



Karlsruhe Institute of Technology

Experimental Physics at Hadron Colliders

CERN Summer Students Lectures, July 17-21, 2023 - Lecture 2/4

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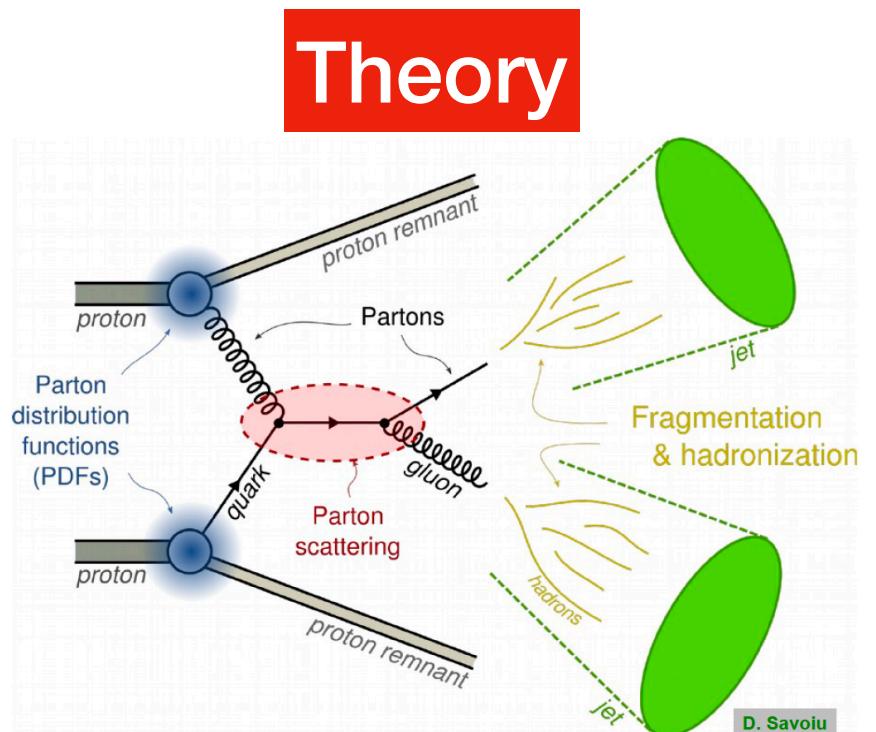


- Lecture 1: Introduction, fundamentals, cross sections
- Lecture 2: Standard model measurements
- Lecture 3: Higgs physics
- Lecture 4: Searches for new physics

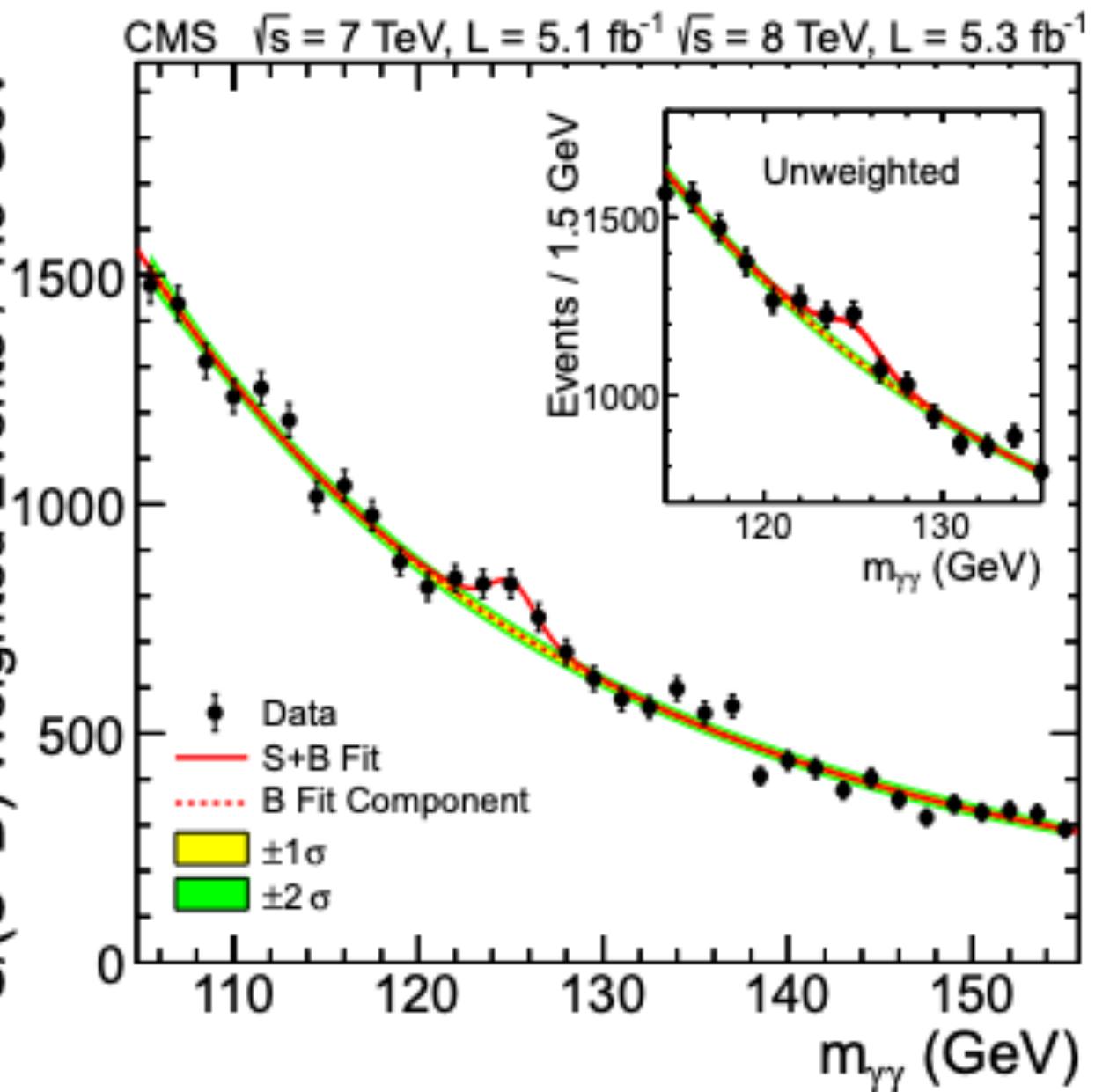
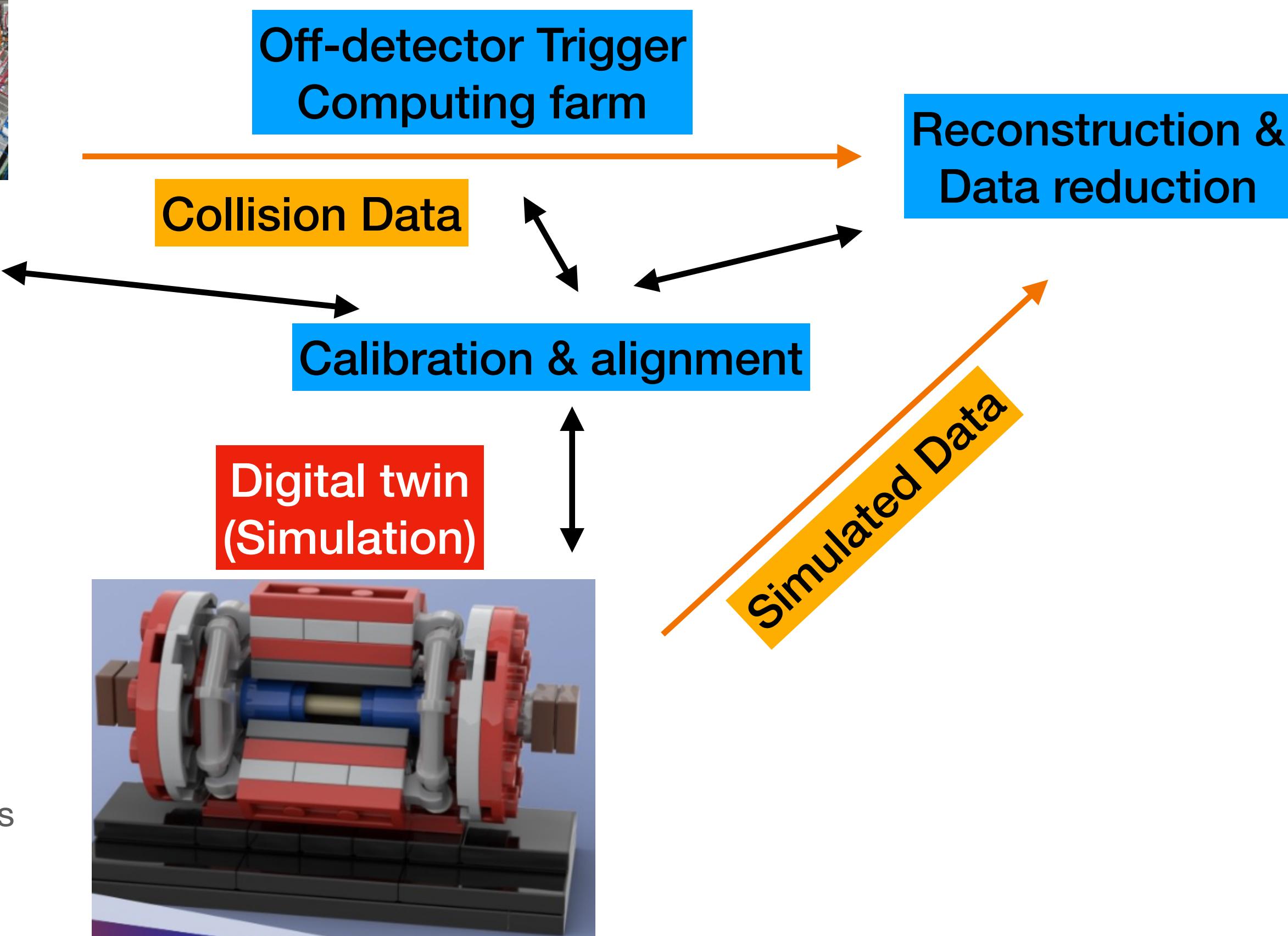
Data and Analysis Chain



On-detector Trigger Electronics



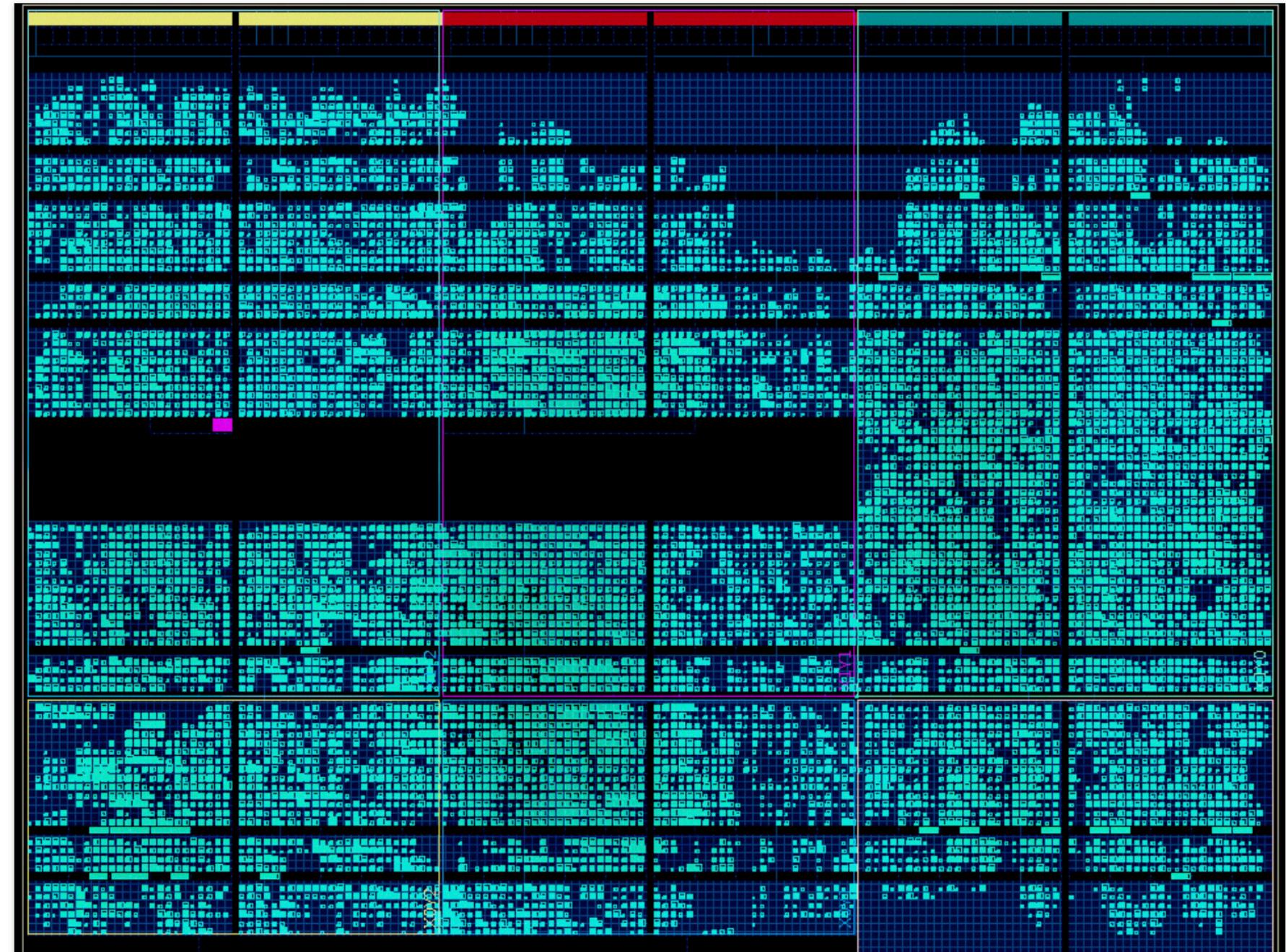
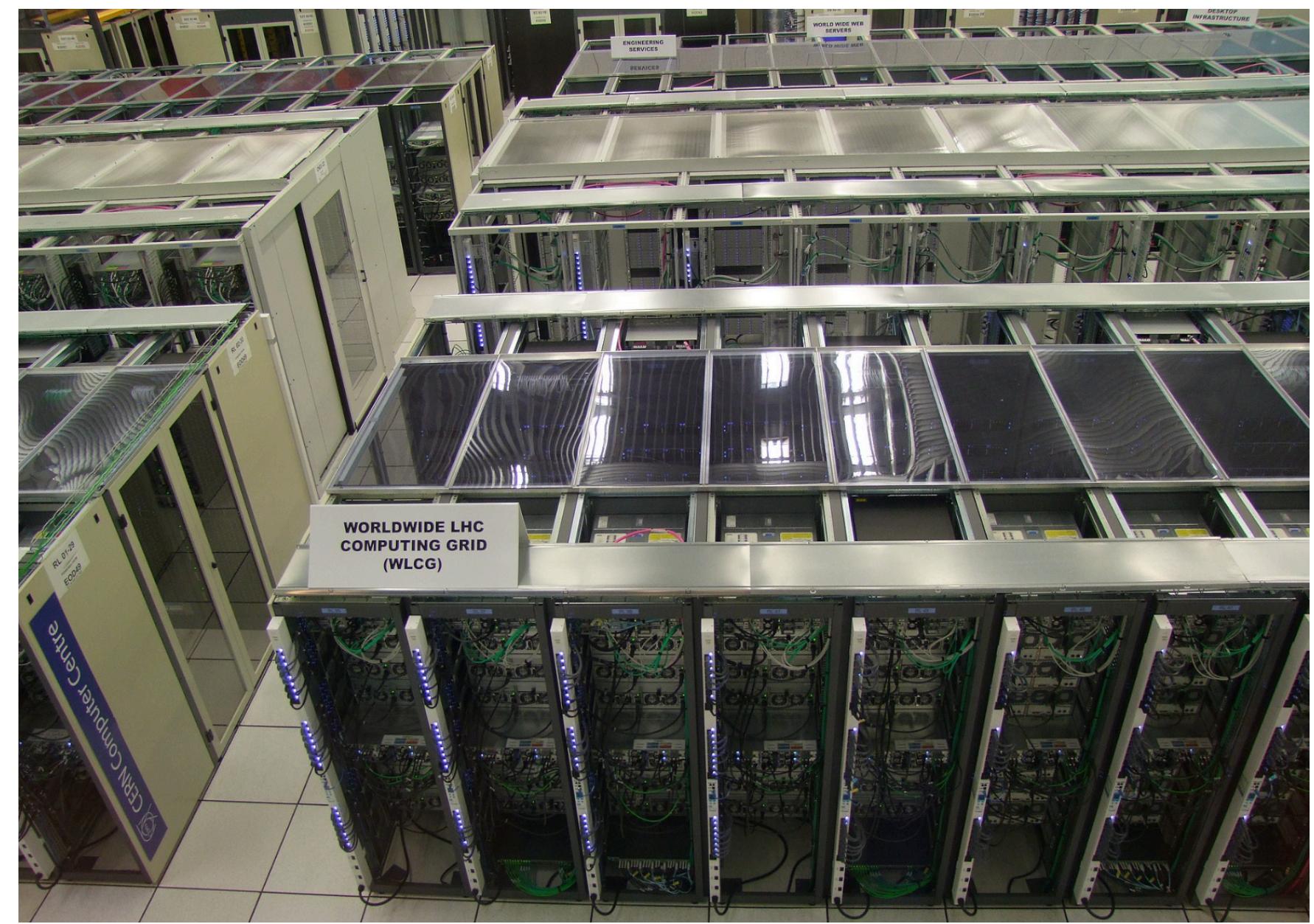
Calculation of physics processes
including hadronization



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



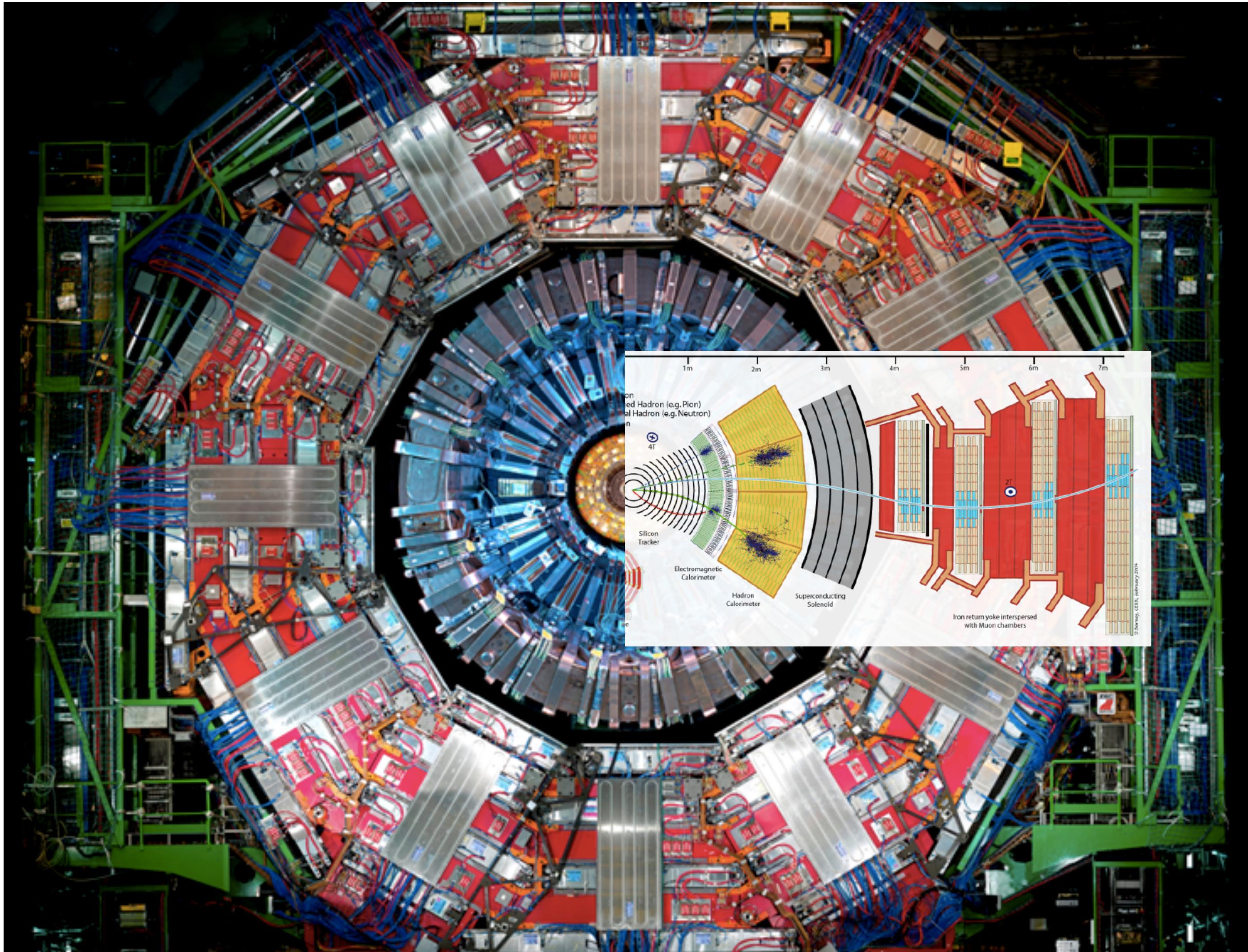
An ultra-compressed deep neural network on a field-programmable gate array. (Image: Sioni P. Summers)

What do we actually reconstruct from collisions?

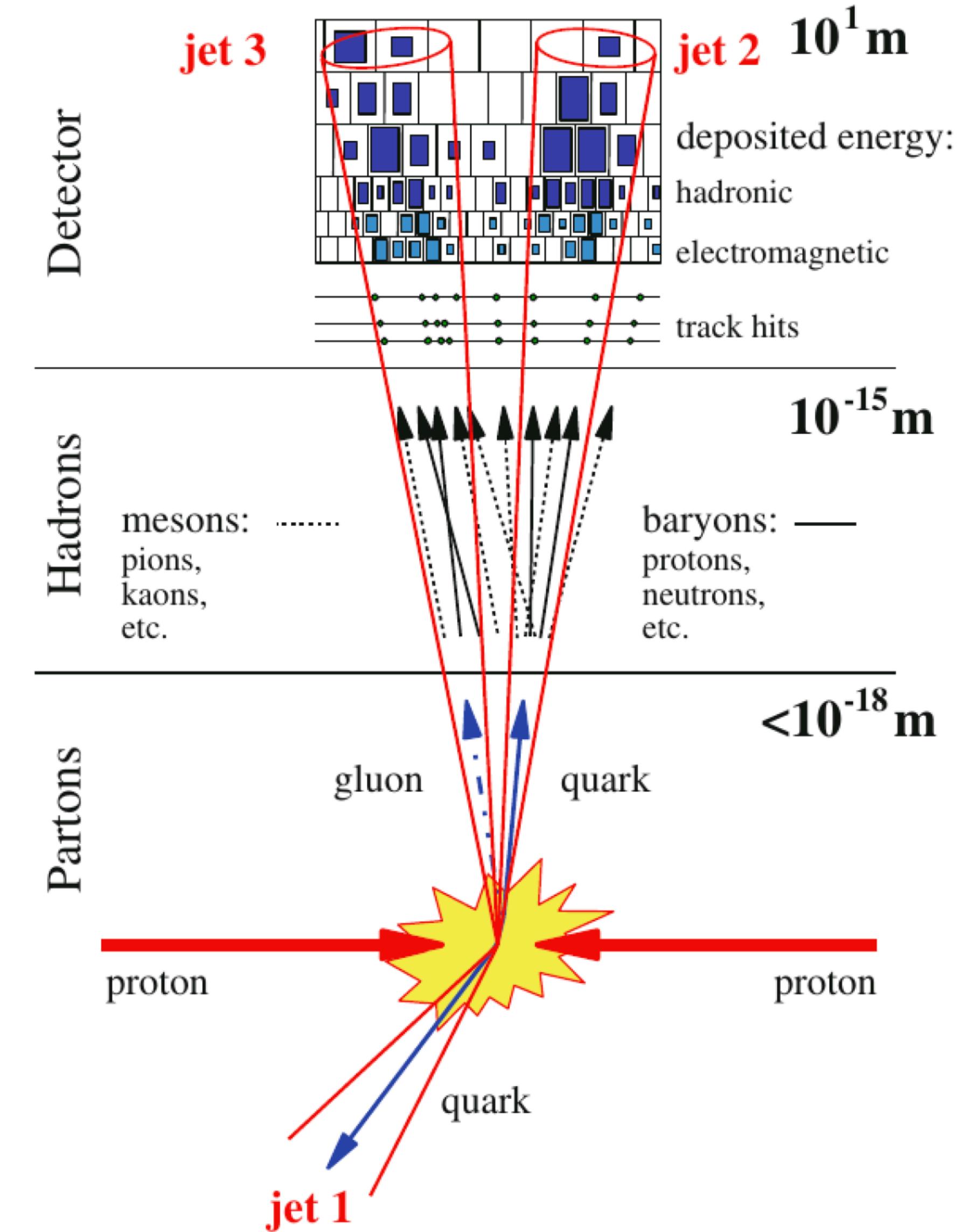


What do we actually reconstruct from collisions?

- 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

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

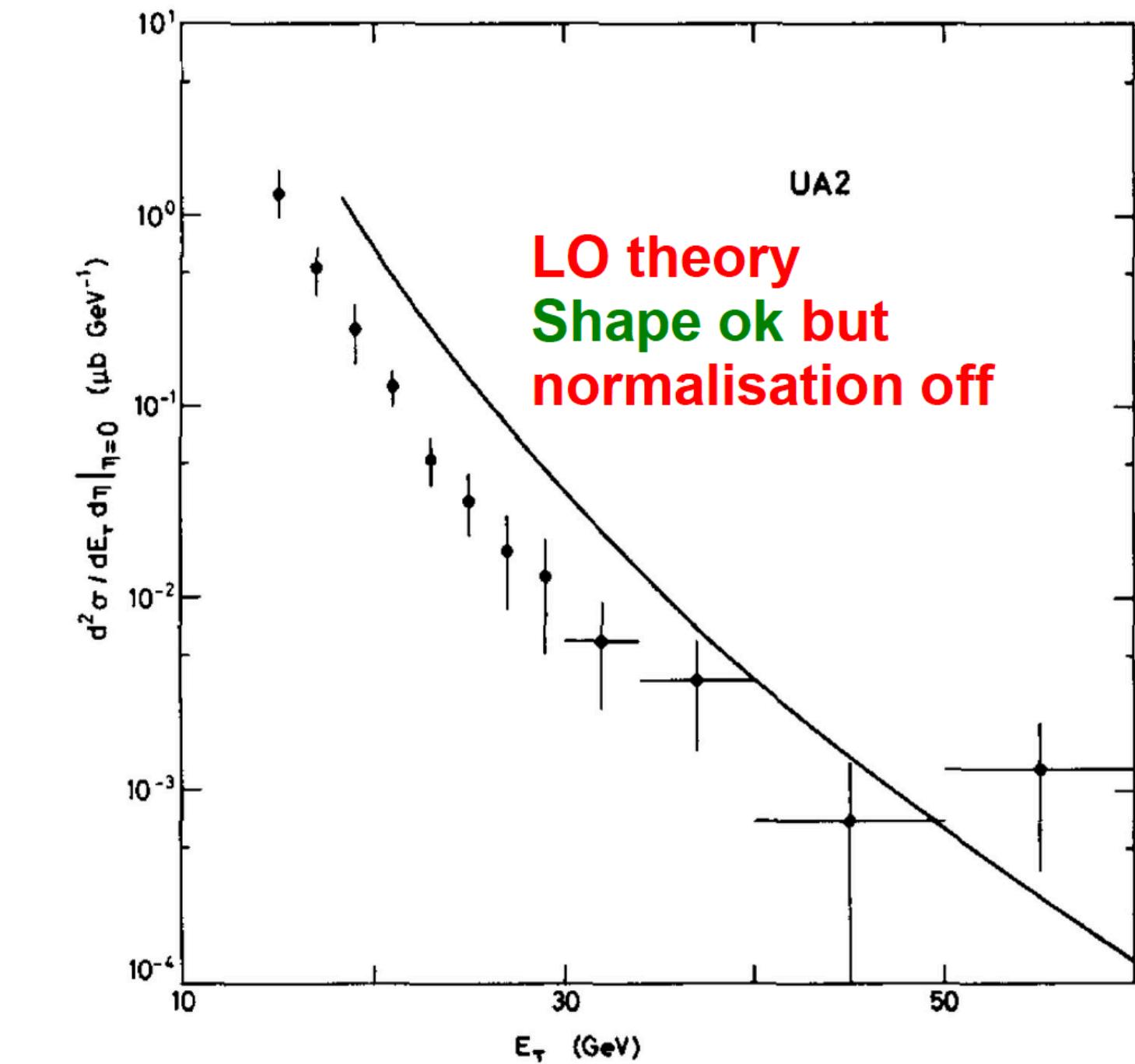
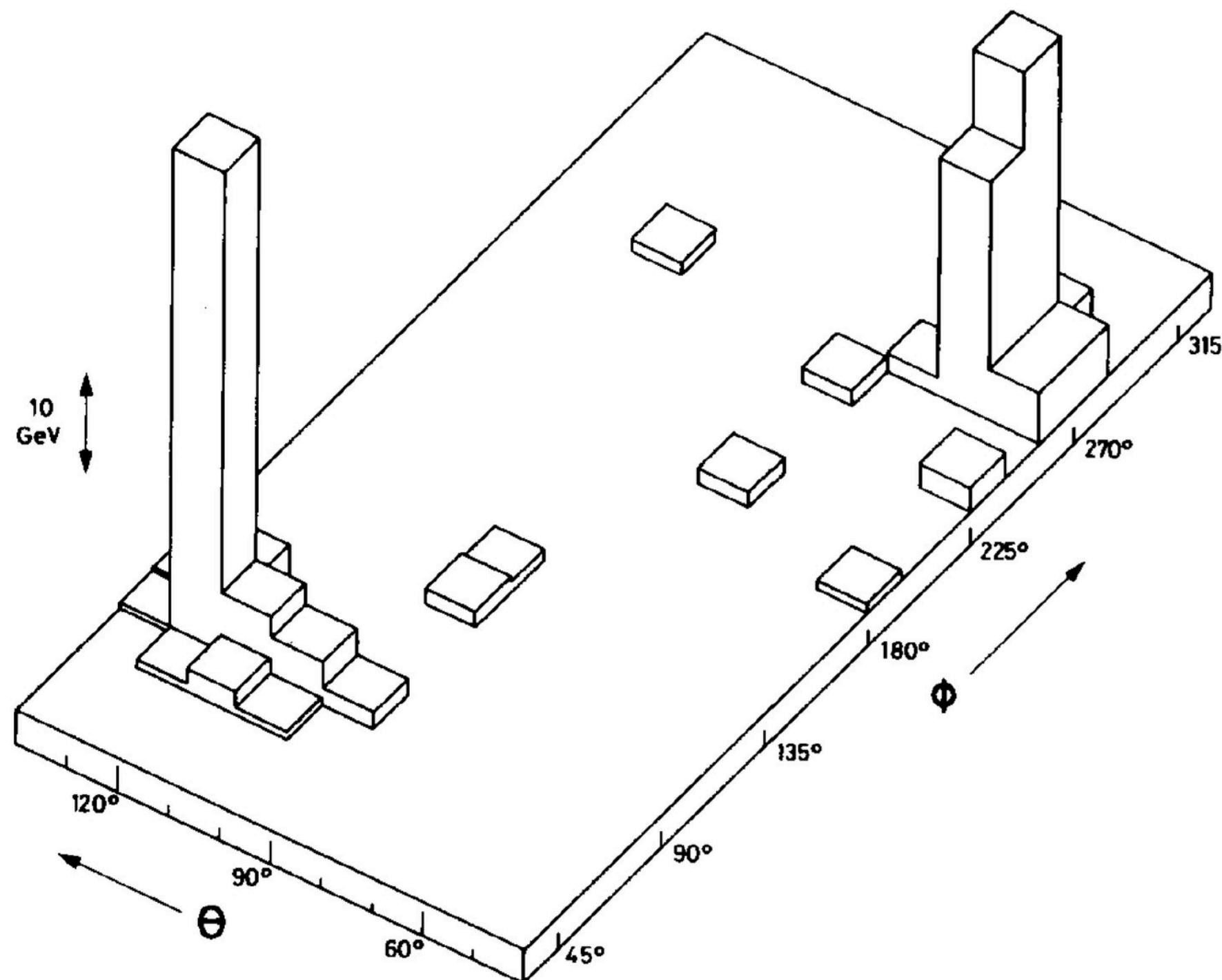


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses $\Lambda = 0.5 \text{ GeV}$ while $\Lambda = 0.15 \text{ GeV}$ would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

Jets at Hadron Collider

- Primary goal is to find correspondence between

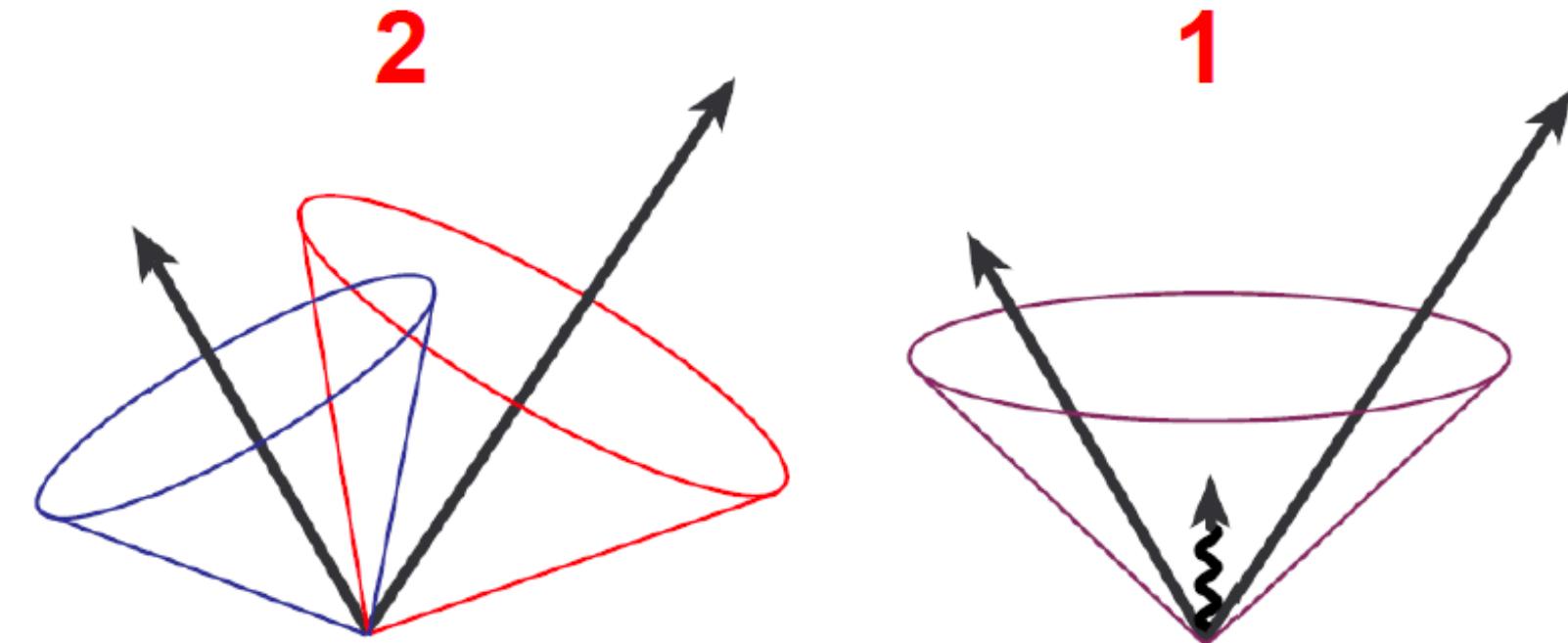
- Detector measurements
- Particles in final state
- Hard partons

- Classes of algorithms

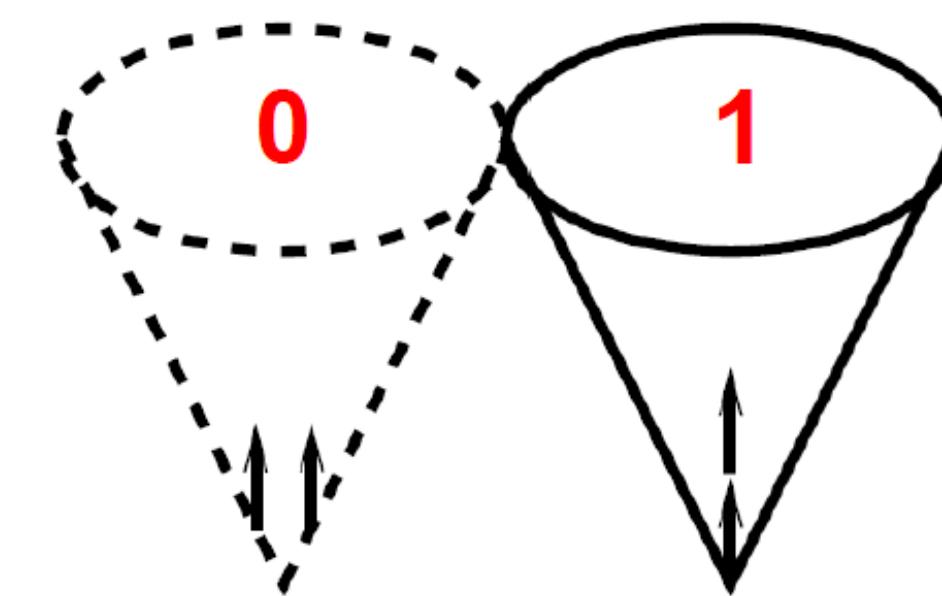
- Cone algorithms
- Sequential recombination

- 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

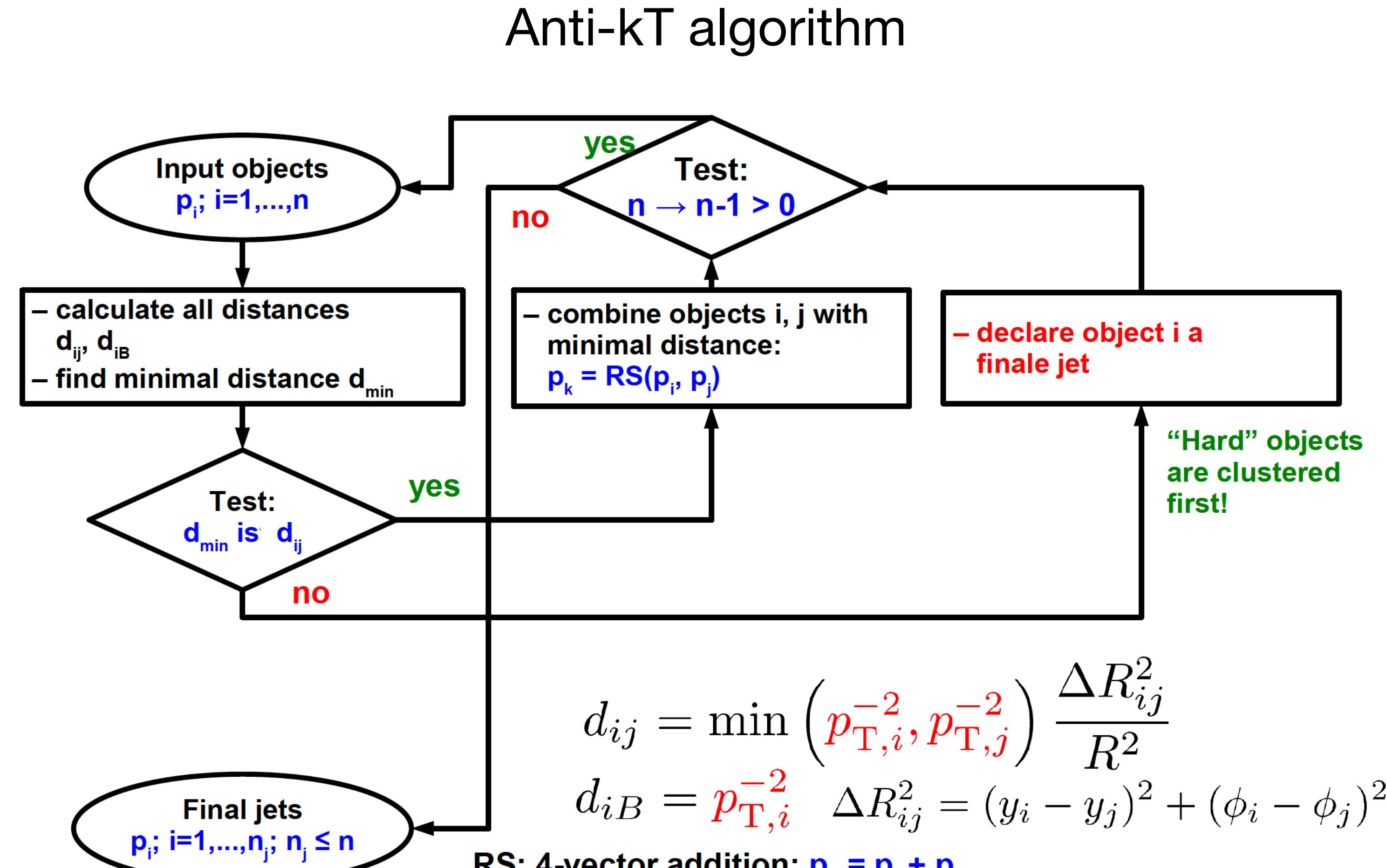
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Classes of algorithms

- Cone algorithms
 - Sequential recombination

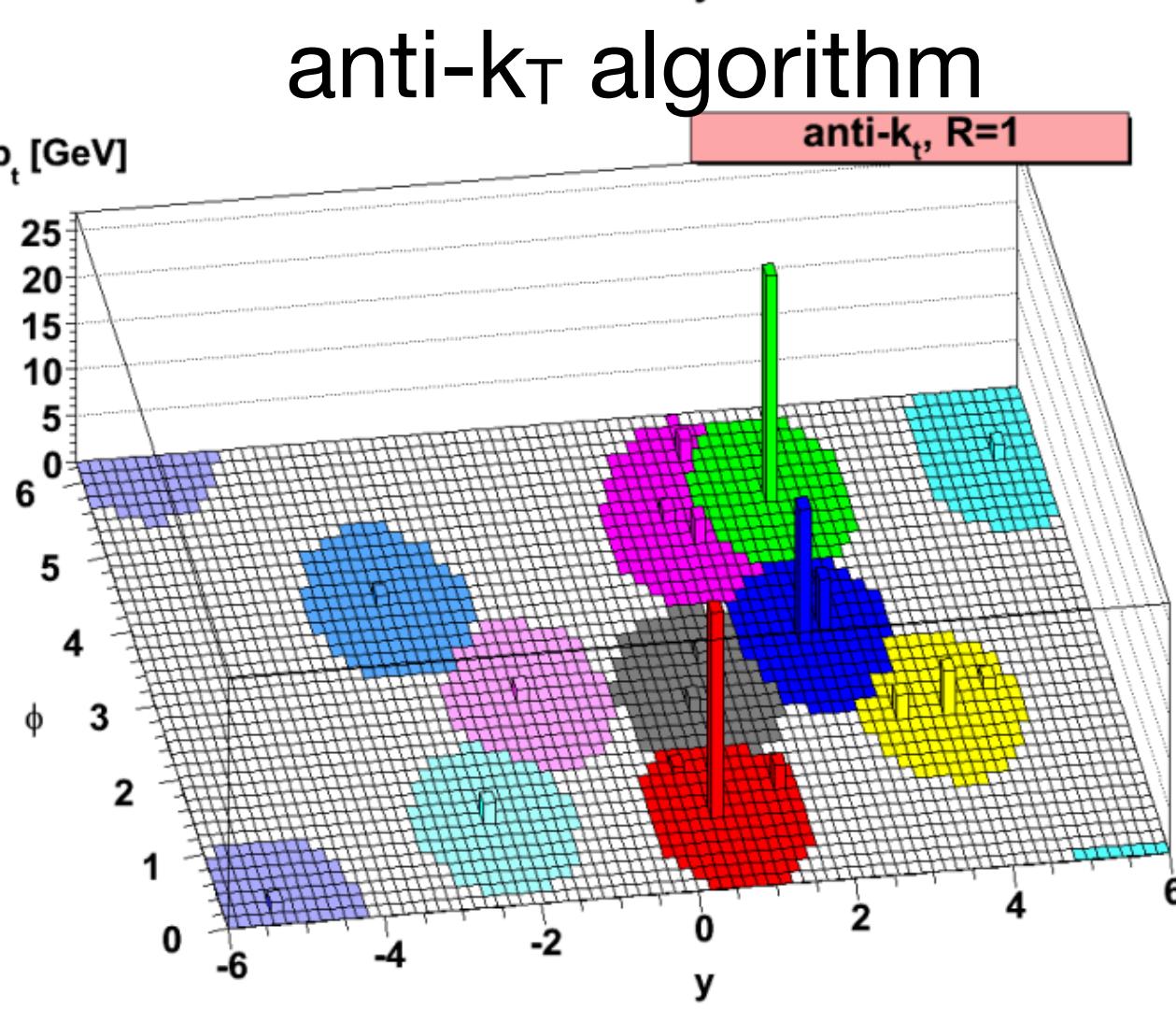
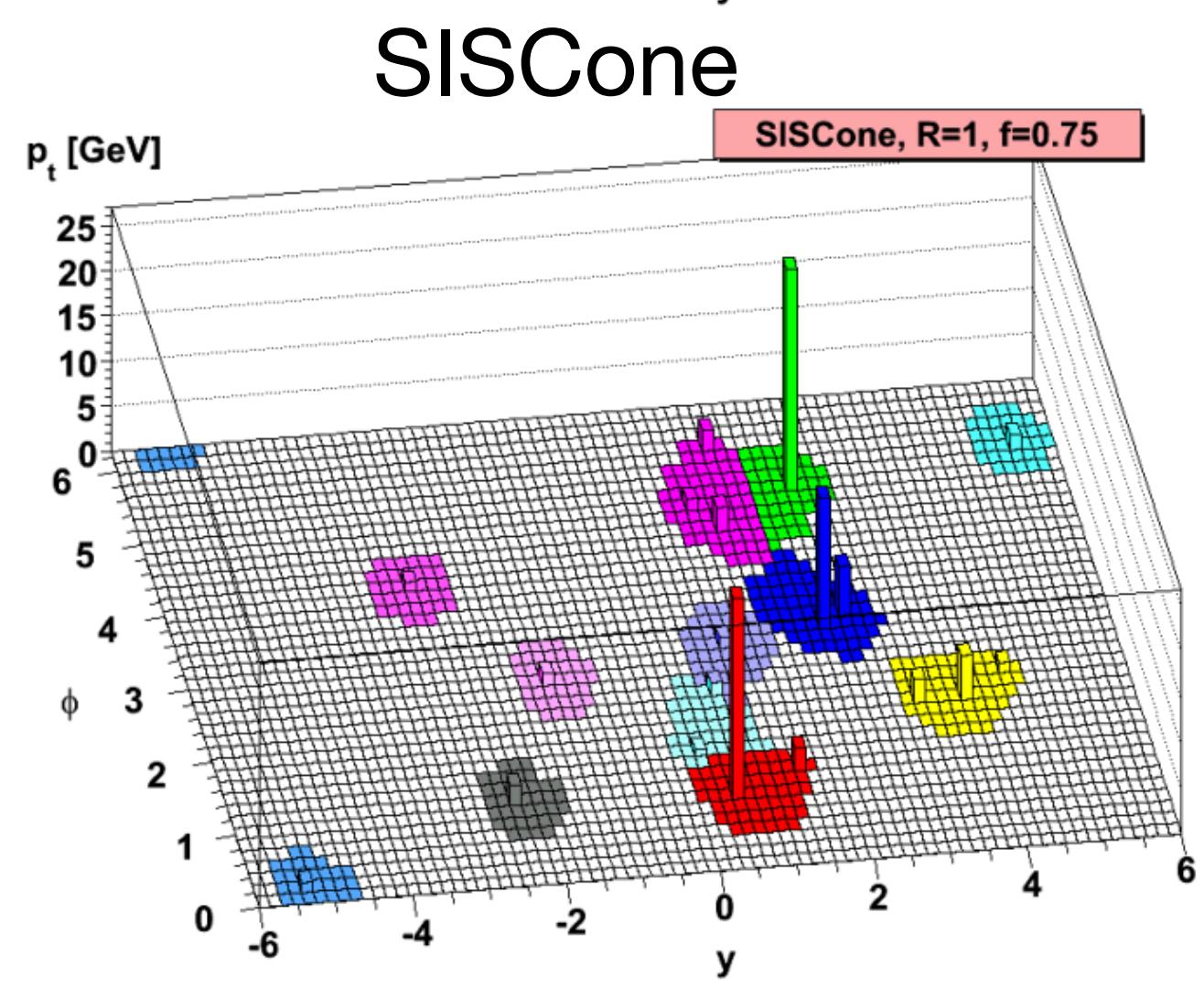
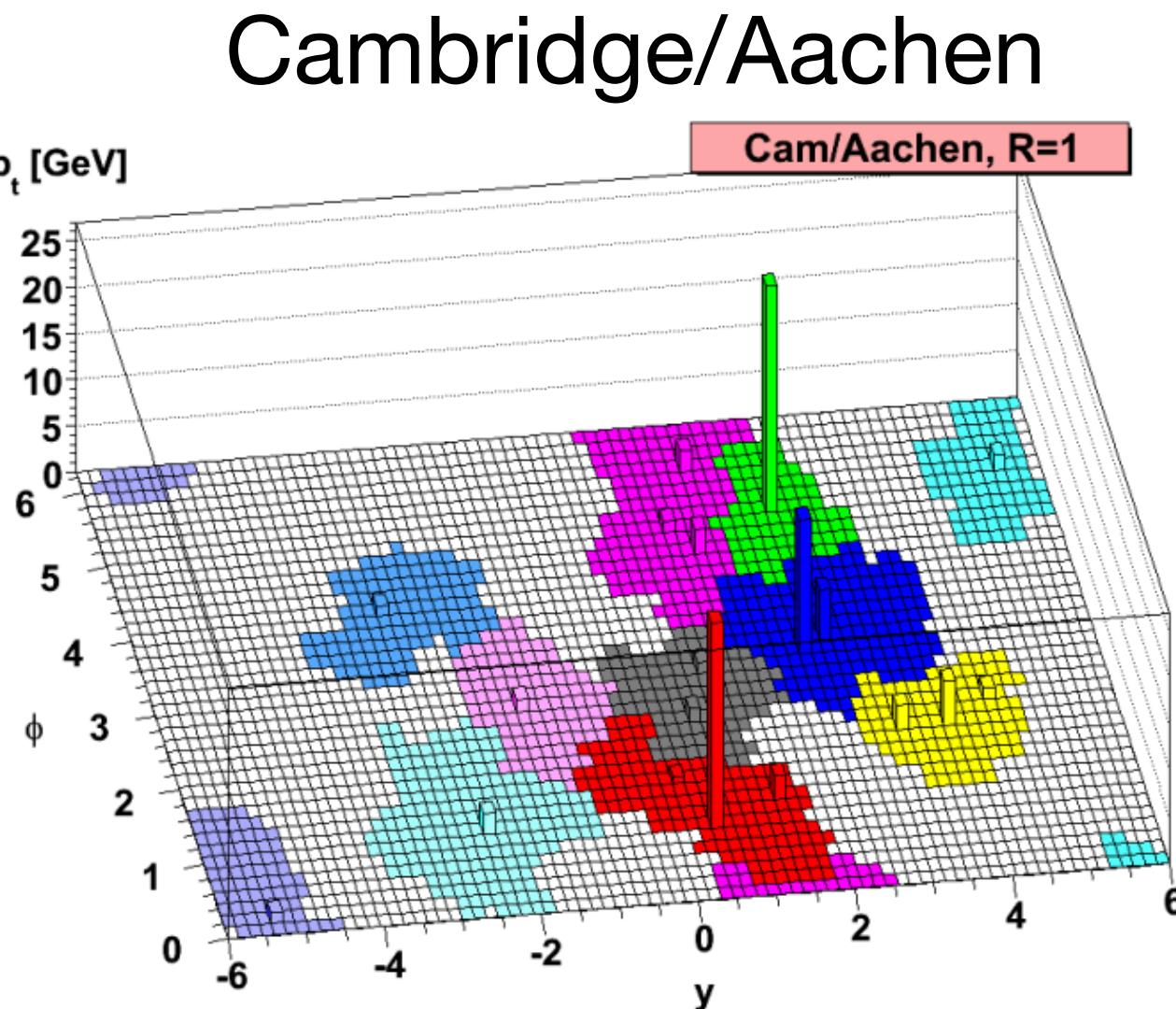
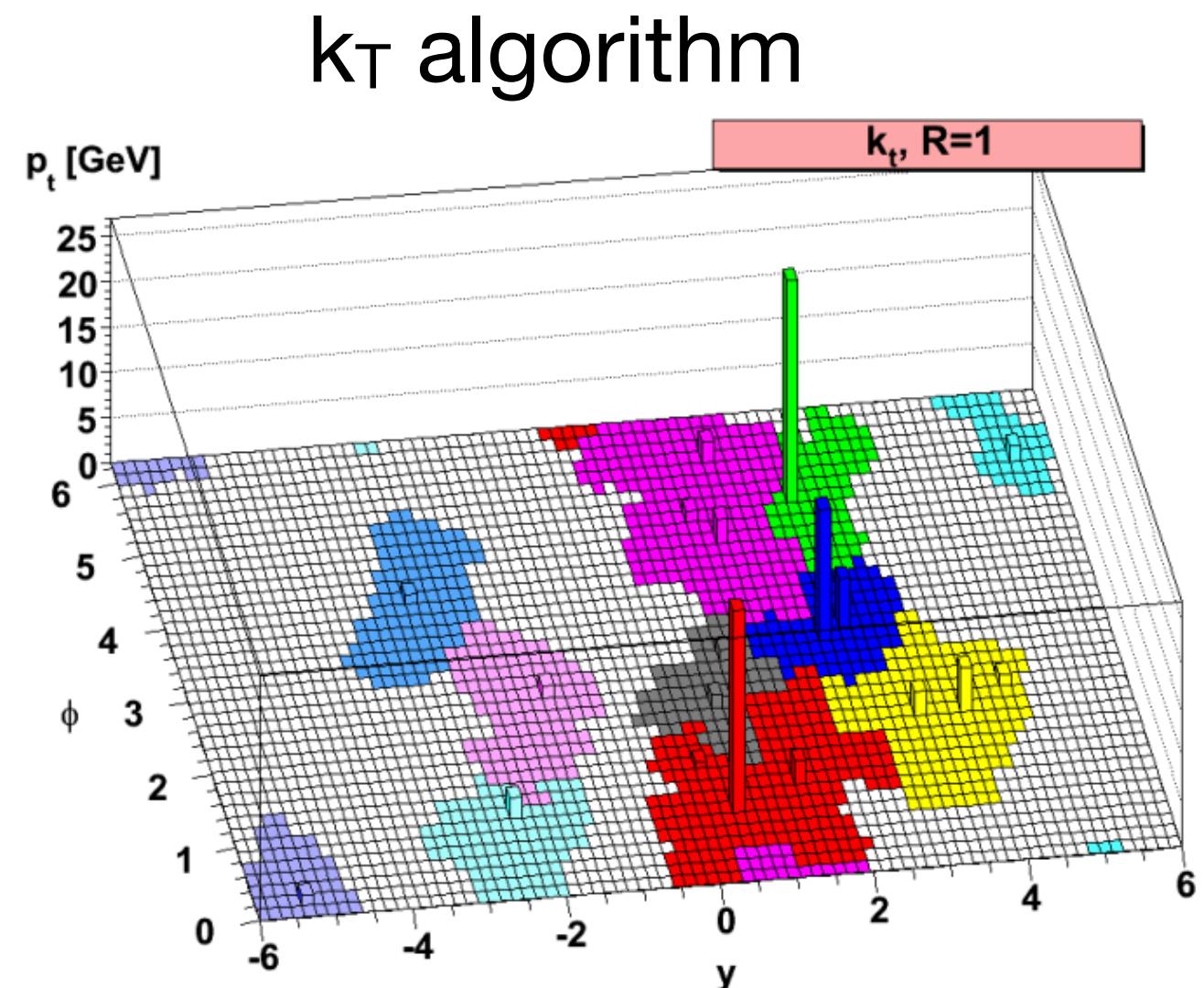
■ Requirements

- Infrared and collinear safe
 - Order independence
 - Ease of implementation



Cacciari, Salam, Soyez, JHEP04 (2008).

Jets at Hadron Collider



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

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

$p=-1$ anti- k_T algorithm
 $p=0$ Cambridge/Aachen
 $p=1$ k_T algorithm

Event rates at the LHC

- Total cross sections

 - $\sim 1.6 \times 10^9 /s$ (80mb, $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$)

 - Bunch crossing rate of 40MHz

- Jets ($E_T^{\text{jet}} > 100 \text{ GeV}$)

 - $\sim 40000 \text{ Hz}$

- W & Z bosons

 - $\sim 4000 \text{ Hz}, \sim 1000 \text{ Hz}$

- Top Quarks

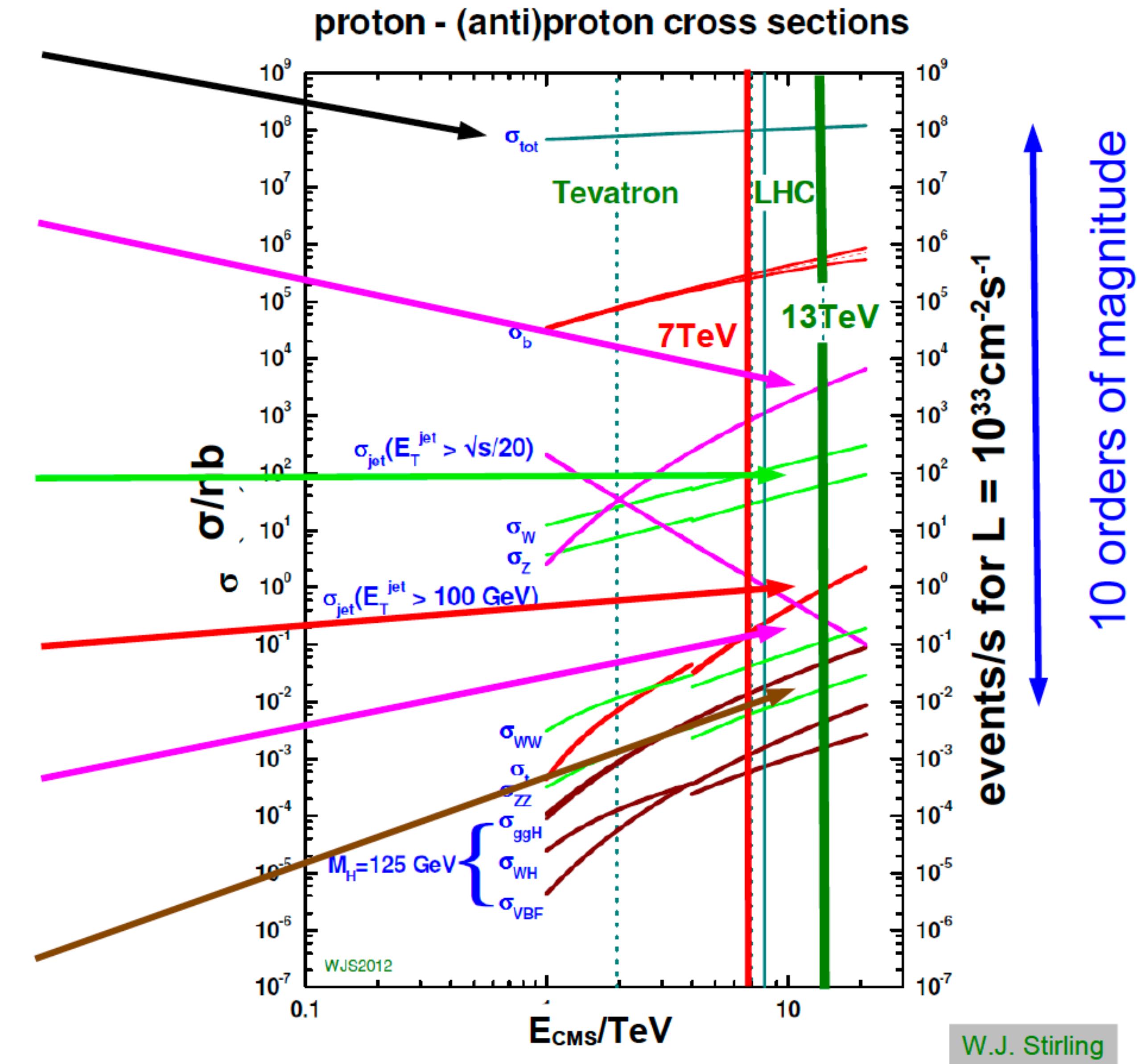
 - $\sim 20 \text{ Hz}$

- Jets ($E_T^{\text{jet}} > 650 \text{ GeV}$)

 - $\sim 6 \text{ Hz}$

- Higgs bosons

 - $\sim 1 \text{ Hz}$ (50pb, $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$)



Why are these jet cross sections so large?

- PDFs
- Coupling is “stronger”

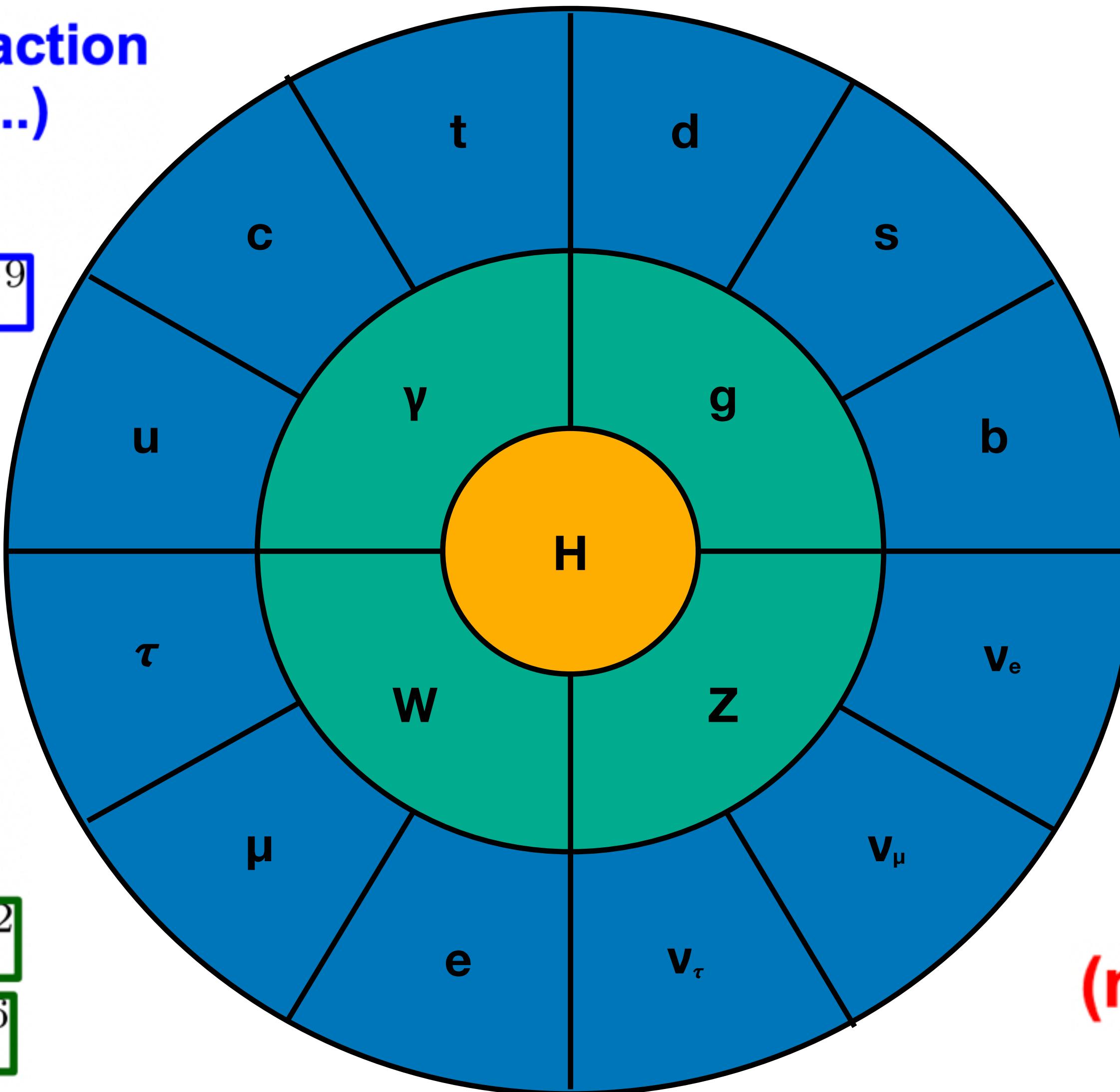


Strong interaction

**Electromagnetic interaction
(magnets, electricity, ...)**

$$\alpha \approx 1/137$$

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



**Weak interaction
(β decays, sun, ...)**

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

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

**Strong interaction
(nuclear forces, ...)**

$$\alpha_s \approx 0.118$$

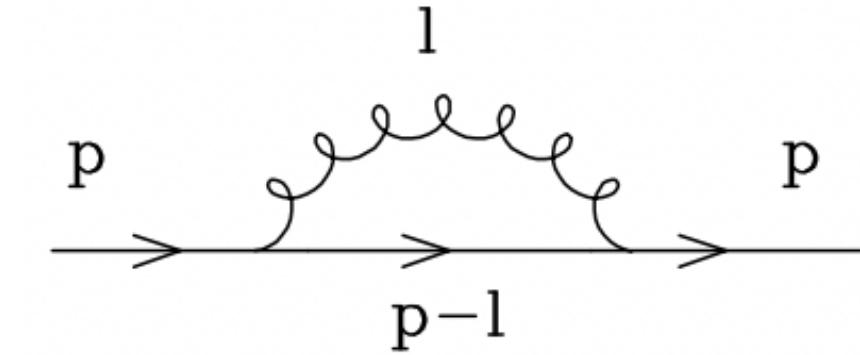
$$\Delta\alpha_s/\alpha_s = 8.5 \cdot 10^{-3}$$

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

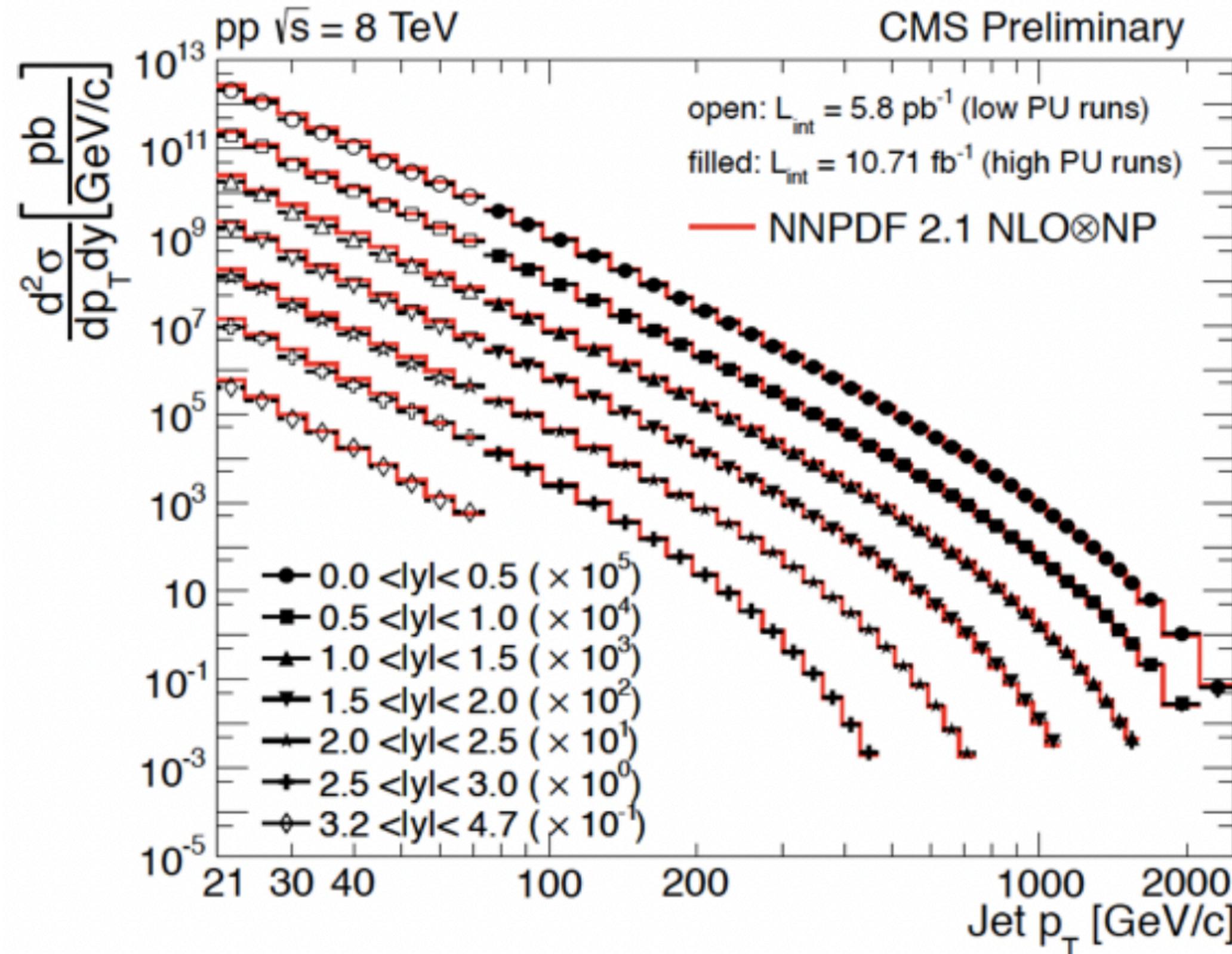


$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln\left(\frac{Q^2}{\mu^2}\right)}$$
$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}$$
$$\beta_0 = \frac{33 - 2 \cdot N_f}{12\pi}$$

Inclusive Jet Cross Sections

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

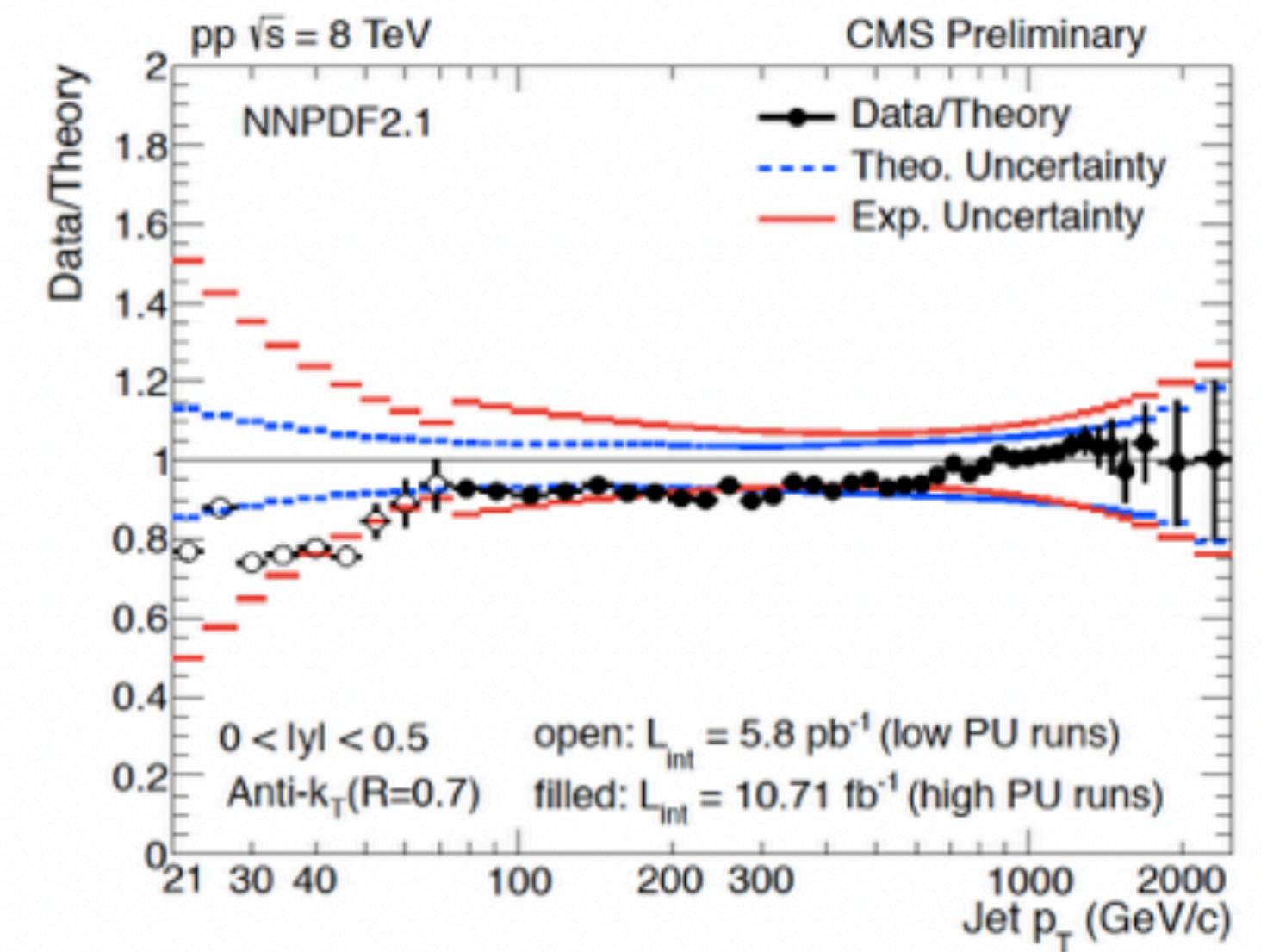
As a function of jet transverse momentum
in bins of rapidity (up to $|y| = 4.7!$)



20 GeV up to $> 2\text{TeV}$ (central)
• JES 2-4%

NLO pQCD describes data
over 14 orders of magnitude!

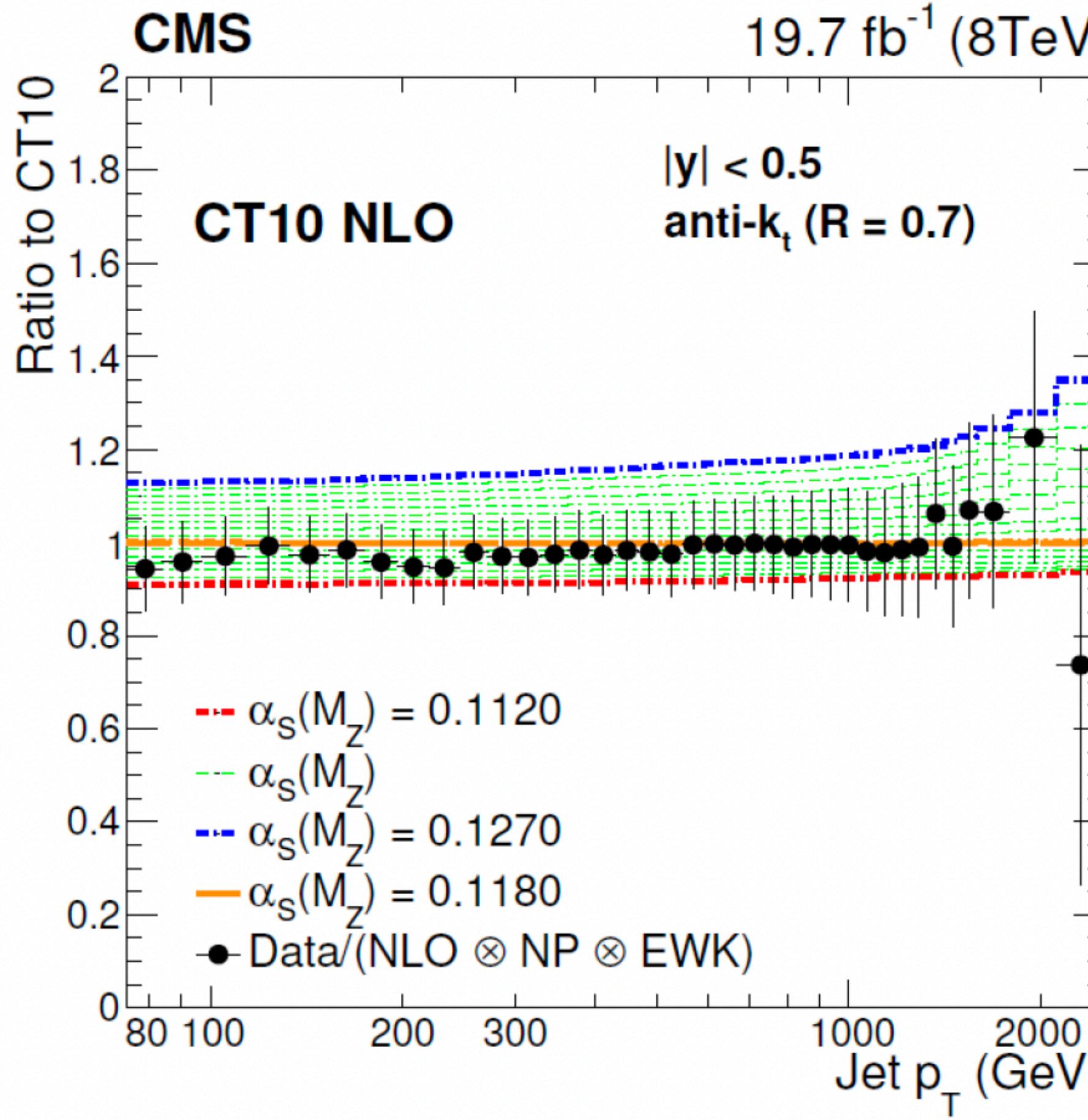
Constraints on gluon PDFs



Inclusive Jets: α_s

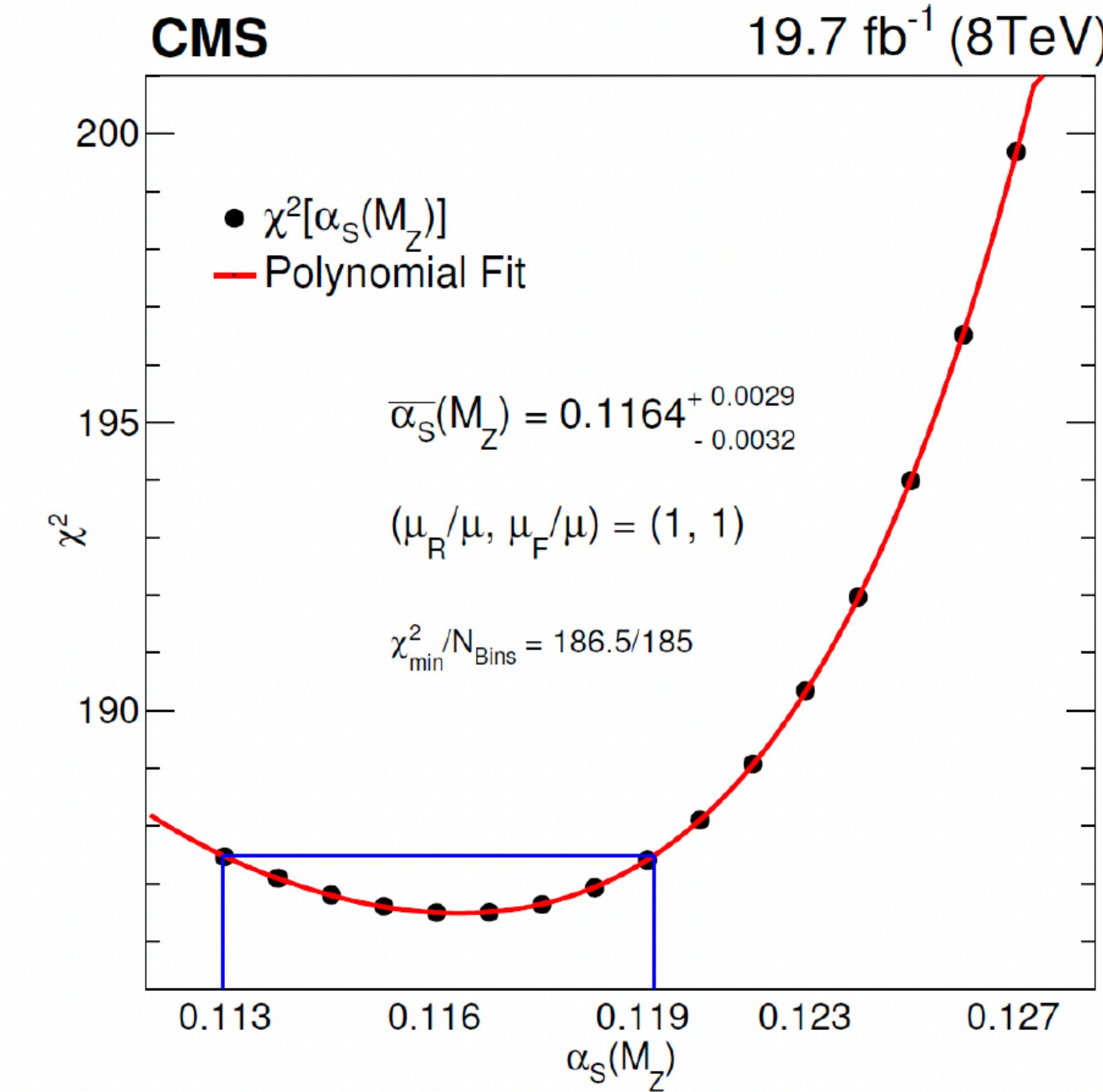
Sensitivity to $\alpha_s(M_Z)$ at NLO

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

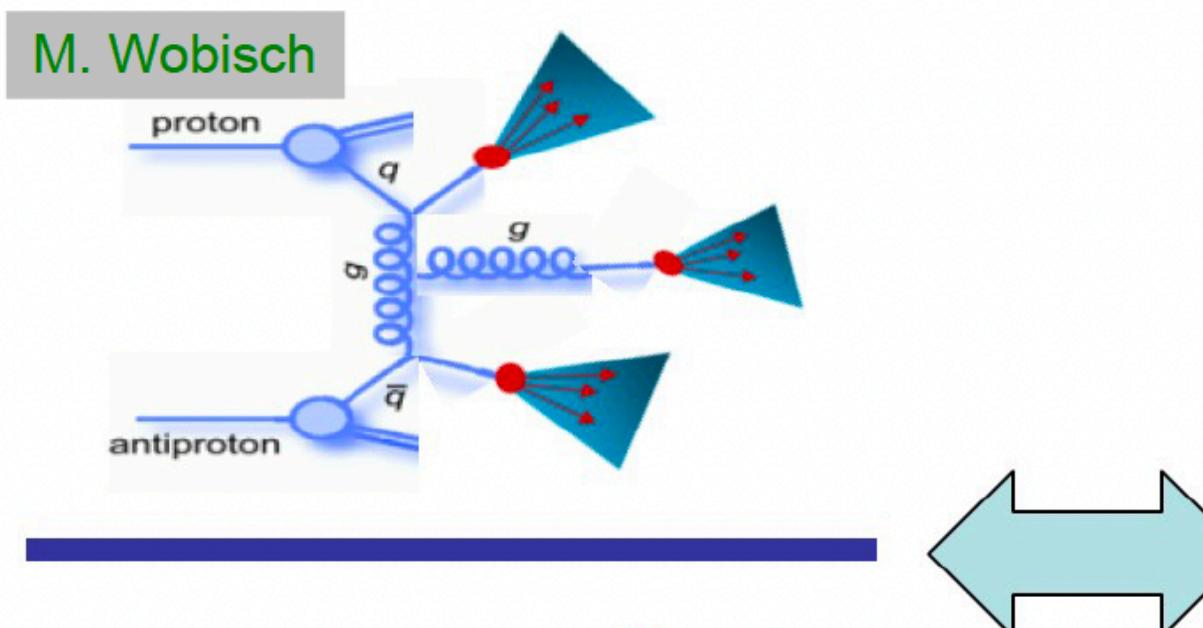


χ^2 fit of $\alpha_s(M_Z)$ for all jet p_T and $|y|$ bins

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



2-jet 3-jet Ratio

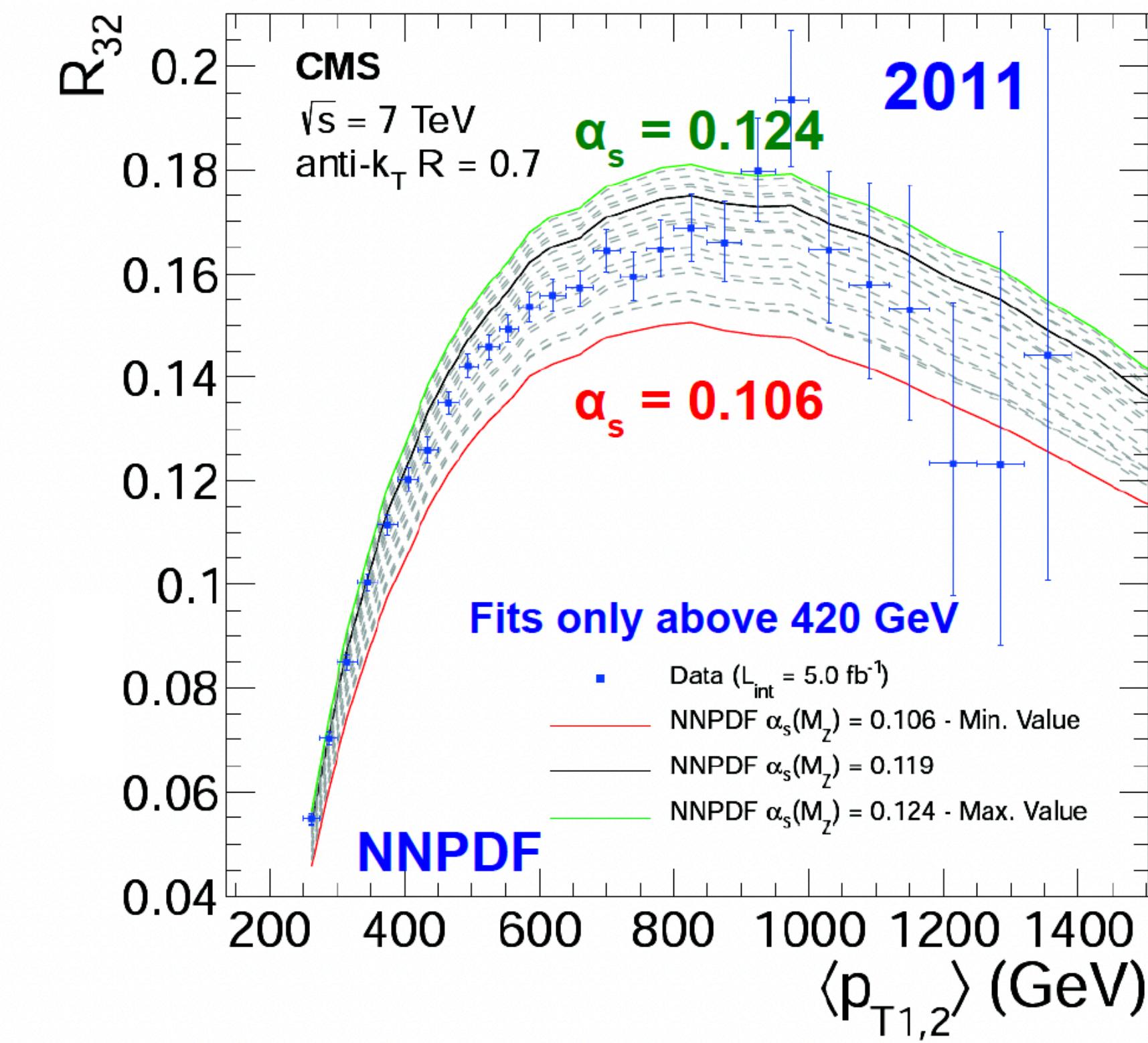

 $R_{3/2}$
 α_s

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

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

CMS: $R_{3/2}$

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

 $\rightarrow \alpha_s$


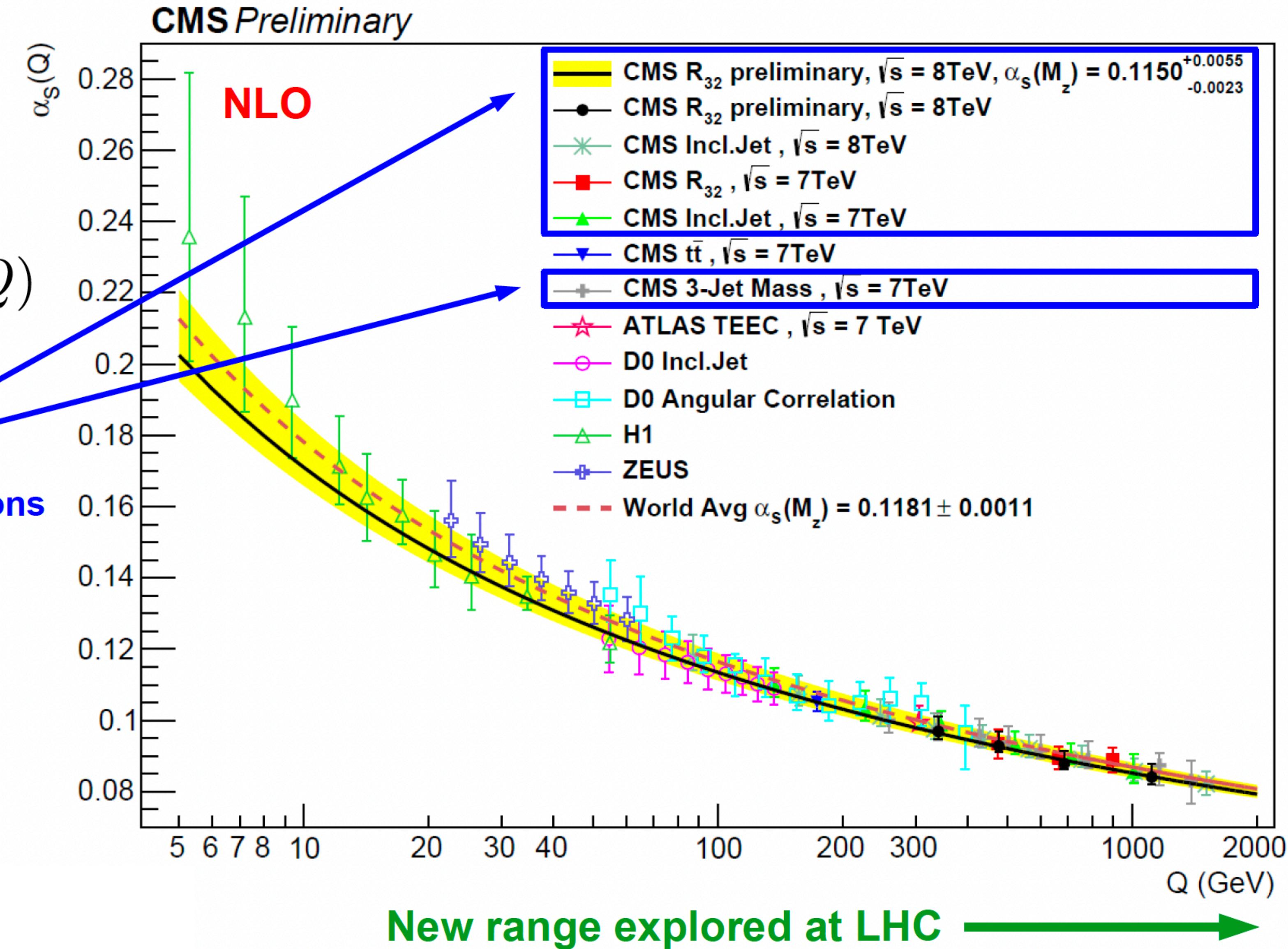
\sqrt{s} [TeV]	lum [fb $^{-1}$]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50

Measurement of α_s

Perform fits in fixed intervals of the chosen scale Q

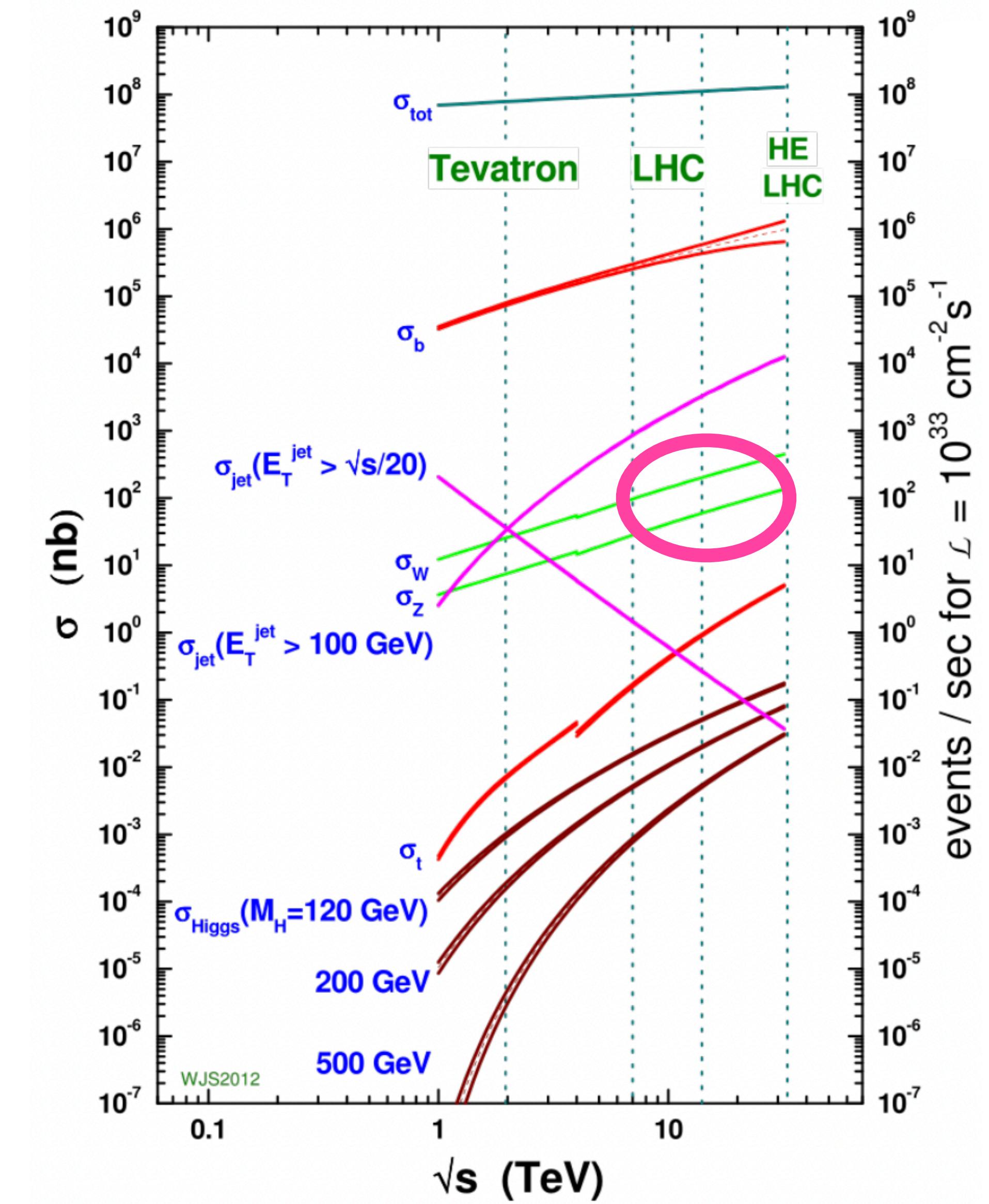
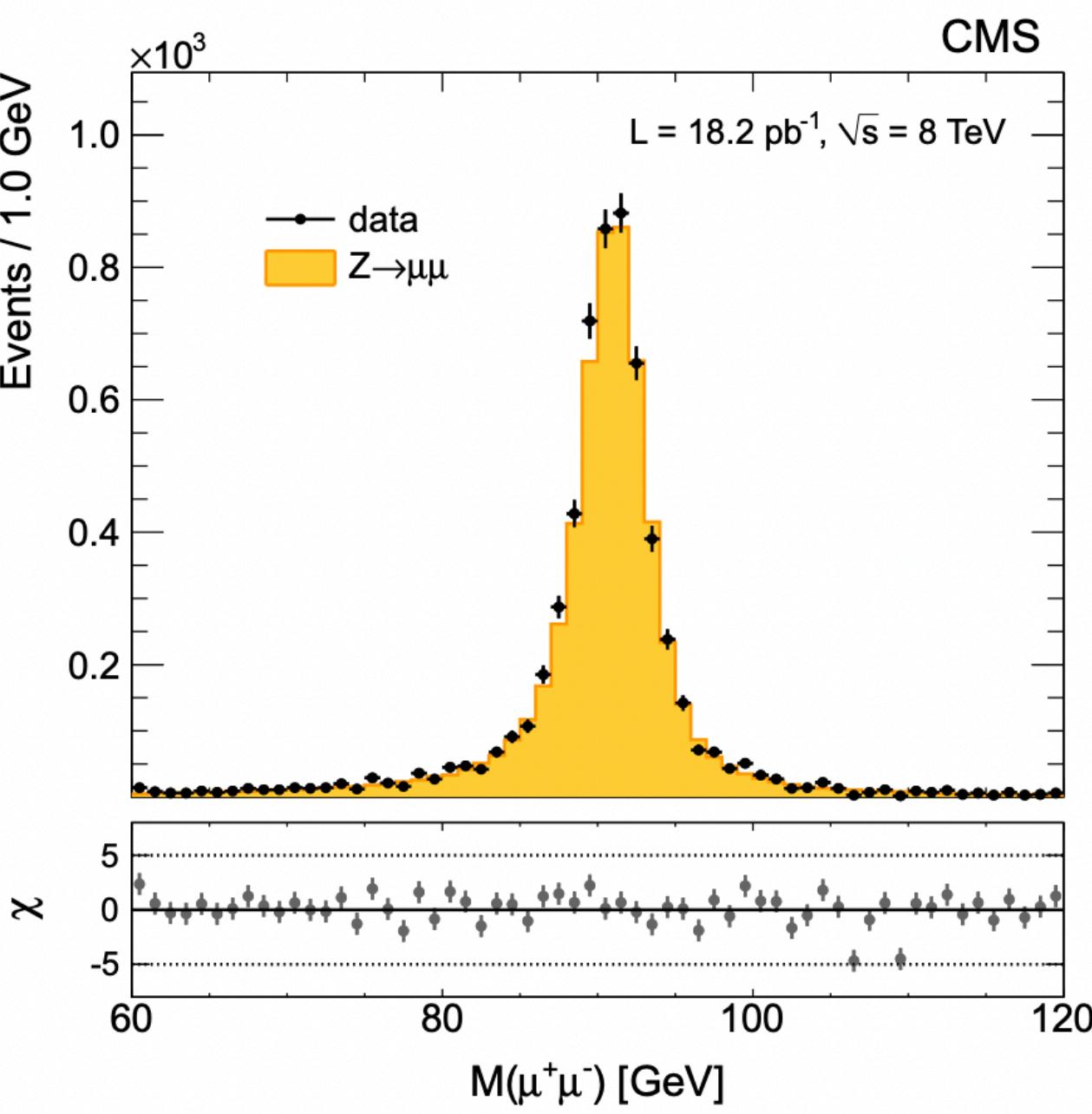
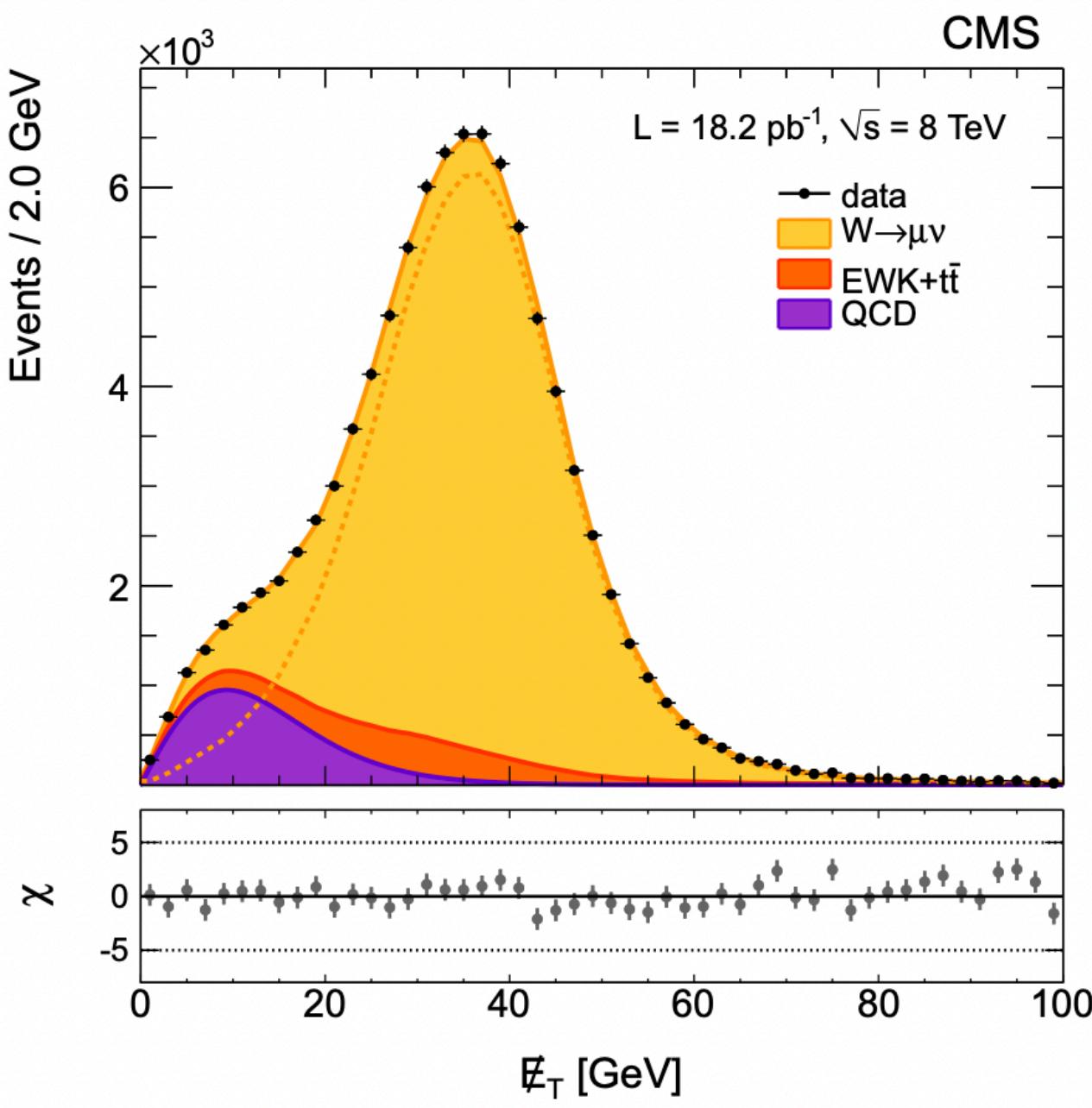
$$\rightarrow \alpha_s(Q)$$

Jet cross sections and ratios



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

$$M_T^2 = 2 p_T(\ell) p_T(\nu) (1 - \cos \Delta\phi(\ell, \nu))$$

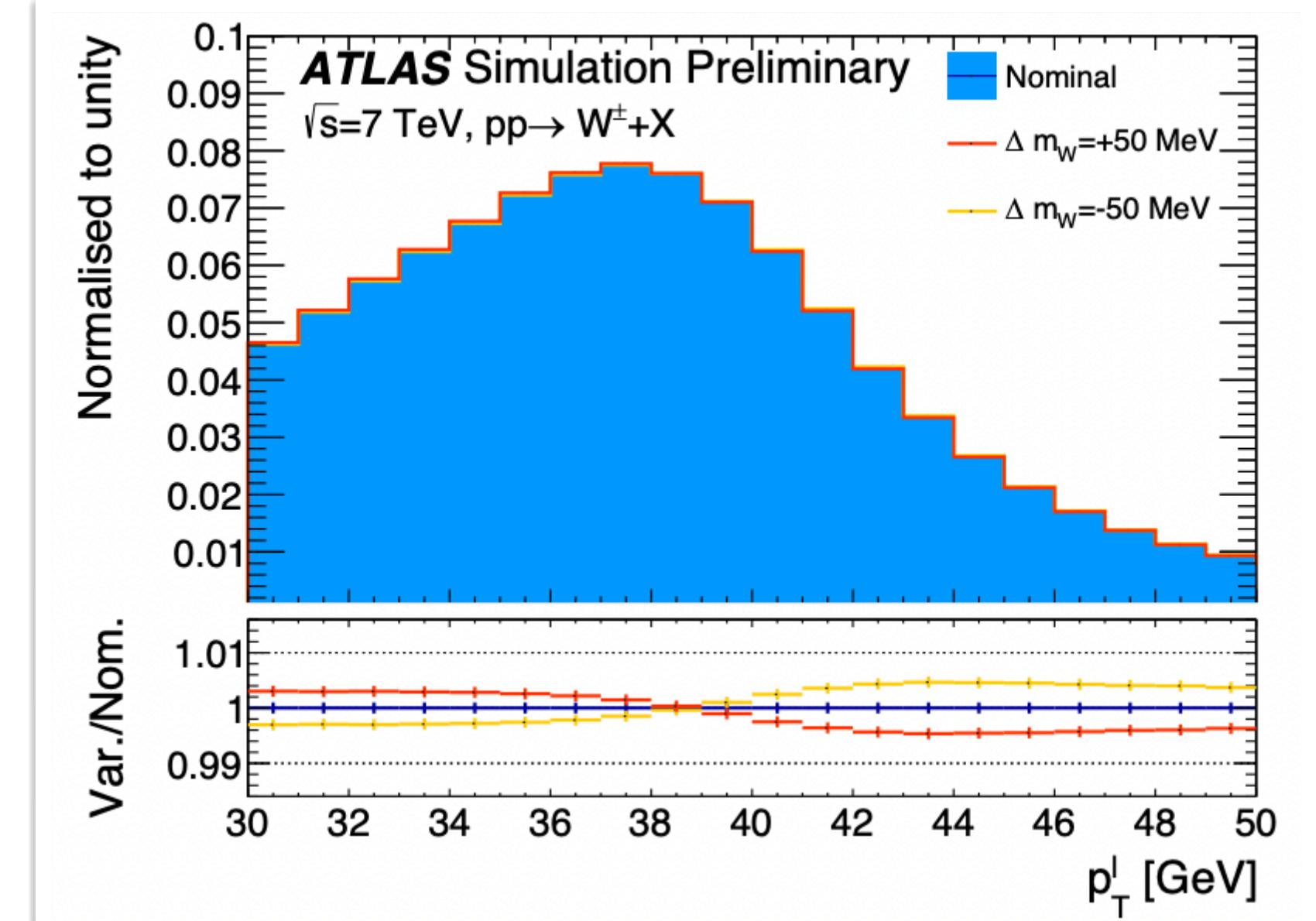
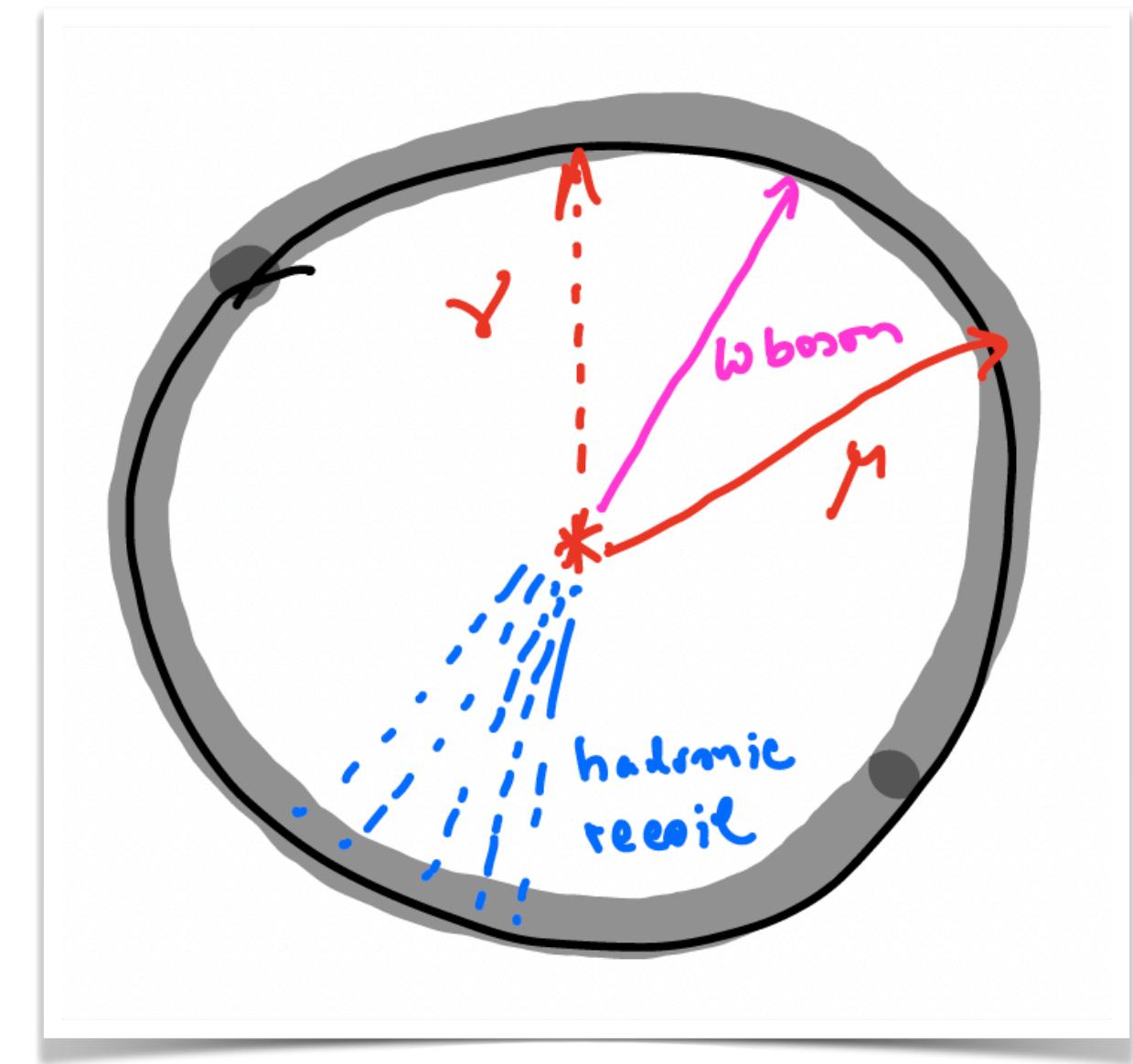
■ Challenges

- Experimental: lepton energy scale; missing transverse energy; pile-up conditions

- Theoretical: W transverse momentum; PDFs

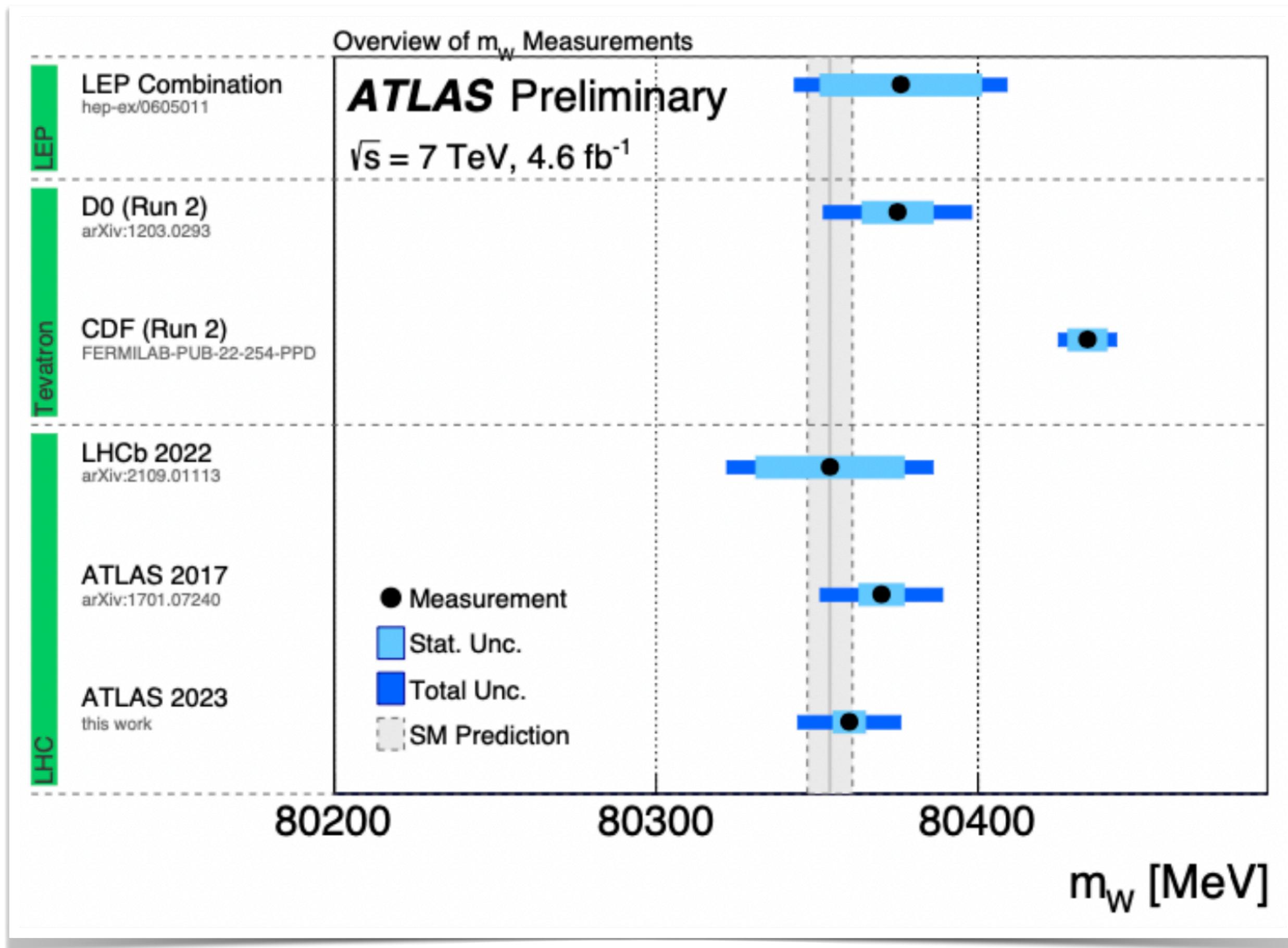
■ Strategy (ATLAS)

- Exploit lepton transverse momentum and transverse mass

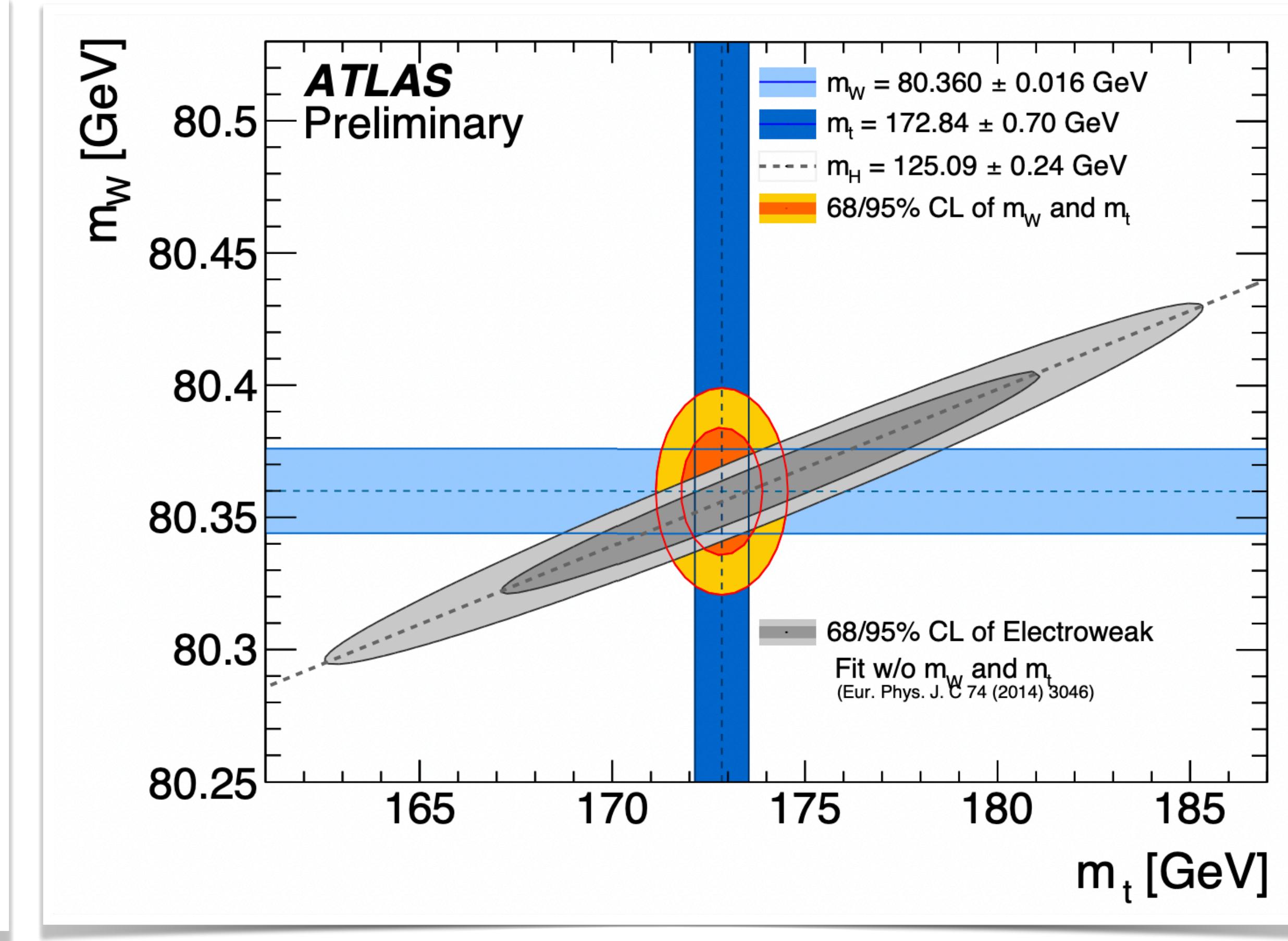


W boson mass measurement

■ Results



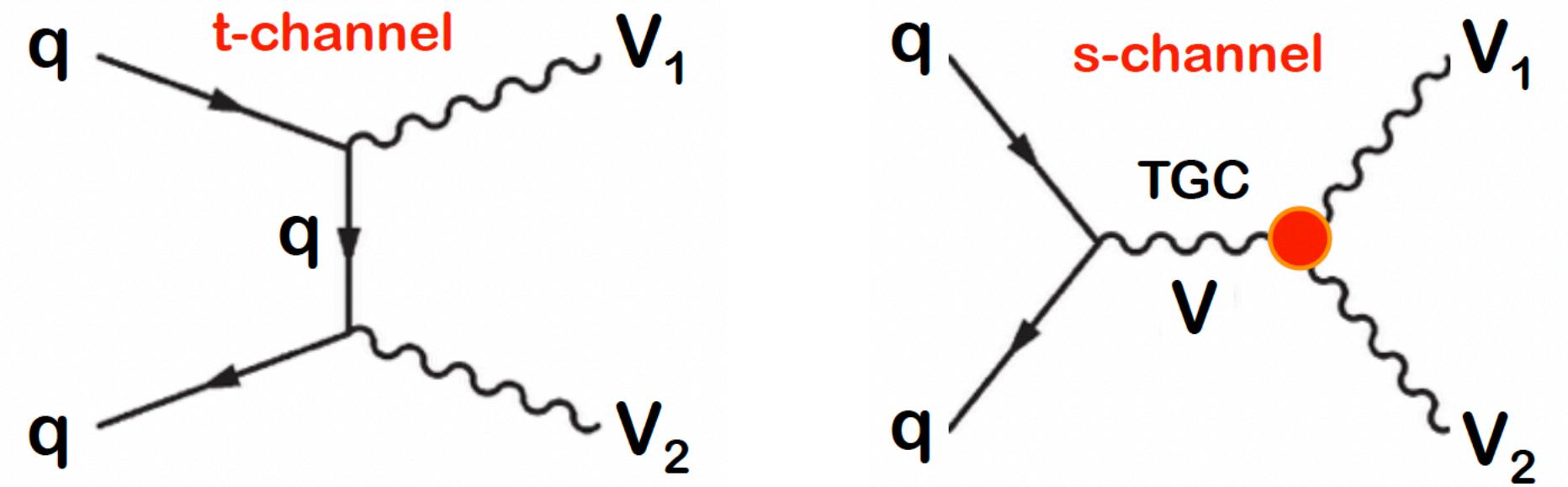
Tension in experiment results!



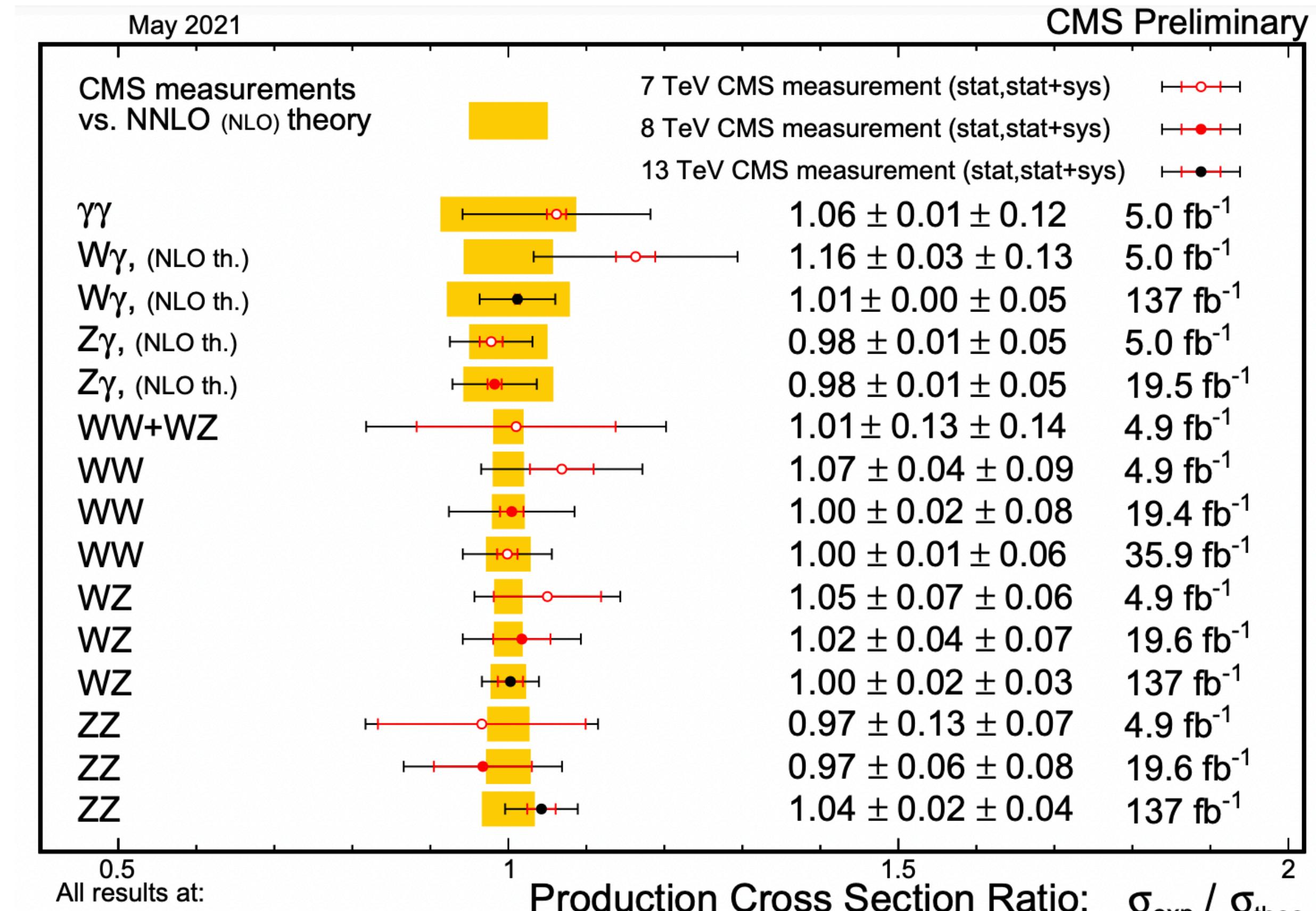
Are Standard Model measurements consistent?

Multi-Boson Production

■ Di-Boson Production



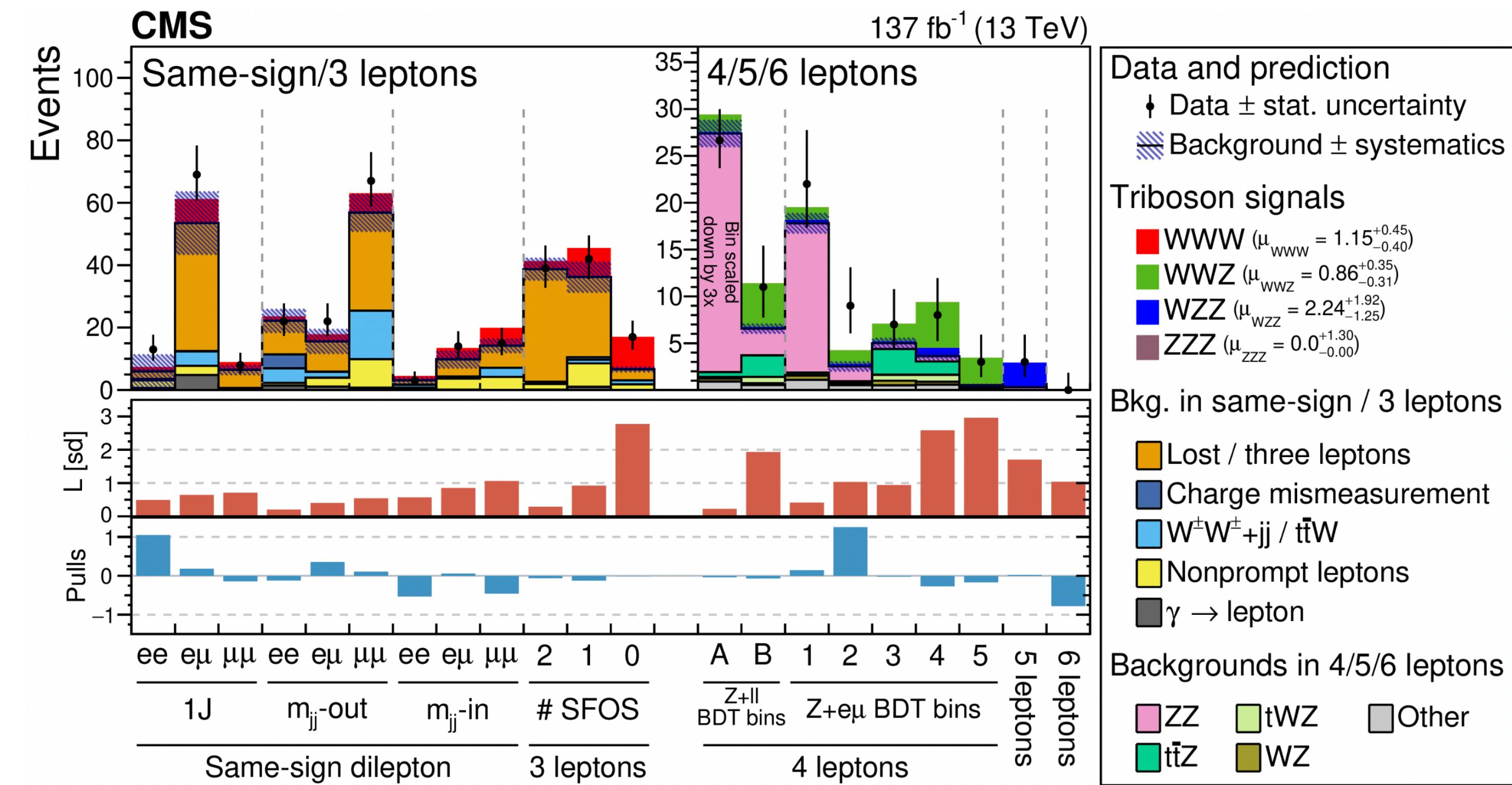
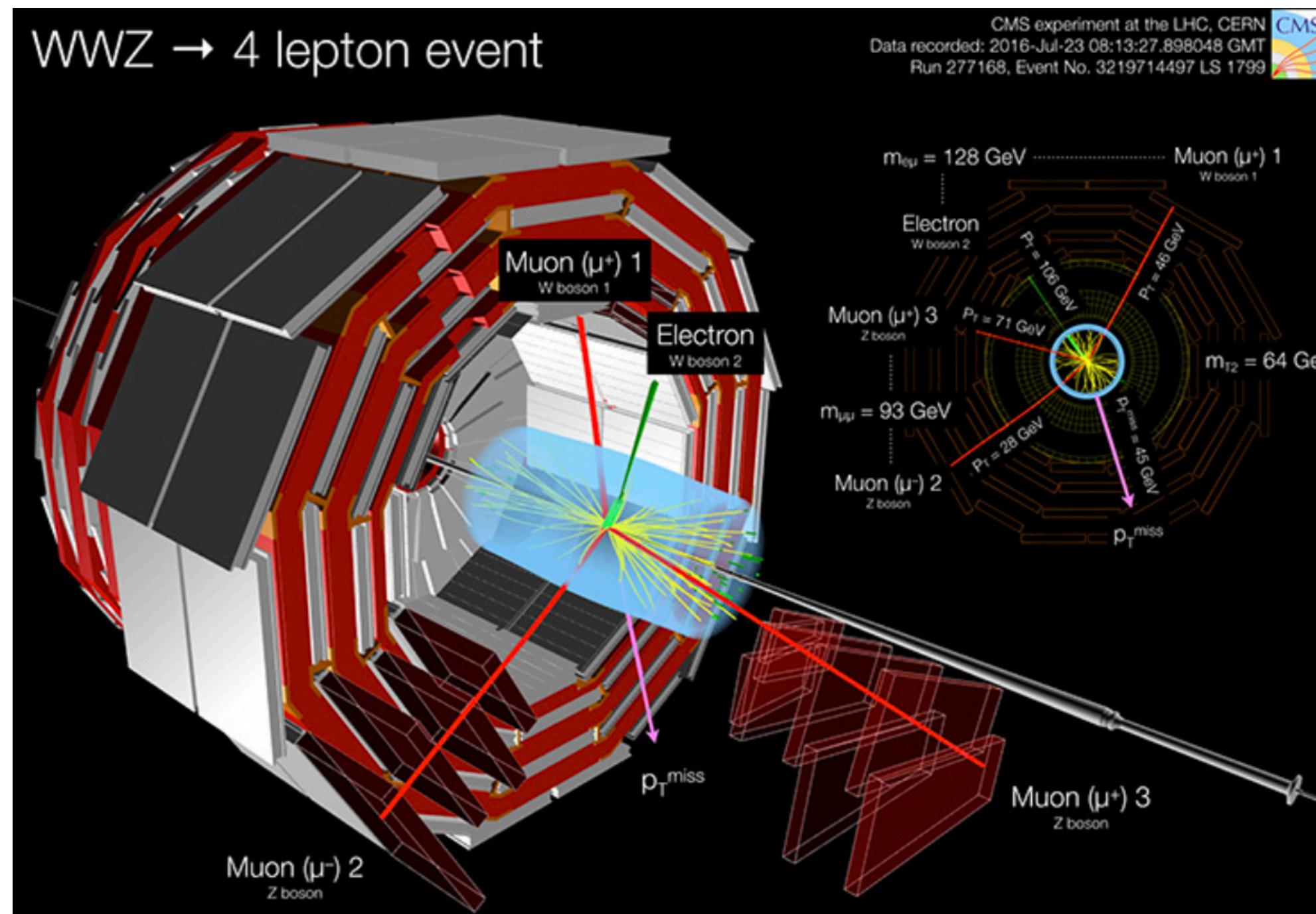
- Large number of processes study
- Generally good agreement between experiment and theory
- Constraint on anomalous couplings



Multi-Boson Production

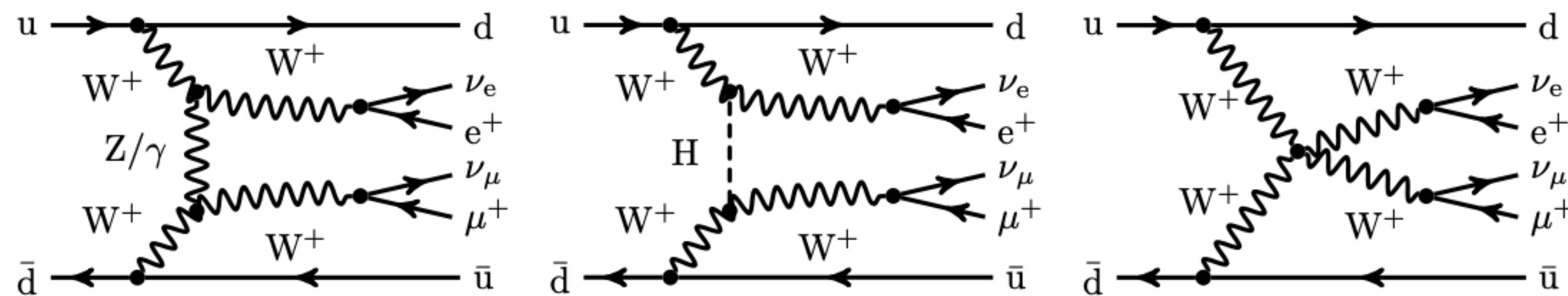
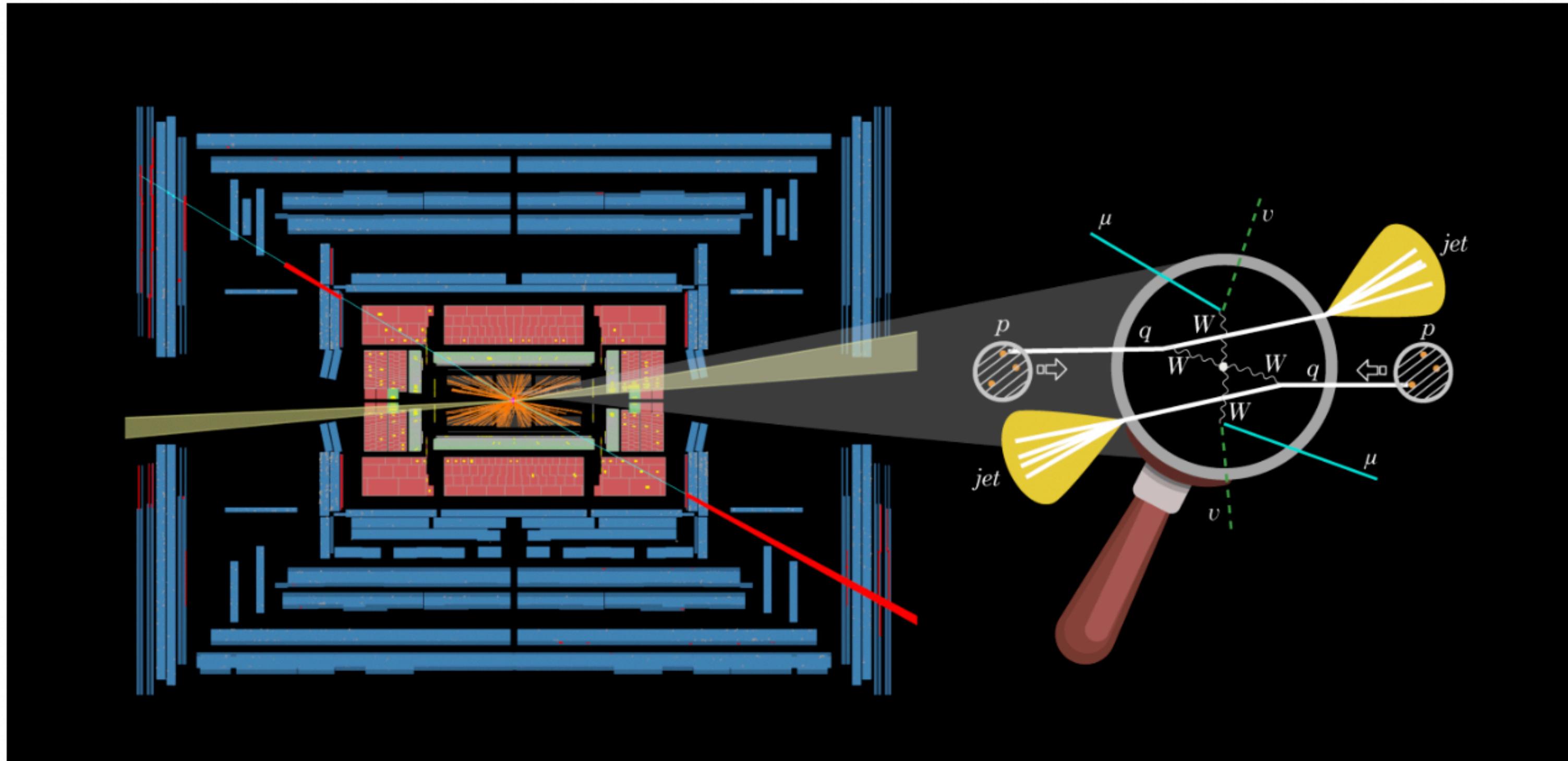
■ Tri-Boson Production

- Observed $WW\gamma$ and $WW\gamma$ processes
- Observation of three massive gauge bosons (W or Z) (CMS result number 1000!)



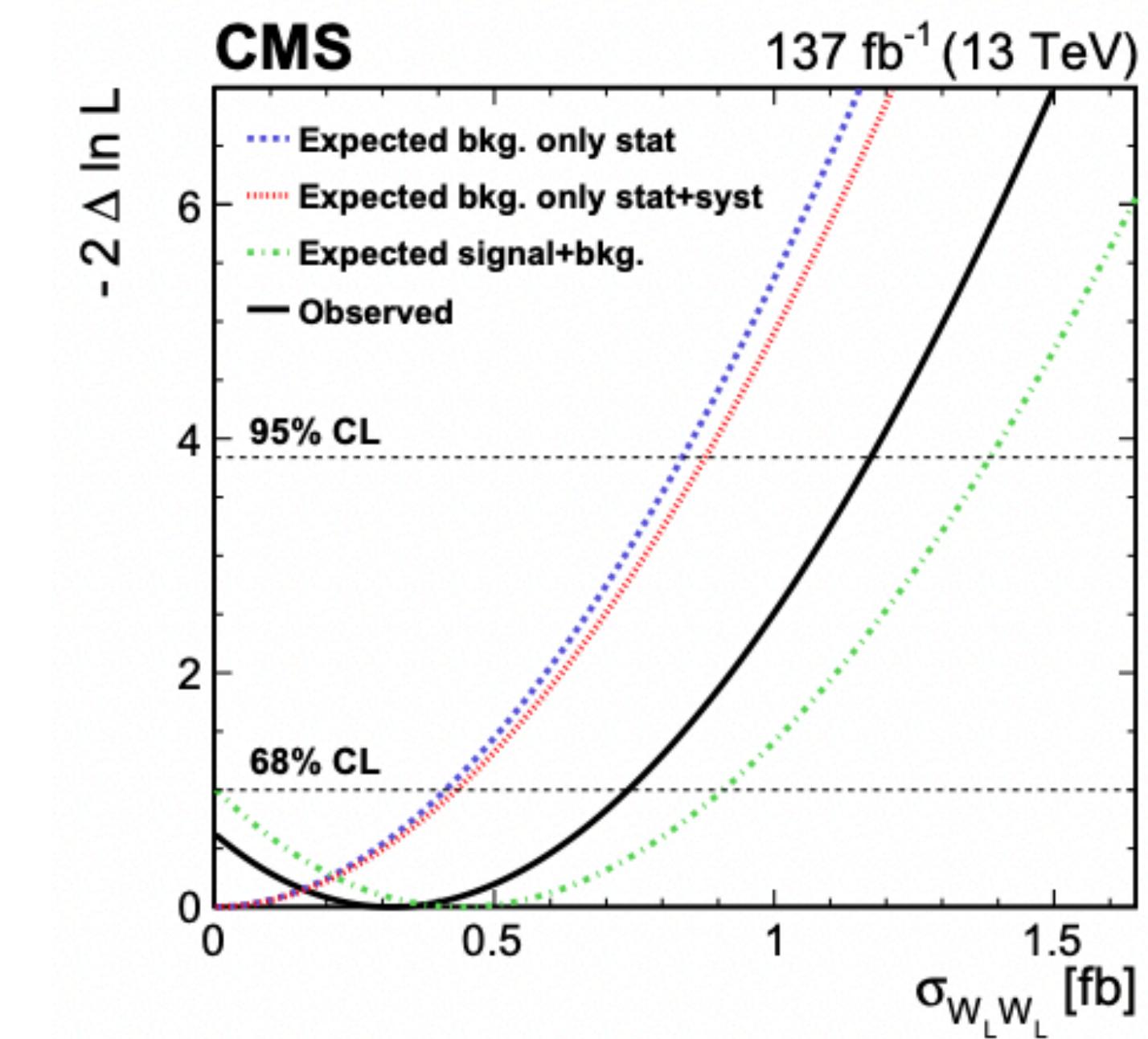
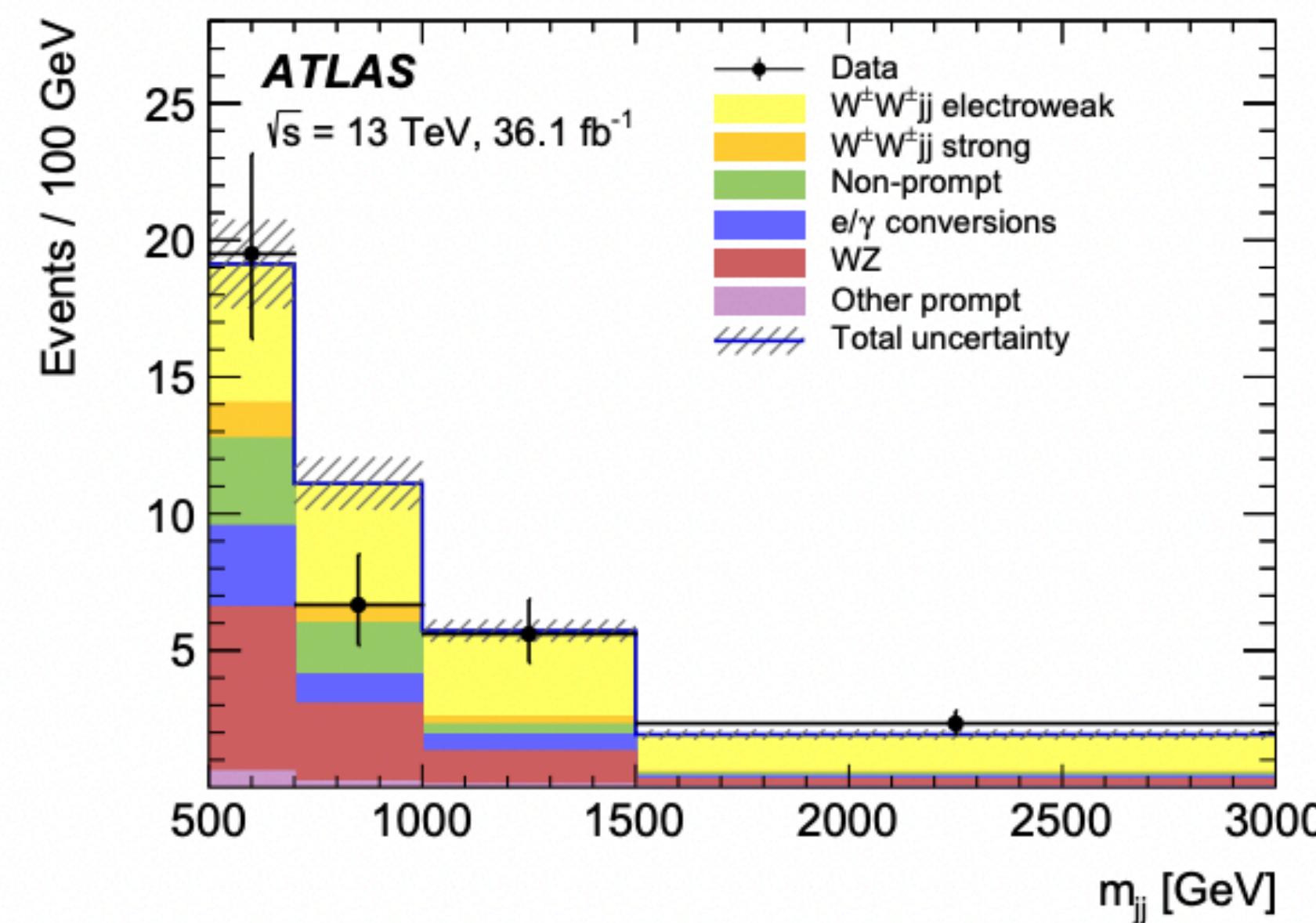
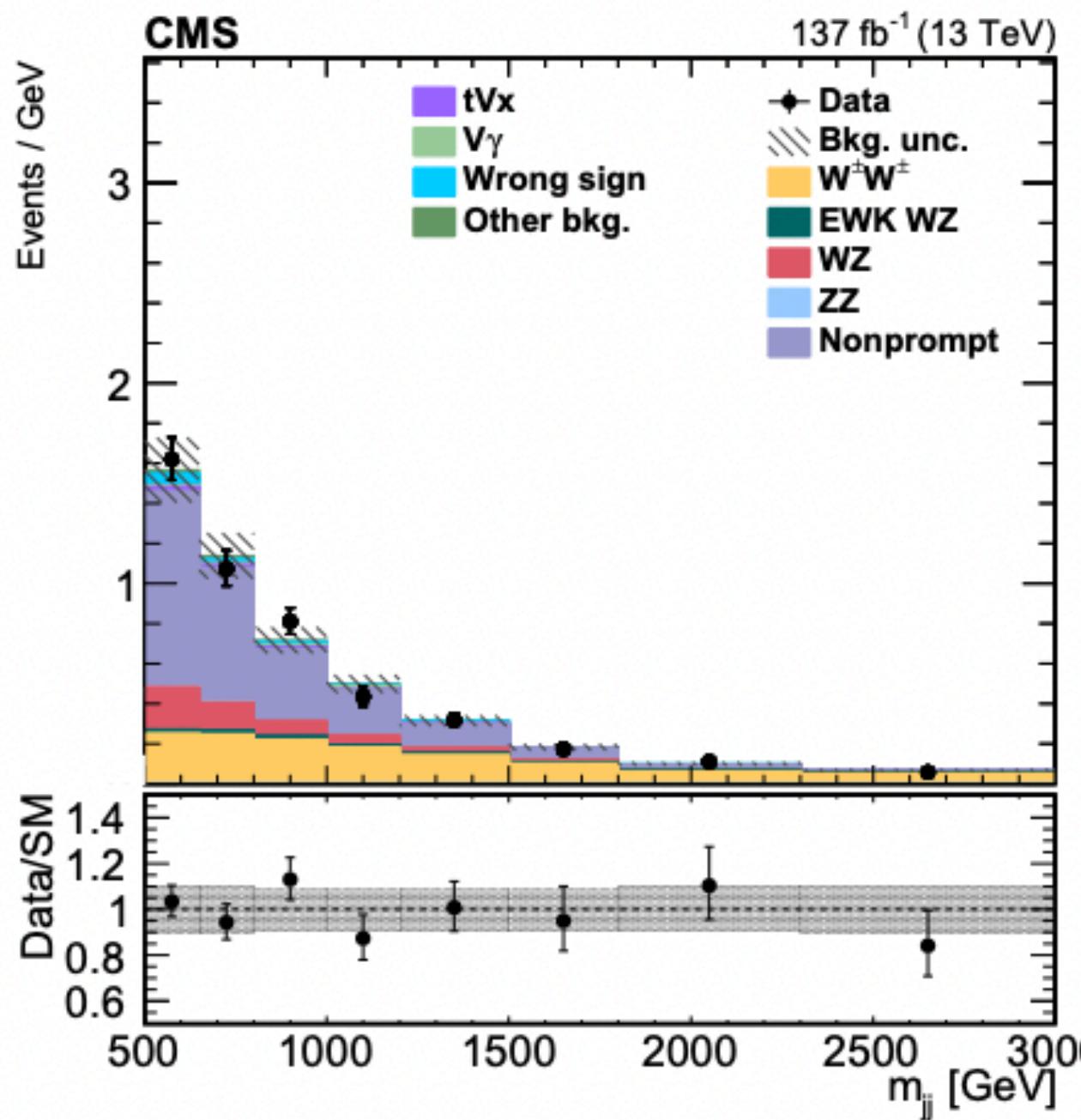
Vector Boson Scattering

- Electroweak production of same-sign W-pairs

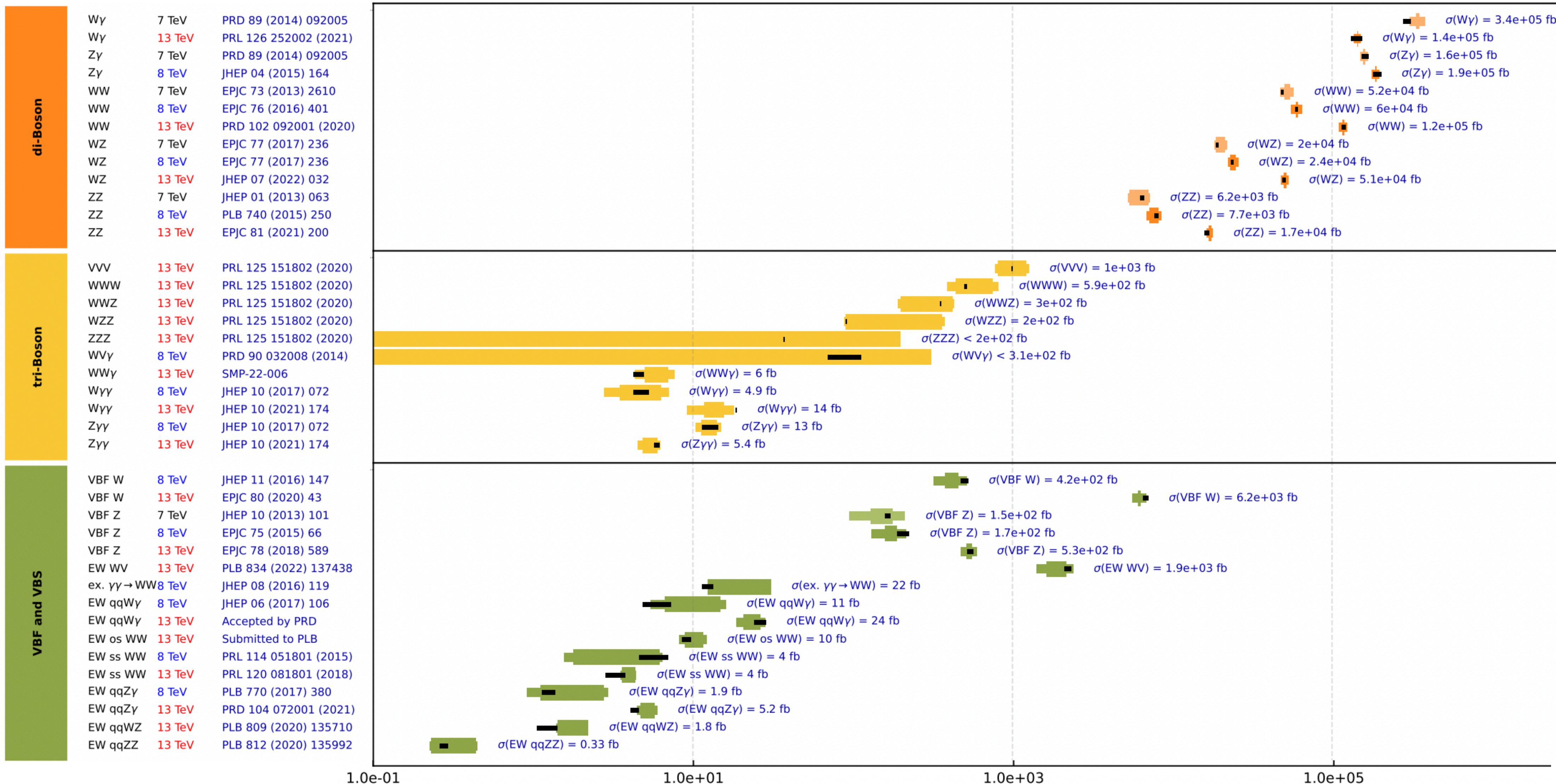


Vector Boson Scattering

- 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

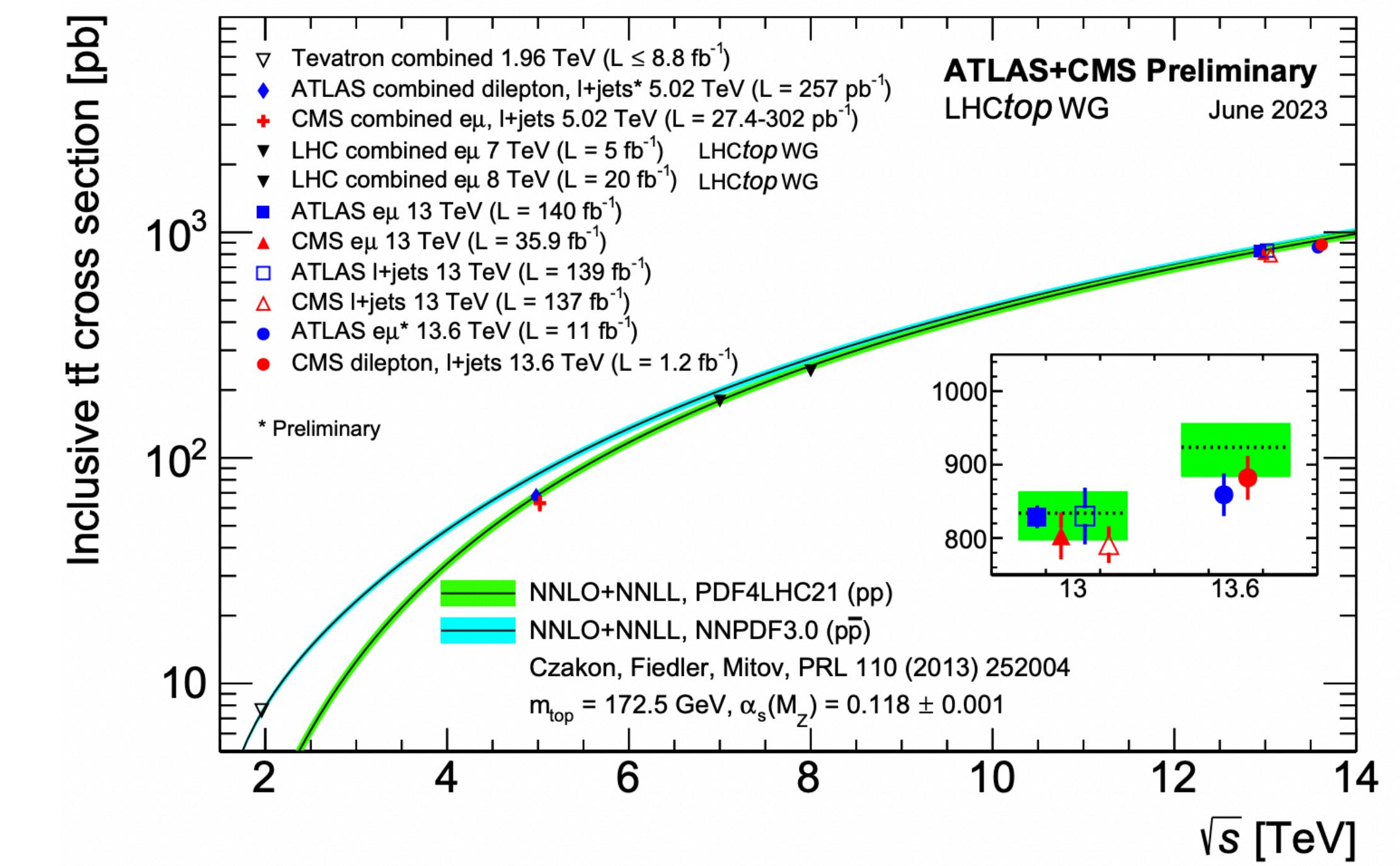
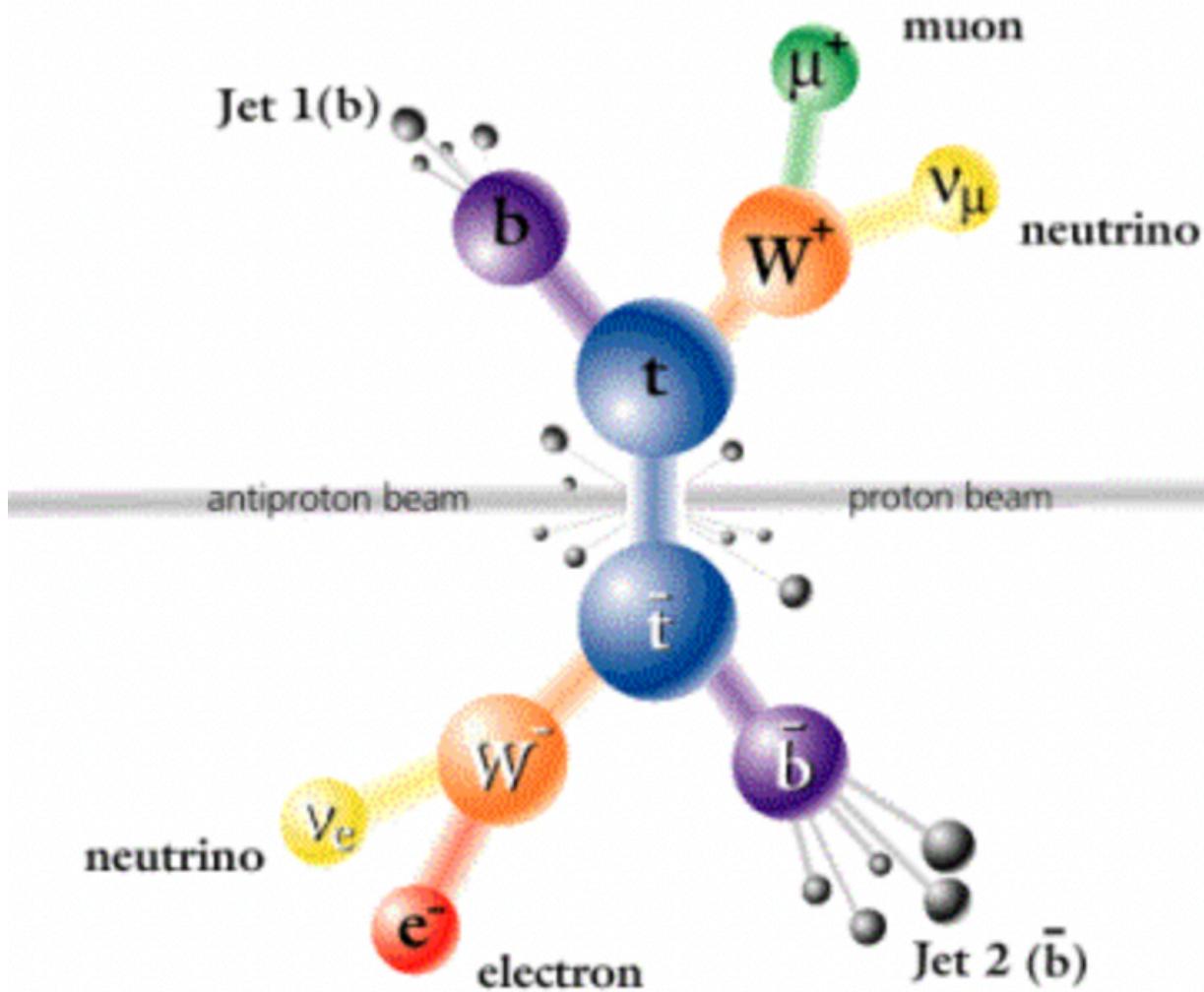
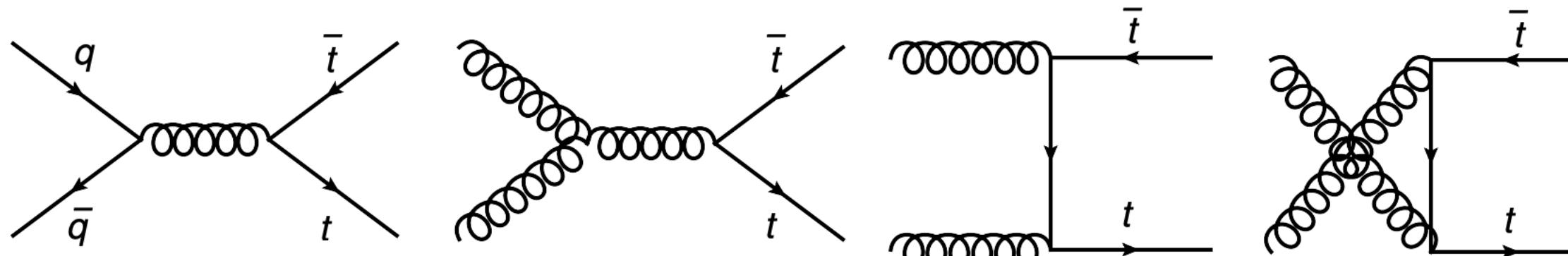


Top Physics

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

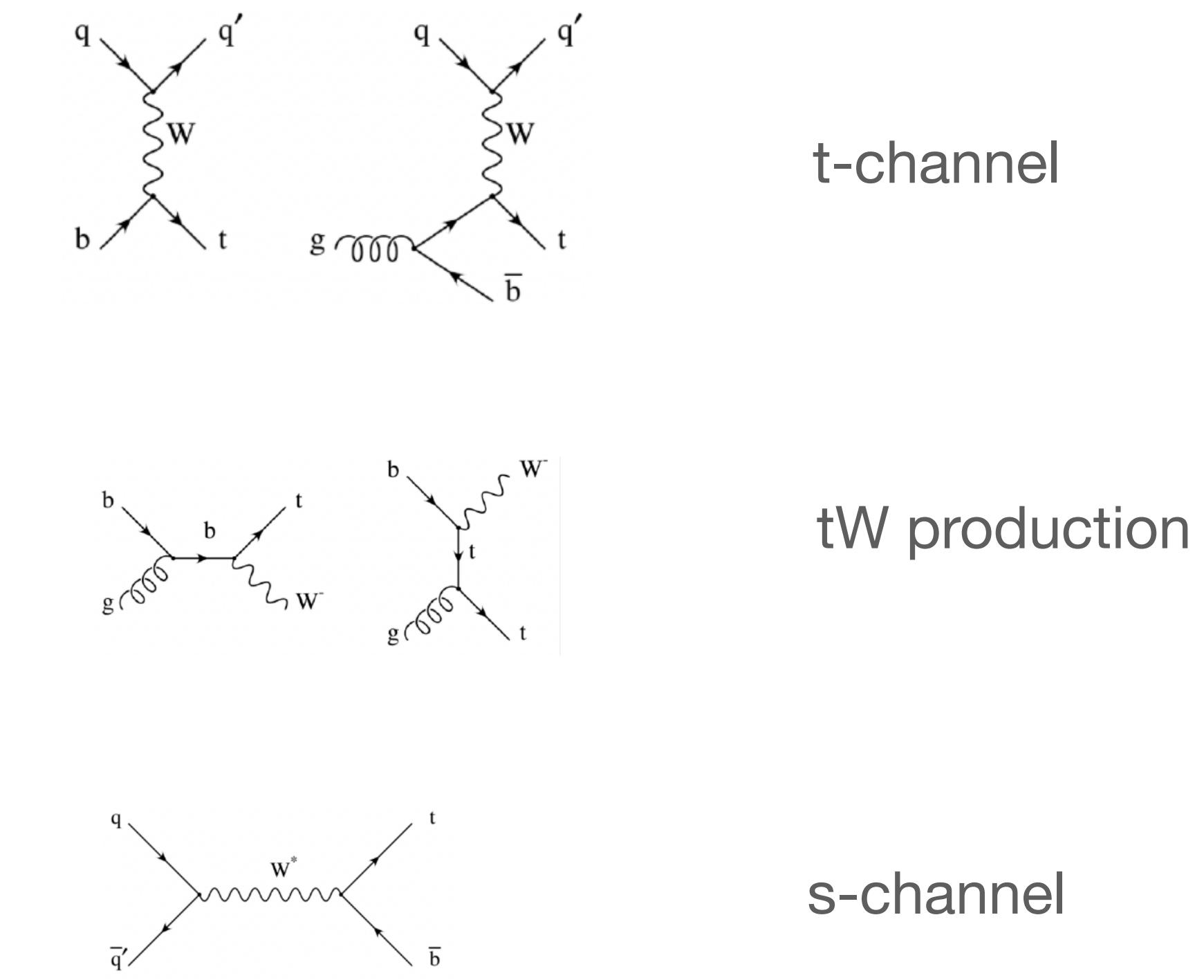
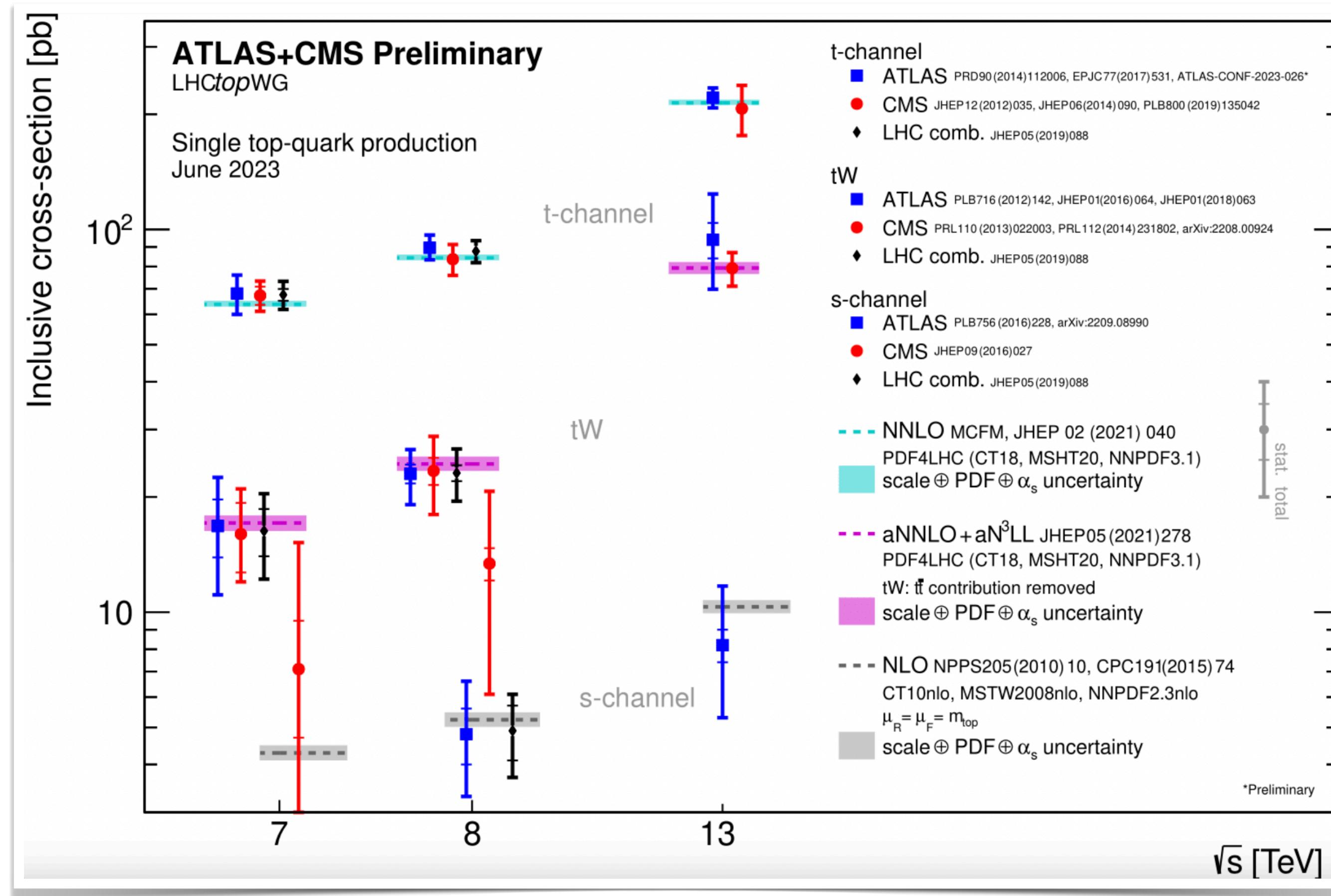
$$y_t = \frac{\sqrt{2}m_t}{v} \sim 1$$

- Predicted to explain CP violation in Kaon system (1973)
- Discovery by CDF and D0 at the Tevatron (1994)
- Decay into a W boson and a b quark
- Top quark decays before it hadronises
- Production at the LHC:



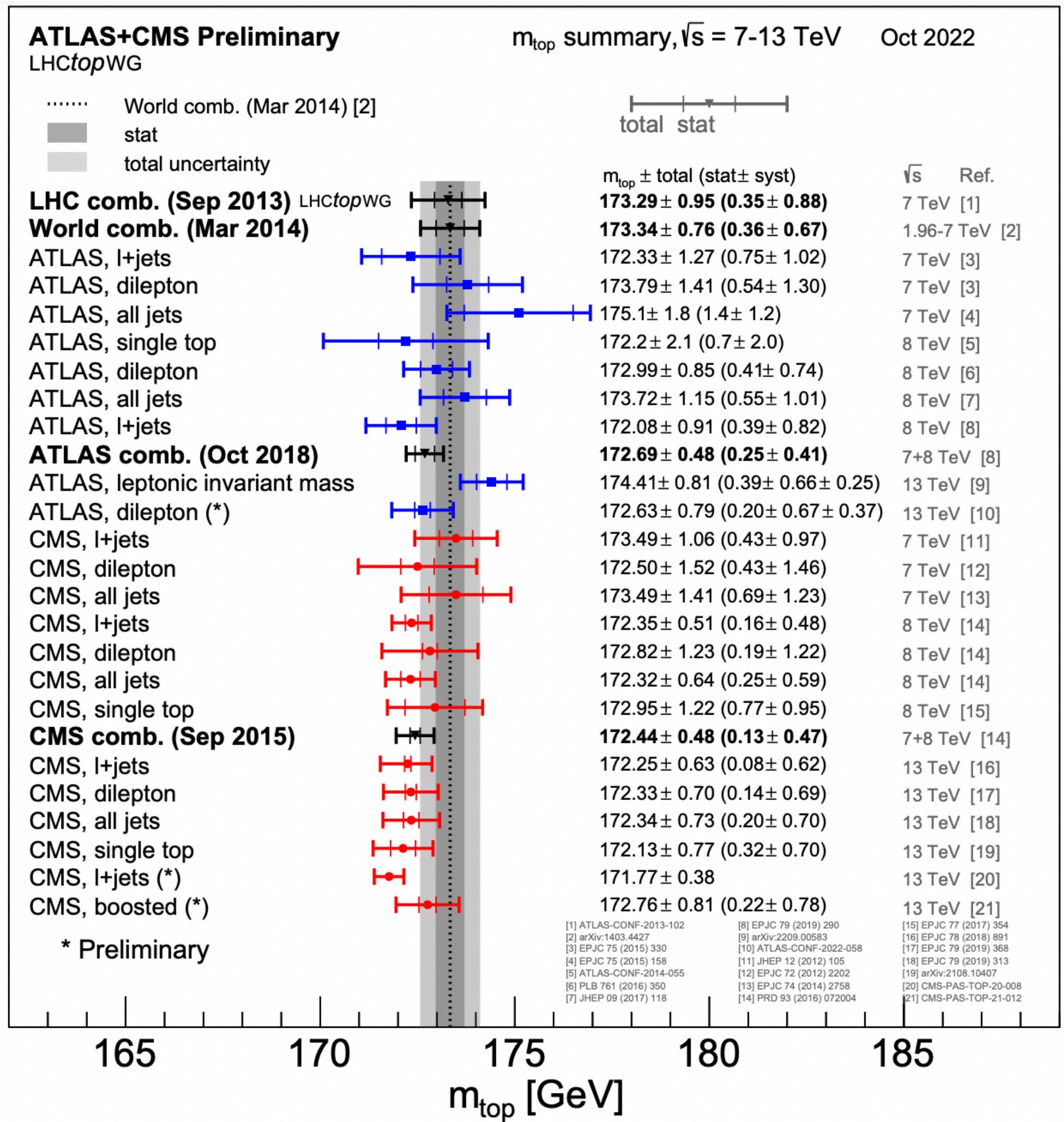
Top Physics

■ Single top production cross sections

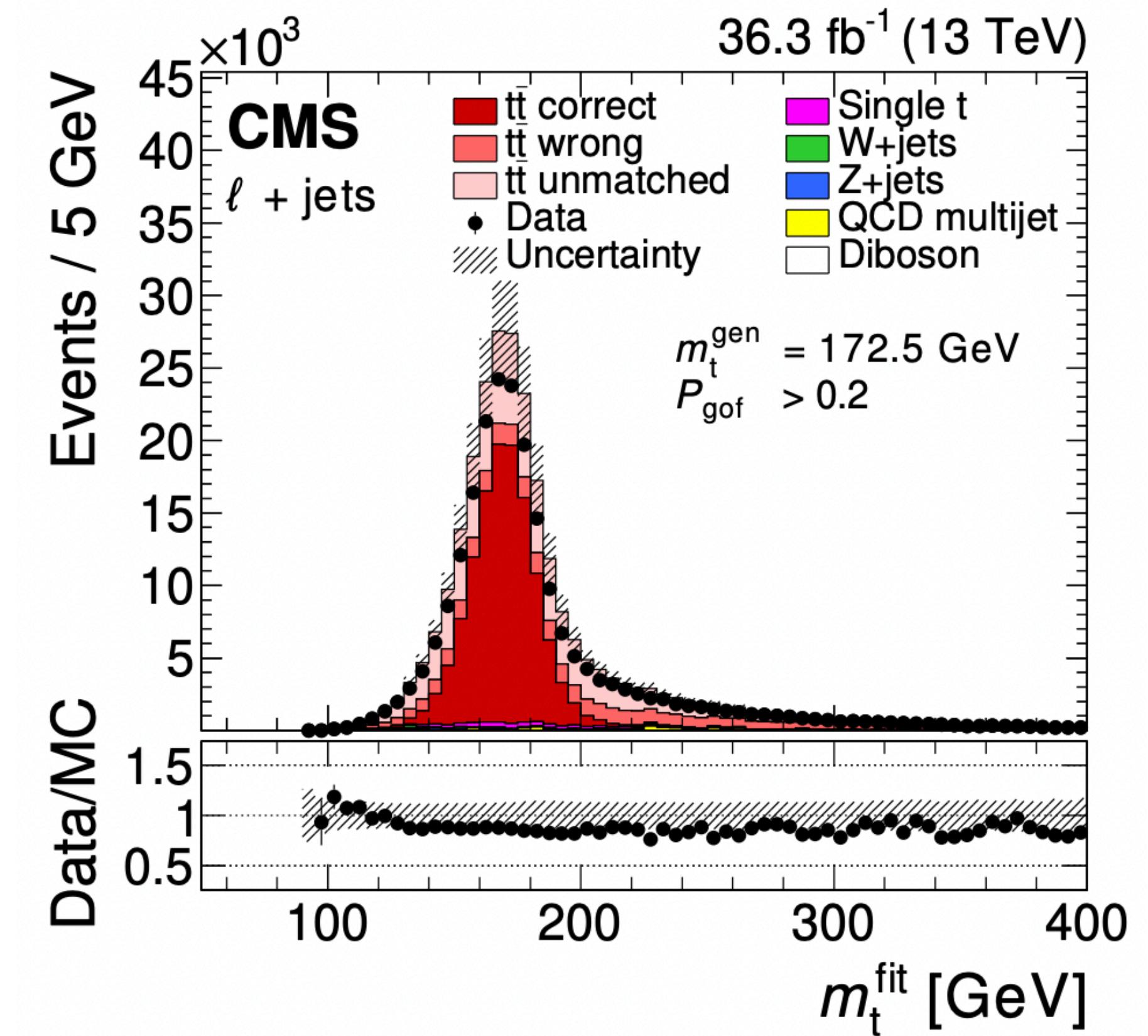


Top Physics

■ Top mass measurements



Direct mass measurement

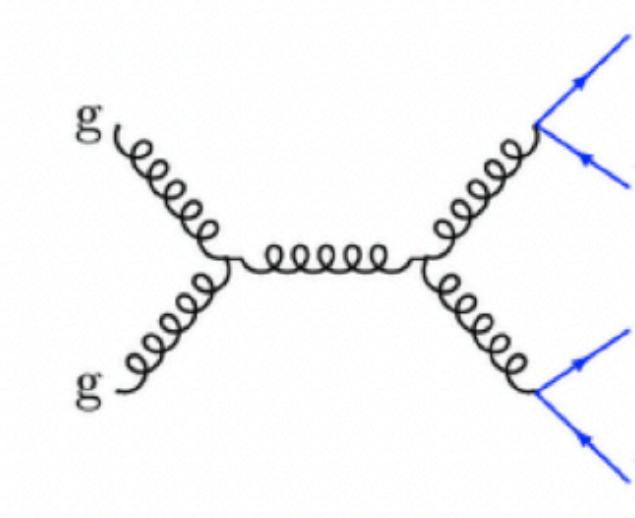
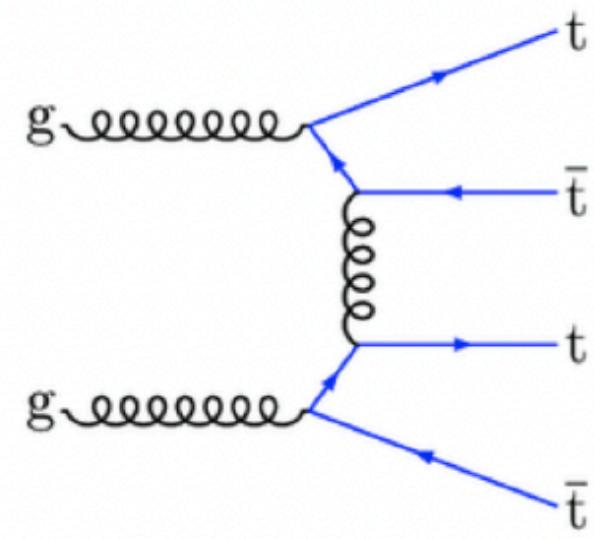


arXiv:2302.01967

171.77 ± 0.37 GeV

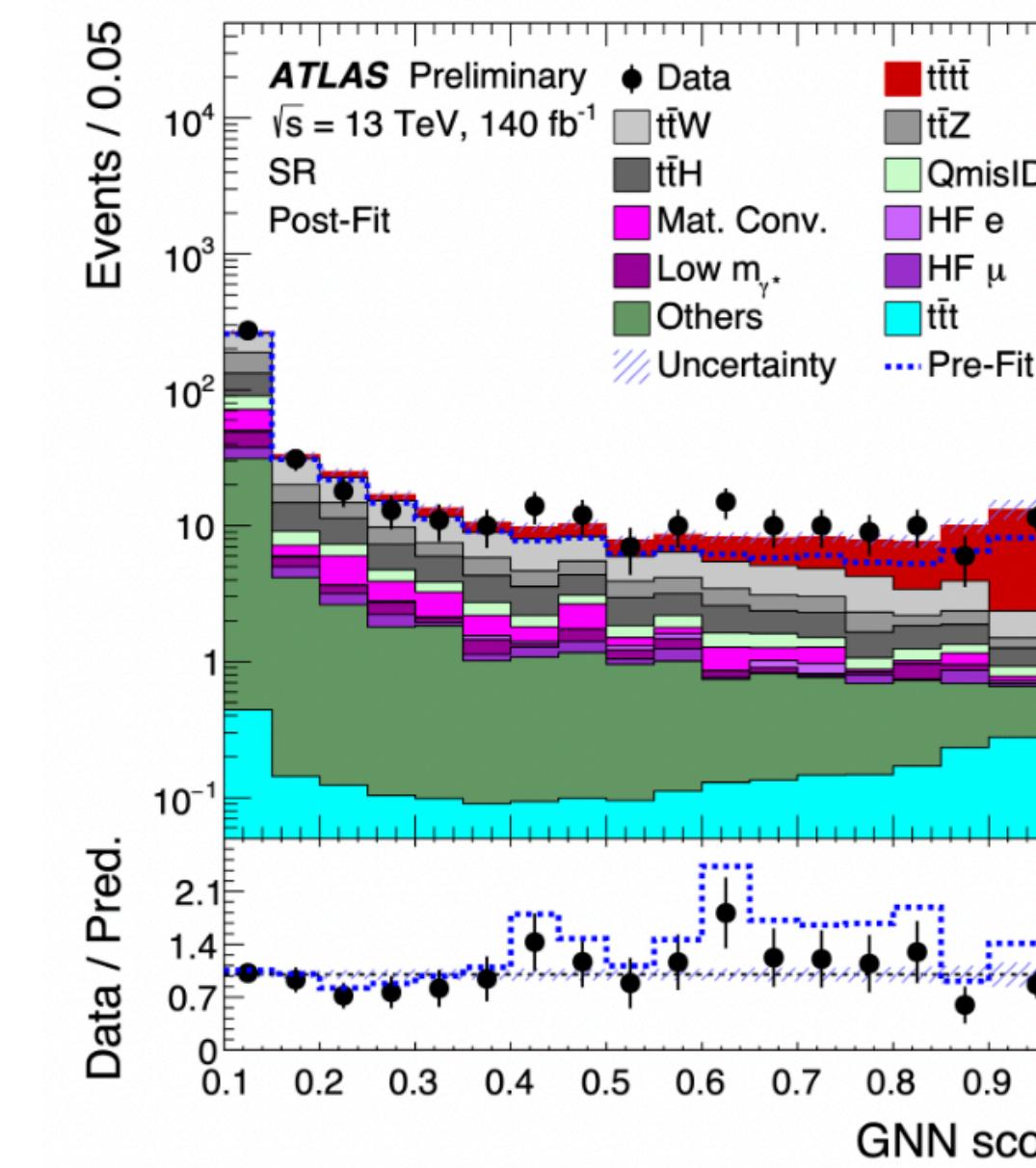
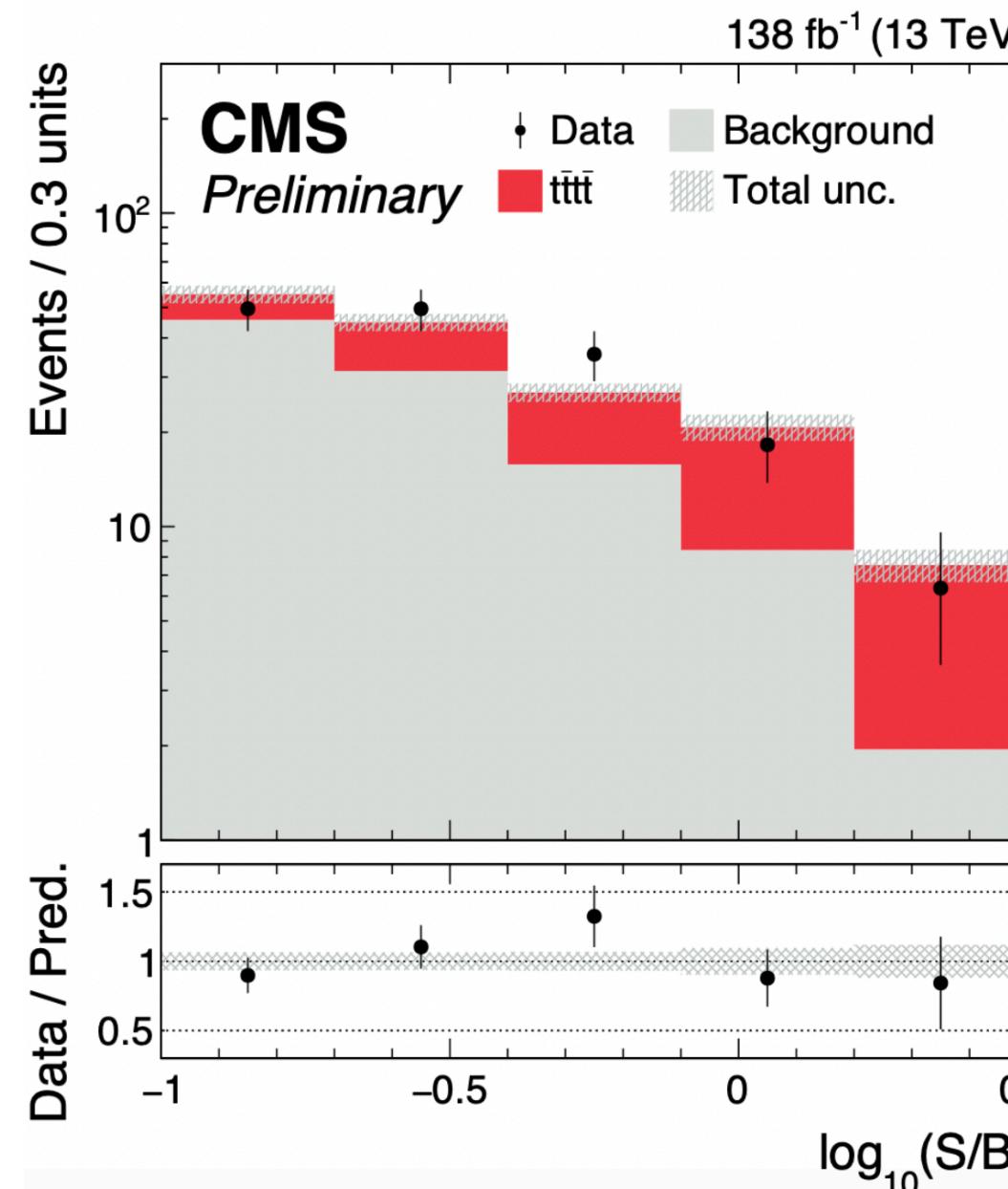
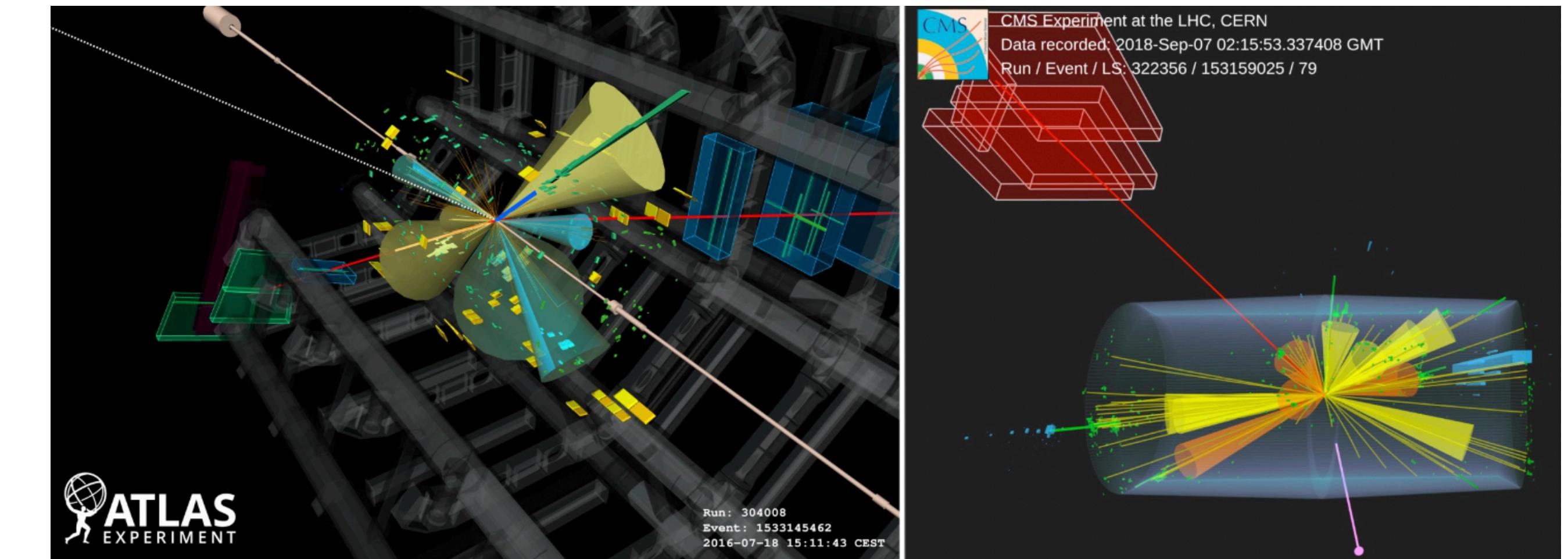
Top Physics

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



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

70,000 smaller than top pair production



Made possible by
modern machine learning

Quiz

- Why is the jet ($\text{ET} > 100 \text{ GeV}$) cross section larger than 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 do 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