Experimental Physics at Hadron Colliders

CERN Summer Students Lectures, July 24-26, 2024 - Lecture 2/4

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Work Plans

- Lecture 1: Introduction, fundamentals, cross sections
- Lecture 2: Standard model measurements
- Lecture 3: Higgs physics
- Lecture 4: Searches for new physics

Data and Analysis Chain

Detector

On-detector Trigger Electronics

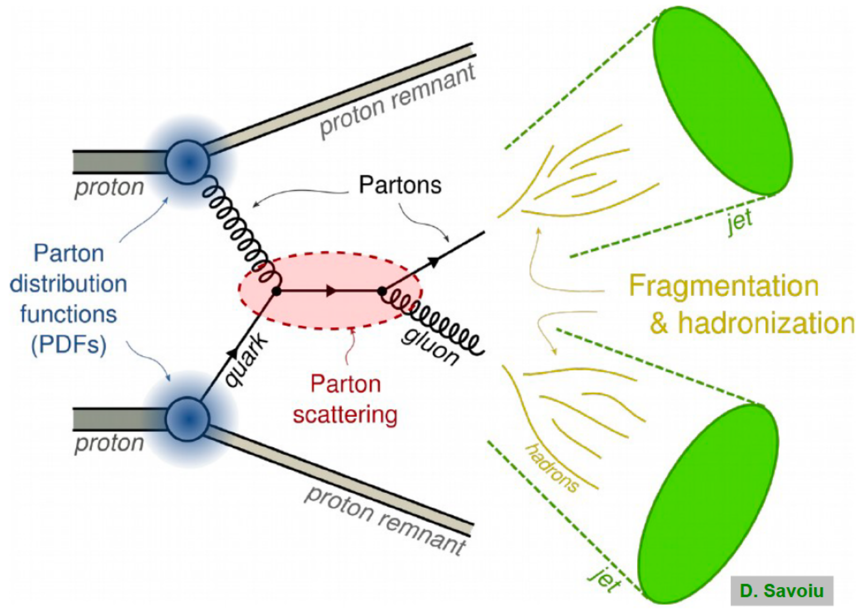
Off-detector Trigger Computing farm

Collision Data

Reconstruction & Data reduction

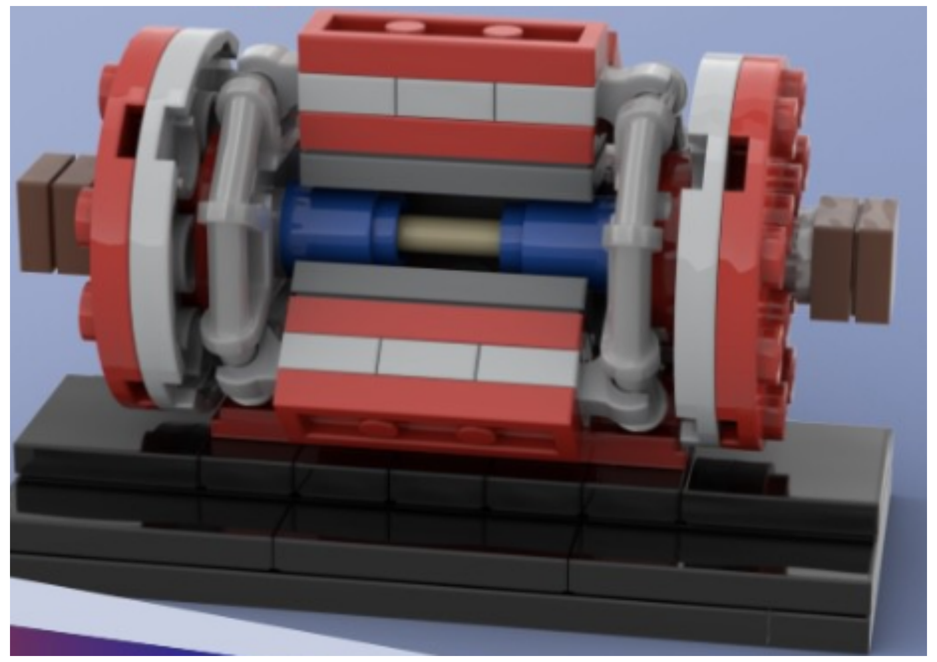
Calibration & alignment

Theory

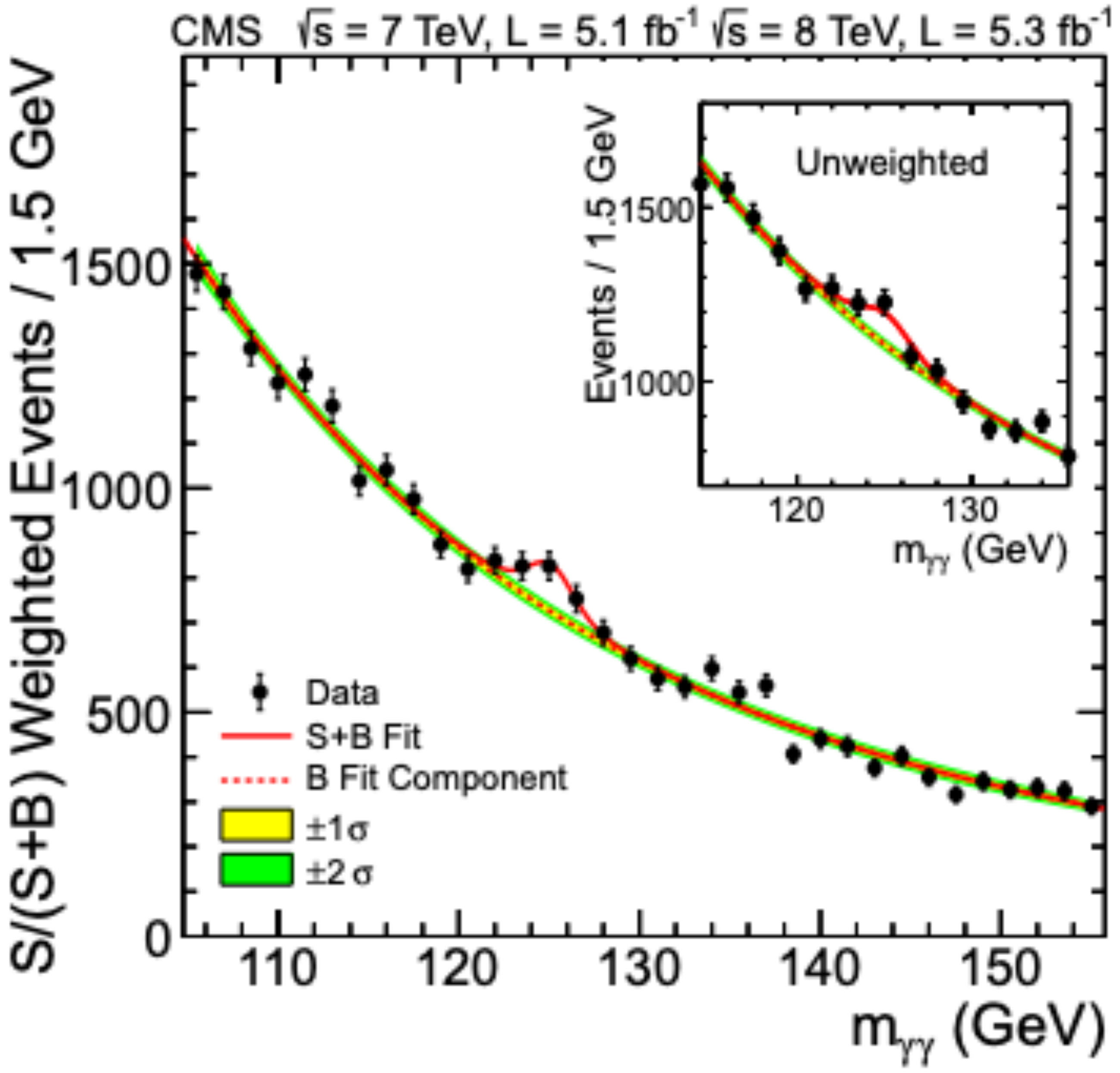


Calculation of physics processes including hadronization

Digital twin (Simulation)



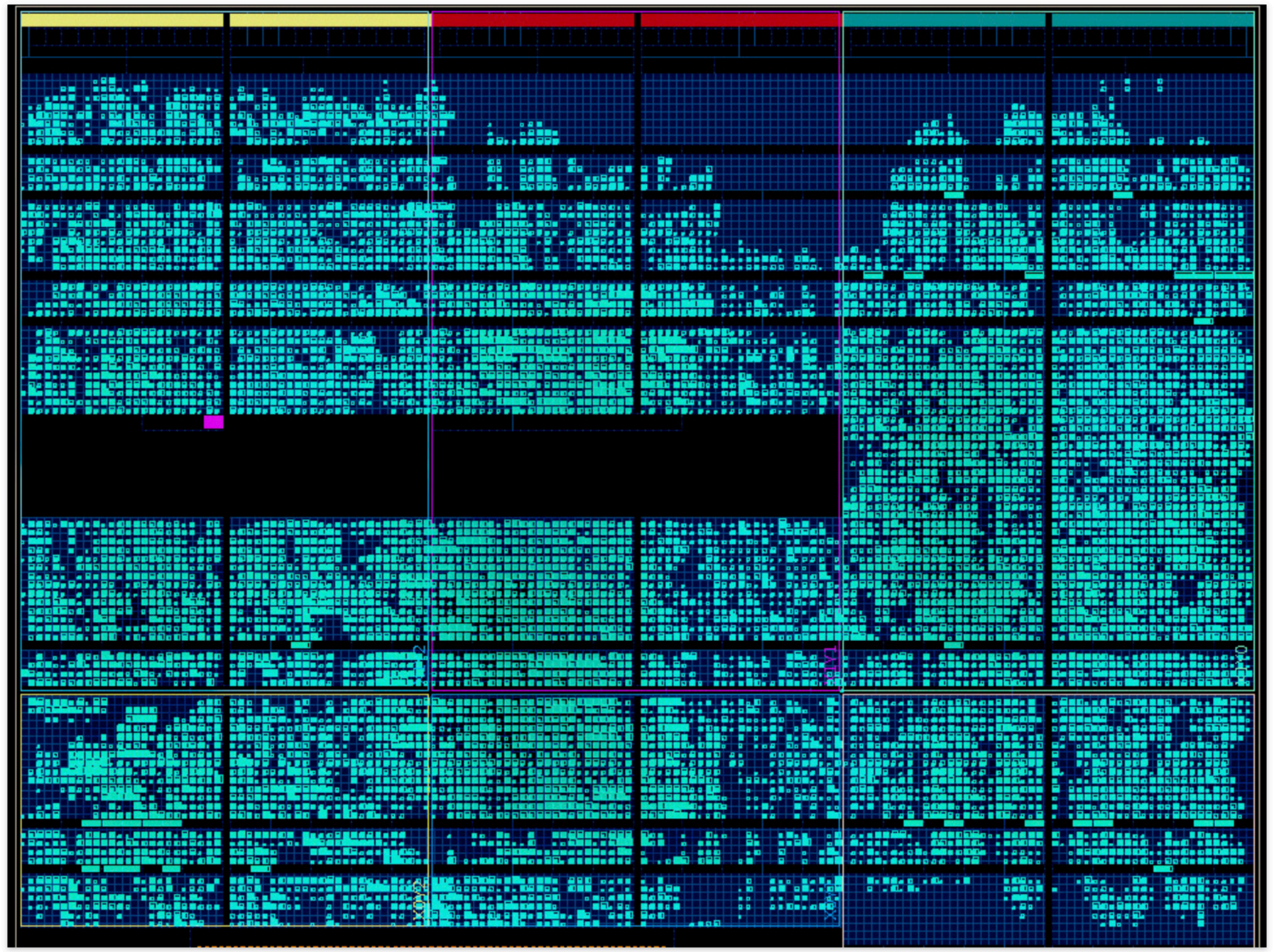
Simulated Data



Statistical analysis

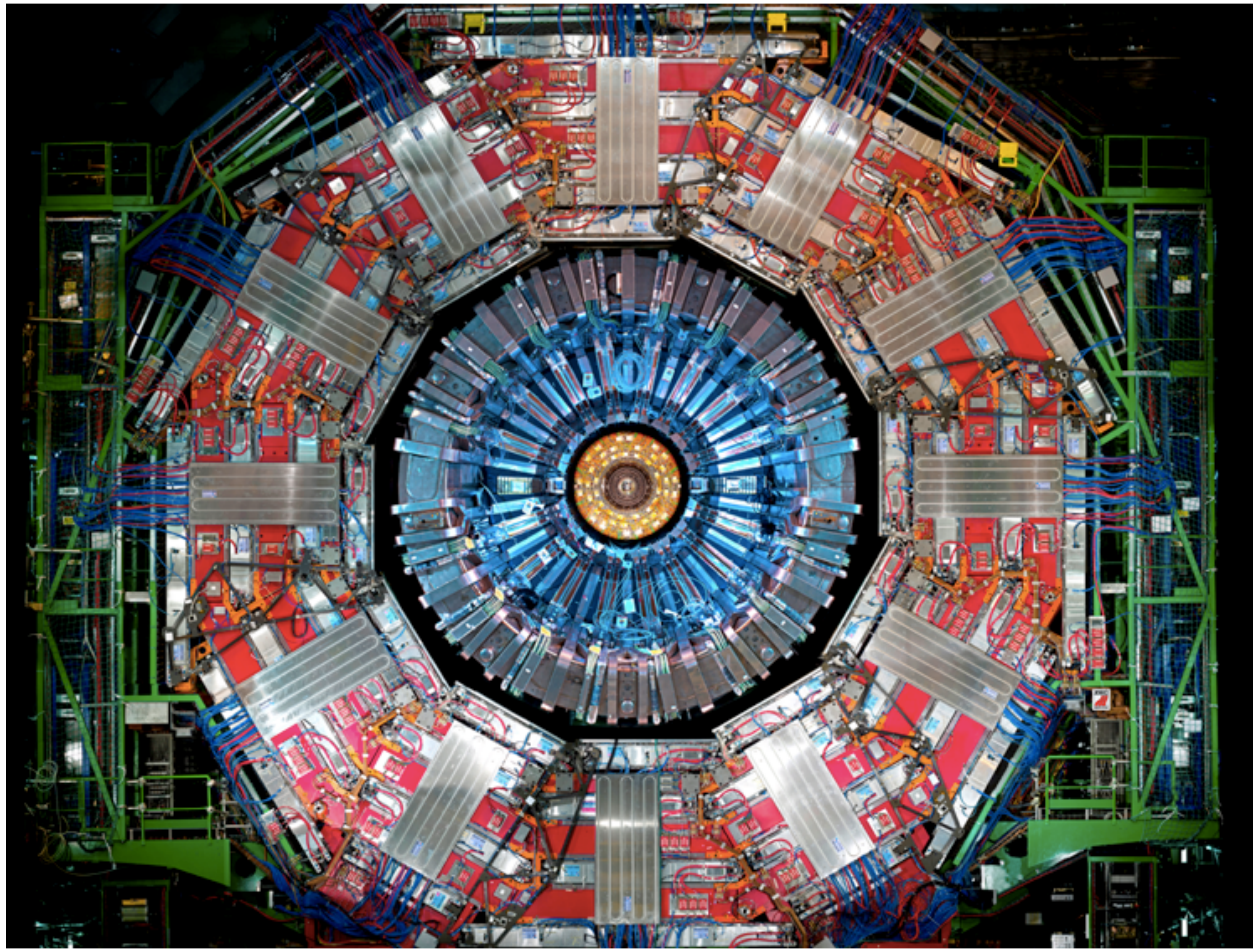
Software & Computing

- LHC computing scale
  - ~1 million cores fully occupied
  - ~1 EB (~500 PB disk, > 500 PB tape)
  - Global networking (~10-100Gbps)
  - ~140 Computing centres in 33 countries
- Challenges
  - Increasing data volume and complexity
  - Maintenance
- Opportunities
  - Heterogeneous computing resources
  - Applications of machine learning



An ultra-compressed deep neural network on a field-programmable gate array. (Image: Sioni P. Summers)

What do we actually reconstruct from collisions?

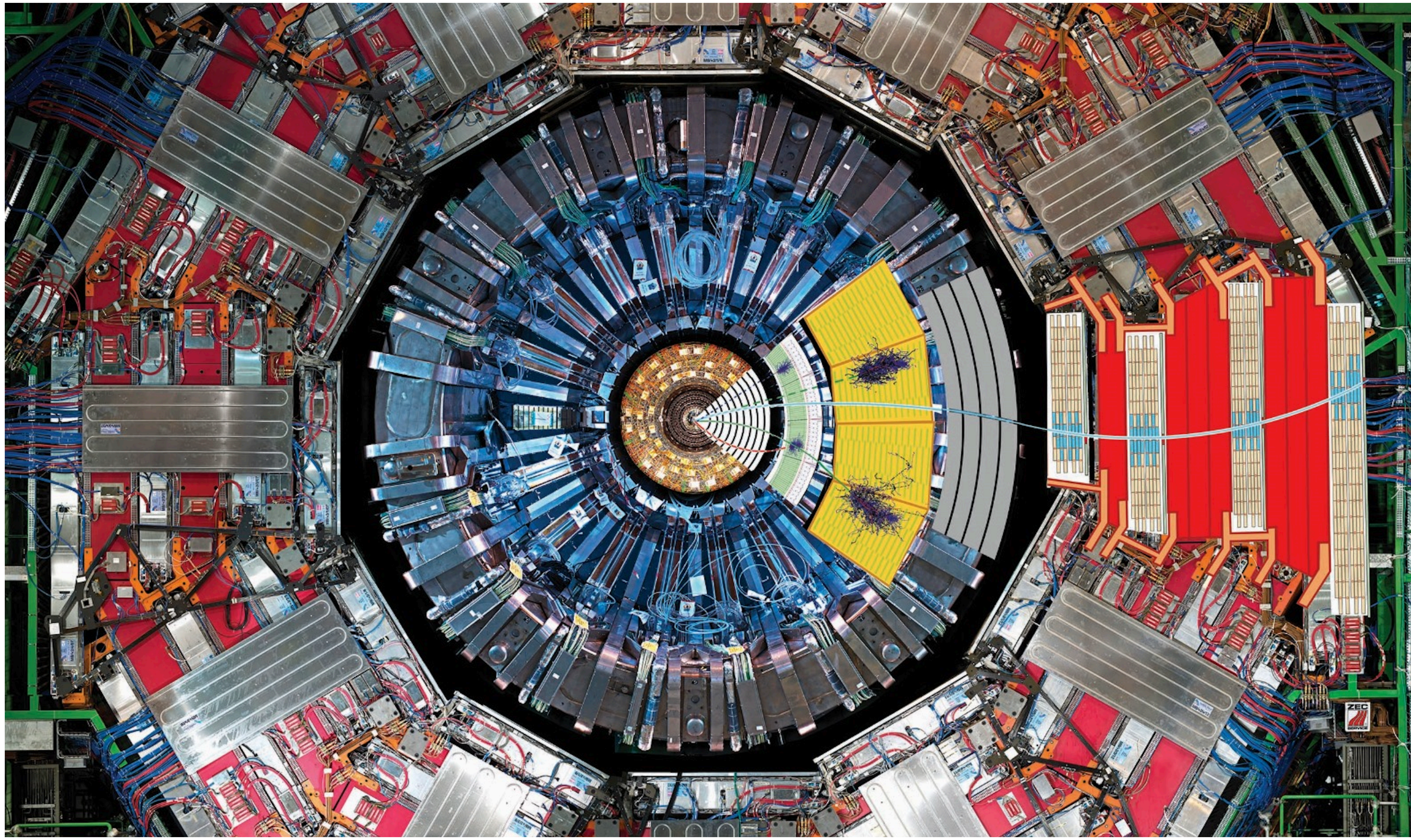


Pingo

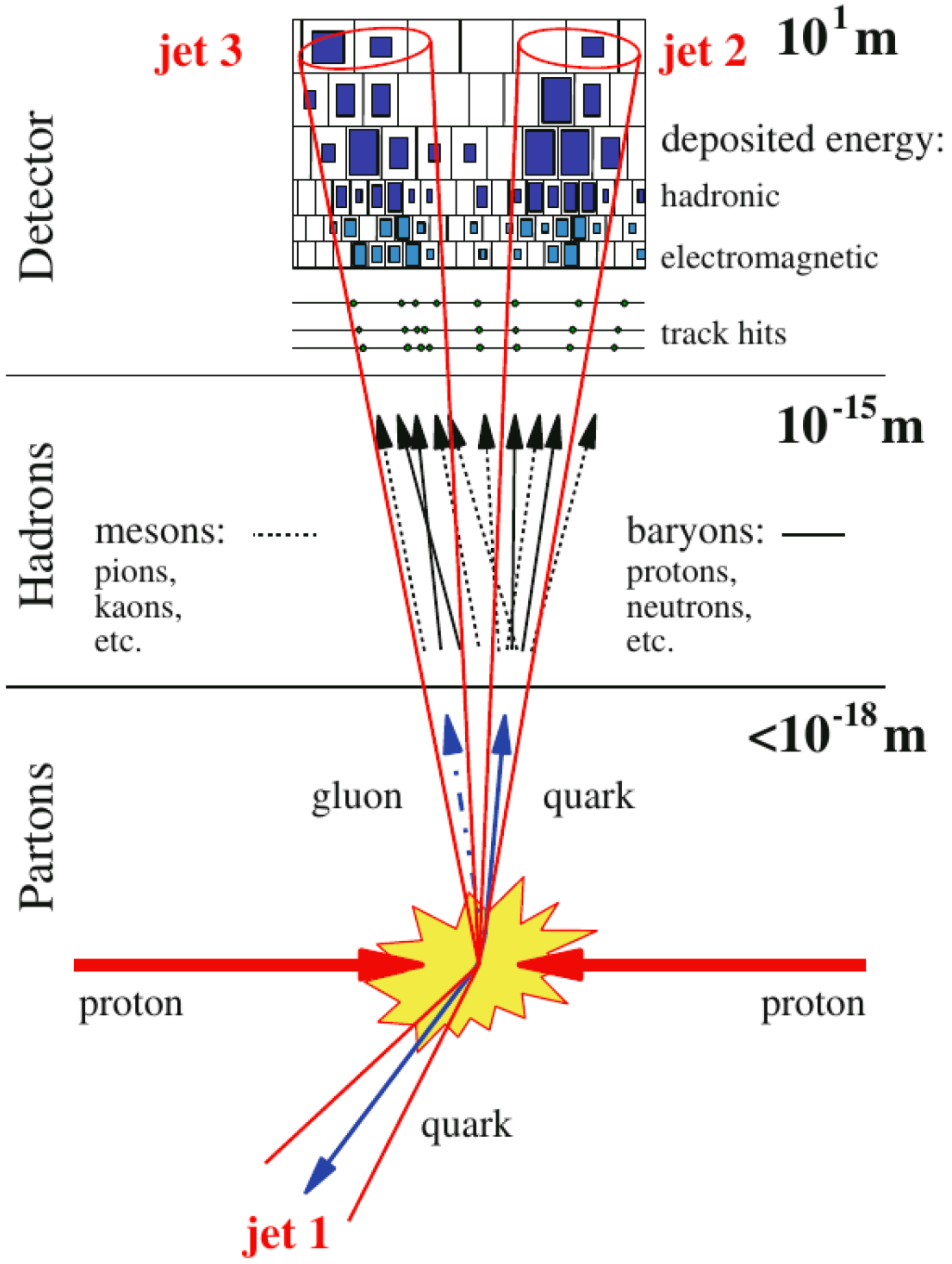
- Which particle does not interact with LHC detectors?
  - 1) proton
  - 2) neutron
  - 3) charged pion
  - 4) neutral pion
  - 5) none of the above

What do we actually reconstruct from collisions?

- Energy and momenta of "stable" particles
  - Electrons, positrons, muons, anti-muons, charged hadrons
  - Photons, neutral hadrons
- Identify particle species
  - Including reconstruction of "unstable" particles from decay products
- Assign proton-proton collisions (pile-up removal)



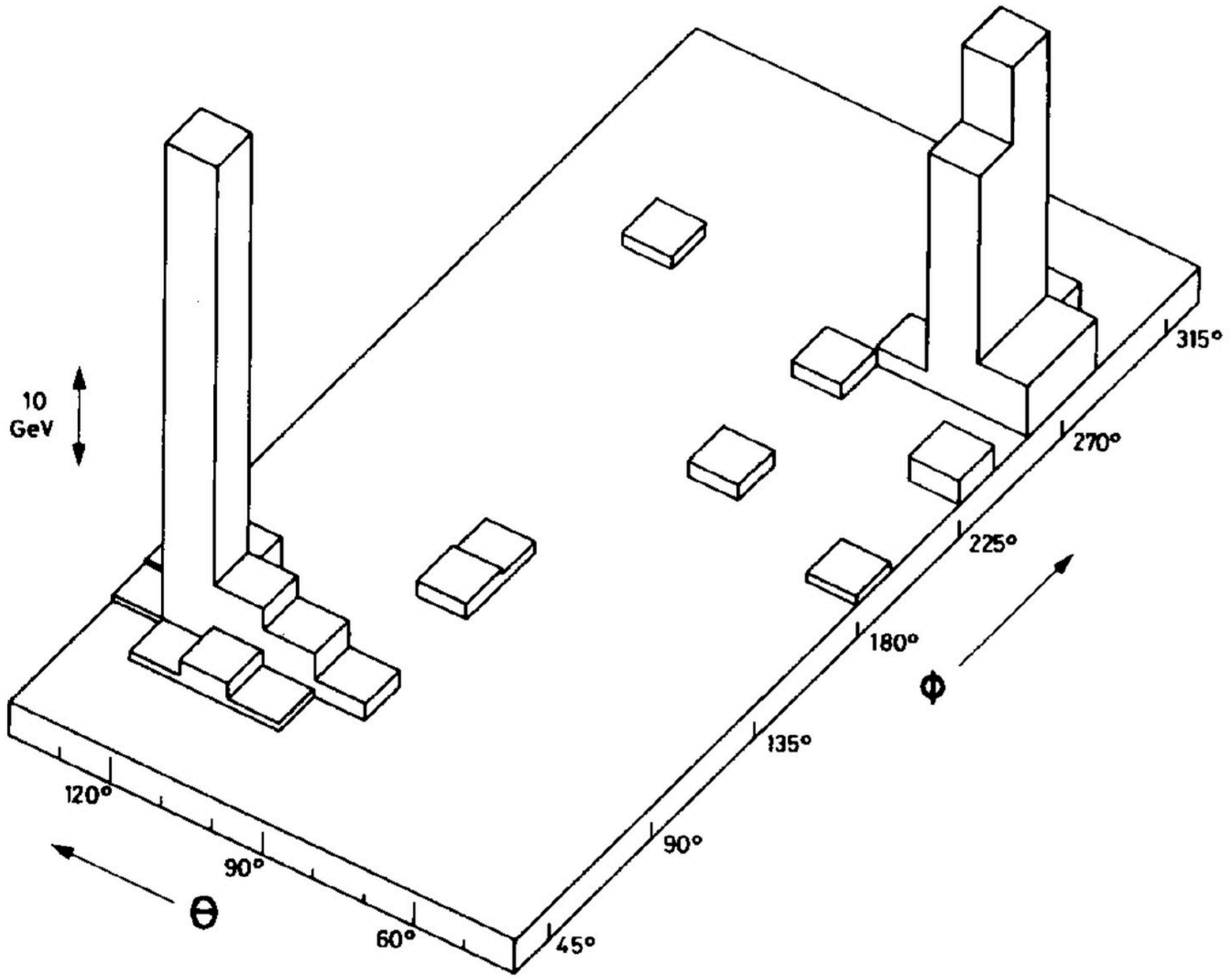
Jets at Hadron Collider



Jet History

- Di-jet events with clearly separated energy depositions
  - "Jet algorithm" based on cell structure of calorimeters (UA1 & UA2)
  - UA1 later also used a cone algorithm with

$$R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



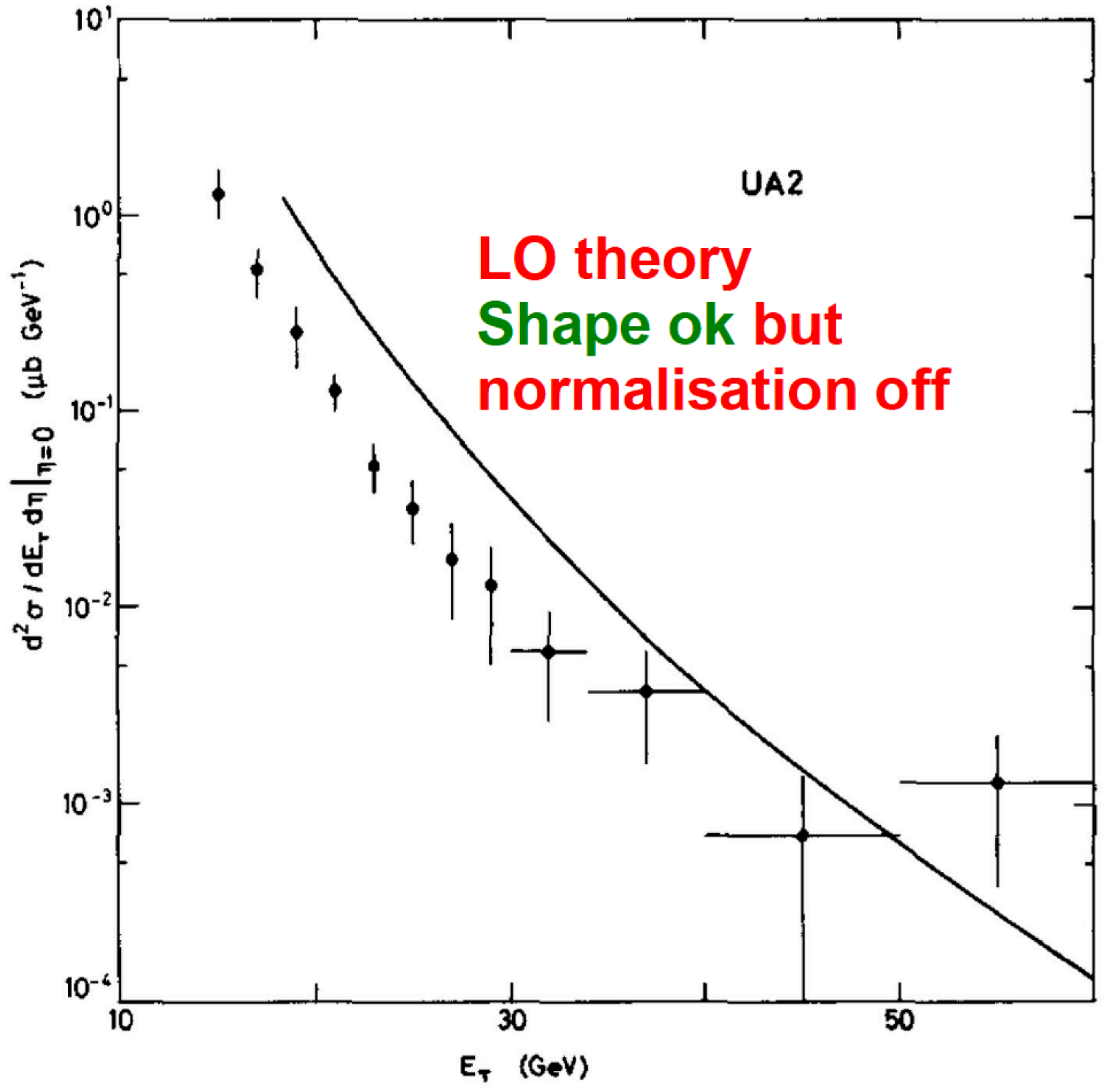
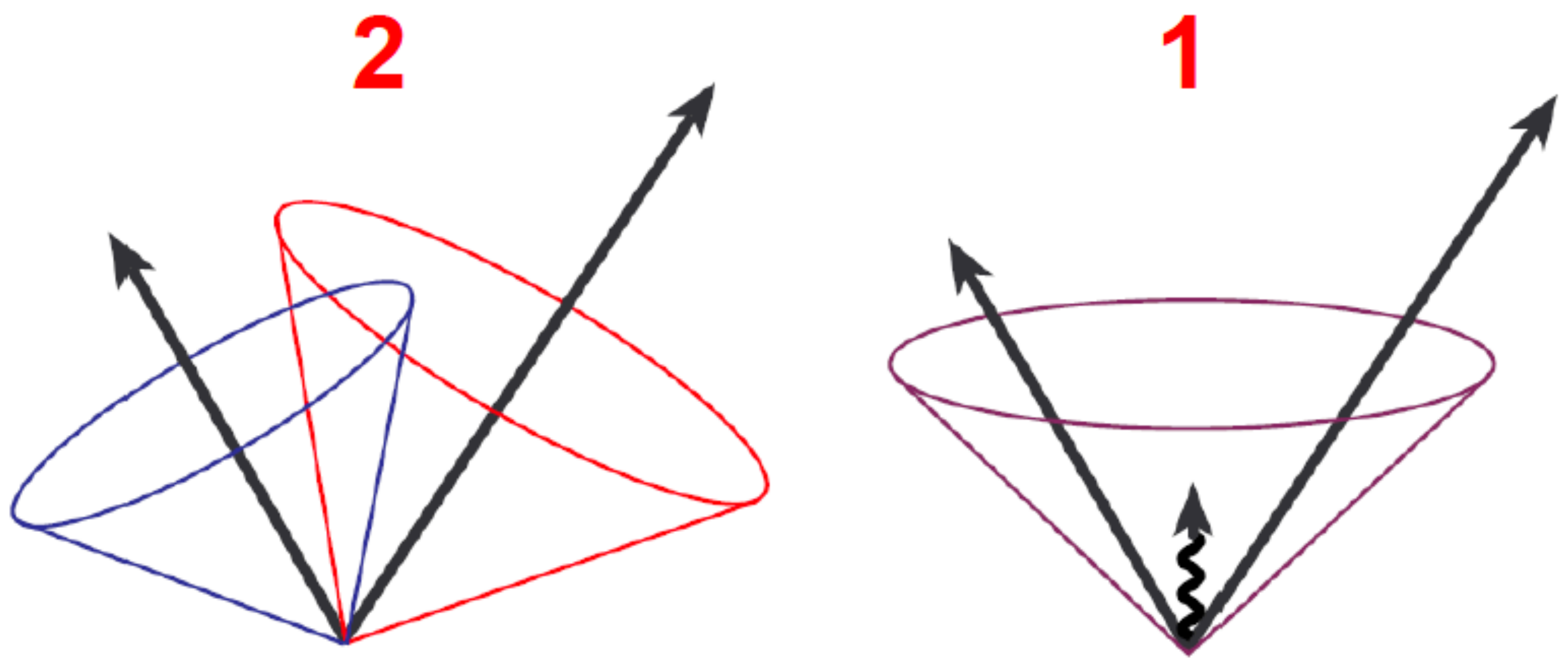


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

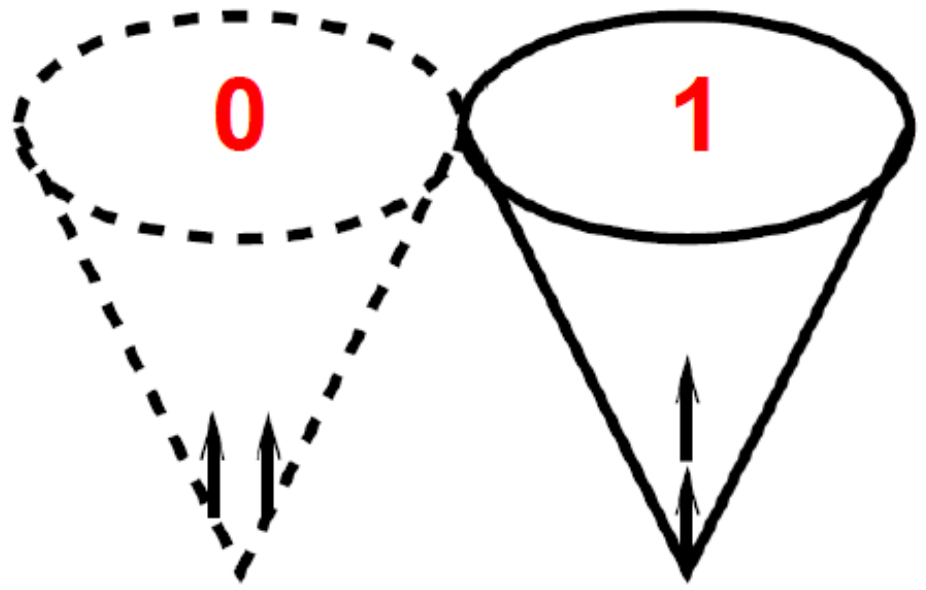
UA2, PLB 118 (1982).

Jets at Hadron Collider

- Primary goal is to find correspondence between
  - Detector measurements
  - Particles in final state
  - Hard partons
- Classes of algorithms
  - Cone algorithms
  - Sequential recombination
- Requirements
  - Infrared and collinear safe
  - Order independence
  - Ease of implementation



IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

Jets at Hadron Collider

- Primary goal is to find correspondence between
  - Detector measurements
  - Particles in final state
  - Hard partons
- Classes of algorithms
  - Cone algorithms
  - Sequential recombination
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  - Infrared and collinear safe
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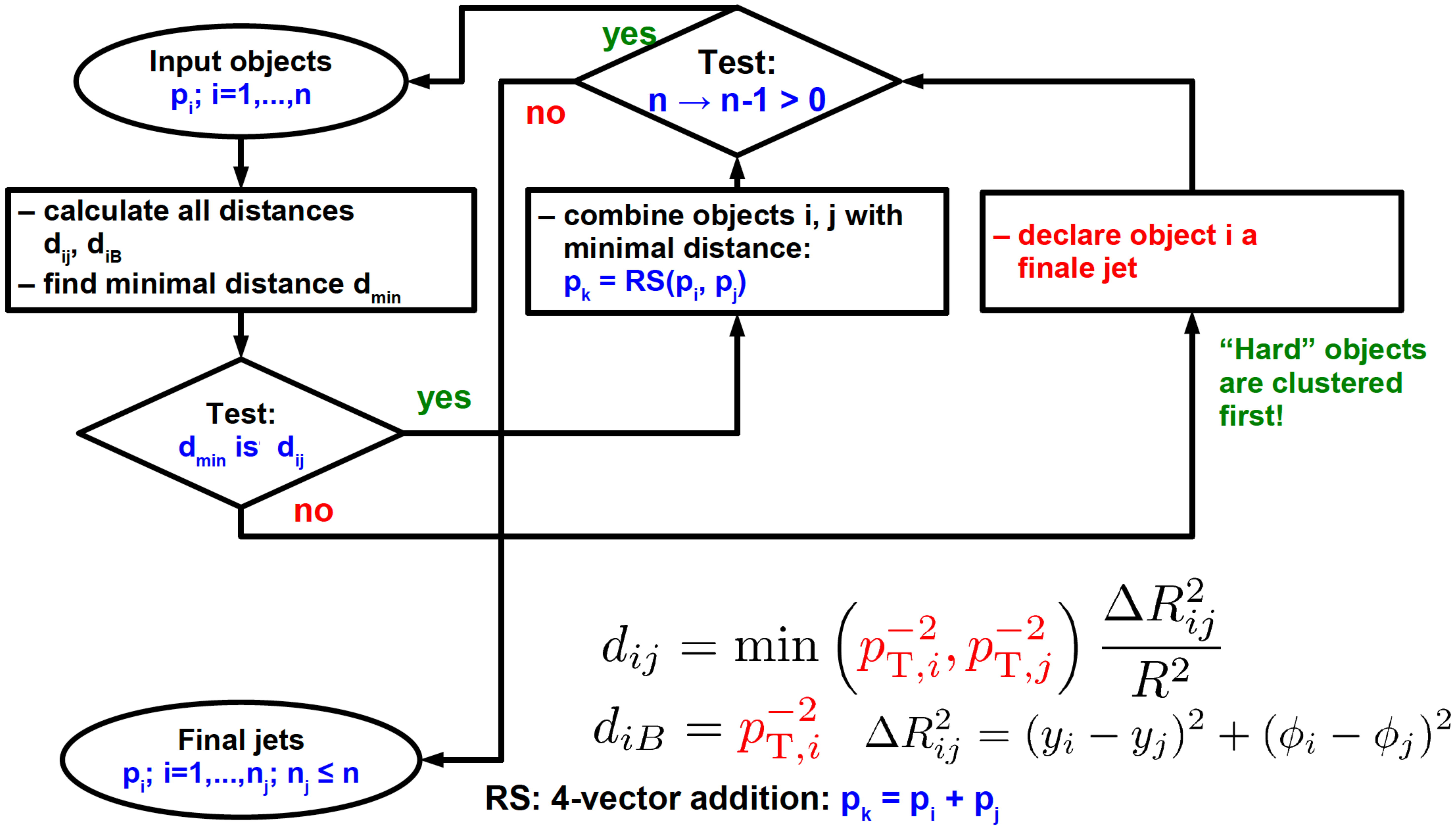
Anti-kT algorithm



$$d_{ij} = \min\left(p_{T,i}^{-2}, p_{T,j}^{-2}\right) \frac{\Delta R_{ij}^2}{R^2}$$

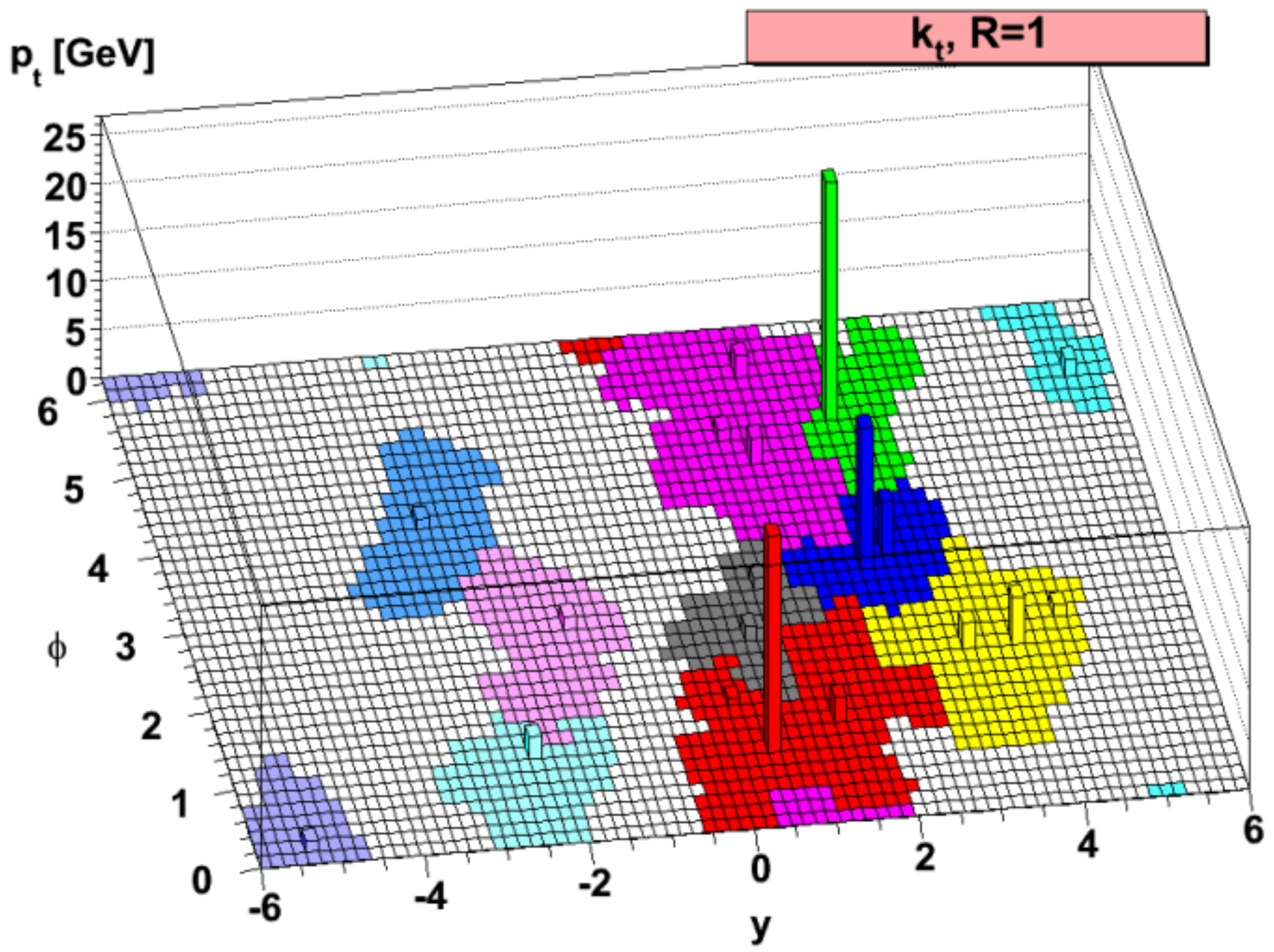
$$d_{iB} = p_{T,i}^{-2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

RS: 4-vector addition: $p_k = p_i + p_j$

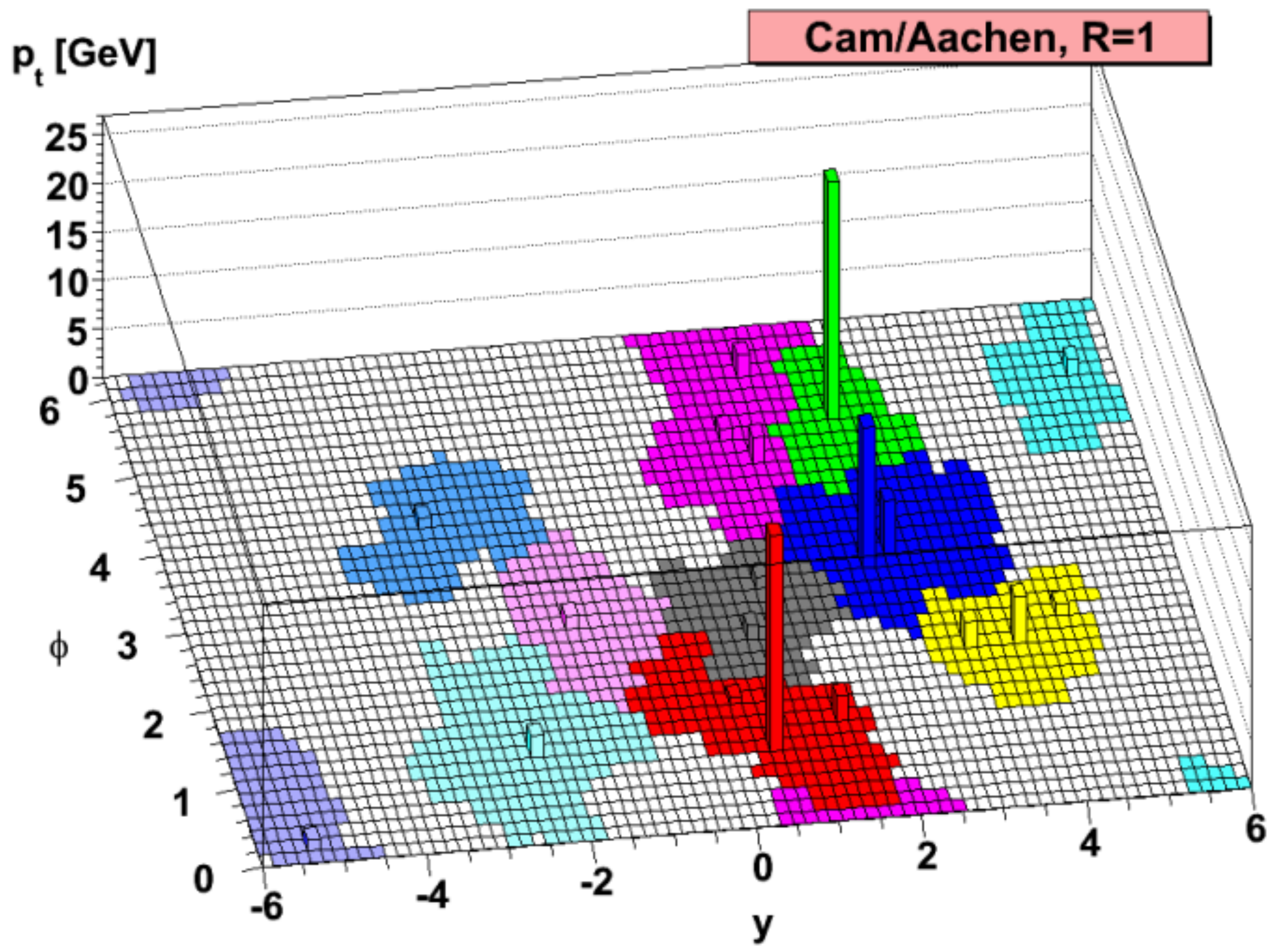
Cacciari, Salam, Soyez, JHEP04 (2008).

Jets at Hadron Collider

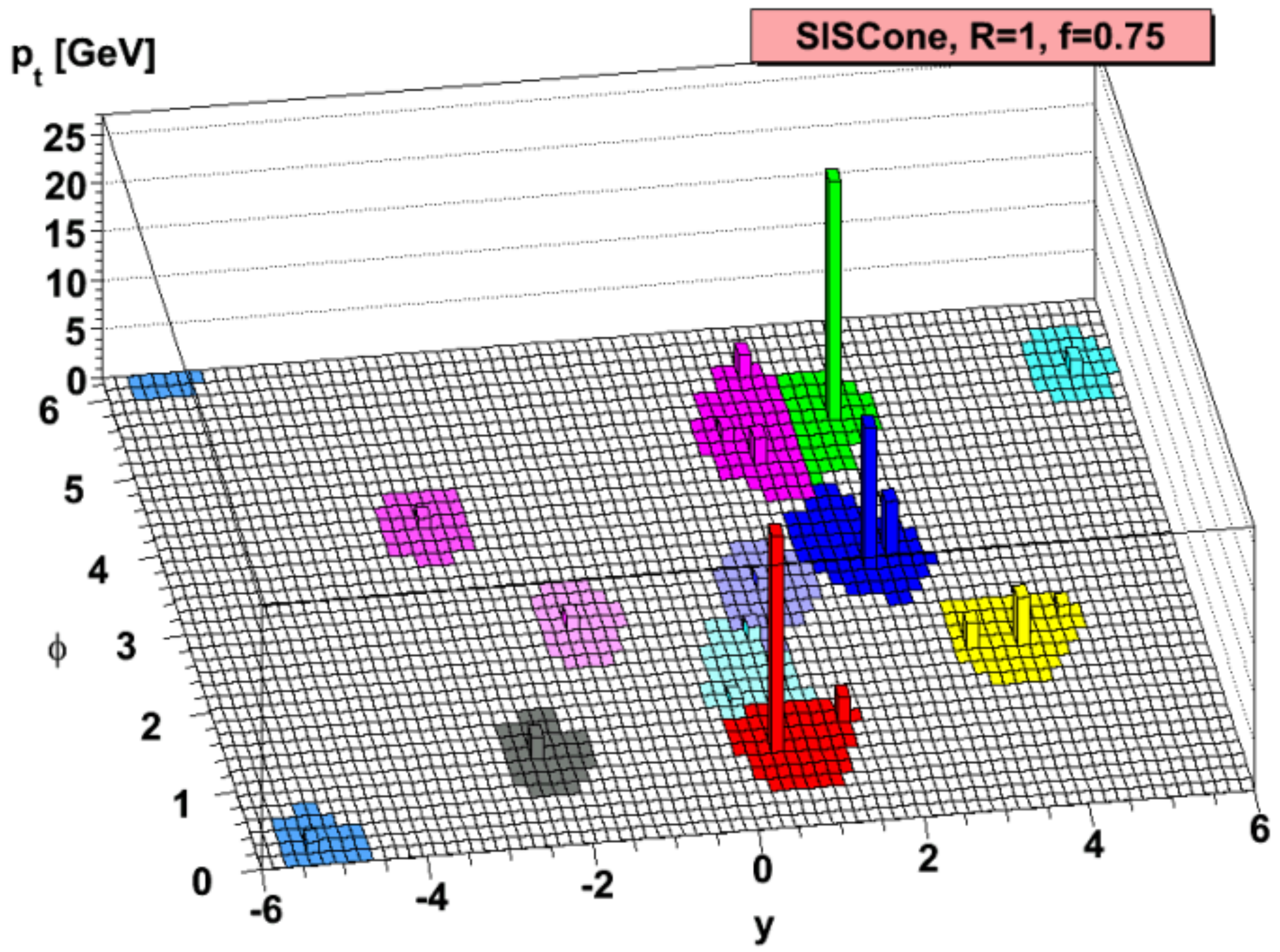
$\mathrm{k_T}$ algorithm



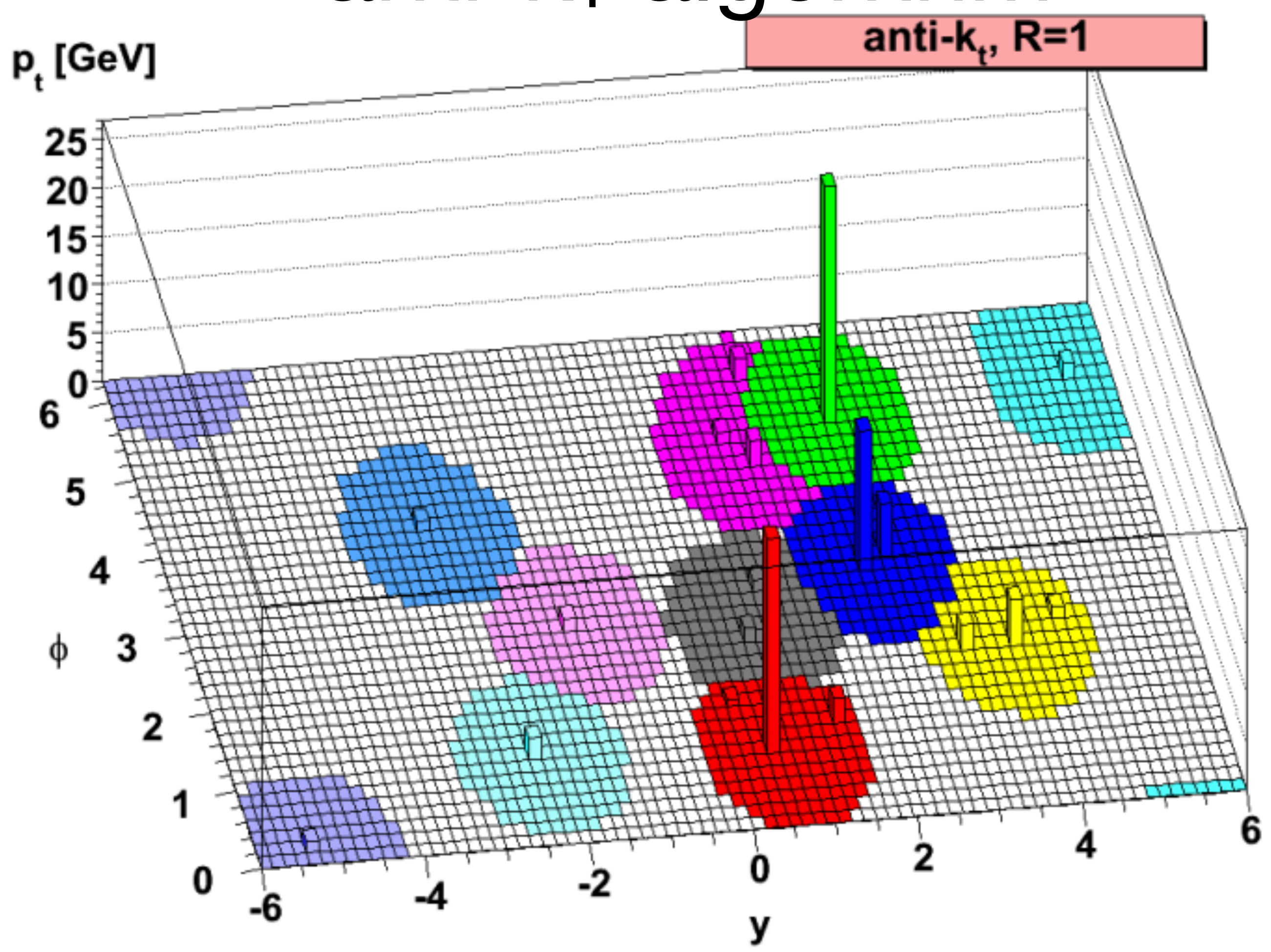
Cambridge/Aachen



SISCone



anti-$\mathrm{k_T}$ algorithm



$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p} \, ,$$

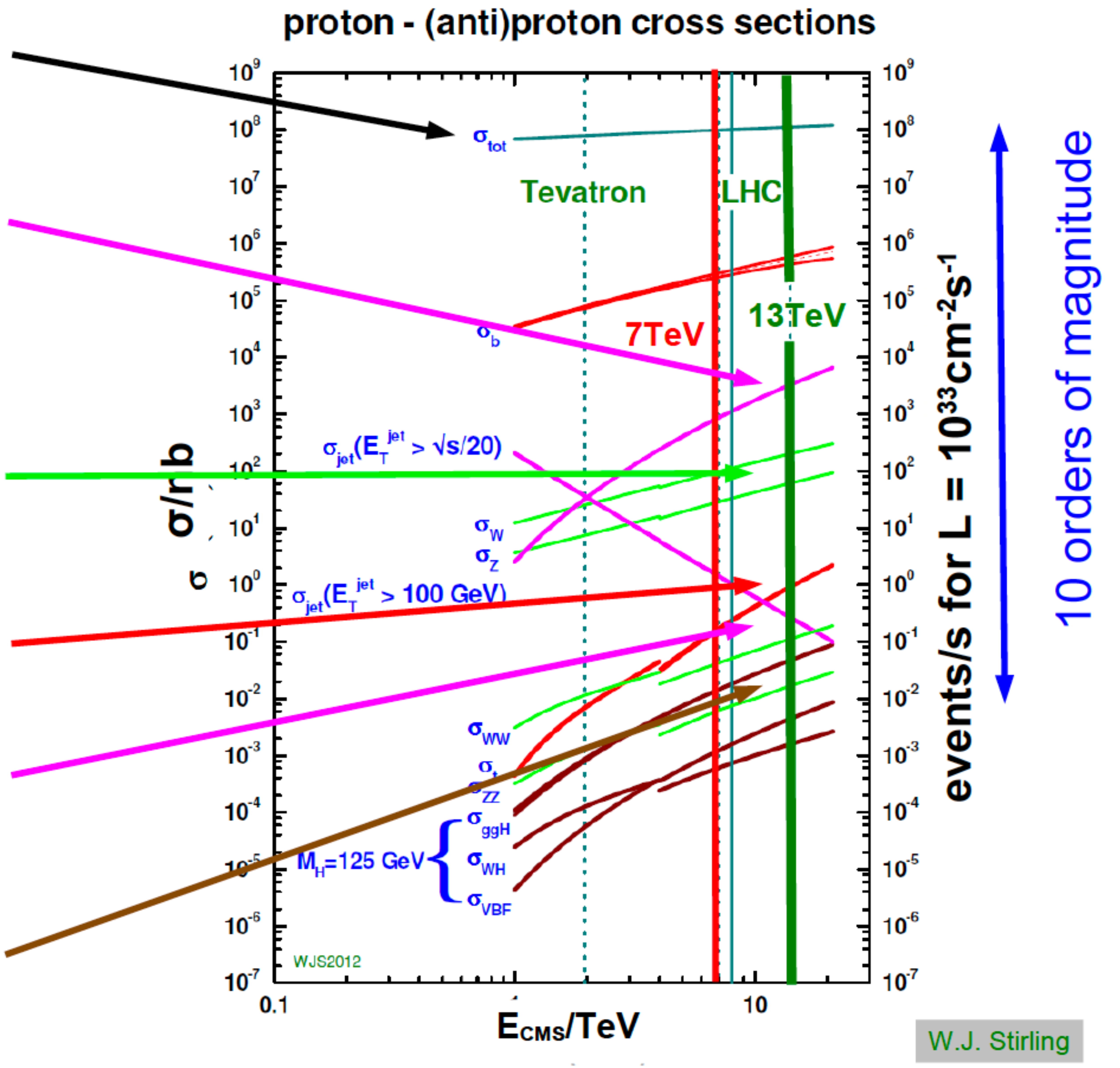
p=-1 anti-$\mathrm{k_T}$ algorithm

p=0 Cambridge/Aachen

p=1 $\mathrm{k_T}$ algorithm

Event rates at the LHC

- Total cross sections
  - ~1.6*10⁹ /s (80mb, 2*10³⁴cm⁻²s⁻¹)
  - Bunch crossing rate of 40MHz
- Jets (E_T^{jet} > 100 GeV)
  - ~40000 Hz
- W & Z bosons
  - ~4000 Hz, ~1000 Hz
- Top Quarks
  - ~20 Hz
- Jets (E_T^{jet} > 650 GeV)
  - ~6 Hz
- Higgs bosons
  - ~1 Hz (50pb, 2*10³⁴cm⁻²s⁻¹)



Pingo

- Why is the jet cross section so large?
  - 1) gluons are massless particles
  - 2) parton distribution functions
  - 3) strength of the strong interaction
  - 4) all of the above

Strong interaction

Electromagnetic interaction (magnets, electricity, ...)

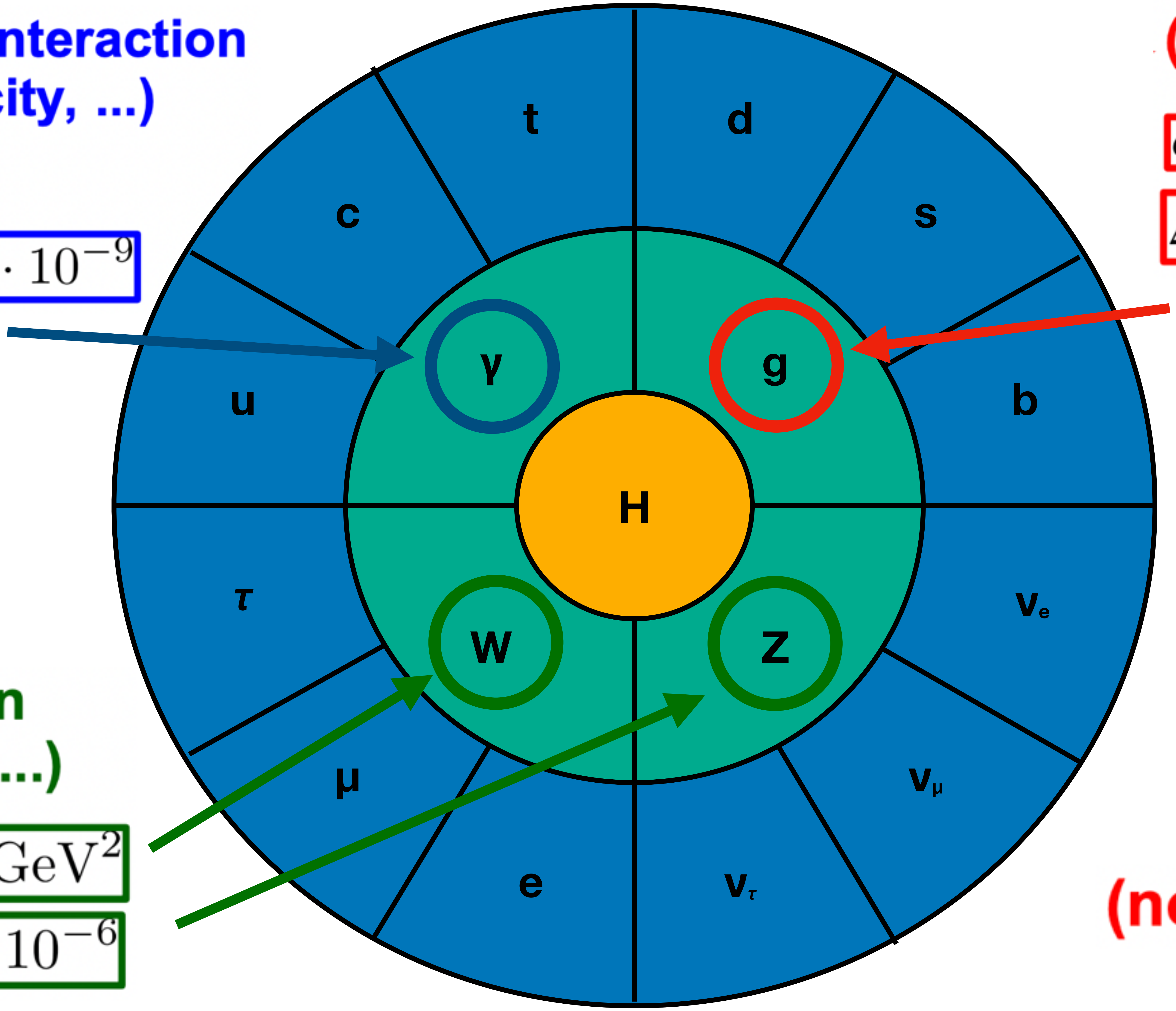
$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

Strong interaction (nuclear forces, ...)

$\alpha_s \approx 0.118$

$\Delta\alpha_s/\alpha_s = 8.5 \cdot 10^{-3}$



Weak interaction (β decays, sun, ...)

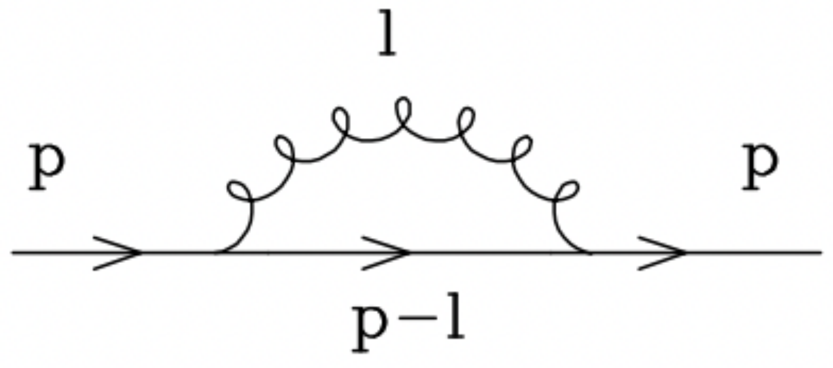
$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

$\Delta G_F/G_F = 0.51 \cdot 10^{-6}$

(no gravity)

Strong interaction

- Theory
  - Some contributions lead to divergences, e.g. quark self-energy



  - These infinities can be reabsorbed in the definitions of fields and parameters, e.g. couplings and masses
  - Described by renormalisation group equation (RGE)
  - Running of coupling at leading order

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln\left(\frac{Q^2}{\mu^2}\right)}$$

  - **Consequence:**

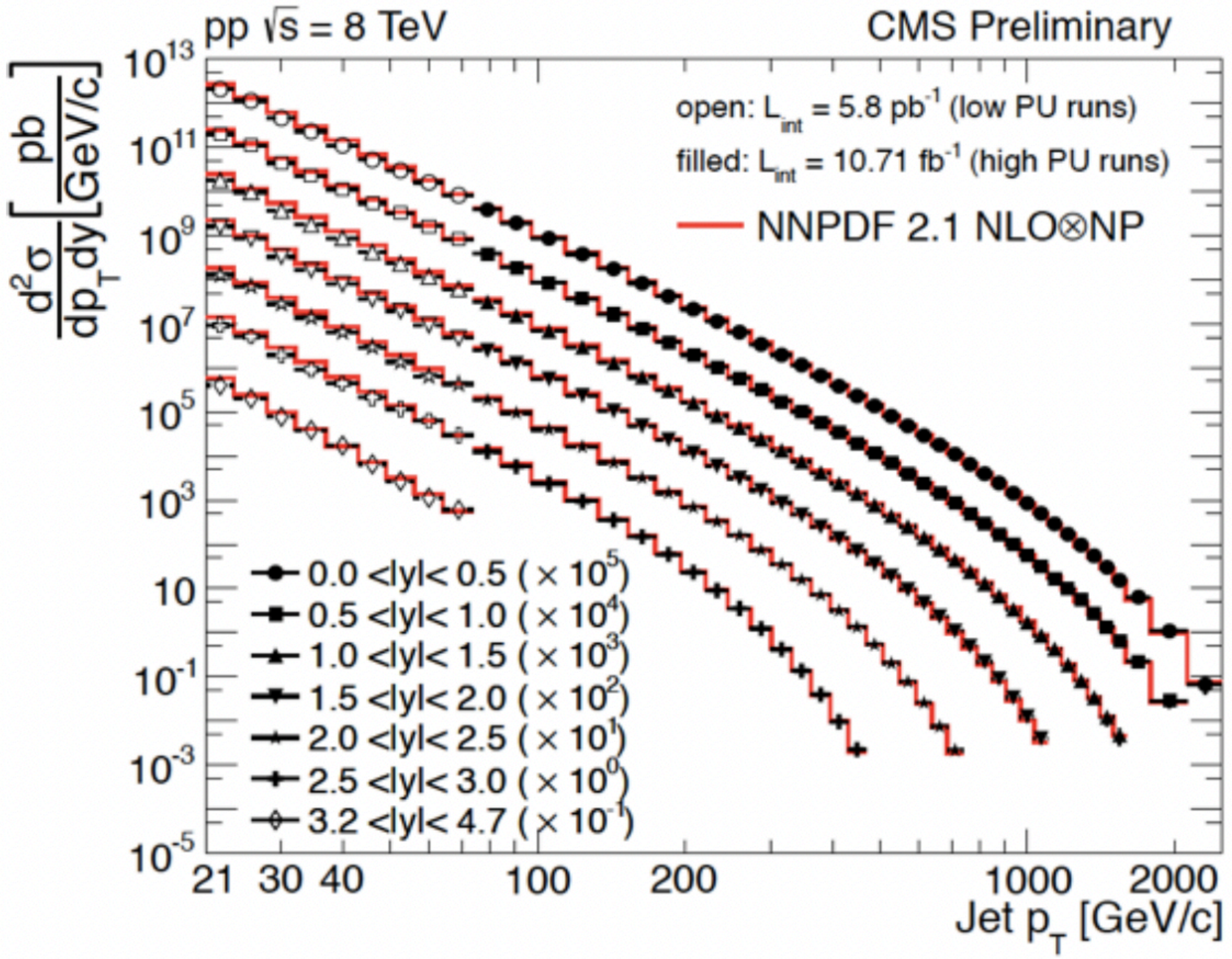
$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)} \qquad \beta_0 = \frac{33 - 2 \cdot N_f}{12\pi}$$

    - $Q^2 \rightarrow 0$? Can not be answered with perturbation theory
    - Q^2 large. Strong coupling becomes weak. Asymptotic freedom. Perturbation theory works.

Inclusive Jet Cross Sections

- Abundant production of jets
- Large dynamic range to study α_s

As a function of jet transverse momentum in bins of rapidity (up to |y| = 4.7!)

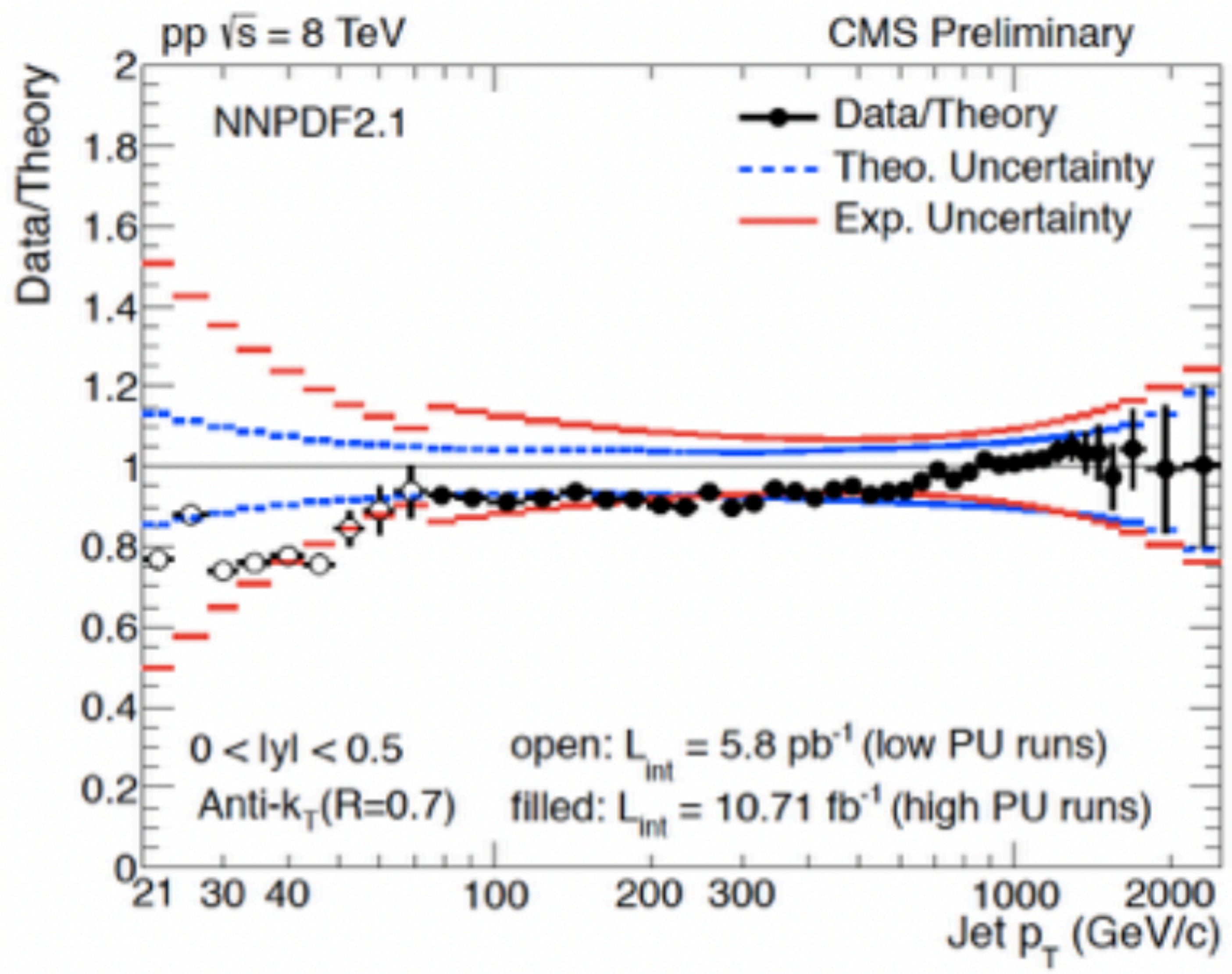


20 GeV up to > 2TeV (central)

- JES 2-4%

NLO pQCD describes data over 14 orders of magnitude!

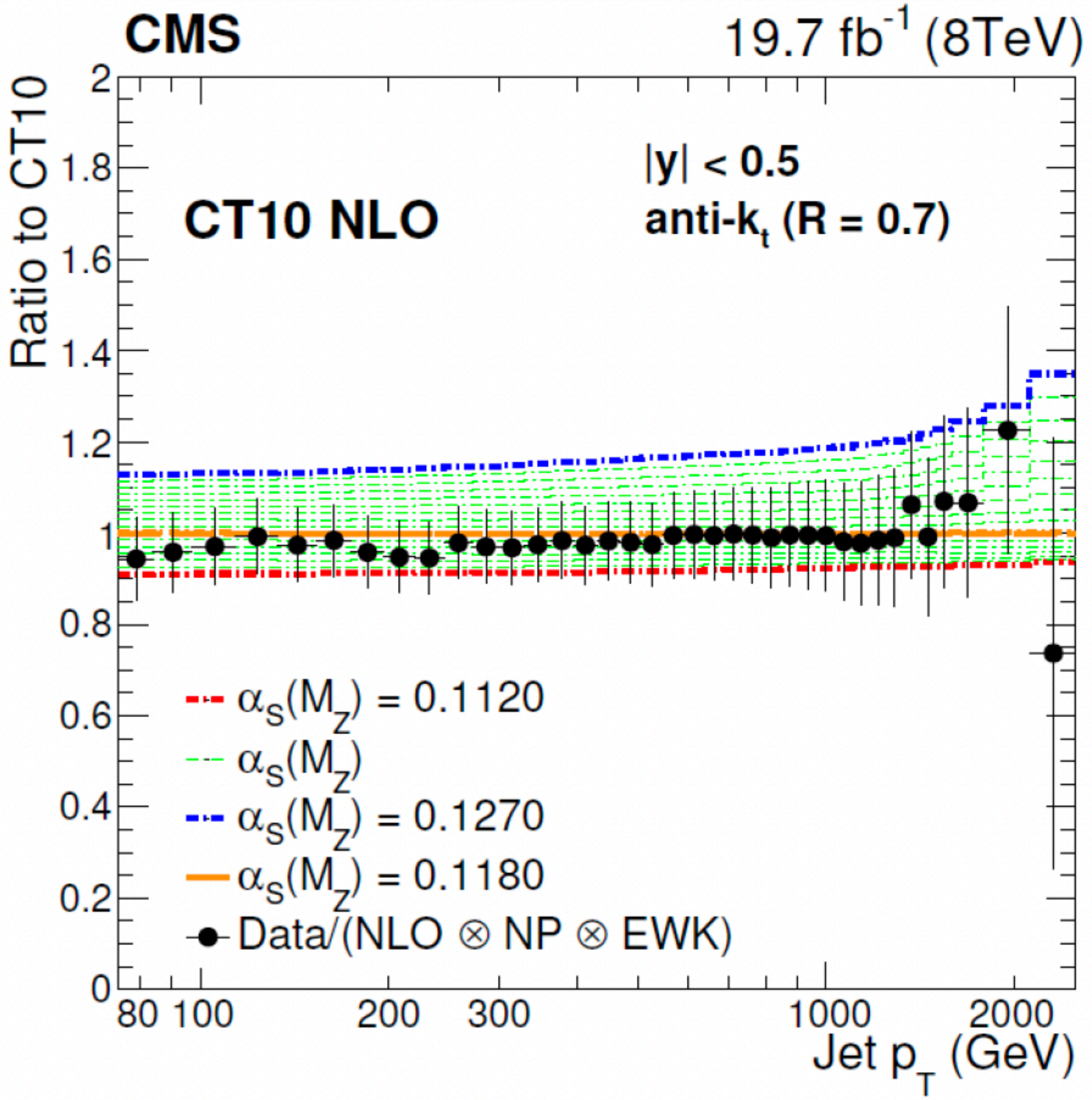
Constraints on gluon PDFs



Inclusive Jets: α_s

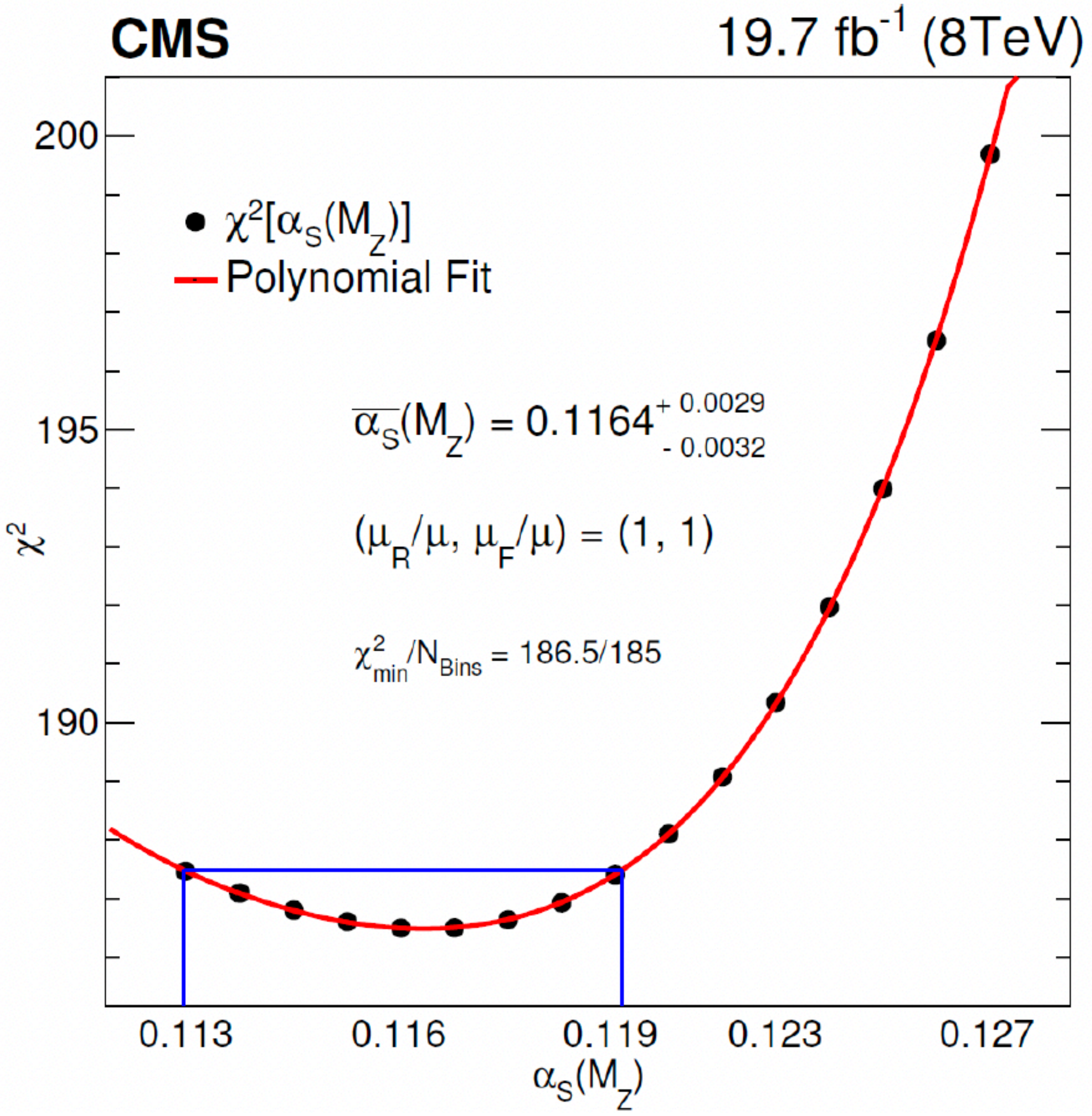
Sensitivity to $\alpha_s(M_Z)$ at NLO

- CMS: anti-k_t R = 0.7 at $\sqrt{s}$ = 8 TeV
- QCD scale choice: $\mu_R = \mu_F = p_{T,jet}$

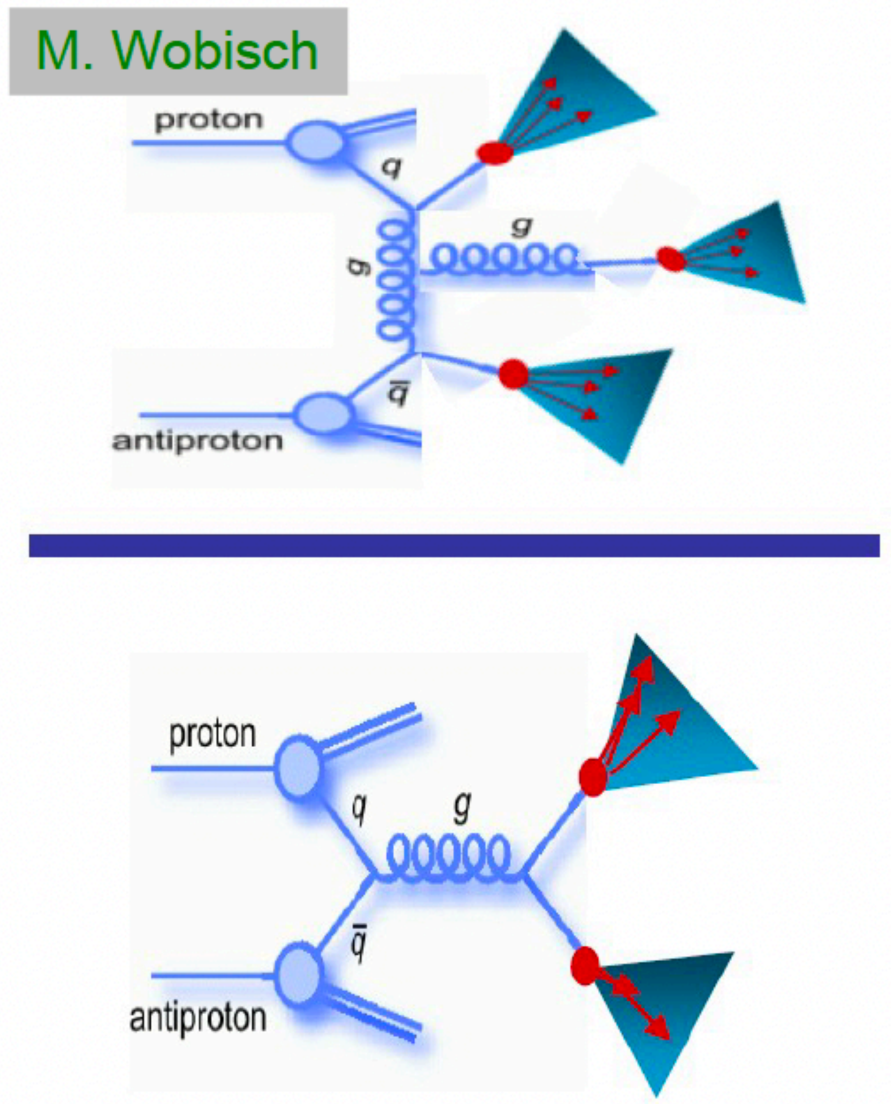


X^2 fit of $\alpha_s(M_Z)$ for all jet p_T and |y| bins

- In fit: all exp. + PDF + NP uncertainties
- PDFs: CT10 NLO PDF sets for various $\alpha_s(M_Z)$



2-jet 3-jet Ratio

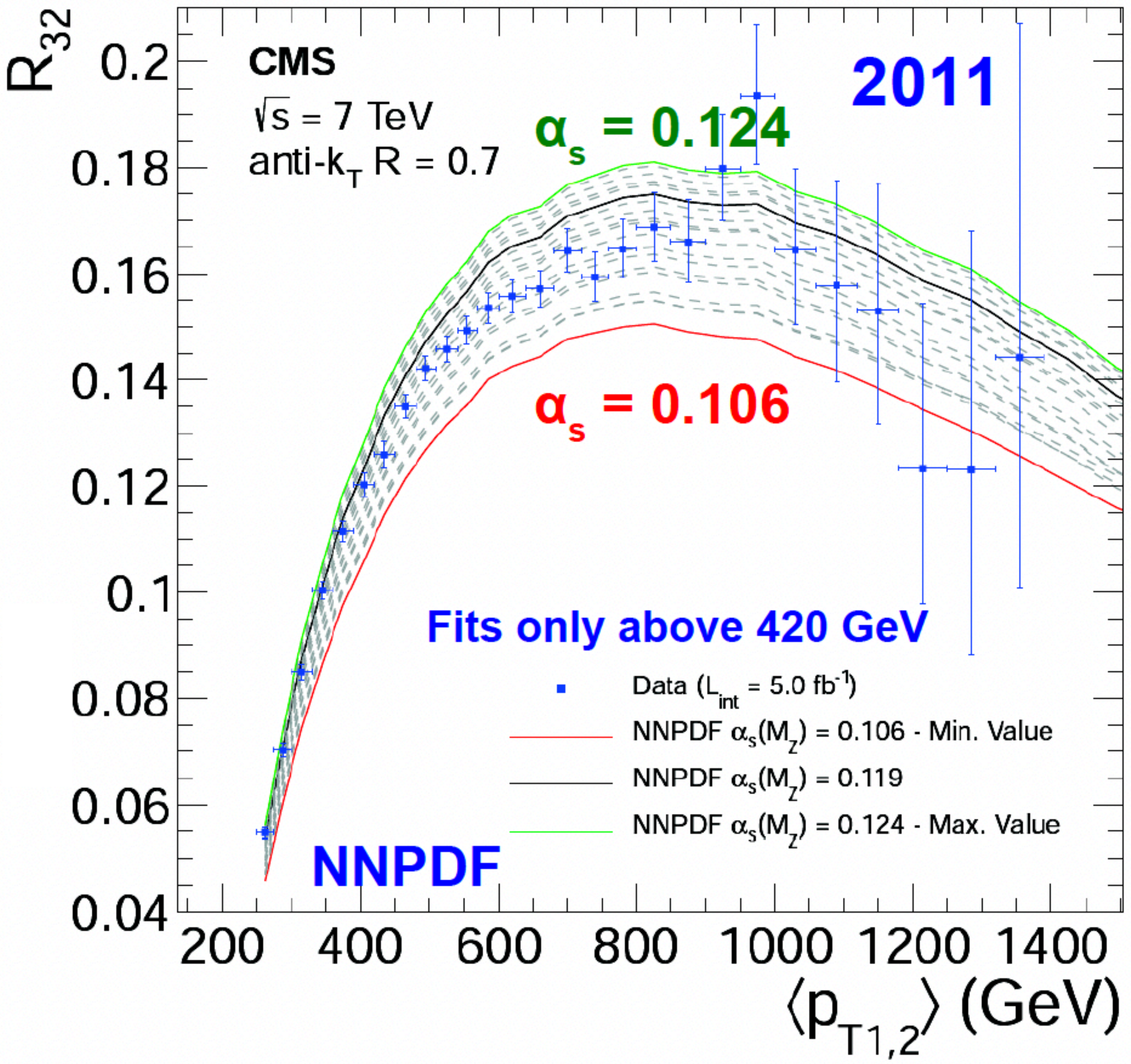


$R_{3/2}$

α_s

$$\frac{\sigma_{3+\text{jet}}}{\sigma_{2+\text{jet}}} \propto \alpha_s^1$$

$$Q = \langle p_{T1,2} \rangle$$



CMS: $R_{3/2}$
- **Ratio of inclusive 3- to inclusive 2-jet events**
- **anti-kT R=0.7**
- **Min. jet pT: 150 GeV**
- **Max. rap.: |y| < 2.5**
- **Data 2011 7 TeV, and 2012 8 TeV prel.**

$\rightarrow \alpha_s$

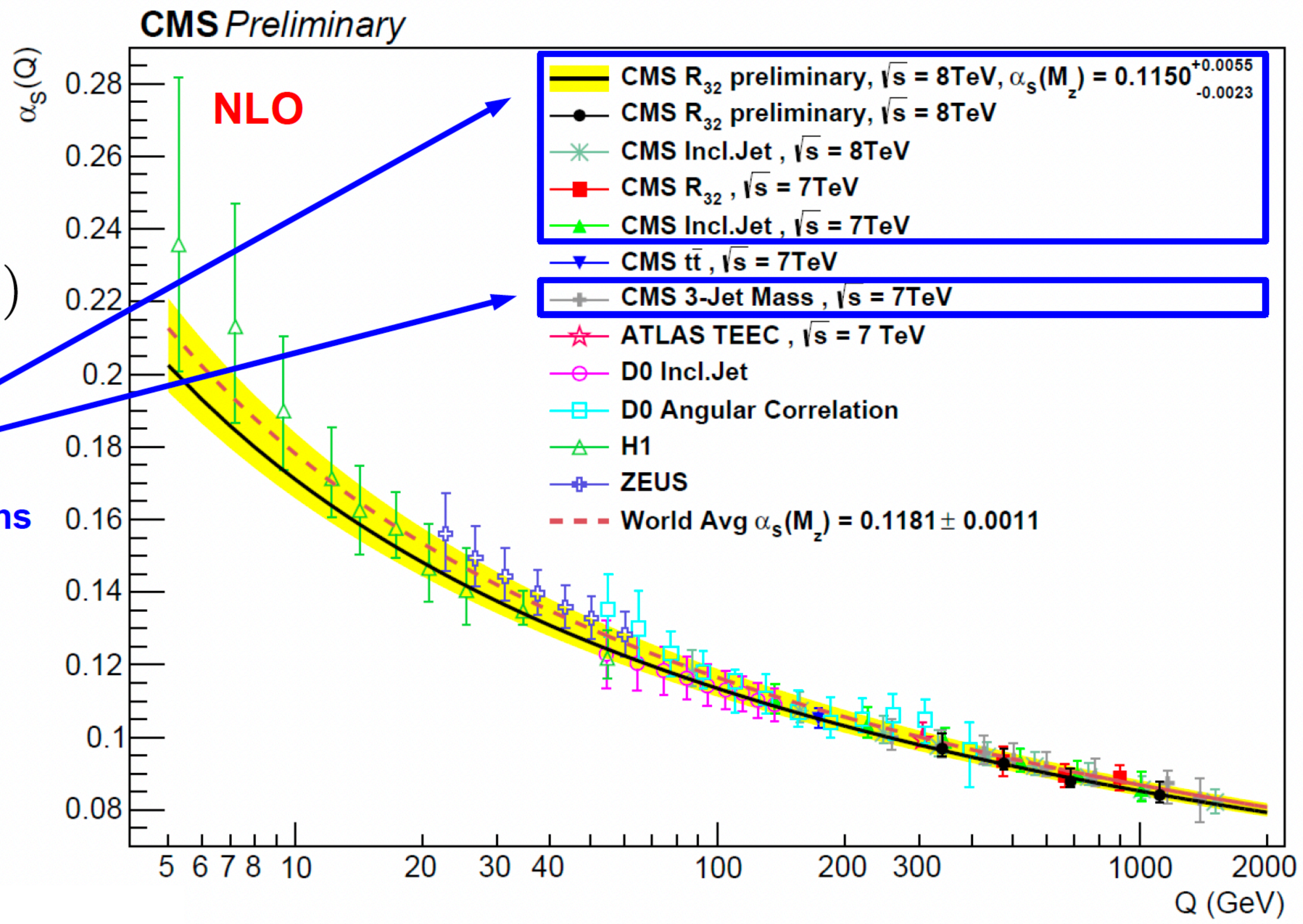
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50

Measurement of α_s

Perform fits in fixed intervals of the chosen scale Q

$\Rightarrow \alpha_s(Q)$

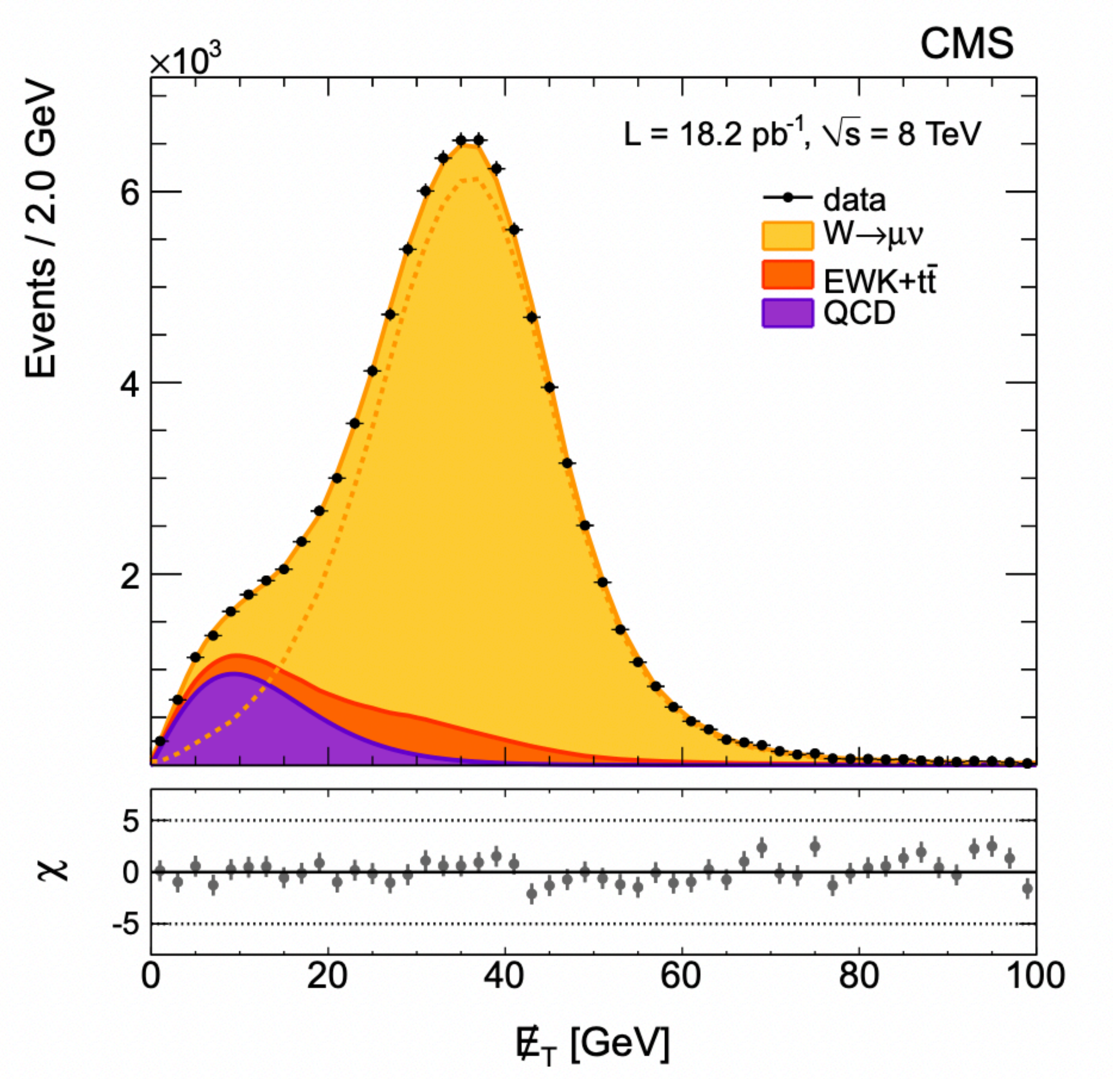
Jet cross sections and ratios

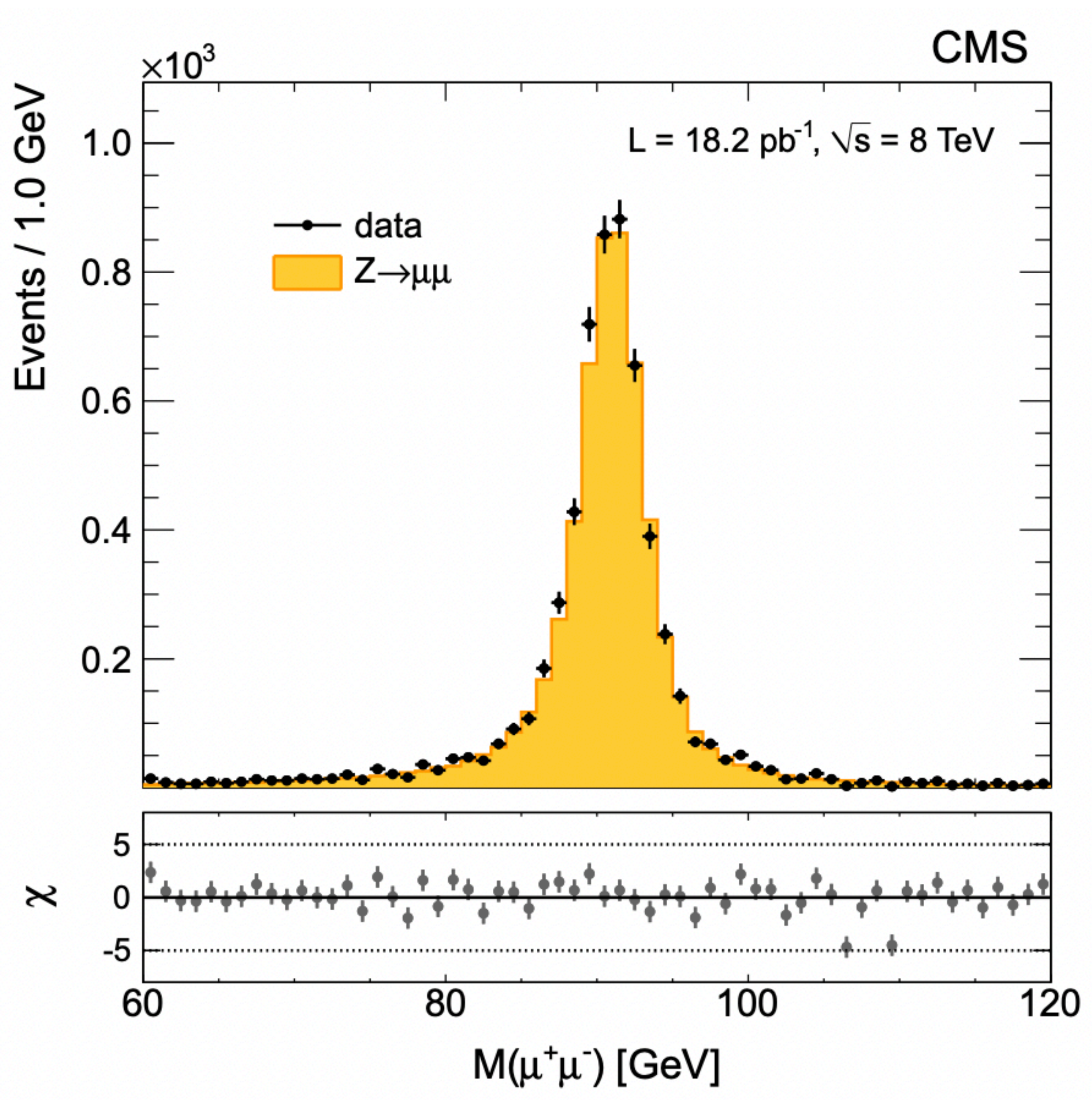


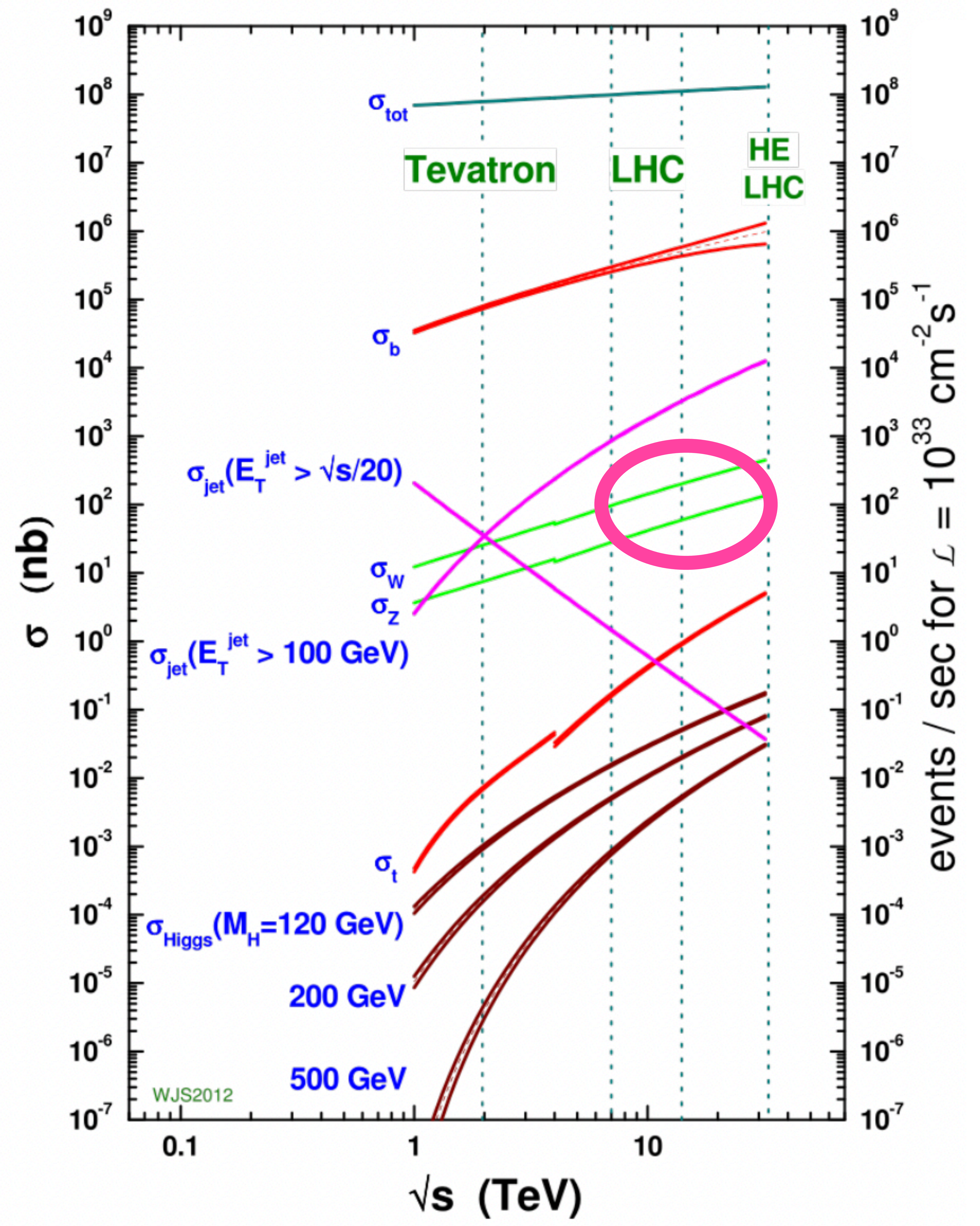
New range explored at LHC →

Physics of the W and Z Boson

- "Standard candle" for calibrations and PDFs
- Testing QCD
- W boson mass measurement
- Asymmetries and weak mixing angle
- Triple and quartic gauge couplings

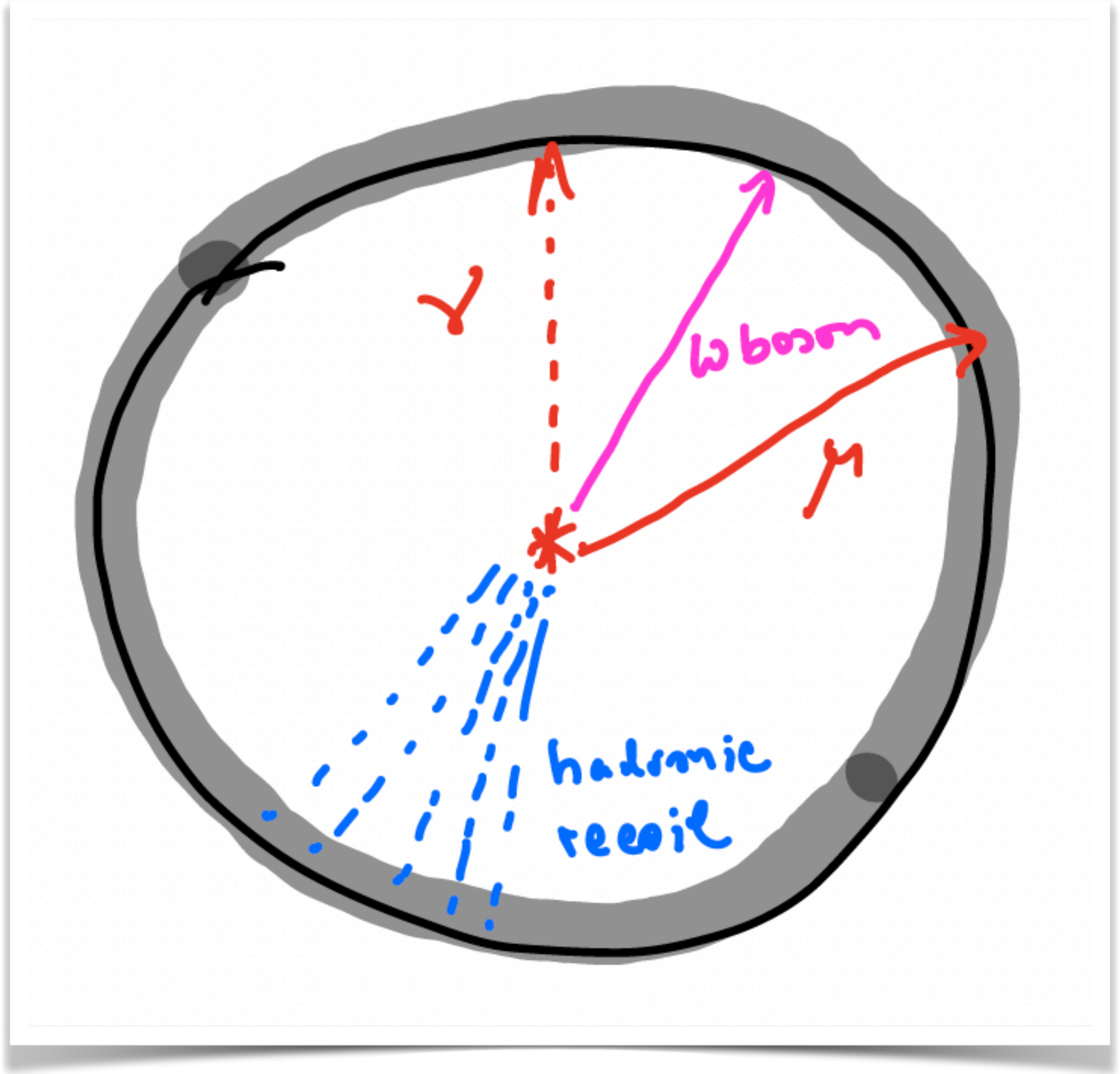


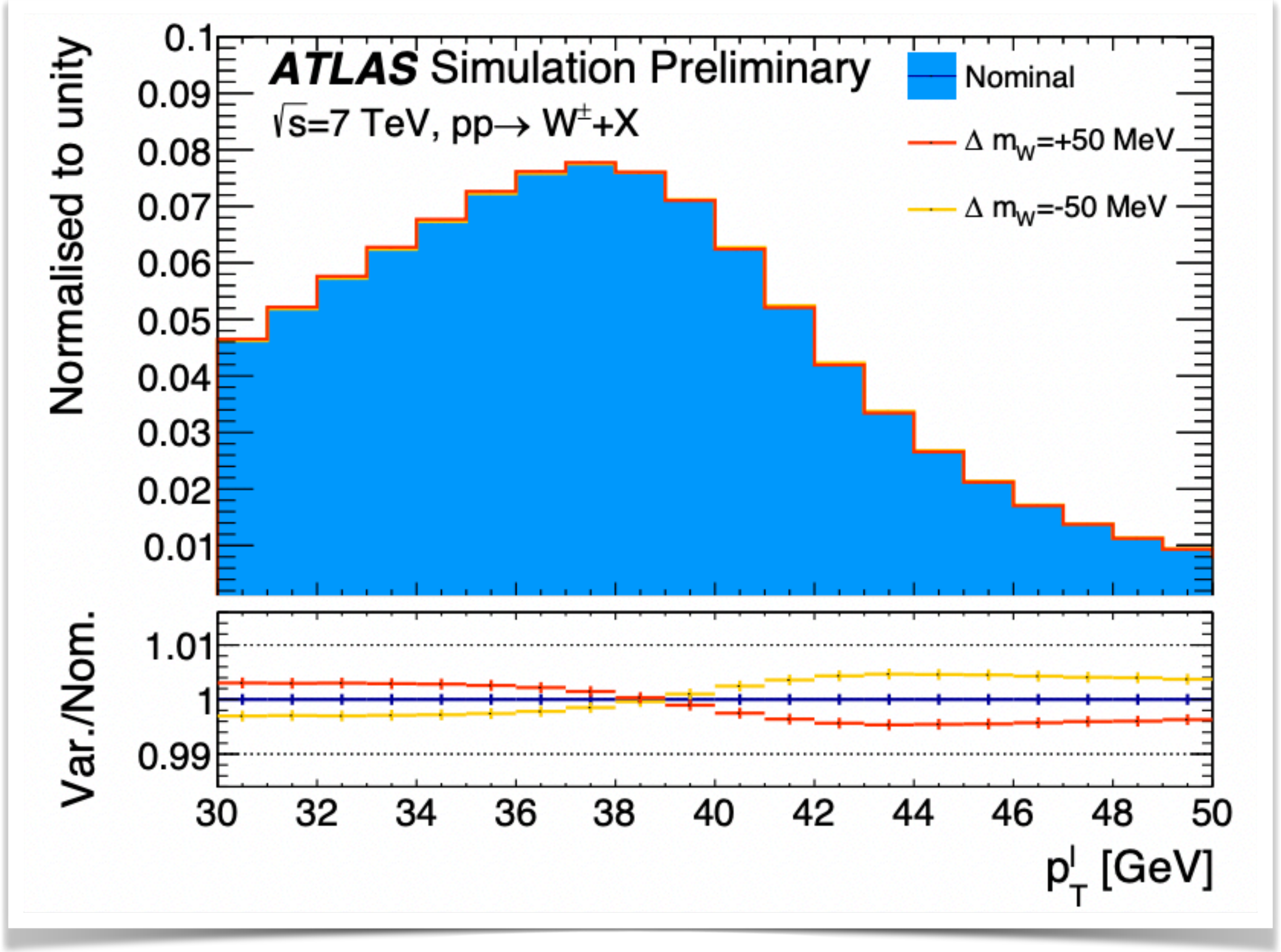




W boson mass measurement

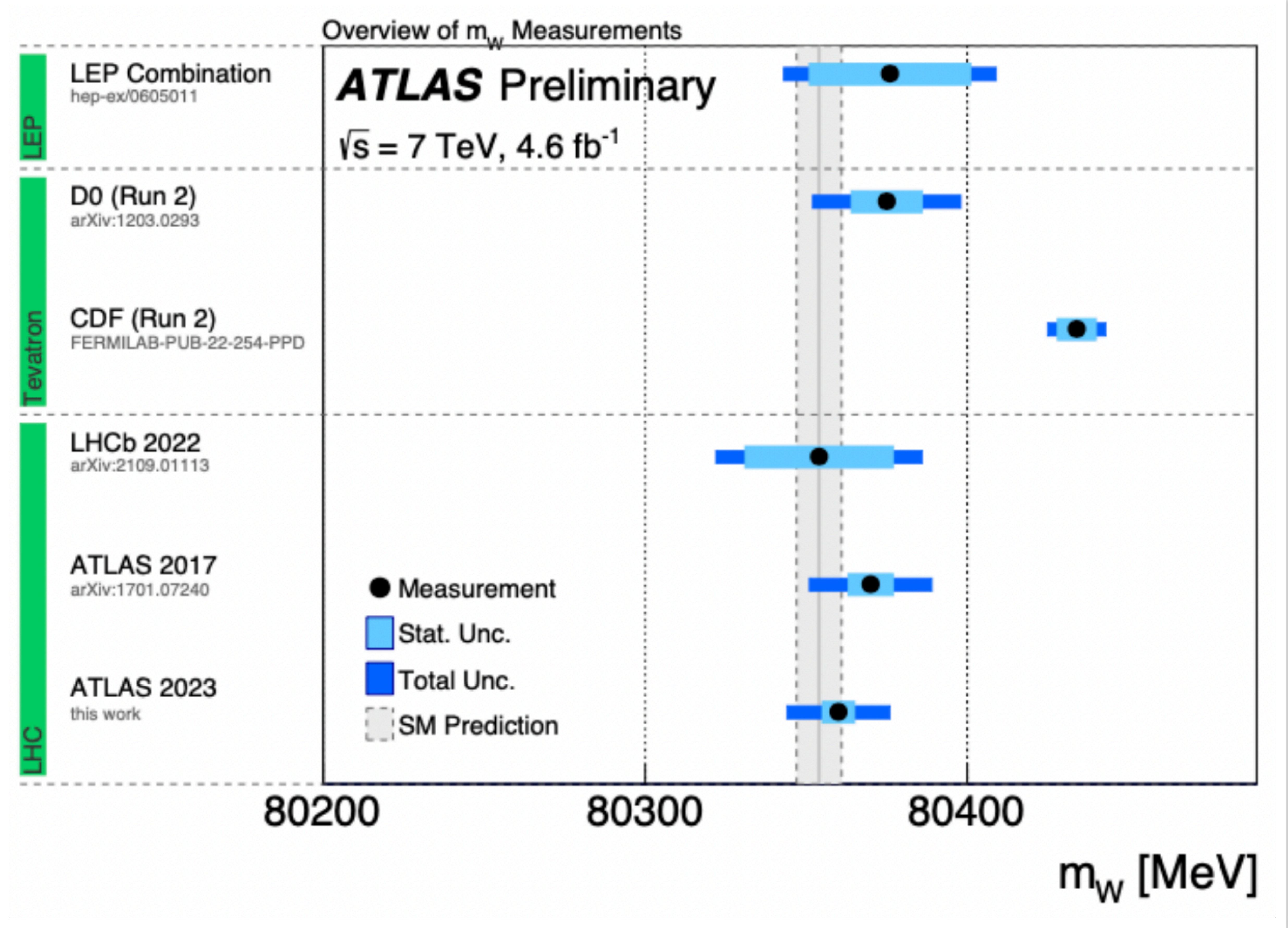
- Observables
  - Lepton transverse momentum
  - Transverse missing energy
  - Transverse mass $M_T^2 = 2\, p_T(\ell) p_T(\nu)\, (1 - \cos\Delta\phi(\ell,\nu))$
- Challenges
  - Experimental: lepton energy scale; missing transverse energy; pile-up conditions
  - Theoretical: W transverse momentum; PDFs
- Strategy (ATLAS)
  - Exploit lepton transverse momentum and transverse mass



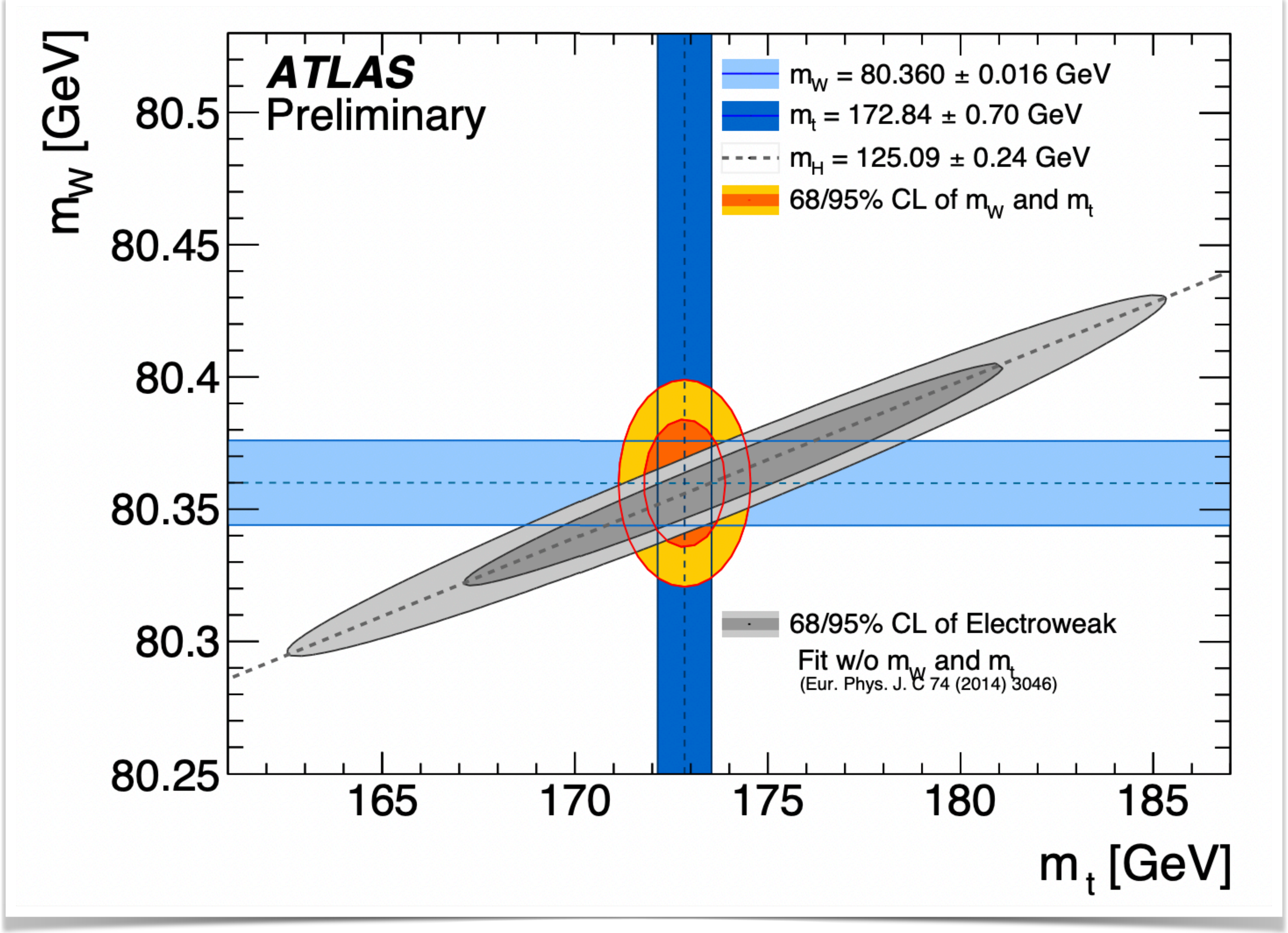


W boson mass measurement

- Results



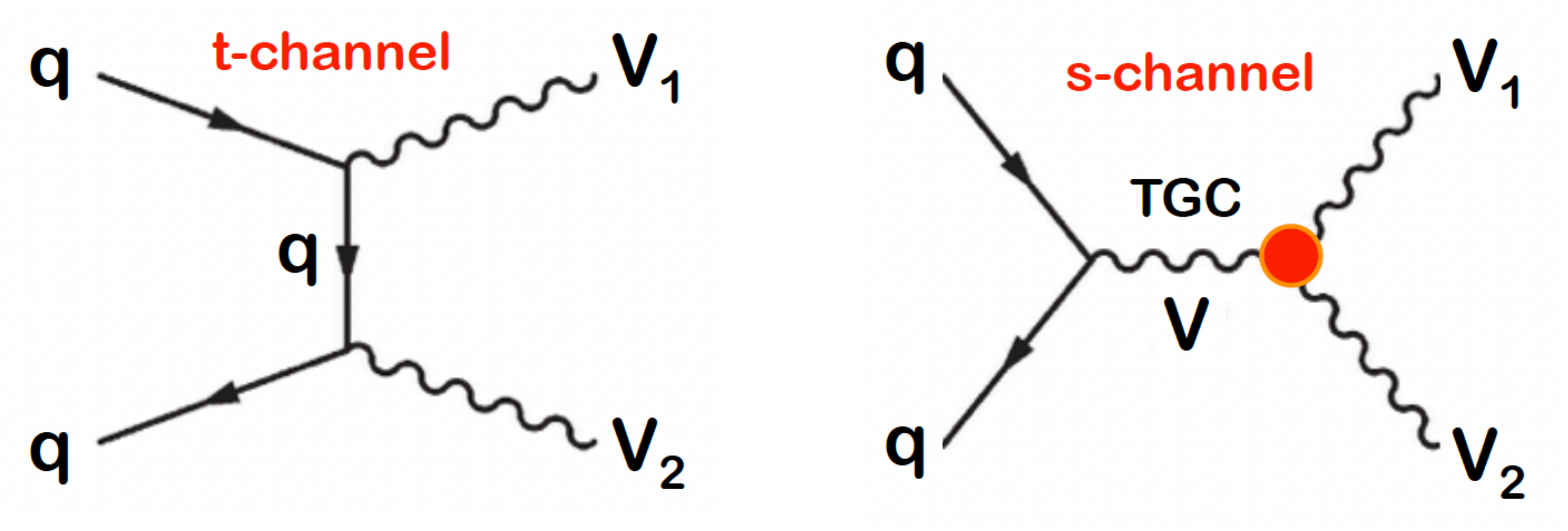
Tension in experiment results!

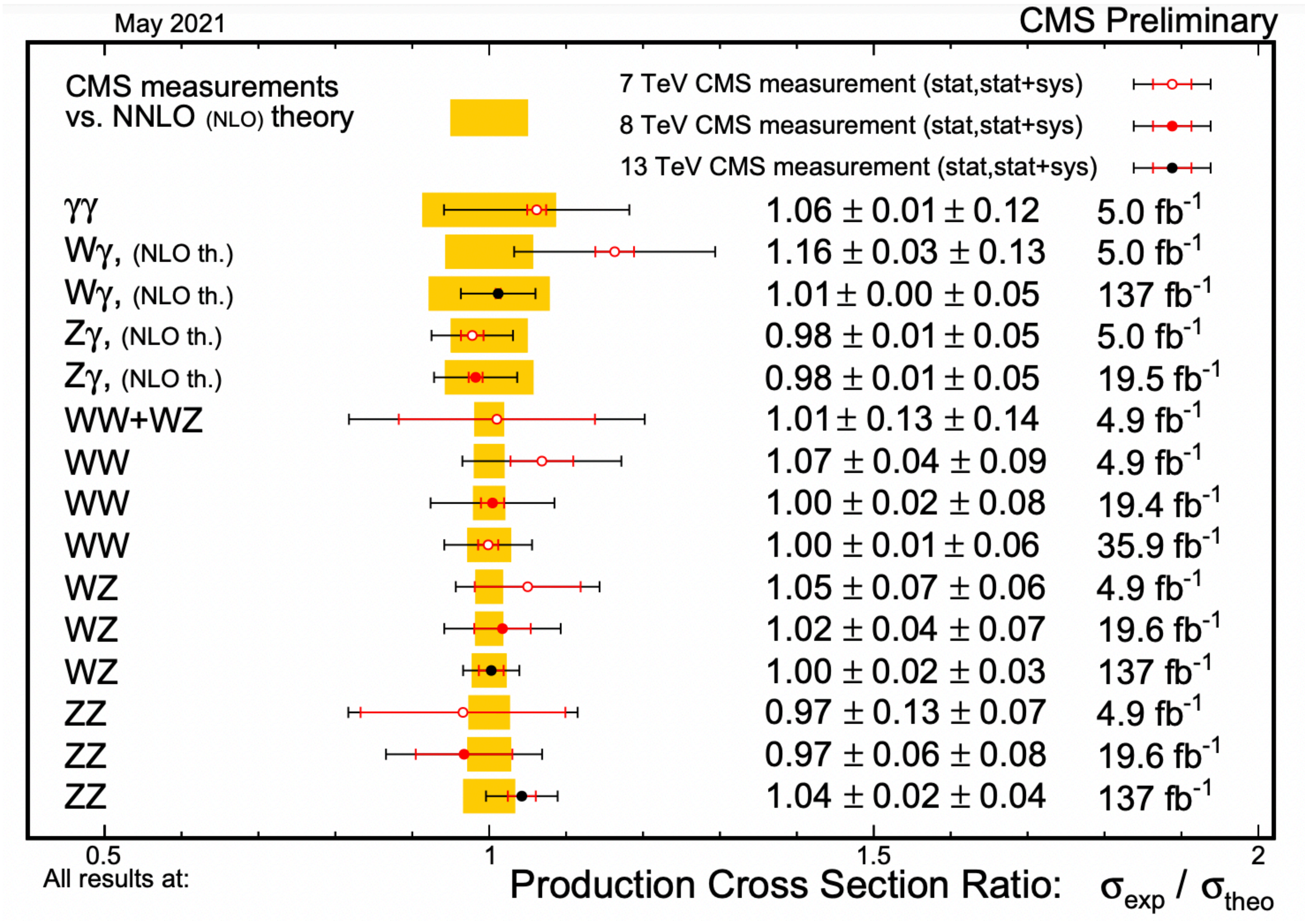


Are Standard Model measurements consistent?

Multi-Boson Production

- Di-Boson Production

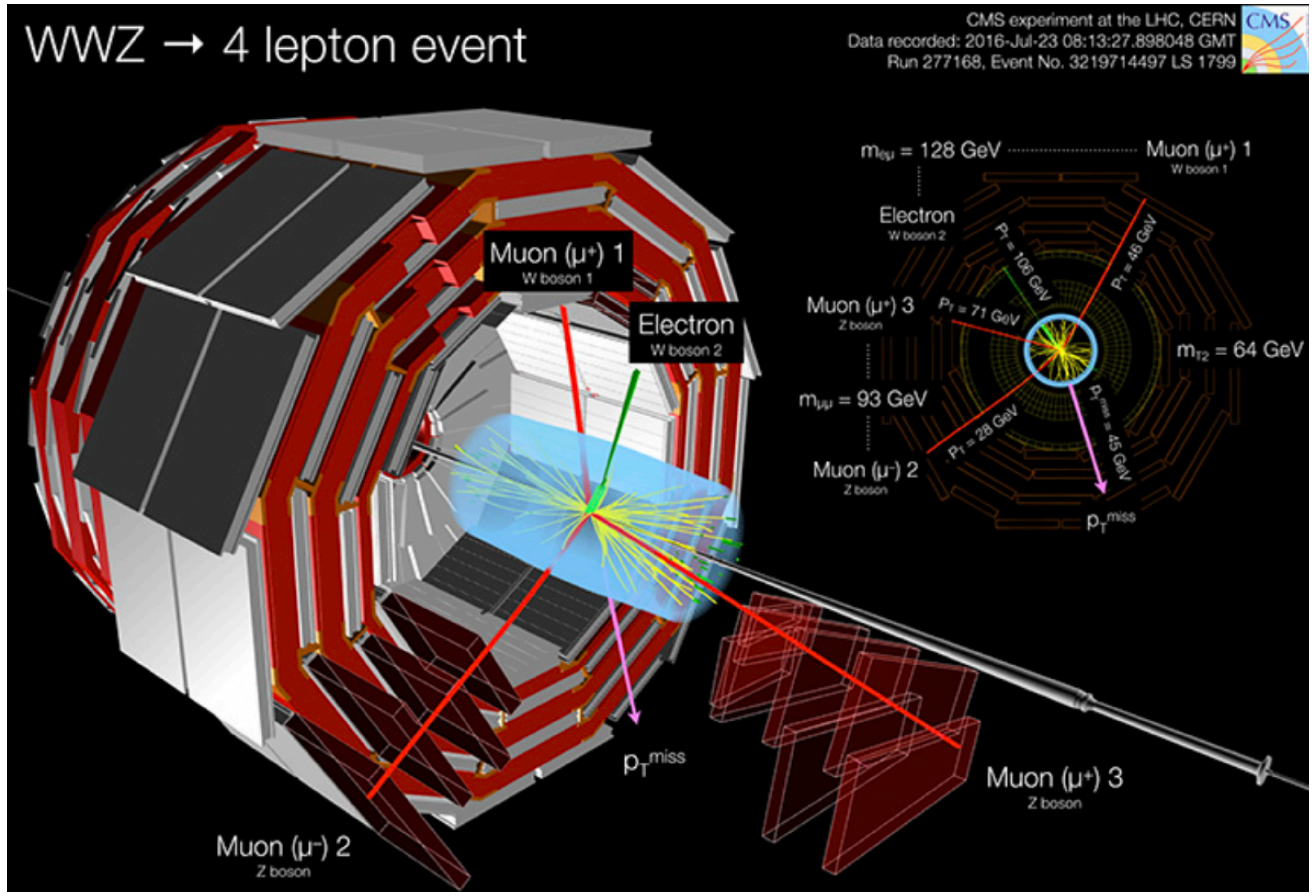


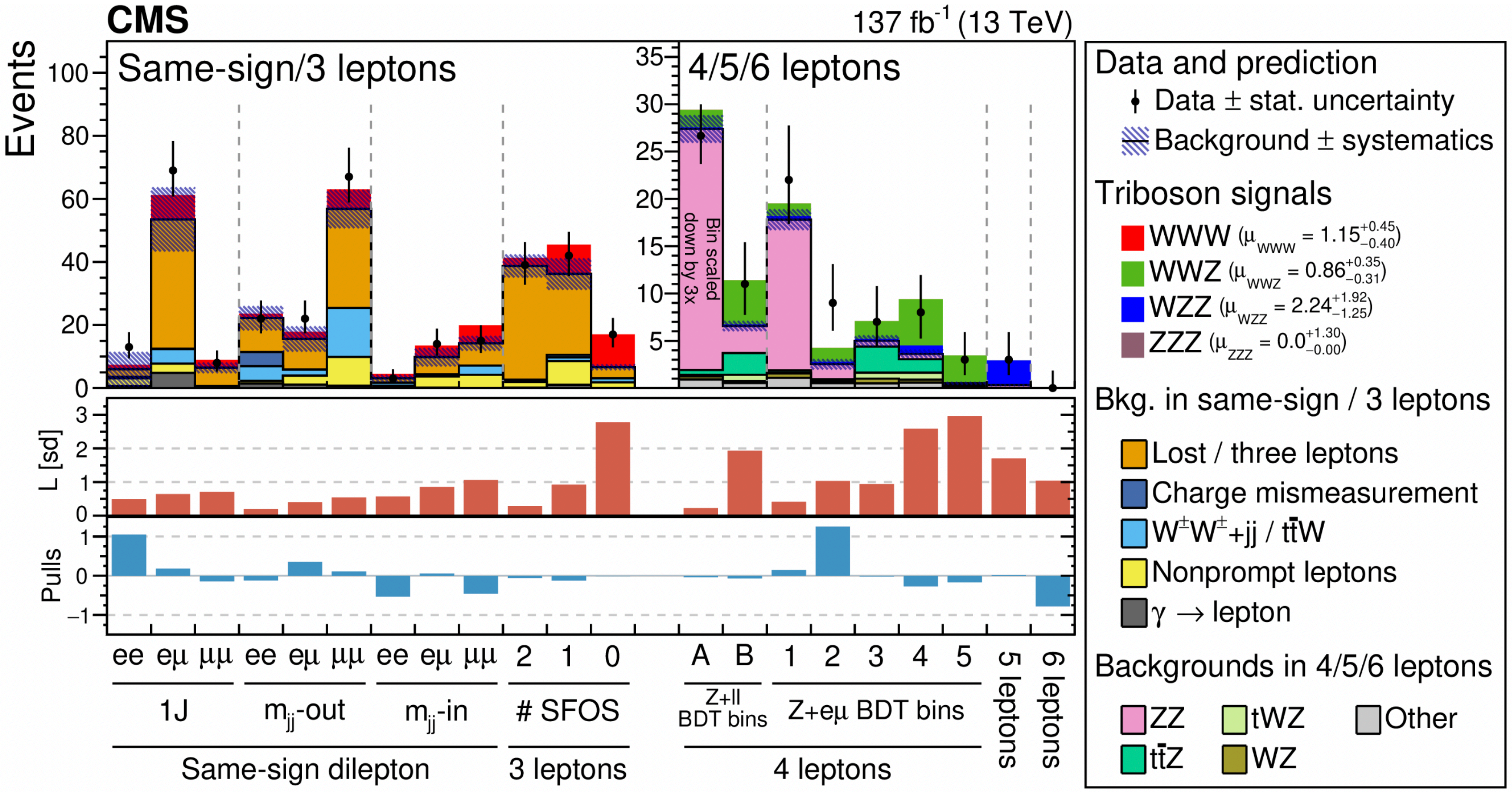


- Large number of processes study
- Generally good agreement between experiment and theory
- Constraint on anomalous couplings

Multi-Boson Production

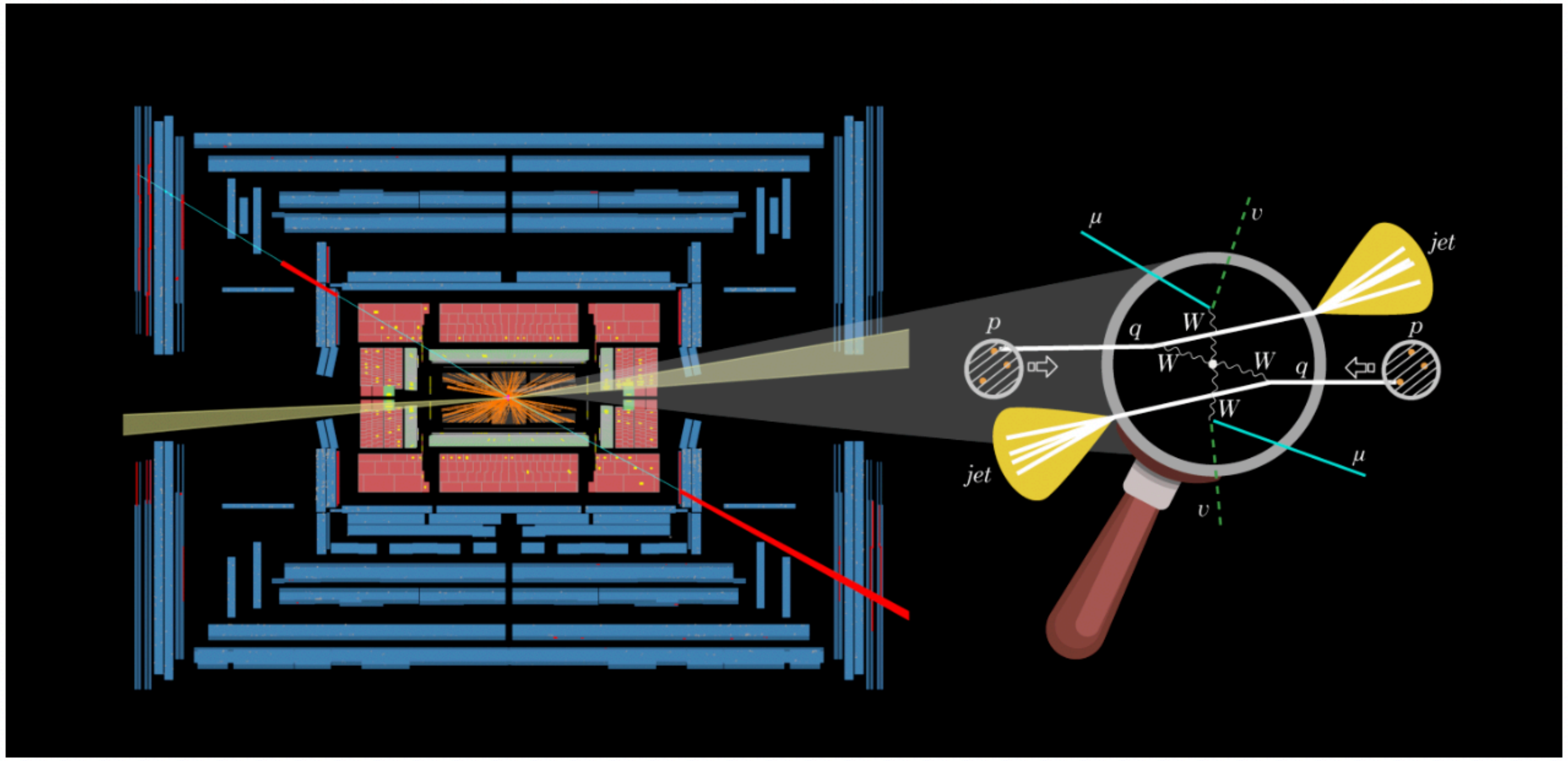
- Tri-Boson Production
  - Observed WWW and WWɣ processes
  - Observation of three massive gauge bosons (W or Z) (CMS result number 1000!)

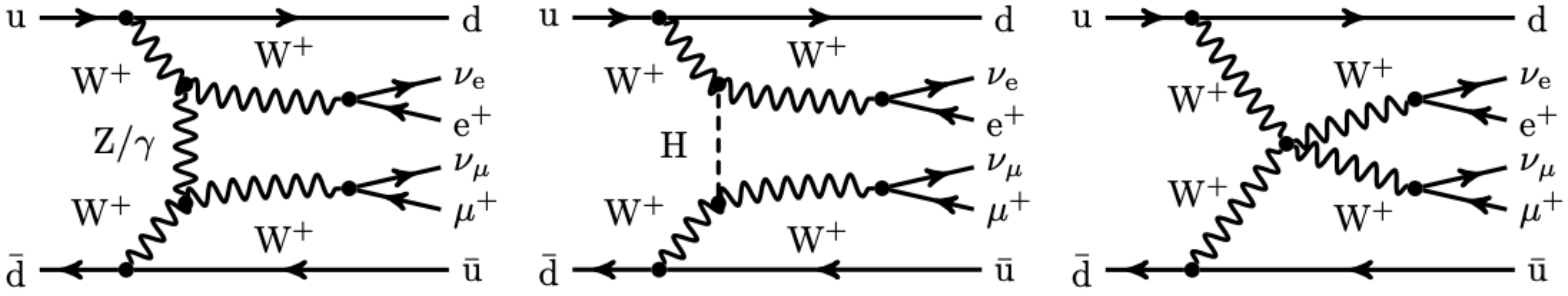




Vector Boson Scattering

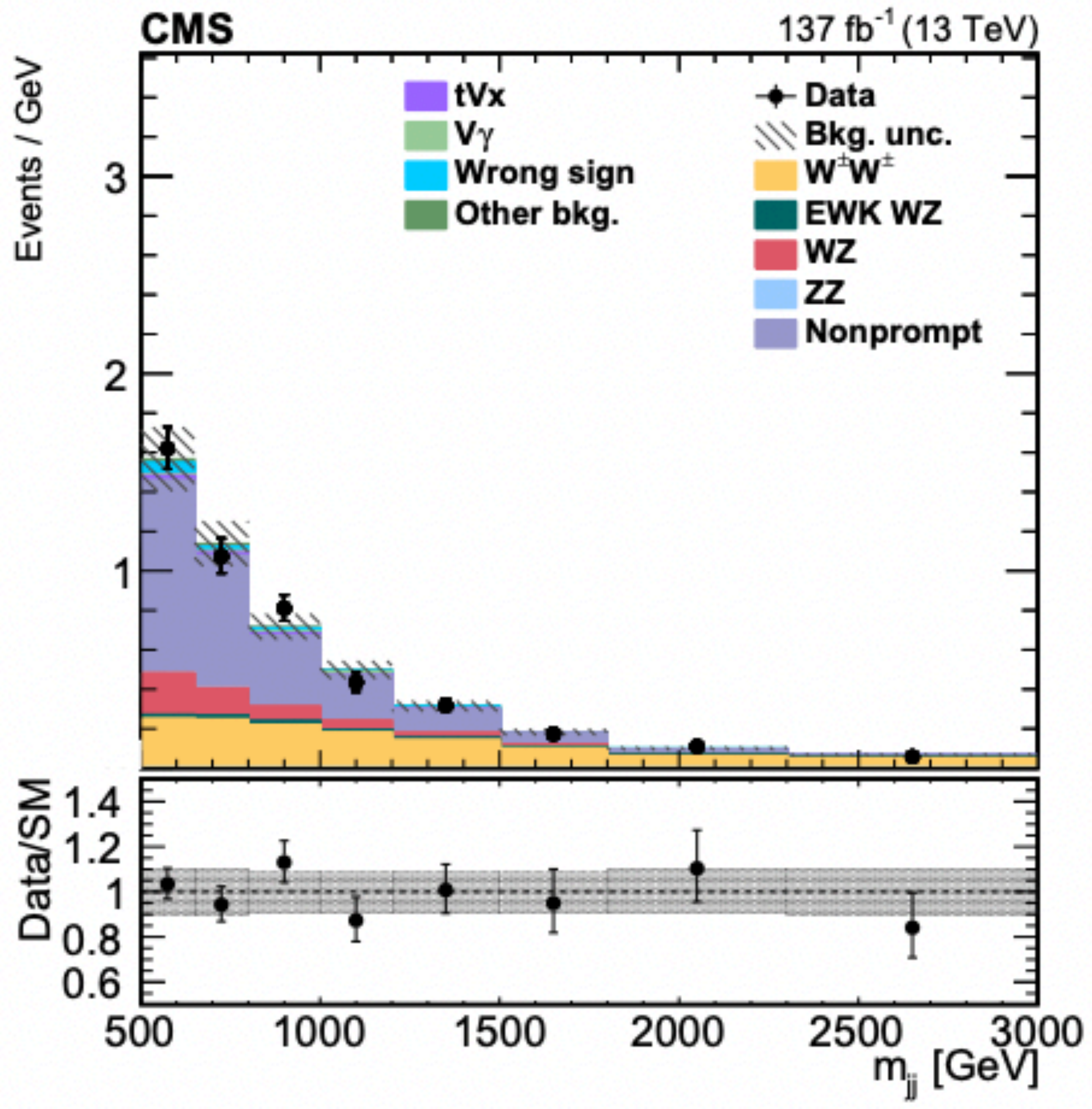
- Electroweak production of same-sign W-pairs

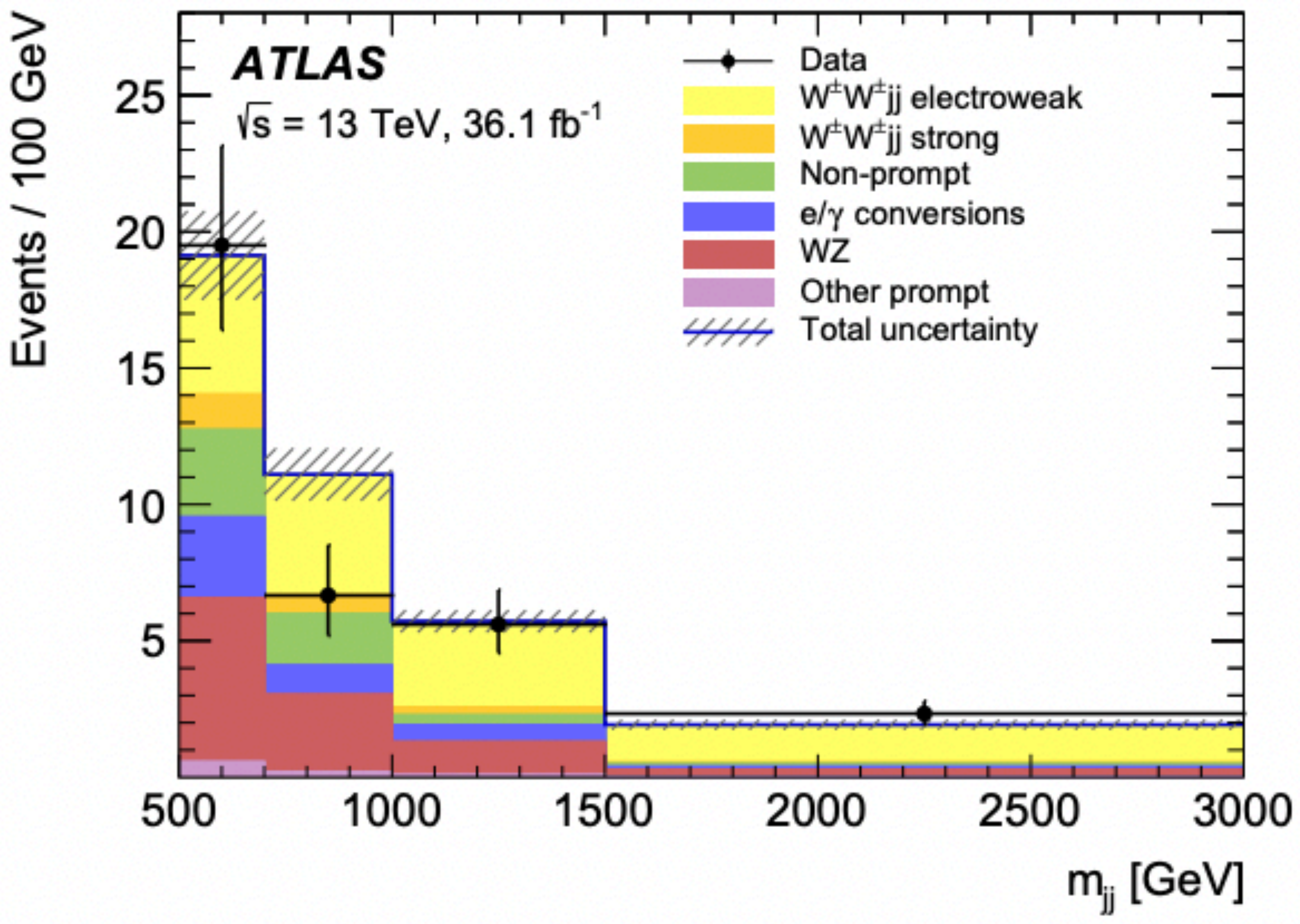


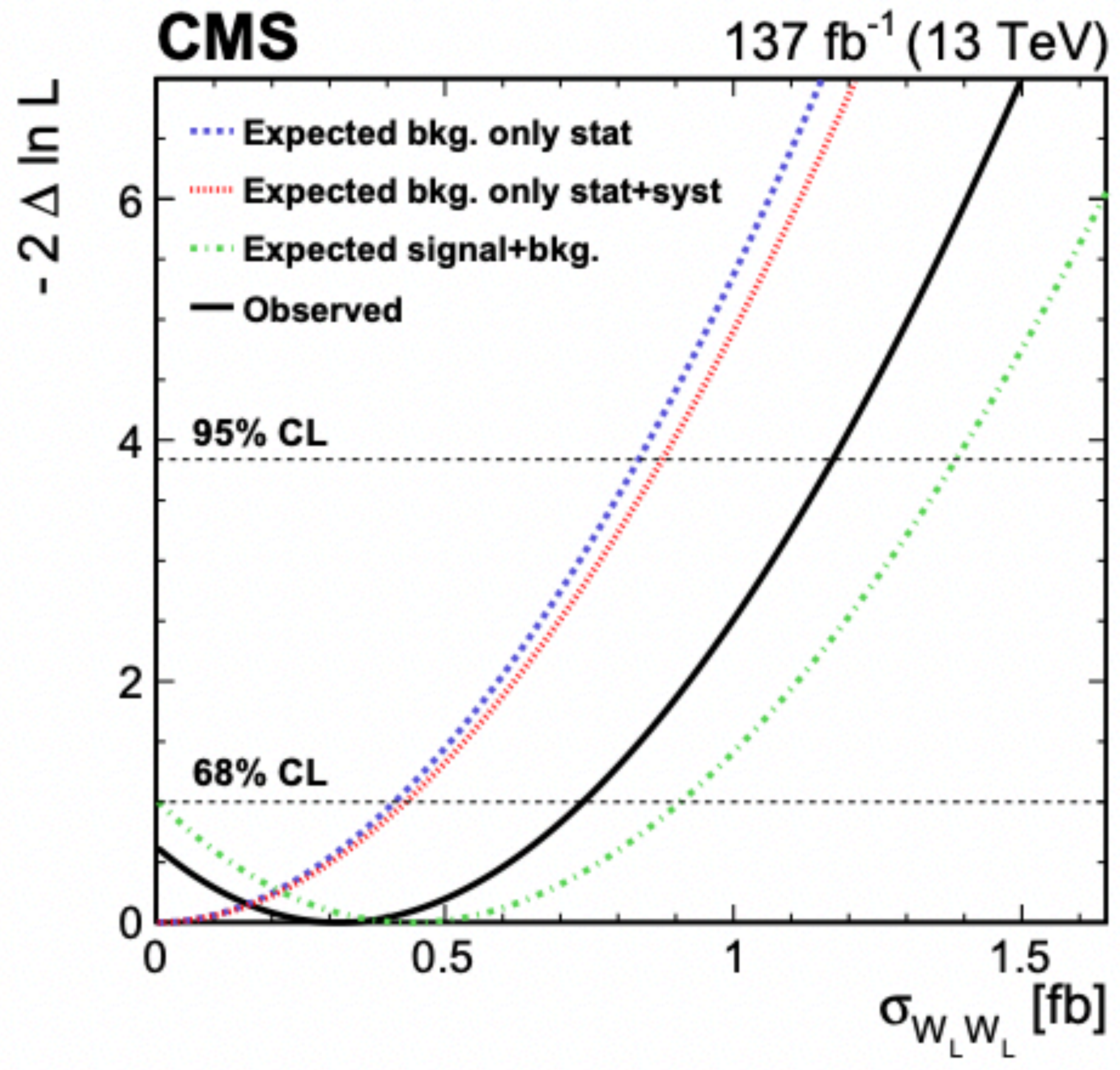


Vector Boson Scattering

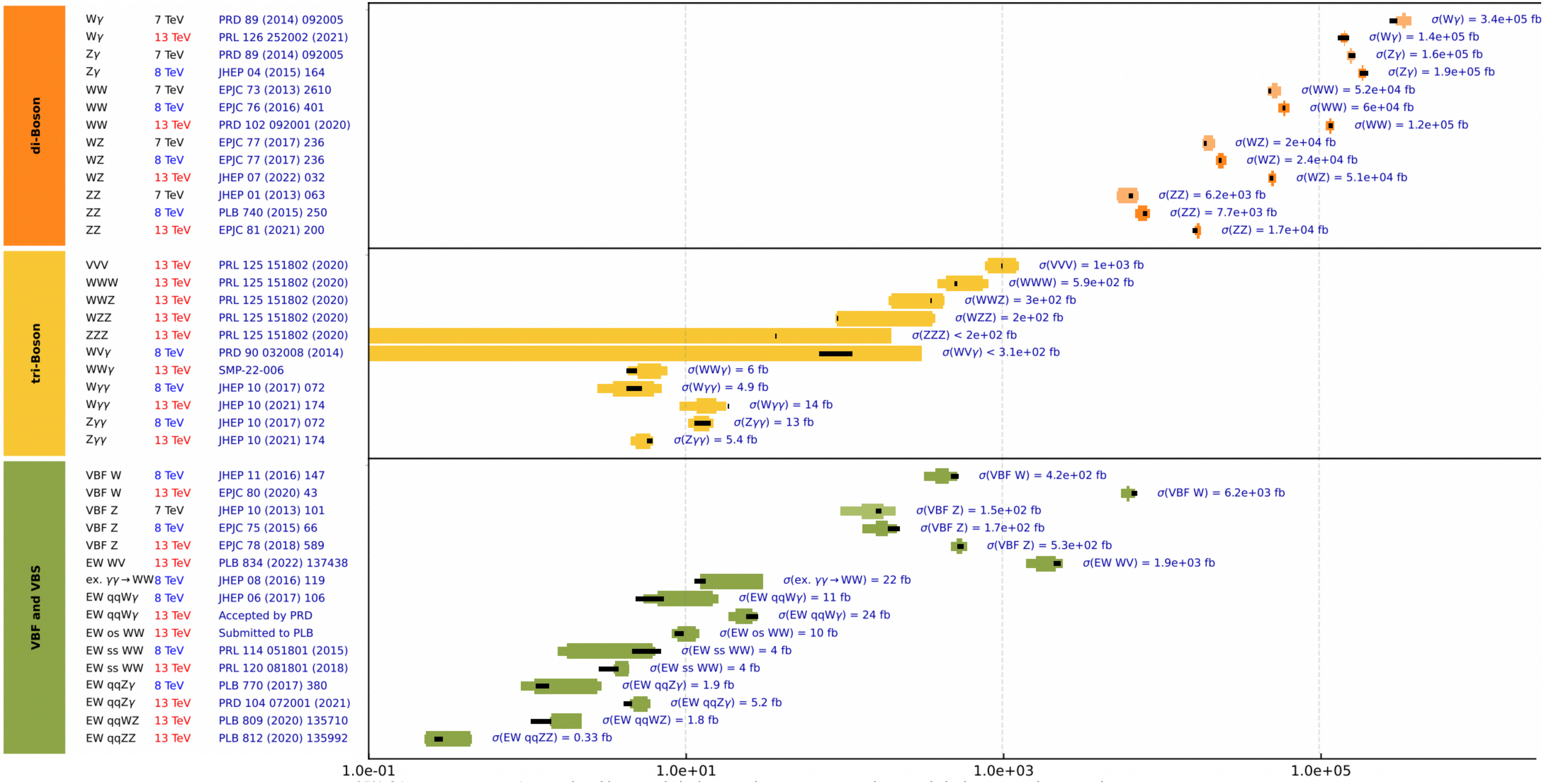
- Important process to check EW physics, probing at high energies
- W/o the Higgs Boson amplitudes violate unitarity
- Processes clearly observed. Extracting contribution from polarised W bosons







Multiboson production overview

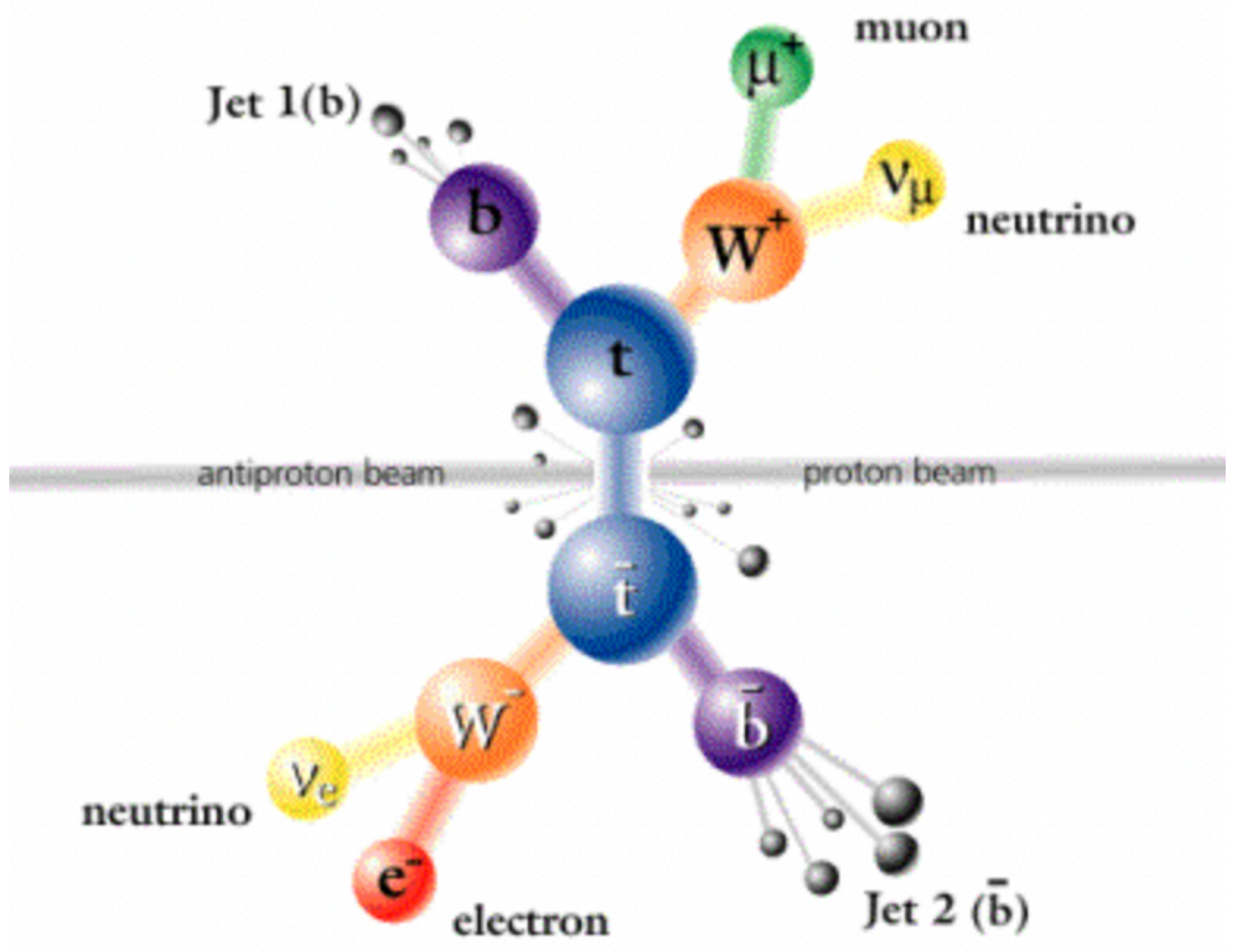


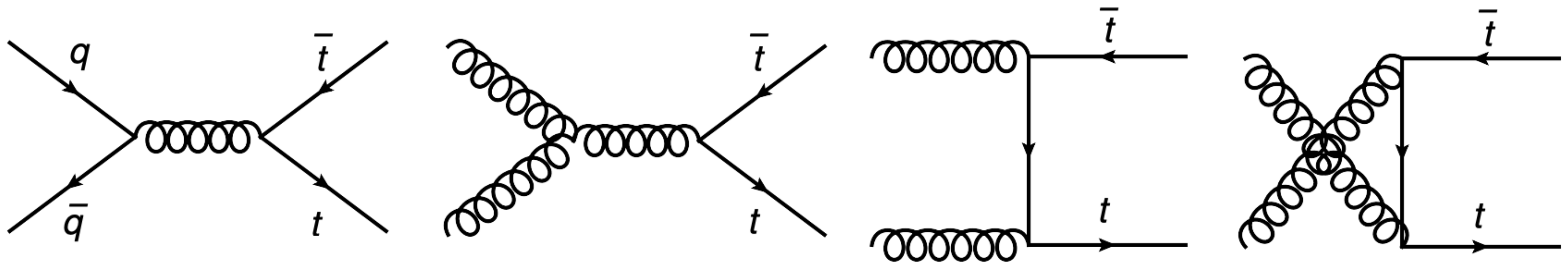
Top Physics

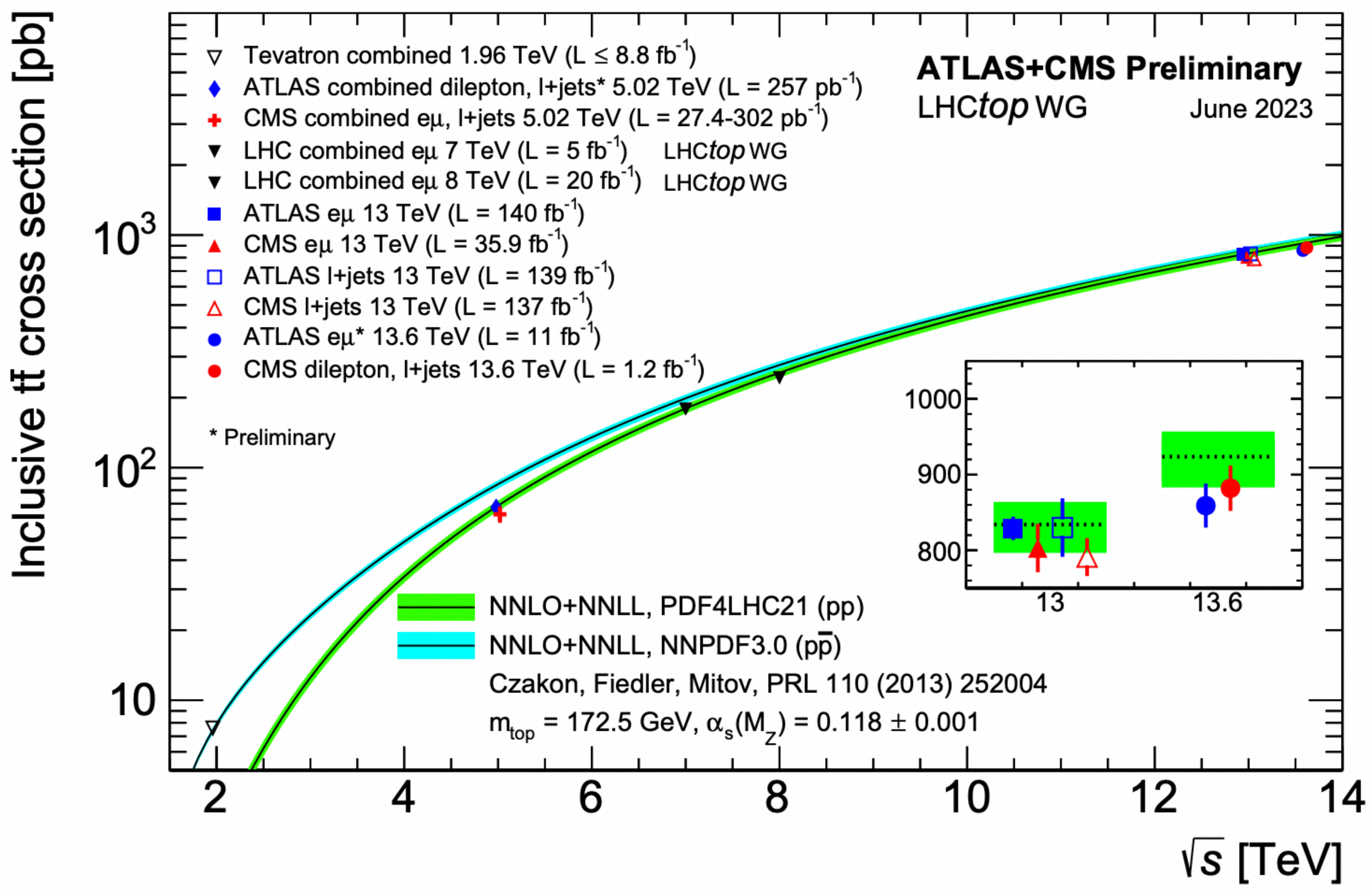
- Heaviest known elementary particle
- Couples with a strength of 1 to the Higgs field

$$y_t = \frac{\sqrt{2} m_t}{v} \sim 1$$

- Predicted to explain CP violation in Kaon system (1973)
- Discovery by CDF and D0 at the Tevatron (1995)
- Decay into a W boson and a b quark
- Top quark decays before it hadronises
- Production at the LHC:

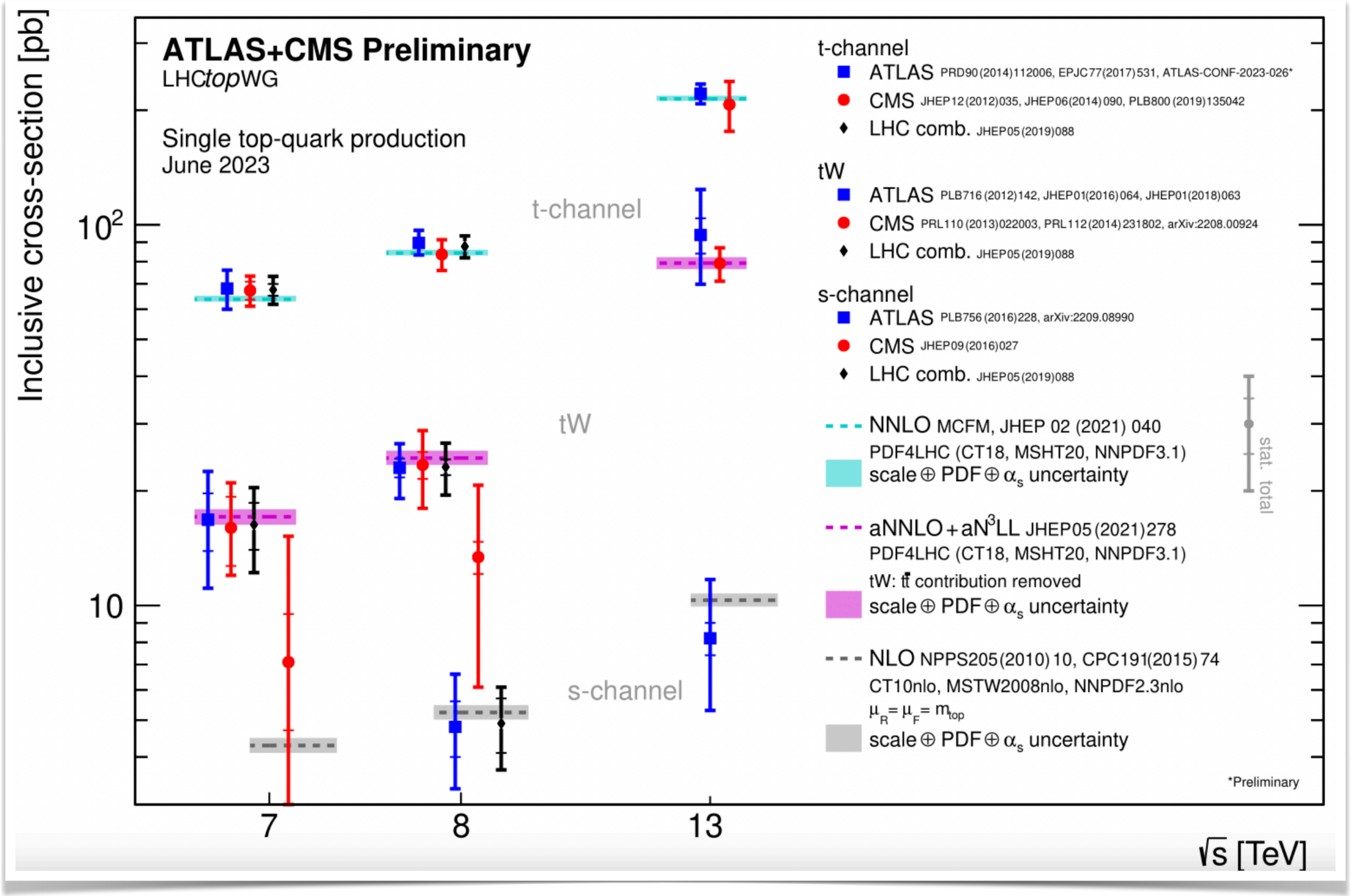


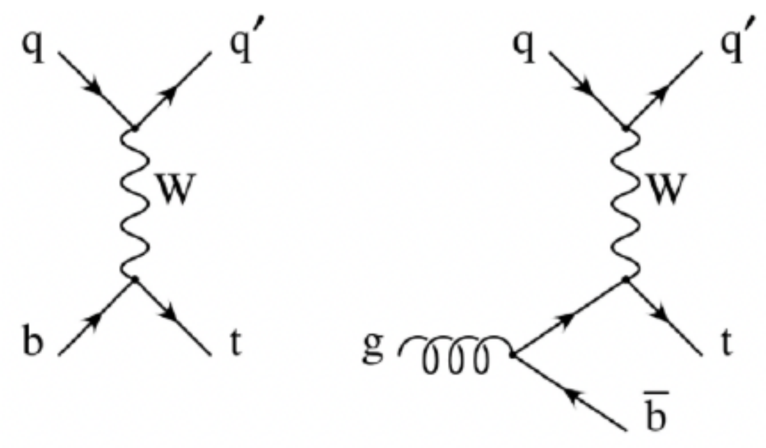




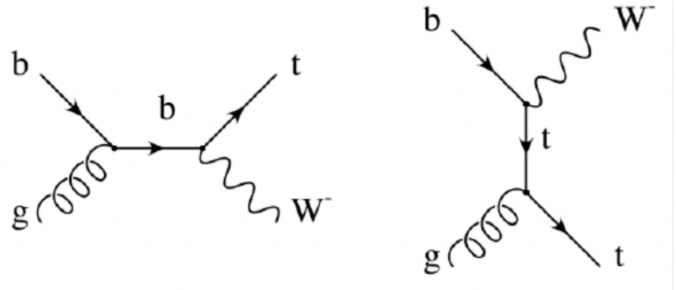
Top Physics

- Single top production cross sections

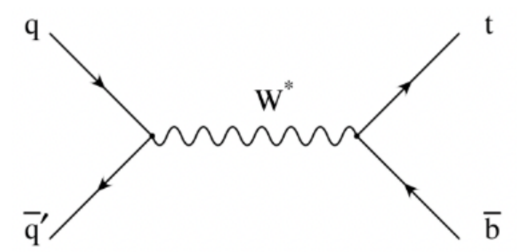




t-channel



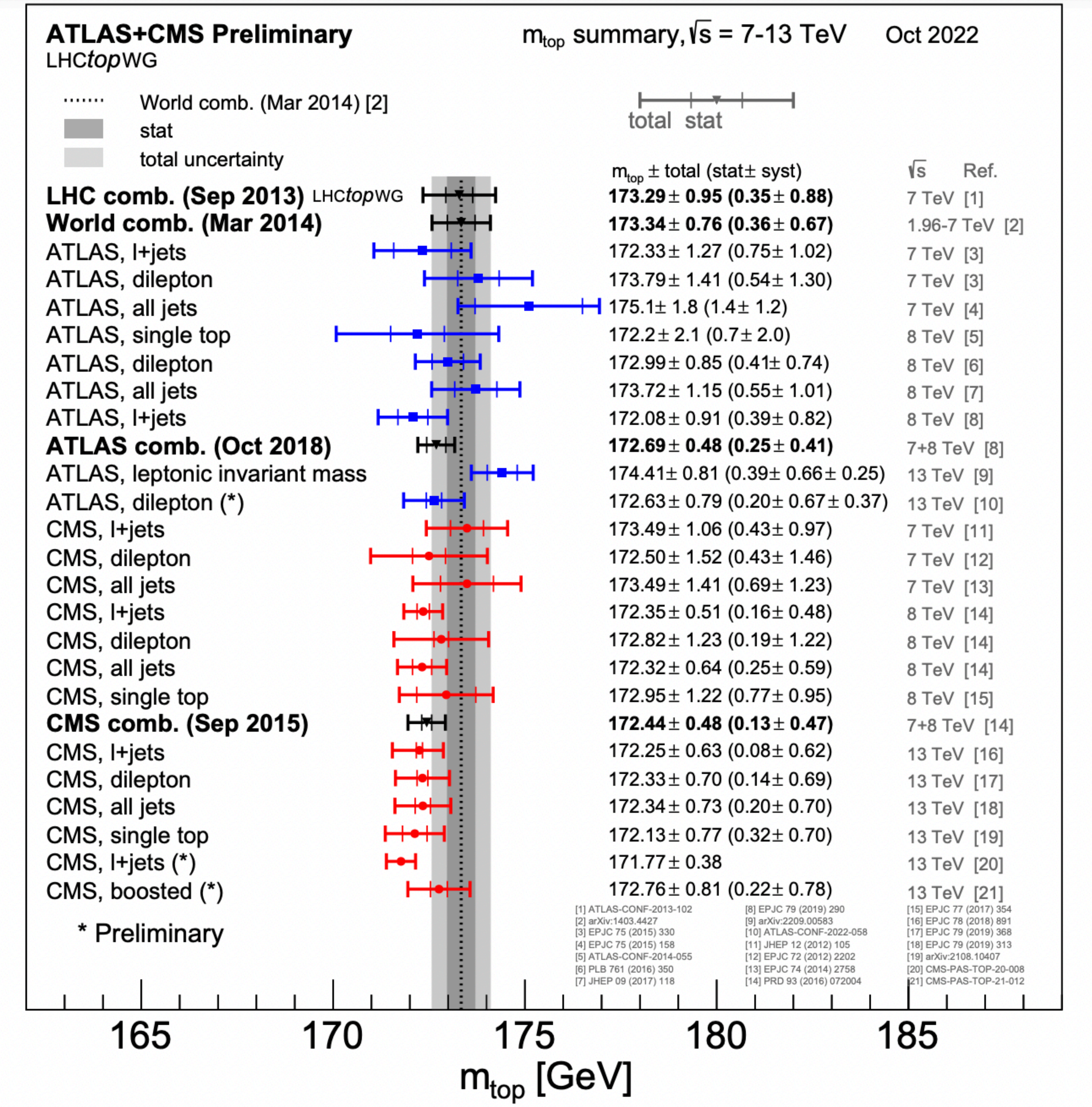
tW production



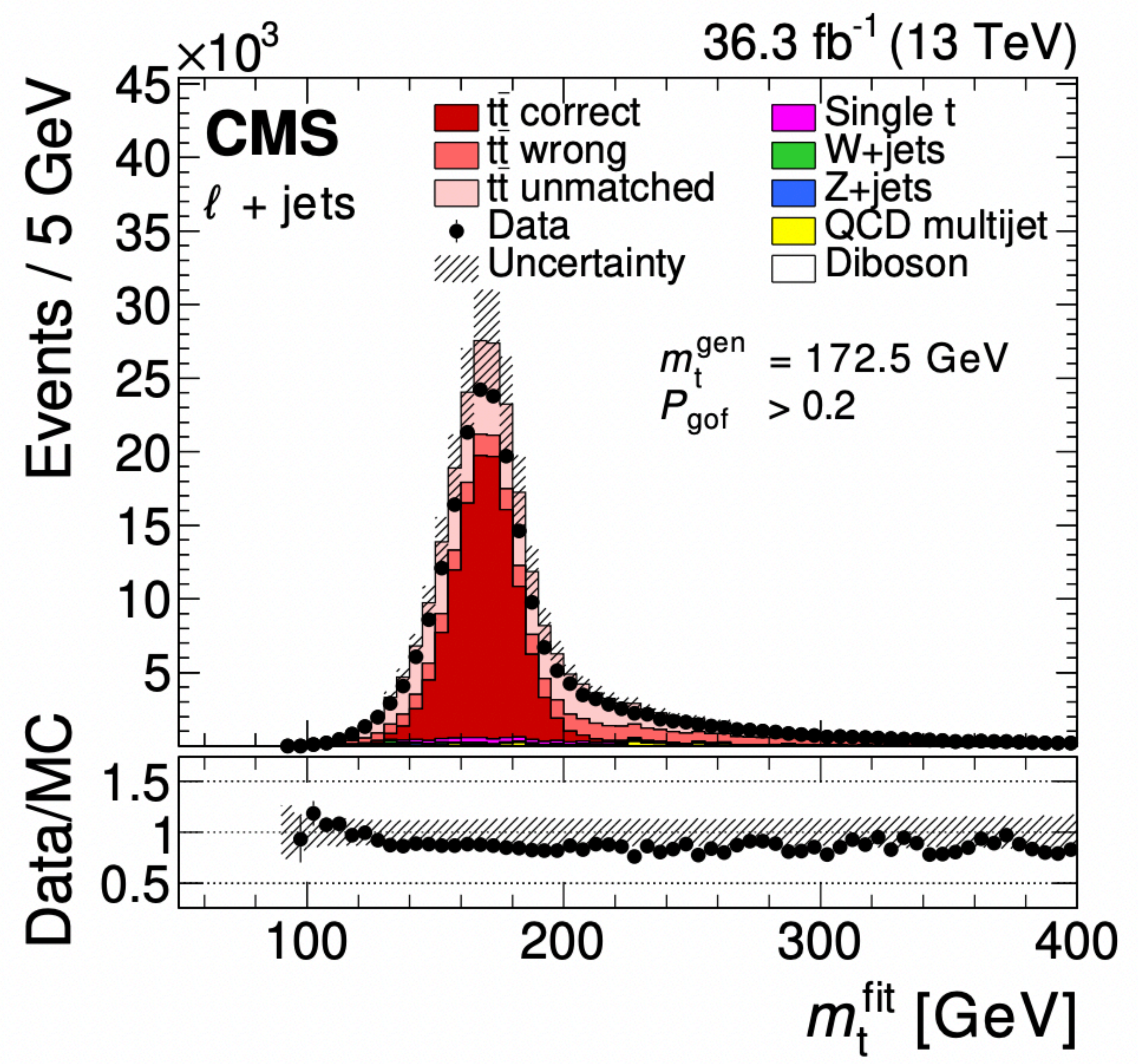
s-channel

Top Physics

- Top mass measurements



Direct mass measurement

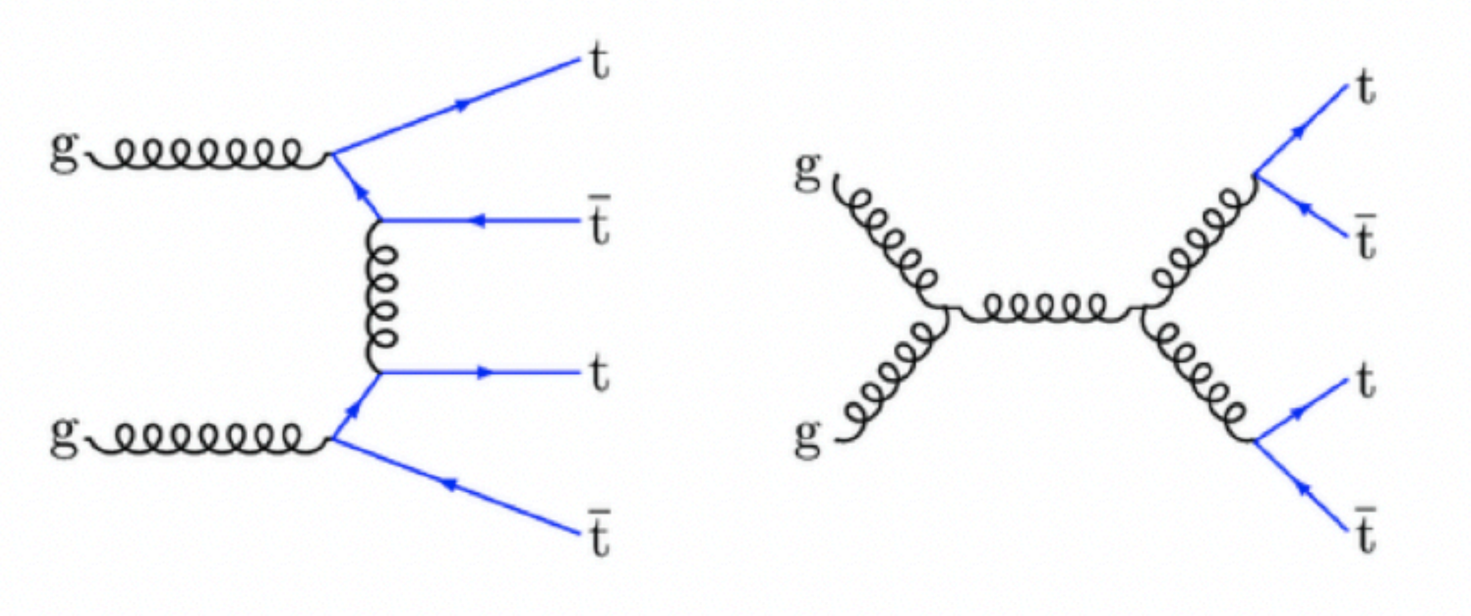


arXiv:2302.01967

$171.77 \pm 0.37\,\mathrm{GeV}$

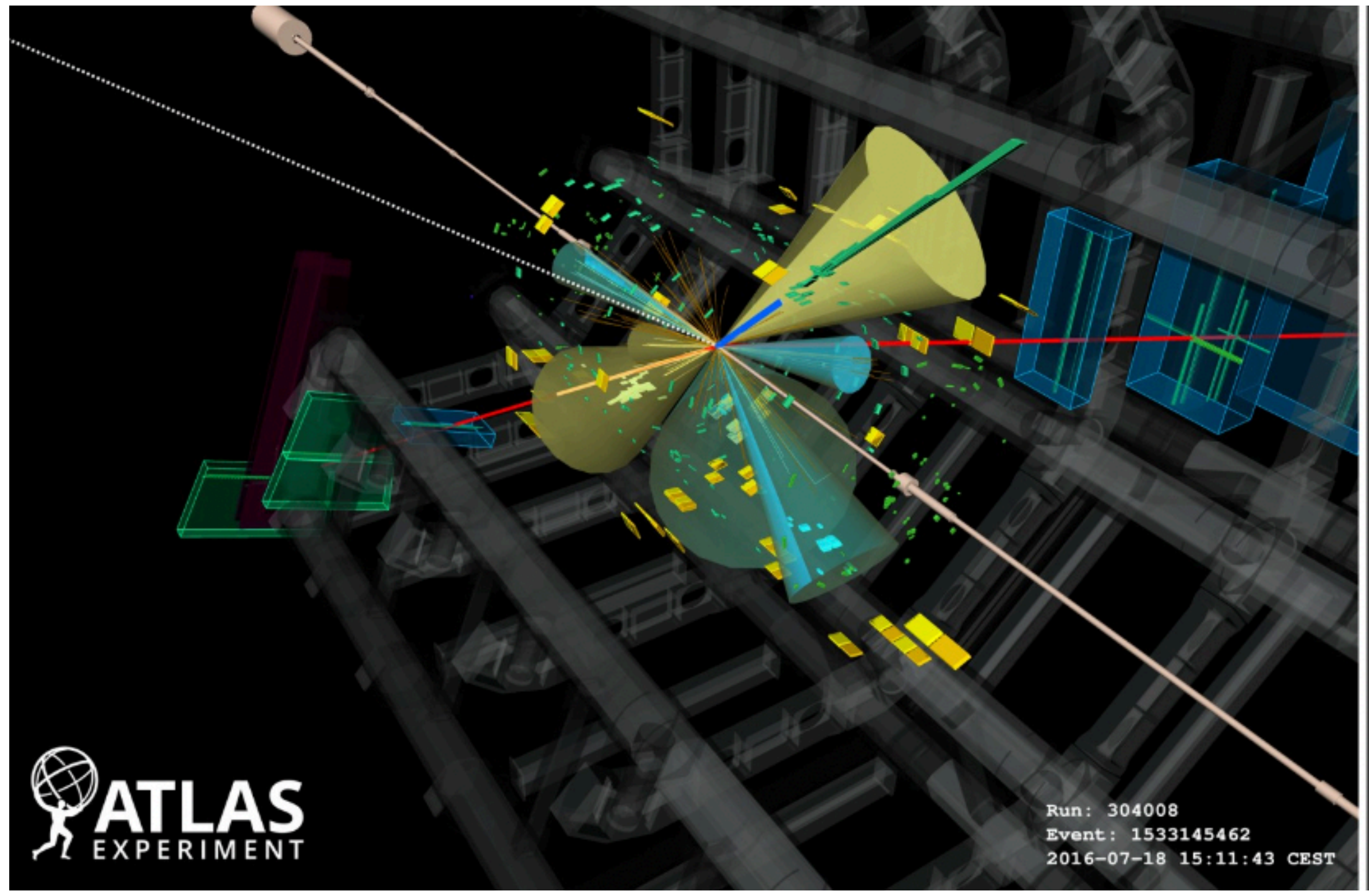
Top Physics

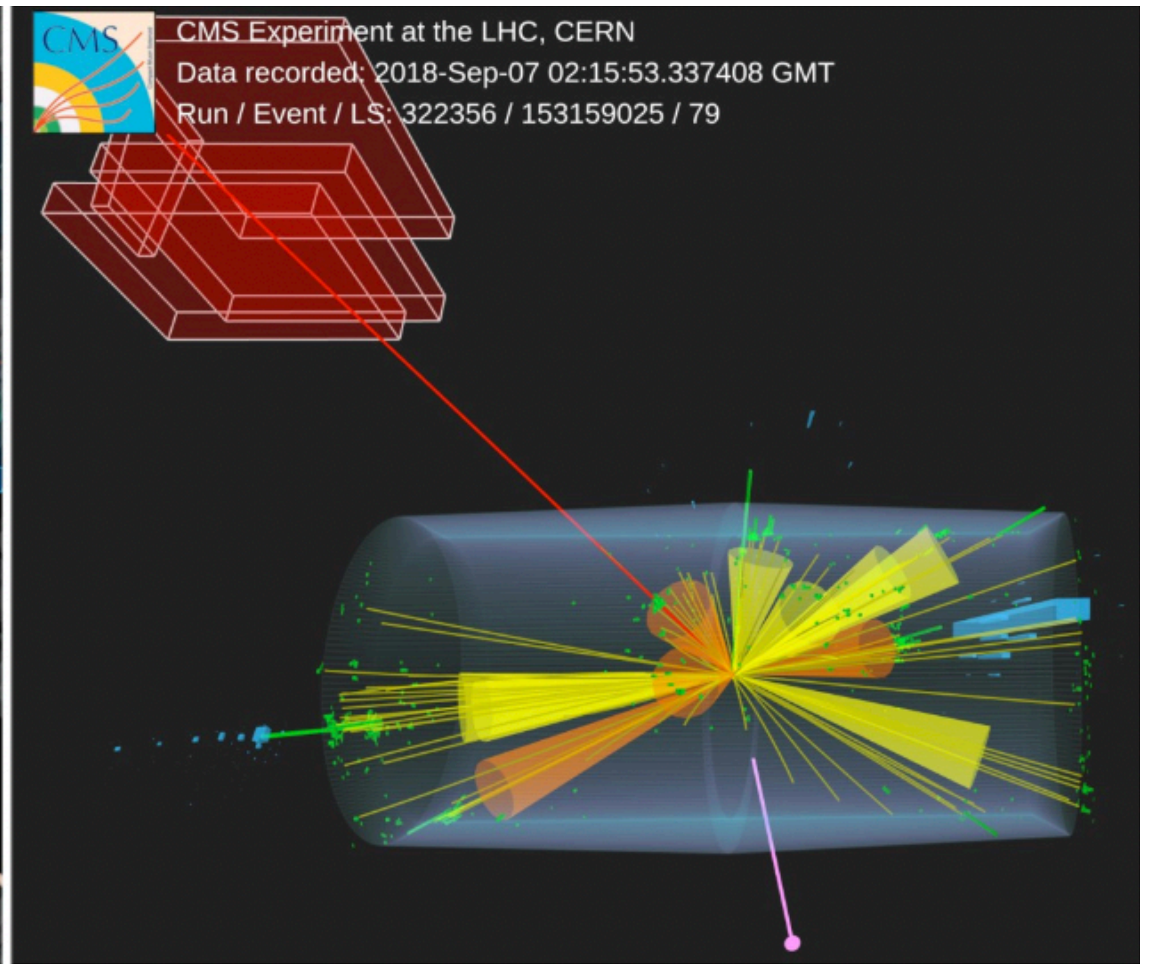
- Production of 4 top quarks; final state with 4 W bosons and 4 b quarks

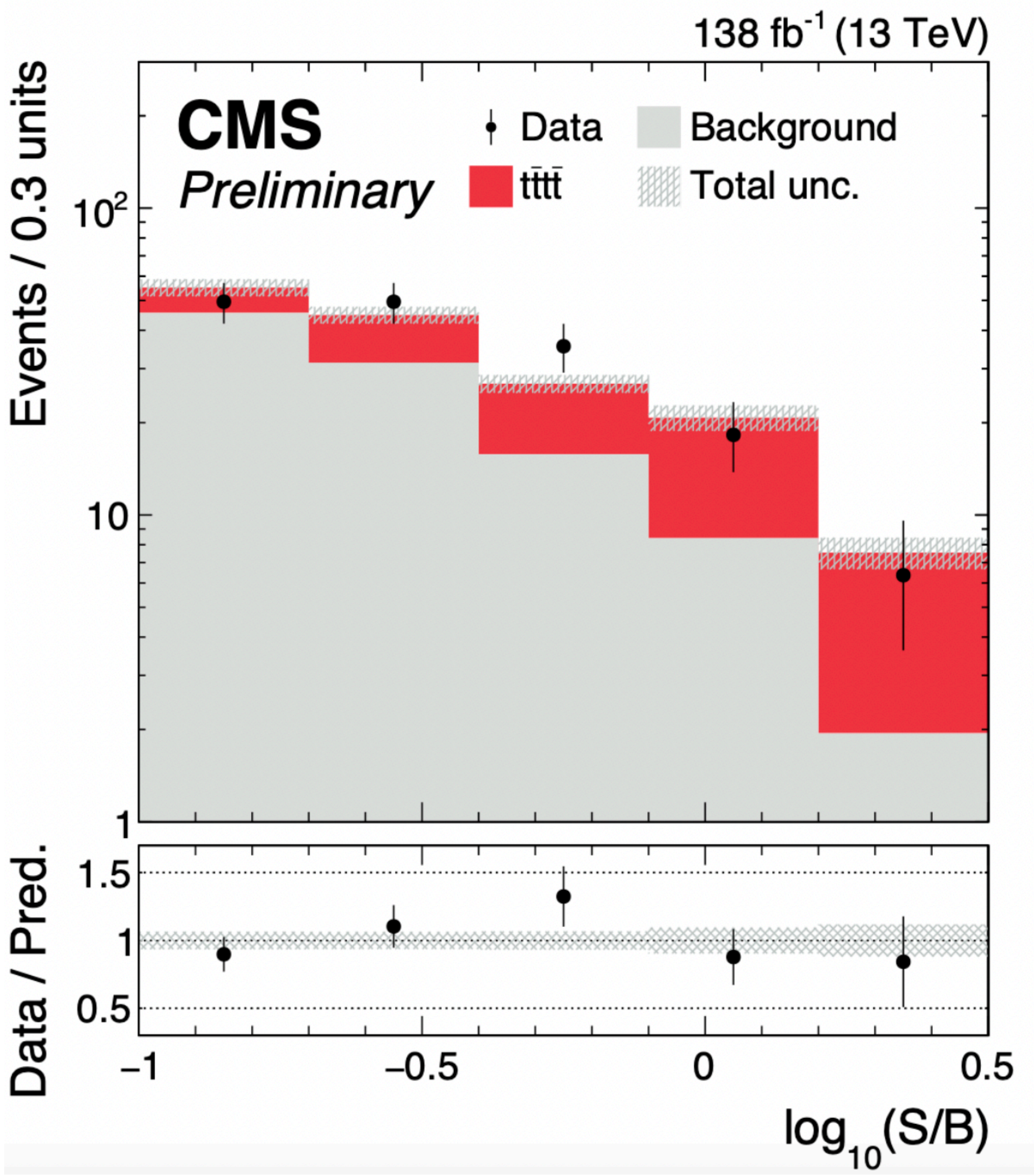


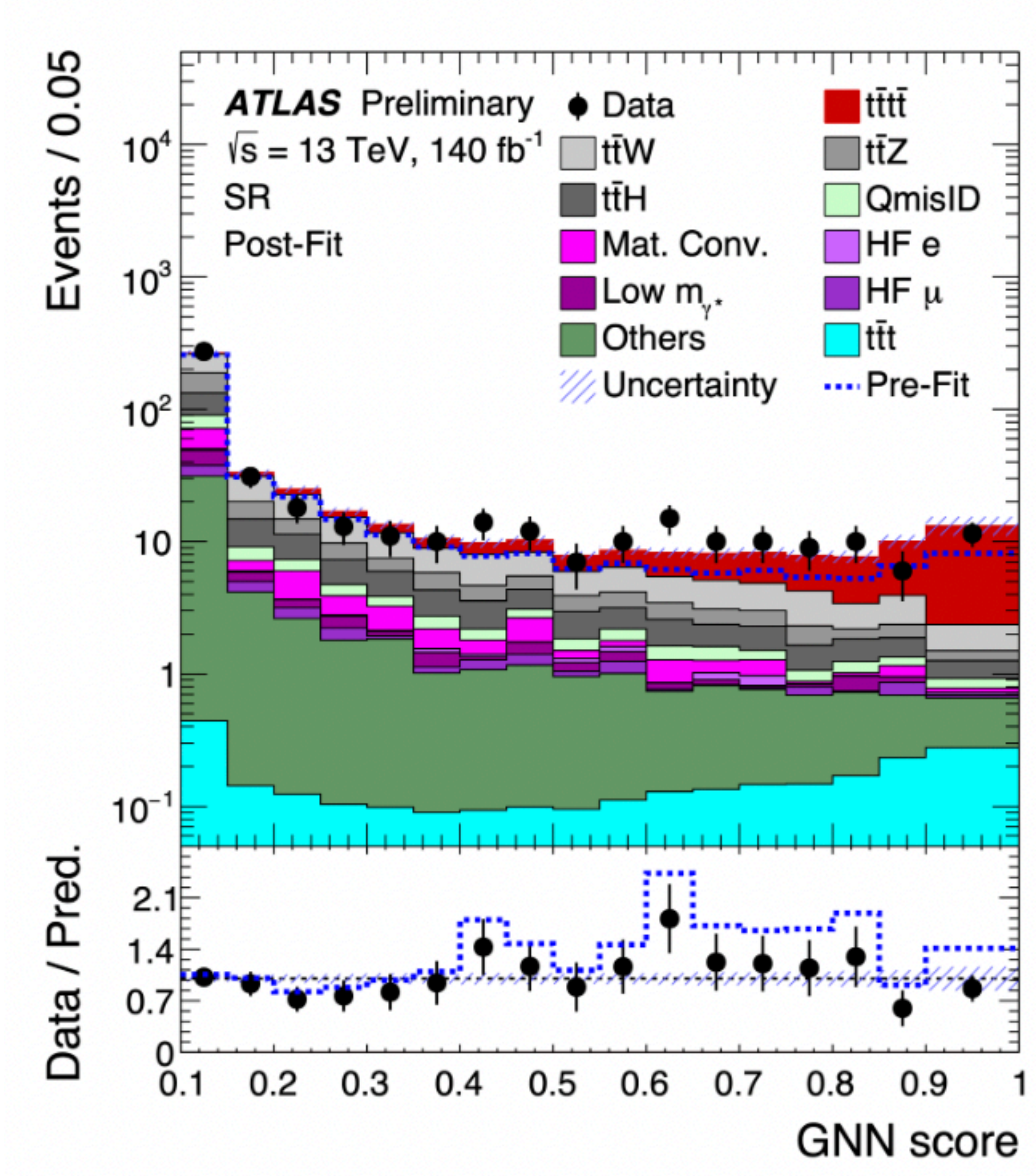
$$\sigma^{SM}_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4 \ \text{fb}$$

70,000 smaller than top pair production









Made possible by modern machine learning

Quiz

- Why is the jet (ET > 100 GeV) cross section larger that the cross section for W or Z boson production?
- Why are coupling constants not constant?
- How is vector boson scattering related to Higgs physics?
- How to we identify top quarks?
- What makes the top quark special?

References and further reading

- Textbooks
  - Modern Particle Physics by Mark Thomson
  - QCD at Colliders by Ellis, Stirling, and Weber
- Pictures
  - CERN Document Server
  - Wikipedia
  - Or reference on page
- References
  - Previous CERN Summer Lectures - https://indico.cern.ch/category/97/
  - MIT's OCW 8.701 and 8.811
  - KIT's Particle Physics master courses (you can contact me)
  - Public results from ATLAS, CMS, and LHC combination groups
  - Or reference on page