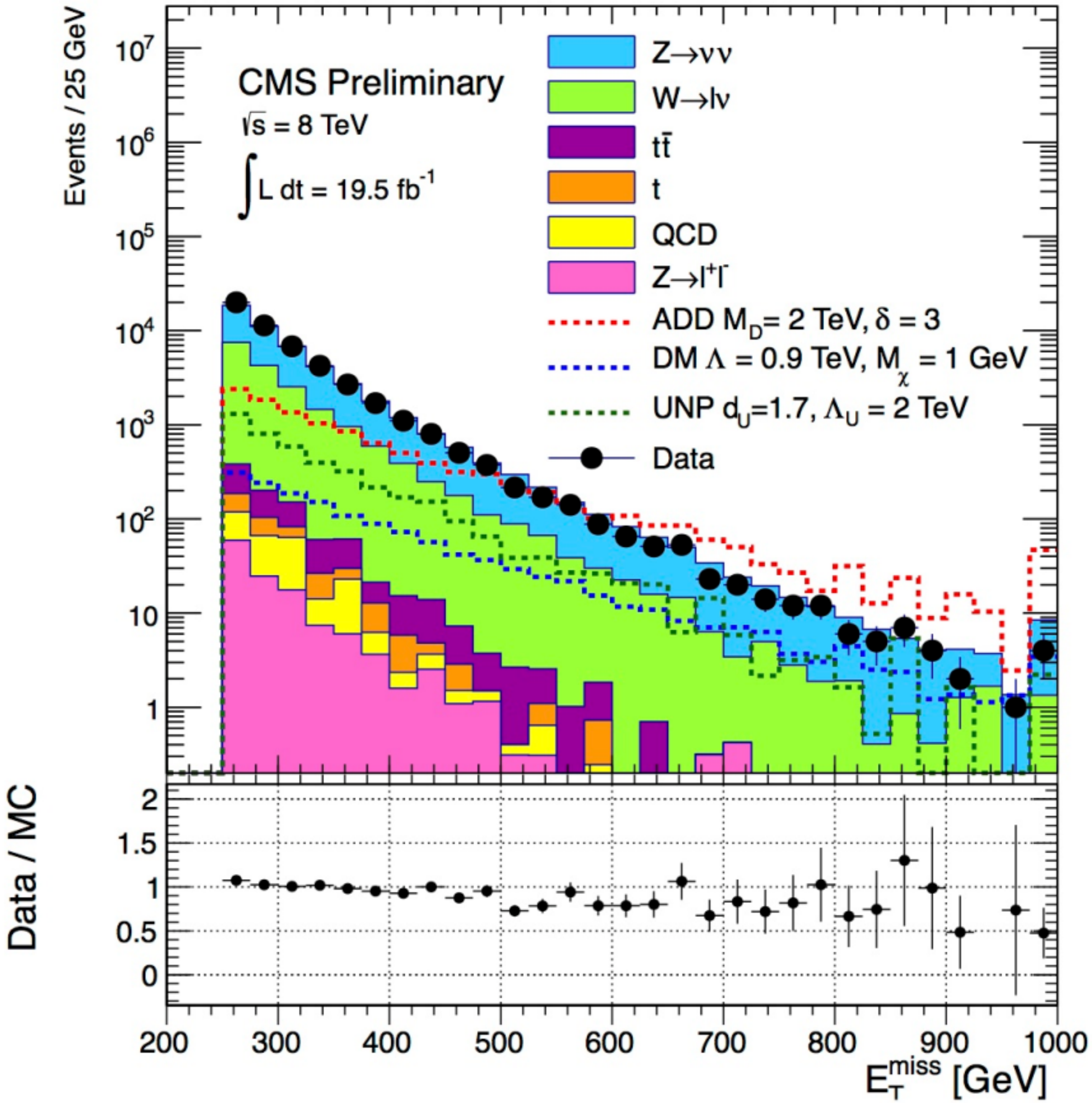
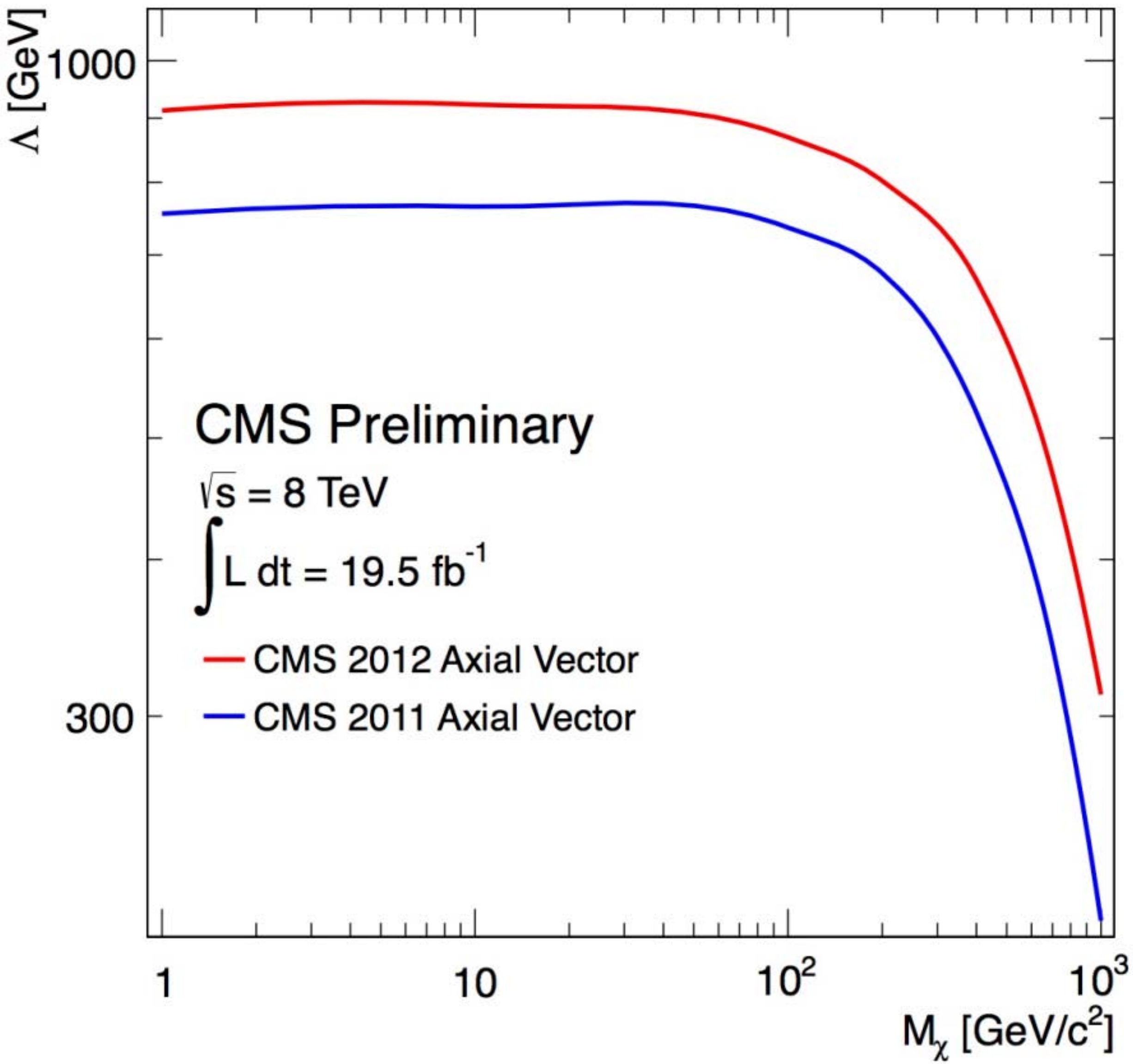
$$N(Z(\nu\nu)) = \frac{N^{\mathrm{obs}} - N^{\mathrm{bgd}}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$$

Missing E_T Distribution after all Selections

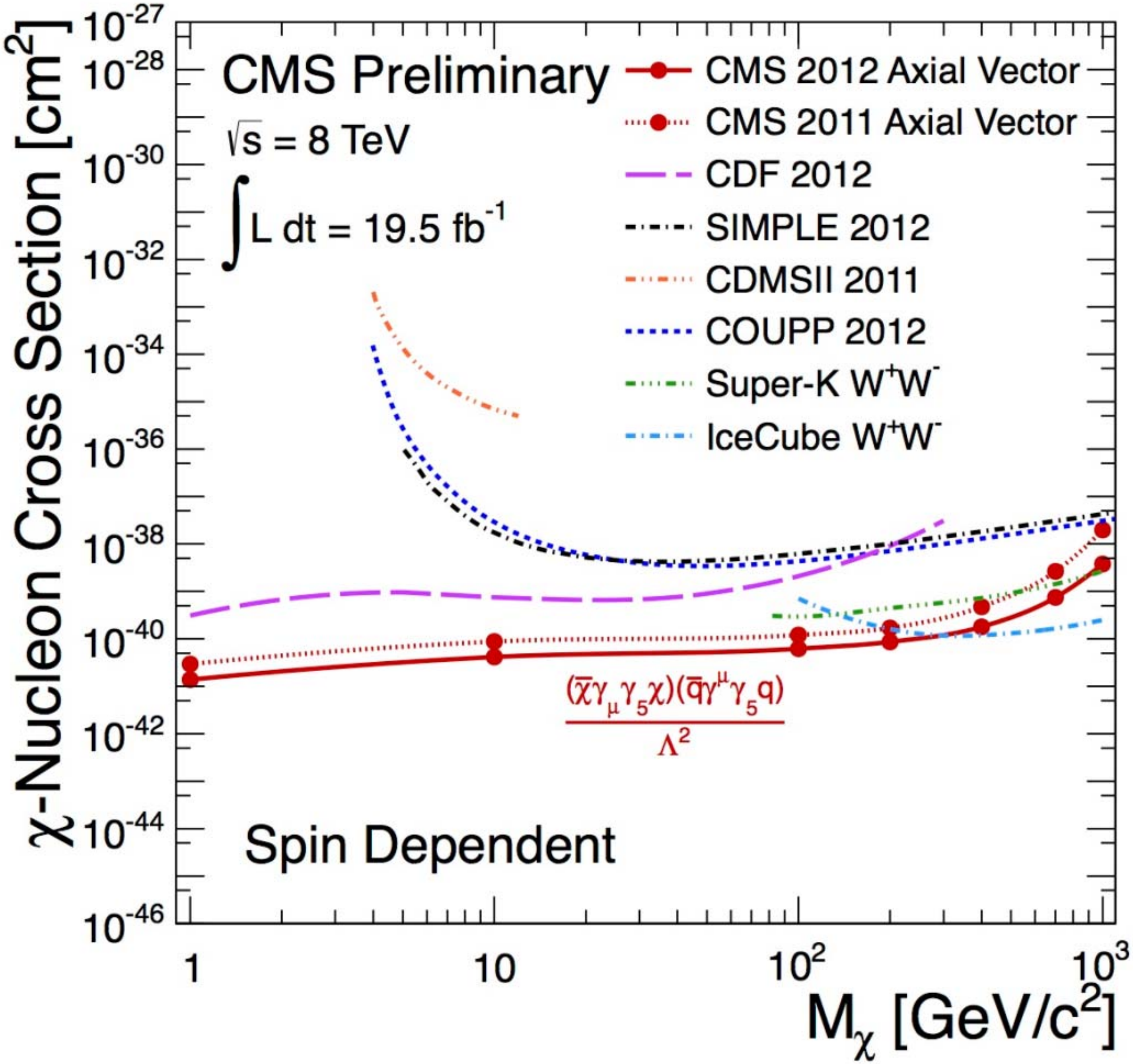


C. Issever, University of Oxford

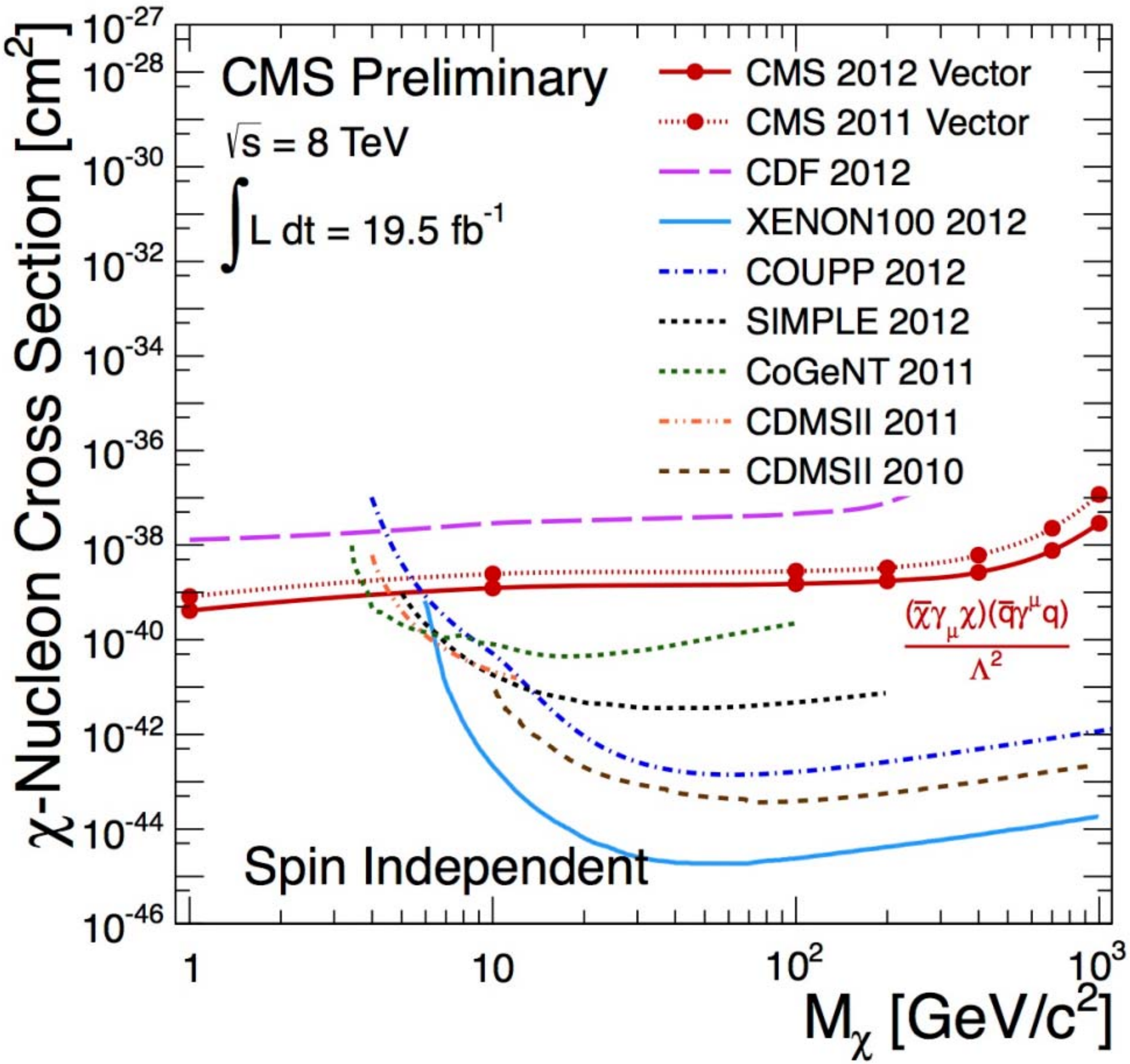
Spin Dependent Limits on Λ



Darkmatter-Nucleon Cross Section Limit



DM-Nucleon cross section upper limits



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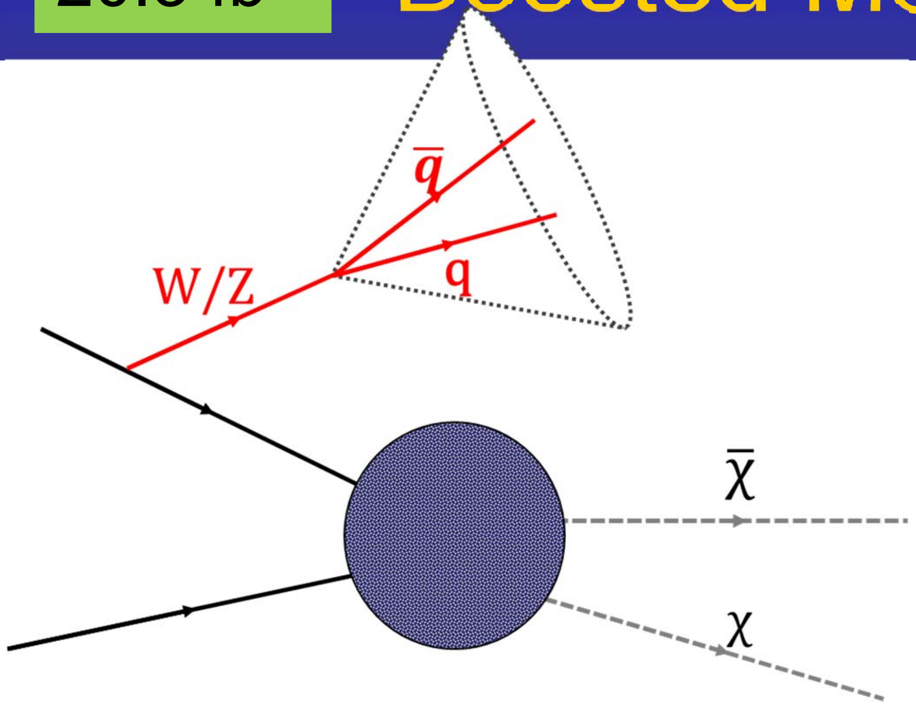
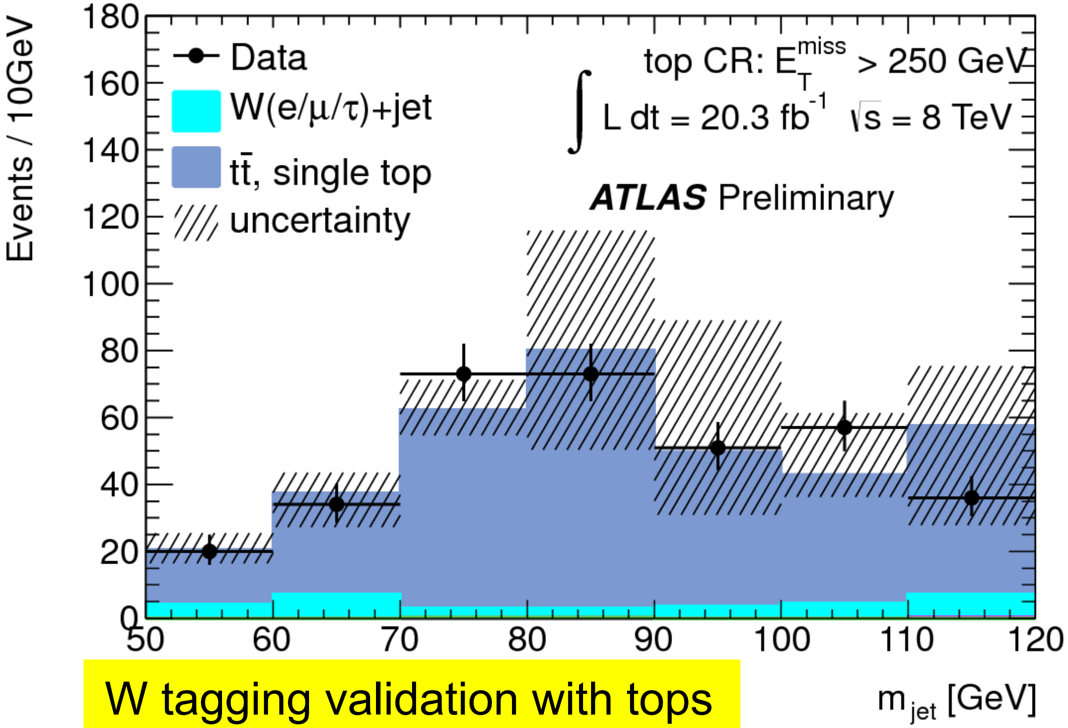
Boosted Mono W/Z Production

ATLAS-CONF-2013-073





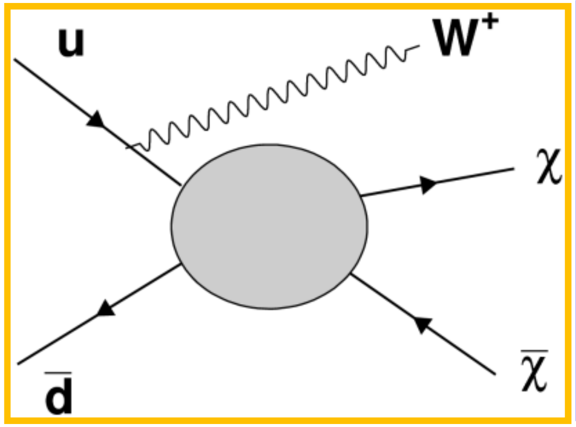
W tagging validation with tops

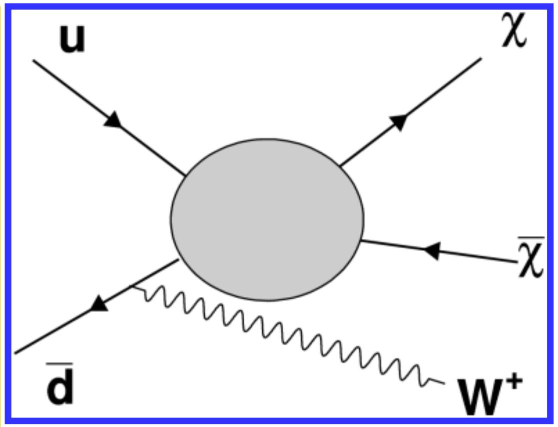
1st time:

- Hadronically decaying W/Z's
- Jet Substructure techniques
  - Cambridge-Aachen 1.2 jets
  - Probe momentum balance
    - $\sqrt{y} = \min(p_{T1}, p_{T2})\,\Delta R / m_{jet}$
- Backgrounds
  - Z → νν + jet and W/Z → lν/ll + jet
    - Use data control regions
  - Diboson, ttbar, single top
    - Use simulation
  - Multijet negligible

new

Signal Samples





Name	Operator	Coefficient
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*{}^2$
D5	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	$1/M_*{}^2$
D1	$\bar{\chi}\chi\bar{q}q$	$m_q/M_*{}^3$
C1	$\chi^{\dagger}\chi\bar{q}q$	$m_q/M_*{}^2$

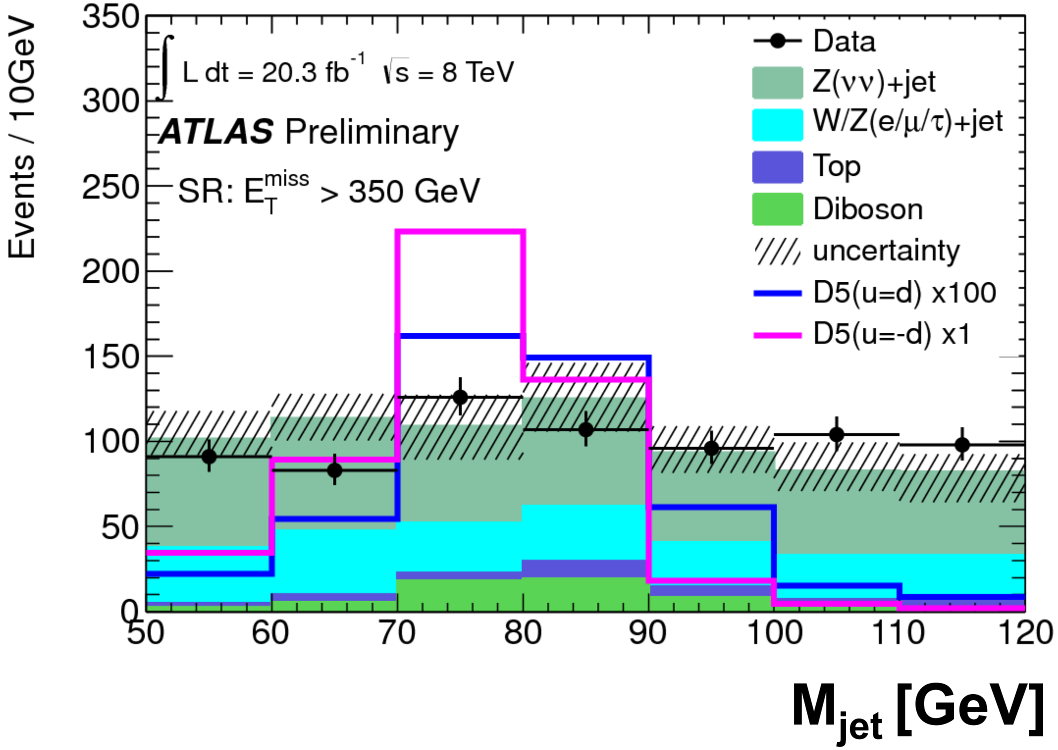
Interference btw diagrams

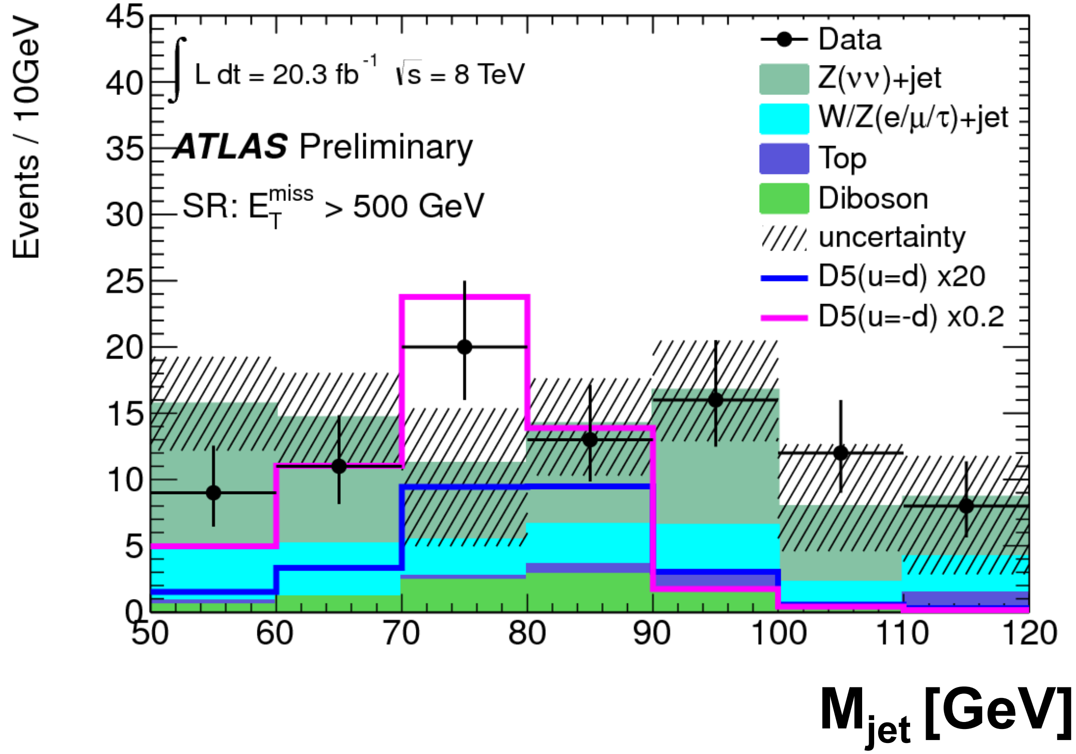
- C(uχ)=C(dχ), C=coupling
  - destructive
  - W's p_T low
- C(uχ) = -C(dχ)
  - Constructive
  - W's p_T high
- D5 signal generated
  - C(uχ)=C(dχ)
  - C(uχ)=-C(dχ)

new

Boosted Mono W/Z Production

2 Signal Regions: **ME_T > 350 GeV** **ME_T > 500 GeV**

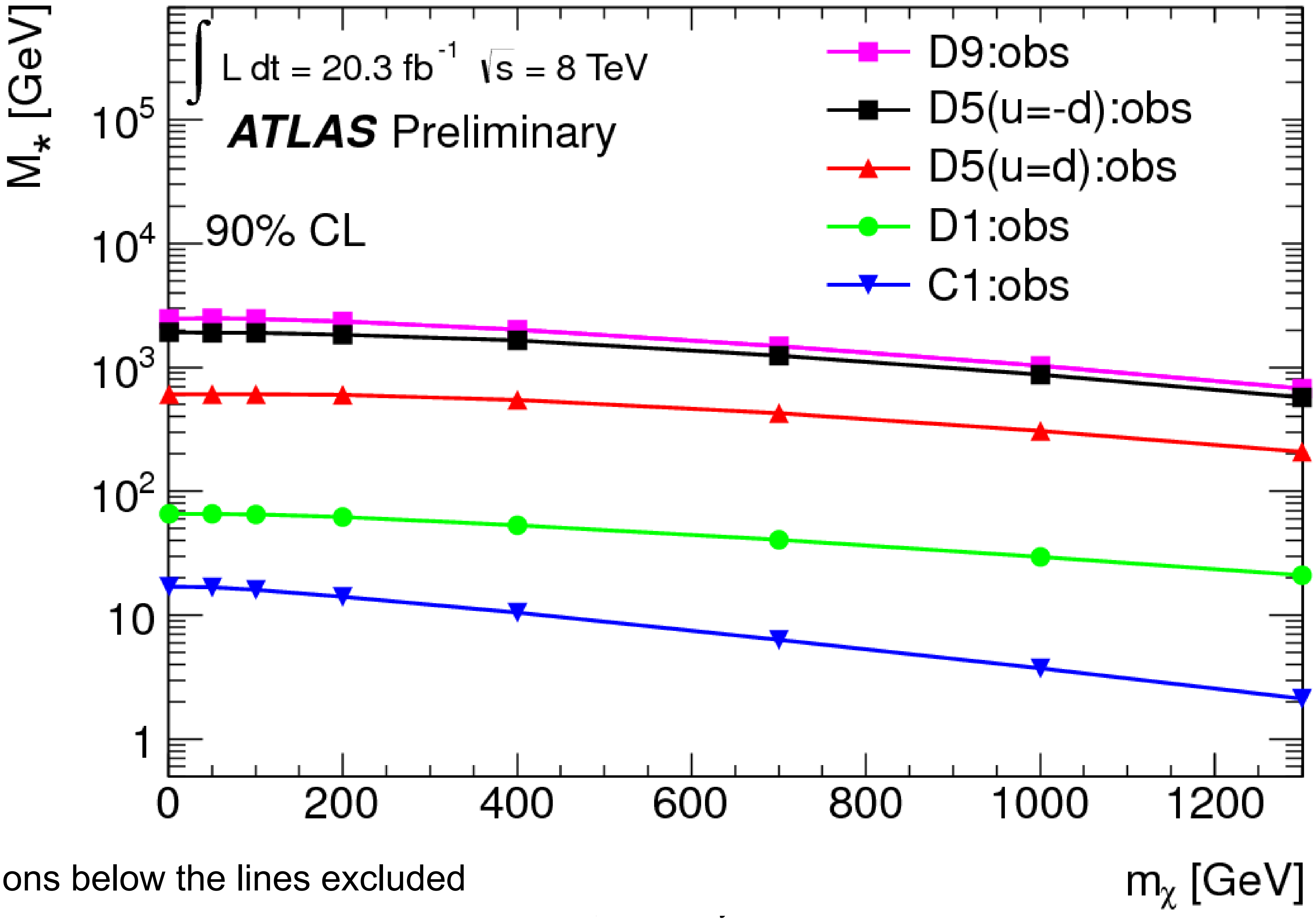




- Good agreement
- Exclusion limits at 90% CL using shape of m_{jet}

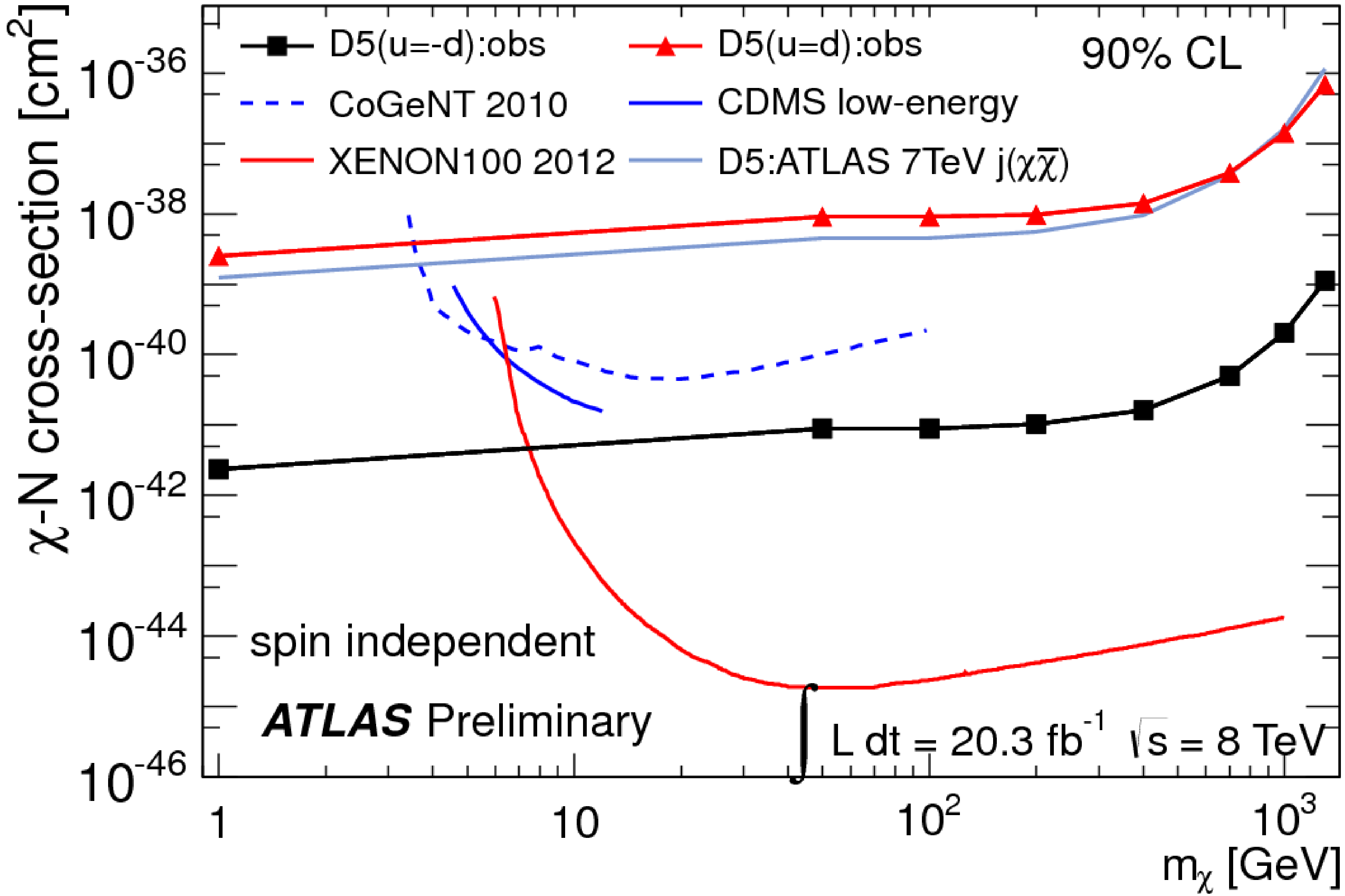
Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	400^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu, Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	710^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

Limits on Parameters of effective DM Model

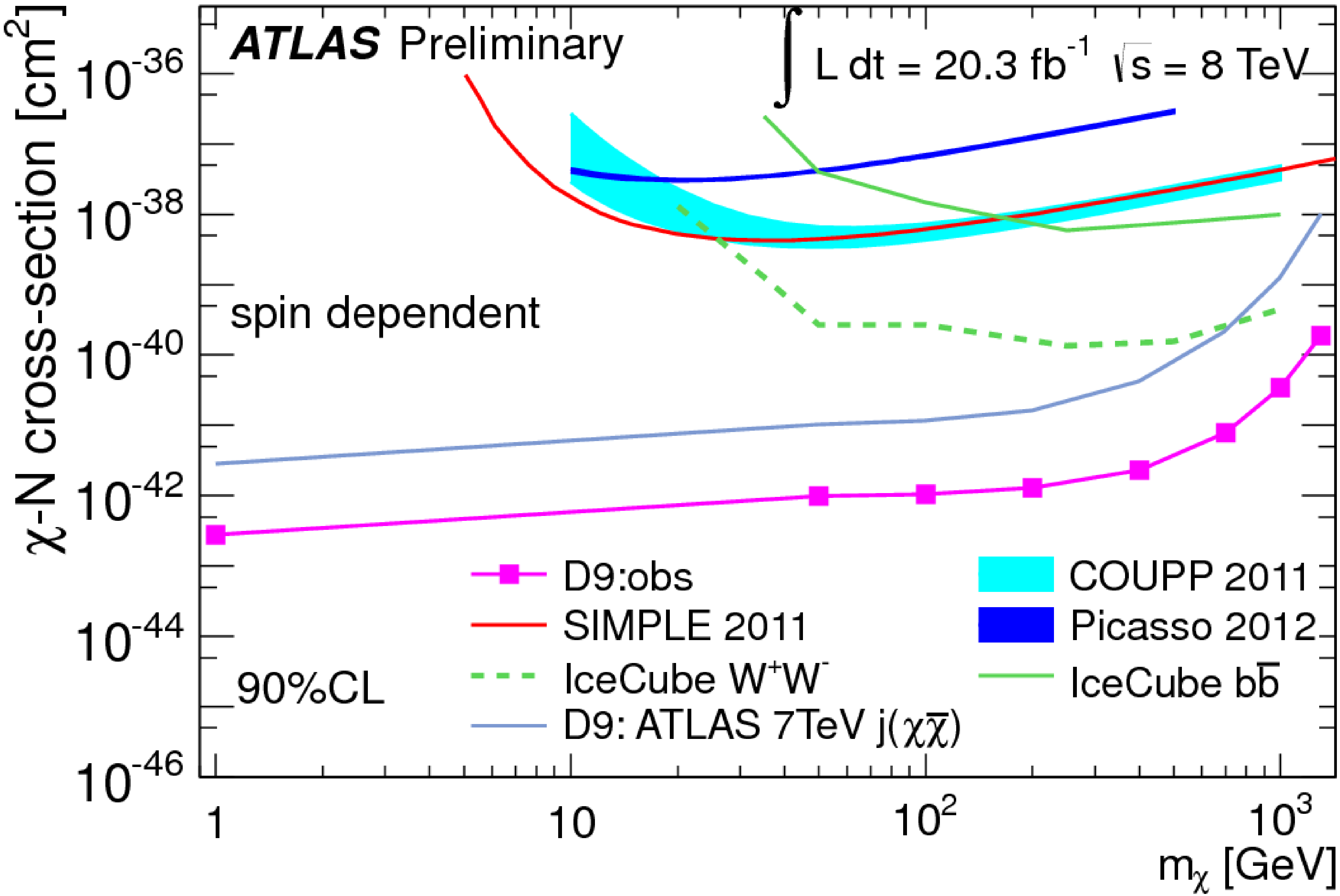


Regions below the lines excluded

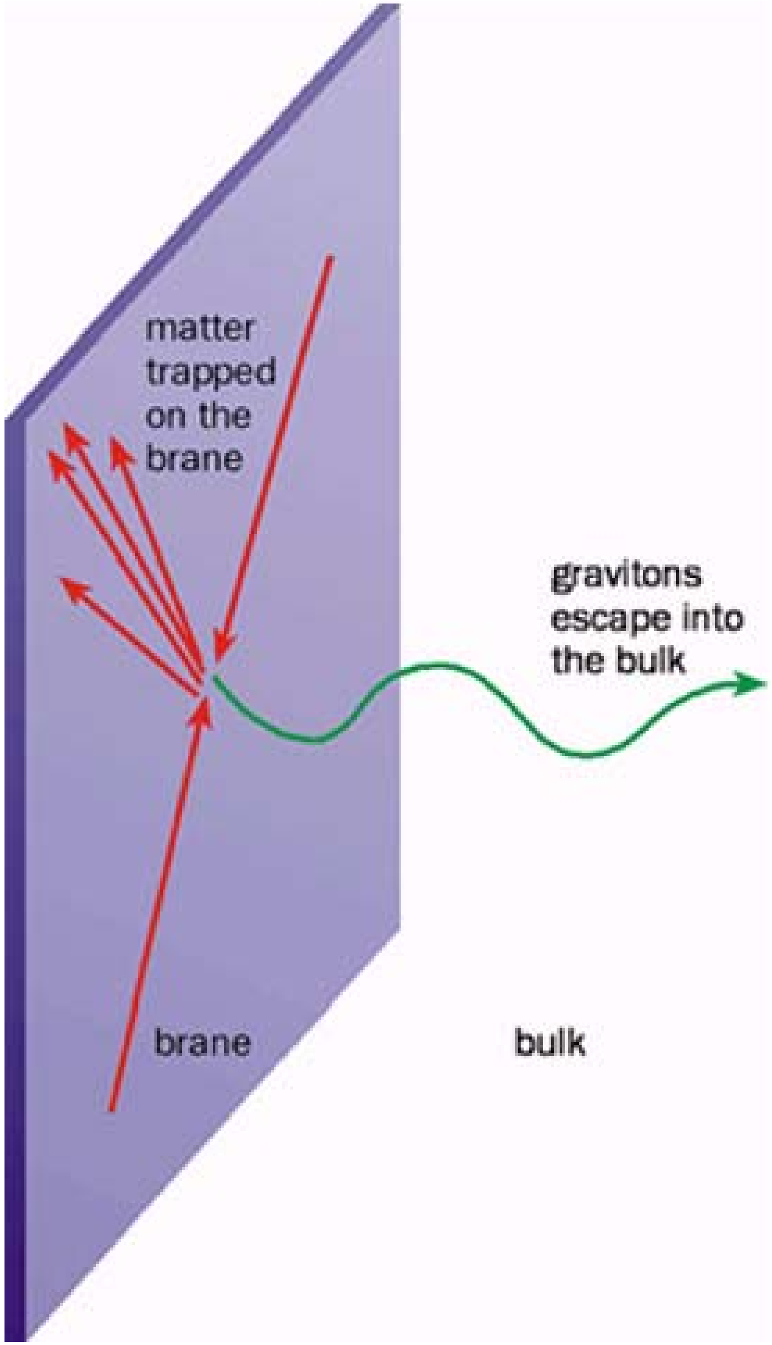
Limits on Nucleon-χ Cross Section

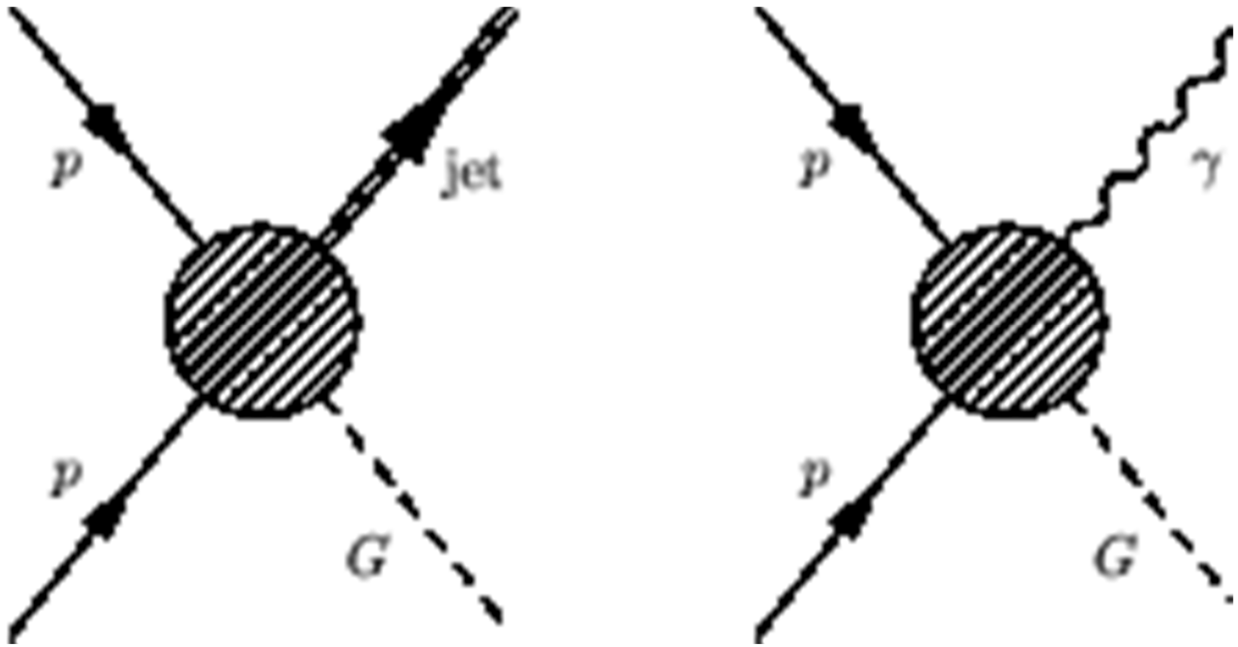


Limits on Nucleon-χ Cross Section



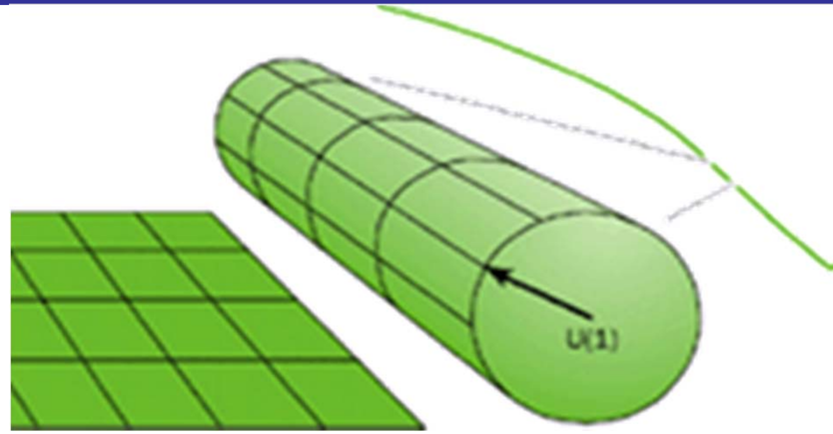
Graviton Production in Extra Dimensions





Extra Dimensions are not a new idea!

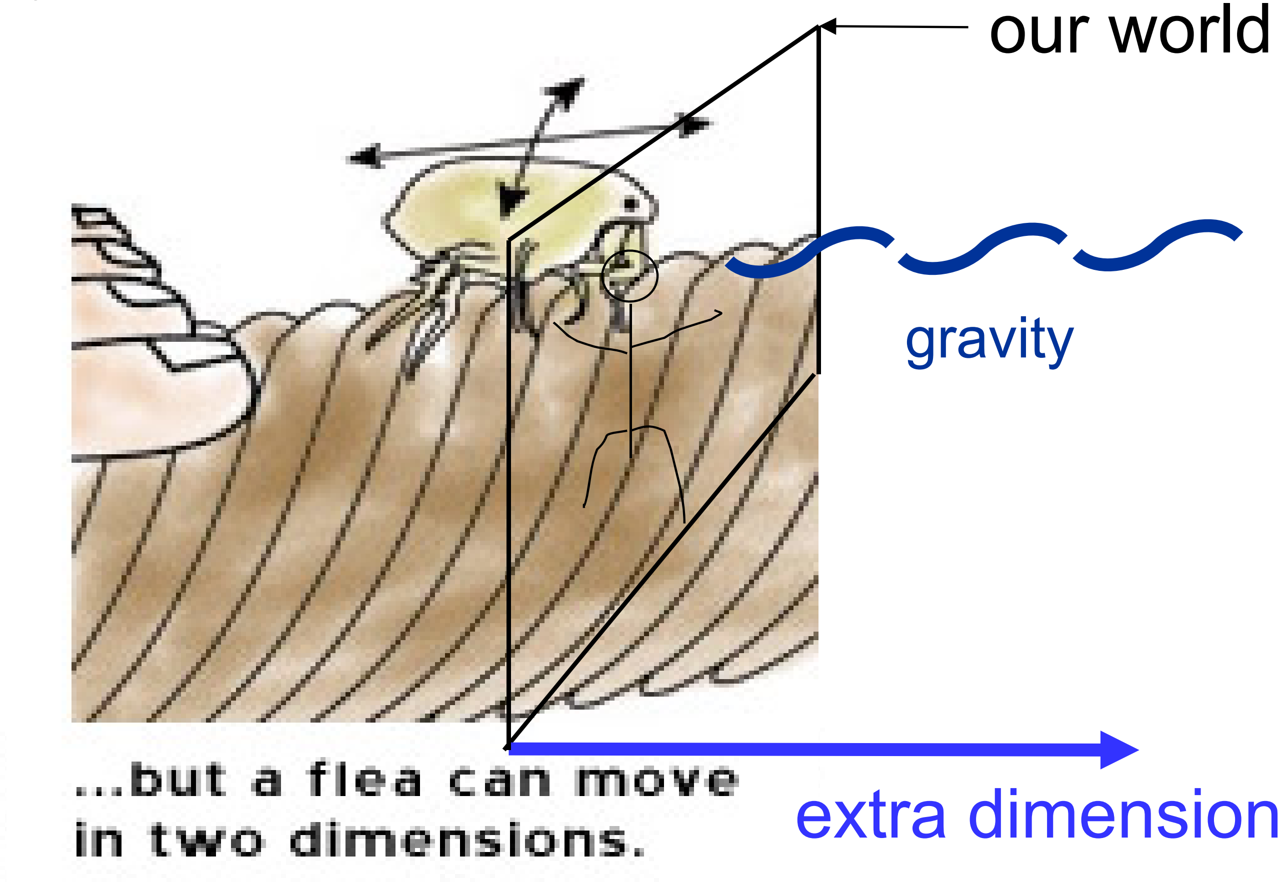
- **1920's Kaluza&Klein unify electromagnetism with gravity**
- **1970 String Theory is born**
- **1971 SUSY enters the stage**
- **1974 Gravitons "pop out" of string theory**



- 1984 Superstring Theory
  - 10, 11 or 26 dimensions needed
  - Compactified
- 1998 Large Extra Dim.
  - Nima Arkani-Hamed, Savas Dimopoulos, and Gia Dvali

Extra Dimension (ED) Models

- ED may explain complexity of particle physics
- Where are they?



http://www.particleadventure.org/frameless/extra_dim.html

Gravity is escaping into the extra dimensions.

Gravity in Extra Dimension

At small distances gravity can be very strong,

up to 10^{38} times stronger:

$$F \approx \frac{G_D}{r^{n+2}}$$

$$G_D = G L^n$$

$$M_D^{n+2} = \frac{(2\pi)^n}{8\pi G_D}$$

At large distances gravity seems weak

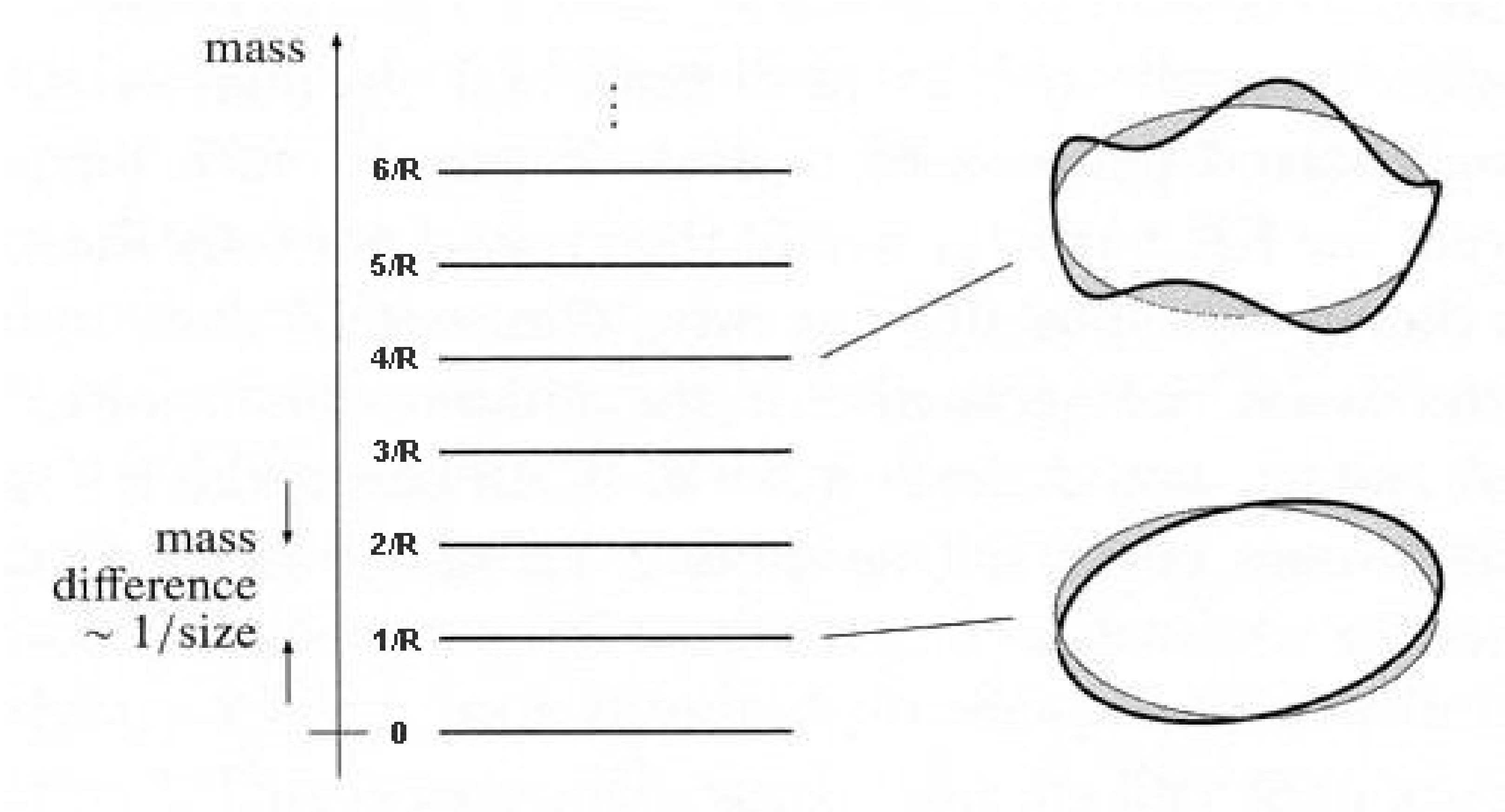
$$F \approx \frac{G_D}{L^n \cdot r^2} \approx \frac{G}{r^2}$$

G is "diluted" strength of gravity in our 3-dim. space.

G_D is the (4+n)-dimensional Newton gravity constant.

Other Predictions of Extra Dimension Models

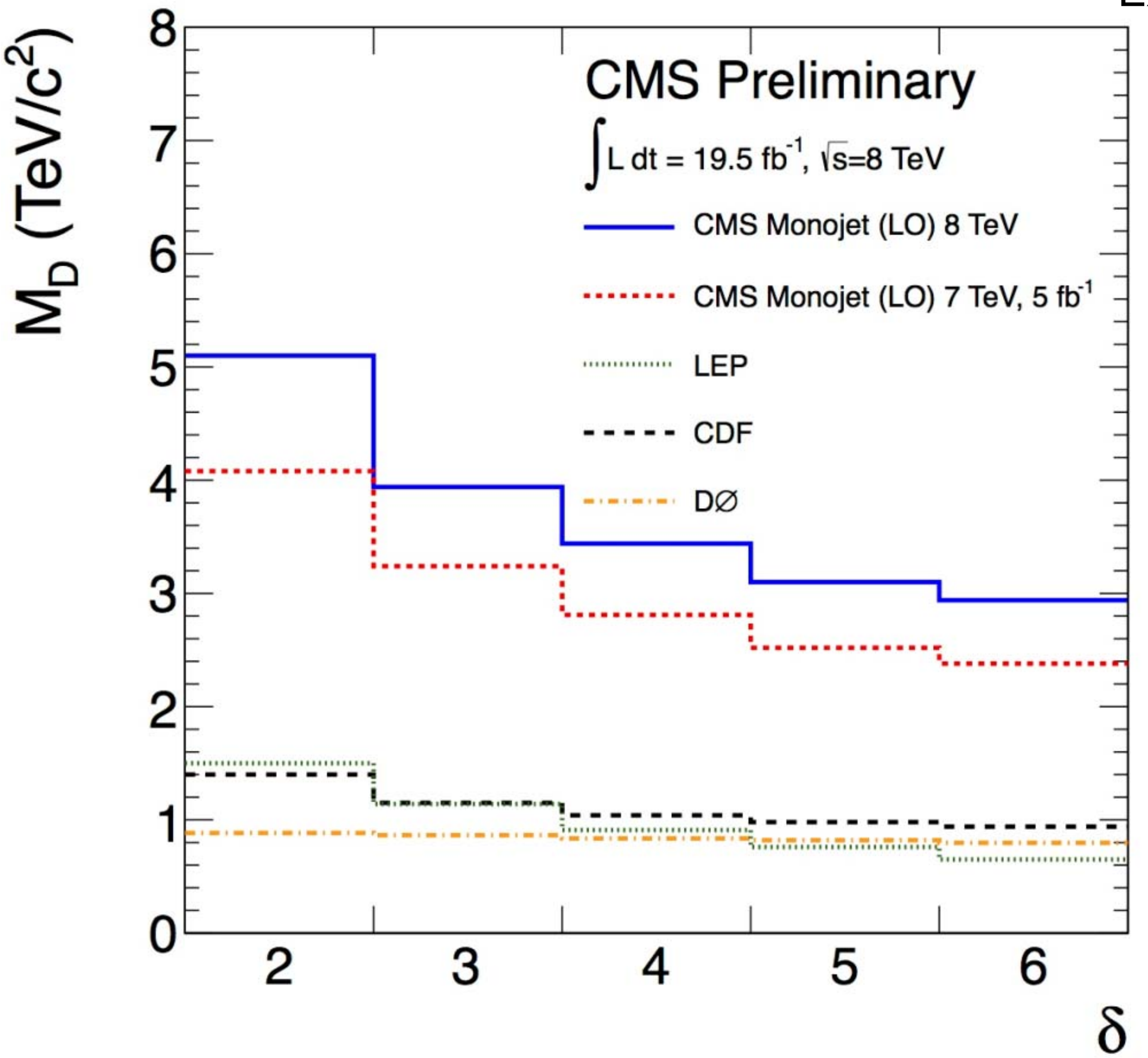
KK particles



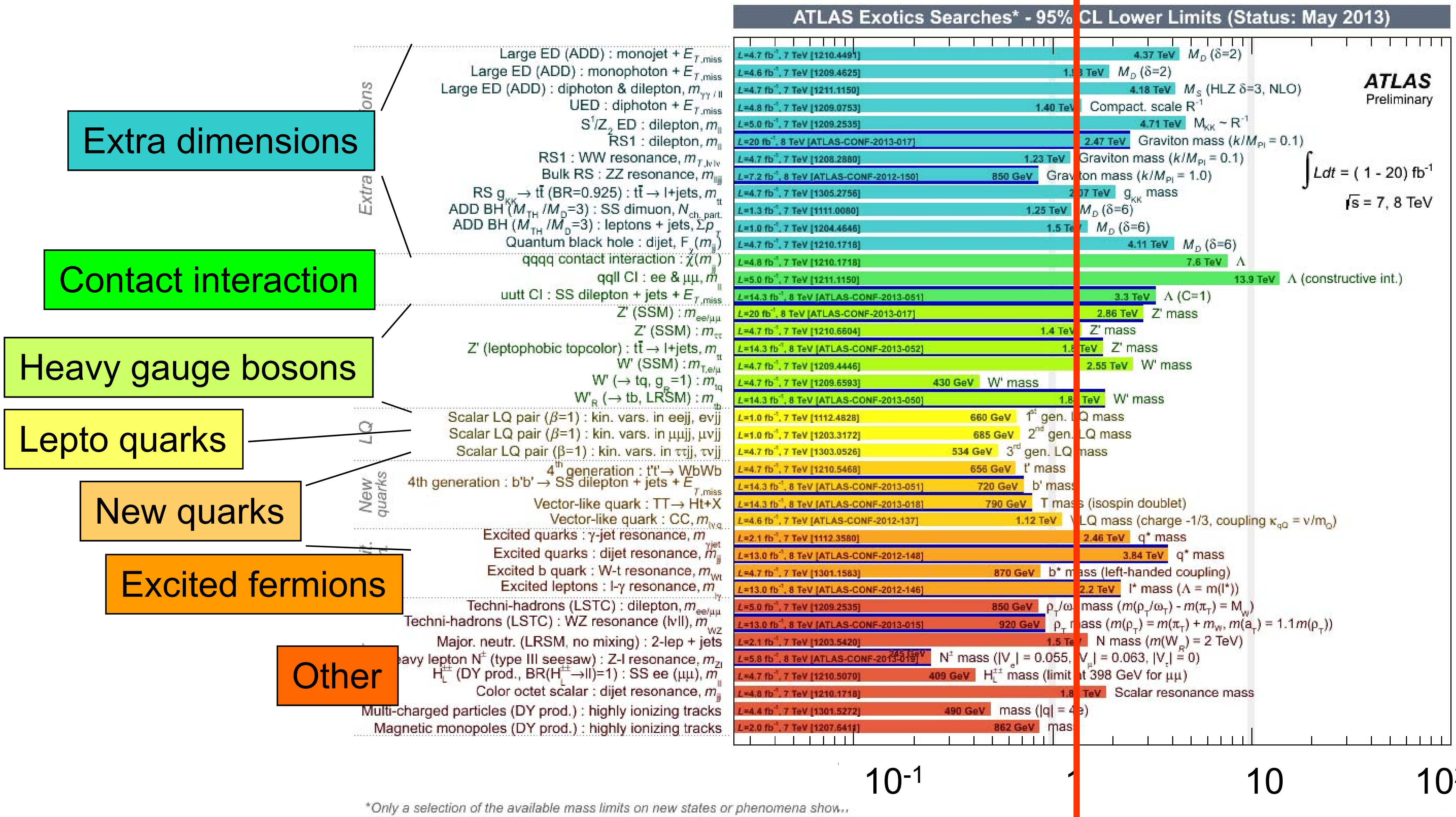
http://universe-review.ca/I15-74-KK.jpg

Exclusion Limits on M_D from CMS

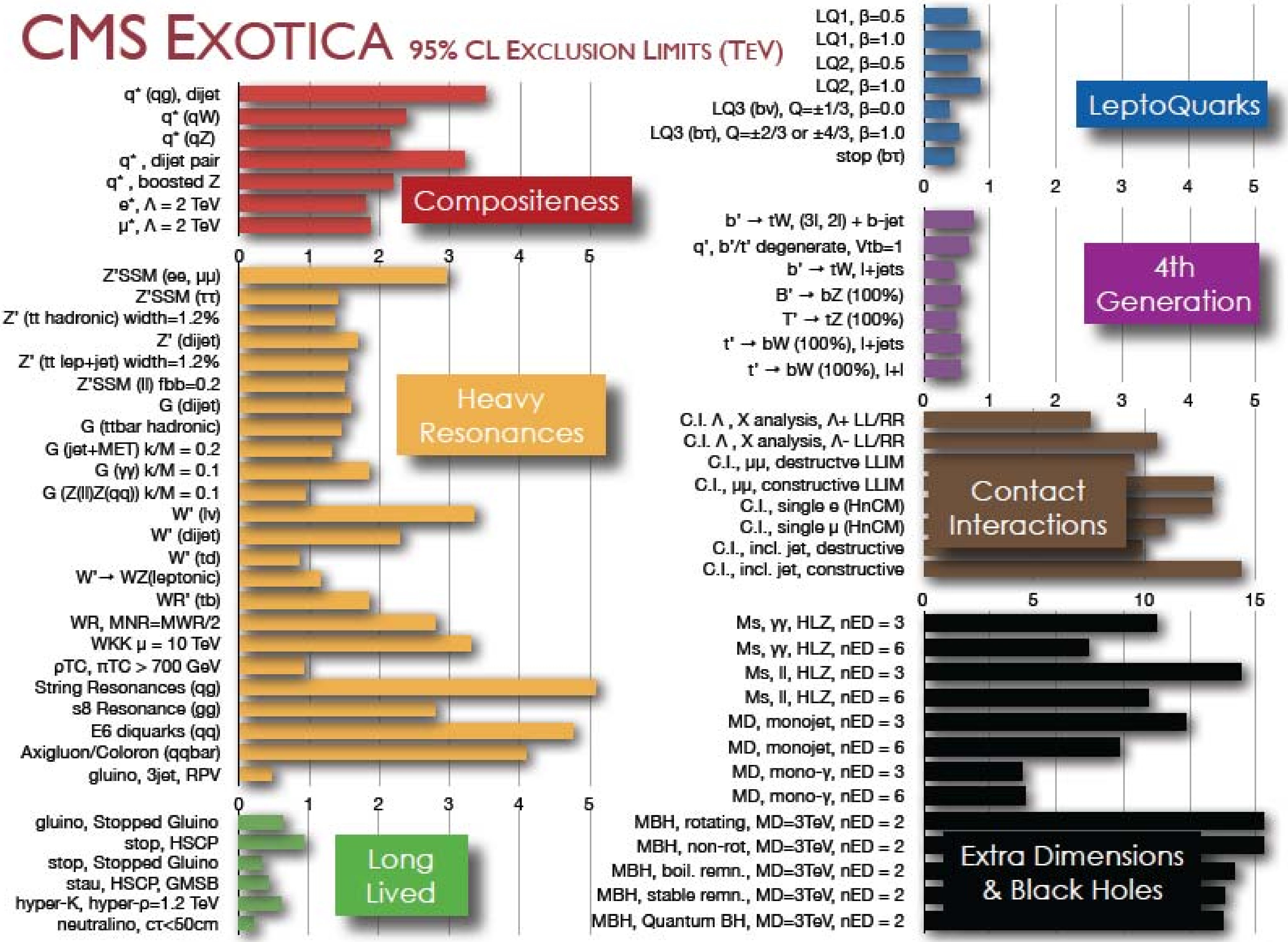
EXO-12-048 PAS



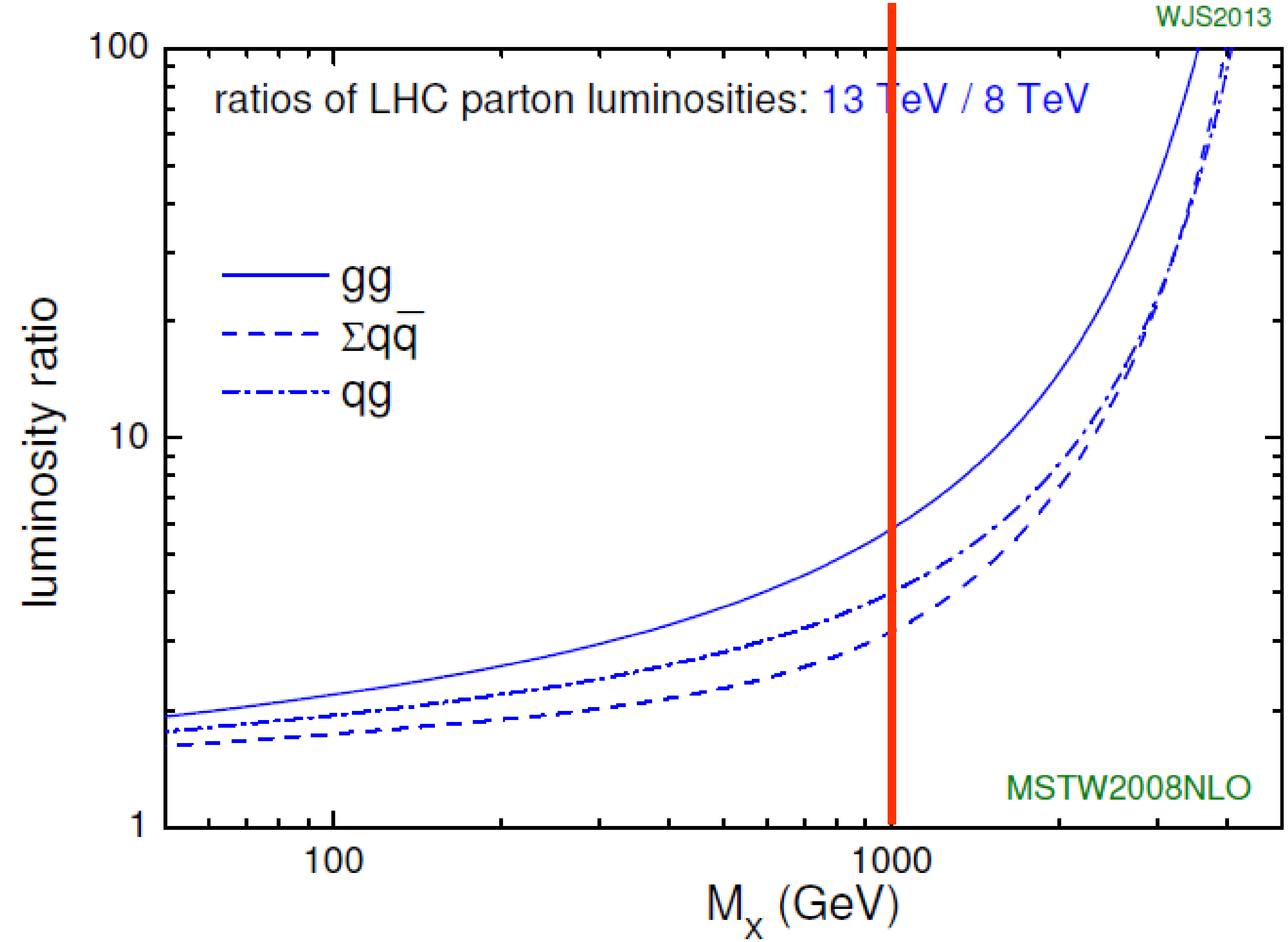
Limits pushed into 1 TeV regime



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults


CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
0 1 2 3 4 5
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lv)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
0 1 2 3 4 5
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bv), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
LeptoQuarks
0 1 2 3 4 5
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
4th Generation
0 1 2 3 4 5
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
0 5 10 15
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes

We are at the beginning….



Up to now, small parton luminosity at high masses

Large discovery potential: 13 TeV

Conclusion

- Role of models in Exotics
  - Models are used map our search reach
  - They give us some guidance where to look
  - But, Exotics searches are mainly model-independent.
- Exotics searches coverage
  - Vast range of final states
  - Vast range of models
  - **Searches with H boson in final state added**
- Searches will continue
  - Continue exploration **beyond TeV regimes**
  - Push σ-limits at **low invariant masses** down.

Literature for Further Reading

- Technicolor and related models
  - http://dx.doi.org/10.1016/0370-1573(81)90173-3
  - http://dx.doi.org/10.1103/RevModPhys.55.449
  - http://inspirehep.net/record/205523?ln=en
  - http://dx.doi.org/10.1016/0146-6410(83)90005-4
- Extra Dimensions
  - http://arxiv.org/pdf/hep-ph/0302189.pdf
  - http://arxiv.org/pdf/gr-qc/0312059.pdf
- Exotics new particles
  - http://dx.doi.org/10.1016/0370-1573(89)90071-9
  - http://dx.doi.org/10.1142/S0217751X88000035
- GUT: http://dx.doi.org/10.1016/0370-1573(81)90059-4