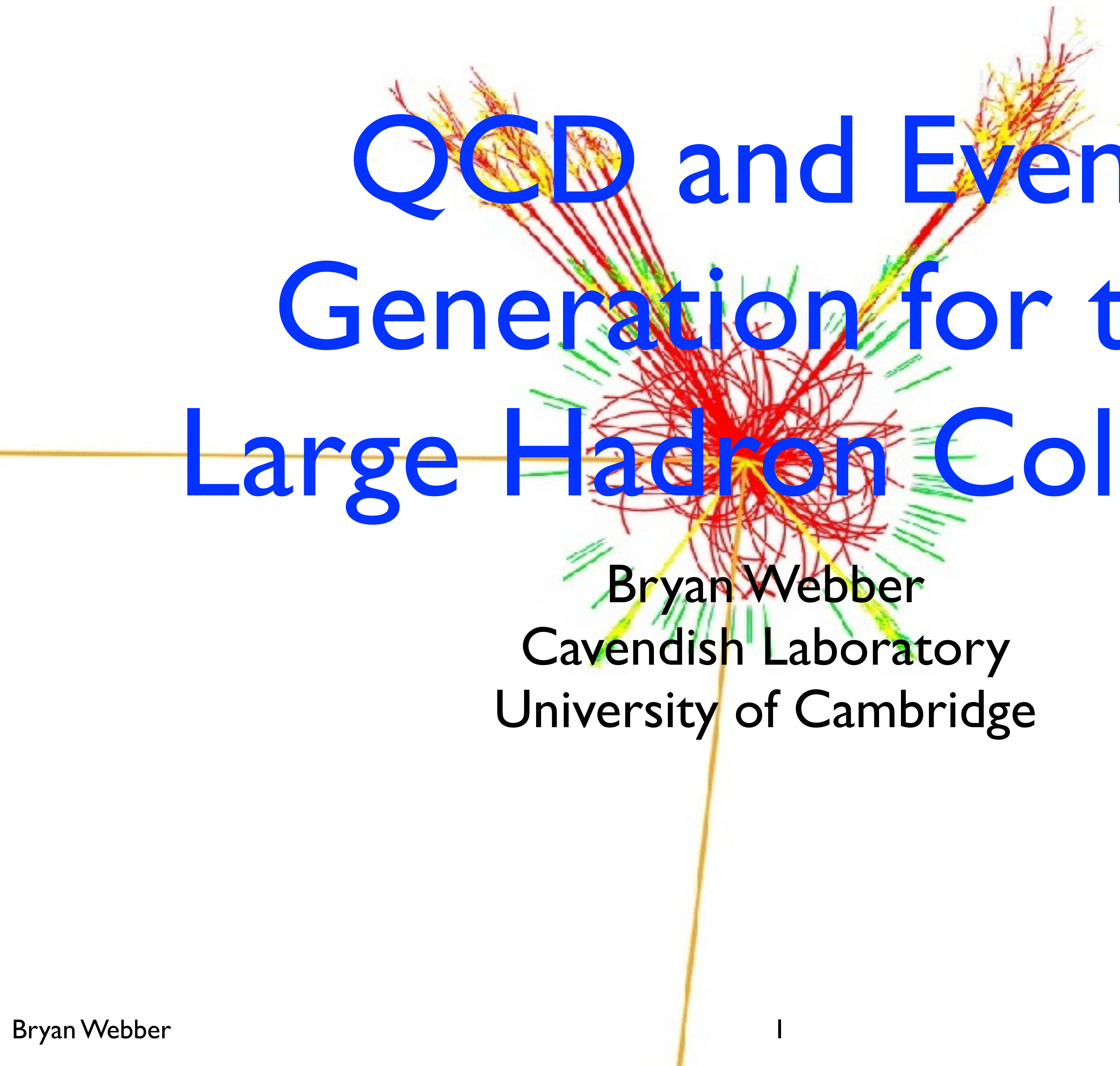
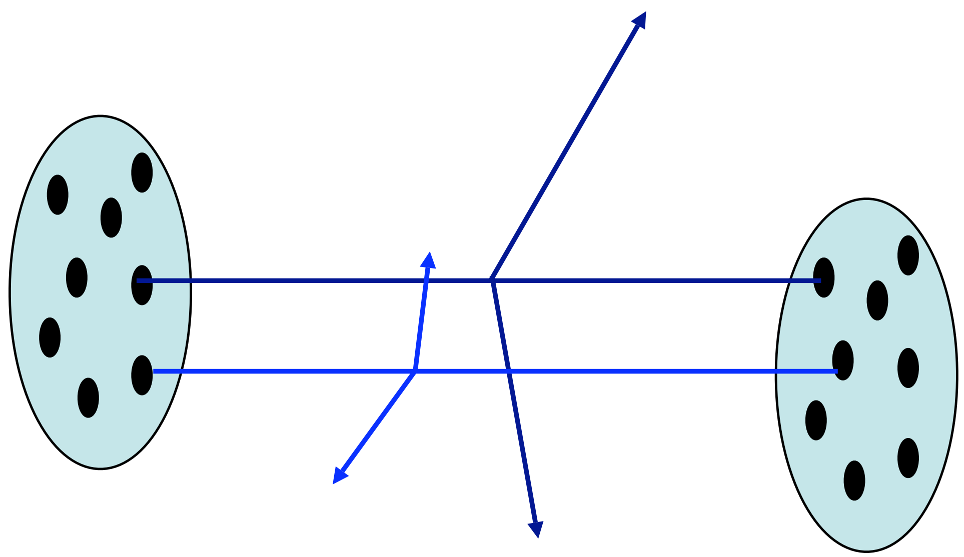


QCD and Event Generation for the Large Hadron Collider

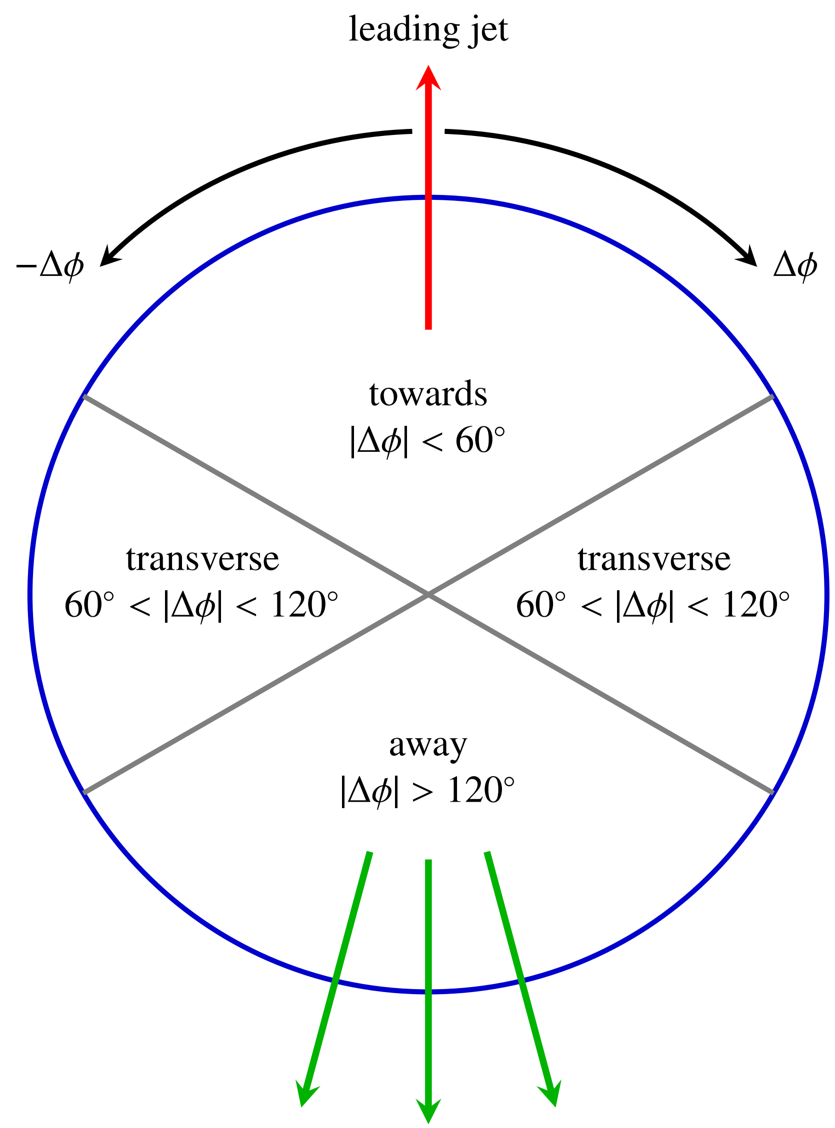
Bryan Webber
Cavendish Laboratory
University of Cambridge

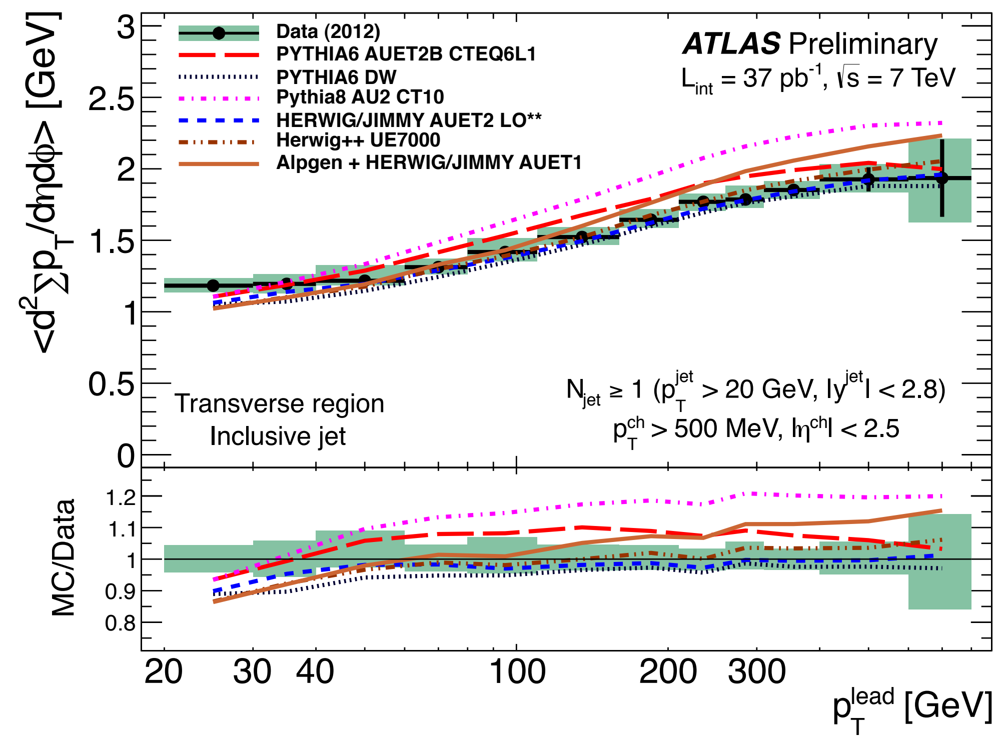
Underlying Event

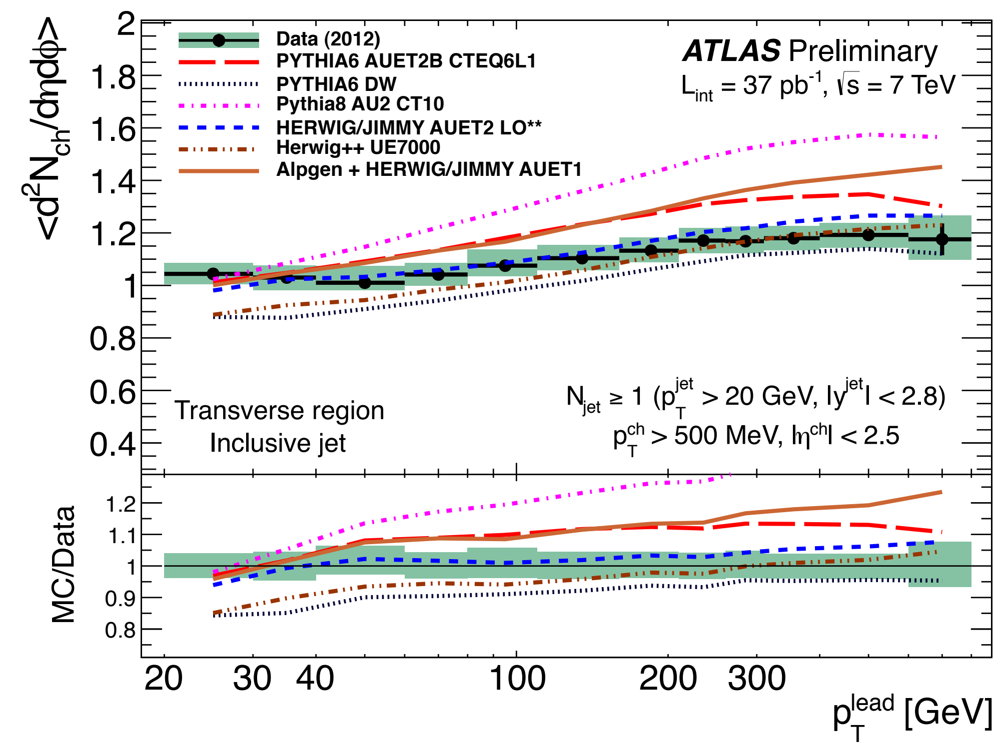


- Multiple parton interactions in same collision
  - Depends on density profile of proton
- Assume QCD 2-to-2 secondary collisions
  - Need cutoff at low p_T
- Need to model colour flow
  - Colour reconnections are necessary

Underlying Event

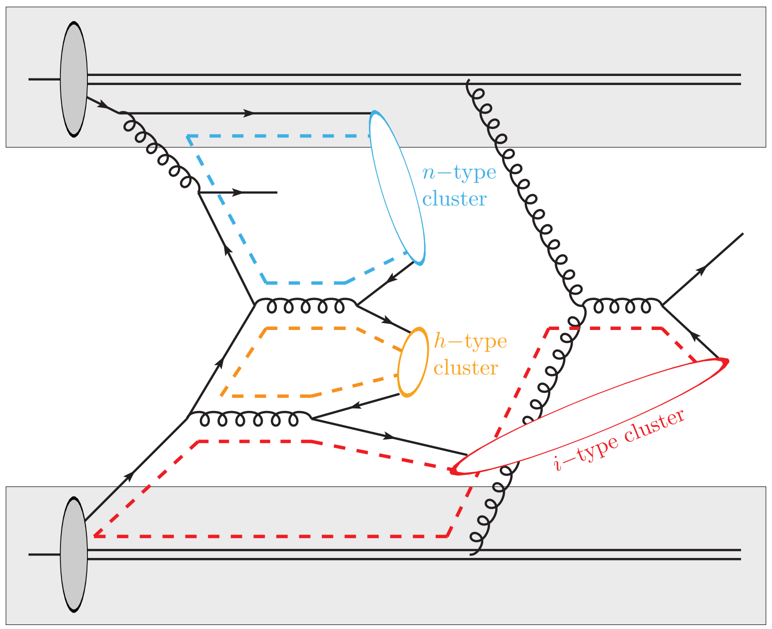


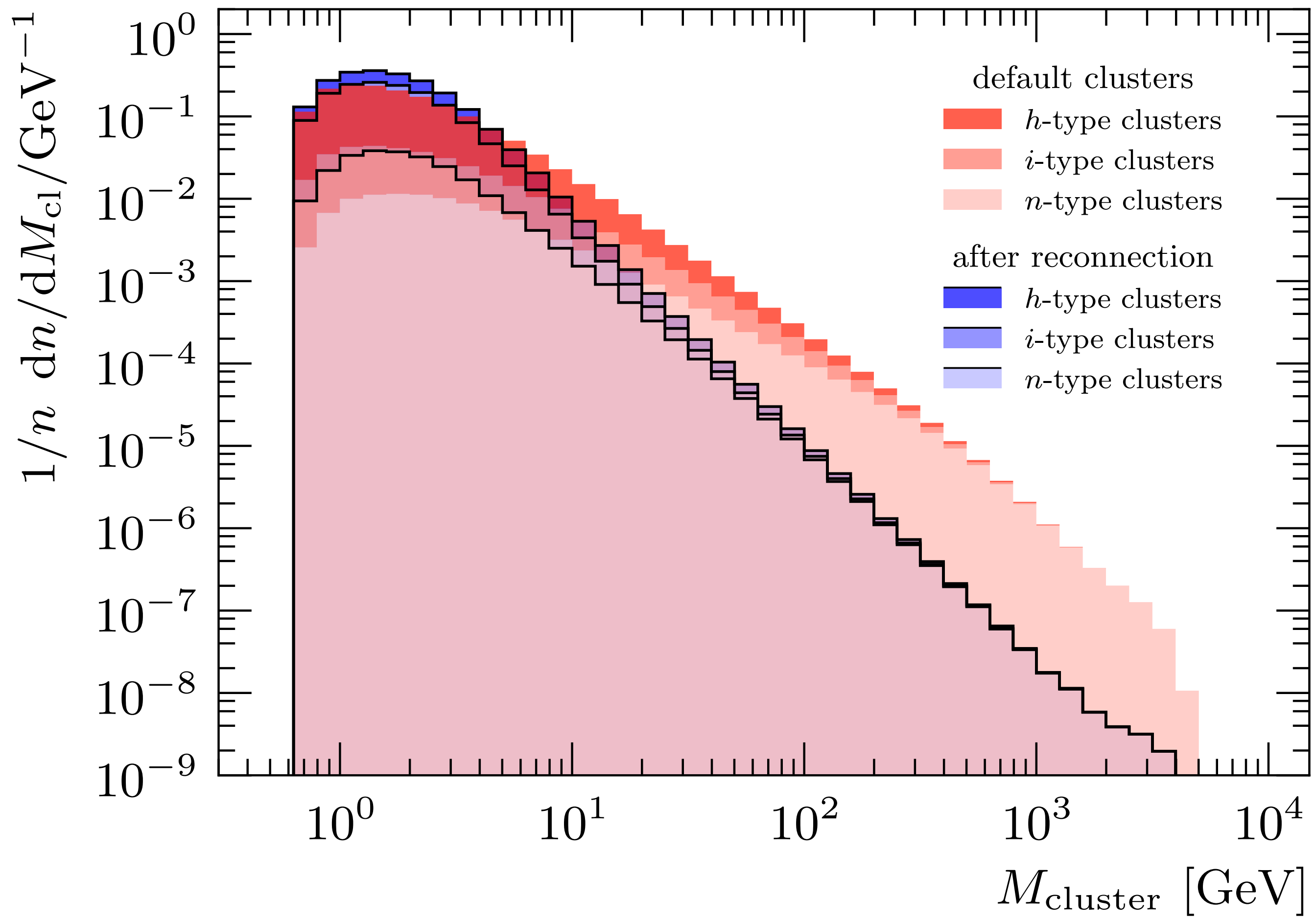


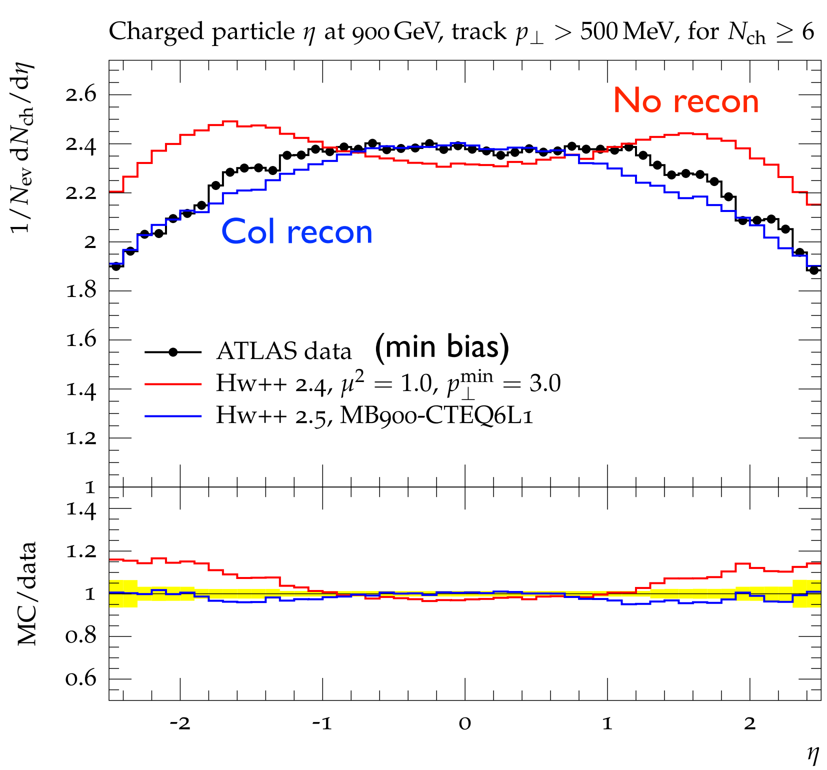


ATLAS CONF-2012-164

Colour Reconnection



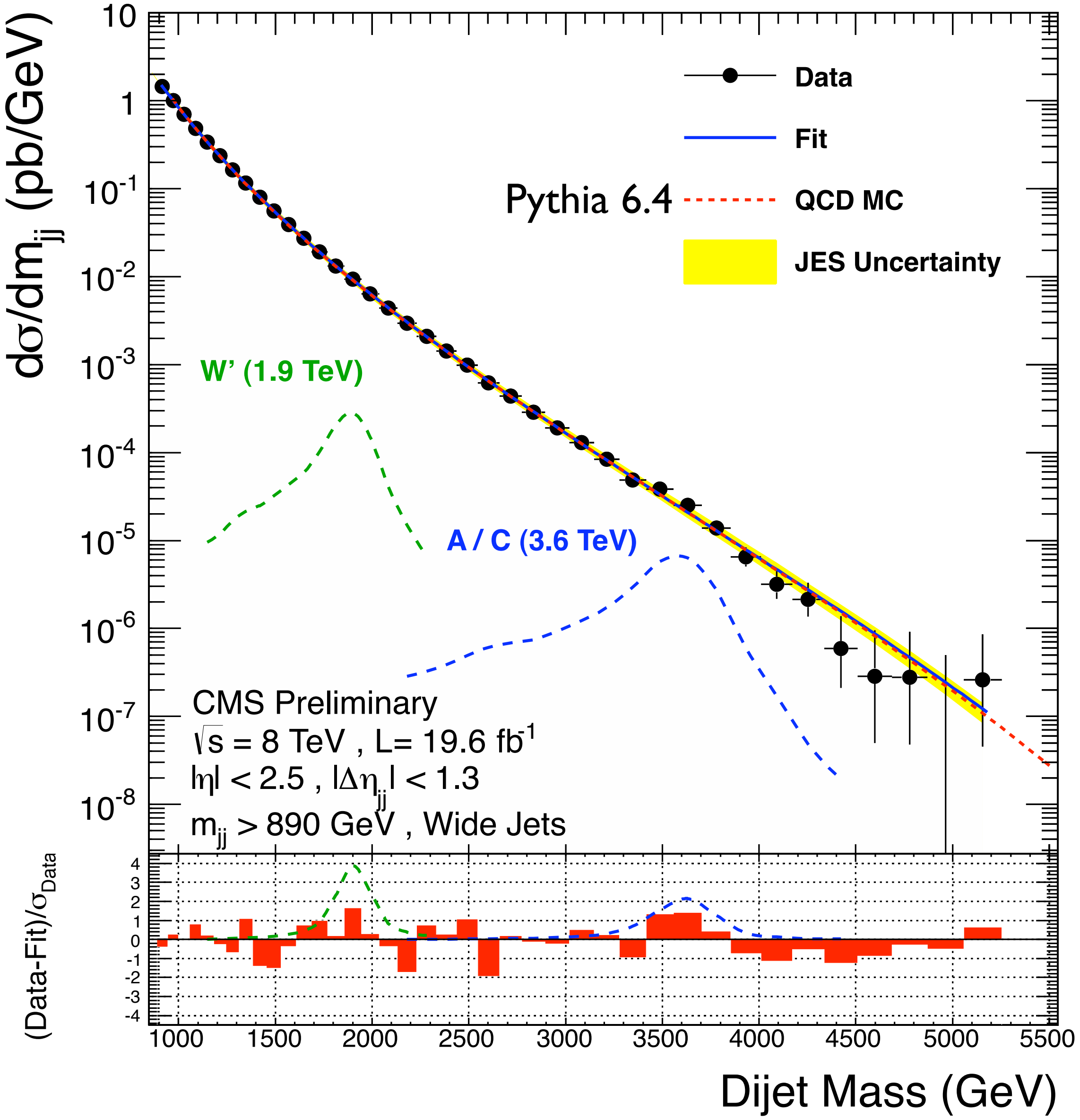


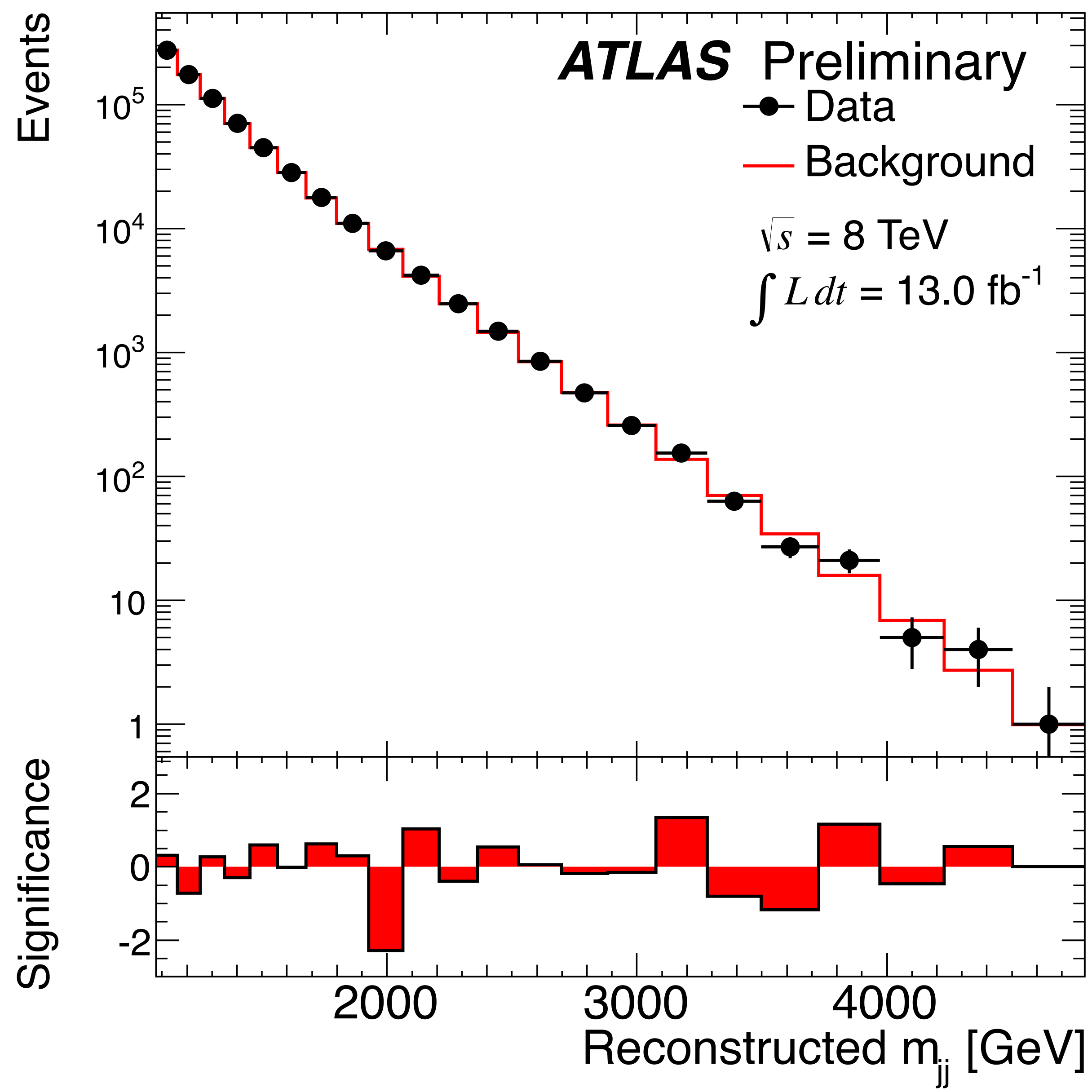


- "Colour length" $\lambda \equiv \sum_{i=1}^{N_{\rm cl}} m_i^2$ reduced by reconnection
- Massive leading clusters reduced
- Similar need in string model

Gieseke, Röhr, Siódmok, arXiv:1206.2205

Dijet Mass Distribution





CMS PAS EXO-12-059

ATLAS CONF-2012-148

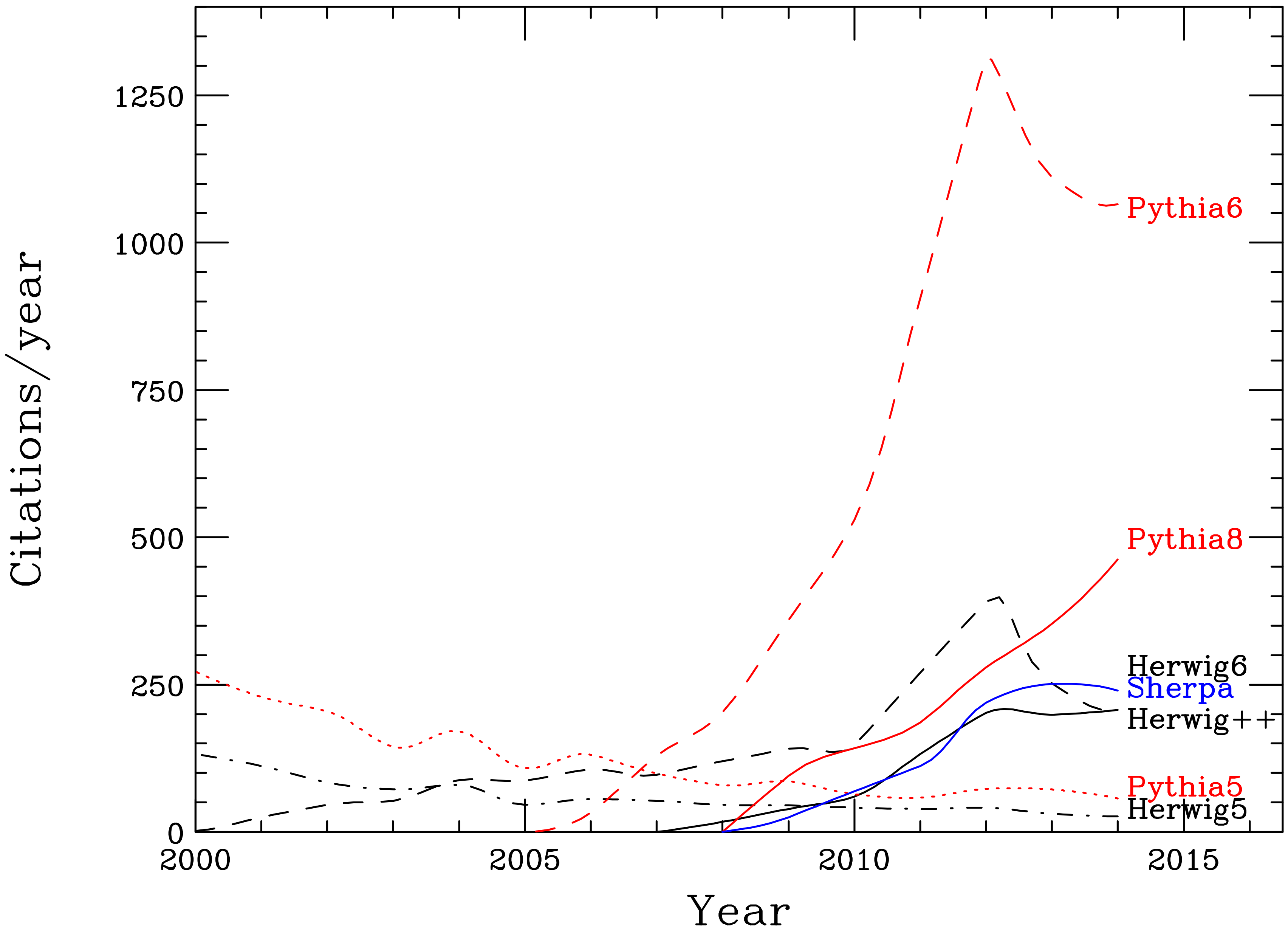
- No sign of deviation from Standard Model (yet)

Event Generators

- **HERWIG** http://projects.hepforge.org/herwig/
  - Angular-ordered parton shower, cluster hadronization
  - v6 Fortran; Herwig++
- **PYTHIA** http://www.thep.lu.se/~torbjorn/Pythia.html
  - Dipole-type parton shower, string hadronization
  - v6 Fortran; v8 C++
- **SHERPA** http://projects.hepforge.org/sherpa/
  - Dipole-type parton shower, cluster hadronization
  - C++

"General-purpose event generators for LHC physics",
A Buckley et al., arXiv:1101.2599, Phys. Rept. 504(2011)145

Generator Citations



- Most-cited article only for each version
- 2014 is extrapolation (Jan to Aug x1.5)

Other relevant software
(with apologies for omissions)

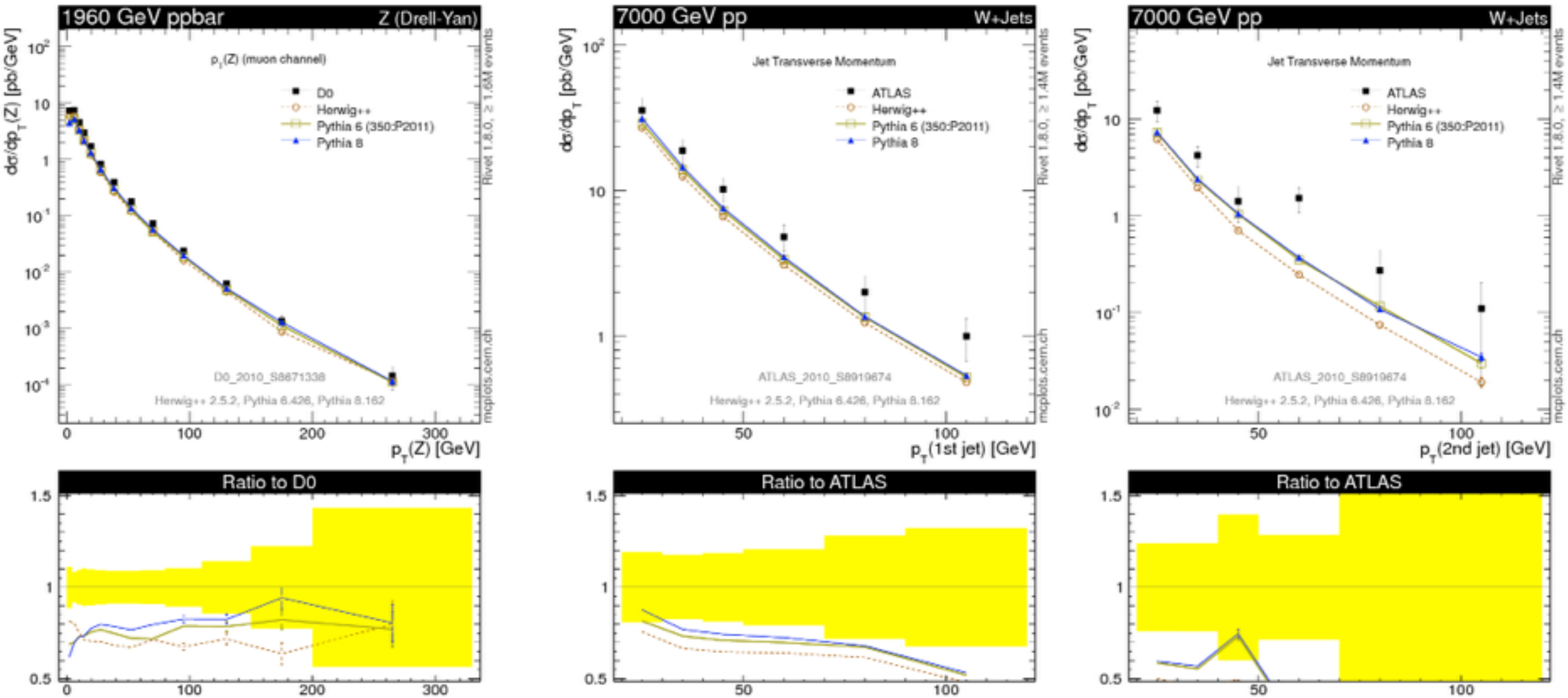
- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino, Charybdis, TrueNoir
- Mass spectra and decays: SOFTSUSY, SPHENO, HDecay, SDecay
- Feynman rule generators: FeynRules
- PDF libraries: LHAPDF
- Resummed ($p_\perp$) spectra: ResBos
- Approximate loops: LoopSim
- Jet finders: anti-$k_\perp$ and FastJet
- Analysis packages: Rivet, Professor, MCPLOTS
- Detector simulation: GEANT, Delphes
- Constraints (from cosmology etc): DarkSUSY, MicrOmegas
- Standards: PDF identity codes, LHA, LHEF, SLHA, Binoth LHA, HepMC

Sjöstrand, Nobel Symposium, May 2013

Parton Shower Monte Carlo

- Hard subprocess: $q\bar{q} \to Z^0/W^\pm$

http://mcplots.cern.ch/



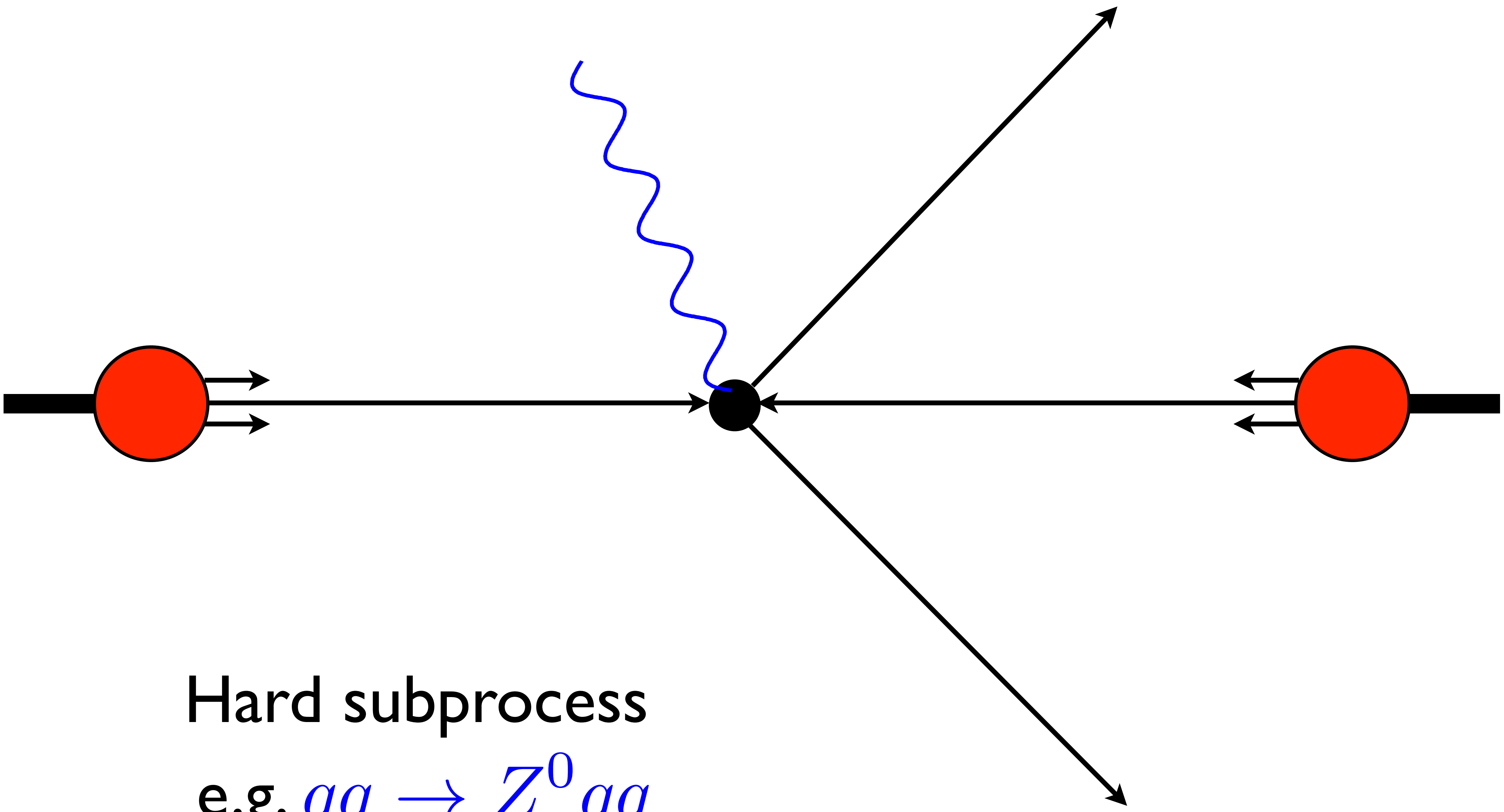
- Leading-order (LO) normalization ➡ need next-to-LO (NLO)
- Worse for high p_T and/or extra jets ➡ need multijet merging

Summary on Event Generators

- Fairly good overall description of data, but…
- Hard subprocess: LO no longer adequate
- Parton showers: need matching to NLO
  - Also multijet merging
  - NLO showering?
- Hadronization: string and cluster models
  - Need new ideas/methods
- Underlying event due to multiple interactions
  - Colour reconnection necessary

Improving Event Generation

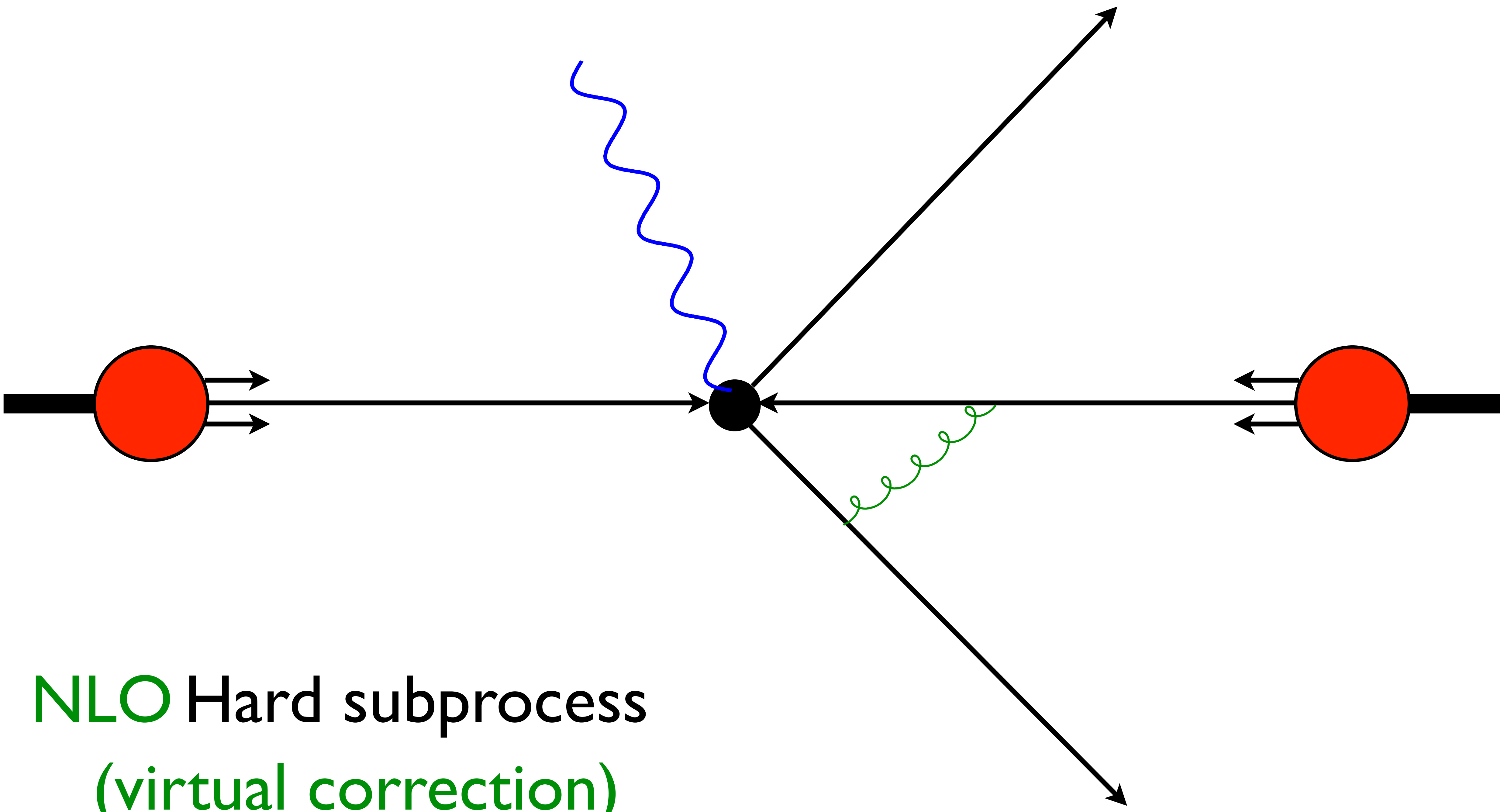
Improving Event Generation



Hard subprocess

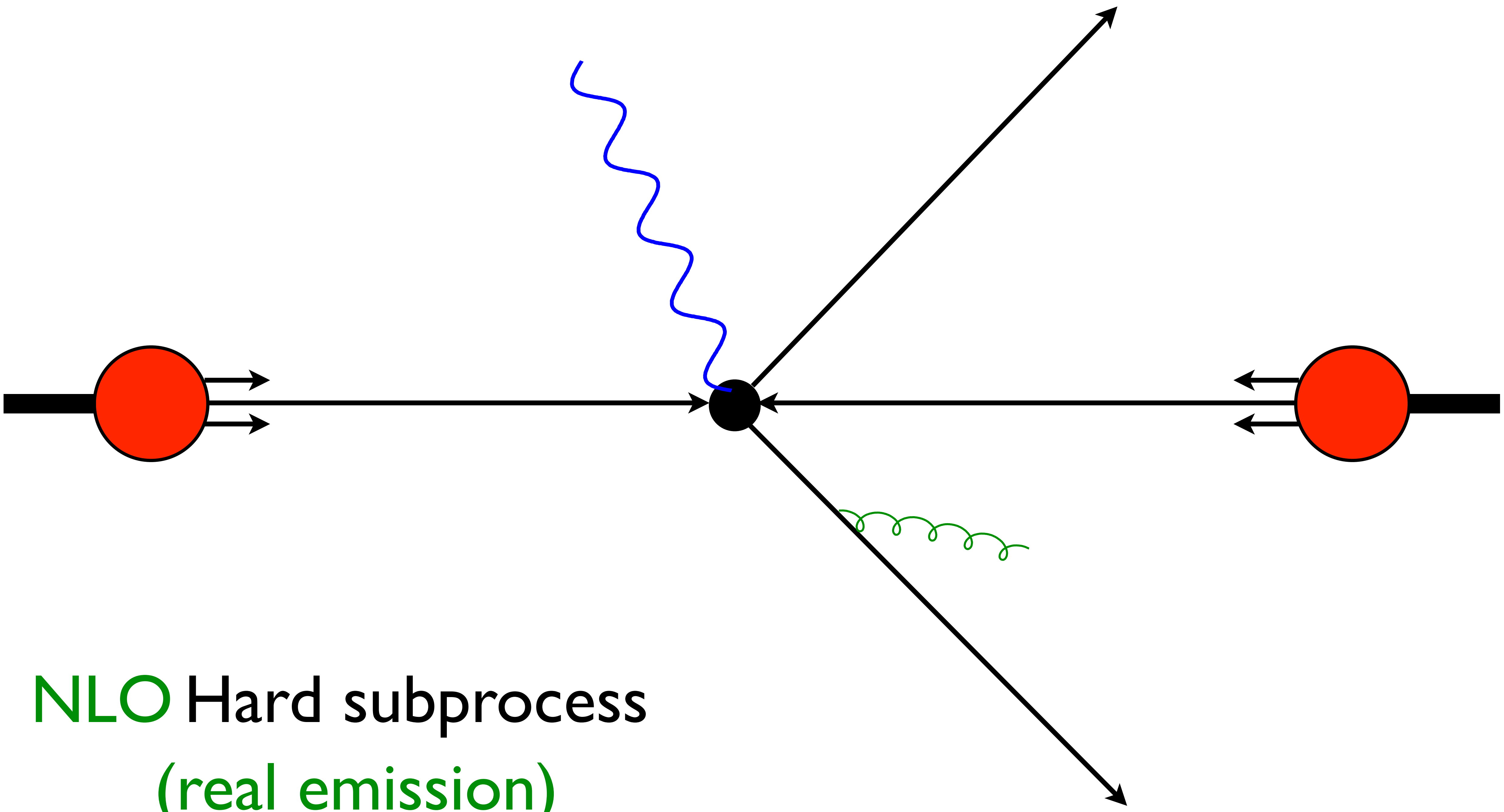
e.g. $qq \to Z^0 qq$

Improving Event Generation



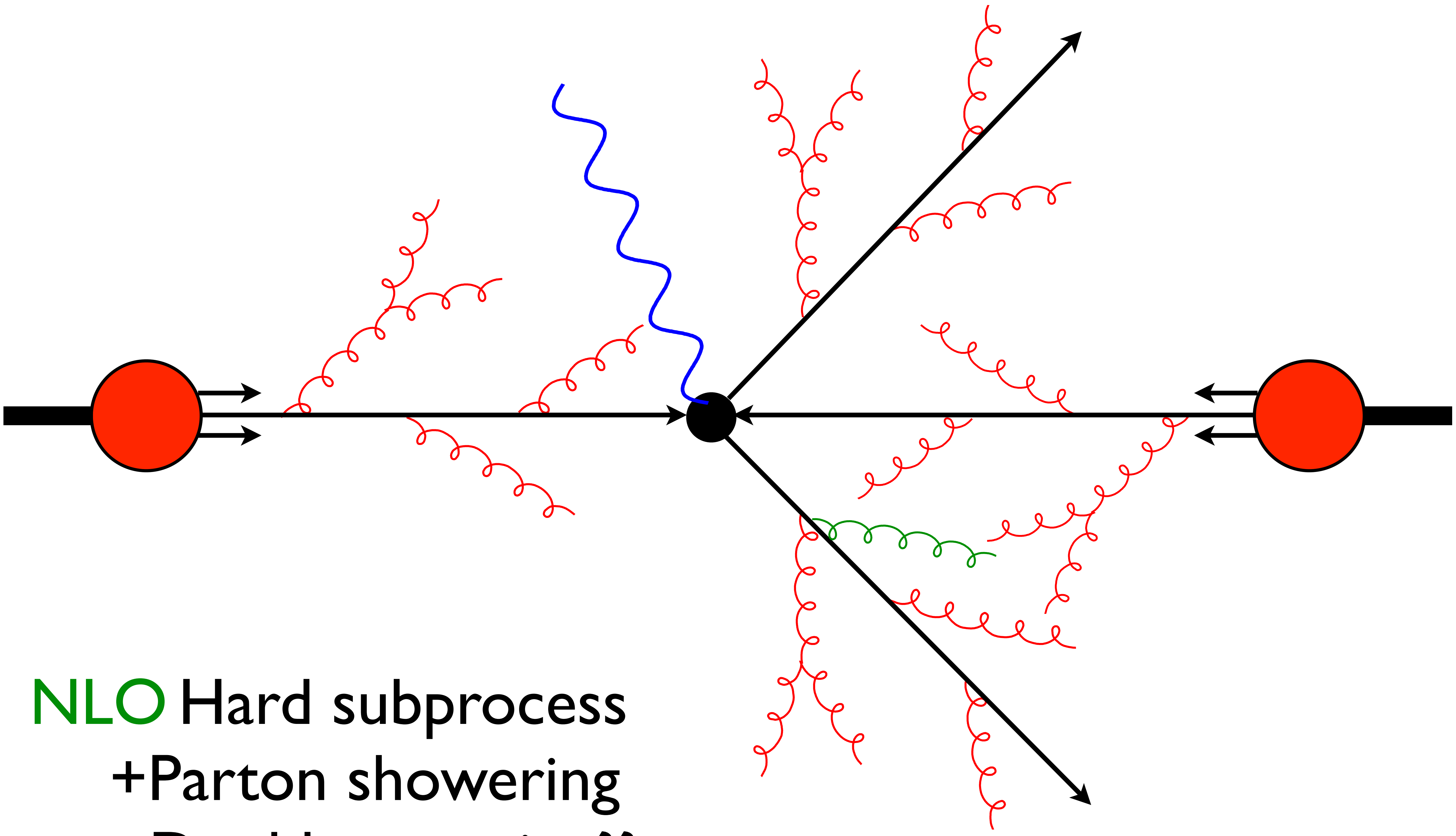
NLO Hard subprocess
(virtual correction)

Improving Event Generation



NLO Hard subprocess
(real emission)

Improving Event Generation

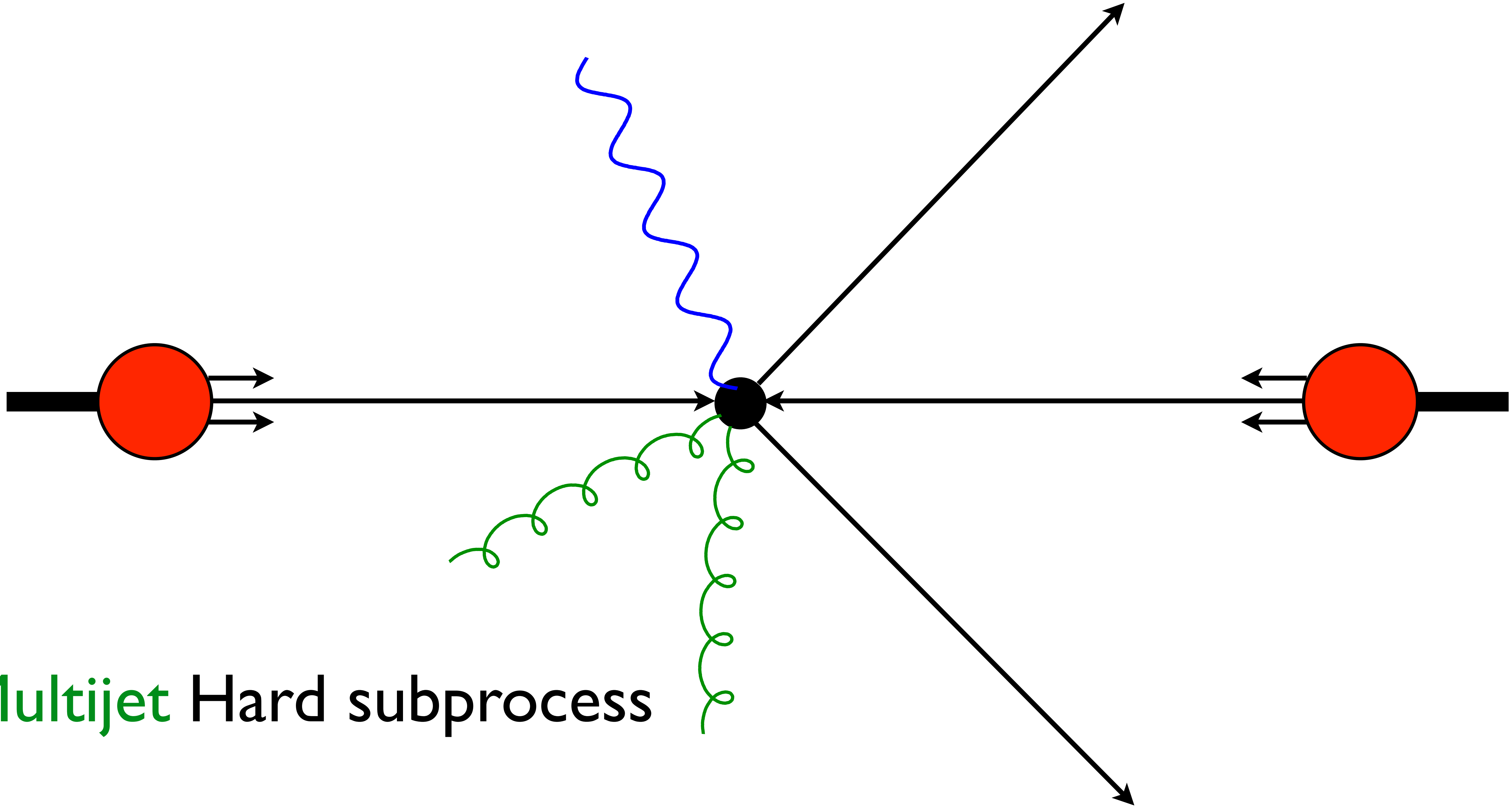


NLO Hard subprocess

+Parton showering

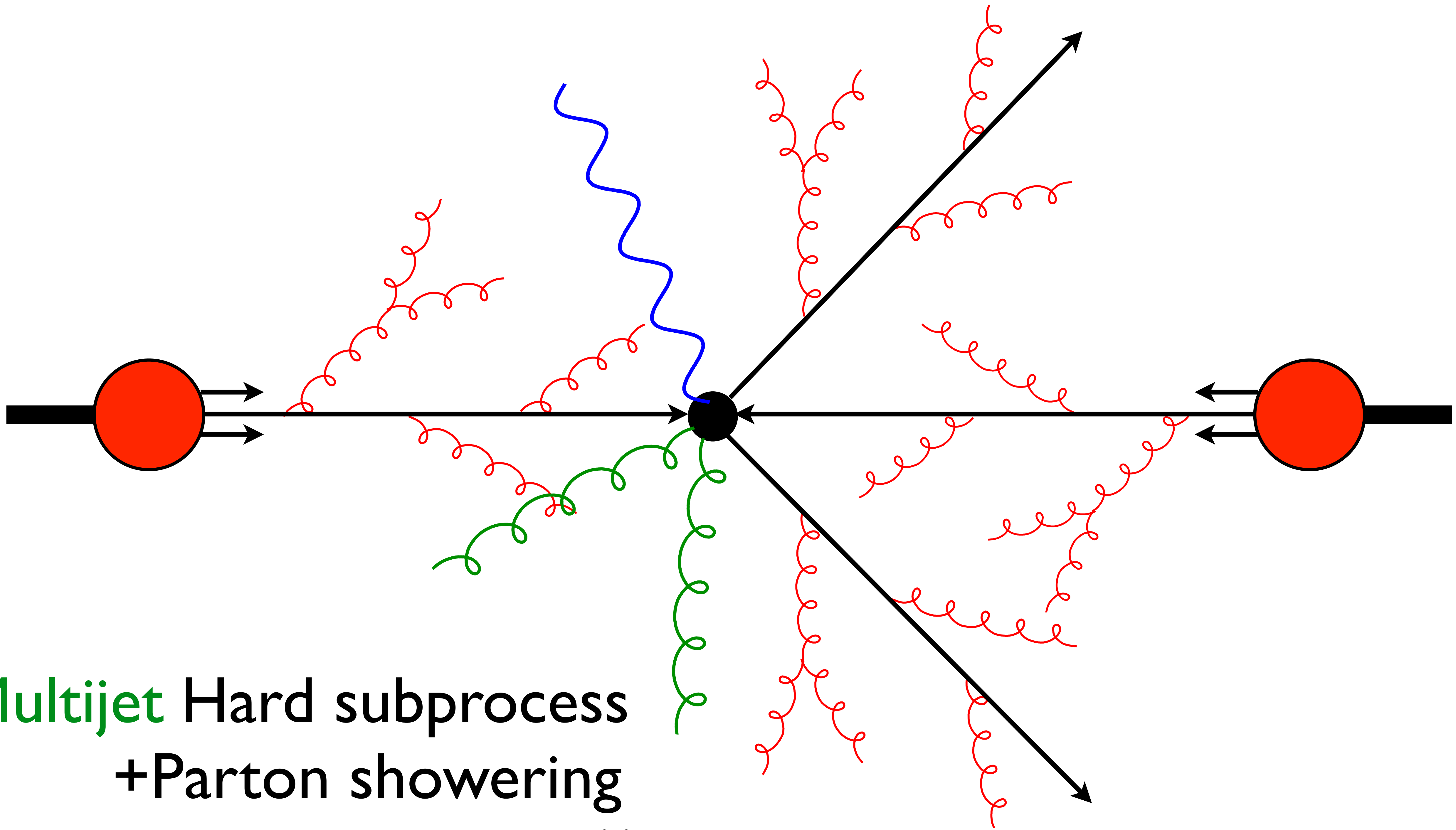
= Double counting??

Improving Event Generation



Multijet Hard subprocess

Improving Event Generation



Multijet Hard subprocess
+Parton showering
= Double counting??

Matching & Merging

- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
  - MC@NLO — Frixione, BW, 2002
  - POWHEG — Nason, 2004
- Merging parton showers with LO n-jet matrix elements, minimizing jet resolution dependence
  - CKKW — Catani, Krauss, Kühn, BW, 2001
  - Dipole — Lönnblad, 2001
  - MLM merging — Mangano, 2002

MC@NLO matching

S Frixione & BW, JHEP 06(2002)029

- Compute parton shower contributions (real and virtual) at NLO
  - Generator-dependent
- Subtract these from exact NLO
  - Cancels divergences of exact NLO!
- Generate modified no-emission (LO+virtual) and real-emission hard process configurations
  - Some may have negative weight
- Pass these through parton shower etc.
  - Only shower-generated terms beyond NLO

MC@NLO matching

S Frixione & BW, JHEP 06(2002)029

finite virtual → V; divergent → C_i, R

$$
\begin{aligned}
d\sigma_{\rm NLO} &= \left[B\left(\Phi_B\right)+V\left(\Phi_B\right)-\int\sum_i C_i\left(\Phi_B,\Phi_R\right)d\Phi_R\right]d\Phi_B+R\left(\Phi_B,\Phi_R\right)d\Phi_B\,d\Phi_R\\
&\equiv \left[B+V-\int C\,d\Phi_R\right]d\Phi_B+R\,d\Phi_B\,d\Phi_R
\end{aligned}
$$

$$
\begin{aligned}
d\sigma_{\rm MC} &= B\left(\Phi_B\right)d\Phi_B\left[\Delta_{\rm MC}(0)+\frac{R_{\rm MC}\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\Delta_{\rm MC}\left(k_T\left(\Phi_B,\Phi_R\right)\right)d\Phi_R\right]\\
&\equiv B\,d\Phi_B\left[\Delta_{\rm MC}(0)+\left(R_{\rm MC}/B\right)\Delta_{\rm MC}\left(k_T\right)d\Phi_R\right]
\end{aligned}
$$

$$
\begin{aligned}
d\sigma_{\rm MC@NLO} = &\left[B+V+\int\left(R_{\rm MC}-C\right)d\Phi_R\right]d\Phi_B\left[\Delta_{\rm MC}(0)+\left(R_{\rm MC}/B\right)\Delta_{\rm MC}\left(k_T\right)d\Phi_R\right]\\
&+\left(R-R_{\rm MC}\right)\Delta_{\rm MC}\left(k_T\right)d\Phi_B\,d\Phi_R
\end{aligned}
$$

finite $\gtrless 0$ (the two bracketed/real terms)

MC starting from no emission

MC starting from one emission

- Expanding gives NLO result

POWHEG matching

P Nason, JHEP 11(2004)040

- POsitive Weight Hardest Emission Generator
- Use exact real-emission matrix element to generate hardest (highest relative p_T) emission configurations
  - No-emission probability implicitly modified
  - (Almost) eliminates negative weights
  - Some uncontrolled terms generated beyond NLO
- Pass configurations through parton shower etc

POWHEG matching

P Nason, JHEP 11(2004)040

$$d\sigma_{\rm MC} = B\left(\Phi_B\right)\, d\Phi_B \left[\Delta_{\rm MC}\left(0\right) + \frac{R_{\rm MC}\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\Delta_{\rm MC}\left(k_T\left(\Phi_B,\Phi_R\right)\right)\, d\Phi_R\right]$$

$$d\sigma_{\rm PH} = \overline{B}\left(\Phi_B\right)\, d\Phi_B \left[\Delta_R\left(0\right) + \frac{R\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\Delta_R\left(k_T\left(\Phi_B,\Phi_R\right)\right)\, d\Phi_R\right]$$

$$\overline{B}\left(\Phi_B\right) = B\left(\Phi_B\right) + V\left(\Phi_B\right) + \int \left[R\left(\Phi_B,\Phi_R\right) - \sum_i C_i\left(\Phi_B,\Phi_R\right)\right] d\Phi_R$$

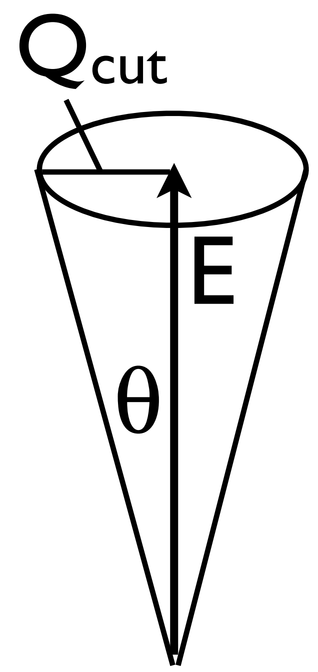
$$\Delta_R\left(p_T\right) = \exp\left[-\int d\Phi_R \frac{R\left(\Phi_B,\Phi_R\right)}{B\left(\Phi_B\right)}\theta\left(k_T\left(\Phi_B,\Phi_R\right) - p_T\right)\right]$$

- NLO with (almost) no negative weights
- High p_T always enhanced by $K = \overline{B}/B = 1 + \mathcal{O}(\alpha_S)$

arbitrary NNLO

Multijet Merging

- Objective: merge LO n-jet matrix elements* with parton showers such that:
  - Multijet rates for jet resolution > Q_{cut} are correct to LO (up to N_{max})
  - Shower generates jet structure below Q_{cut} (and jets above N_{max})
  - Leading (and next) Q_{cut} dependence cancels



* ALPGEN or MadGraph, $n \lesssim N_{max}$

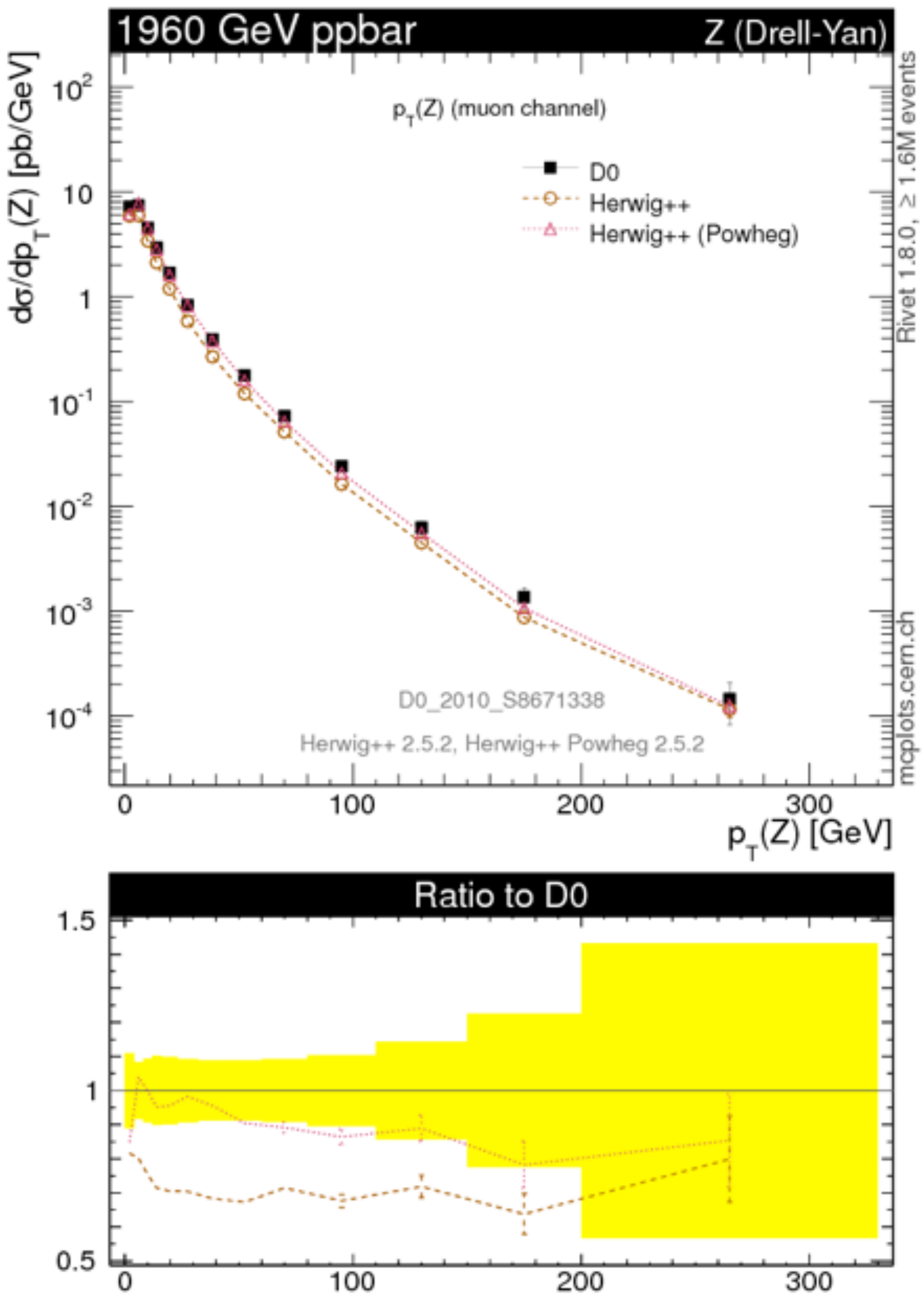
CKKW: Catani et al., JHEP 11(2001)063

-L: Lonnblad, JHEP 05(2002)063

MLM: Mangano et al., NP B632(2002)343

Vector boson production

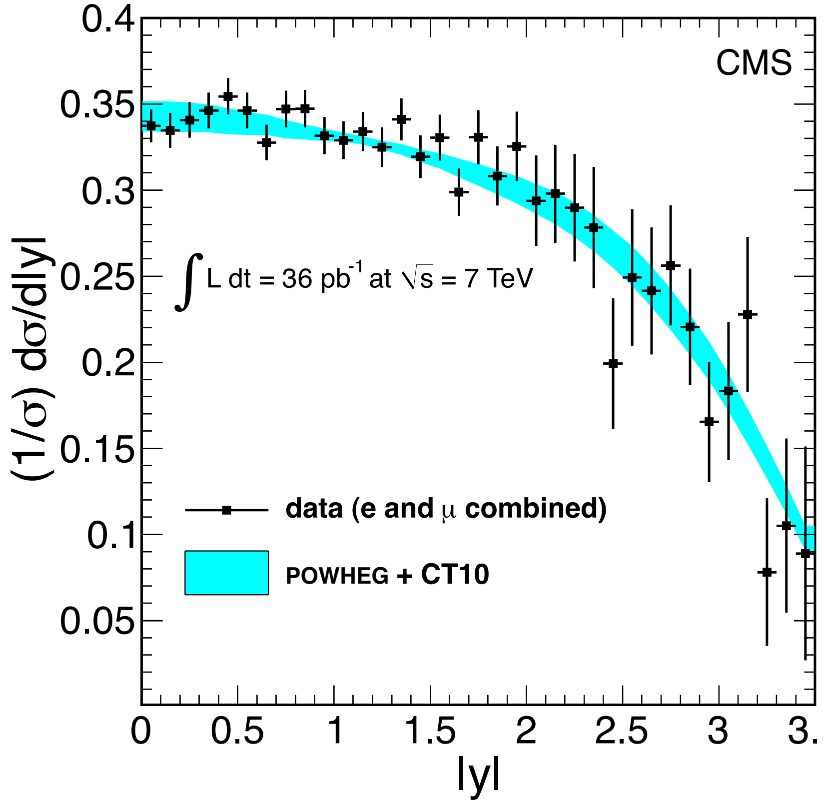
Z^0 at Tevatron

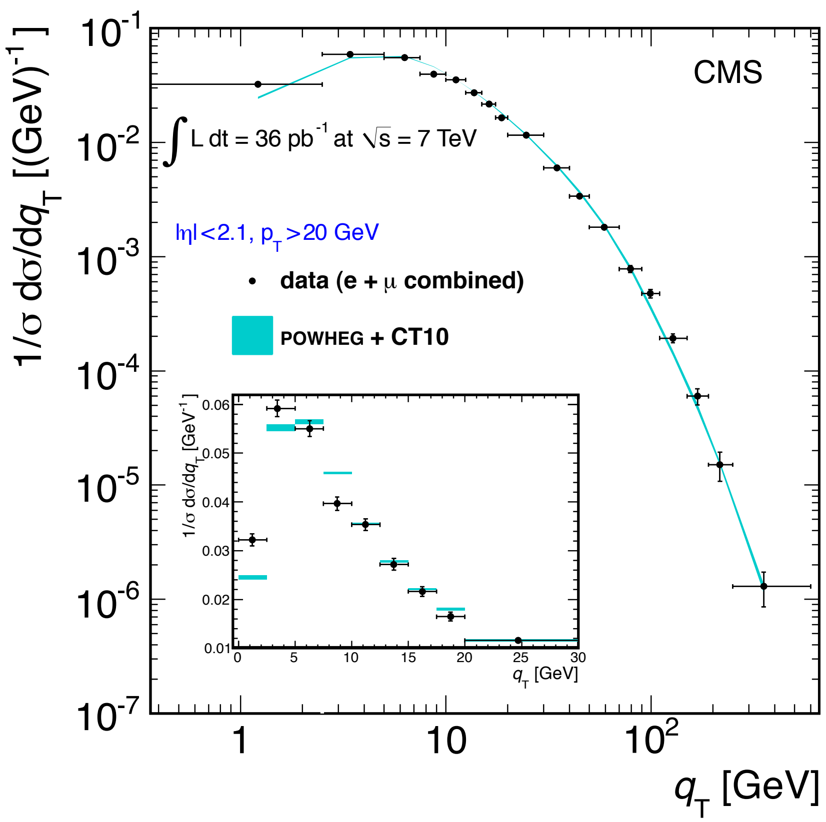


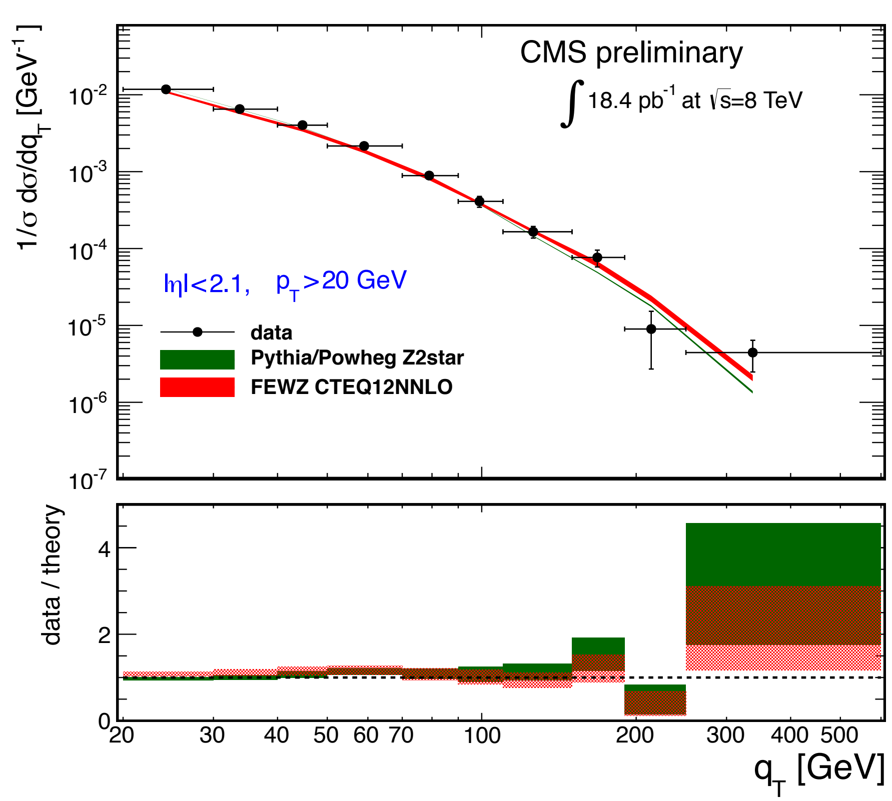
http://mcplots.cern.ch/

- Absolute normalization: LO too low
- POWHEG agrees with rate and distribution

Z^0 at LHC





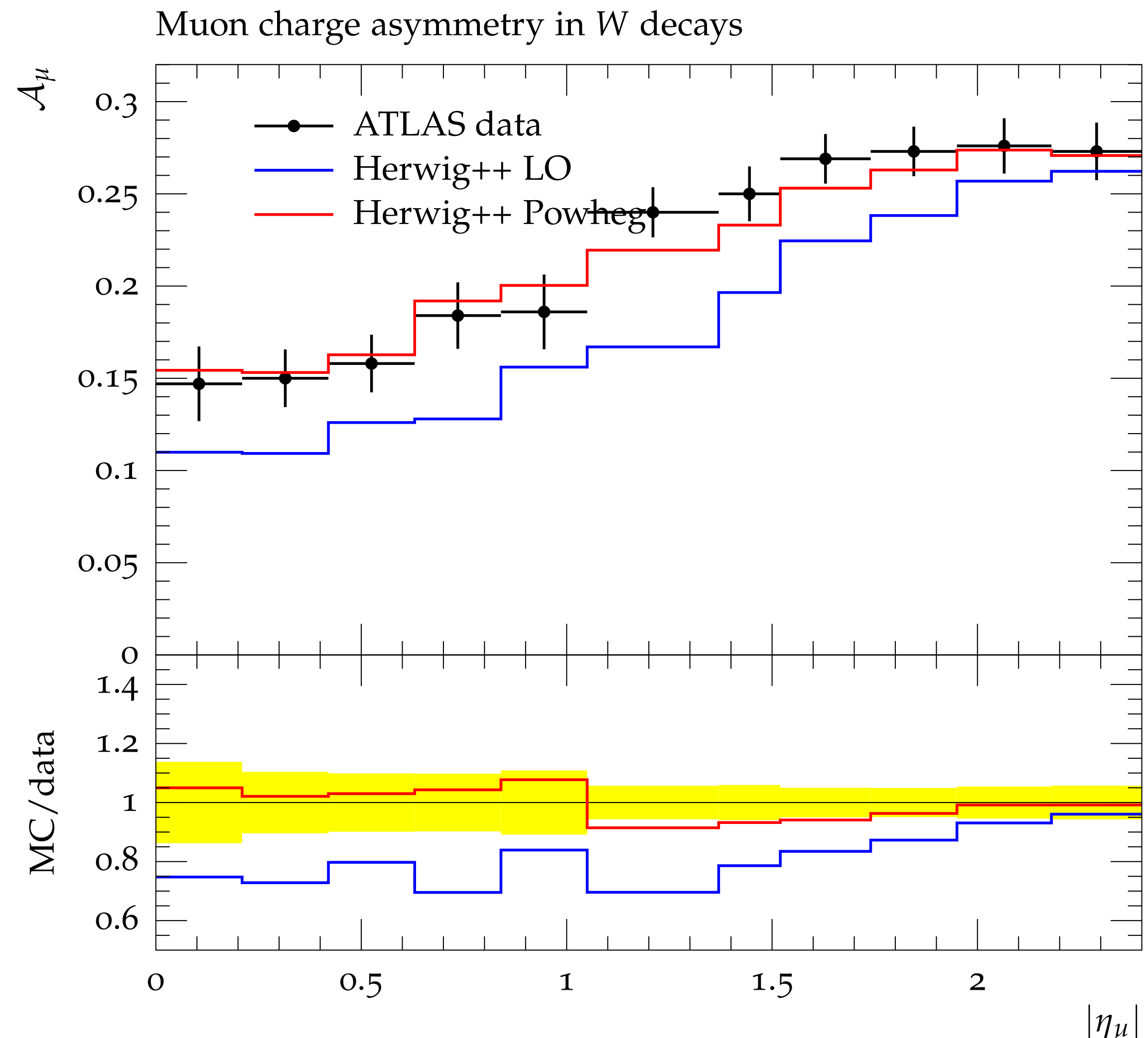


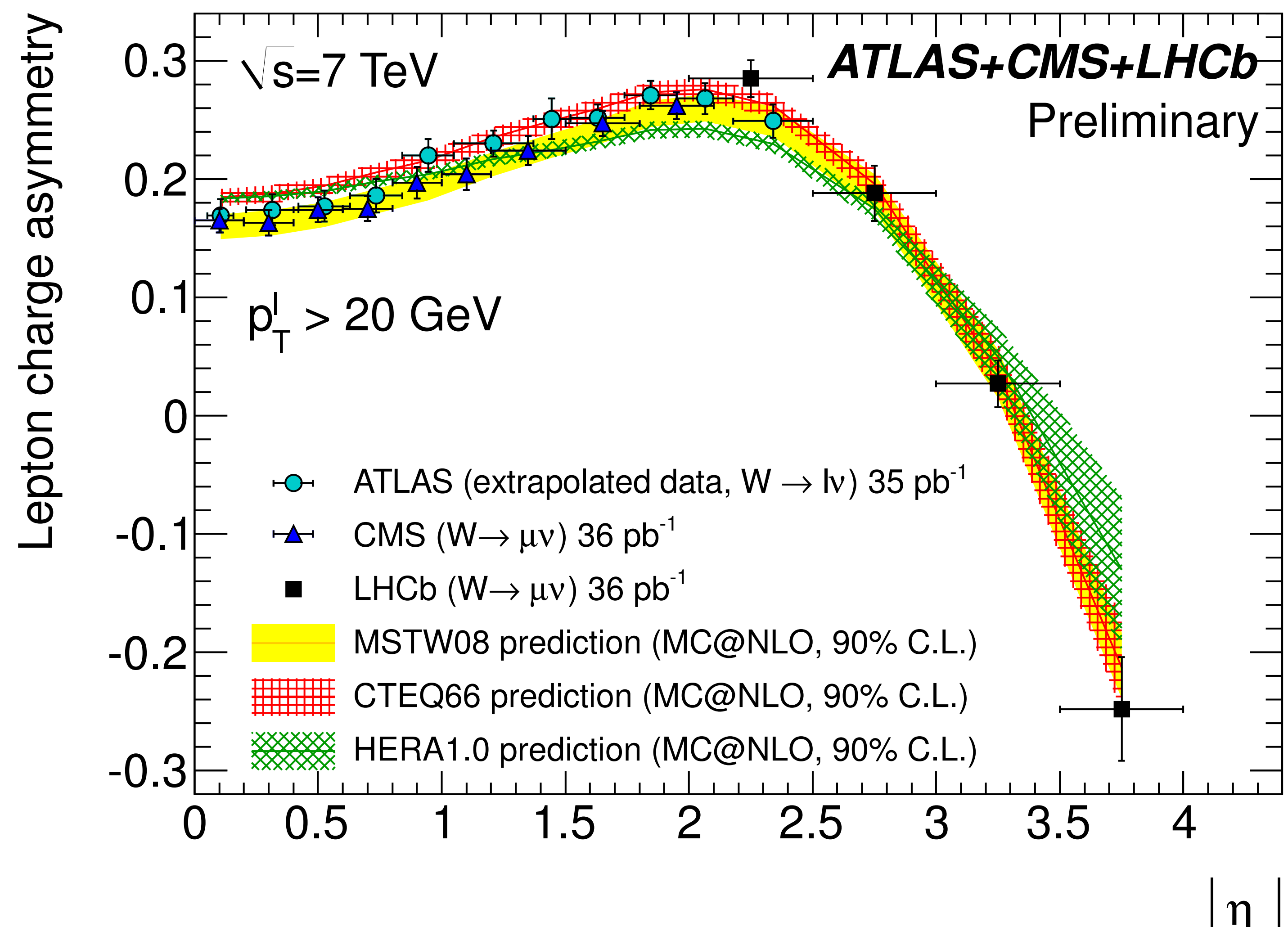
CMS, PRD85(2012)032002

CMS PAS SMP-12-025

- Normalized to data
- POWHEG agrees with distribution (and NNLO)

W asymmetry at LHC





$$A_\mu = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)} \qquad \eta_\mu = \log\tan(\theta_\mu/2)$$

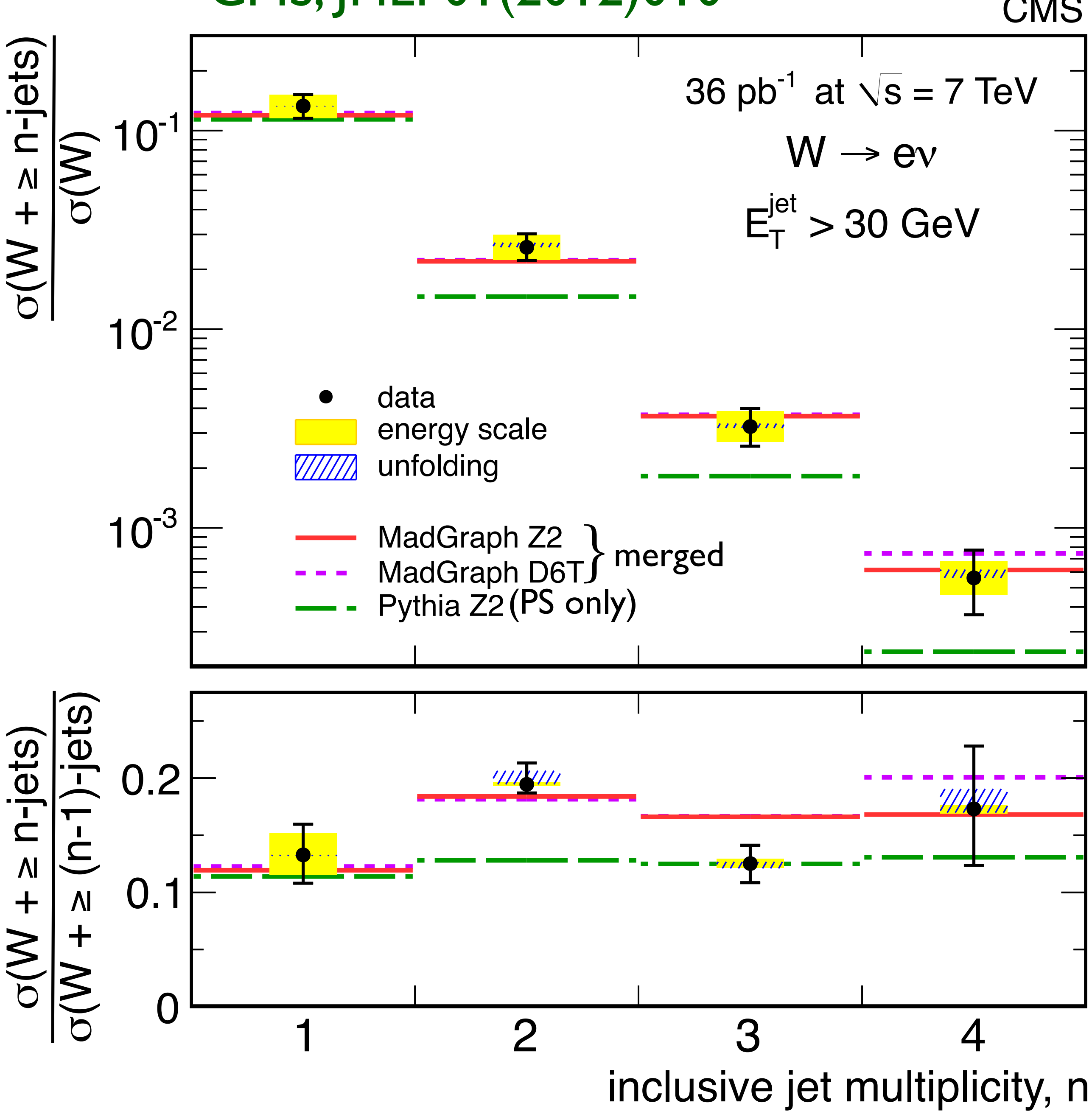
ATLAS-CONF-1211-129

- Asymmetry probes parton distributions

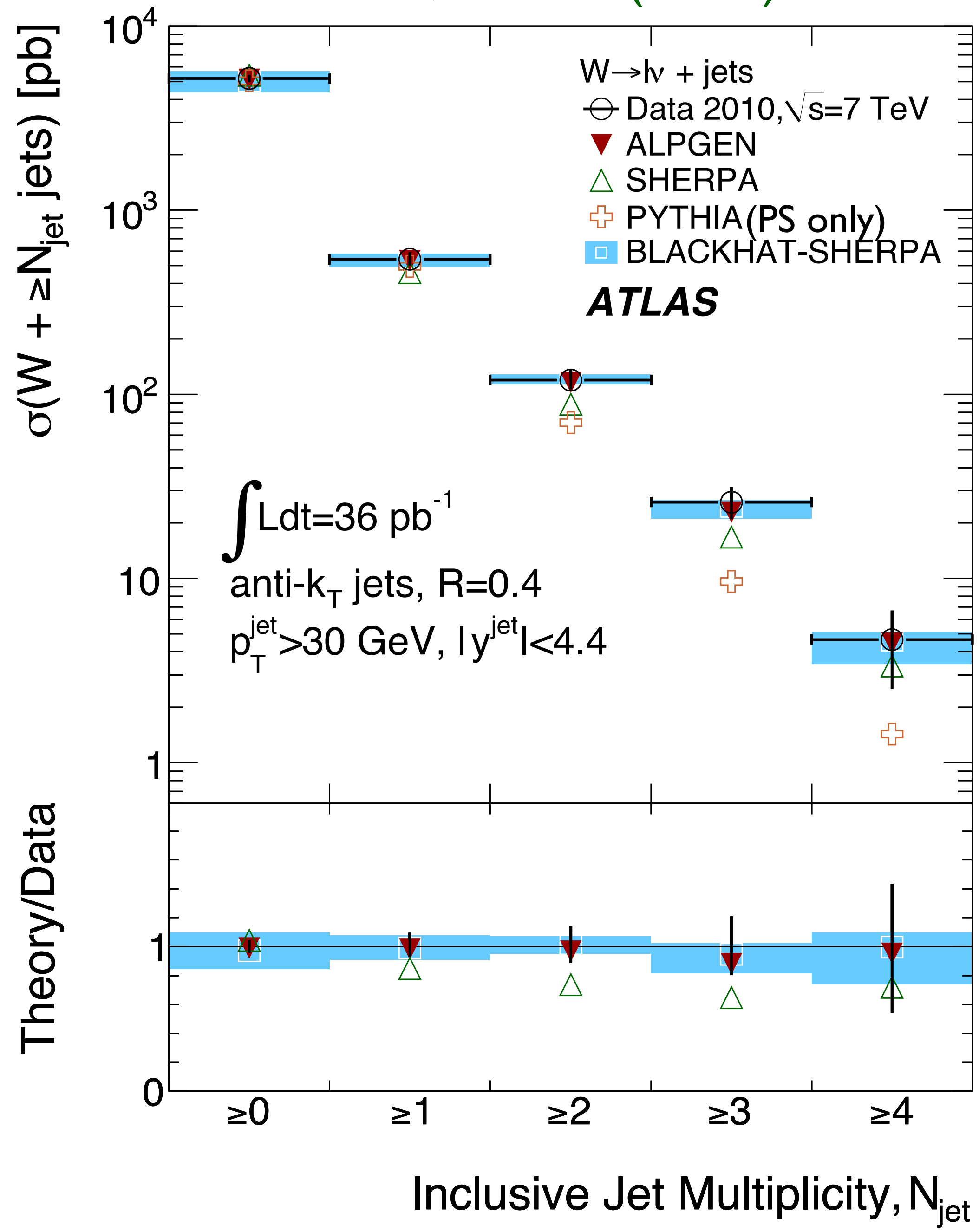
$$u\bar{d} \to W^+ \to \mu^+\nu_\mu \quad \textbf{vs} \quad d\bar{u} \to W^- \to \mu^-\bar{\nu}_\mu$$

W+jets at LHC

CMS, JHEP01(2012)010



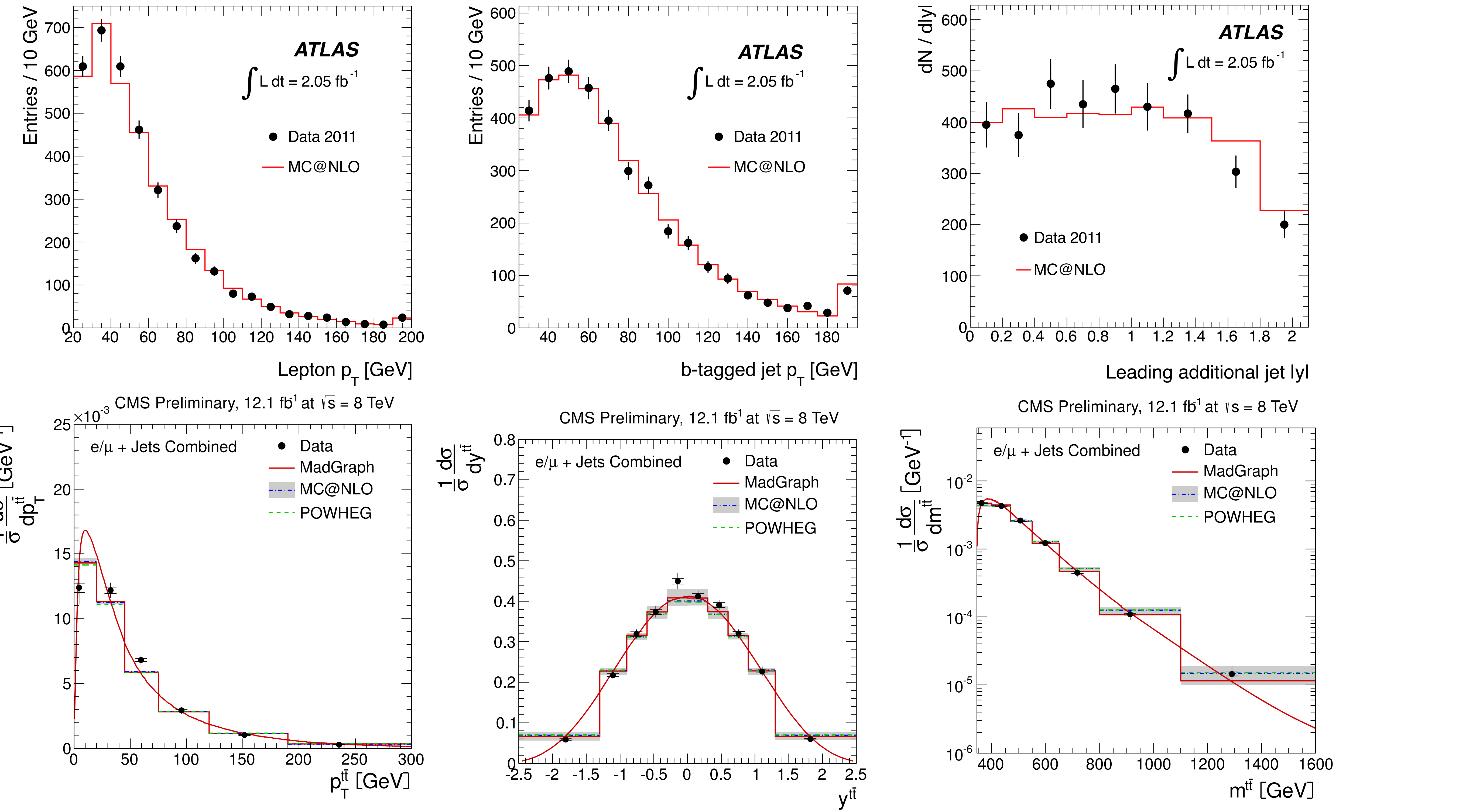
ATLAS, PRD85(2012)092002



- Very good agreement with predictions from merged simulations, while parton shower alone starts to fail for $n_{jet} \geq 2$

Top quark pair production

Top pair production



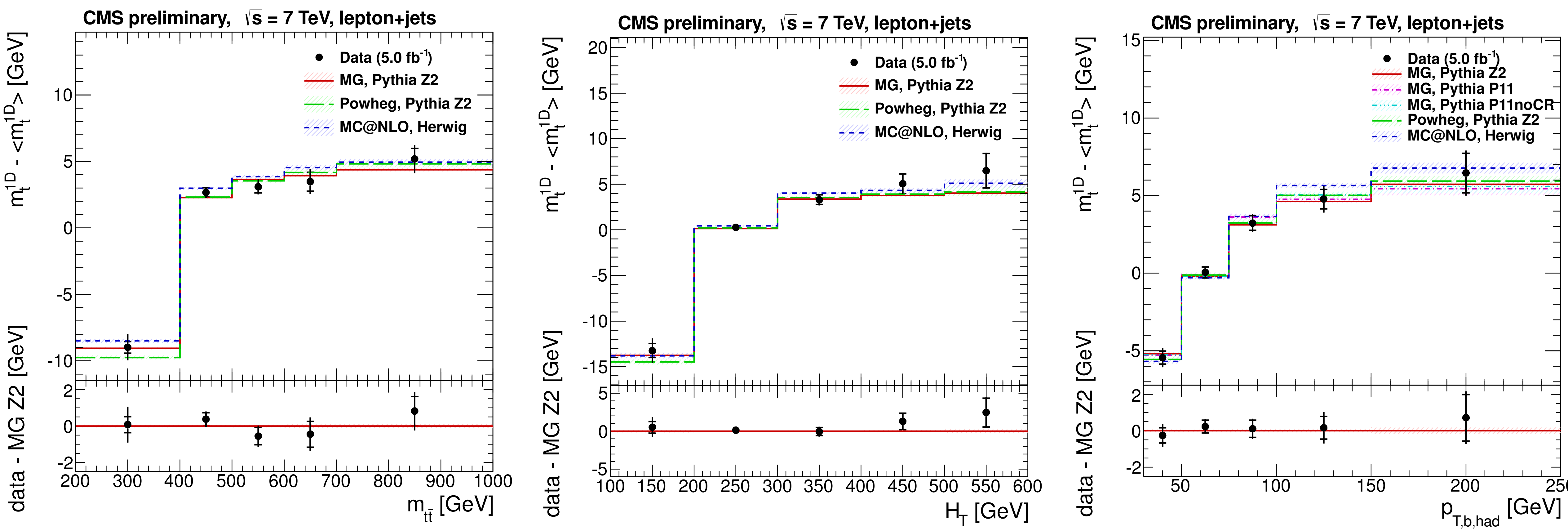
ATLAS, arXiv:1203.5015

CMS PAS TOP-12-027

Frixione, Nason, BW, JHEP 08(2003)007

Alioli, Nason, Oleari, Re, JHEP 06(2010)043

Top mass & kinematics



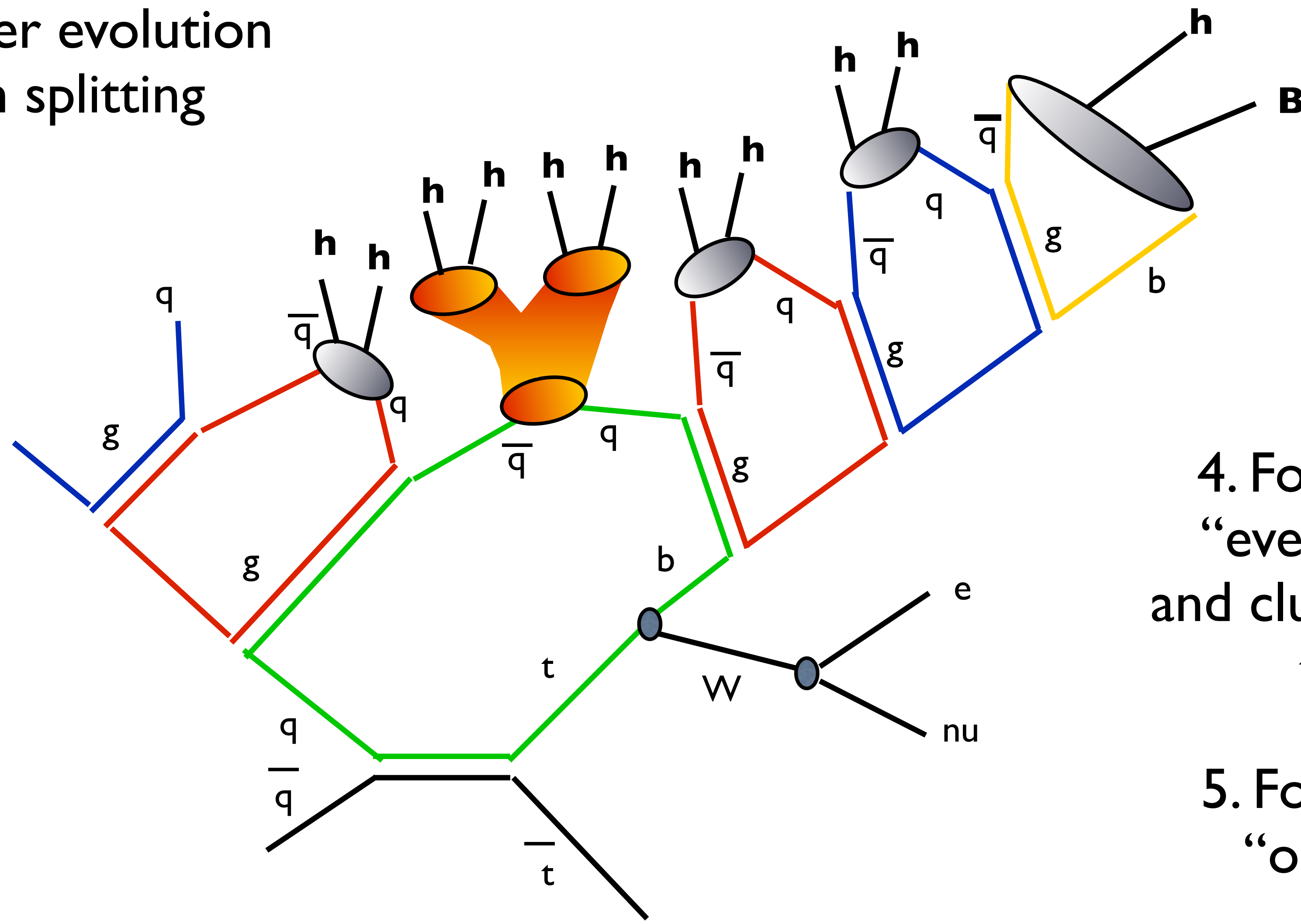
CMS PAS TOP-12-029

- Reconstructed top mass depends on kinematics
- But different generators track data well with a common input mass

Top mass & hadronization

Mangano, Top LHC WG, July 2012

1. Hard Process
2. Shower evolution
3. Gluon splitting



4. Formation of "even" clusters and cluster decay to hadrons

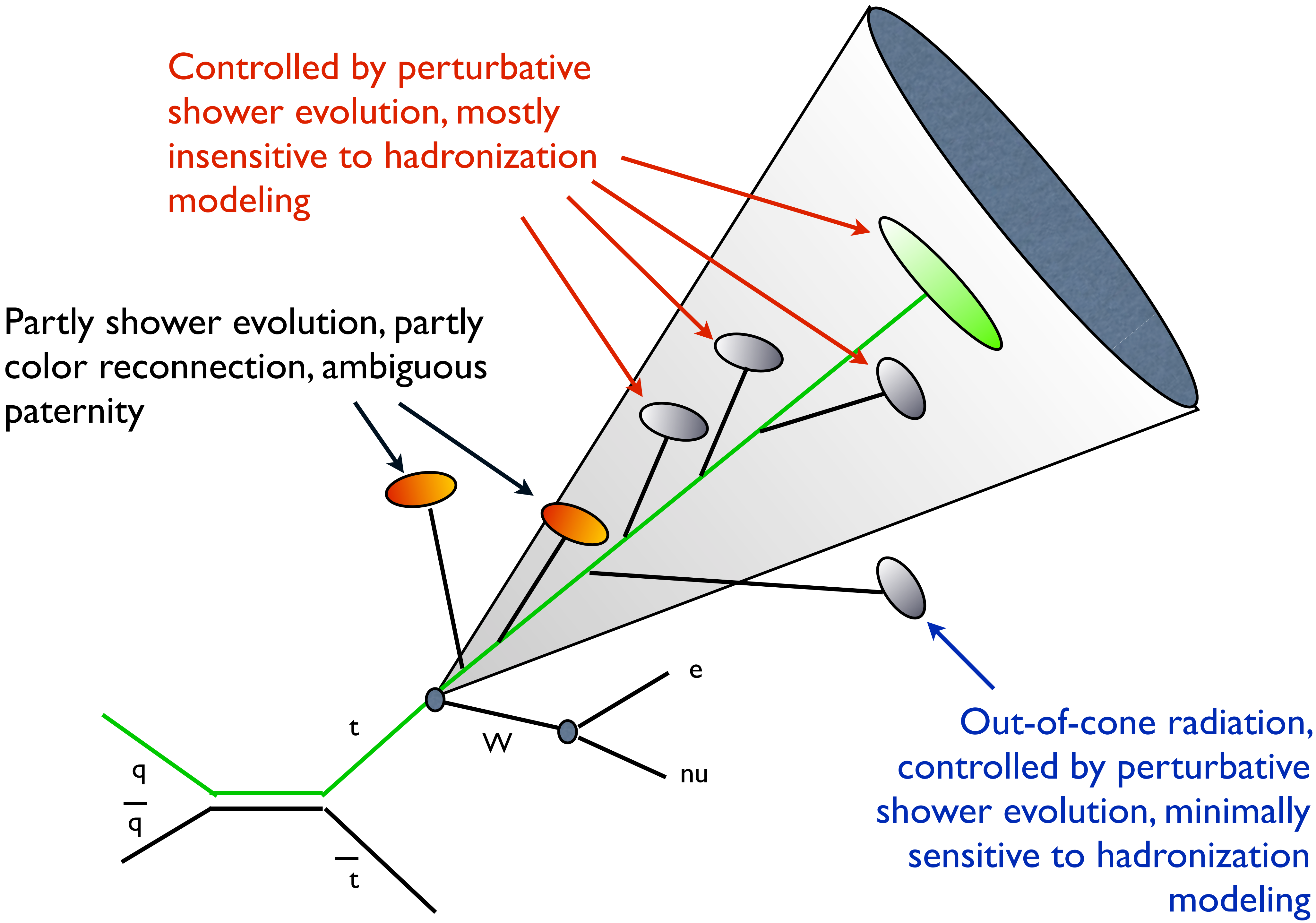
5. Formation of "odd" cluster

6. Decay of "odd" clusters, if large cluster mass, and decays to hadrons

- Study dependence of reconstructed mass on "odd" clusters

Top mass & hadronization

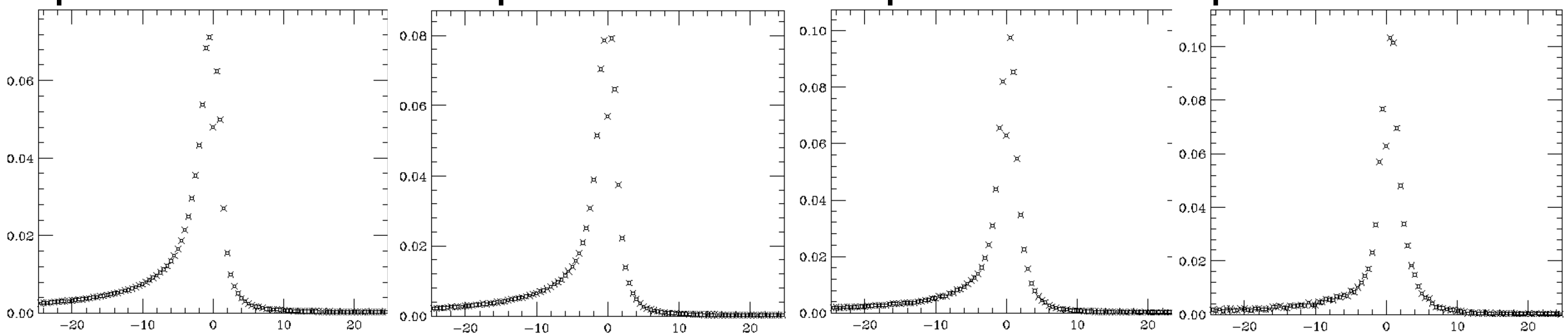
Mangano, Top LHC WG, July 2012



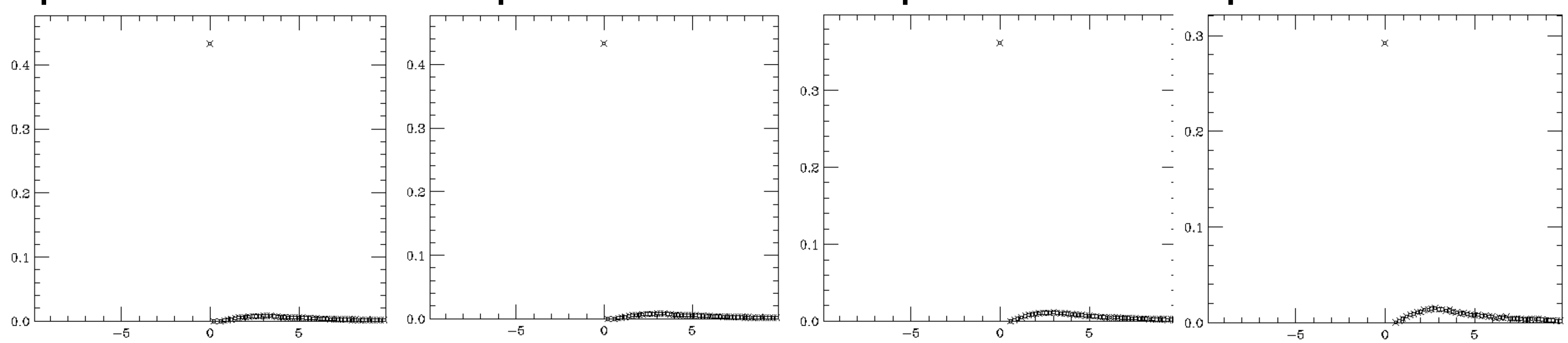
Top mass & hadronization

m_{top} vs pt(top)

m_{top}(E+O) – 172.5



m_{top}(E+O) – m_{top}(E)



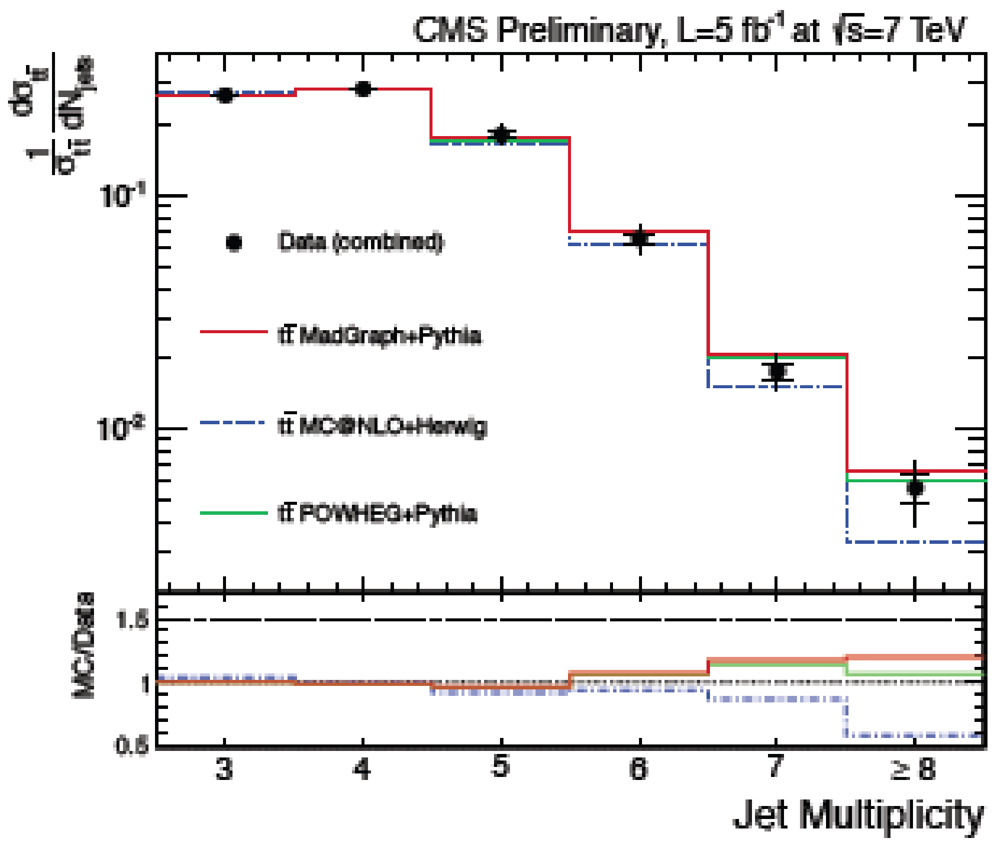
- Dependence of reconstructed mass on “odd” clusters ~ 1 GeV

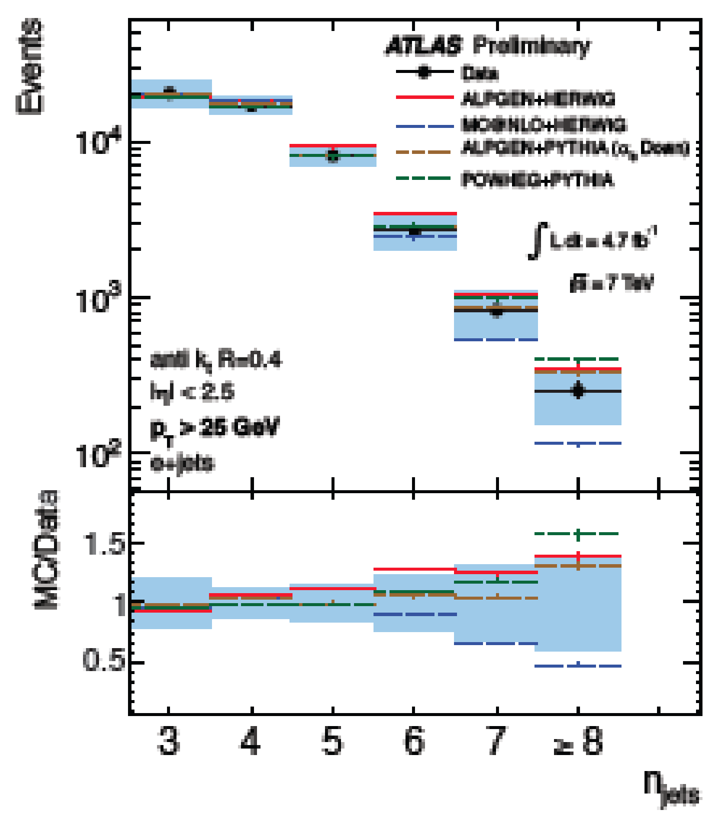
Top+jets

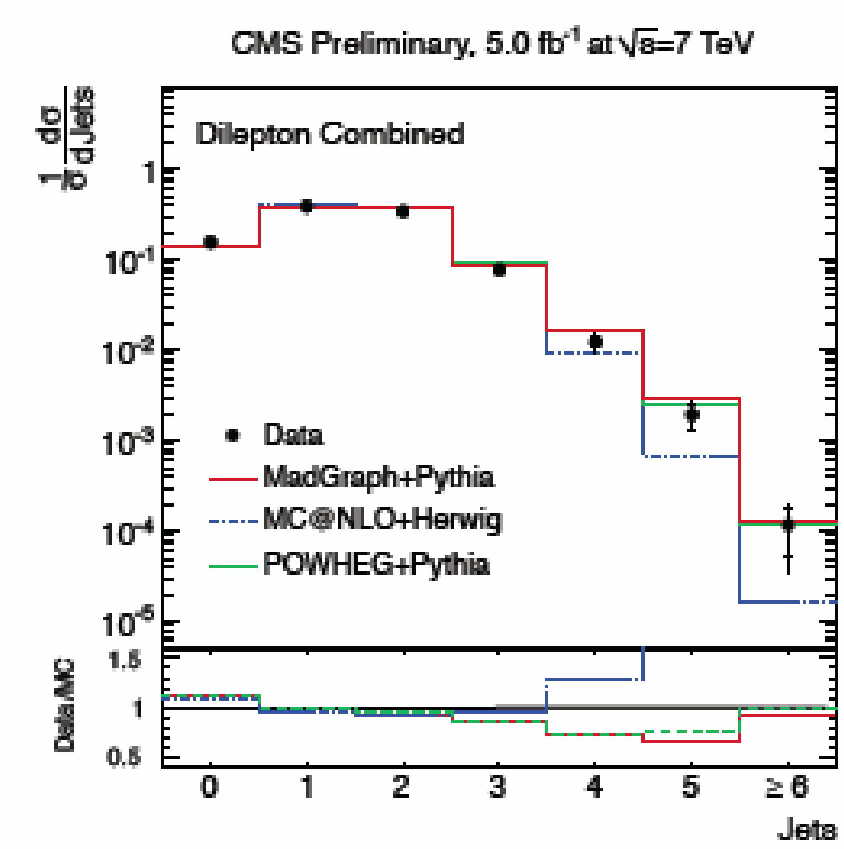
CMS PAS TOP-12-018 (l+jets)
ATLAS-CONF-2012-155 (l+jets)

$$\frac{1}{\sigma}\frac{d\sigma(N_{jets})}{dN_{jets}}$$

CMS PAS TOP-12-023
(dilepton)

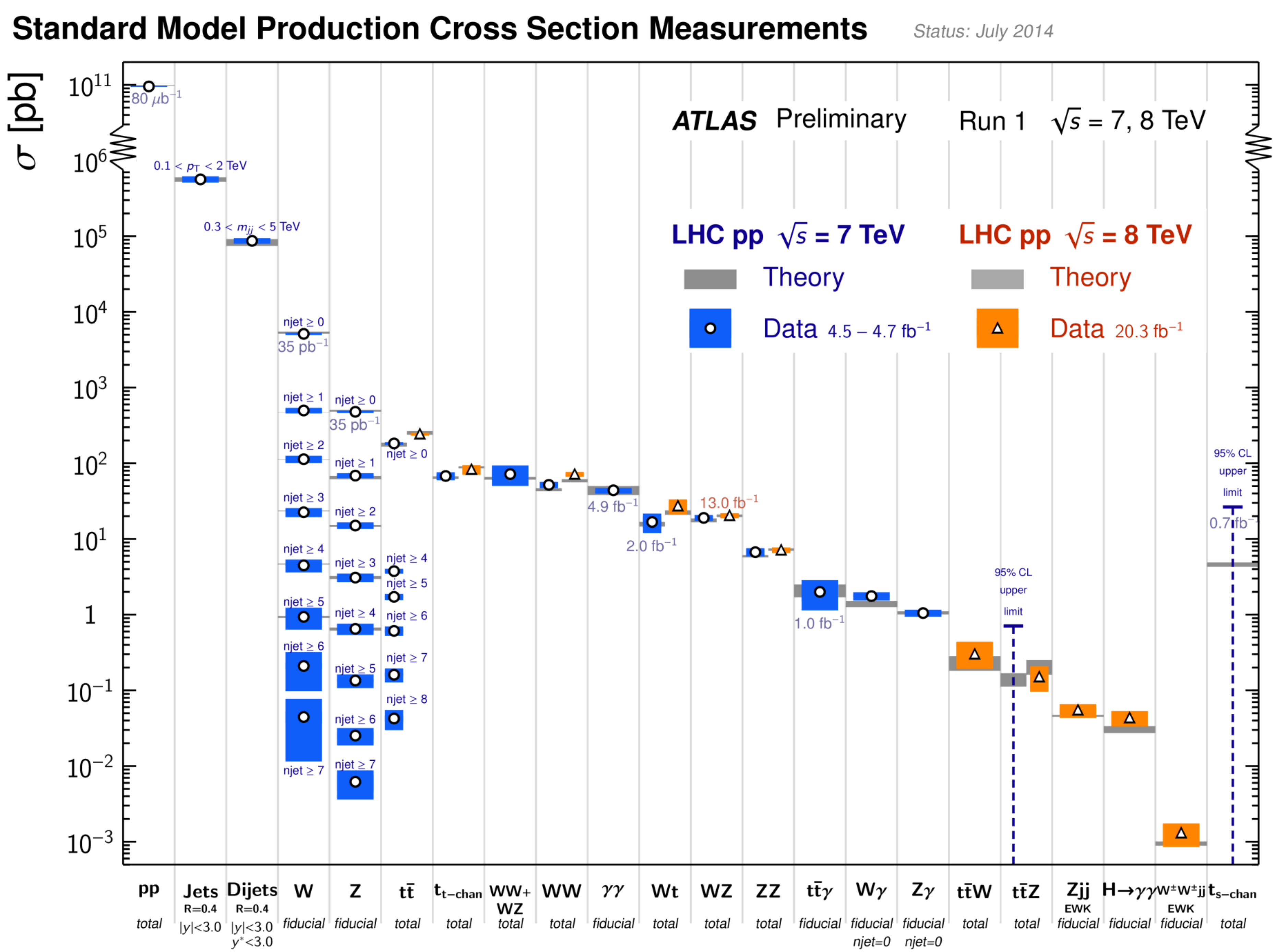






- Matched NLO not adequate for >2 extra jets
- Merged multijets better there (for $d\sigma/\sigma$)

LHC Cross Section Summary

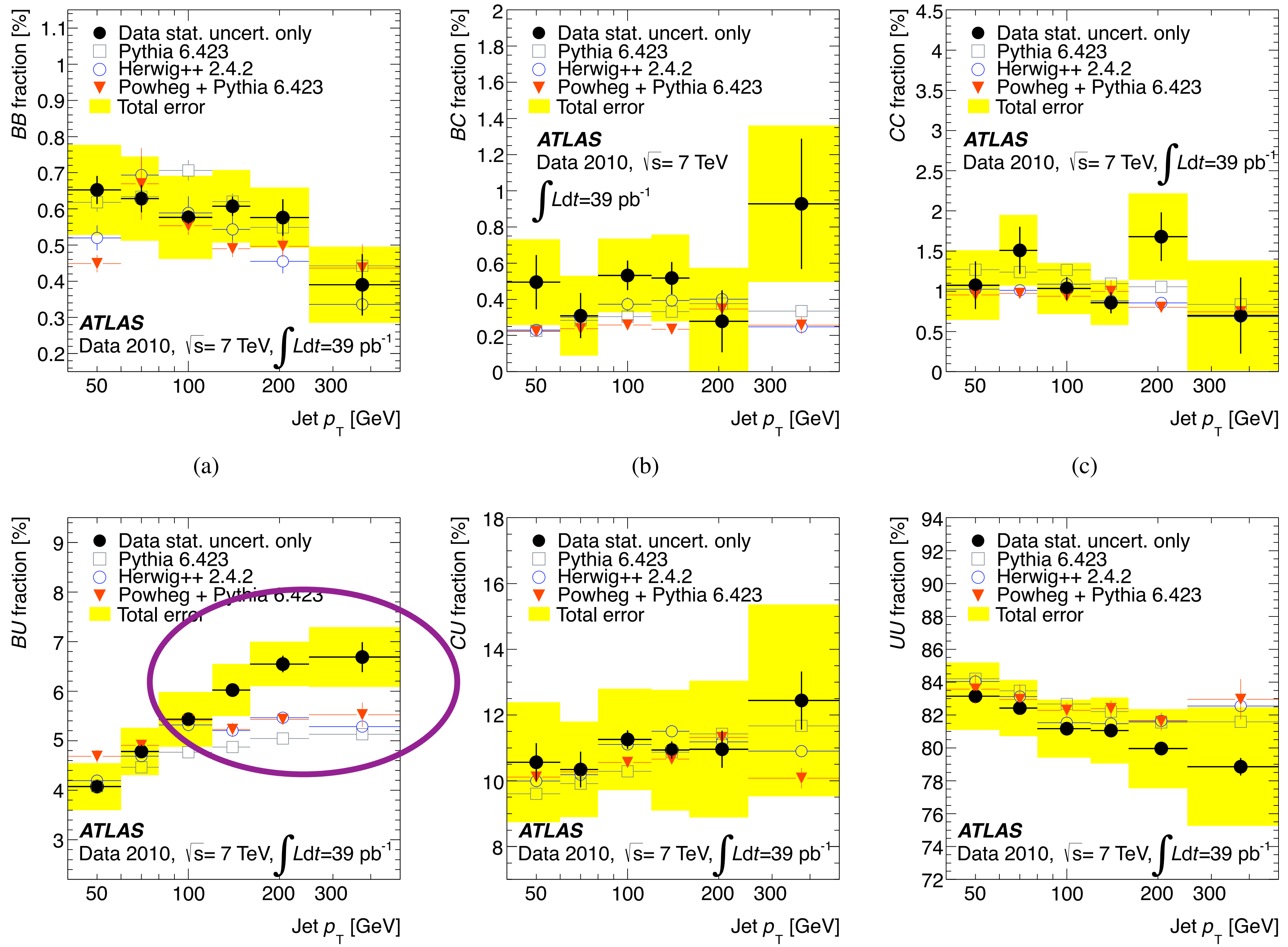


- No significant deviations from SM (yet)

But all is not perfect ...

- Dijet flavours versus jet p_T

ATLAS, arXiv:1210.0441



- Interesting excess of (single) b quark jets

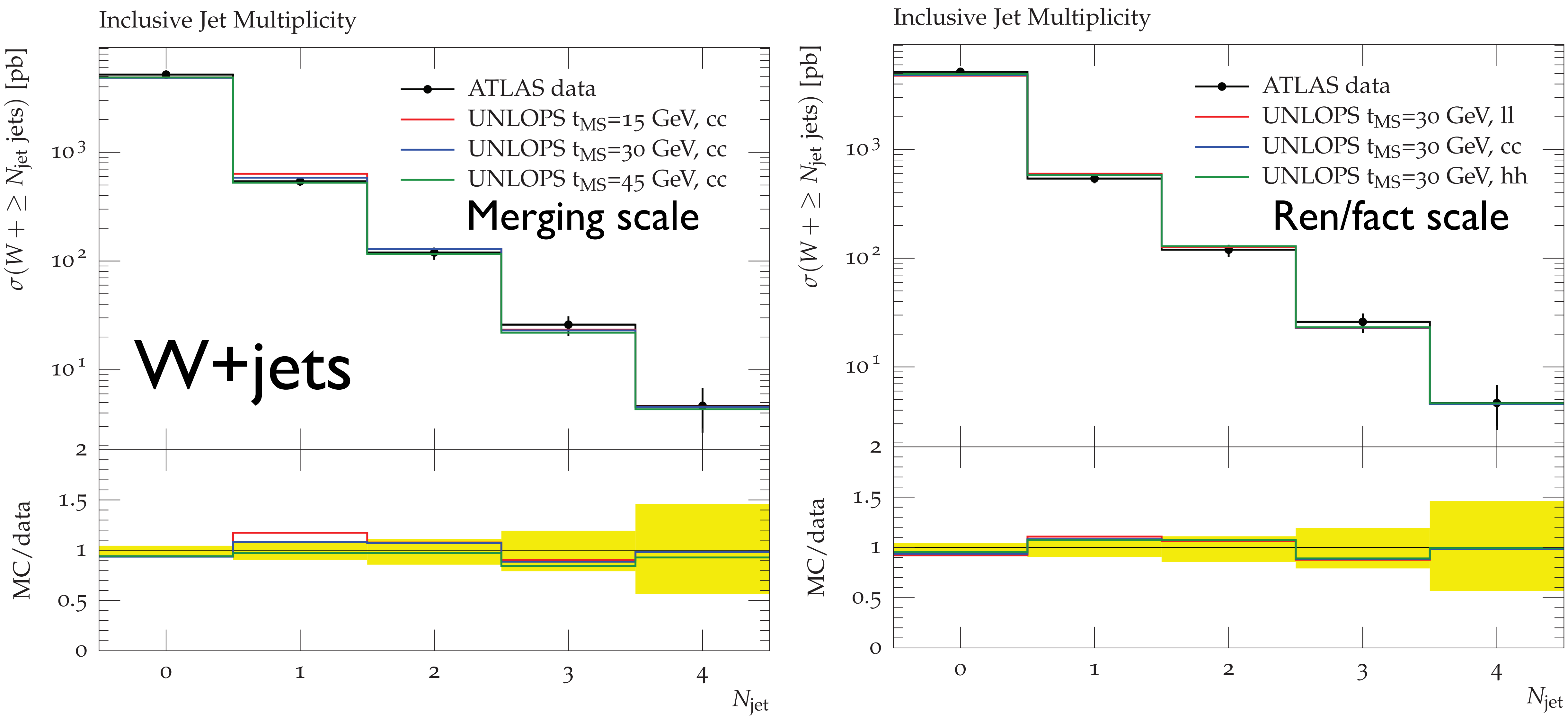
Combined matching+merging

- NLO calculations generally refer to inclusive cross sections e.g. $\sigma(W+\geqslant n \text{ jets})$
- Multijet merging does not preserve them, because of mismatch between exact real-emission and approximate (Sudakov) virtual corrections
- When correcting this mismatch, one can simultaneously upgrade them to NLO
- There remains the issue of merging scale dependence beyond NLO (large logs)

Combined matching+merging

- Many competing schemes (pp, under development)
  - MEPS@NLO (SHERPA) Höche et al., arXiv:1207.5030
  - FxFx (aMC@NLO) Frederix & Frixione, arXiv:1209.6215
  - UNLOPS (Pythia 8) Lönnblad & Prestel, arXiv:1211.7278
  - MatchBox (Herwig++) Plätzer, arXiv:1211.5467
  - MiNLO (POWHEG) Hamilton et al., arXiv:1212.4504
  - GENEVA Alioli, Bauer et al., arXiv:1212.4504
- Some key ideas in LoopSim Rubin, Salam & Sapeta, JHEP1009, 084

Combined matching+merging



UNLOPS: Lönnblad & Prestel, arXiv:1211.7278

- Scale dependences almost eliminated

Higgs boson production

Higgs Signal and Background Simulation

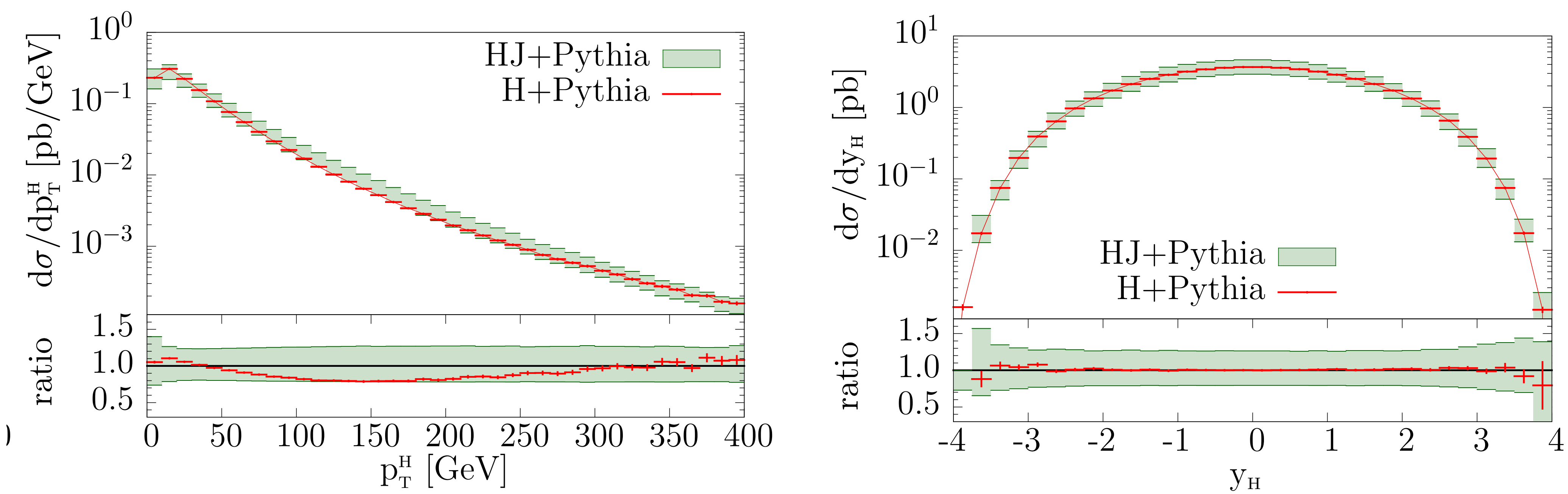
Process	Generator
ggF, VBF	POWHEG [57, 58]+PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
W+jets, Z/γ^*+jets	ALPGEN [59]+HERWIG
$t\bar{t}, tW, tb$	MC@NLO [60]+HERWIG
tqb	AcerMC [61]+PYTHIA
$q\bar{q} \to WW$	MC@NLO+HERWIG
$gg \to WW$	gg2WW [62]+HERWIG
$q\bar{q} \to ZZ$	POWHEG [63]+PYTHIA
$gg \to ZZ$	gg2ZZ [64]+HERWIG
WZ	MadGraph+PYTHIA, HERWIG
$W\gamma$+jets	ALPGEN+HERWIG
$W\gamma^*$ [65]	MadGraph+PYTHIA
$q\bar{q}/gg \to \gamma\gamma$	SHERPA

ATLAS, Phys.Lett.B716(2012)1

gg→Higgs(+jet)

Higgs boson production total cross sections in pb at the LHC, 8 TeV							
K_R, K_F	1, 1	1, 2	2, 1	$1, \frac{1}{2}$	$\frac{1}{2}, 1$	$\frac{1}{2}, \frac{1}{2}$	2, 2
`HJ-MiNLO` NLO	13.33(3)	13.49(3)	**11.70(2)**	13.03(3)	**16.53(7)**	16.45(8)	11.86(2)
`H` NLO	13.23(1)	13.28(1)	**11.17(1)**	13.14(1)	**15.91(2)**	15.83(2)	11.22(1)
`HJ-MiNLO` LO	8.282(7)	8.400(7)	**5.880(5)**	7.864(6)	**18.28(2)**	17.11(2)	5.982(5)
`H` LO	5.741(5)	5.758(5)	**4.734(4)**	5.644(5)	**7.117(6)**	6.996(6)	4.748(4)

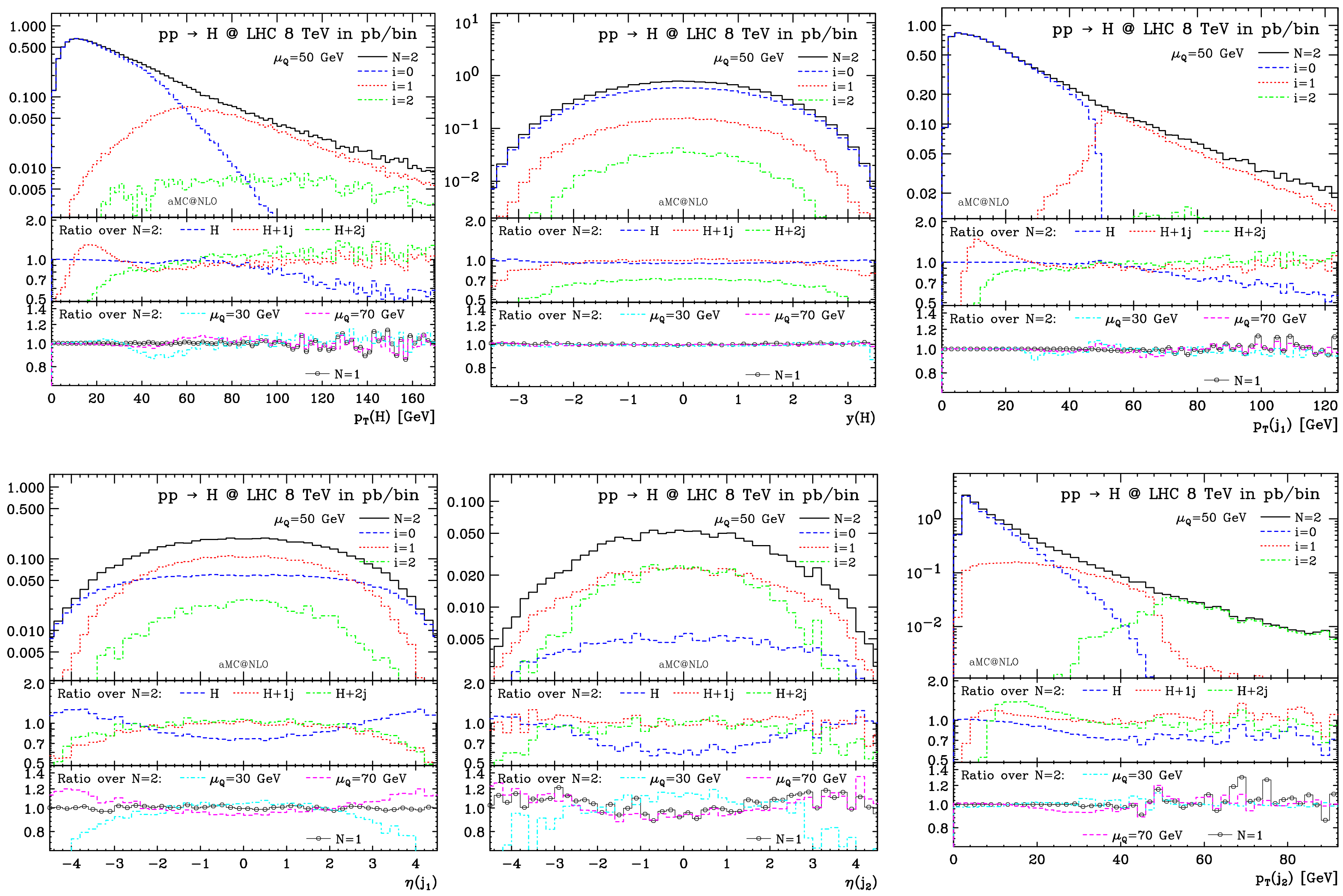
Table 1: Total cross section for Higgs boson production at the 8 TeV LHC, obtained with the `HJ-MiNLO` and the `H` programs, both at full NLO level and at leading order, for different scales combinations. The maximum and minimum are highlighted.



- Match/merge MiNLO+Pythia6

Hamilton, Nason, Oleari & Zanderighi, arXiv:1212.4504

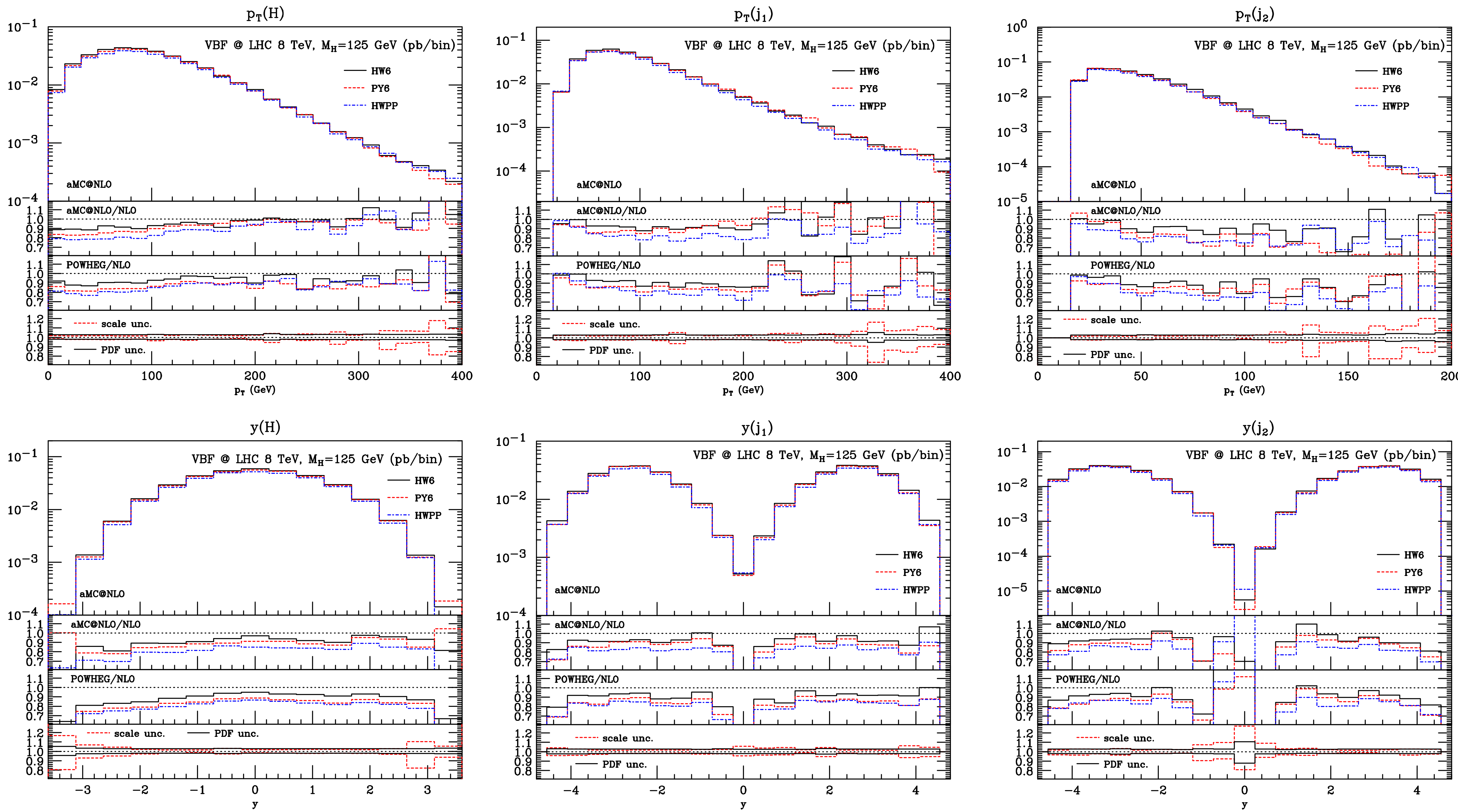
Higgs+jets



- FxFx: Match/merge MC@NLO+Herwig6

Frederix & Frixione, arXiv:1209.6215

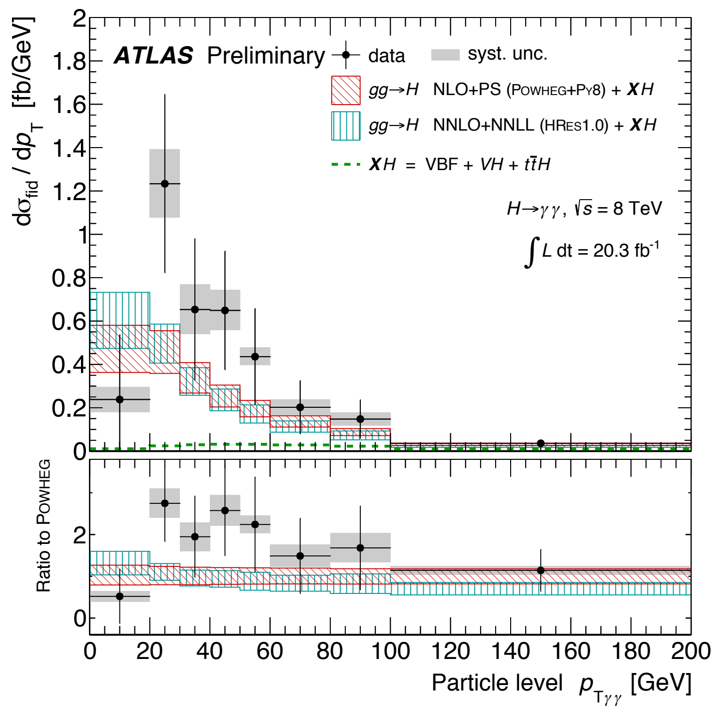
VBF Higgs+jets



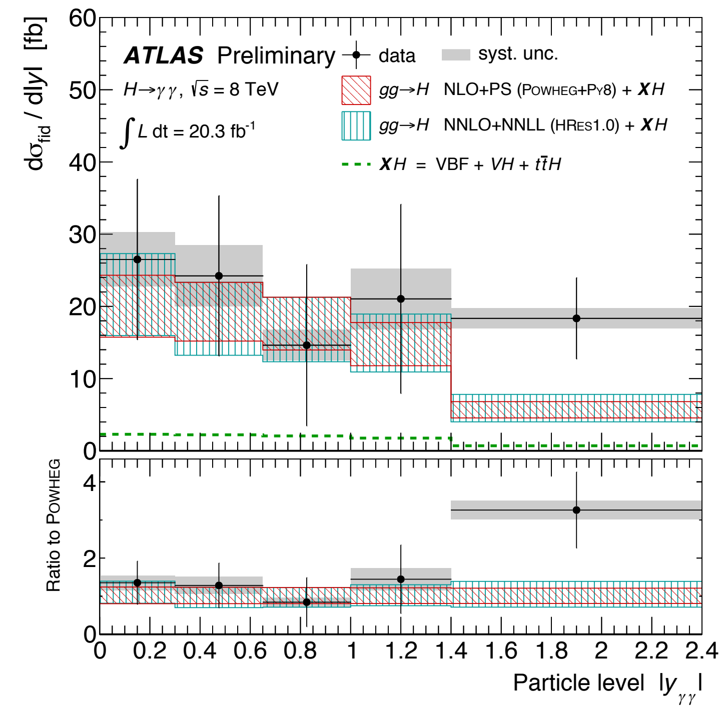
- Matched MC@NLO and POWHEG

Frixione, Torrielli, Zaro, arXiv:1304.7927

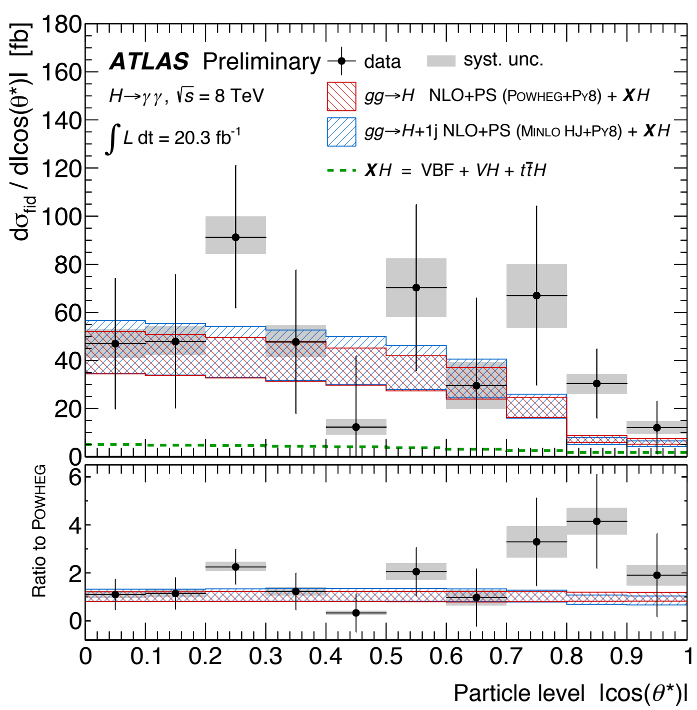
Comparisons to data (γγ mode)



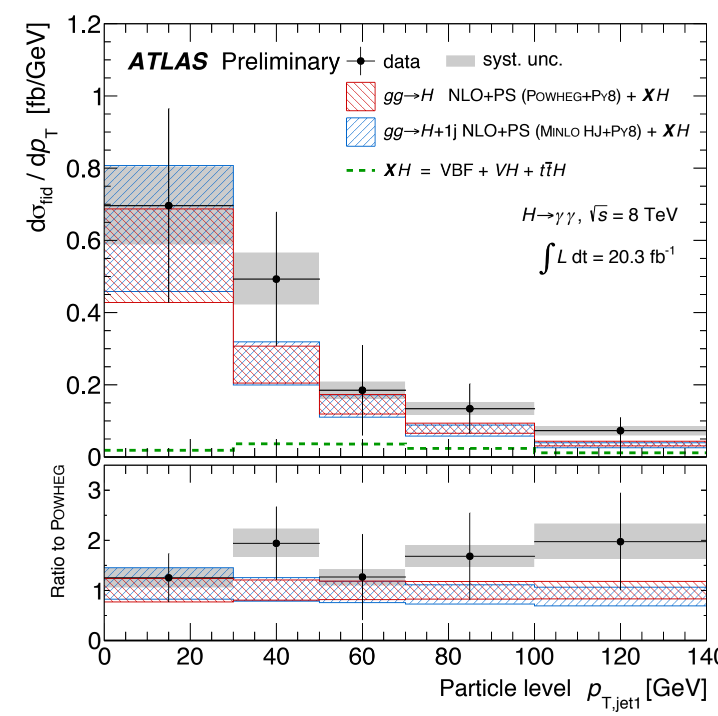
(a) $p_{\mathrm{T}}^{\gamma\gamma}$



(b) $|y^{\gamma\gamma}|$



(c) $|\cos\theta^{*}|$



(d) $p_{\mathrm{T}}^{j_1}$

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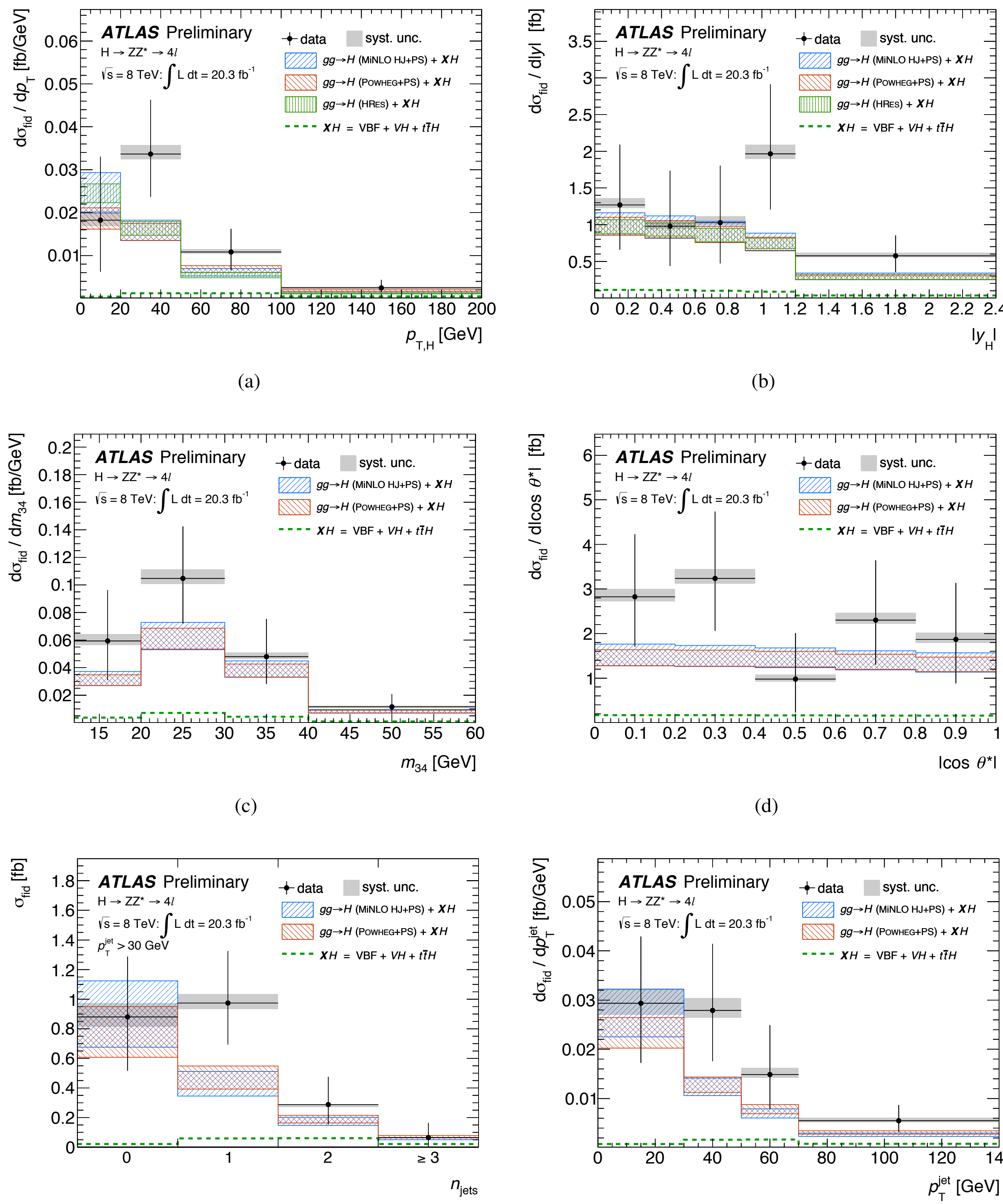
Comparisons to data (ZZ* mode)



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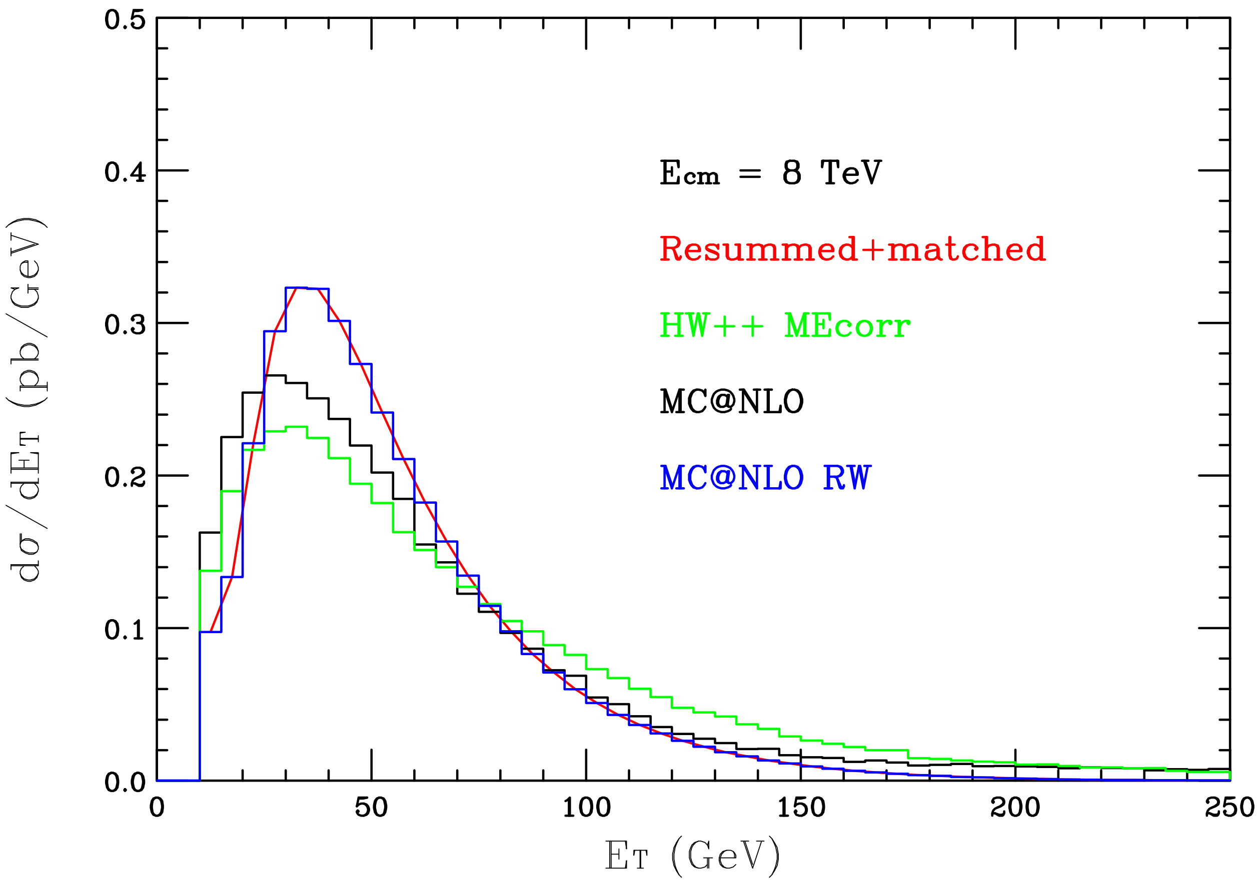
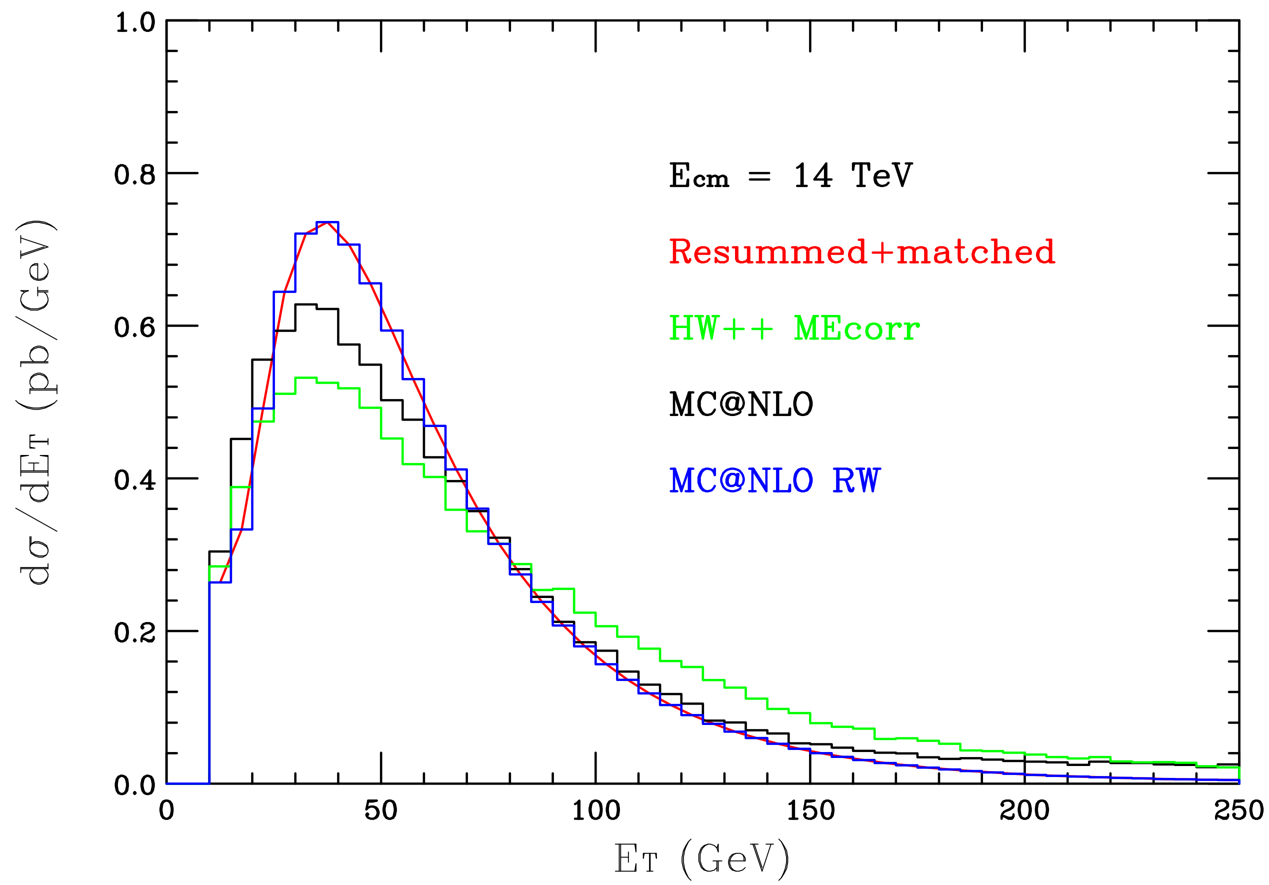
Monte Carlo Higgs E_T

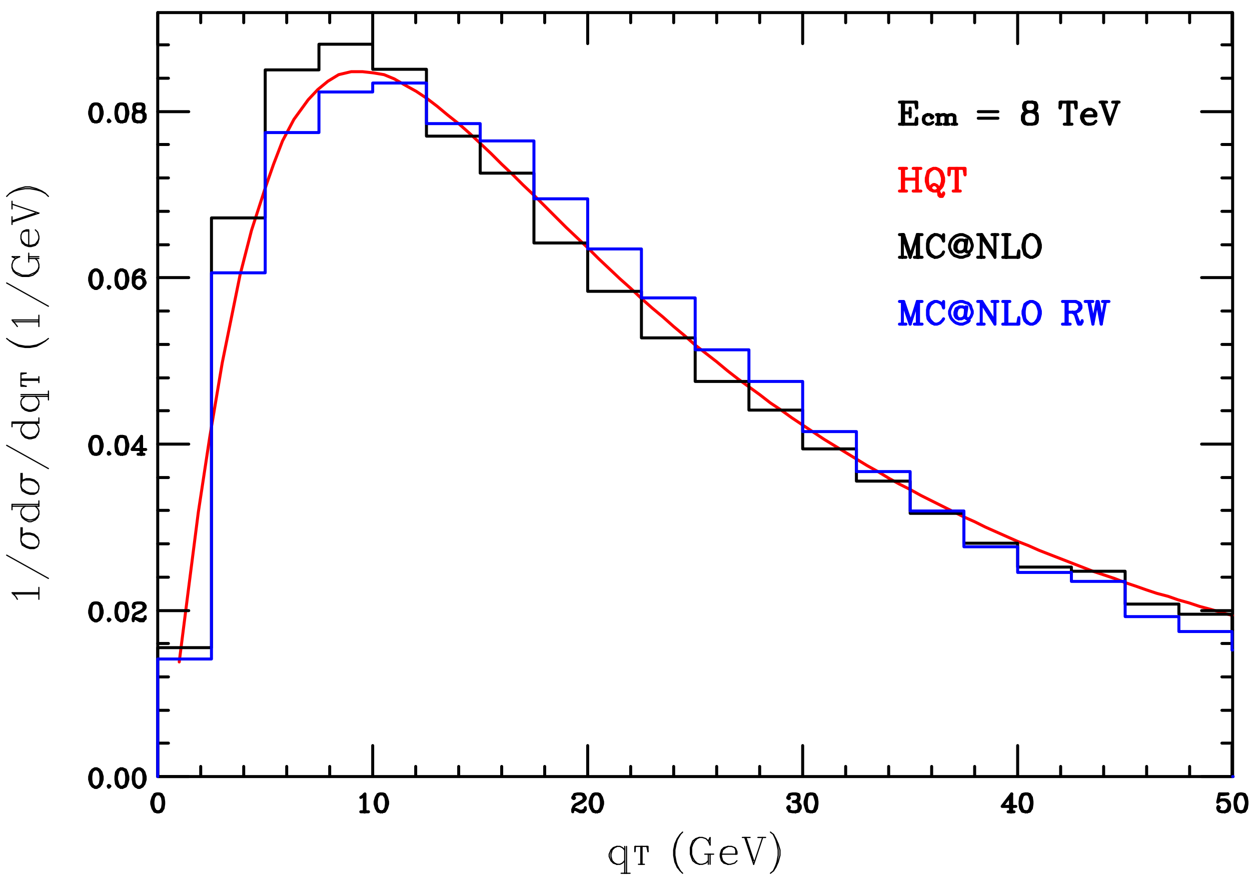


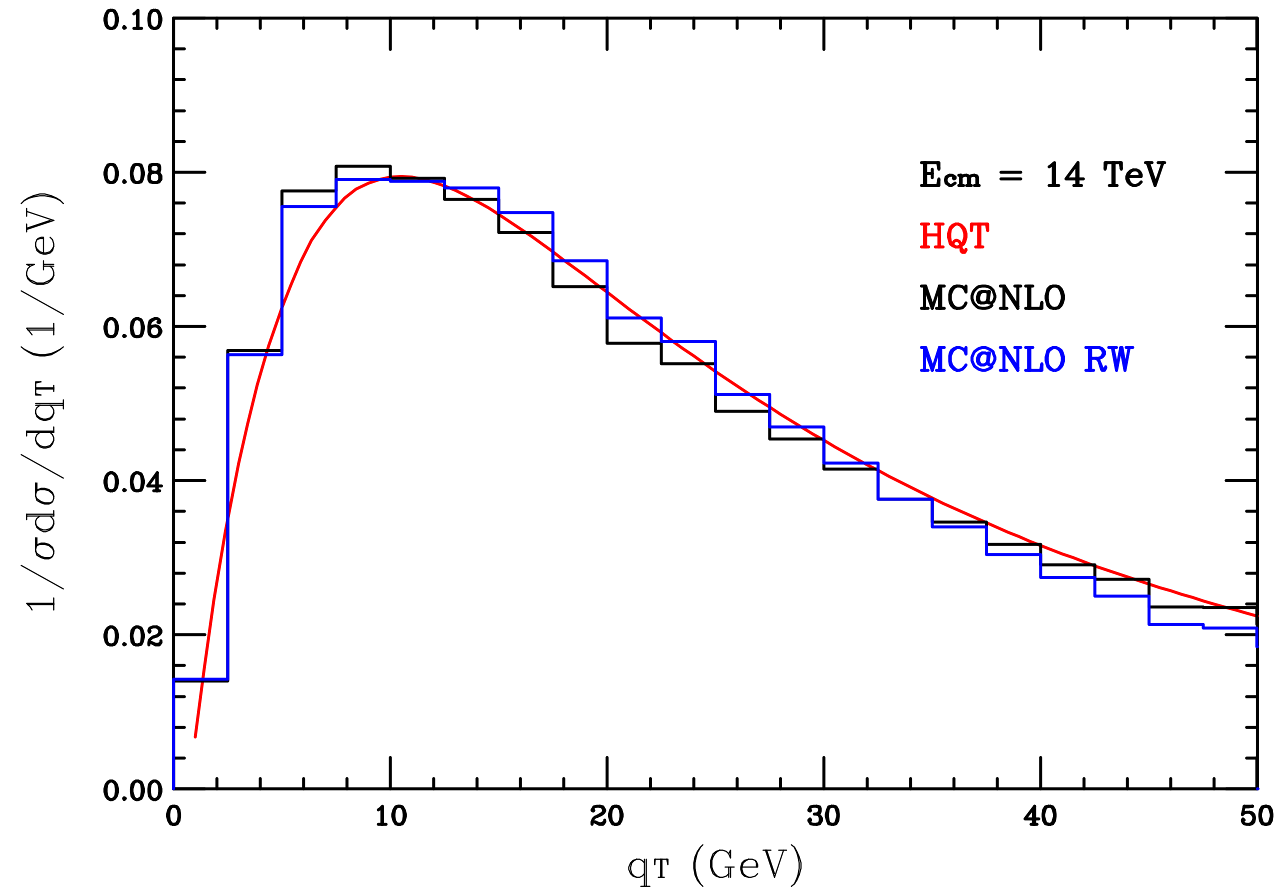


- RW = reweighted to agree with resummed+matched E_T
- Underlying event and hadronization NOT included

Grazzini, Papaefstathiou, Smillie, BW, 1403.3394

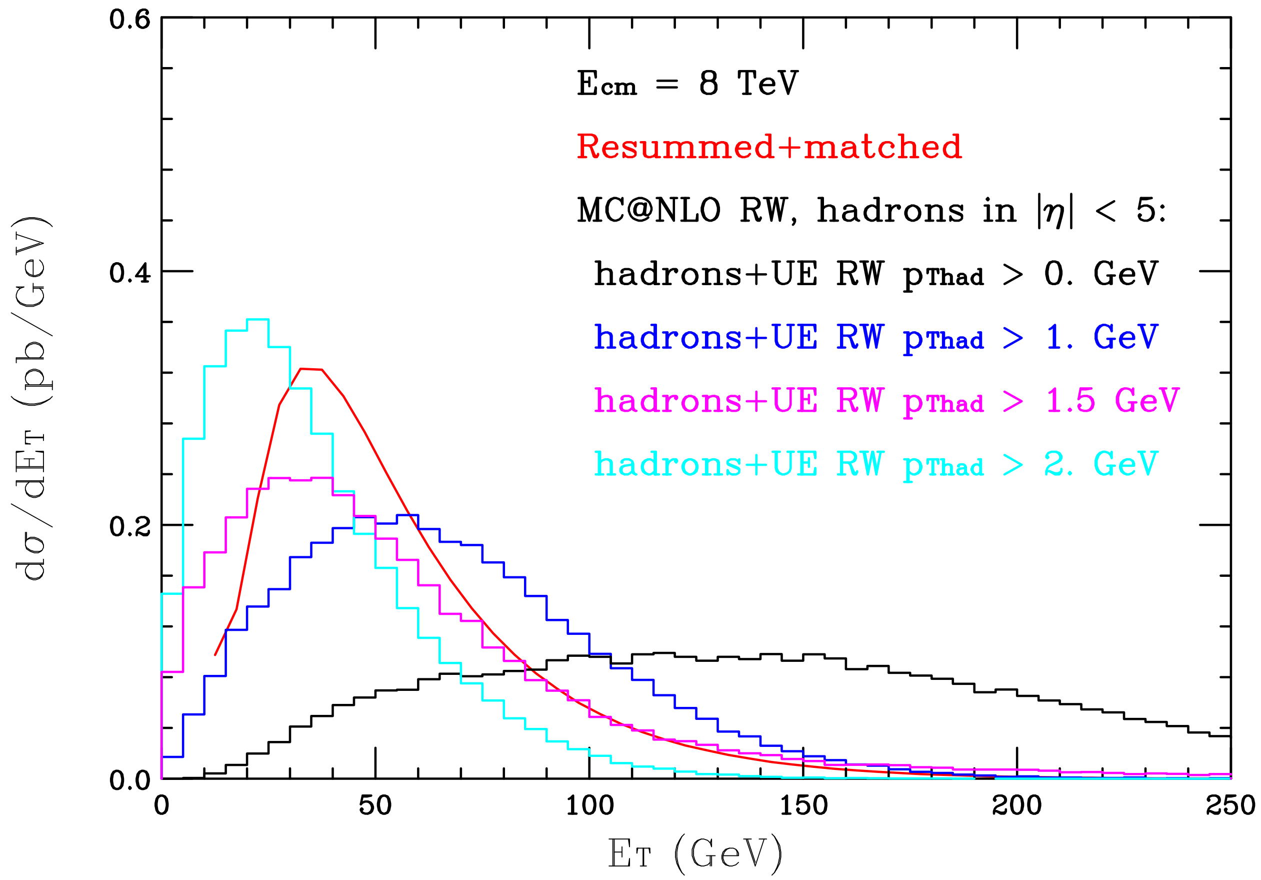
Monte Carlo Higgs q_T

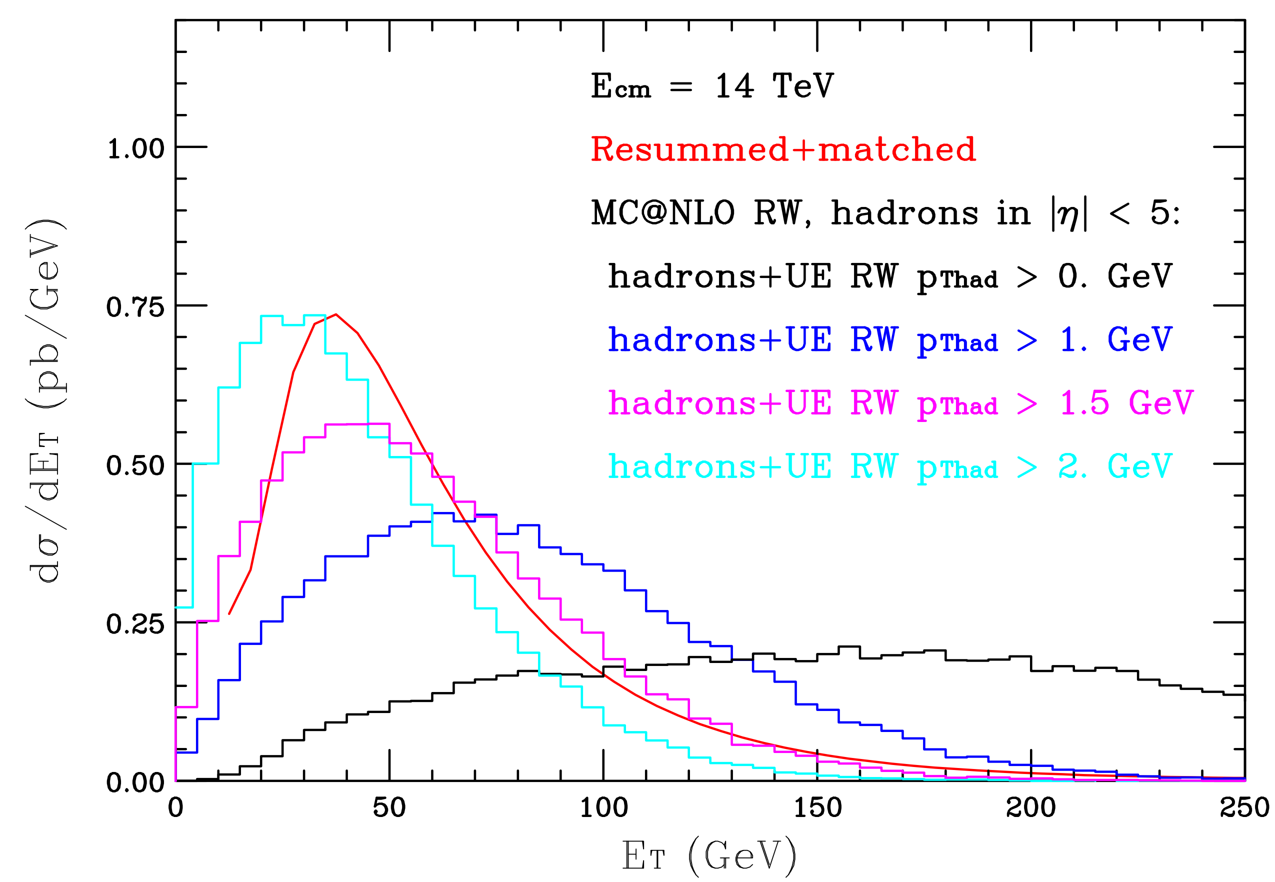




- RW = reweighted to agree with resummed+matched E_T
- Reweighting improves agreement with HQT (= resummed+matched q_T)

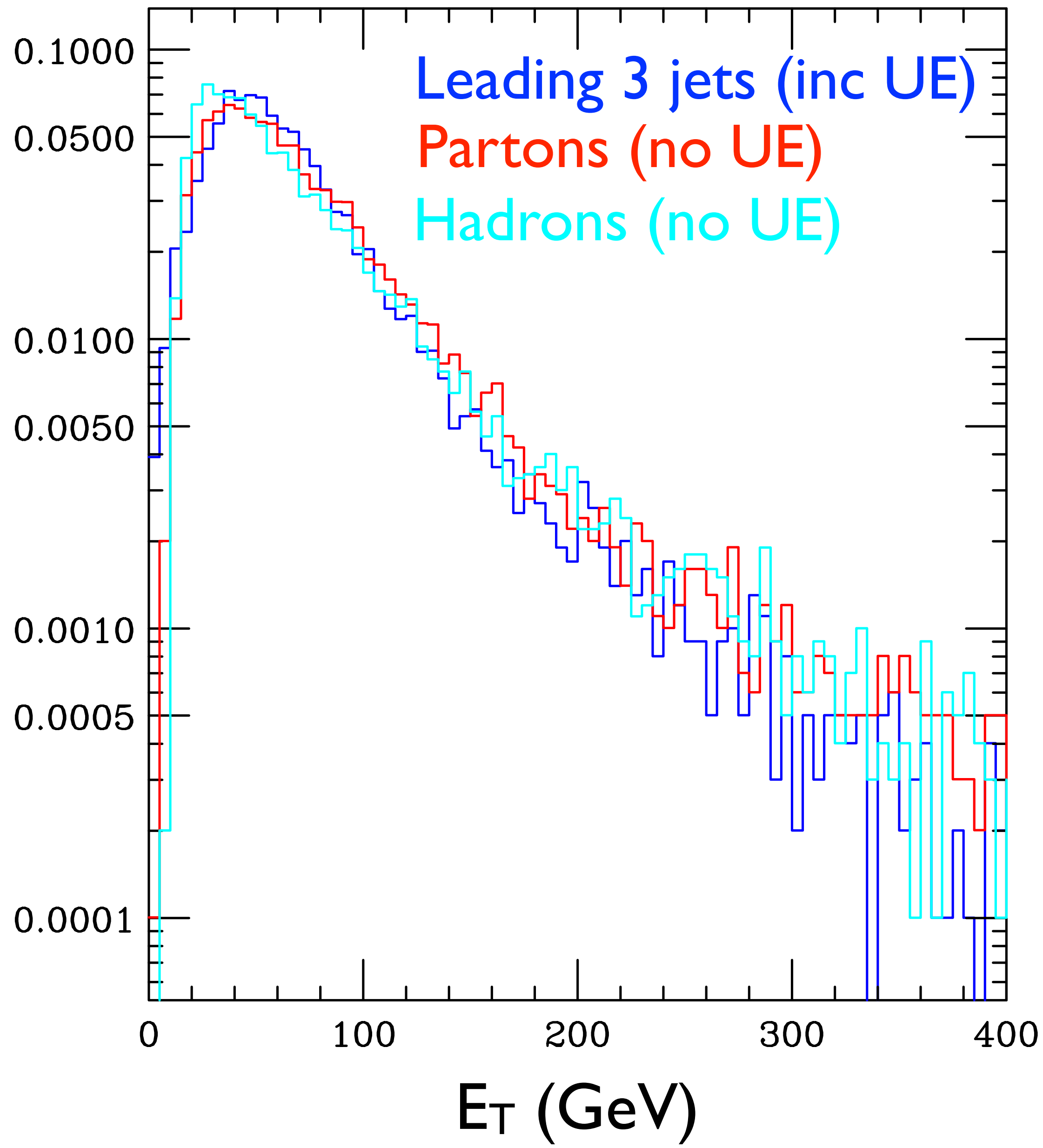
Monte Carlo Higgs E_T





- RW = reweighted to agree with resummed+matched E_T
- Underlying event and hadronization INCLUDED
- Strong dependence on minimum hadron p_T

Higgs E_T from jets?

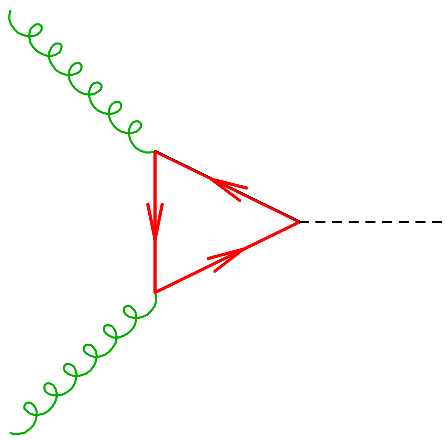


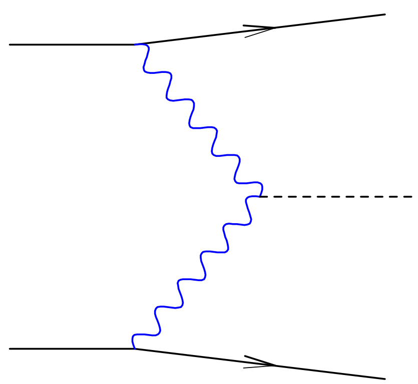
- Suggested by G Salam:
- Parton level ≈ E_T of leading n jets (anti-kt, R=0.7)
- Less sensitive to underlying event and hadronization

Papaefstathiou, BW, prelim.

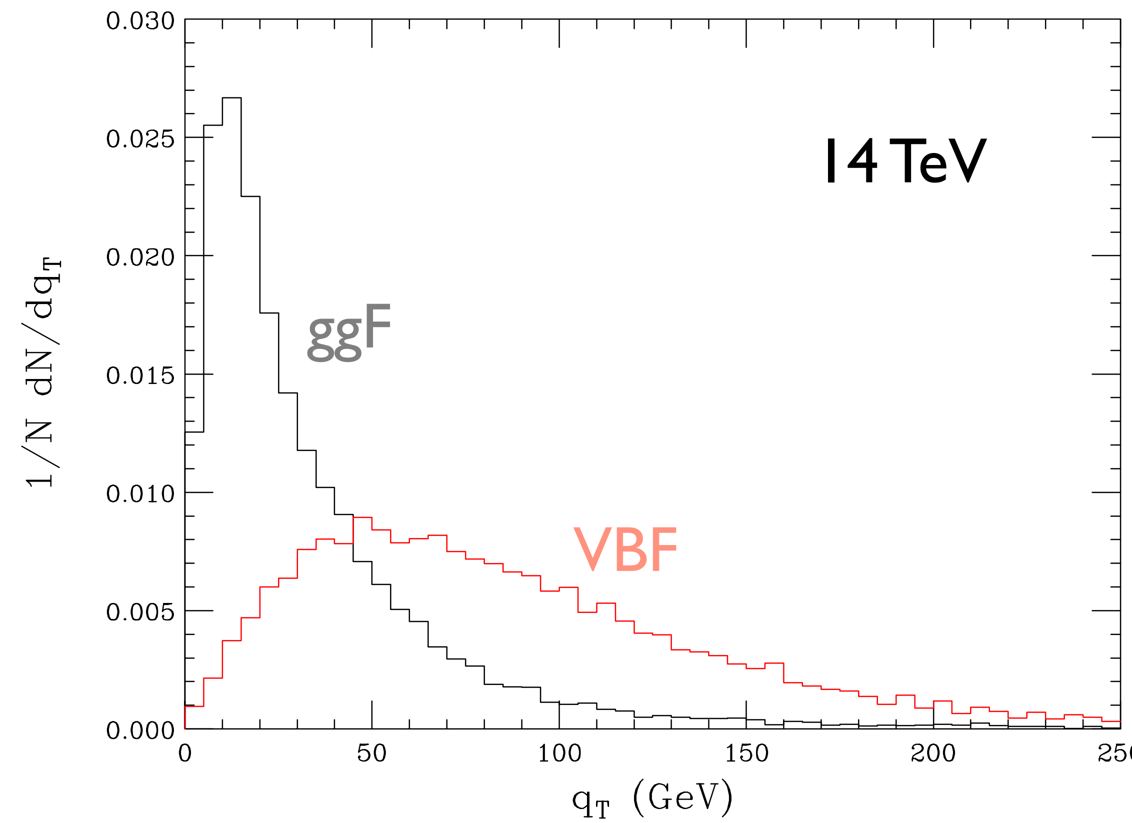
Selecting VBF

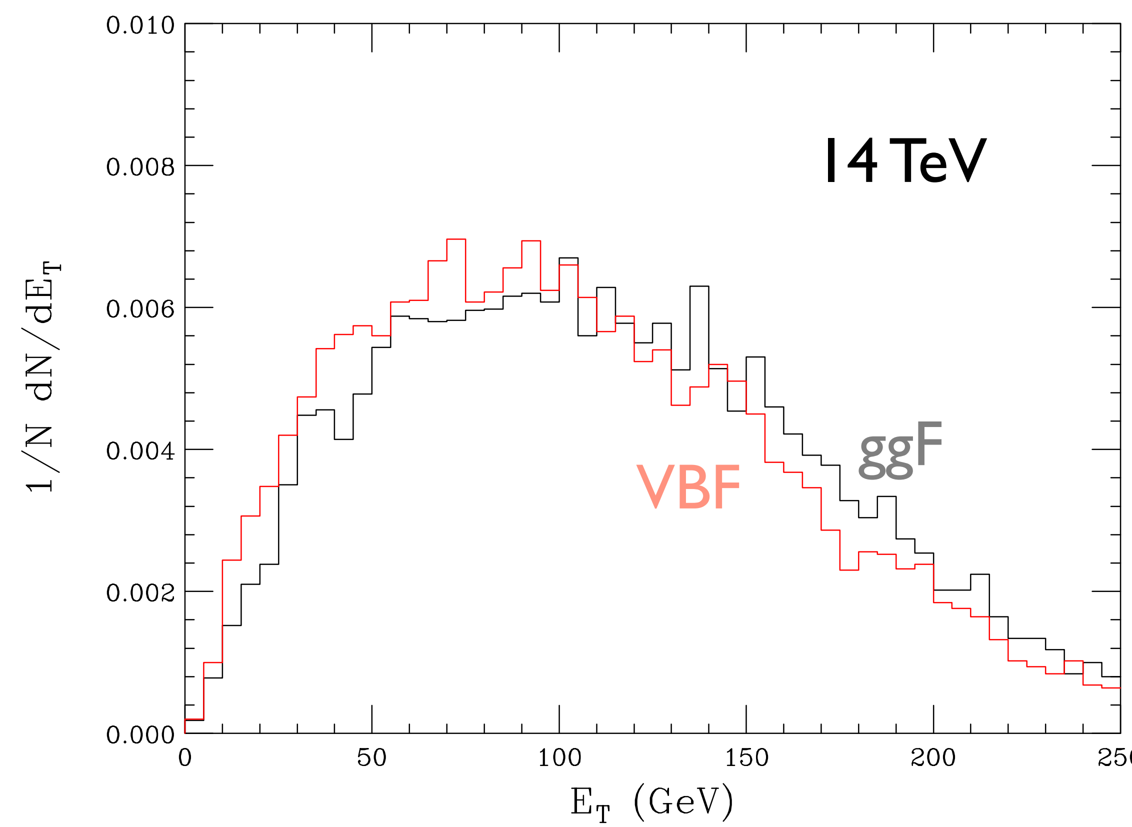
Monte Carlo Higgs q_T & E_T





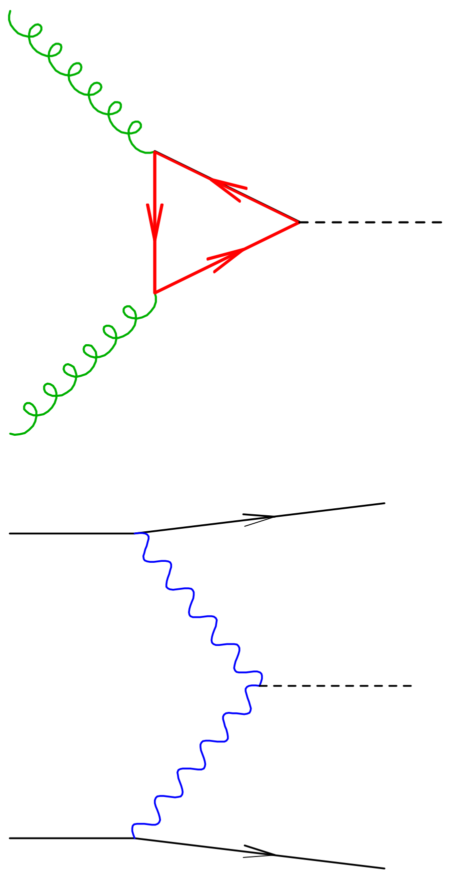
- Massless coloured vs massive colourless exchange
  - Big difference in q_T
  - Small difference in E_T

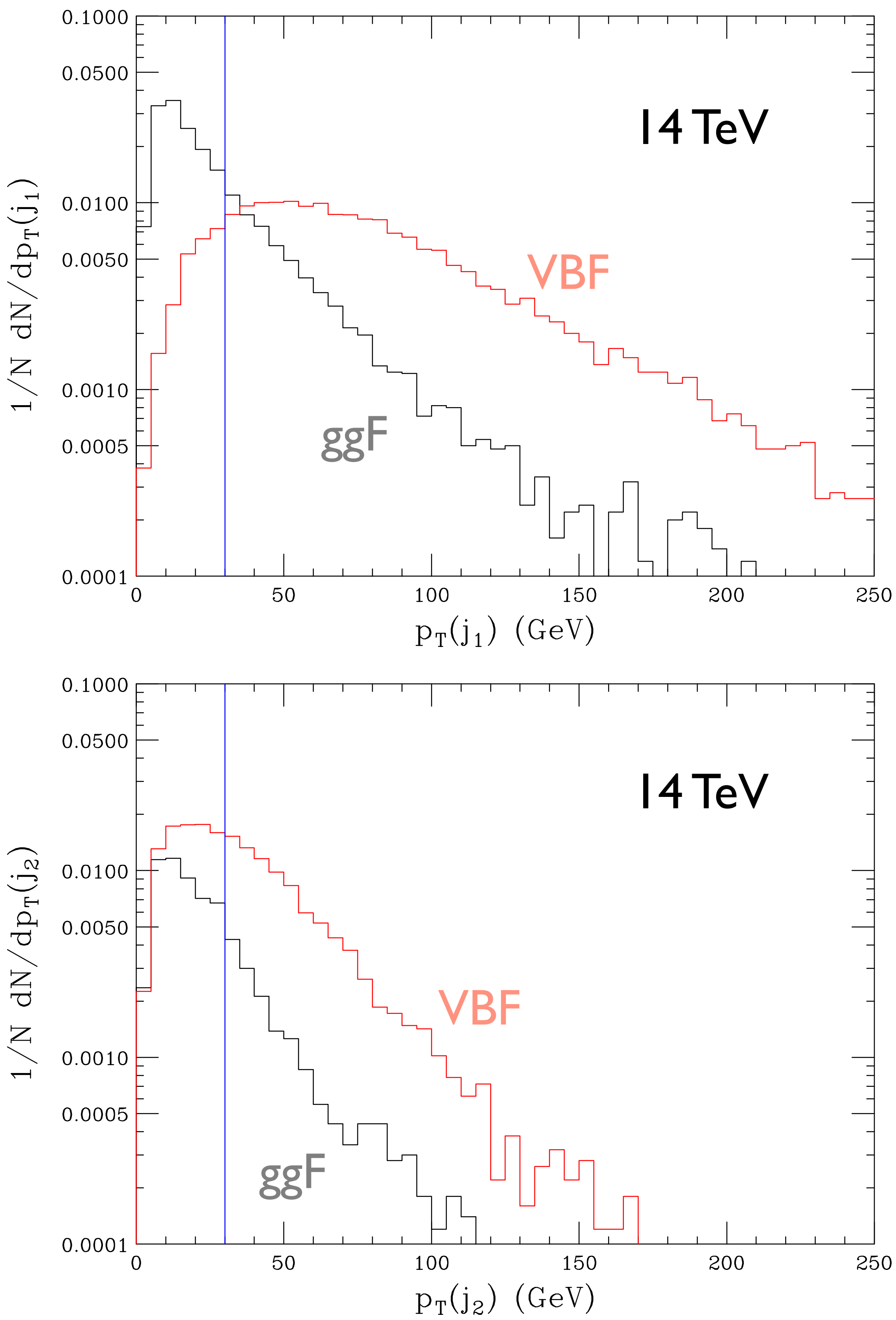




A Papaefstathiou, BW

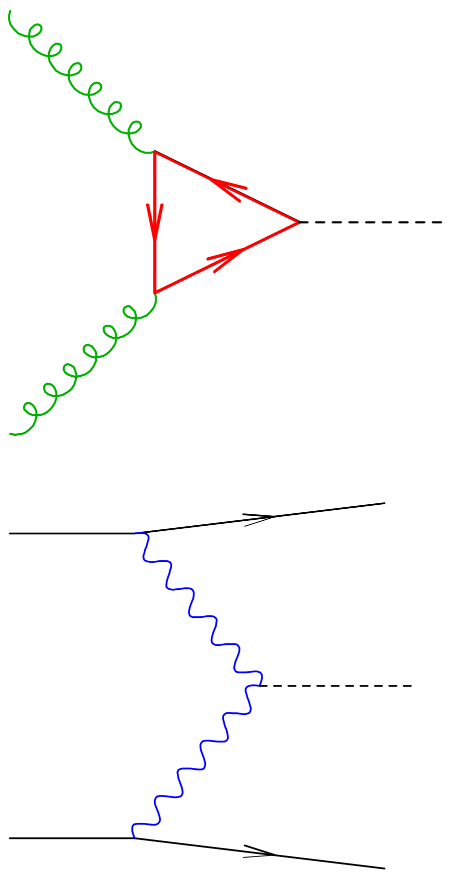
Leading jets p_T

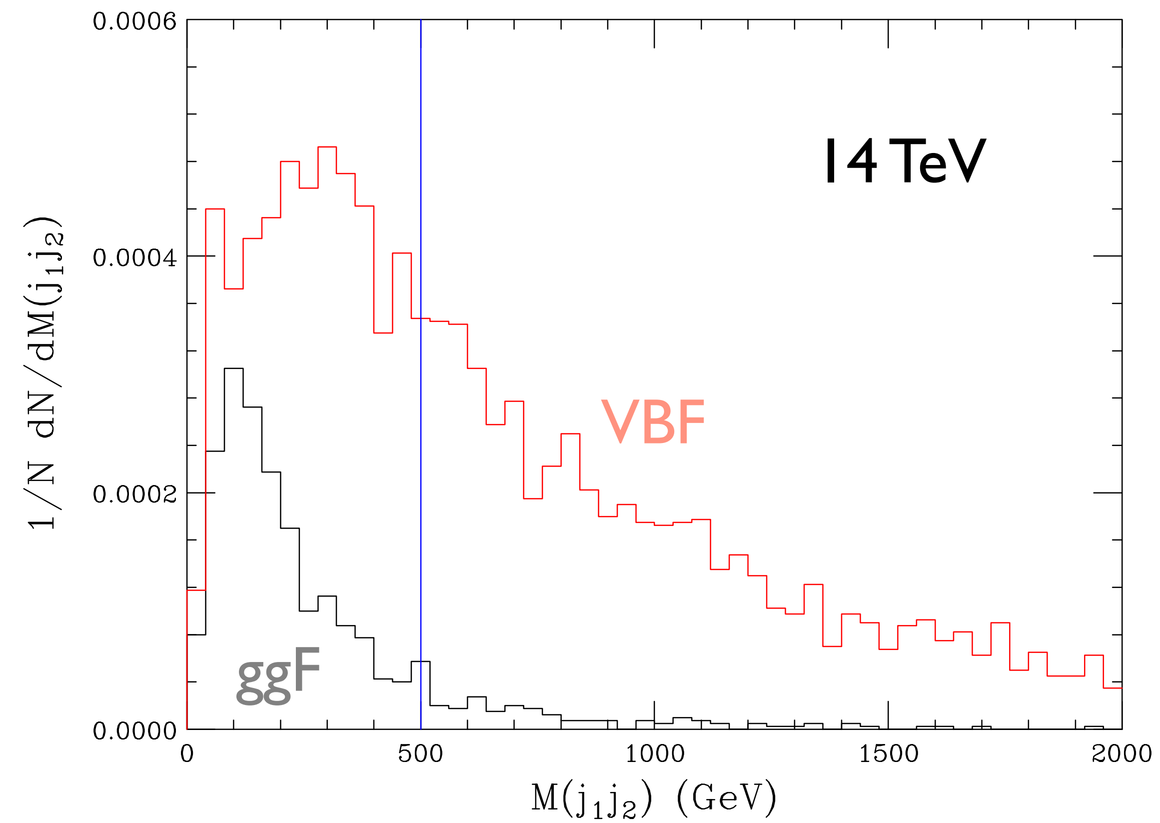


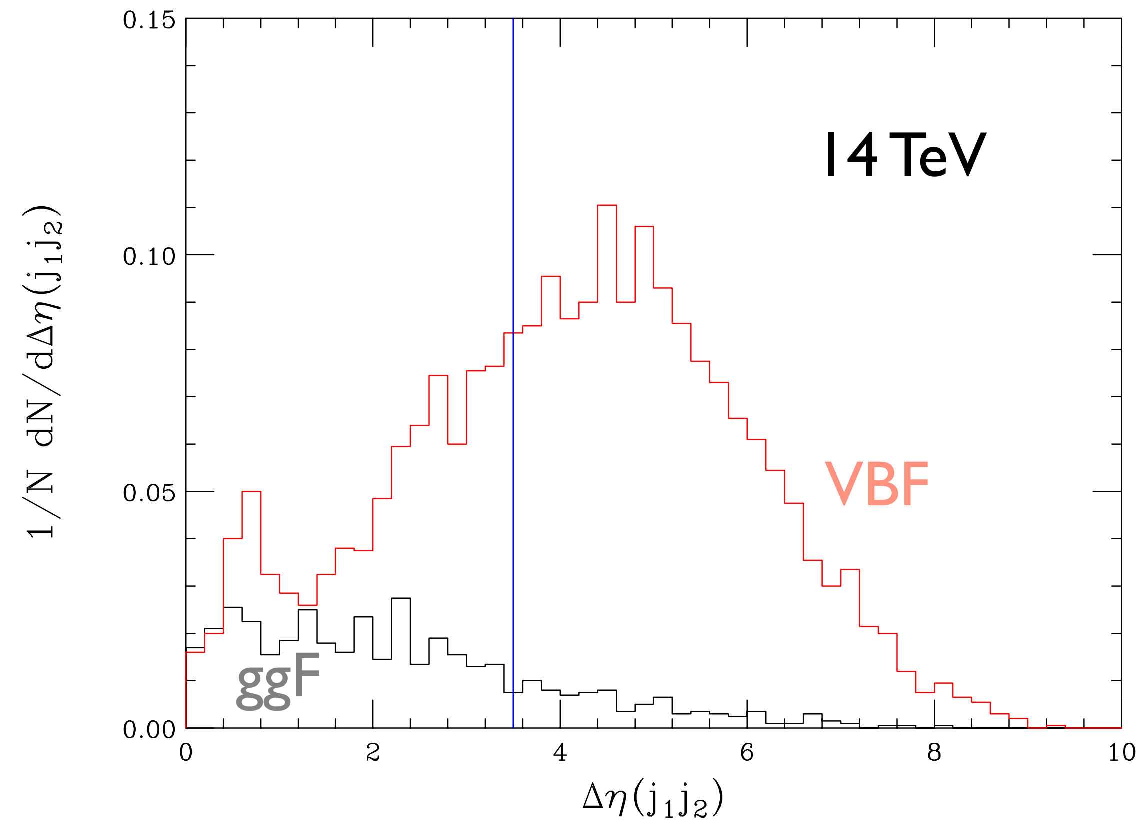


- Two hard leading jets in VBF

Leading jets M_{jj} and $\Delta\eta_{jj}$







- Cuts (~CMS):
  - $p_T(j_1), p_T(j_2) > 30$ GeV
  - $M(j_1 j_2) > 500$ GeV
  - $\Delta\eta(j_1 j_2) > 3.5$

Selecting VBF

- Cuts enhance VBF/ggF by ~25
- For 300 fb^{-1} at 14 TeV:

Mode	BR%	ggF(raw)	VBF(raw)	ggF(cut)	VBF(cut)
bb	56.10	10,000,000	720,000	96,000	170,000
WW	23.13	4,200,000	300,000	40,000	71,000
gg	8.49	1,500,000	110,000	15,000	26,000
tt	6.16	1,100,000	79,000	11,000	19,000
ZZ	2.90	520,000	37,000	5,000	8,900
cc	2.83	510,000	37,000	4,800	8,700
$\gamma\gamma$	0.23	41,000	2,900	390	710
Zγ	0.16	29,000	2,100	270	490

Beyond Standard Model Simulation

BSM Simulation

- Main generators have some BSM models built in
  - Pythia 6 has the most models
  - Herwig++ has careful treatment of SUSY spin correlations and off-shell effects
- Trend is now towards external matrix element generators: FeynRules + MadGraph, ...
- QCD corrections and matching/merging still needed

Searching for new signals

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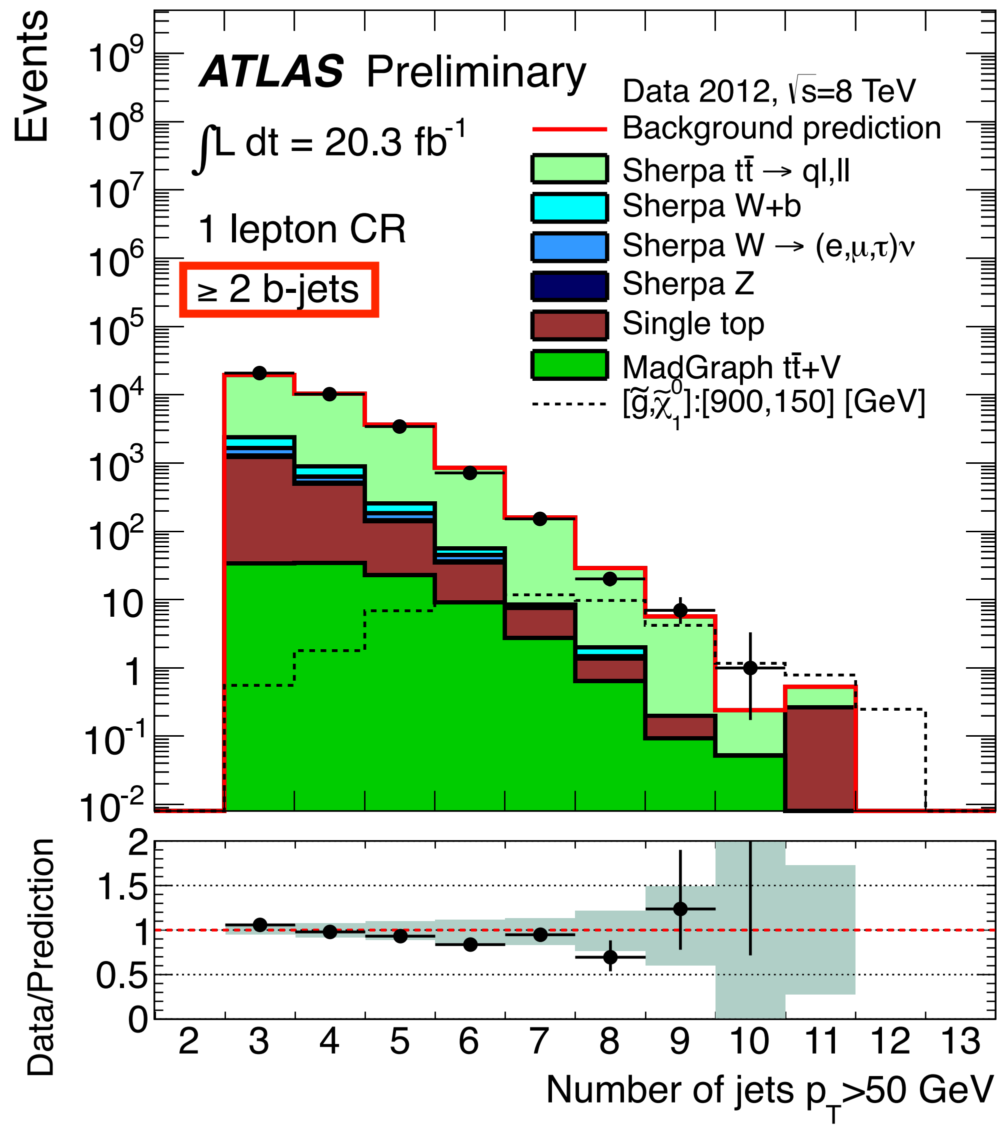
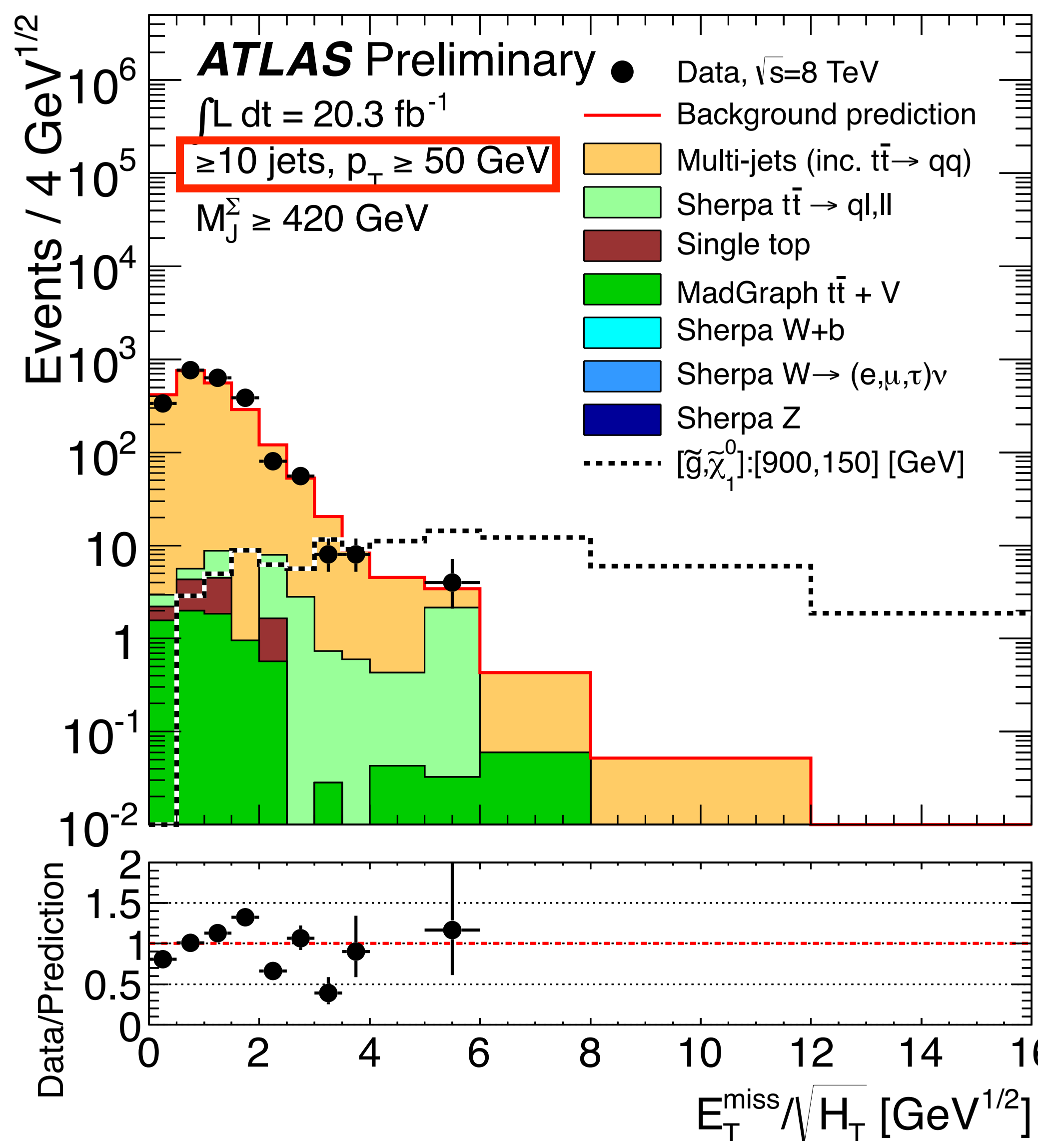
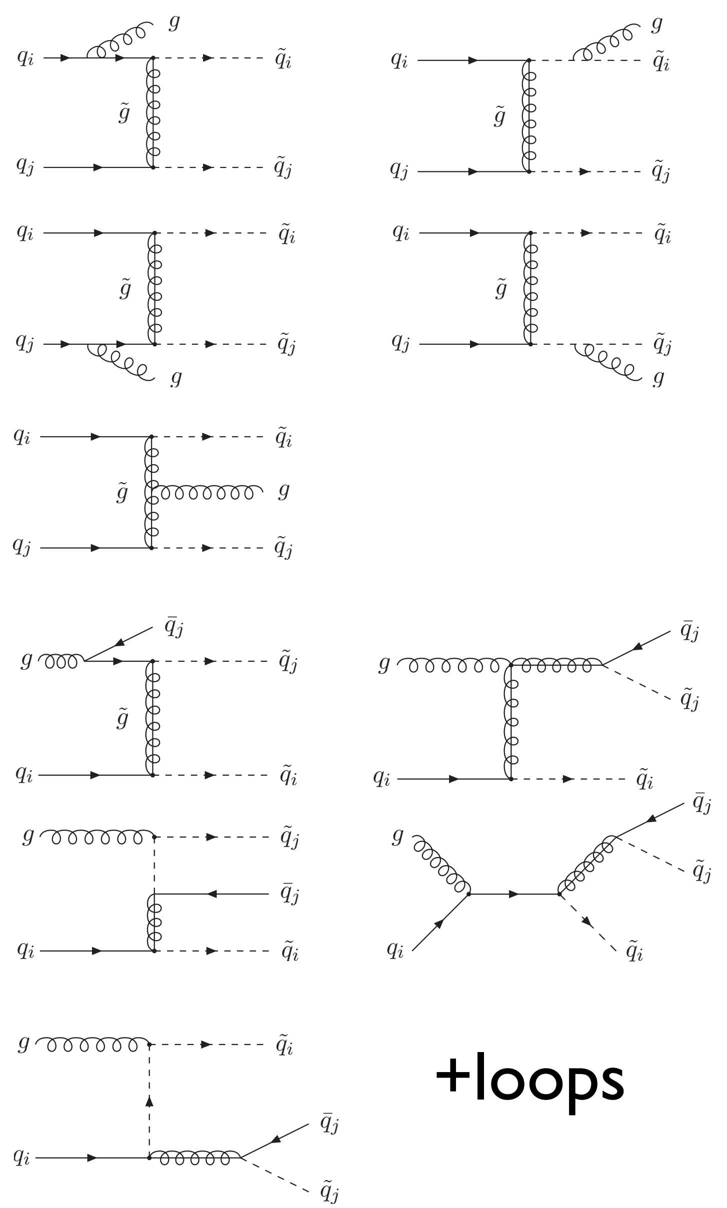


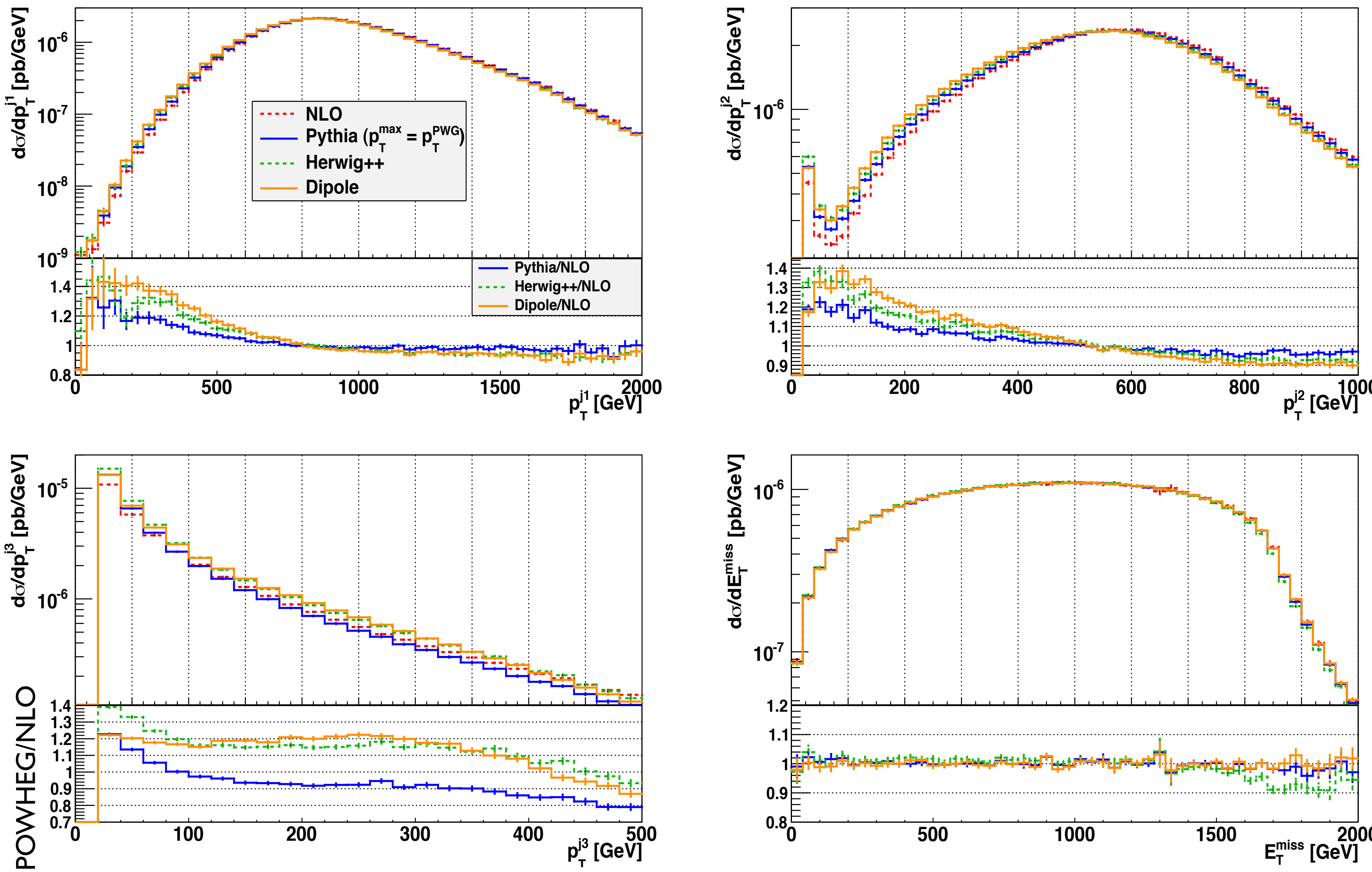


$$\tilde{g}\tilde{g},\ \tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0$$

NLO Squark Production



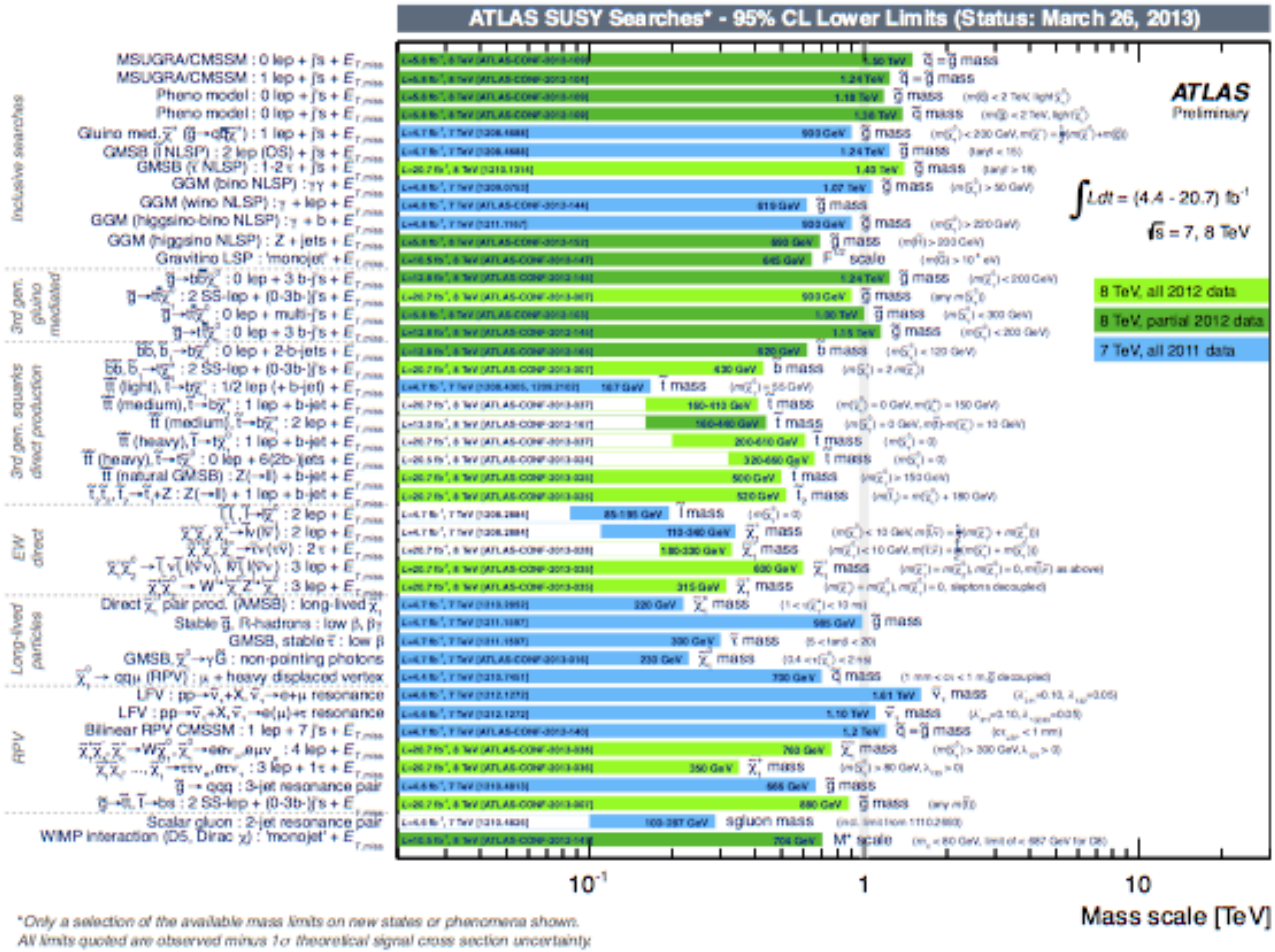
+loops



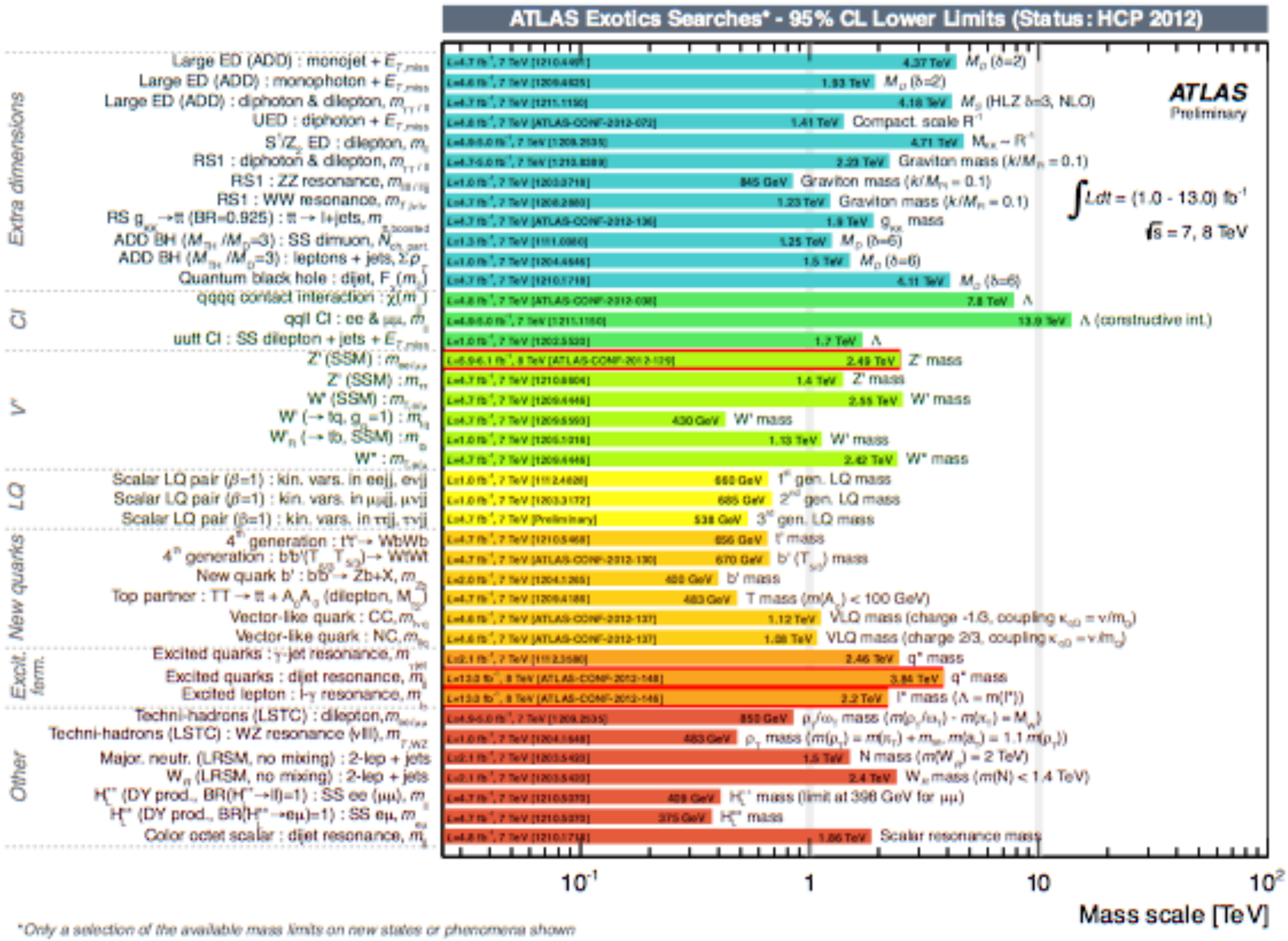
- NLO with POWHEG matching to different generators

Gavin et al., arXiv:1305.4061

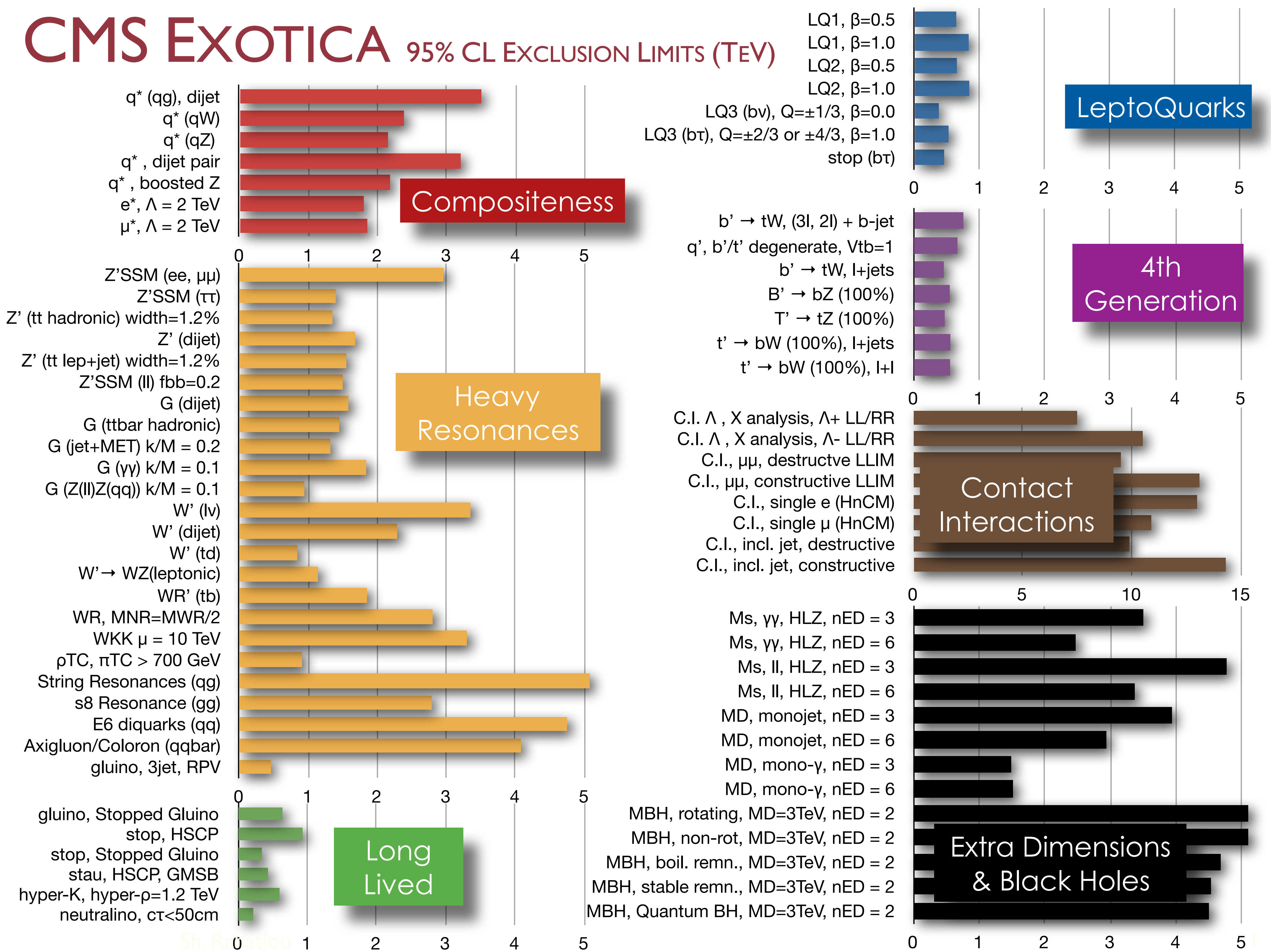
ATLAS SUSY Search



ATLAS Exotica Search



CMS Exotica Search



Conclusions and Prospects

- Standard Model has (so far) been spectacularly confirmed at the LHC
- Monte Carlo event generation of (SM and BSM) signals and backgrounds plays a big part
- Matched NLO and merged multi-jet generators have proved essential
  - Automation and NLO merging in progress
  - NNLO much more challenging
- Still plenty of scope for new discoveries!

Thanks for listening!