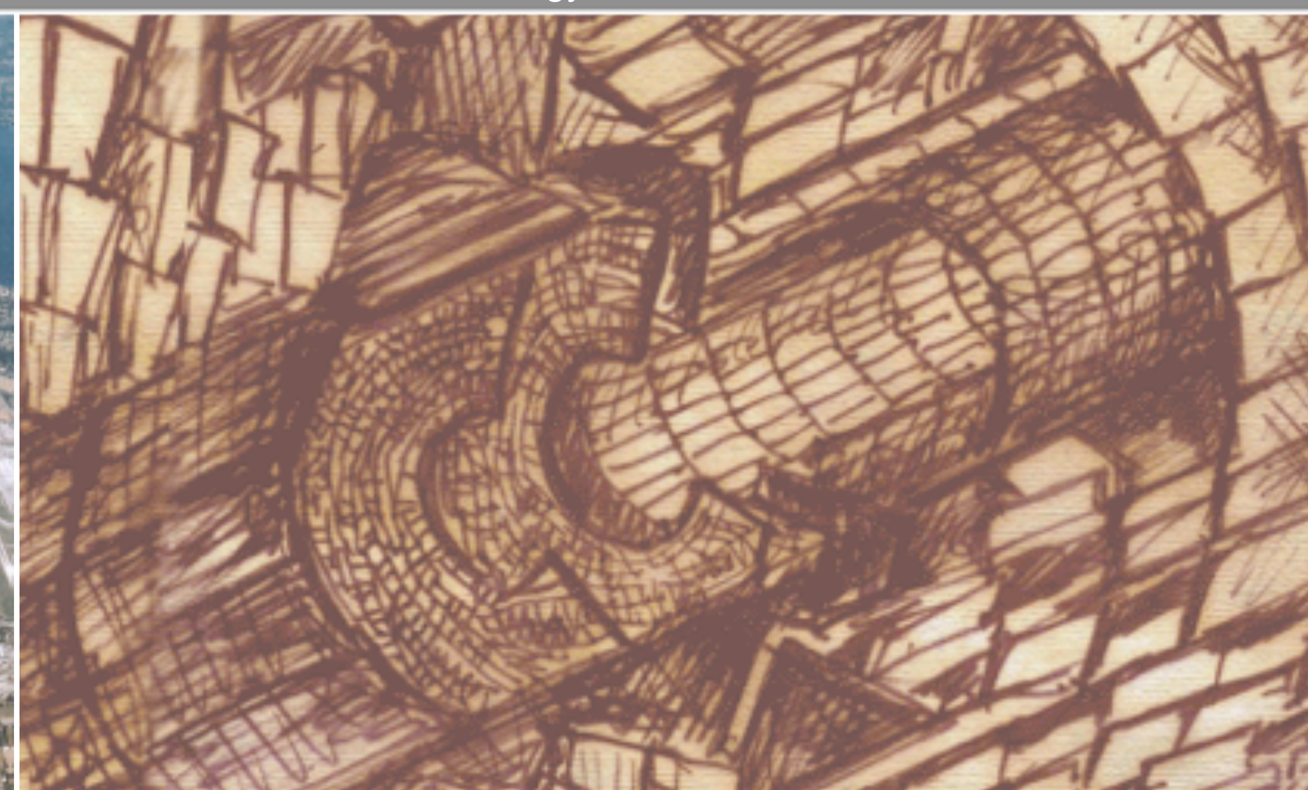
# Top Quark Physics and Silicon Detectors: Key Ingredients for the LHC Menu

**Annual Workshop of the DFG Research Training Group 1694**
**“Elementary Particle Physics at Highest Energy and Precision”**

**Bad Liebenzell, October 5–7, 2011**

Ulrich Husemann
Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology

# Your Server's Scientific Life on One Slide

- PhD thesis: HERA–B (Universität Siegen)
  - Fixed-target spectrometer using the HERA proton beam
  - Muon pretrigger, nuclear effects in J/ψ production
- Postdoc: CDF (University of Rochester, Yale University)
  - Properties of the top quark, especially
    search for flavor changing neutral currents in top decays
  - Co-leader of the CDF silicon group
  - Co-convener of the CDF tracking group
- Young Investigator Group leader: ATLAS (DESY)
  - Preparation for the upgrade of the ATLAS silicon detectors
  - Precision measurements of the top production cross section
  - Co-convener of the ATLAS top reconstruction group
- Professor at KIT since July 2011: CMS

# Your LHC Menu for Today

Karlsruhe Institute of Technology

**Appetizers: Little Bites of Top and Silicon**

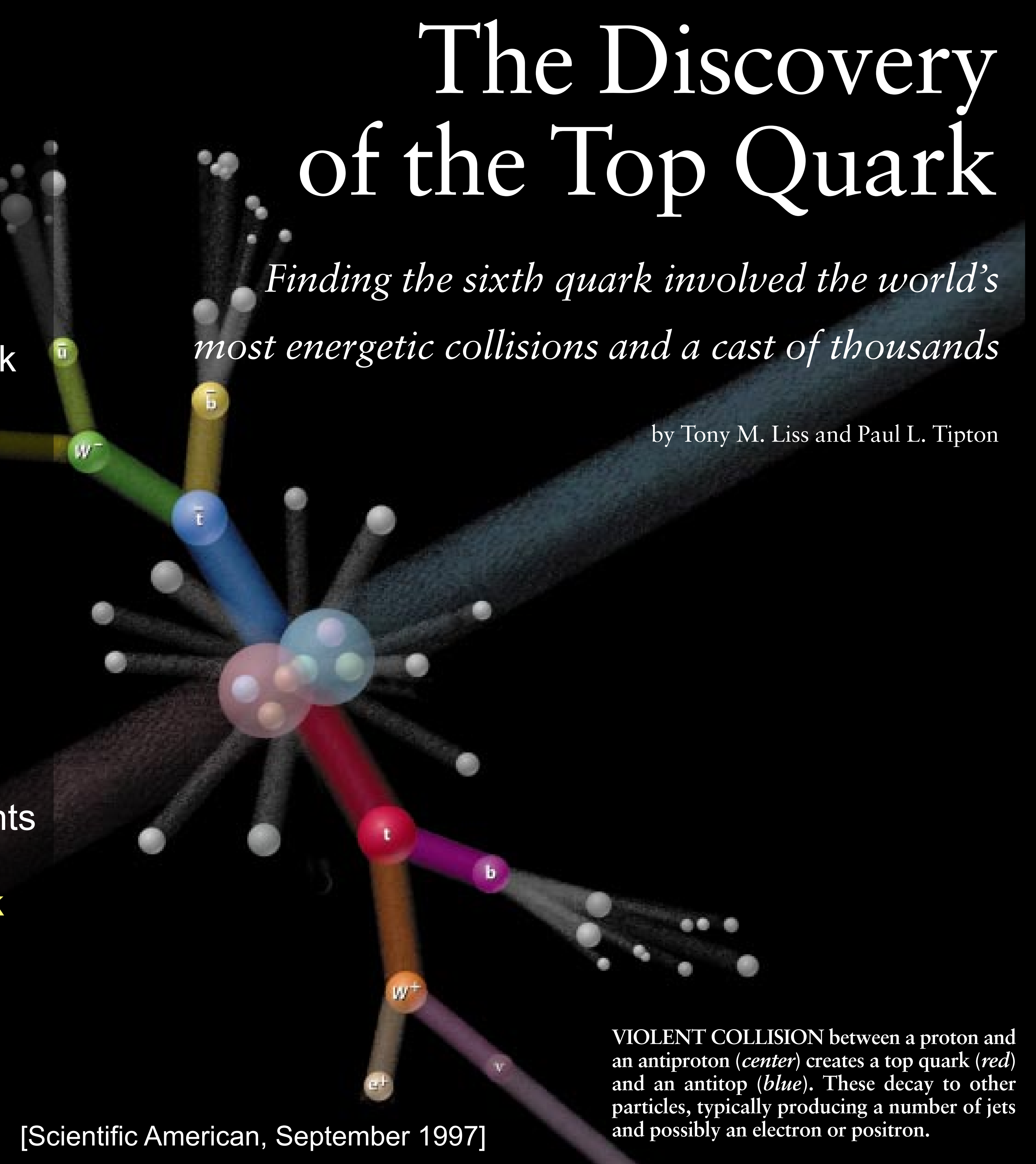
**Main Course: Top Physics**

**Dessert: What's Next at the LHC?**

# Appetizers

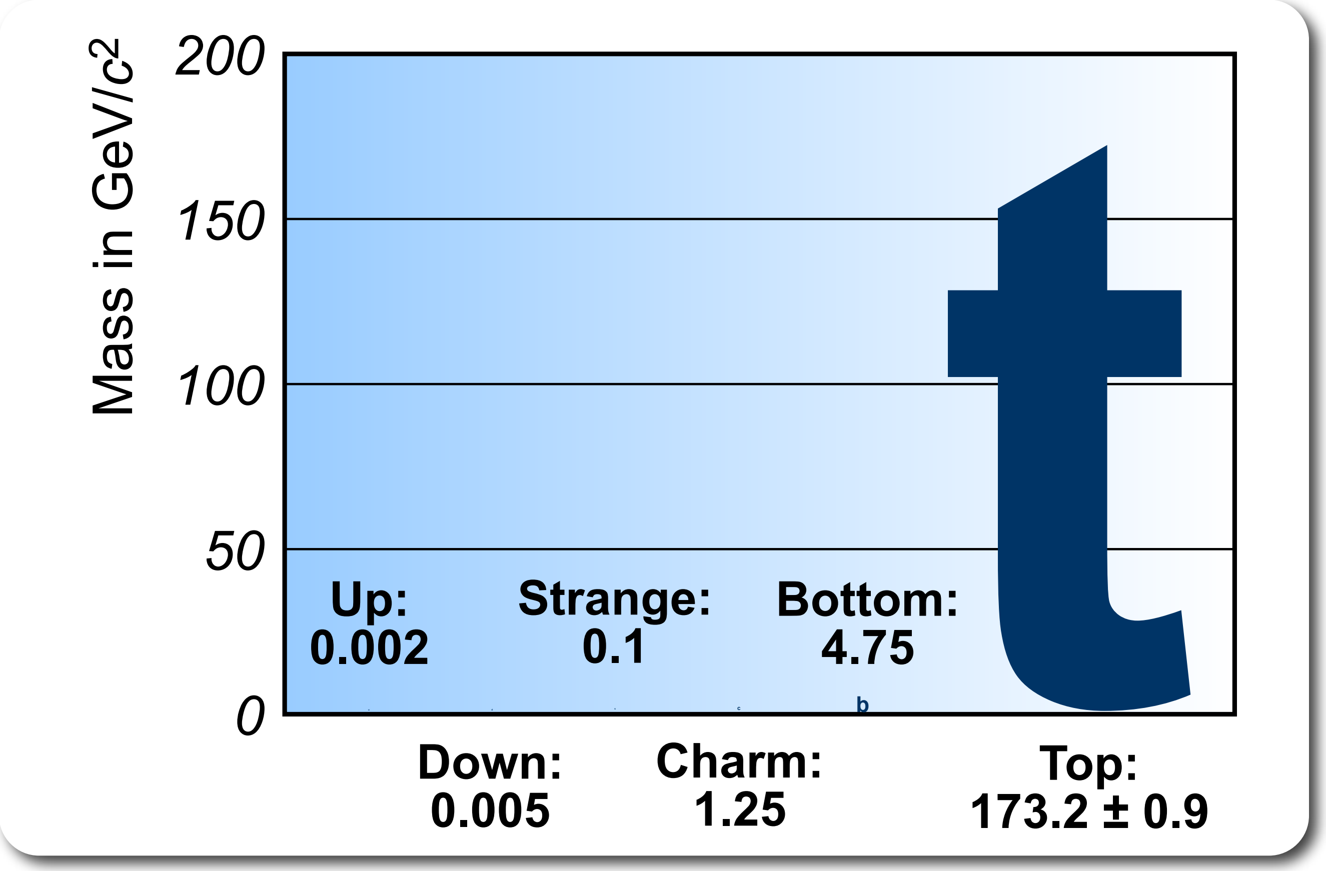
## A Brief History of the Top Quark

- 1977: discovery of the bottom quark → first quark of the 3rd generation
- 1980ies: search for “light” top quarks in the decay $W^+ \rightarrow t\bar{b}$
- 1992: first indication for “heavy” top quarks at the Tevatron (Fermilab, near Chicago)
- 1995: Tevatron experiments CDF and DØ publish discovery of the top quark with a mass of about 175 GeV




[Scientific American, September 1997]

# Top – The Special One





- Large mass: $m_t \approx 173$ GeV (40×$m_b$, approx. mass of a gold atom)
- Mass close to scale of electroweak symmetry breaking (EWSB)
  → Yukawa coupling f ≈1:

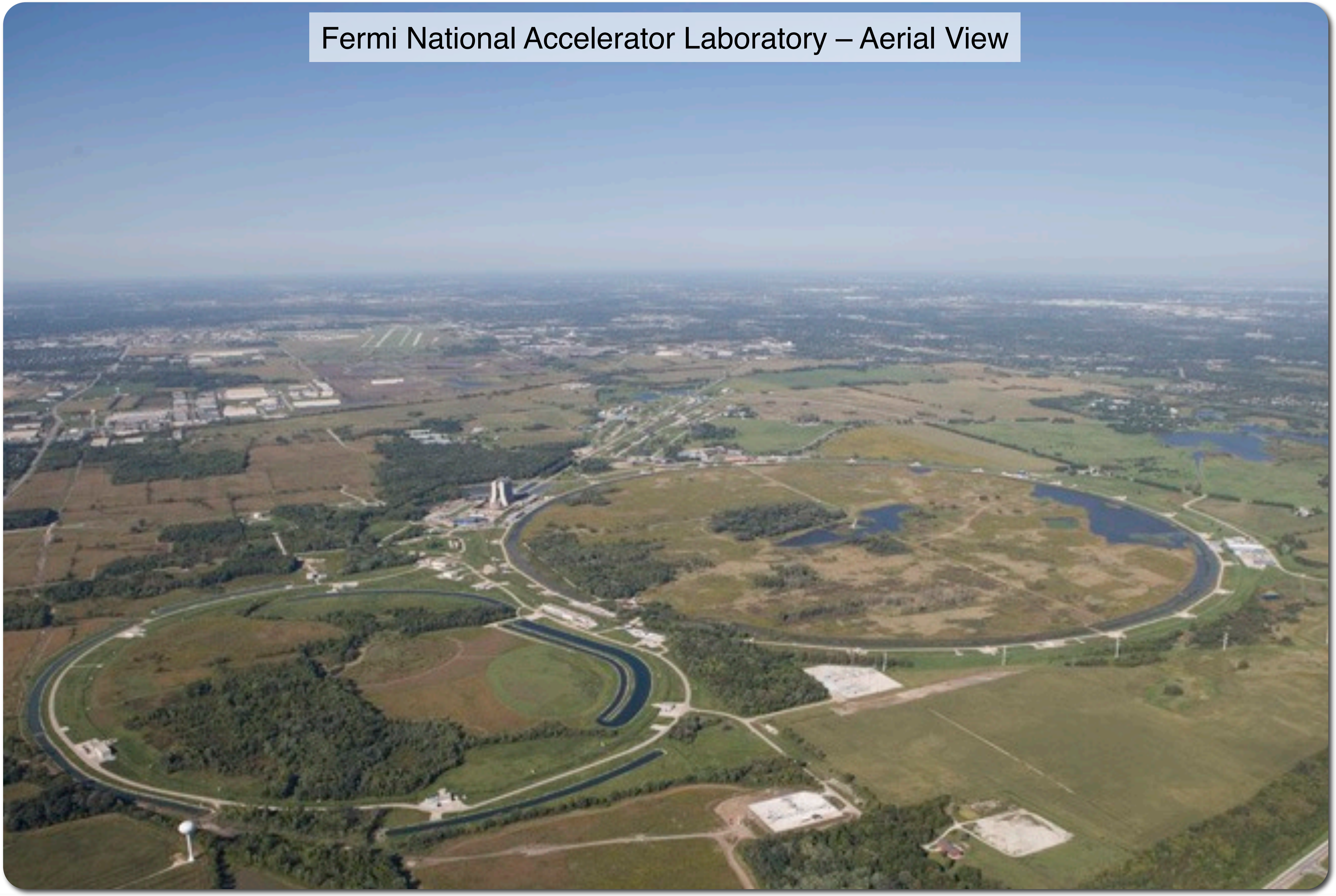
$$\mathcal{L}_{Y,t} = f \frac{v}{\sqrt{2}} \bar{t}_L t_R \equiv m_t \bar{t}_L t_R$$

  → important role in models that explain EWSB
- Top is the only „free" quark: life time much smaller than hadronization time

$$\tau = \frac{1}{\Gamma} \approx (1.5\,\mathrm{GeV})^{-1} < \frac{1}{\Lambda_{\mathrm{QCD}}} \approx (0.2\,\mathrm{GeV})^{-1}$$

  → No bound states
  → Spin transfered to decay products

# Tevatron Run II: 2001–2011



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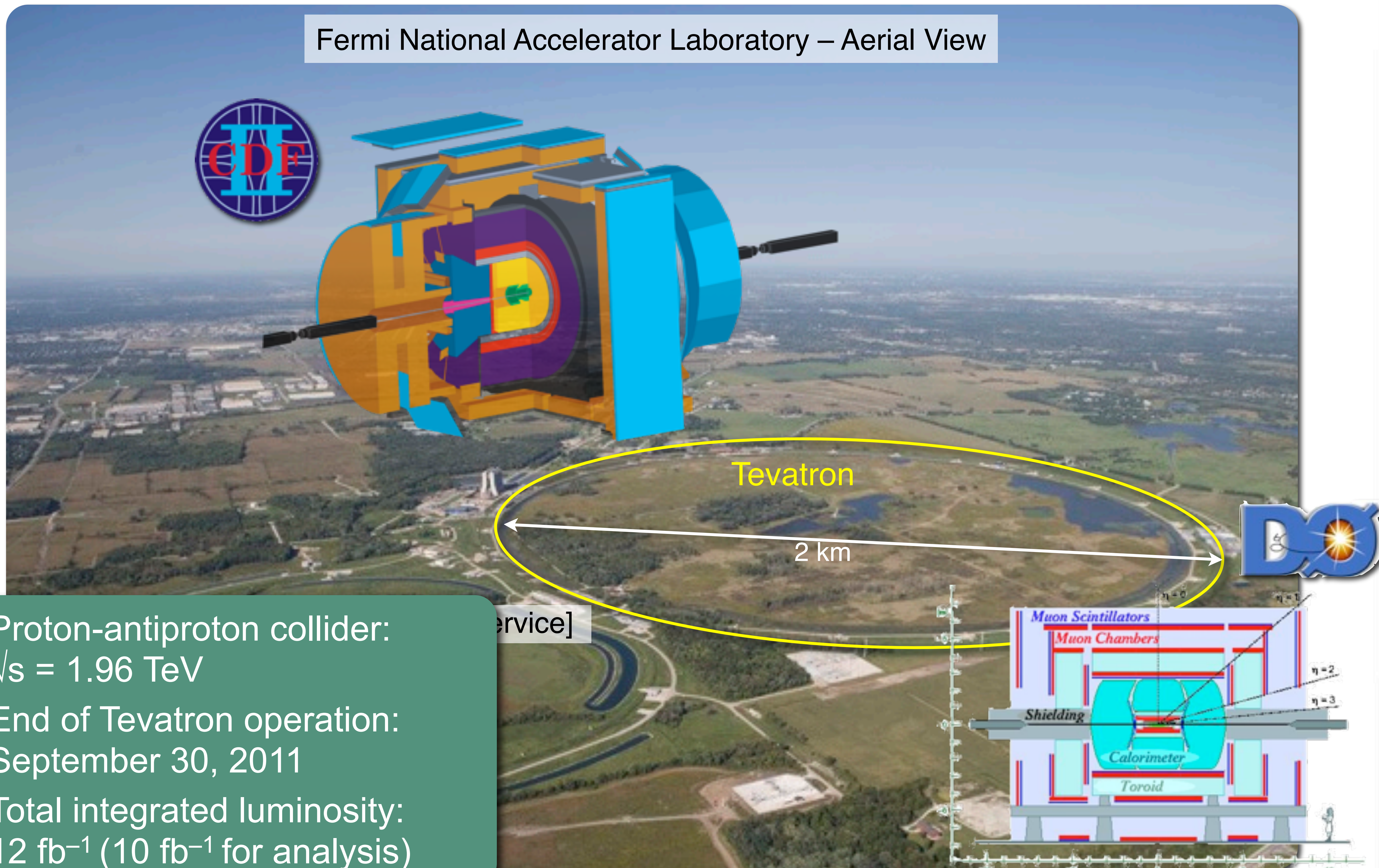
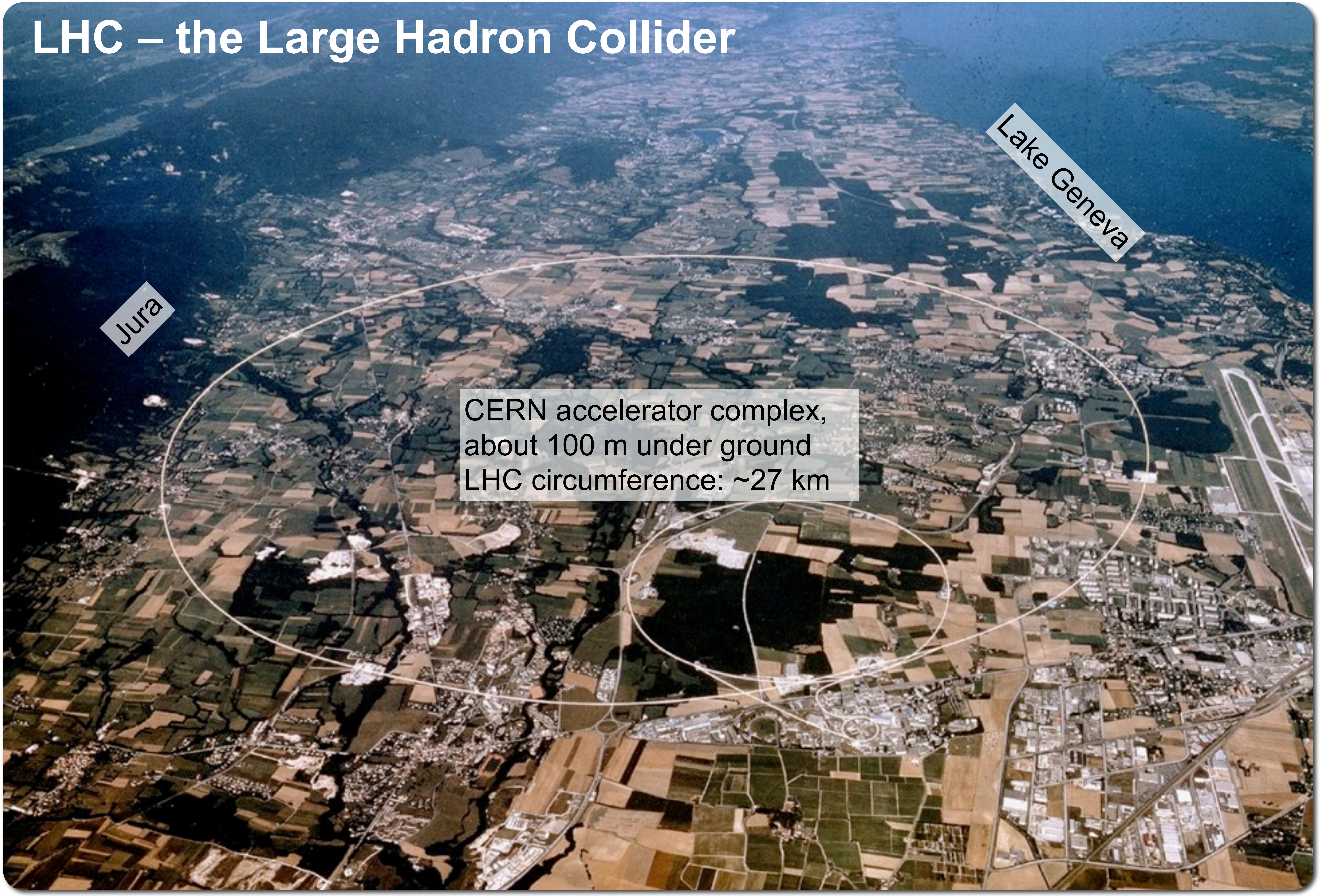



- Proton-antiproton collider: $\sqrt{s}$ = 1.96 TeV
- End of Tevatron operation: September 30, 2011
- Total integrated luminosity: 12 $fb^{-1}$ (10 $fb^{-1}$ for analysis)

# LHC – the Large Hadron Collider



# LHC – the Large Hadron Collider

**LHC Accelerator:**
proton-proton and
lead-lead collisions

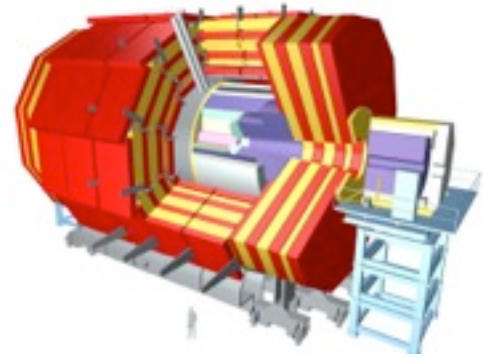

CERN accelerator complex,
about 100 m under ground
LHC circumference: ~27 km

# LHC – the Large Hadron Collider

Lake Geneva

**LHC Accelerator:**
proton-proton and
lead-lead collisions

**CMS Experiment:**
multi-purpose experiment



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LHC circumference: ~27 km

**ATLAS Experiment:**
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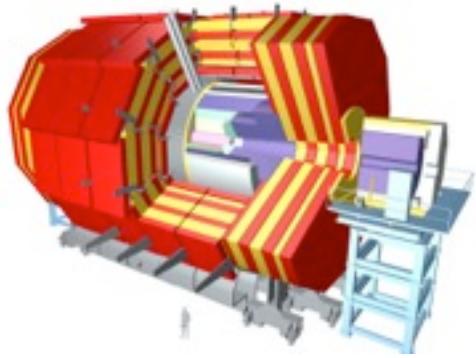

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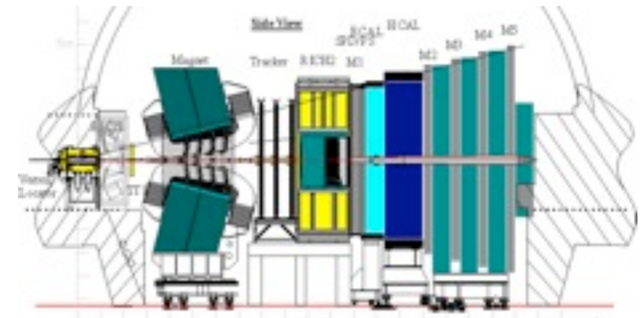
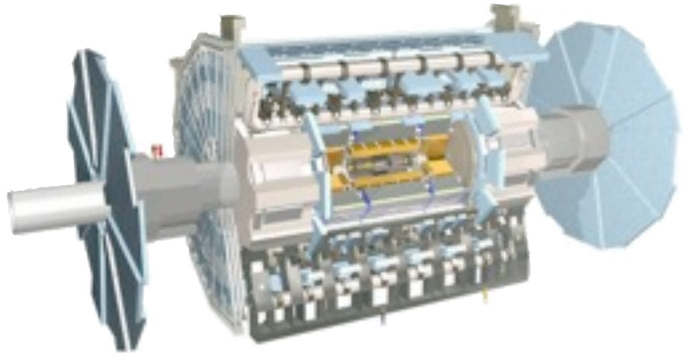
**LHCb Experiment:**
matter/antimatter symmetry

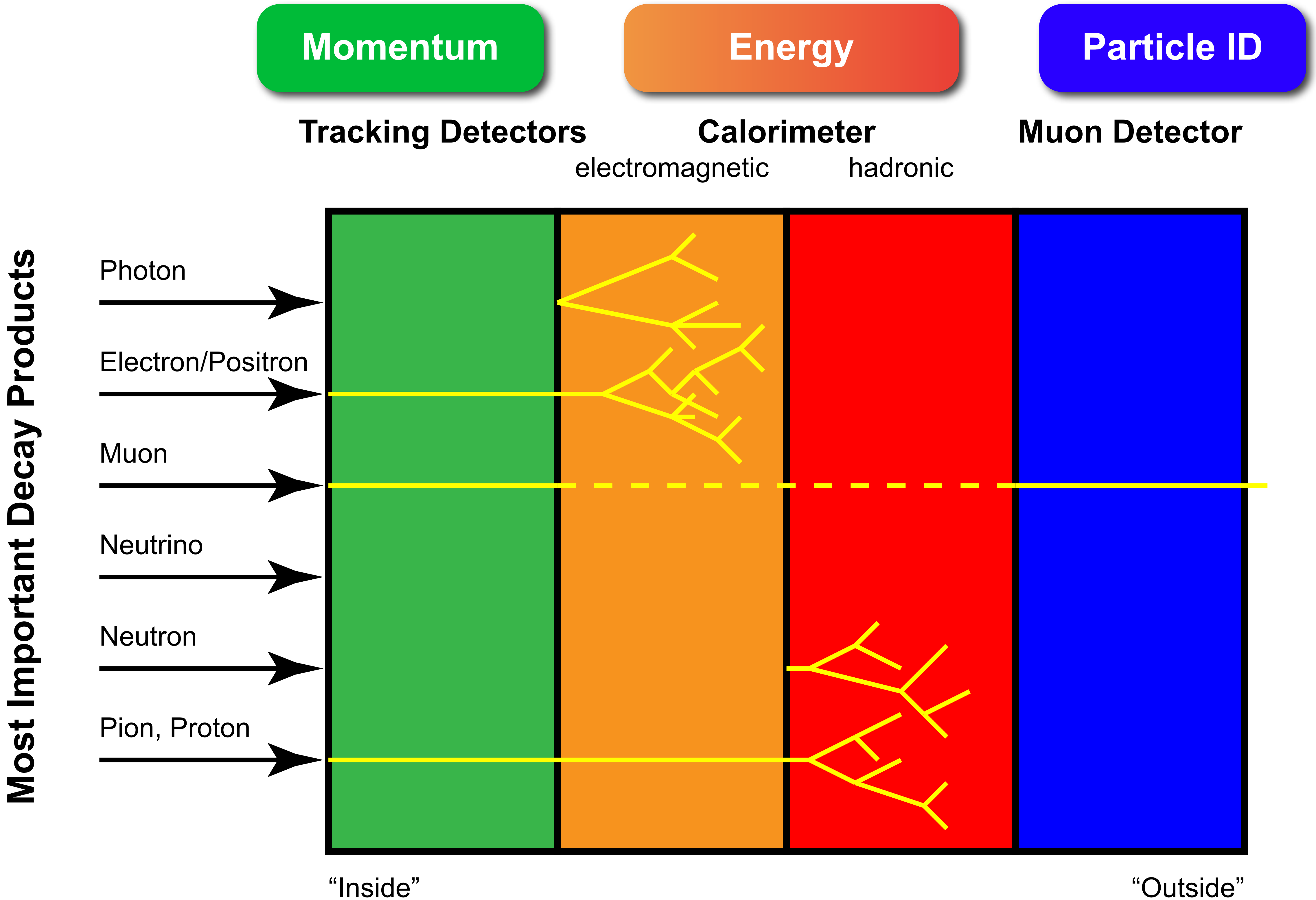


**ALICE Experiment:**
heavy ion physics

**ATLAS Experiment:**
multi-purpose experiment

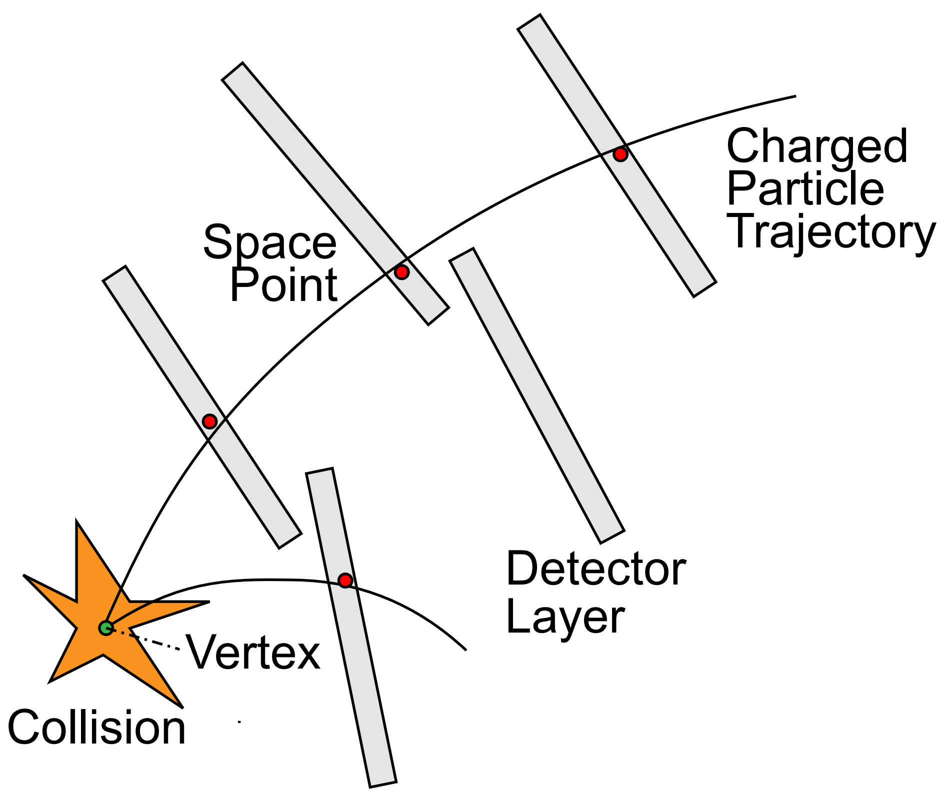


# Basic Ingredients of a Collider Detector



# Tracking, Vertexing, B-Tagging

- Tracking & vertexing
  - Charged particle tracking at small distances (~5 cm) from collision point: precise reconstruction of vertices
  - Charged particle tracking at large distances (~1 m): precise momentum measurement



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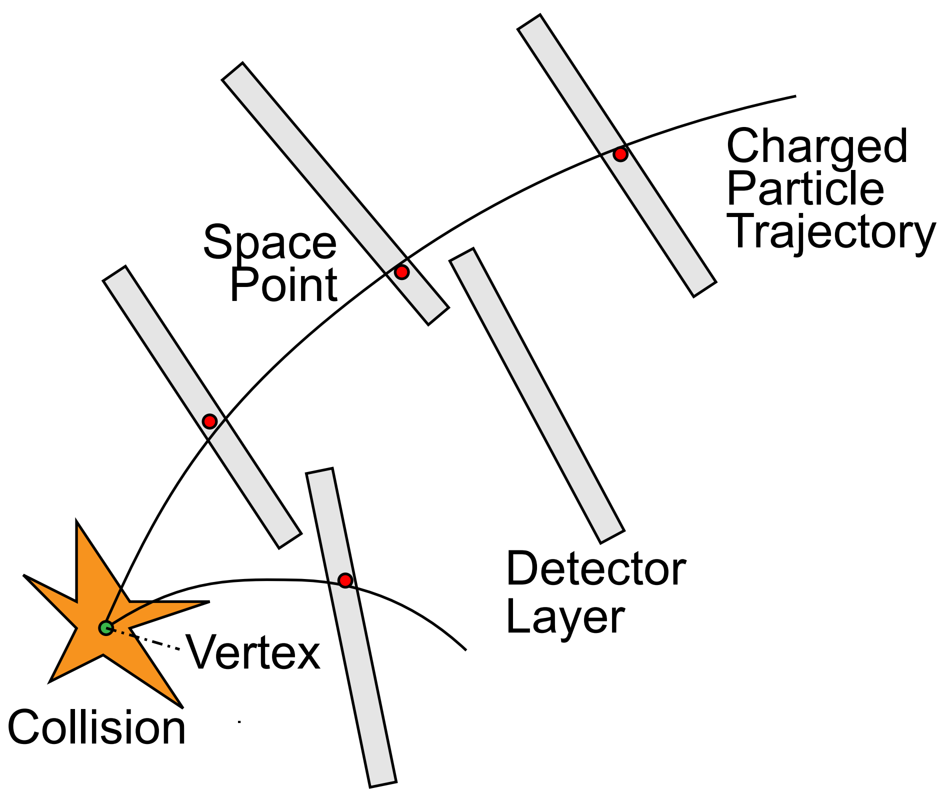


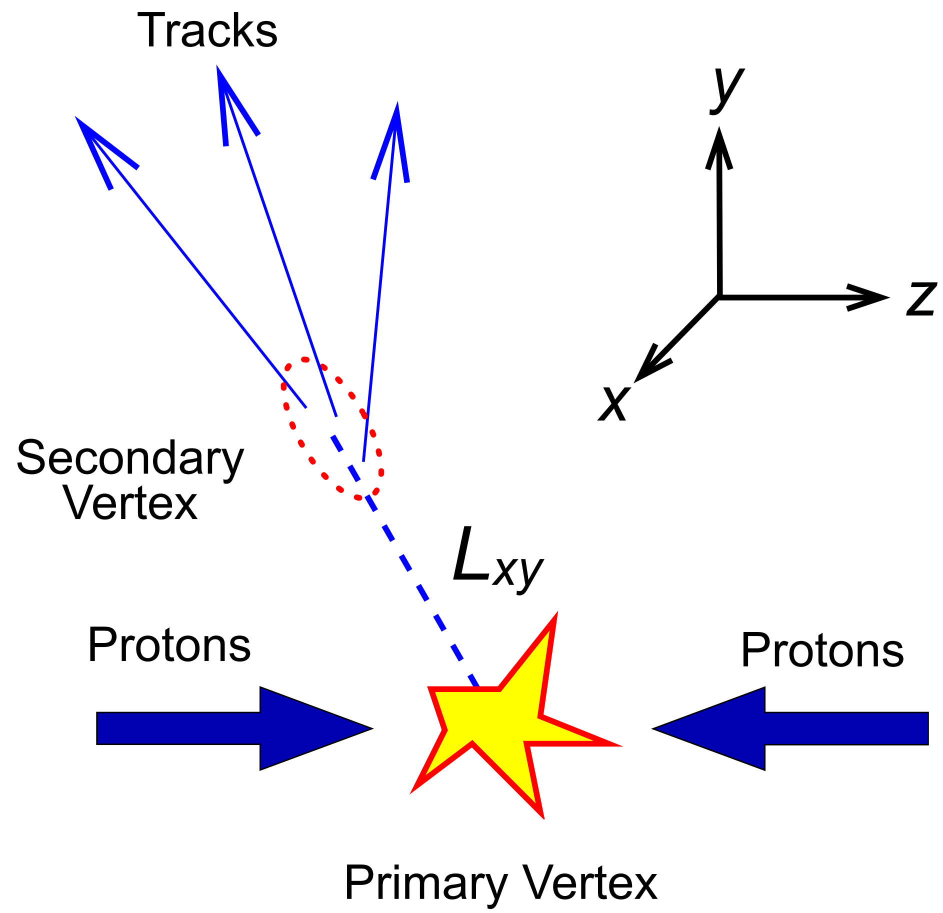


- Identify hadrons with b-quarks via their long lifetimes (picoseconds) → parts of the tracks come from displaced secondary vertex

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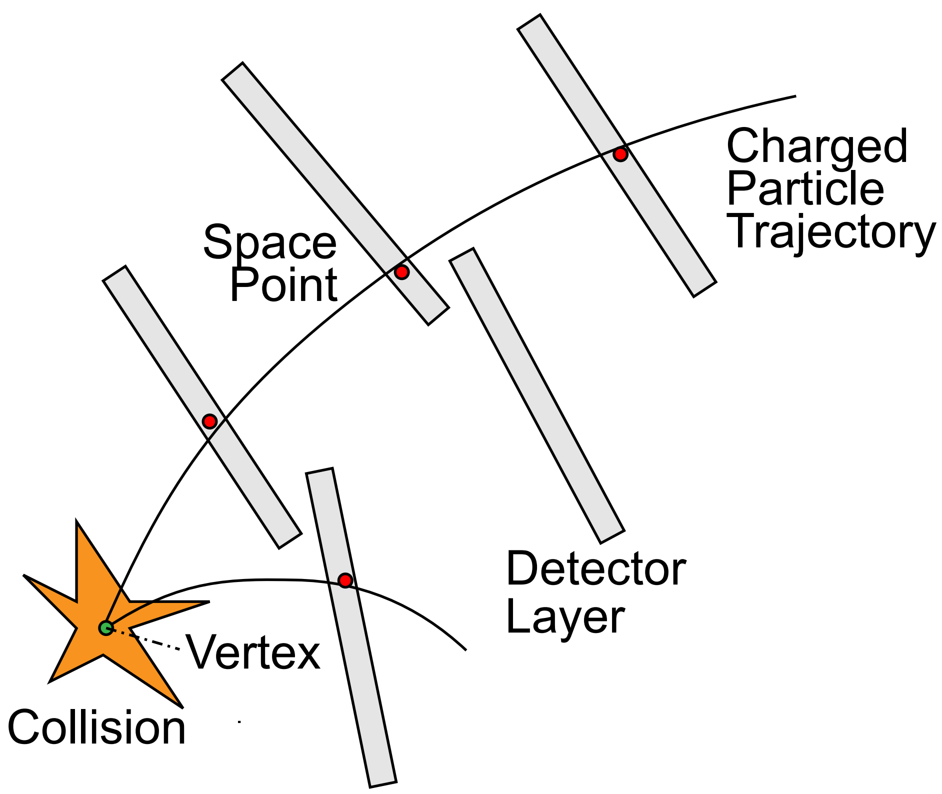
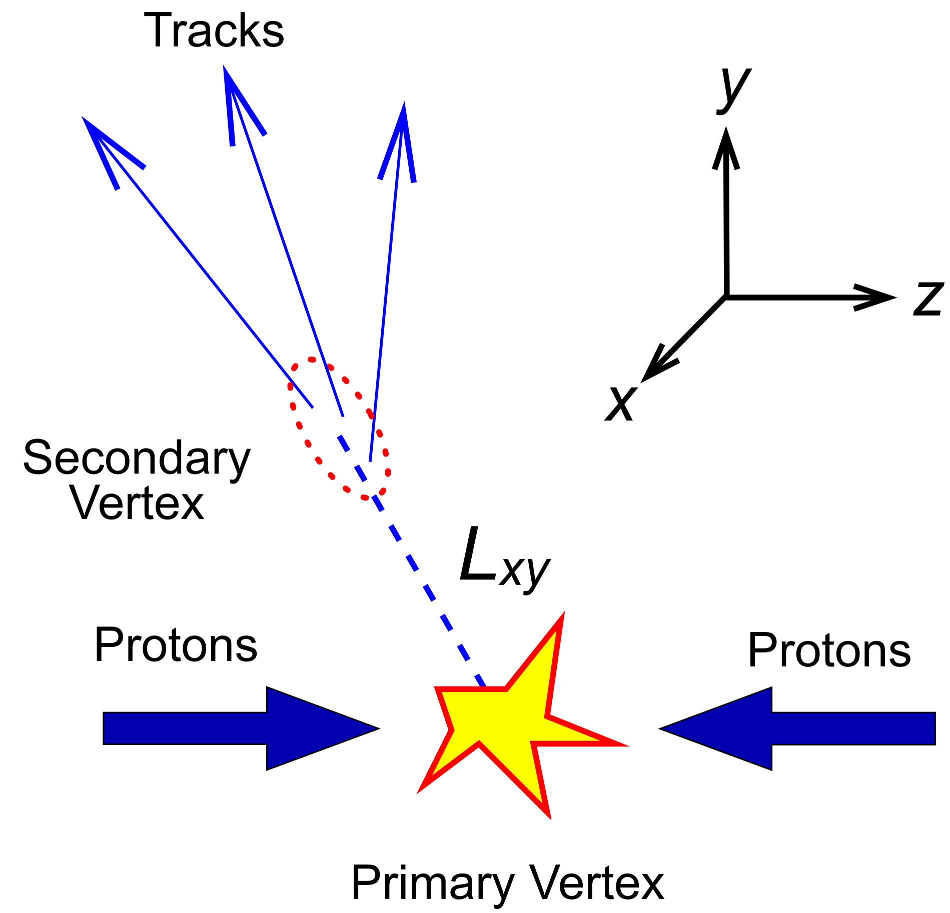


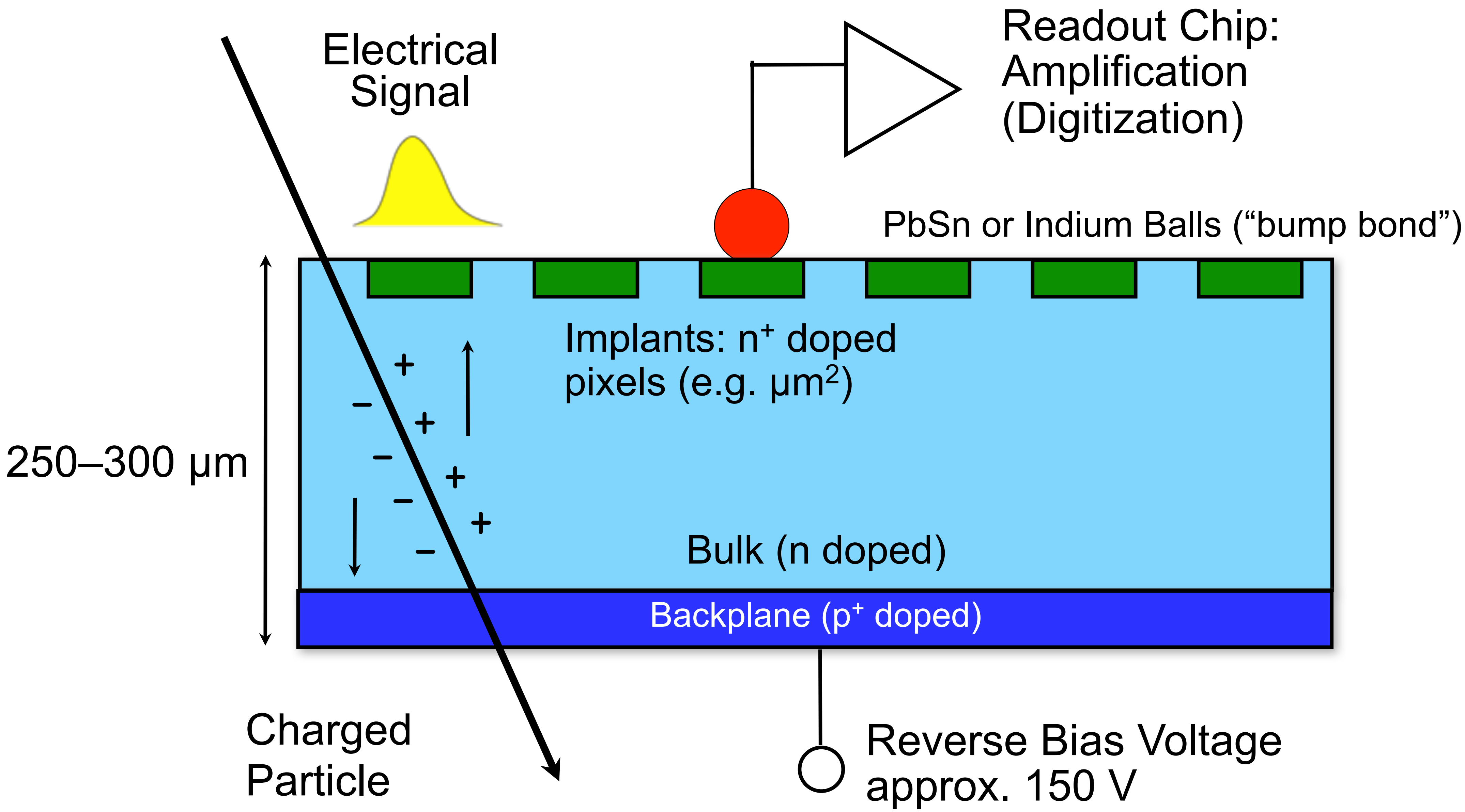




- Identify hadrons with b-quarks via their long lifetimes (picoseconds) → parts of the tracks come from displaced secondary vertex

CMS: “particle flow” integrates tracking and calorimetry → improved jet reconstruction

# LHC Choice for Tracking Detectors: Silicon

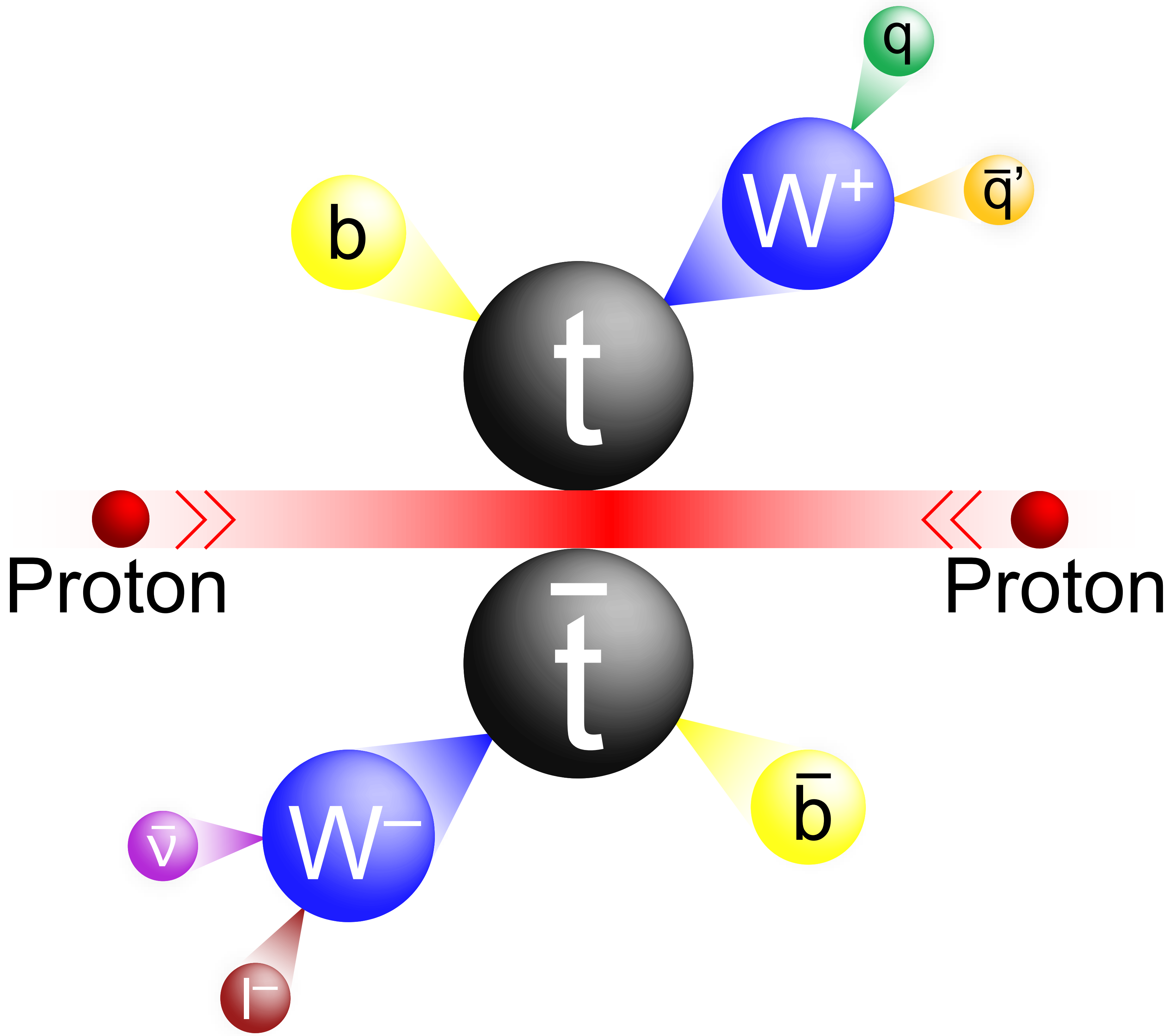
- Example: hybrid pixel detectors
  - Detector = semiconductor diode with pn junction in reverse bias → depletion zone
  - Charged particles ionize detector material → electron/hole pairs induce signal




Main Course

# Central Questions in Top Quarks Physics





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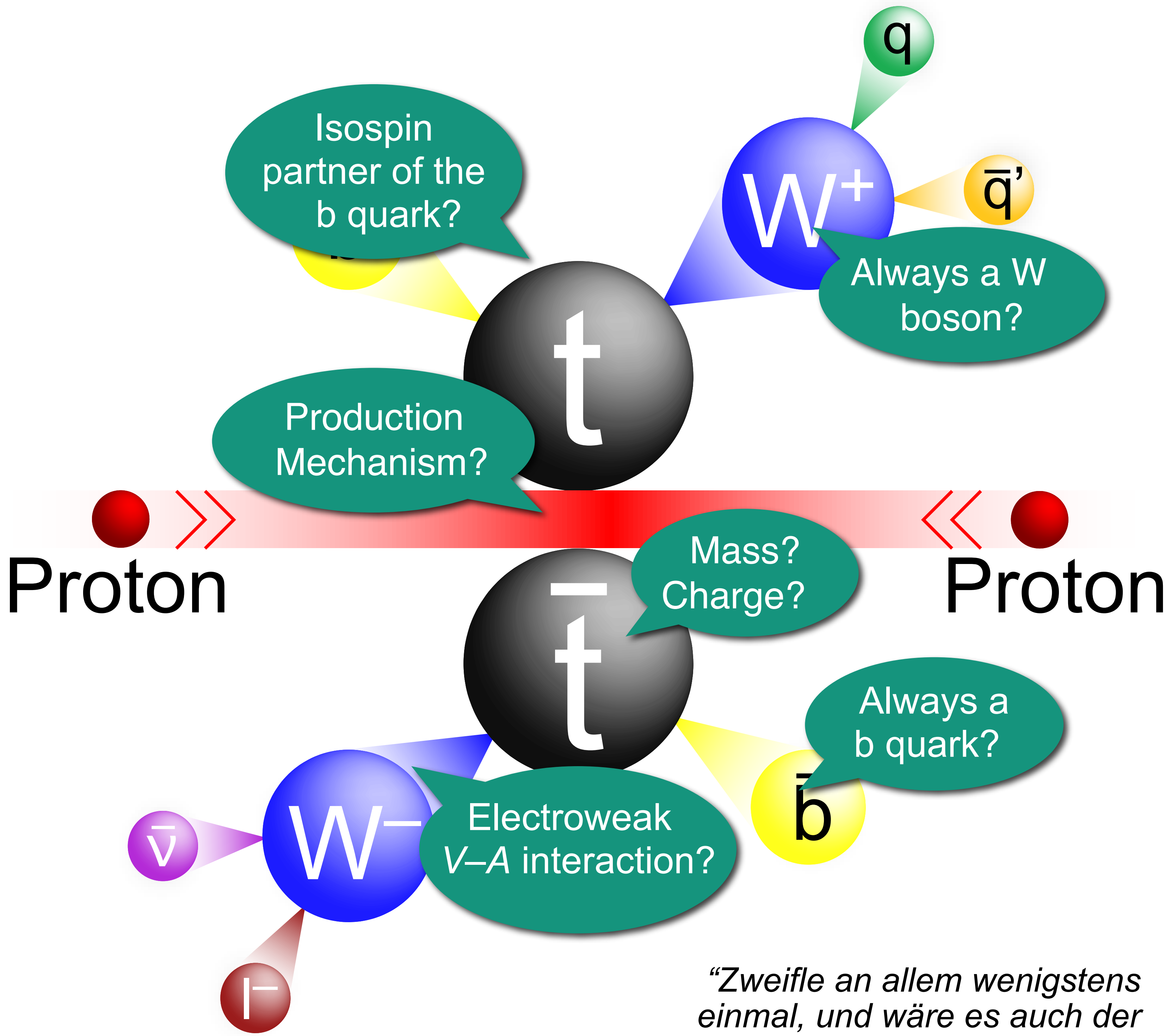


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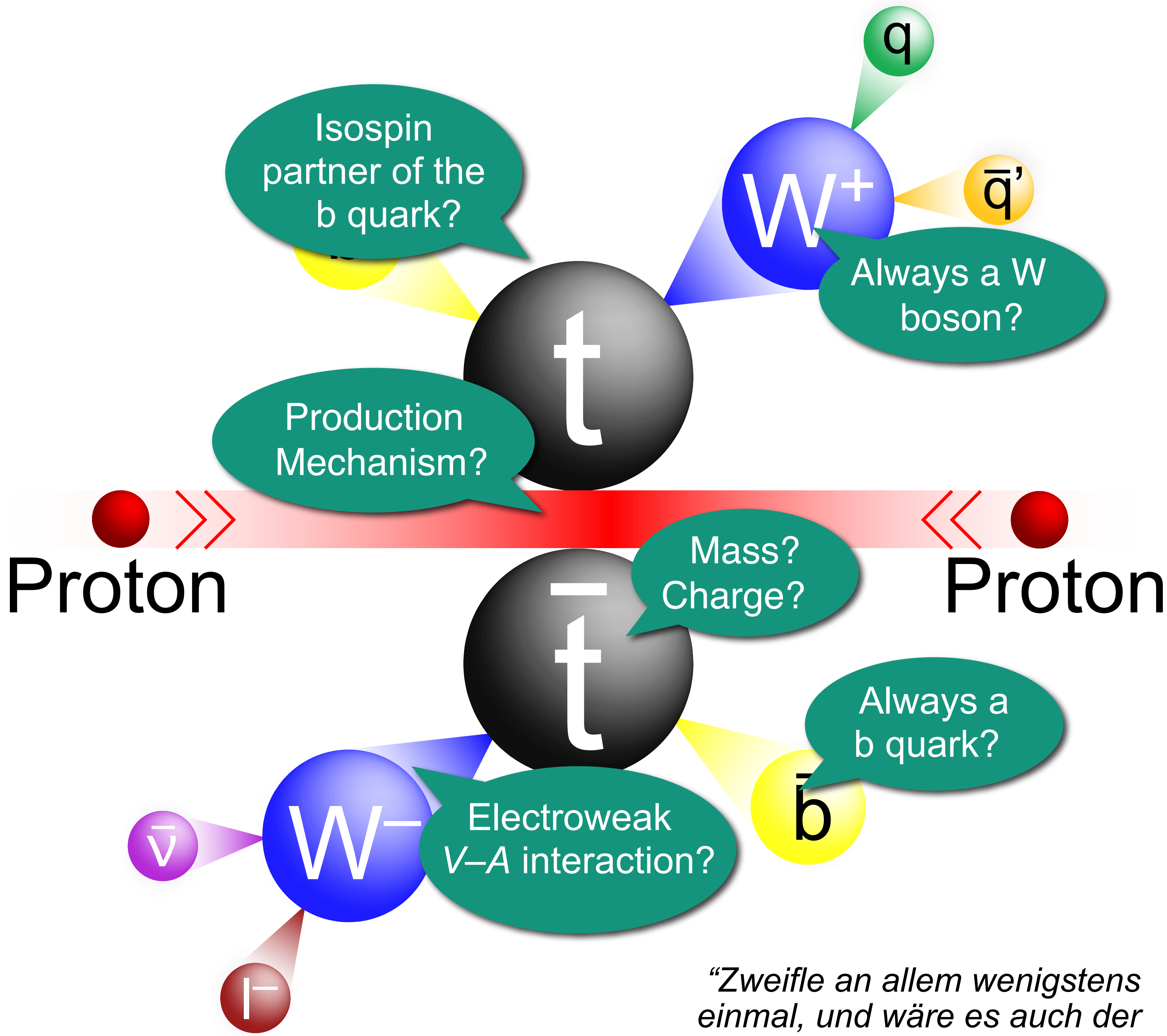


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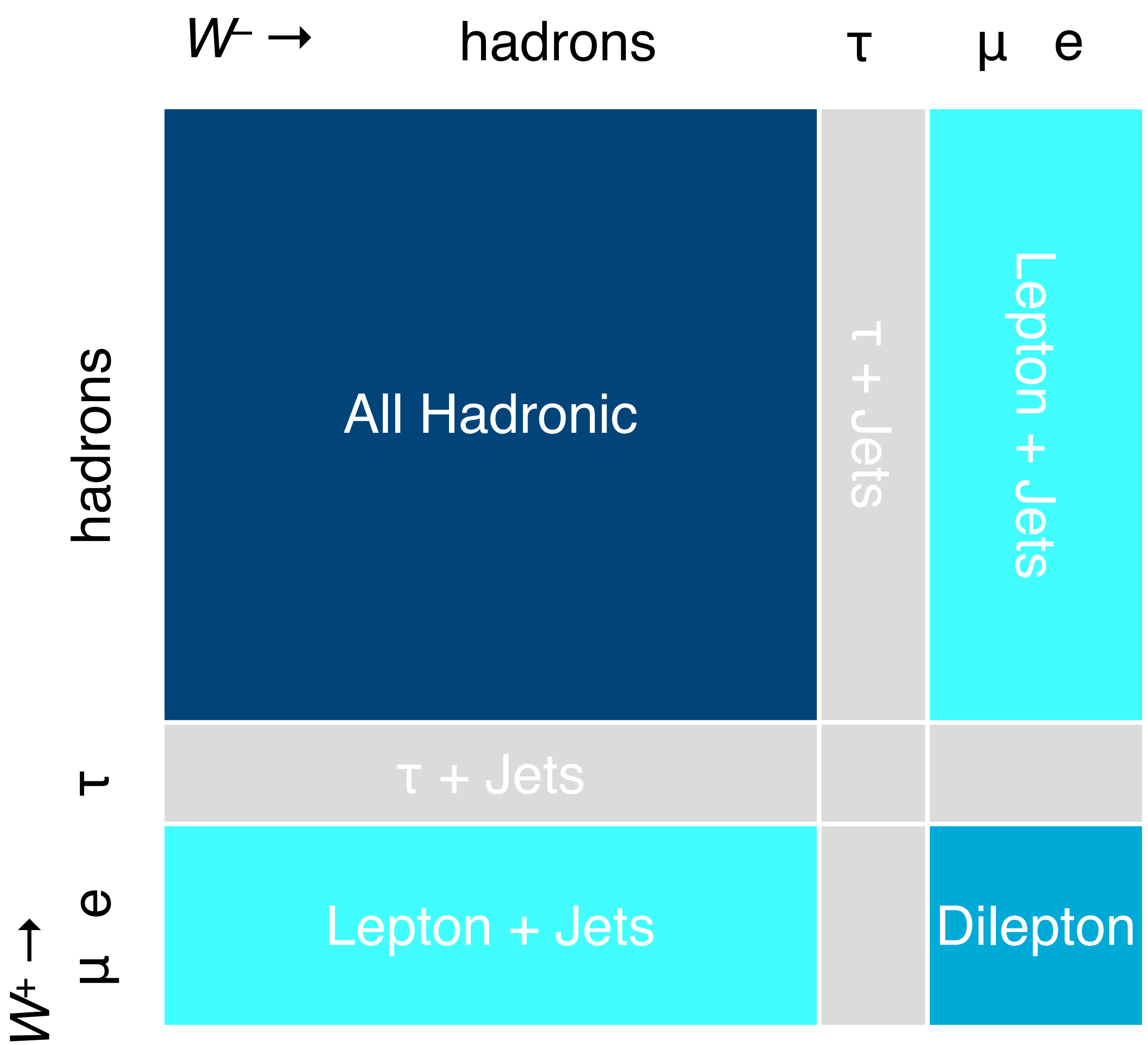
On today's menu:

- Search for flavor changing neutral current top decays with CDF
  [PRL 101 (2008), 192002]
- Precision measurement of top pair production at ATLAS
  [publication in preparation]

# Analyzing Top Quark Events

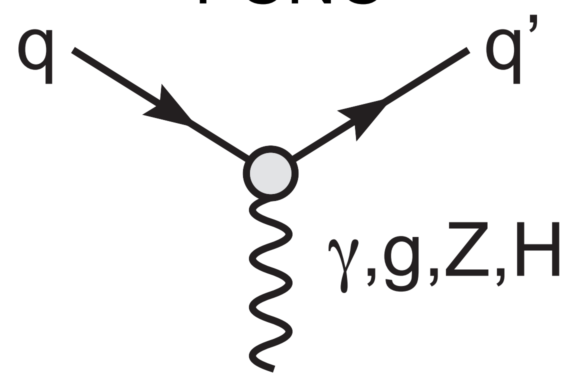



- Top decay in the standard model: $B(t \to Wb) \approx 100\%$
- Challenging signature: multiple leptons & jets, missing $E_T$ (MET)
- $t\bar{t}$ decay signatures characterized by W decays:
  - All-Hadronic: 45% of all decays, large QCD background
  - Lepton+Jets: 30% of all decays, moderate backgrounds
  - Dilepton: 5% of all decays, very clean, but small branching fraction

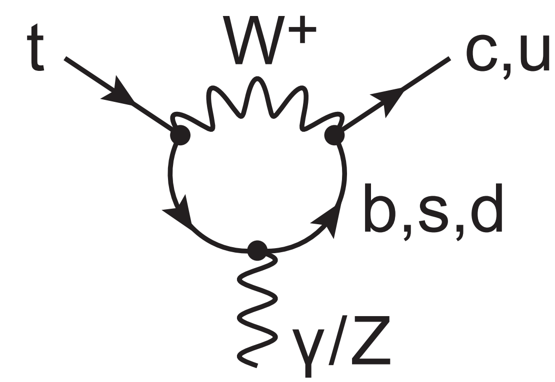
# Top Flavor-Changing Neutral Currents

- Flavor-changing neutral currents (FCNC)
  - Standard model: no FCNC on tree level
  - Quantum corrections: suppression via GIM mechanism
- FCNC in top physics
  - Extremely small branching fractions in the standard model, e.g. $B(t \to Zq) \approx 10^{-14}$
  - Some new physics models: $B(t \to Zq)$ up to $10^{-4}$
- Tevatron (also HERA and LHC): Search for FCNC both in top quark production and decay

Generic FCNC



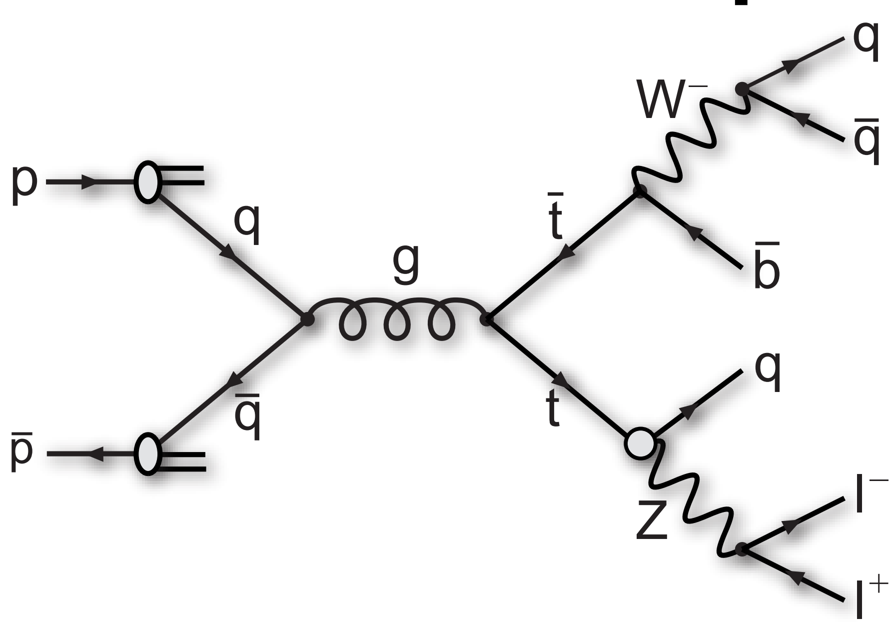

Pinguin Diagram for $t \to Zq$



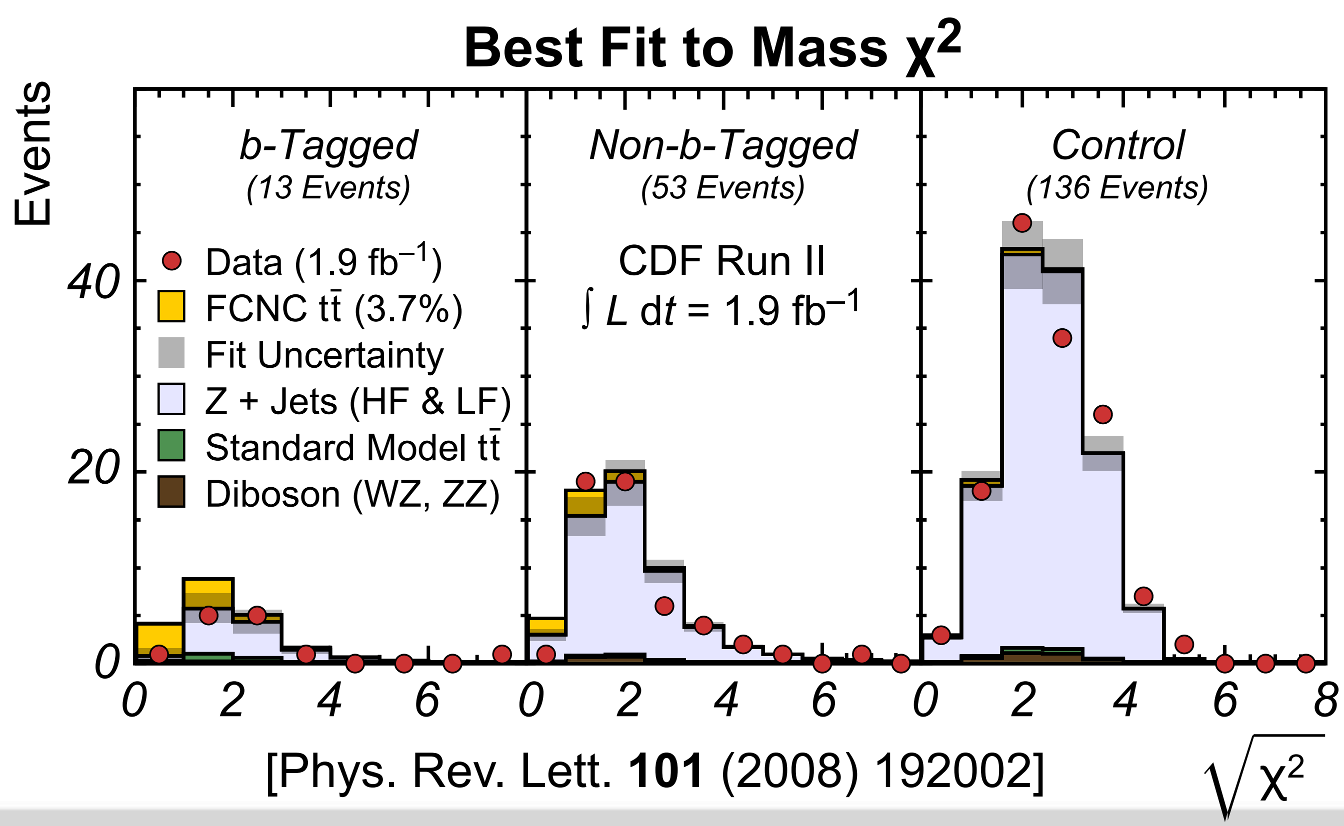

| Model | $B(t \to Zc)$ |
|---|---|
| Standard Model | $O(10^{-14})$ |
| Quark Singlet with q = 2/3 | $O(10^{-4})$ |
| Two Higgs Doublets | $O(10^{-7})$ |
| MSSM | $O(10^{-6})$ |
| SUSY with R-Parity Violation | $O(10^{-5})$ |

[after J.A. Aguilar-Saavedra, Acta Phys. Polon. **B35** (2004) 2695]

# Search for FCNC in Top Decays




$$\chi^2 = \left(\frac{m_{W,rec} - m_W}{\sigma_W}\right)^2 + \left(\frac{m_{t\to Wb,rec} - m_t}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,rec} - m_t}{\sigma_{t\to Zq}}\right)^2$$




[Phys. Rev. Lett. **101** (2008) 192002]

- Search for $t \to Zq$ at CDF
  - Challenge: irreducible background from SM Z+jets production → mass $\chi^2$
  - Template fit to determine signal and background contributions
- No evidence for a signal:
  - Limit on FCNC branching fraction $B(t \to Zq) < 3.7\%$ (95% C.L.)
  - Improved only recently by DØ: $B(t \to Zq) < 3.2\%$ (95% C.L.)
  - First LHC result from 2010 data (ATLAS): $B(t \to Zq) < 17\%$ → will be competitive very soon

# Search for FCNC in Top Decays

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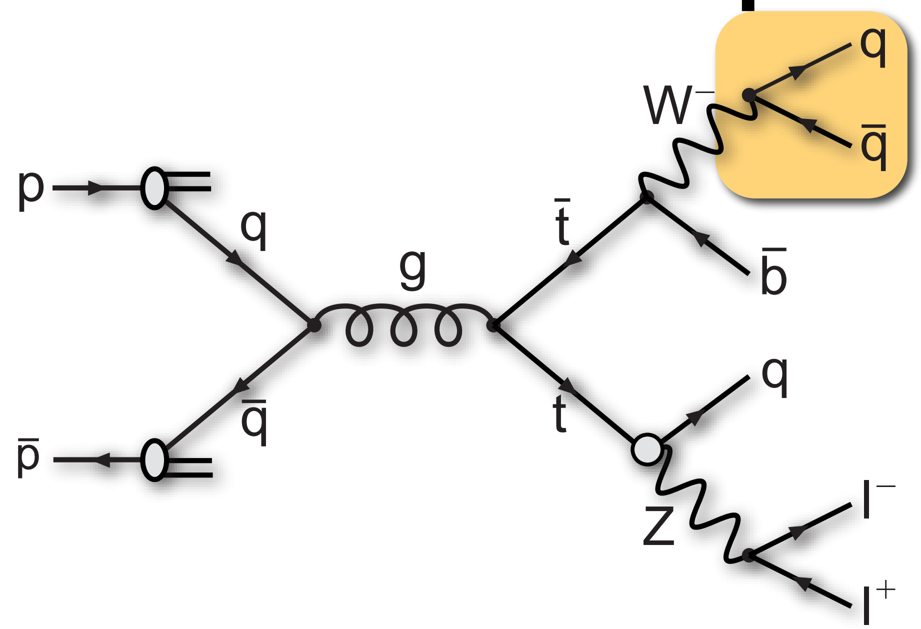


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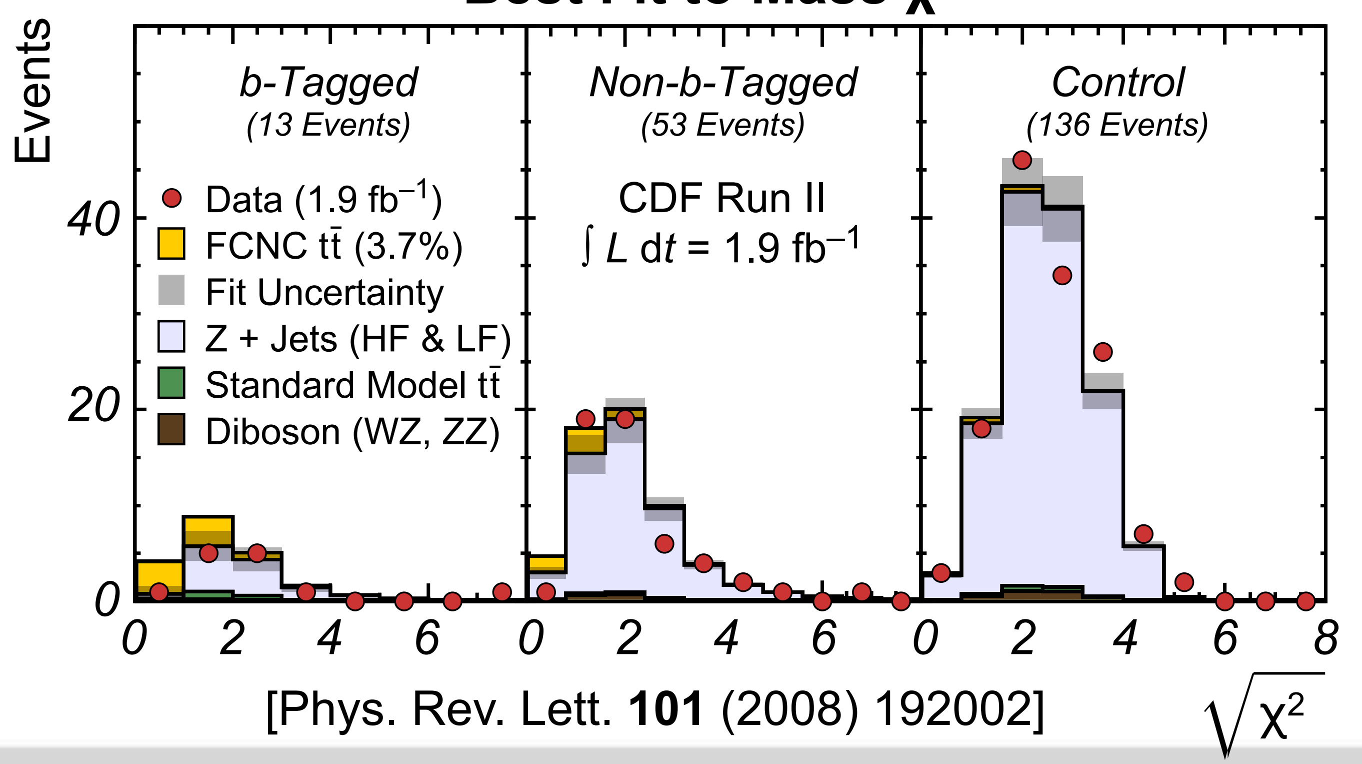
**Best Fit to Mass $\chi^2$**

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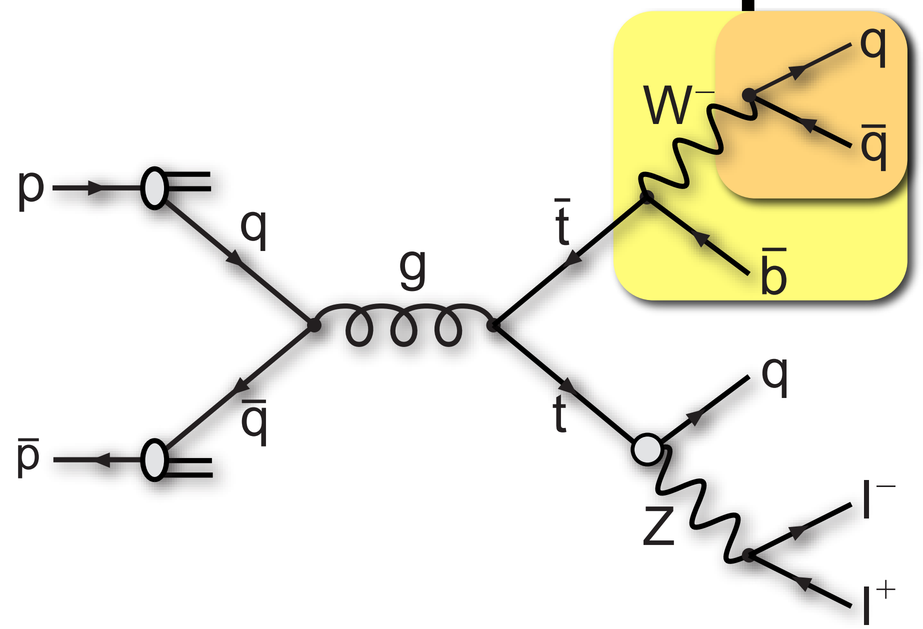


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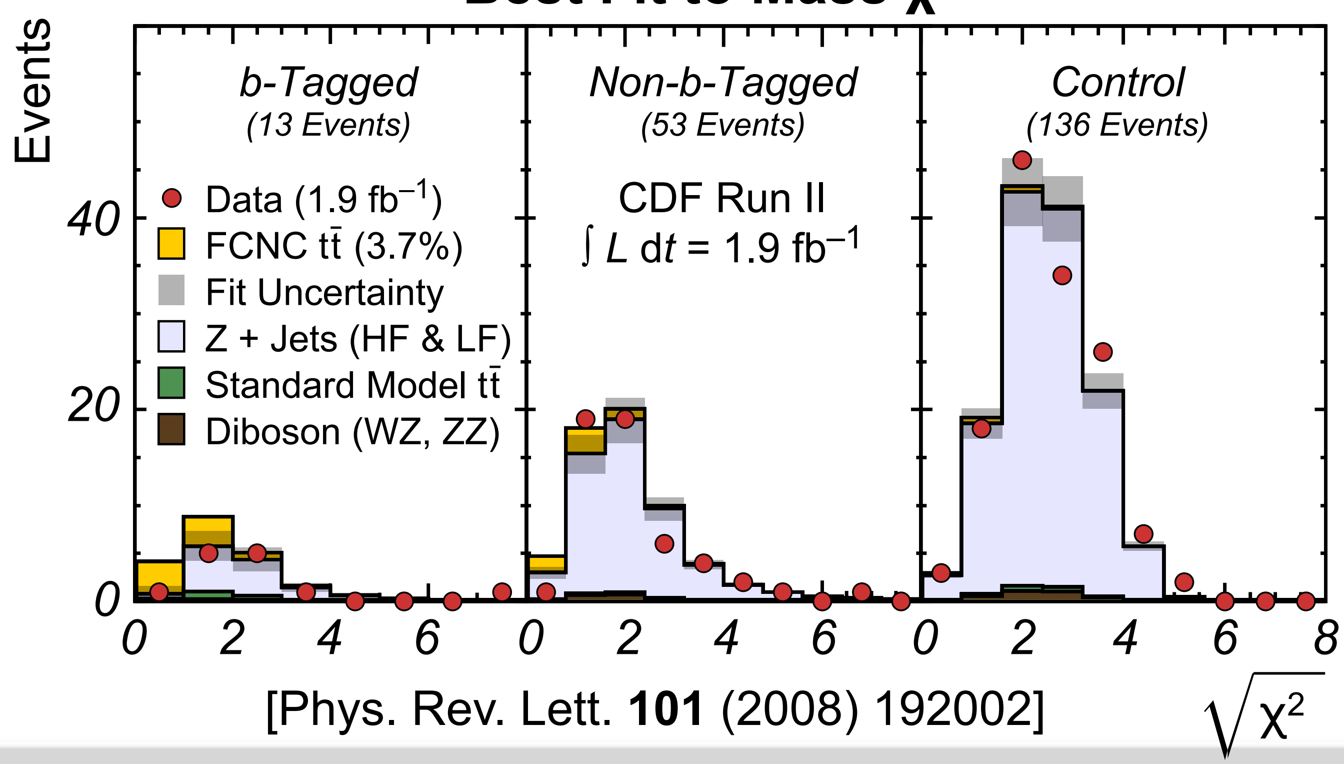


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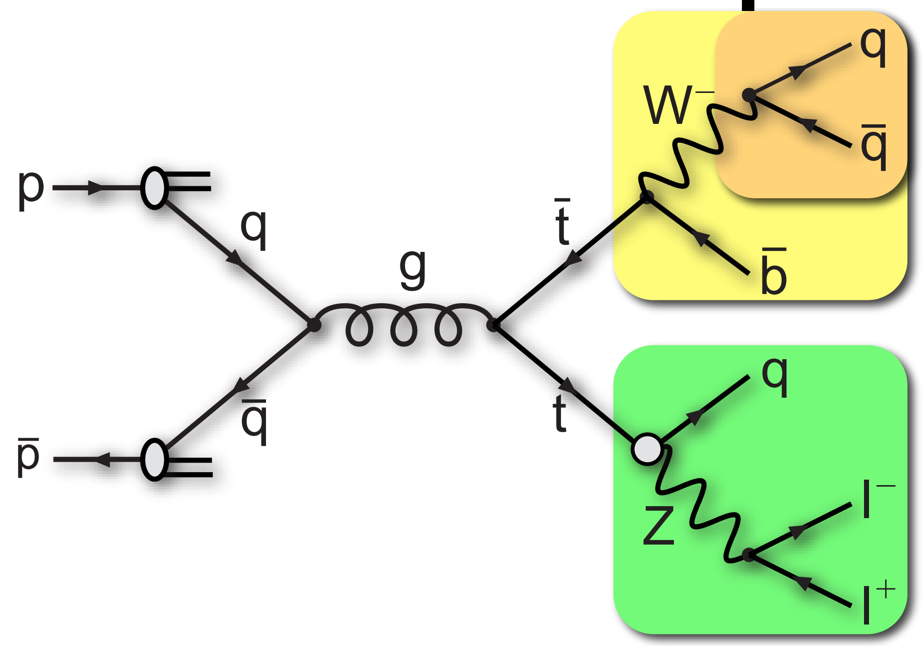


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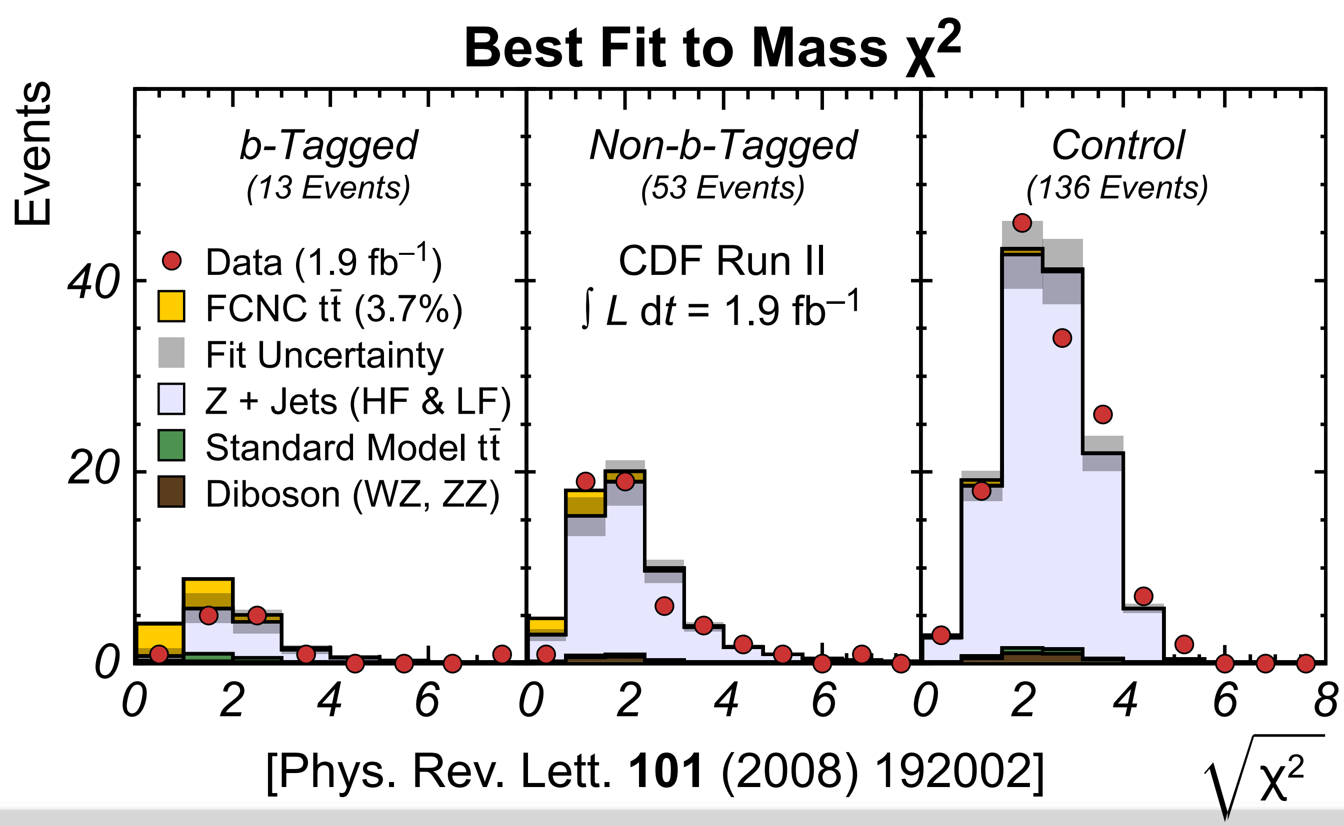


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# Intermezzo: What is Template Fitting?

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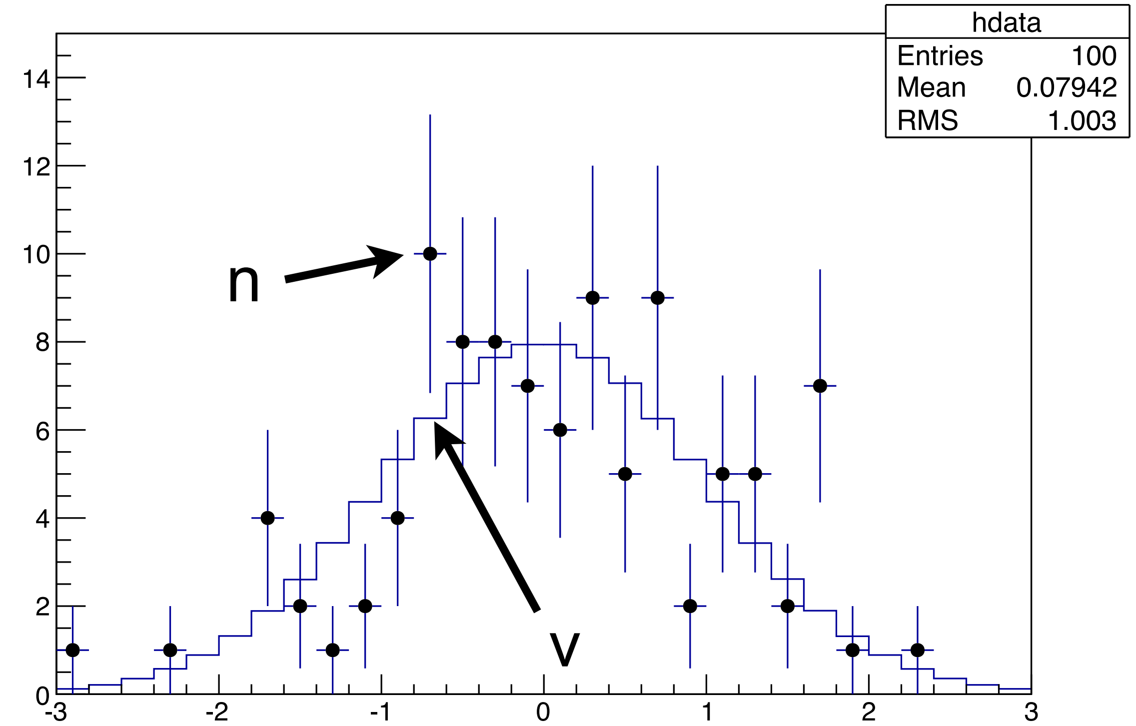
- Poisson likelihood function:

$$L(\beta) = \prod_{\text{bins } i} \frac{\nu_i(\beta)_i^n e^{-\nu_i(\beta)}}{n_i!}$$

  - Compare number of events n in each bin to expected number ν(β)
  - Maximize L (minimize –ln L) best “overall compromise” for parameter of interest β




- Limitations of this approach:
  - Underlying assumption: template shape is perfectly known
  - Reality: templates are often built from MC simulation or data “sidebands” → limited statistics, systematic shape uncertainties (e.g. non-perfect simulation)

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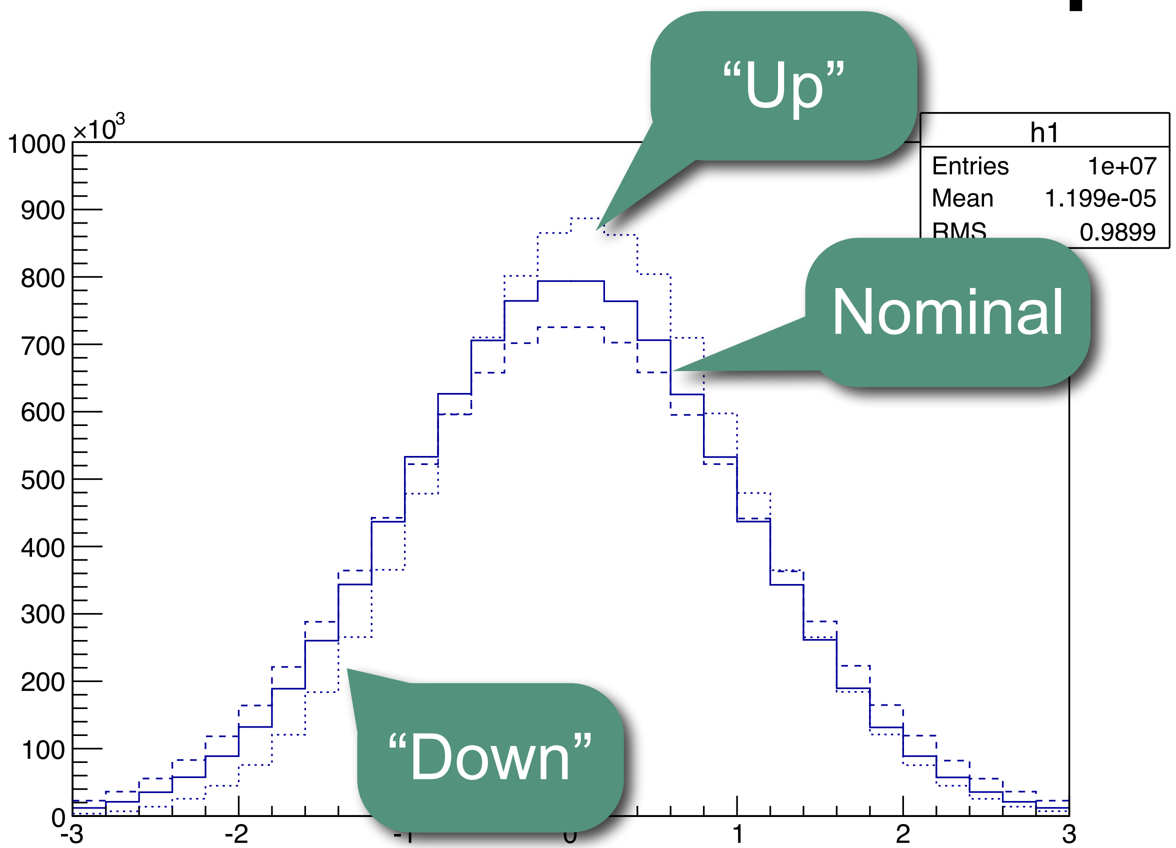
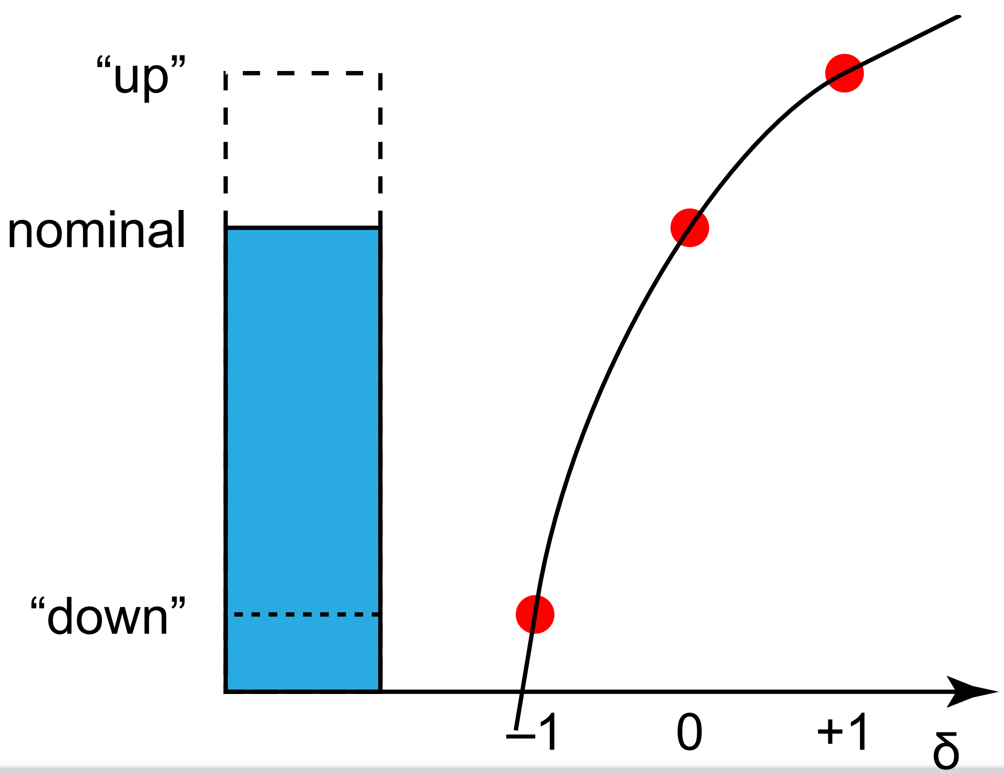


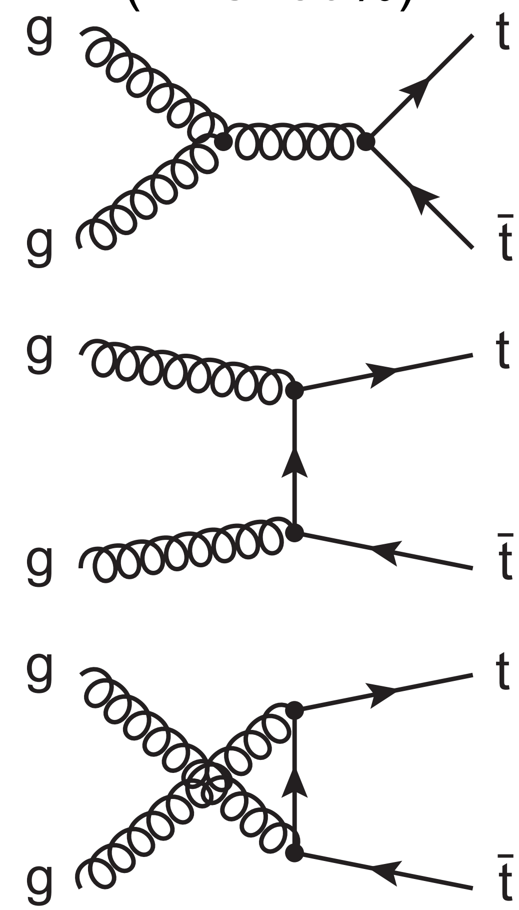

- Improvement: template morphing
  - Allow templates shape to vary within the uncertainties
  - Interpolate between few templates with a “morphing parameter” δ (e.g. δ = 0 for nominal shape)
  - Add morphing parameter as additional “nuisance parameter” in the fit → let the data constrain the uncertainty (improves with size of dataset)
- Final maximum likelihood fit
  - Fit for parameter of interest (e.g. FCNC branching fraction) and several nuisance parameters simultaneously
  - Advanced techniques to extract parameter of interest: “profiling” and “marginalization”

# Top Cross Section Measurement with ATLAS

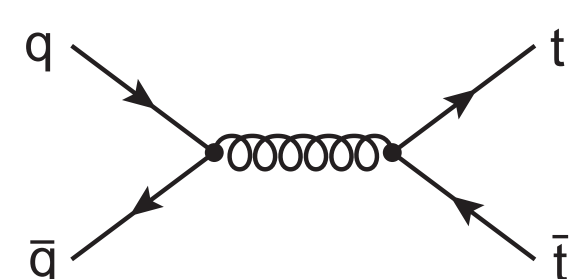
- Top pair production cross section at current LHC energies:
  - Theory: full next-to-leading order (NLO) calculation and large parts of NNLO calculation available → uncertainties below 10%
  - LHC experiments: best 2010 analyses with approx. 13% uncertainty (10% after combination), lots of ideas how to reduce uncertainties with 2011 dataset
  - At the LHC: top is becoming the new "standard candle" of particle physics – abundant and precisely known

- Basic analysis idea
  - Decay channel: muon/electron + jets
  - Extract cross section from event kinematics
  - Multivariate discriminant: projective likelihood estimator build from few well-modeled kinematic variables
  - Profile likelihood template fit

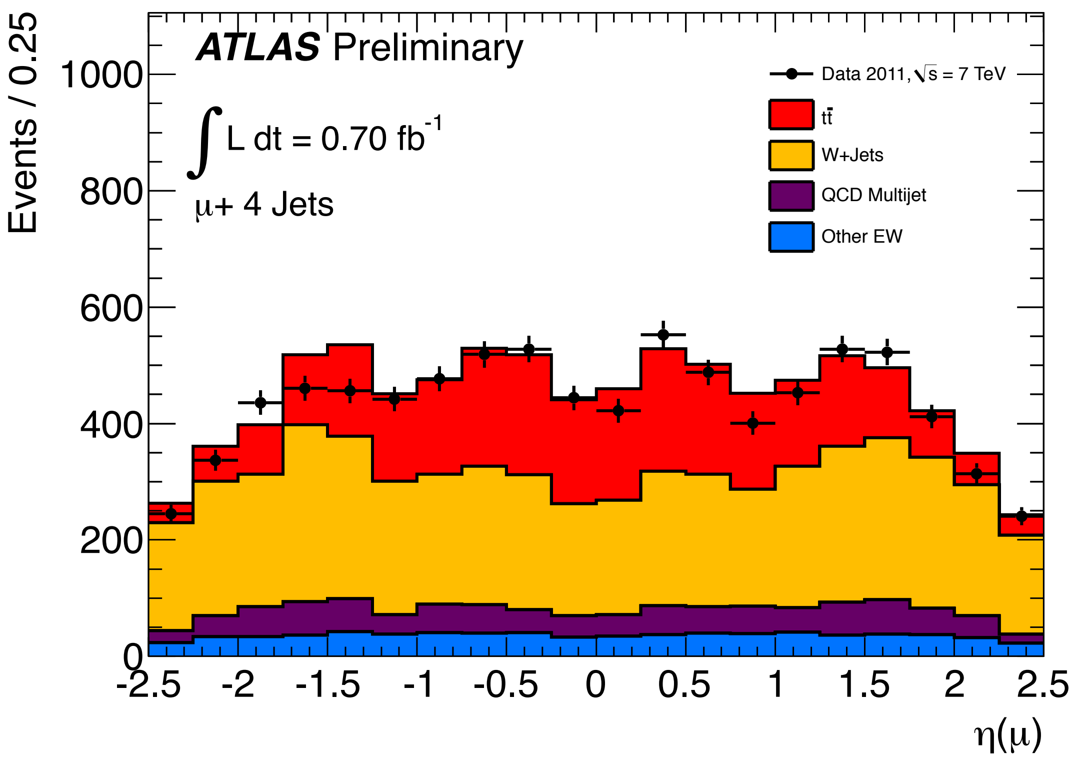
Gluon-Gluon Fusion
(LHC: 80%)

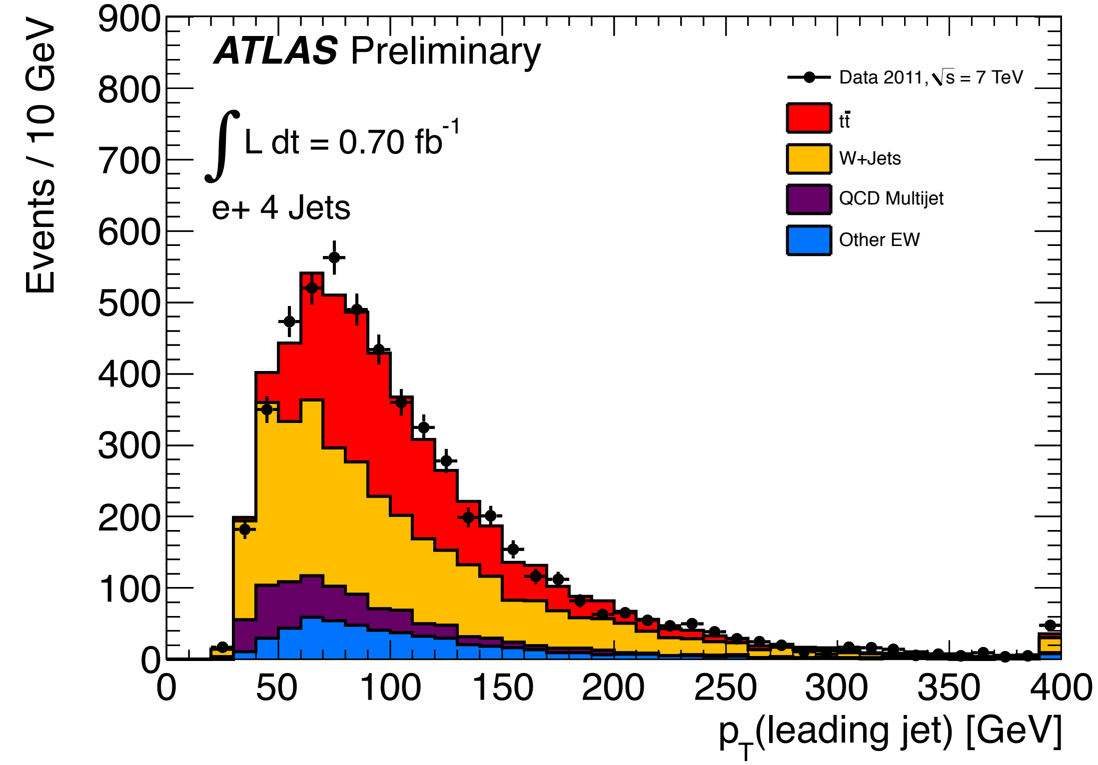


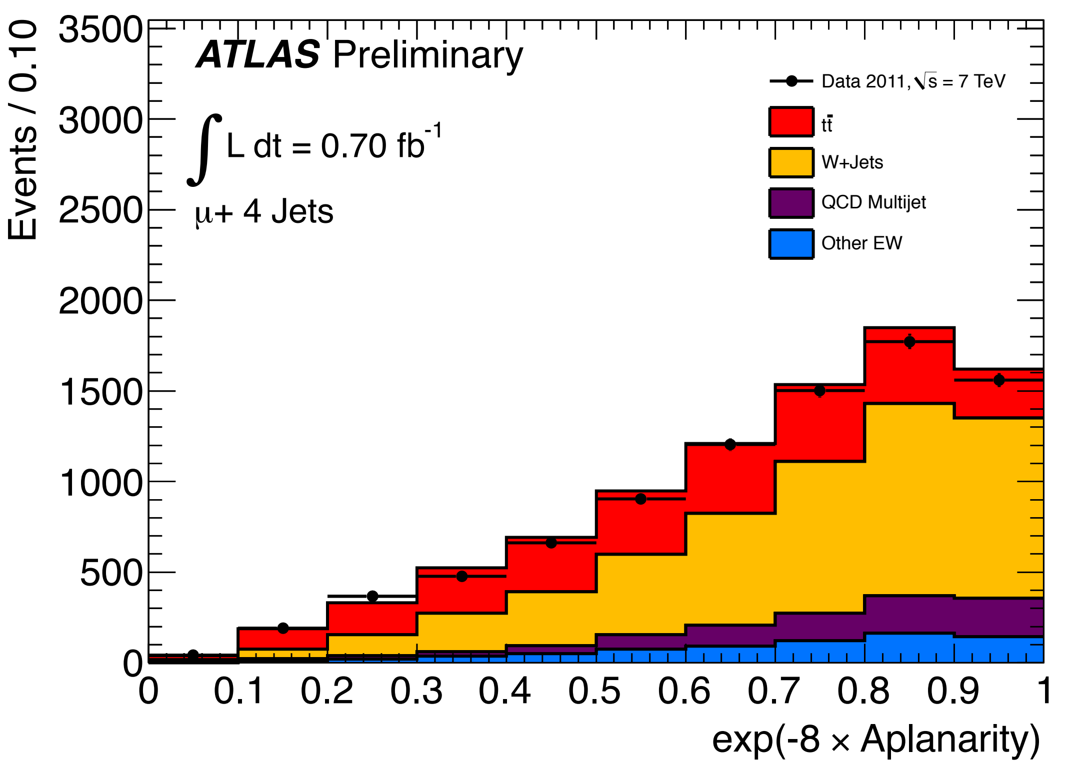

Quark-Antiquark
Annihilation (LHC: 20%)

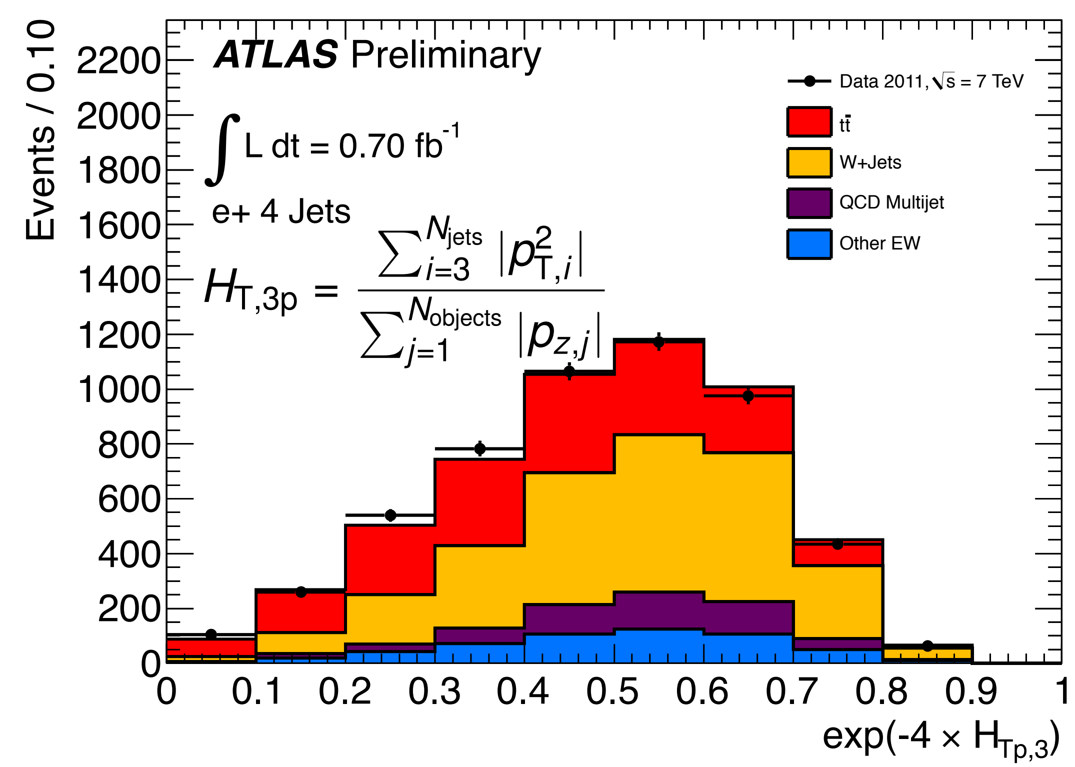


# Top Cross Section: Input Variables



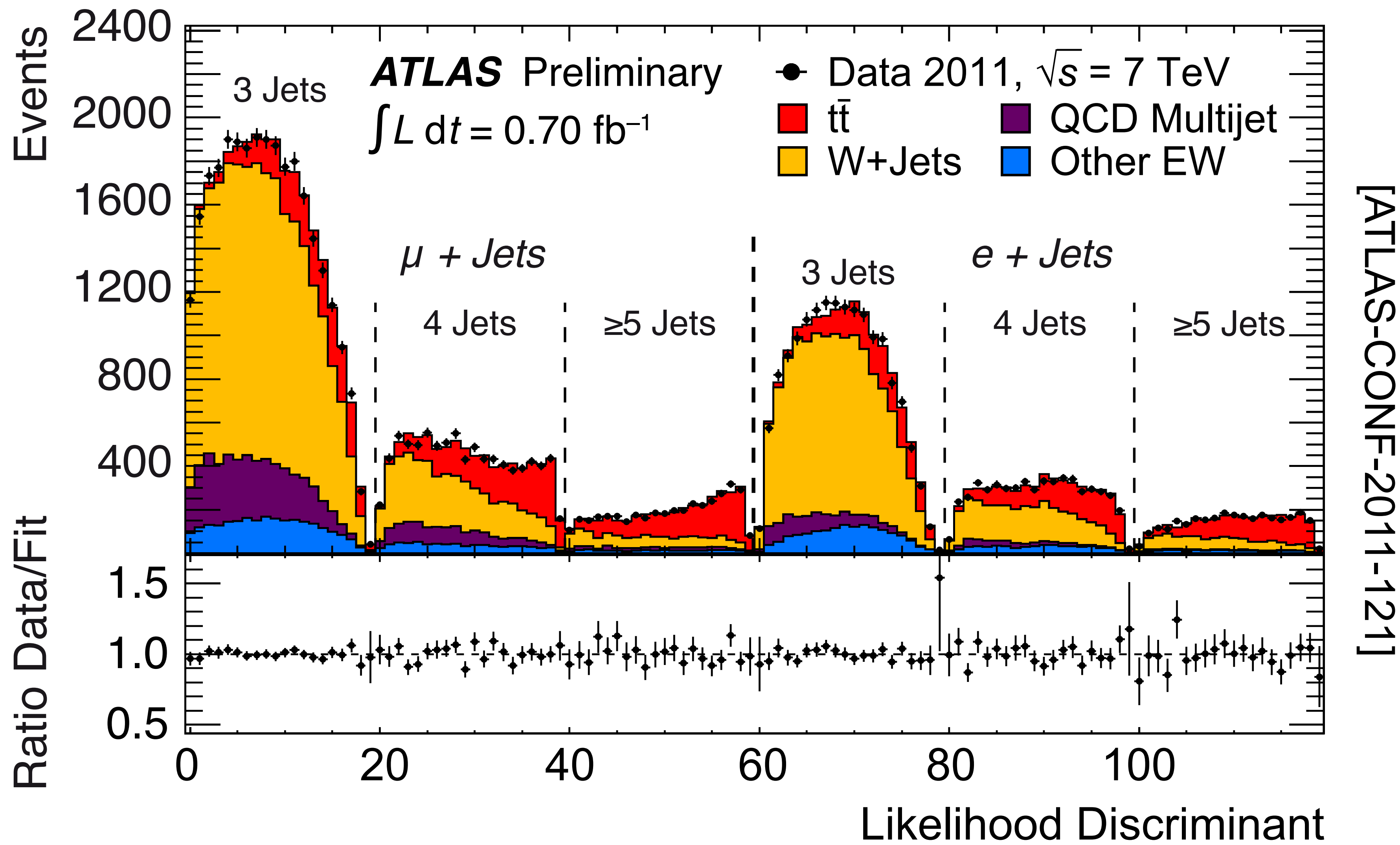




[ATLAS-CONF-2011-121]

# Top Cross Section: Result

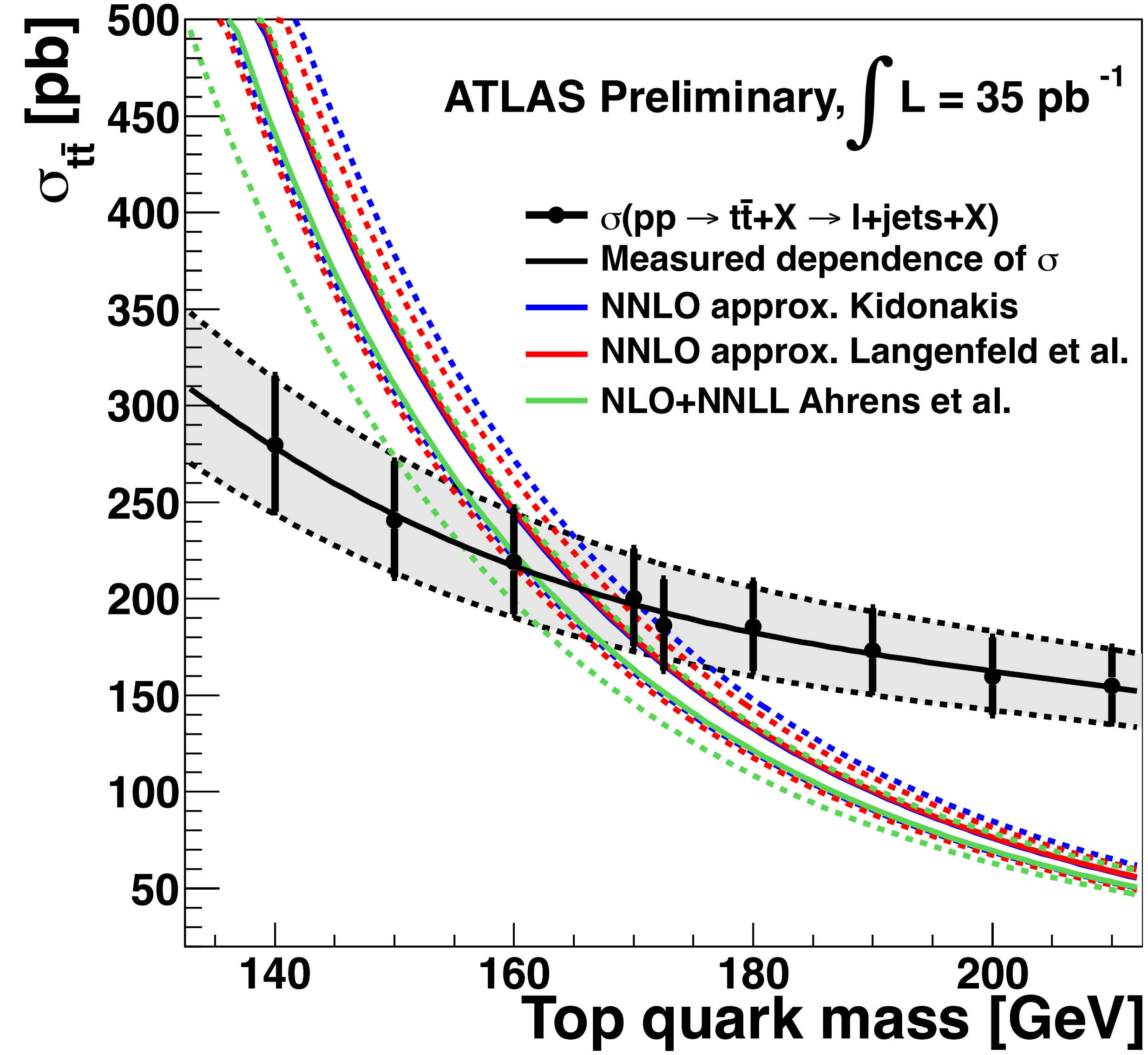
- Final fit to discriminant in six regions (muon/electron+ 3,4,≥5 jets)




- Result: $\sigma_{t\bar{t}} = 179.0\,^{+9.8}_{-9.7}$ (stat.+syst.) $\pm$ 6.6 (lumi) pb
  - Most precise top cross section at the LHC → 6.6% relative uncertainty
  - Good agreement with theory (QCD at approx. NNLO): $\sigma_{t\bar{t}} = 165\,^{+11}_{-16}$ pb

# Top Mass from Cross Section

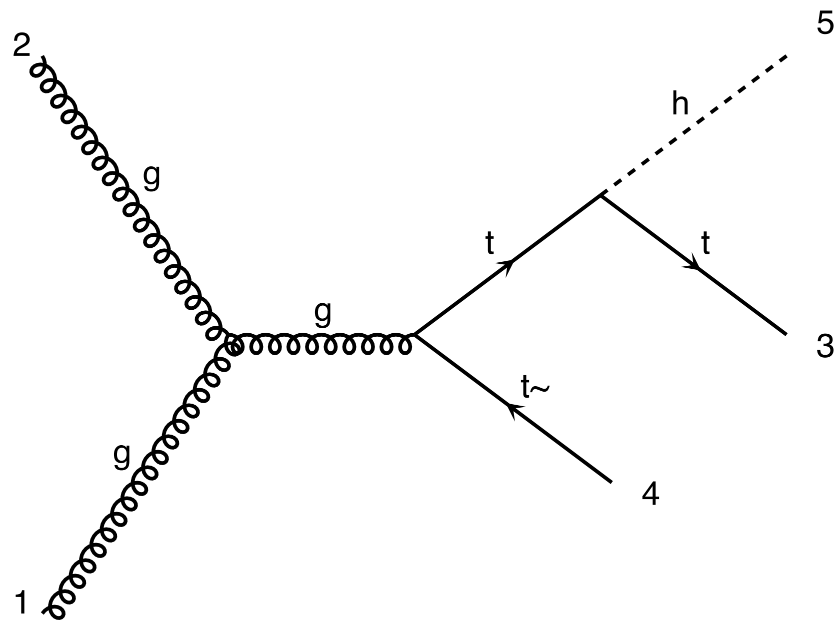
- Which top mass is measured at Tevatron and LHC?
  - Short answer: it's the mass parameter in the MC simulation
  - MC mass parameter expected close to the pole mass (certainly < 1 GeV)
- Alternative way to extract mass: relation to production cross section
  - Method pioneered in DØ, now also results from ATLAS & CMS
  - Theory: strong mass dependence (mainly due to top propagator)
  - Experiment: weak mass dependence (acceptance effects)



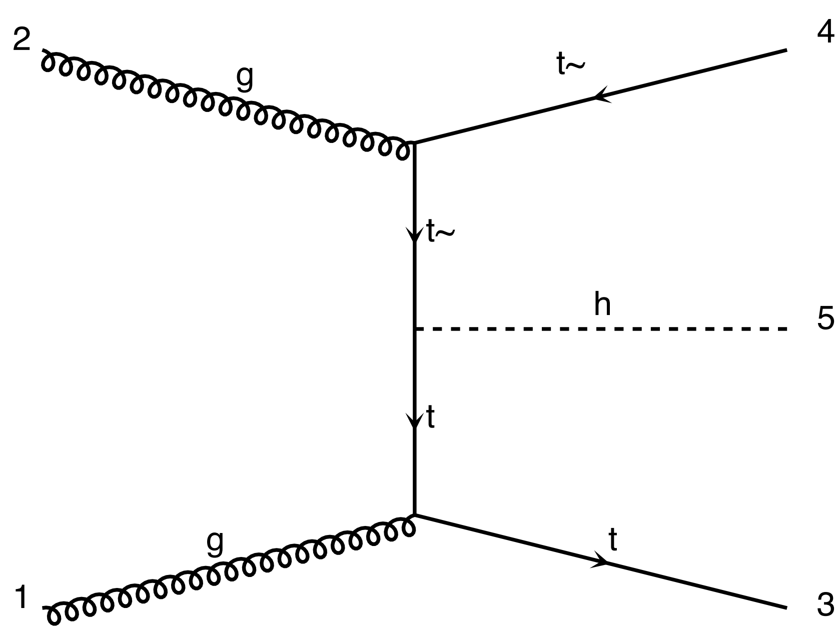

[ATLAS-CONF-2011-054]

- Result (2010 data): $m_t^{\mathrm{pole}} = 166.4\,^{+7.8}_{-7.3}$ GeV

# Our Plans for the Near Term Future

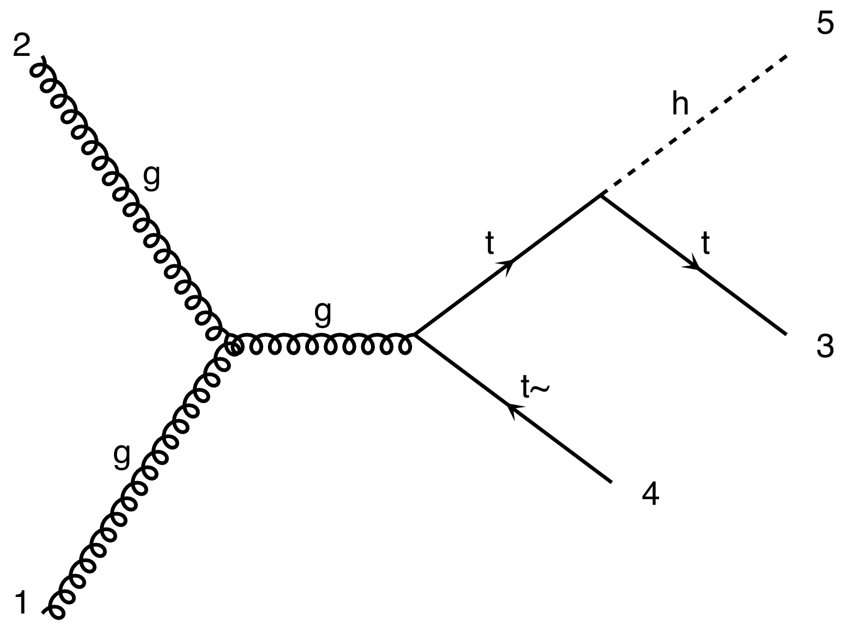



**Leading order Feynman diagrams for $t\bar{t}H$ production [MadGraph 5]**

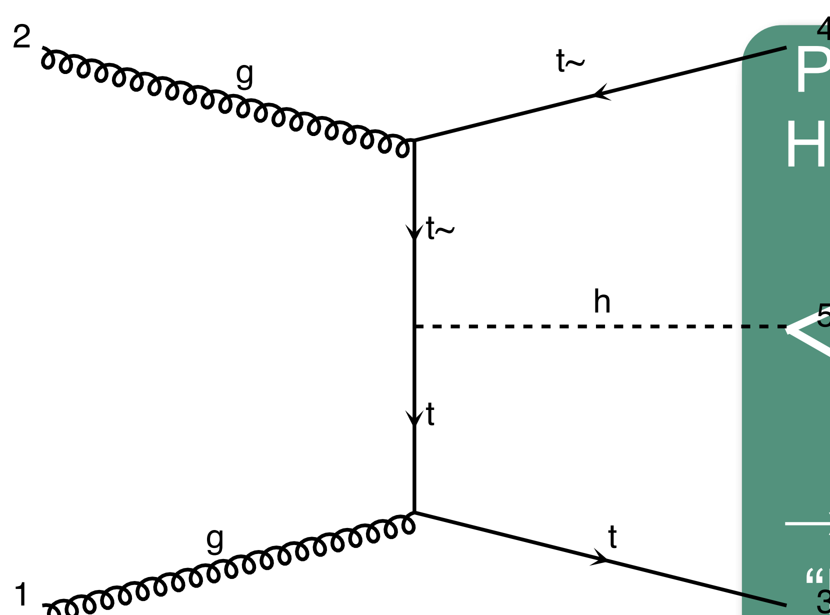



- Guiding question: what else is going on in top events?
- Topic I: Top & additional (b-)jets
  - "As busy as it gets in the SM…"
  - Test of perturbative QCD
  - Several new physics models predict additional jets as well
- Topic II: $t\bar{t}H$ production
  - Large background from $t\bar{t}$+jets (especially $t\bar{t}b\bar{b}$)
    → not a "Higgs discovery channel"
  - Measurement of Yukawa couplings at the LHC
  - Very challenging channel
    → start preparatory work now

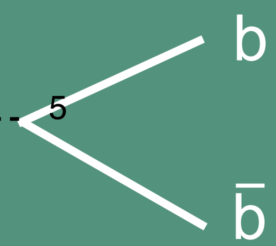
# Our Plans for the Near Term Future




**Leading order Feynman diagrams for $t\bar{t}H$ production [MadGraph 5]**




Preferred decay: $H \rightarrow b\bar{b}$ (BR≈50%)




→ have to exploit "boosted Higgs" techniques to be sensitive

- Guiding question: what else is going on in top events?
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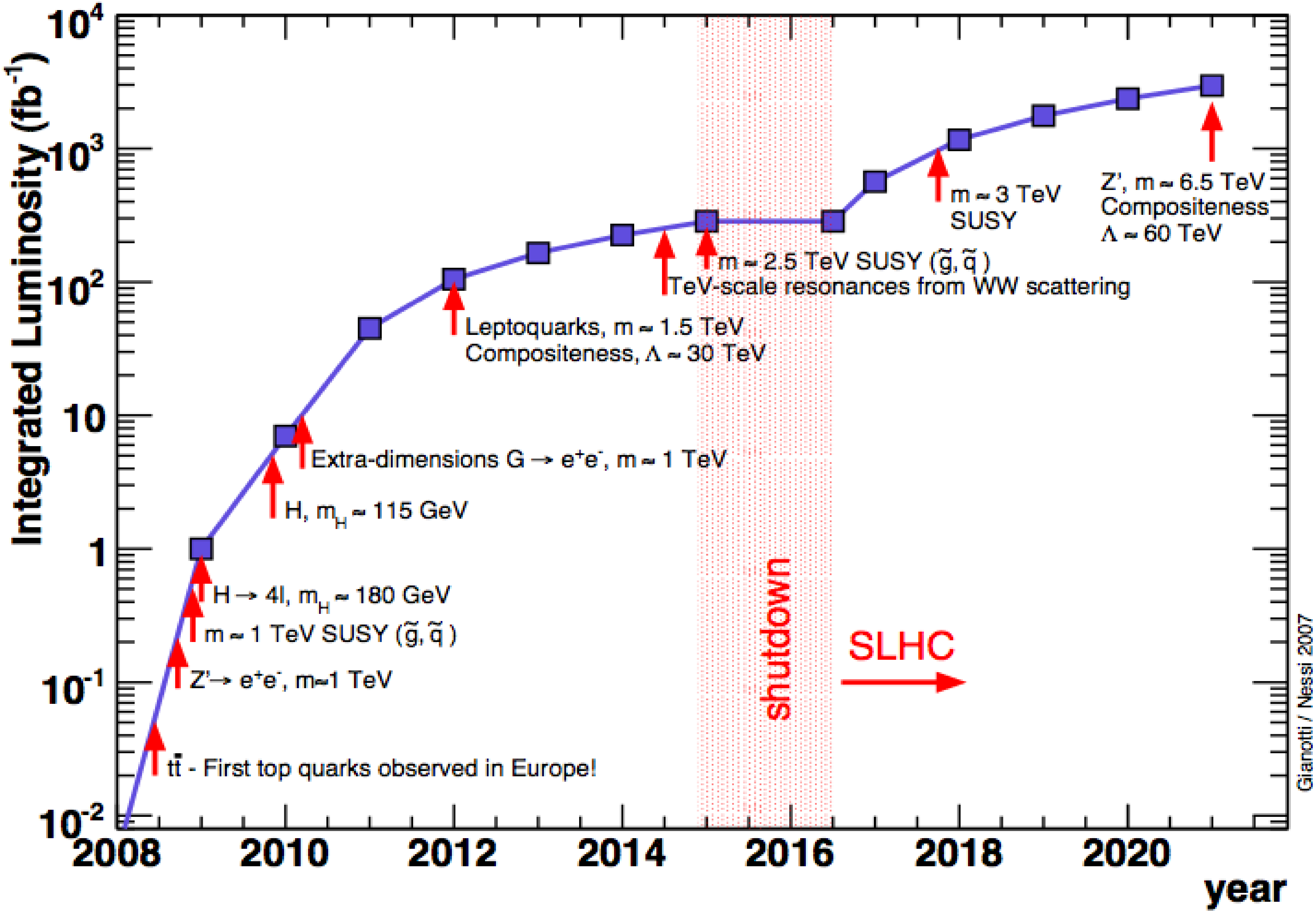
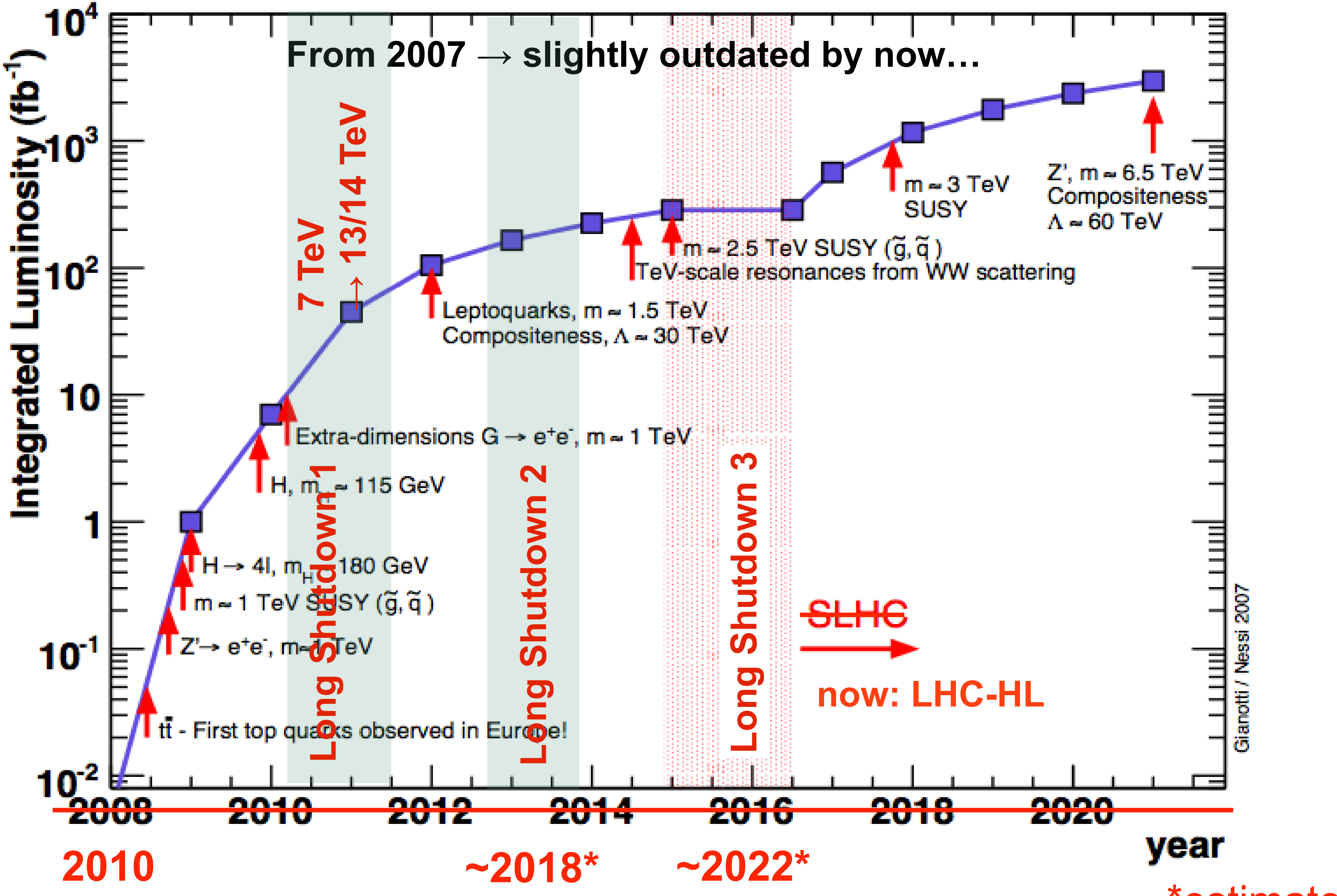
# Dessert

# LHC High Luminosity Upgrade: Physics Case

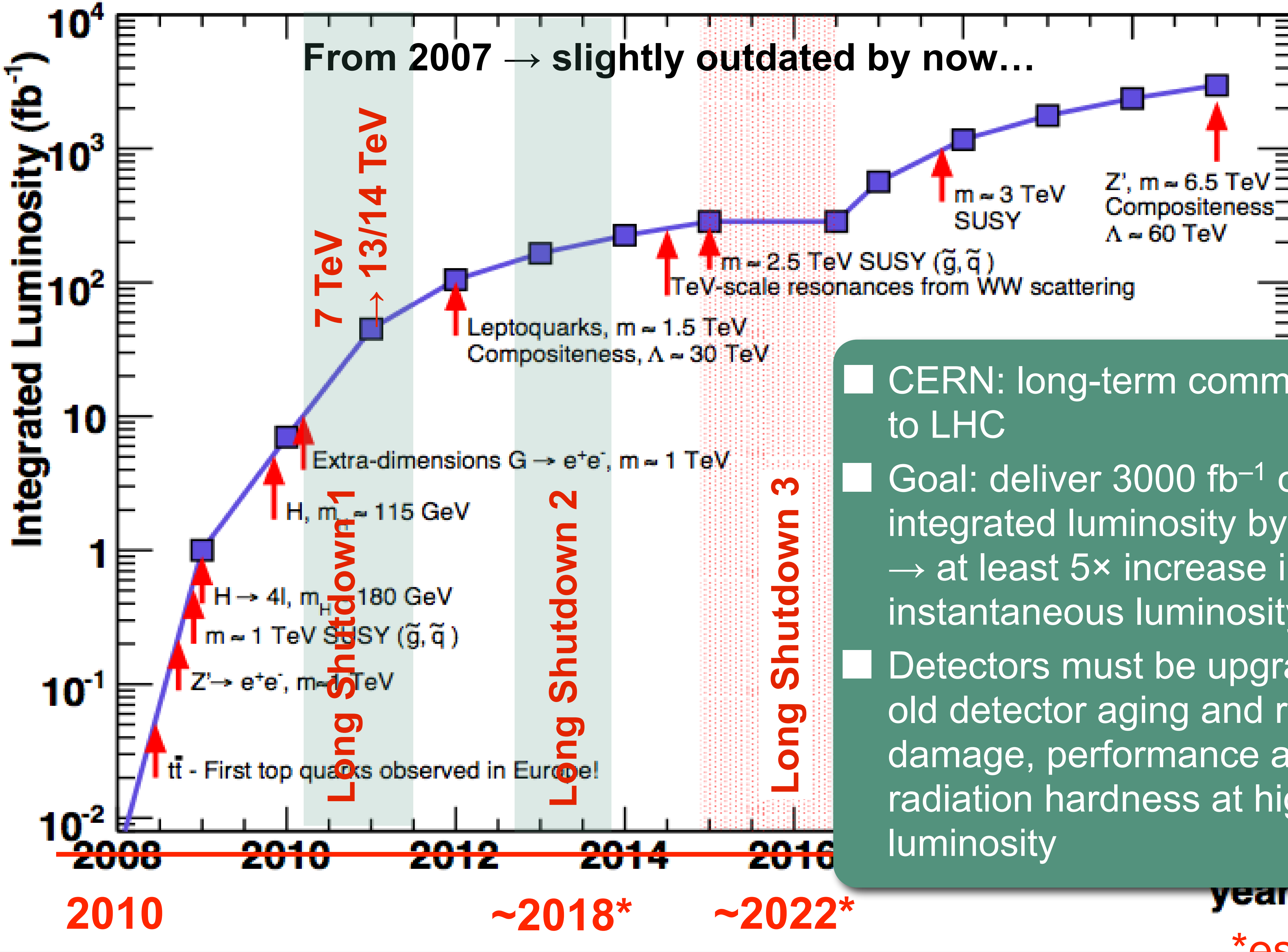


# LHC High Luminosity Upgrade: Physics Case



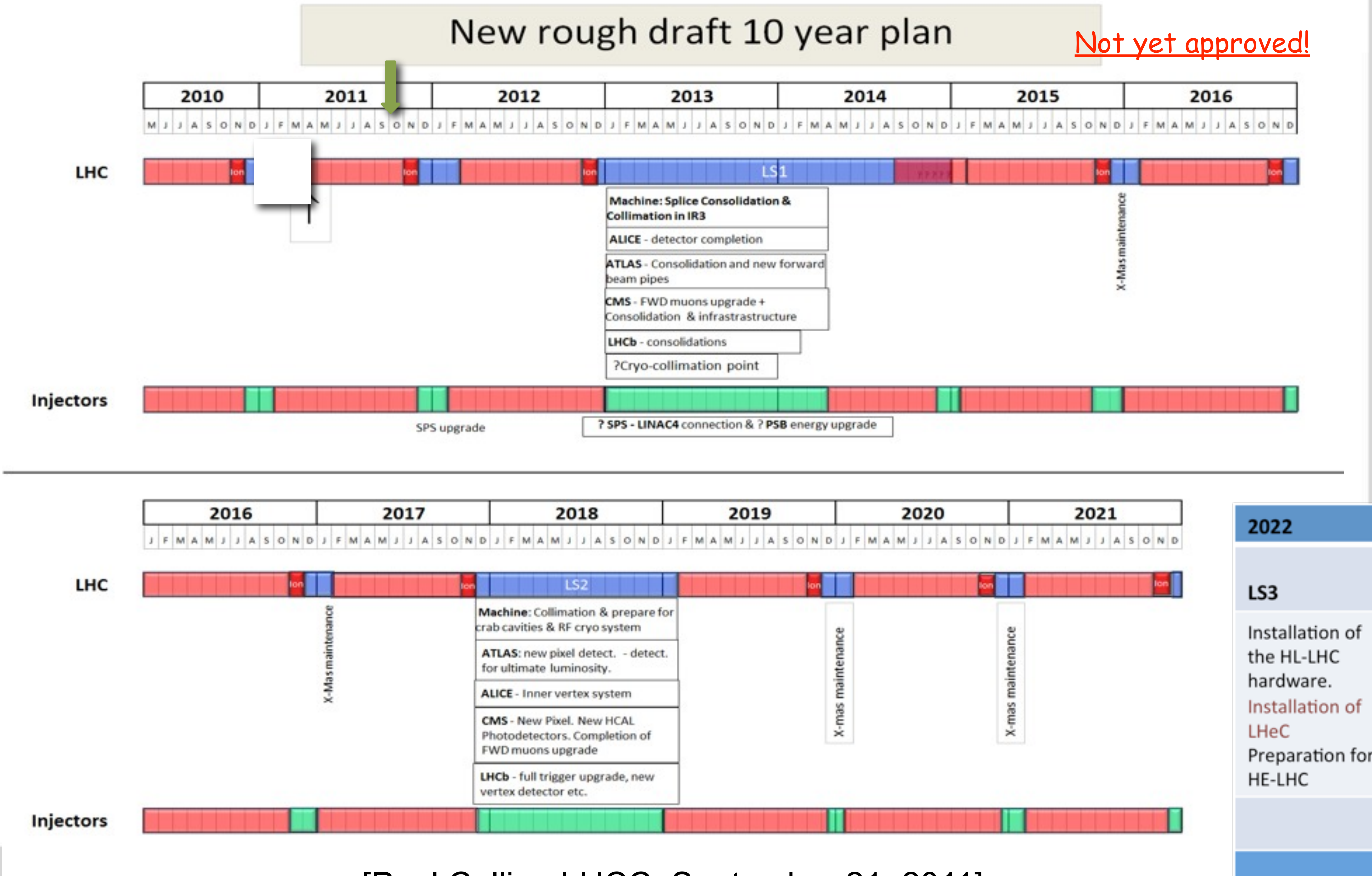
# LHC High Luminosity Upgrade: Physics Case

Karlsruhe Institute of Technology



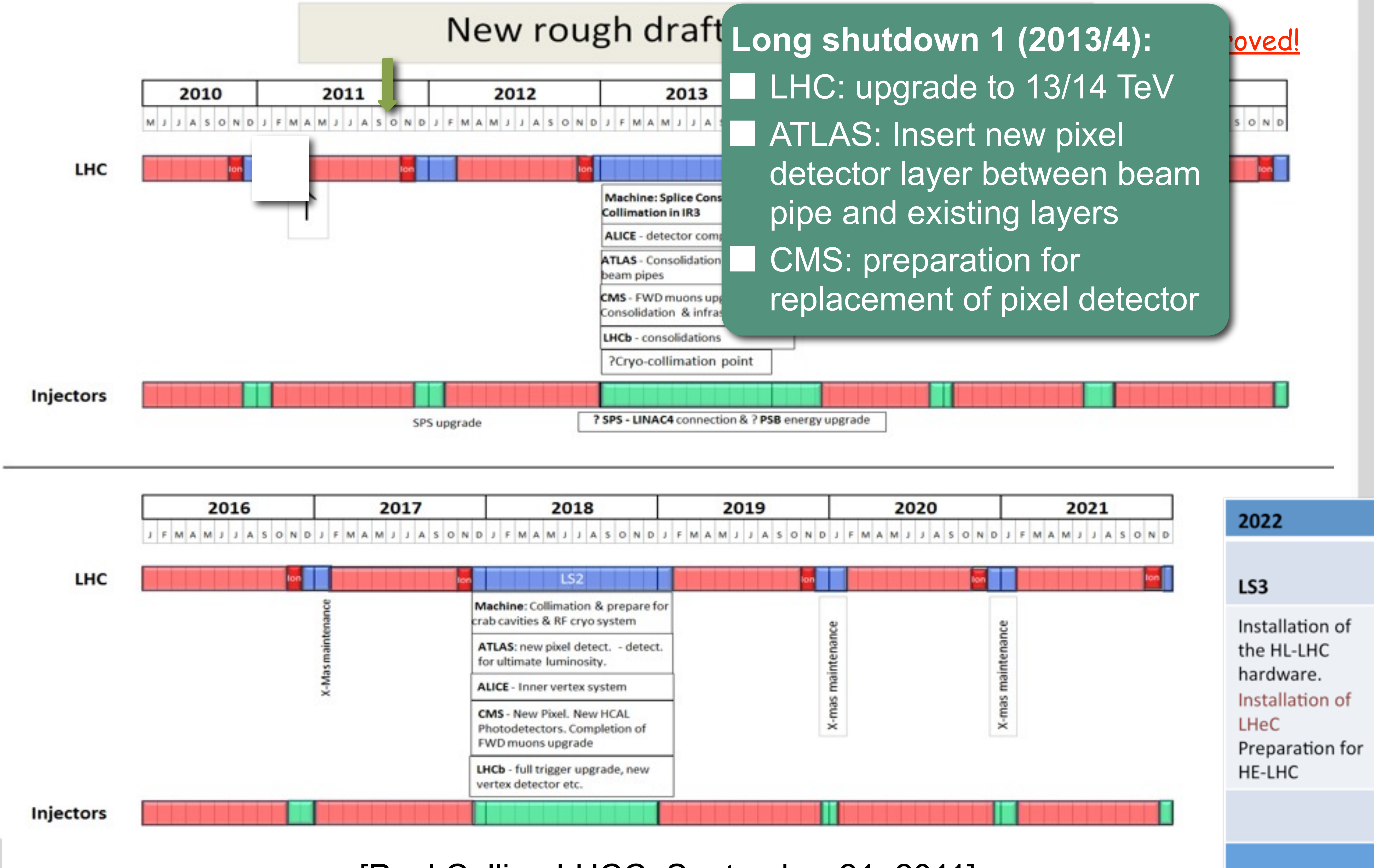

- CERN: long-term commitment to LHC
- Goal: deliver 3000 fb$^{-1}$ of integrated luminosity by 2030 → at least 5× increase in instantaneous luminosity
- Detectors must be upgraded: old detector aging and radiation damage, performance and radiation hardness at high luminosity

# Longer Term Planning




[Paul Collier, LHCC, September 21, 2011]

# Longer Term Planning



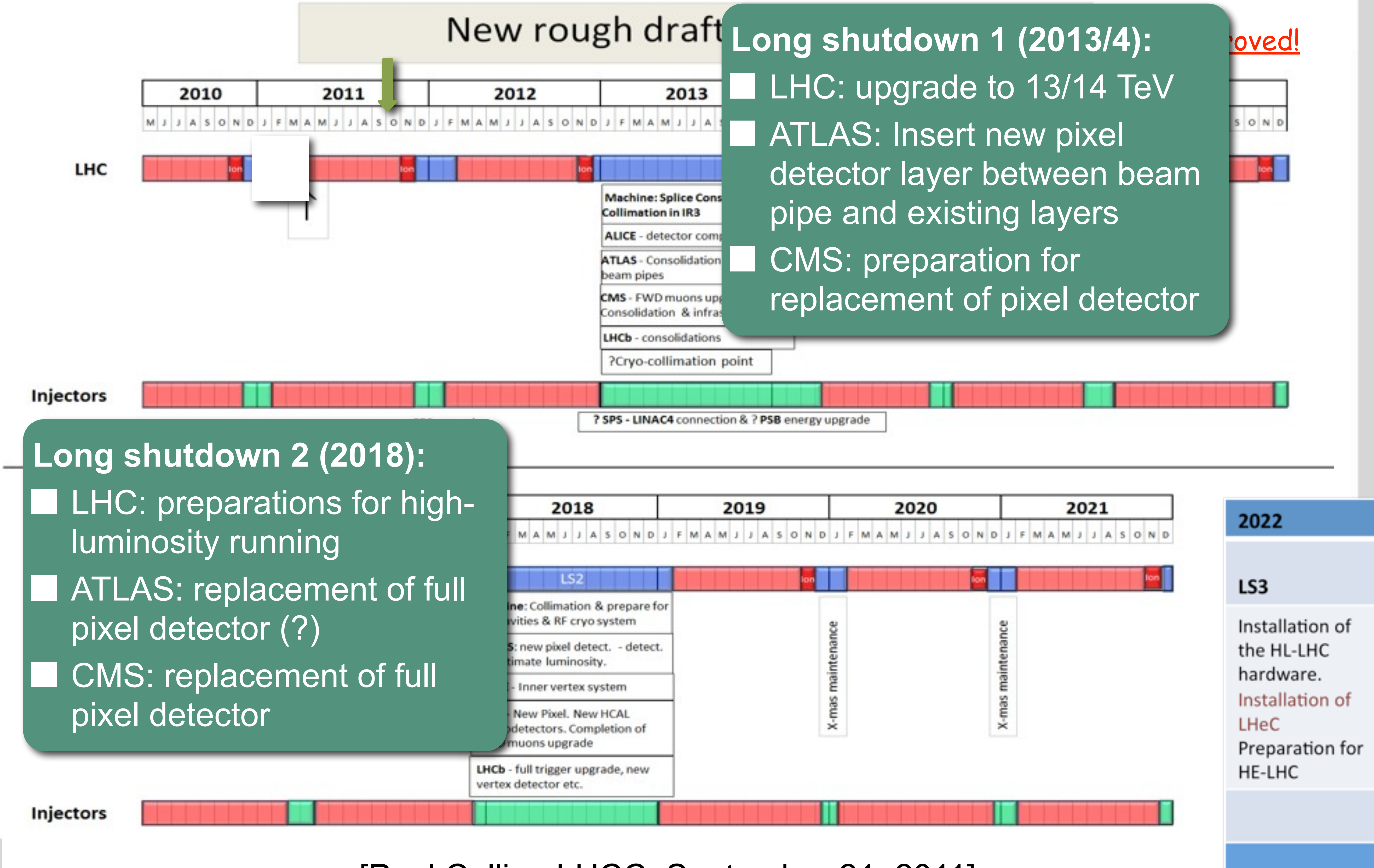

**Long shutdown 1 (2013/4):**

- LHC: upgrade to 13/14 TeV
- ATLAS: Insert new pixel detector layer between beam pipe and existing layers
- CMS: preparation for replacement of pixel detector

[Paul Collier, LHCC, September 21, 2011]

# Longer Term Planning

Karlsruhe Institute of Technology

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**Long shutdown 2 (2018):**

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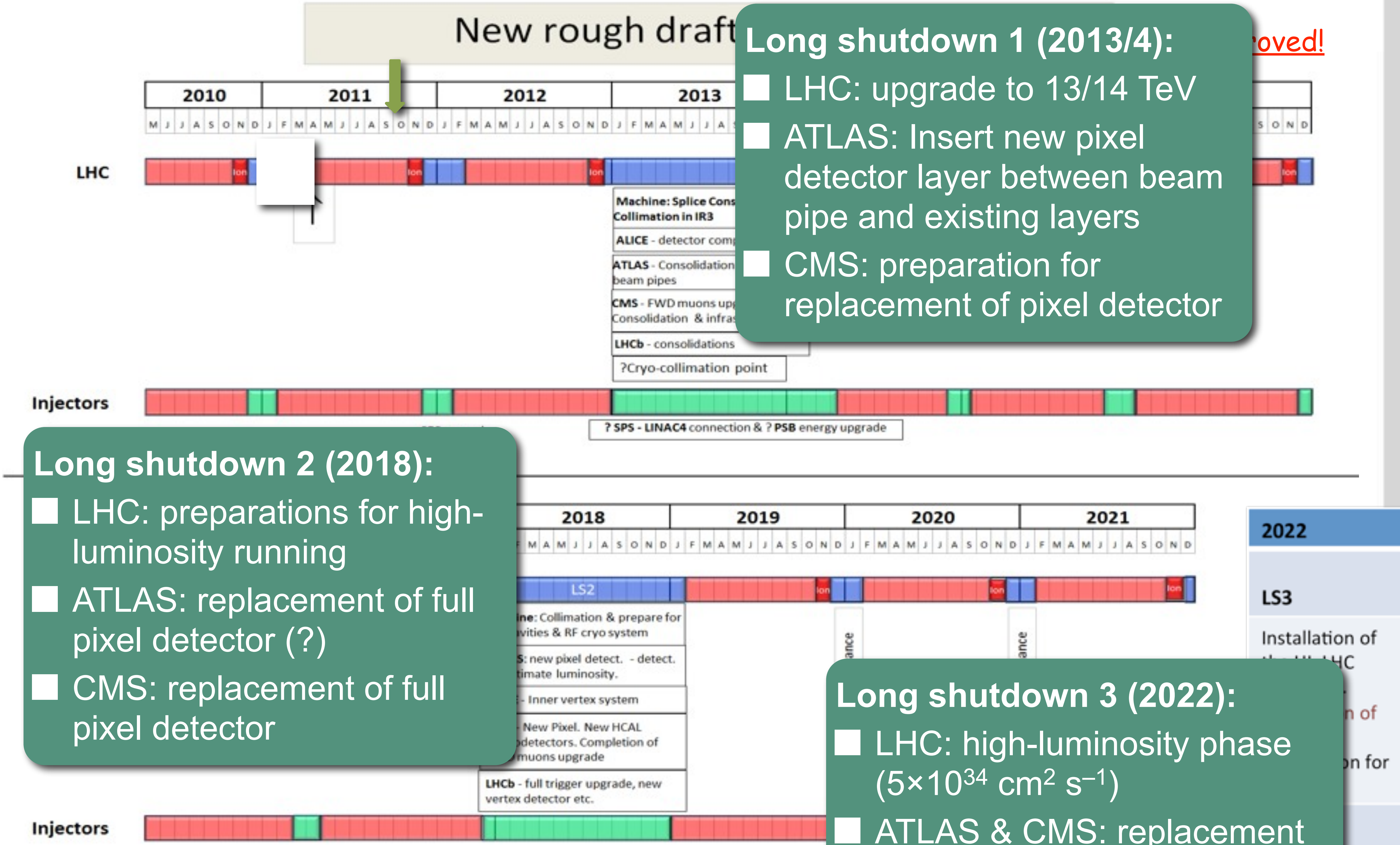
- ATLAS: replacement of full pixel detector (?)
- CMS: replacement of full pixel detector

[Paul Collier, LHCC, September 21, 2011]

# Longer Term Planning

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- ATLAS: replacement of full pixel detector (?)
- CMS: replacement of full pixel detector

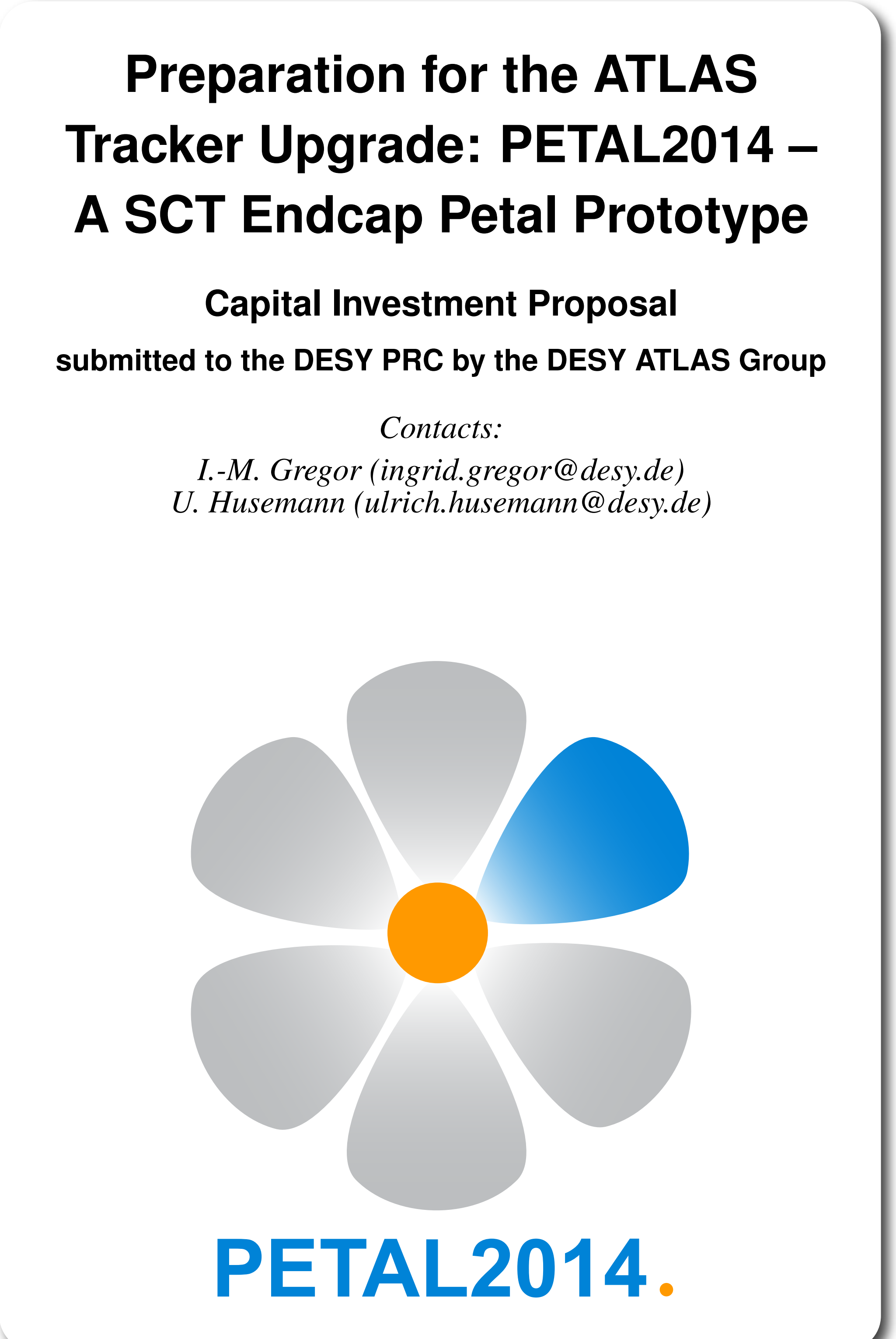
**Long shutdown 3 (2022):**

- LHC: high-luminosity phase ($5\times10^{34}$ $cm^2$ $s^{-1}$)
- ATLAS & CMS: replacement of all tracking detectors

[Paul Collier, LHCC, Septembe

# LS3: New Trackers

Karlsruhe Institute of Technology


**Preparation for the ATLAS Tracker Upgrade: PETAL2014 – A SCT Endcap Petal Prototype**

**Capital Investment Proposal**

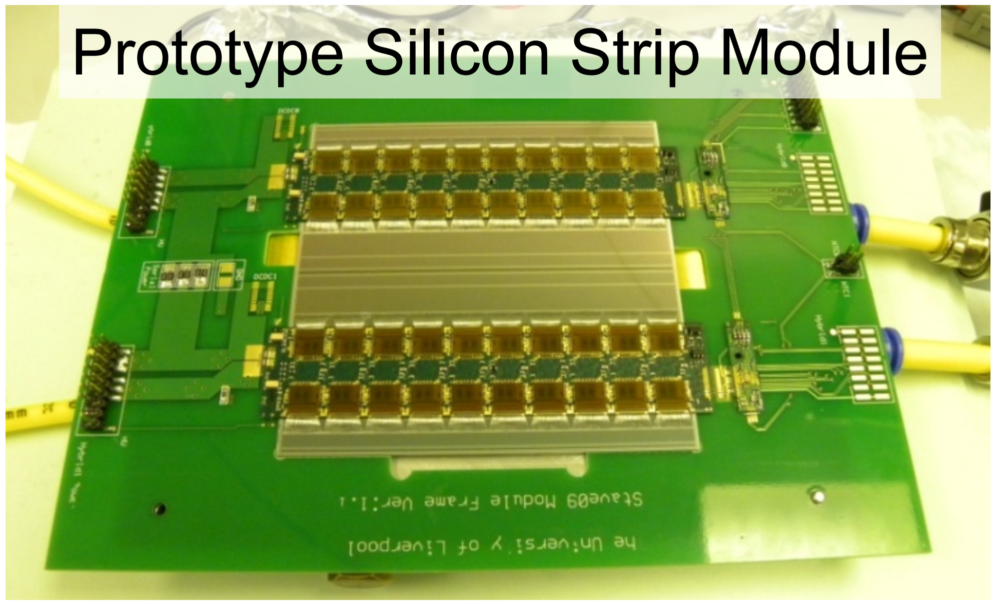
**submitted to the DESY PRC by the DESY ATLAS Group**

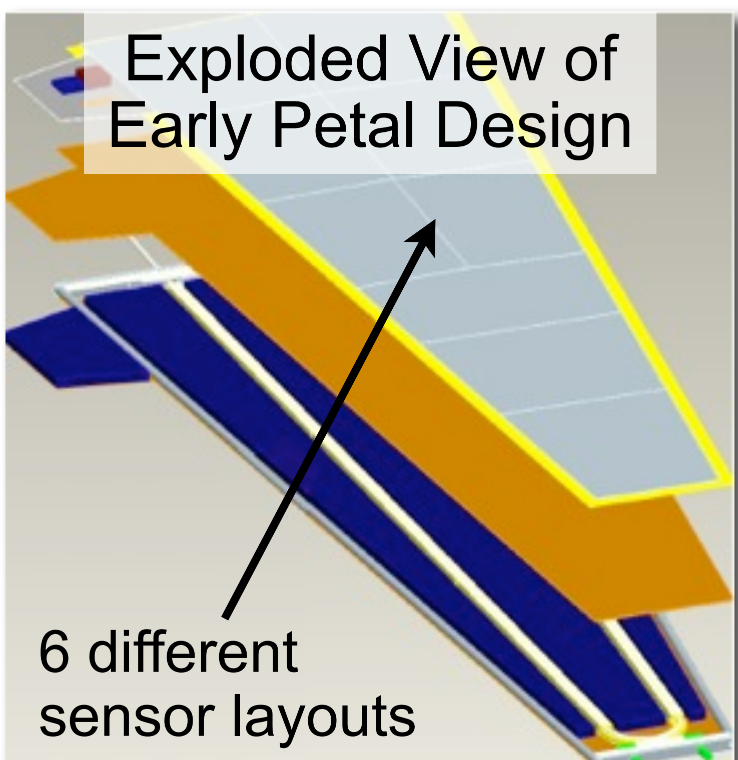
*Contacts:*
*I.-M. Gregor (ingrid.gregor@desy.de)*
*U. Husemann (ulrich.husemann@desy.de)*

**PETAL2014.**

- Long shutdown 3: ATLAS (and CMS) replaces entire tracking system
  - Current ATLAS tracking: silicon pixels – silicon strips (SCT) – transition radiation tracker (TRT)
  - Replacement: all-silicon tracker with higher granularity
- DESY involvement: endcaps of the new silicon strip detector
  - Geometry: wheels made out of 32 “petals” (diameter: 2 meters)
  - Development of light-weight petals: silicon strip module + readout cables glued on a light-weight carbon fiber structure with cooling tubes embedded
  - Currently: construction and tests of prototype detector modules

# LS3: New Trackers

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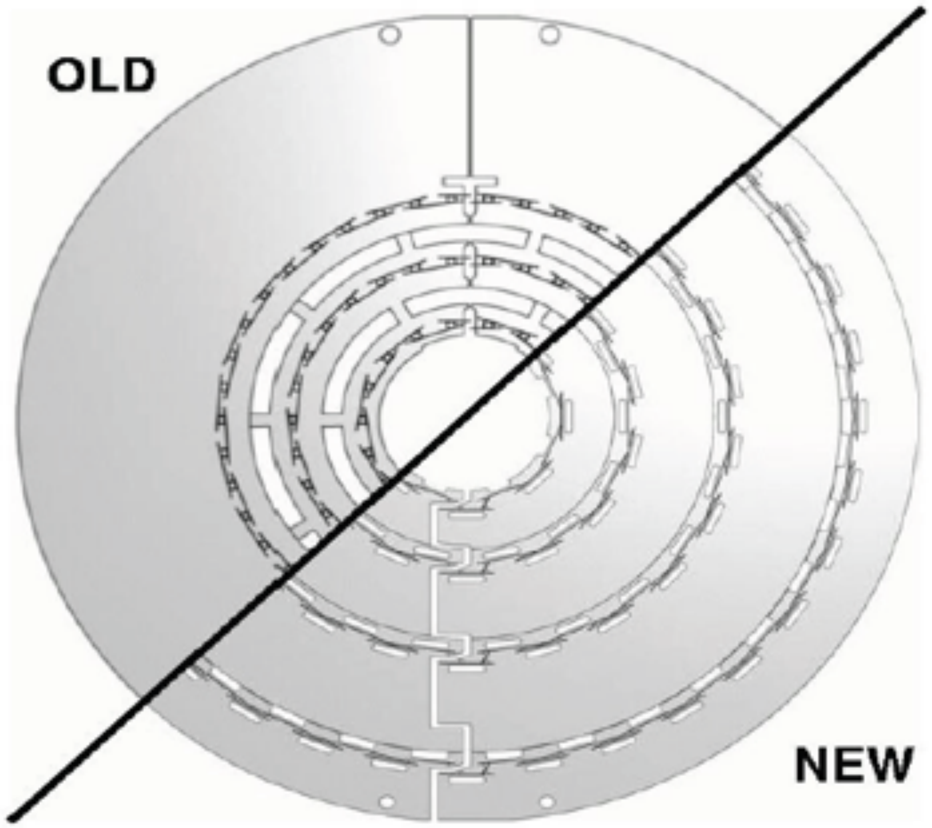
# LS2: CMS Pixel Detector Replacement

Current CMS Barrel Pixel Detector




- Motivation
  - Current detector suffering from aging and radiation damage → replace, add redundancy
  - Need to cope with much larger number of particles per bunch crossing than today → more readout channels
- Upgrade plans
  - New geometry: 3 layers → 4 layers, innermost layer closer to collision point, outermost layer further away
  - One advantage: better resolution for impact parameters of charged particle track → improved B-tagging
  - Basic building blocks: pixel modules → only small changes (next slide)
  - To be installed around 2016–2018 → (almost) plug & play

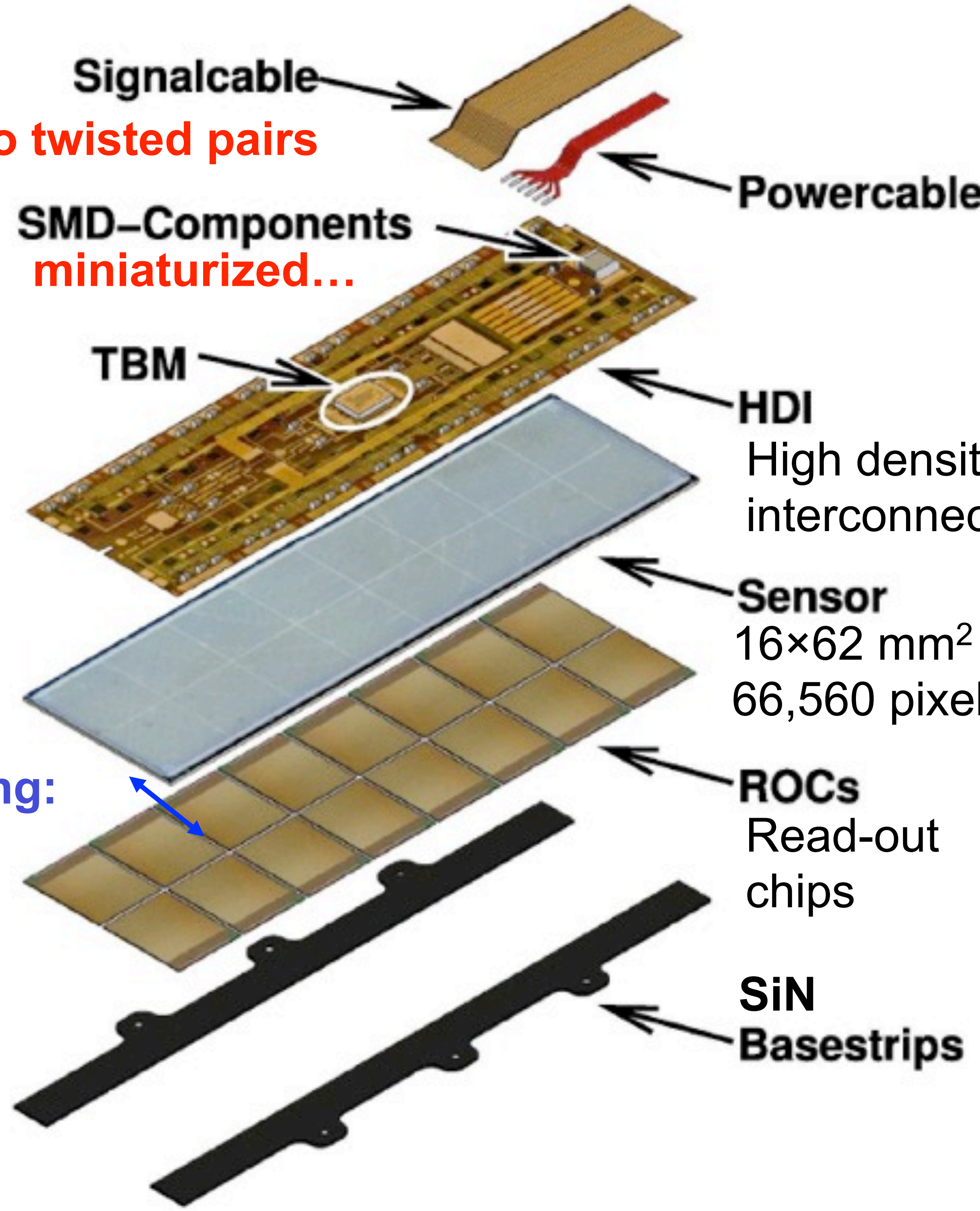
# CMS Barrel Pixel Module

upgrade: micro twisted pairs

miniaturized…

Token bit manager

bump bonding:

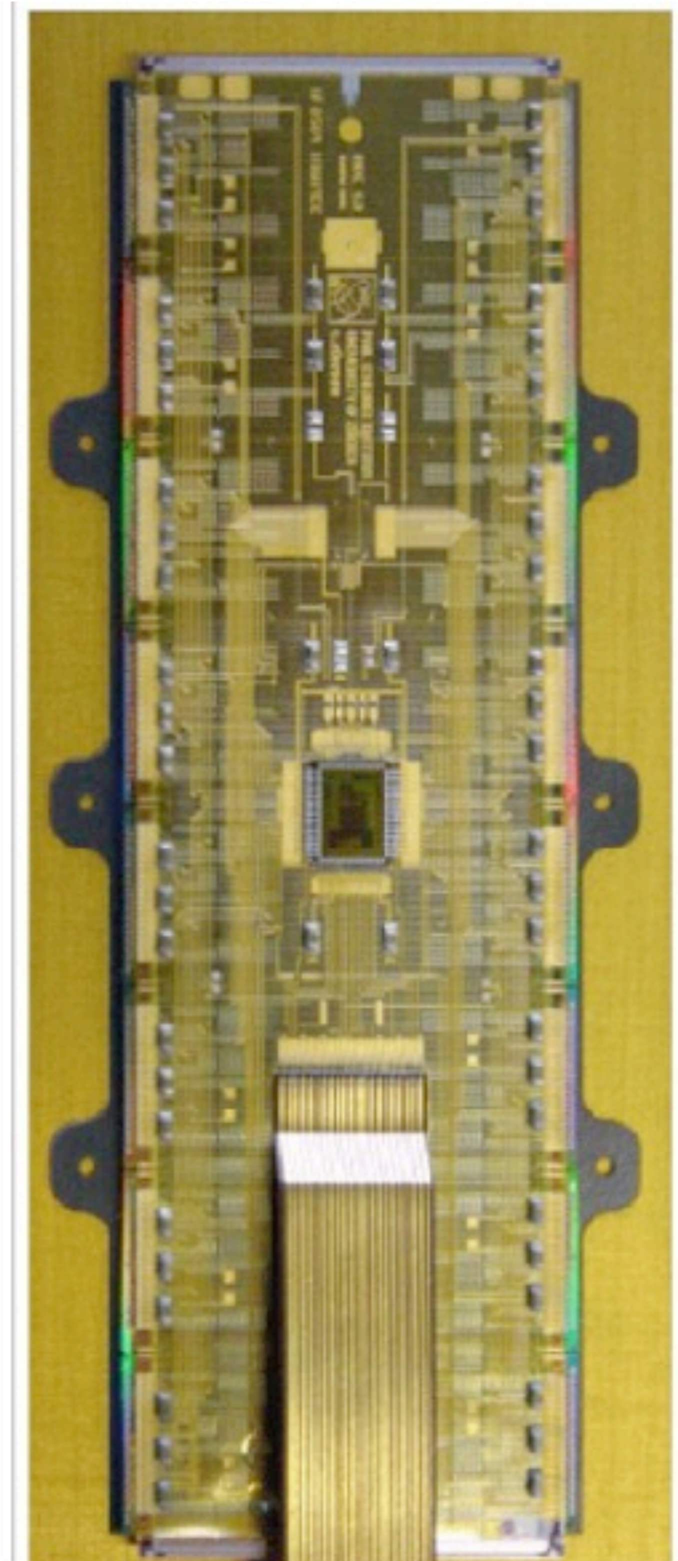



HDI: High density interconnect

Sensor: $16 \times 62$ mm$^2$, 66,560 pixels

ROCs: Read-out chips

[G. Steinbrück after W. Erdmann]



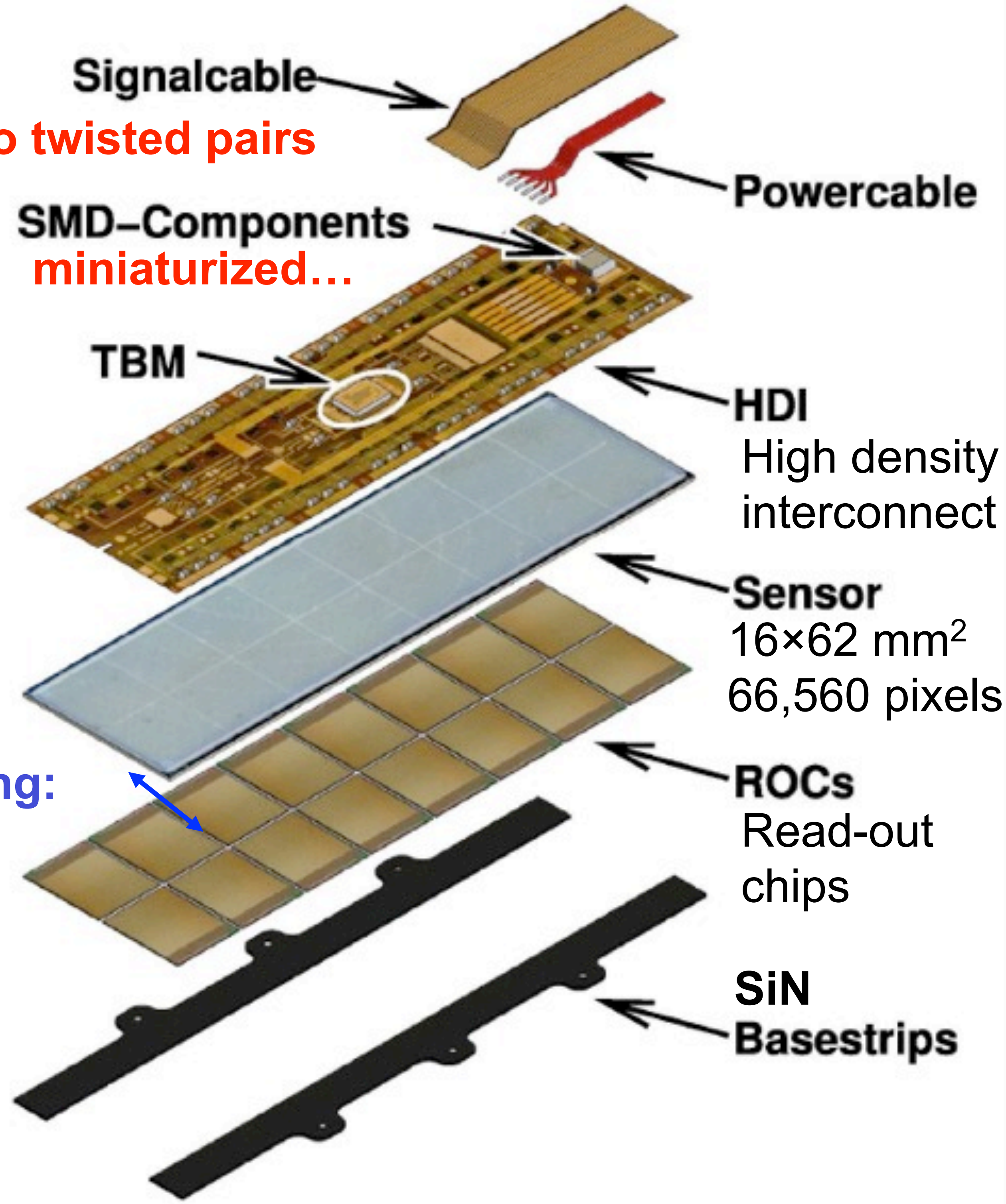
full–module ≙ 16 ROCs

# CMS Barrel Pixel Module

upgrade: micro twisted pairs

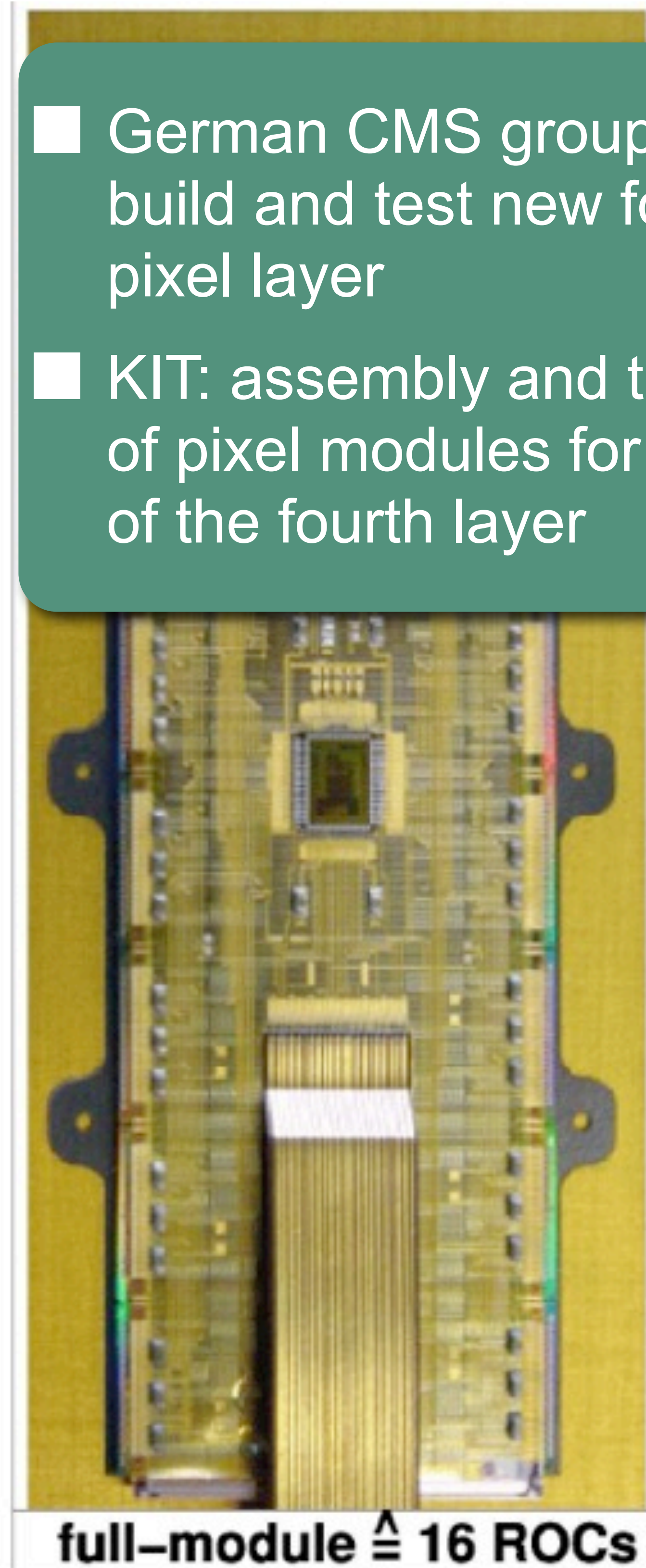
Token bit manager

bump bonding:




[G. Steinbrück after W. Erdmann]

- German CMS groups: build and test new fourth pixel layer
- KIT: assembly and tests of pixel modules for half of the fourth layer



# L'Addition S.V.P.


- Top quark physics:
  key element of LHC physics
  - Challenging decay patterns: prototype for any high-$p_T$ analysis at the LHC
  - Heaviest known elementary particle: key to new physics?
  - Associated top-Higgs production: access to Yukawa couplings
- Silicon detectors: key element of LHC detectors
  - Precision tracking and vertexing, identification of B hadrons
  - Silicon detector upgrades: ensure reliable tracking/vertexing performance in an increasingly harsh hadronic environment