V10 – Electroweak measurements at the LHC

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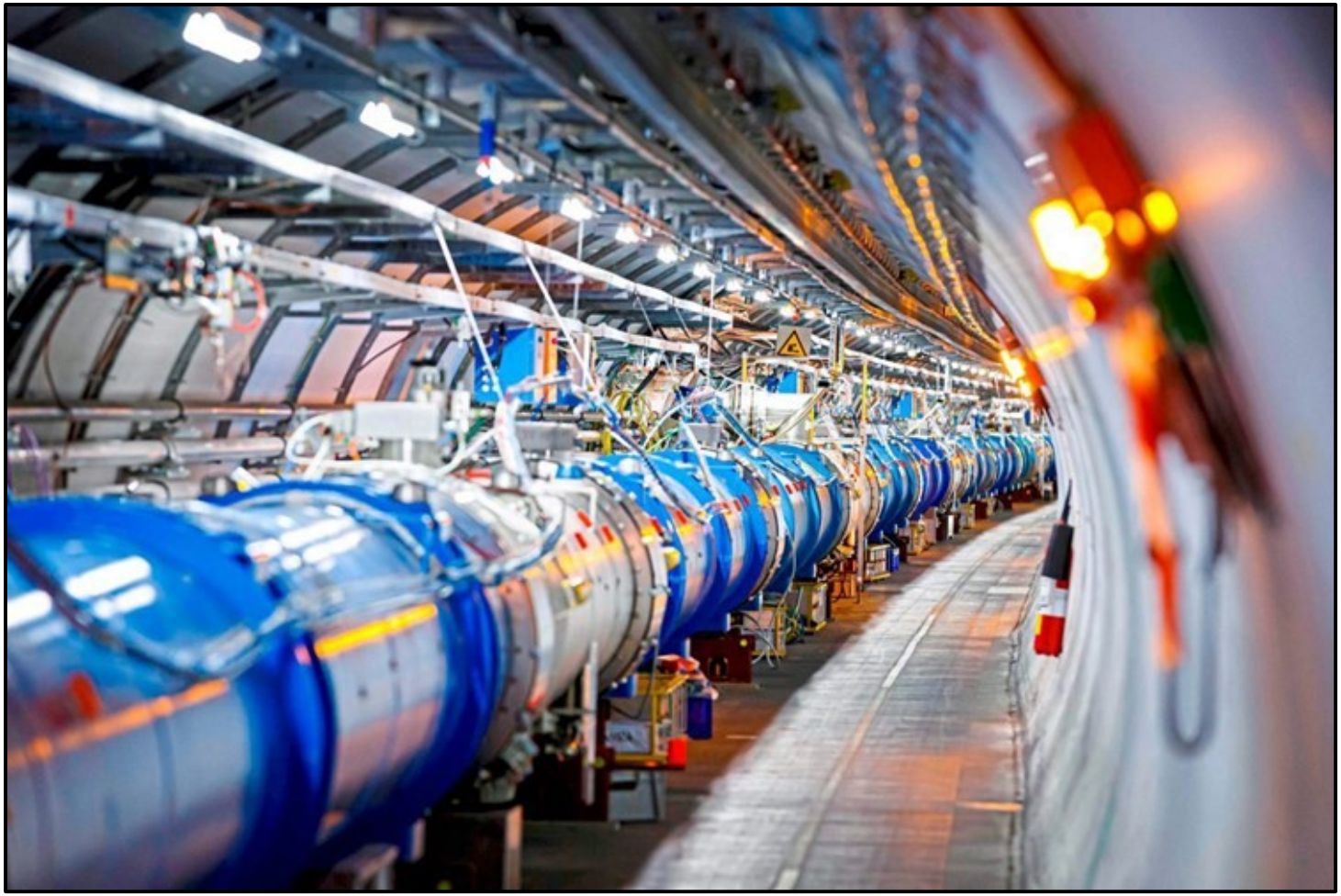
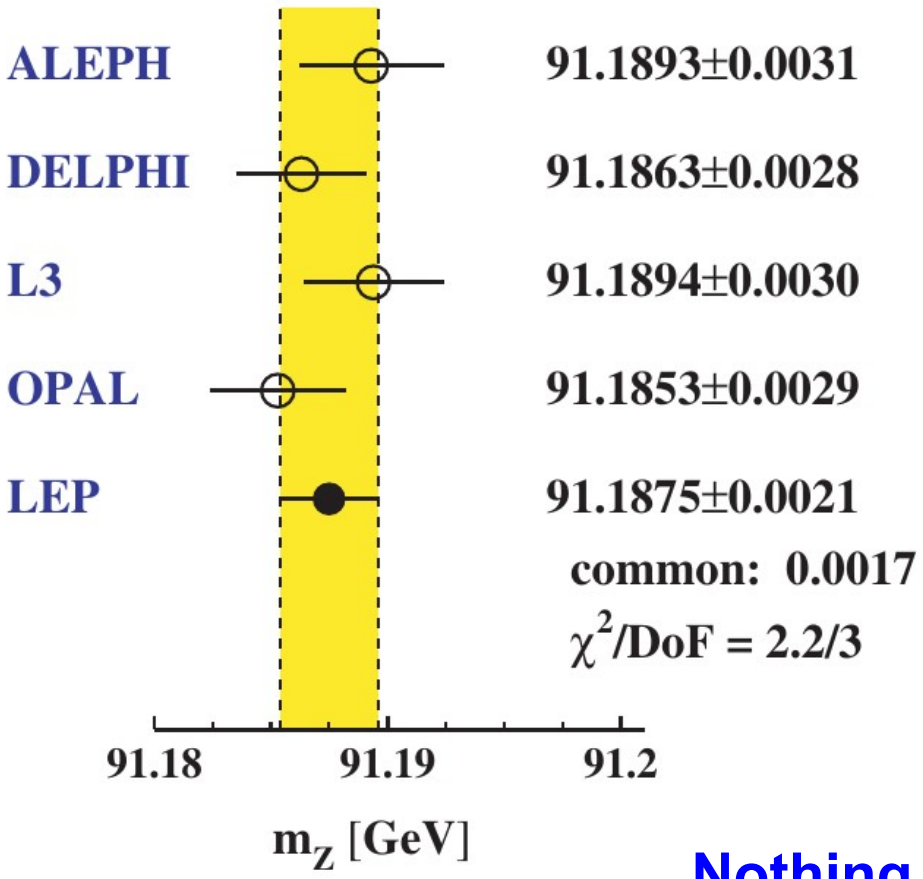
W & Z at the LHC



Z boson mass

Phys. Rept. 427 (2006) 257.



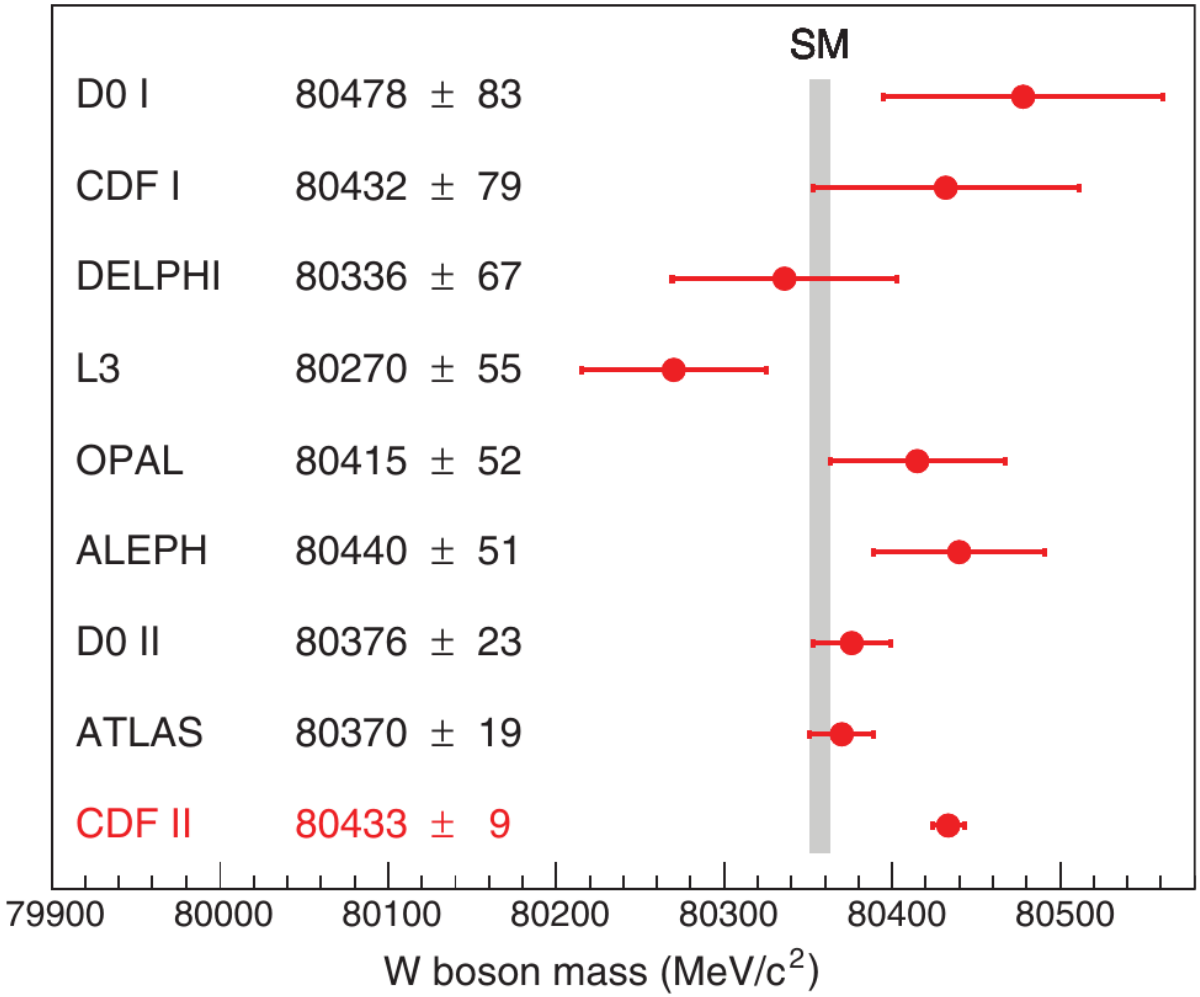
VALUE (GeV)	
91.1876 ± 0.0021	PDG 2023.
91.1852 ±0.0030	OPAL
91.1863 ±0.0028	DLPH
91.1898 ±0.0031	L3
91.1885 ±0.0031	ALEP

Nothing to report from LHC …

Precision measurement from LEP unsurpassed!

W boson mass

Science 376, No. 6589 (2022) 170.



Phys. Rept. 427 (2006) 257.

80.412 ± 0.042 **LEP 2006**

PDG 2023.

80.377 ± 0.012 **PDG fit pre 2022**

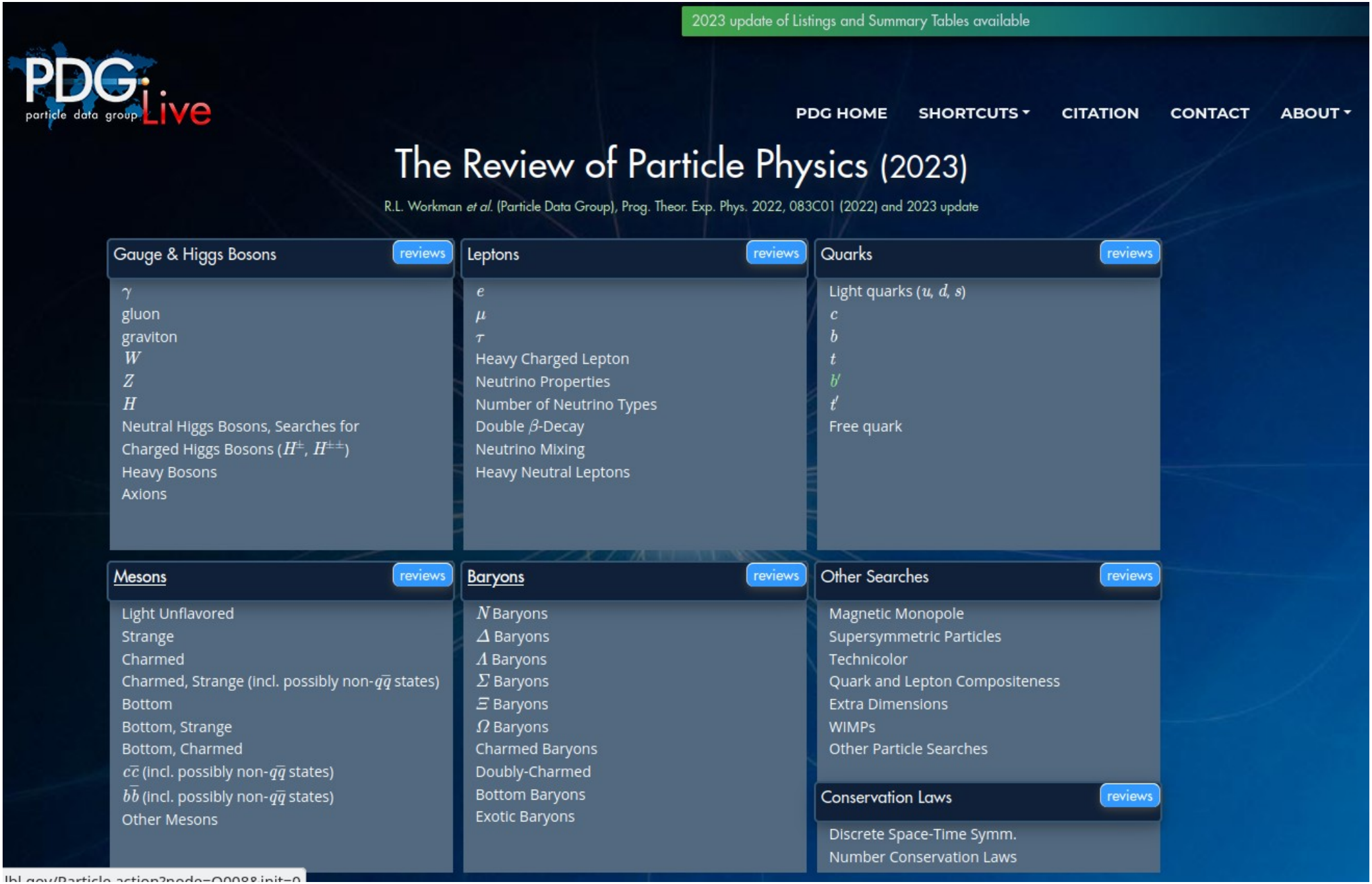
80.4335 ± 0.0094 **CDF 2022**

New precise result from Tevatron …

→ discussed in exercise 3

In contradiction to rest of the world!

PDG live


2023 update of Listings and Summary Tables available
PDG Live
particle data group
PDG HOME
SHORTCUTS
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ABOUT
The Review of Particle Physics (2023)
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update
Gauge & Higgs Bosons
reviews
γ
gluon
graviton
W
Z
H
Neutral Higgs Bosons, Searches for
Charged Higgs Bosons (H±, H±±)
Heavy Bosons
Axions
Leptons
reviews
e
μ
τ
Heavy Charged Lepton
Neutrino Properties
Number of Neutrino Types
Double β-Decay
Neutrino Mixing
Heavy Neutral Leptons
Quarks
reviews
Light quarks (u, d, s)
c
b
t
b′
t′
Free quark
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Light Unflavored
Strange
Charmed
Charmed, Strange (incl. possibly non-qq̄ states)
Bottom
Bottom, Strange
Bottom, Charmed
cc̄ (incl. possibly non-qq̄ states)
bb̄ (incl. possibly non-qq̄ states)
Other Mesons
Baryons
reviews
N Baryons
Δ Baryons
Λ Baryons
Σ Baryons
Ξ Baryons
Ω Baryons
Charmed Baryons
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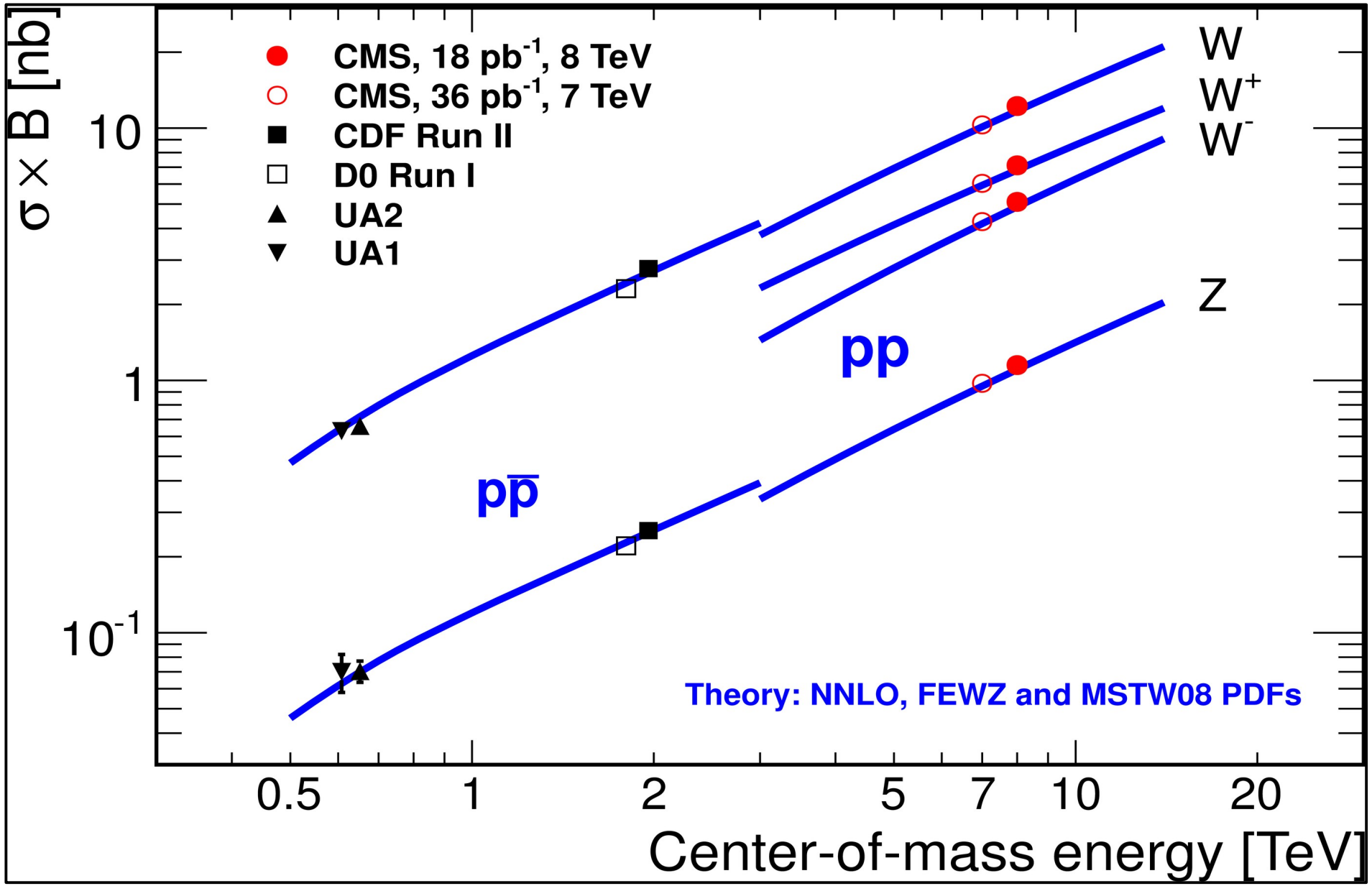
Magnetic Monopole
Supersymmetric Particles
Technicolor
Quark and Lepton Compositeness
Extra Dimensions
WIMPs
Other Particle Searches
Conservation Laws
reviews
Discrete Space-Time Symm.
Number Conservation Laws

PDG 2023 on W mass

In April 2022 the CDF collaboration published a determination of the W mass based on their full Run-2 dataset of 8.8 fb^{-1} [AALTONEN 2022], with much reduced uncertainty: 80433.5 ± 9.4 MeV. This new CDF result, which includes the data of their previous result [AALTONEN 2012E] and thus supersedes it, is of higher precision than our world average quoted above. However, the two determinations disagree significantly.

The Tevatron-LHC W-boson mass combination working group, consisting of experts from the hadron collider experiments, ATLAS, CDF, CMS, D0, and LHCb, is examining in detail all aspects of the measurements, paying attention to corrections and correlated uncertainties in order to treat all results on an equal footing and properly account for correlations in various averages. The report from the combination group is awaited.

Inclusive $W^{\pm}$ cross sections



Drell-Yan $pp \to l^+l^-$

- Idea:
  - Same initial-state momenta: Z at rest
  - Deduce initial-state momenta from Z speed of flight

→ **probes directly parton density**

$$Y = \frac{1}{2} \ln \left(\frac{E(\mu\mu) + p_z(\mu\mu)}{E(\mu\mu) - p_z(\mu\mu)} \right) = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right)$$

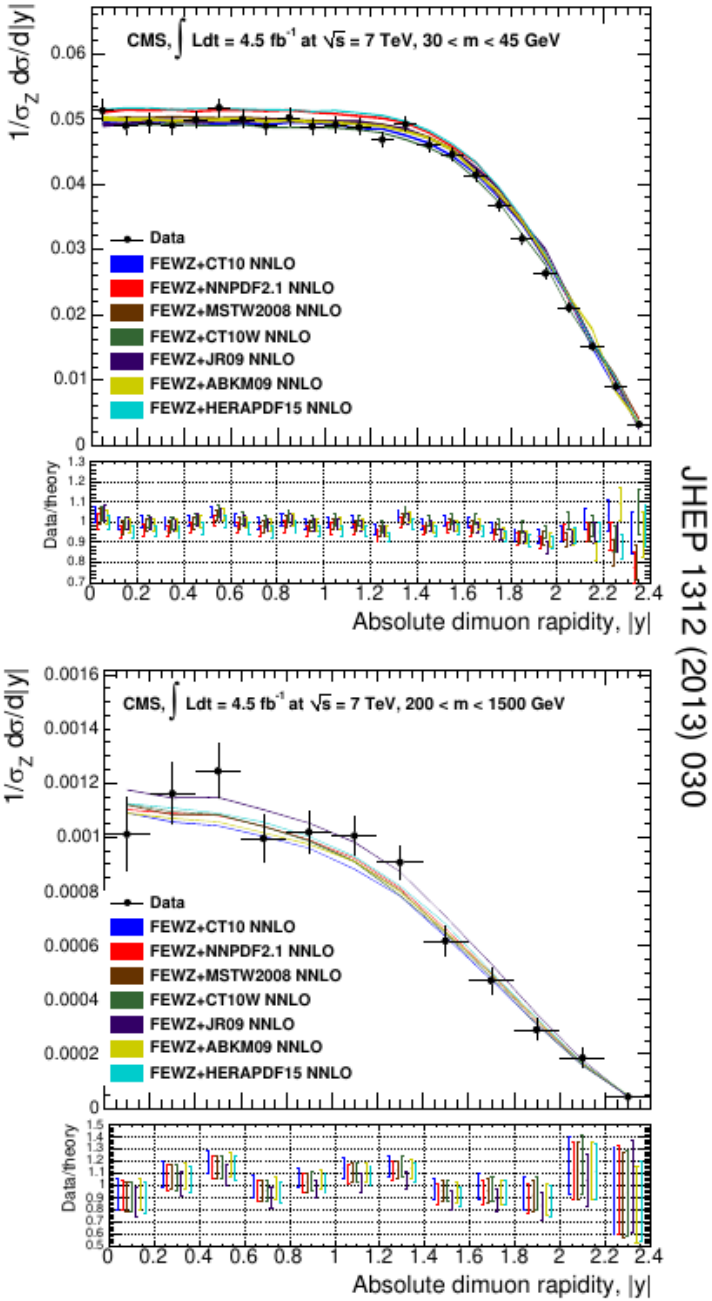
(see Exercises No 1)

- **Double-differential cross-section**

$$\frac{\mathrm{d}^2\sigma(\mathrm{pp} \to \mu\mu)}{\mathrm{d}m\,\mathrm{d}Y}$$

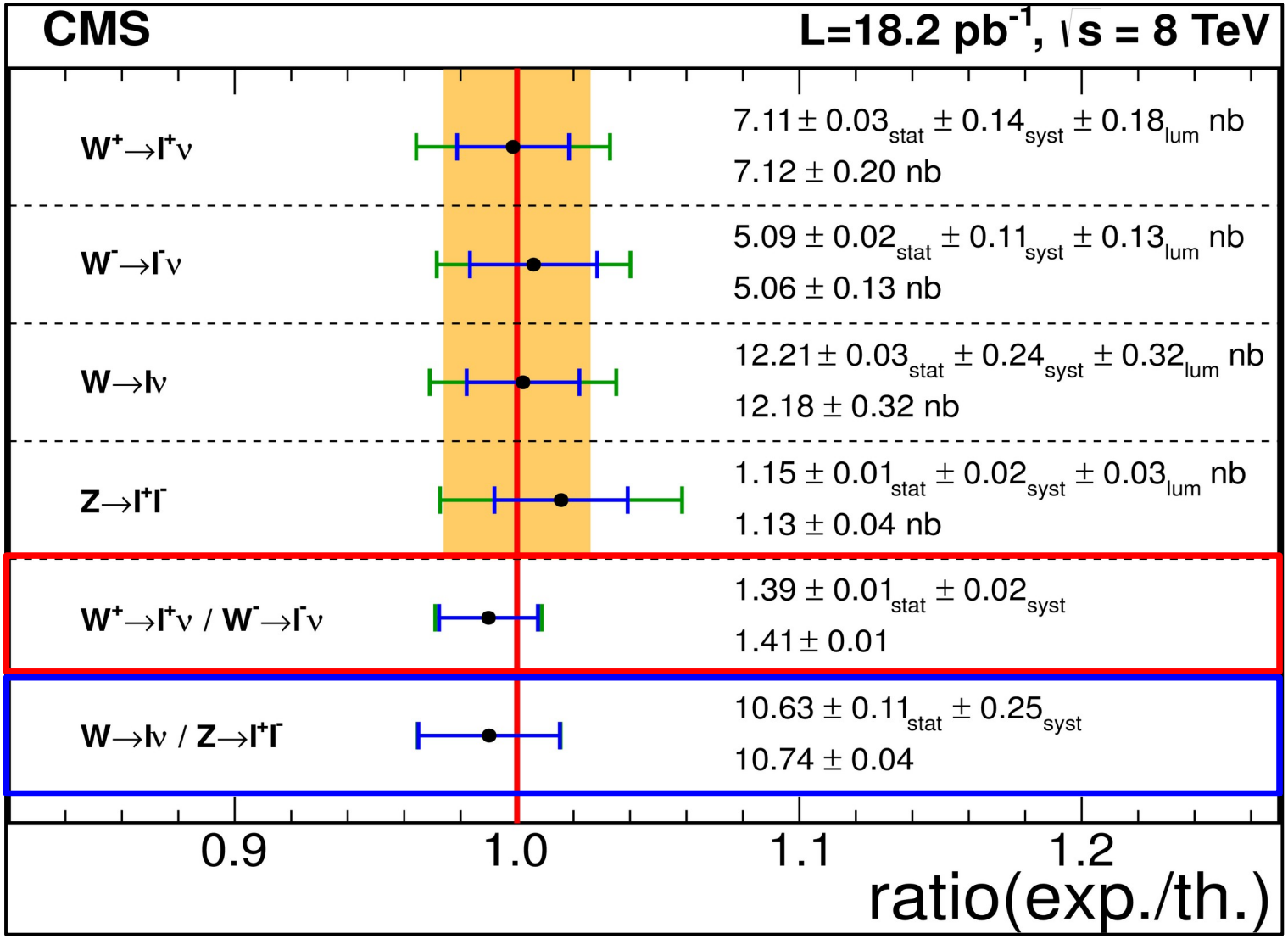
  - Di-μ mass m
  - Di-μ rapidity Y

→ **Compare to different PDFs**



JHEP 1312 (2013) 030

Inclusive V cross section ratios

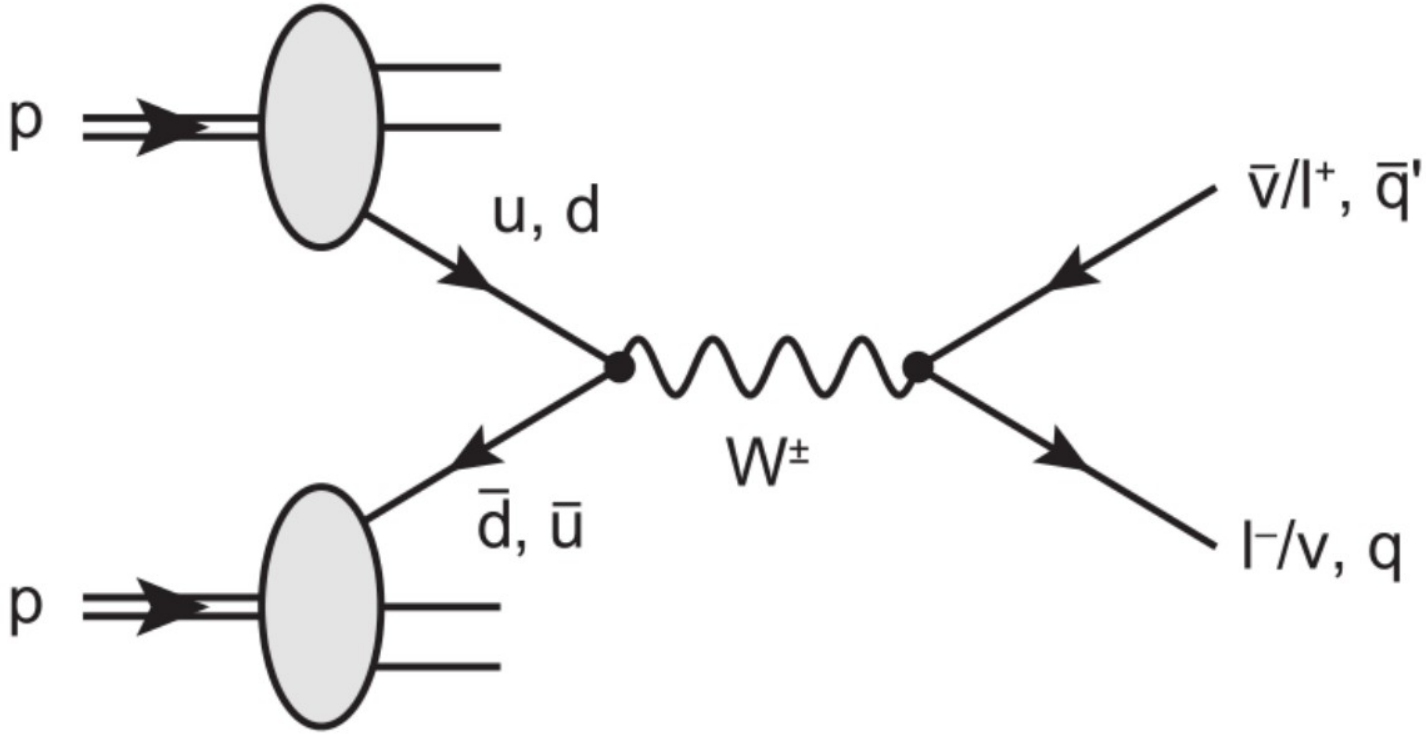


$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx 1.4$$

$$\frac{\sigma_W}{\sigma_Z} \approx 10$$

Charge asymmetry

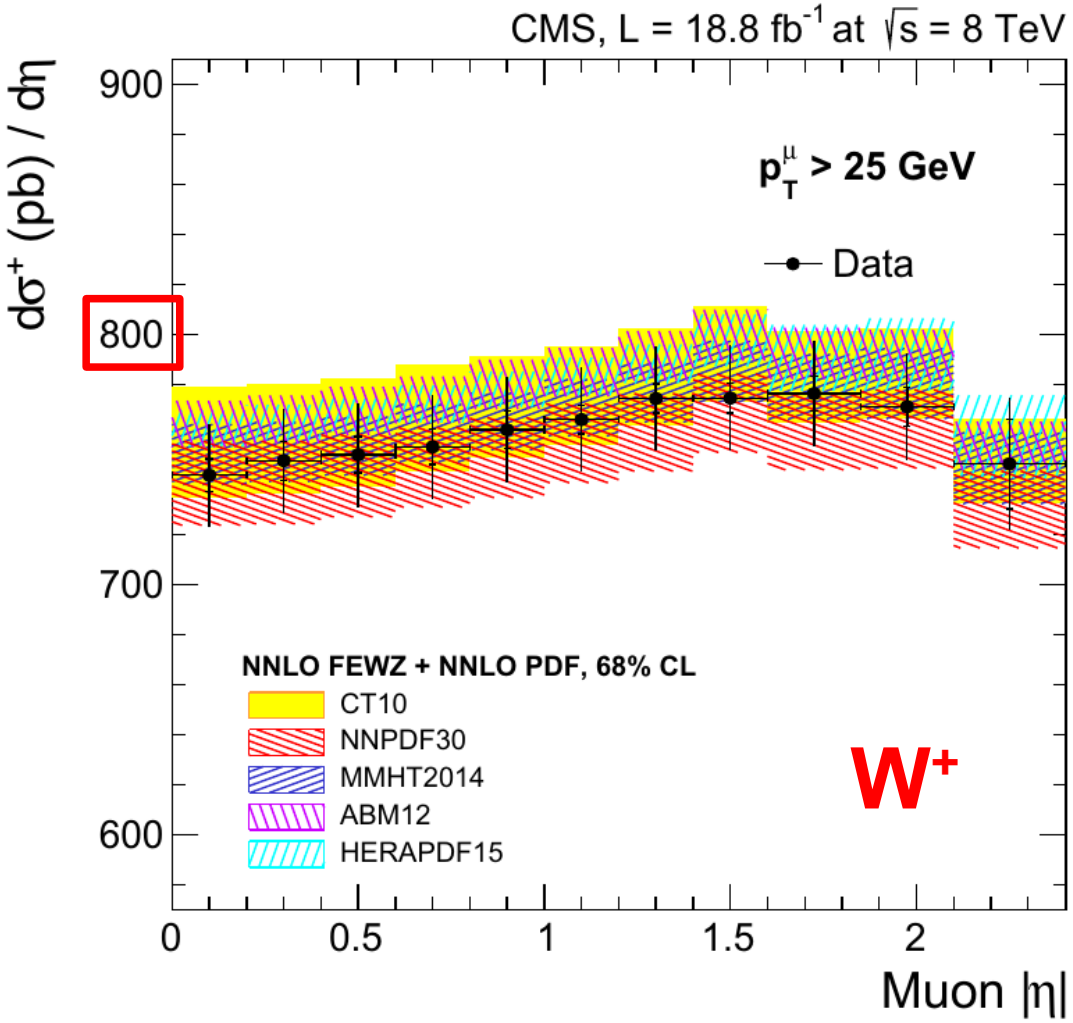
$$W^+ \to \mu^+ \nu_\mu \quad \text{needs} \quad u\bar{d}$$

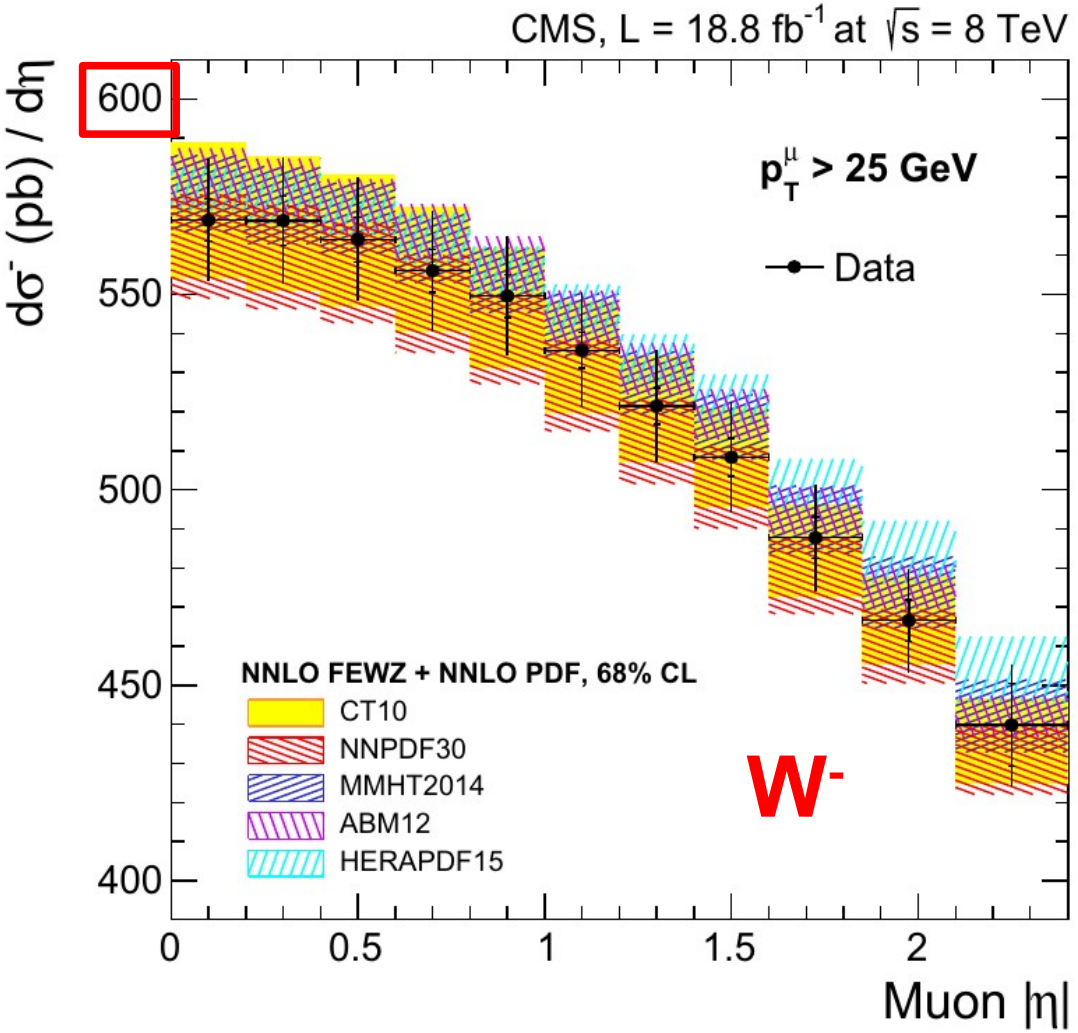


$$W^- \to \mu^- \overline{\nu_\mu} \quad \text{needs} \quad \bar{u}d$$

Charge asymmetry

→ **investigate asymmetry:** $A(\eta) = \dfrac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$

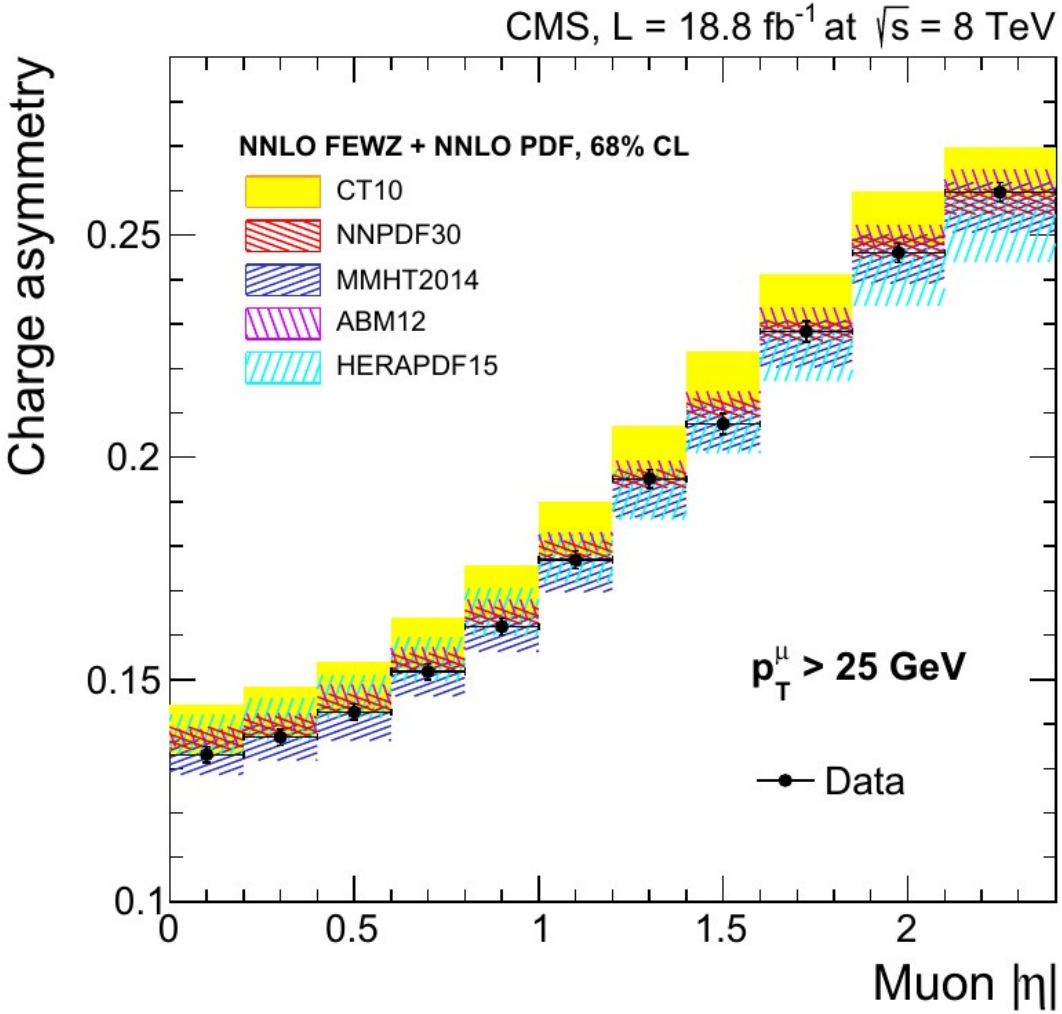




CMS, Eur. Phys. J. C76 (2016) 469.

Charge asymmetry

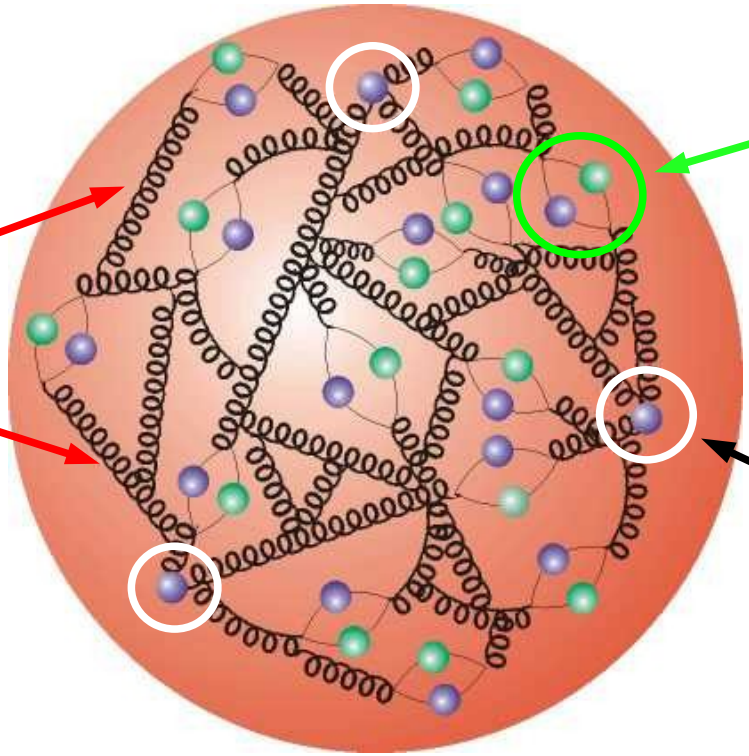
→ **investigate asymmetry:** $A(\eta) = \dfrac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$



→ **constrain u/d ratio in proton PDF!**

CMS, Eur. Phys. J. C76 (2016) 469.

Constraining PDFs



- **Example of generic functional form of proton structure:**

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

Normalisation

Behaviour for $x \to 0$

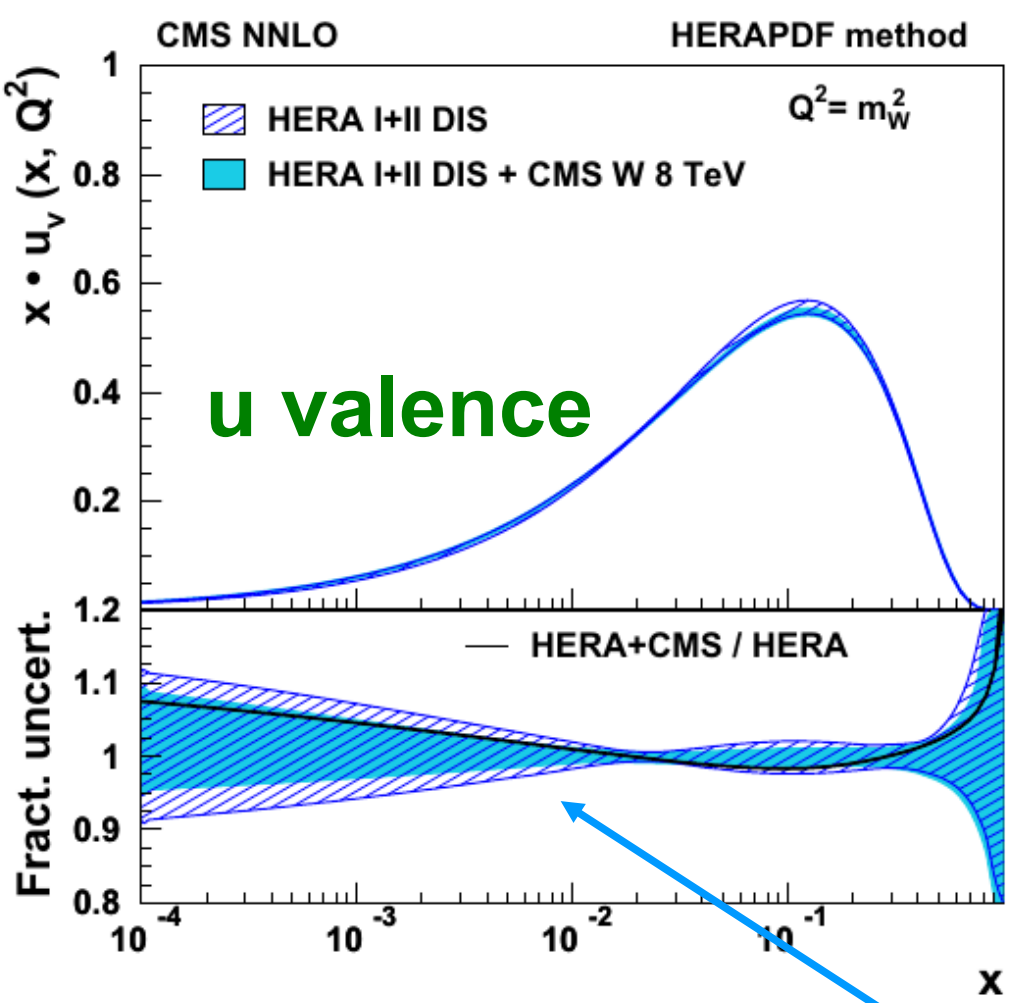
Behaviour for $x \to 1$

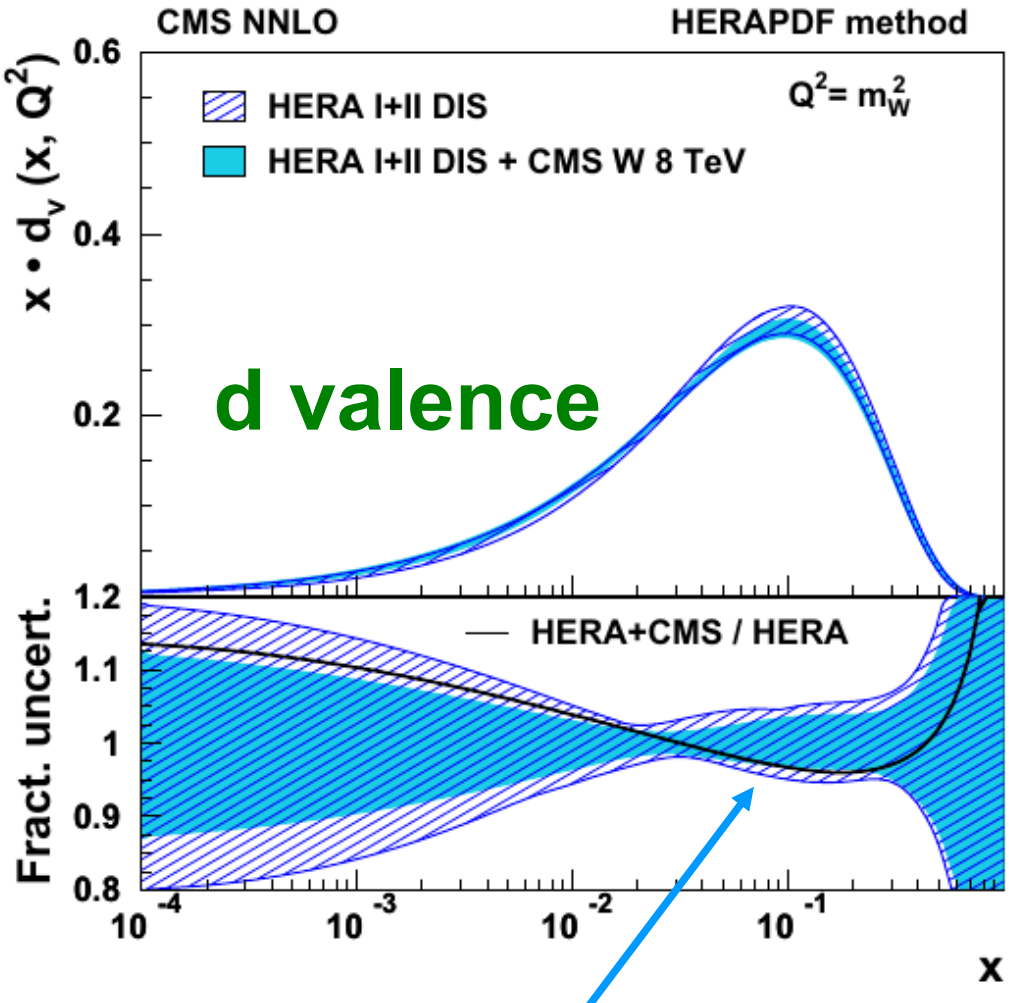
Middle region largest variability

Constraints on u and d valence

$x \cdot u_v(x, Q^2)$

$x \cdot d_v(x, Q^2)$





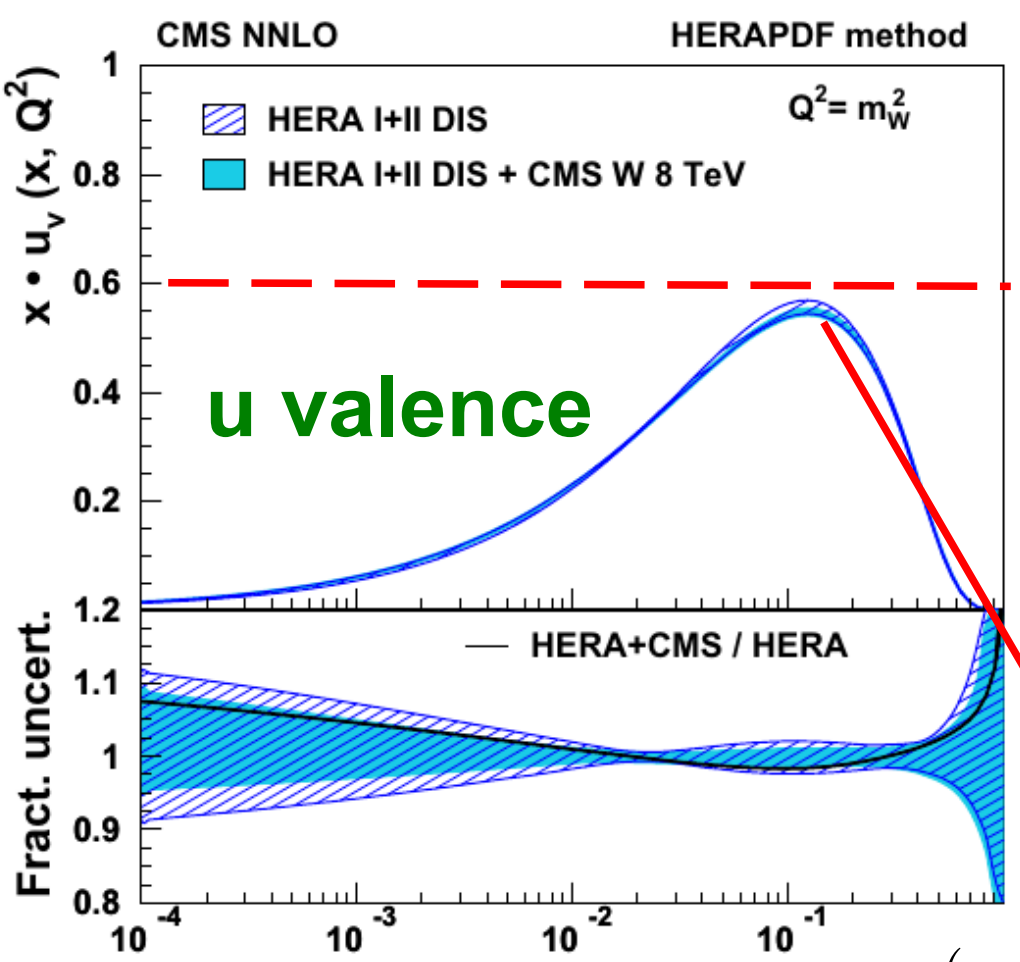
→ reduced uncertainty

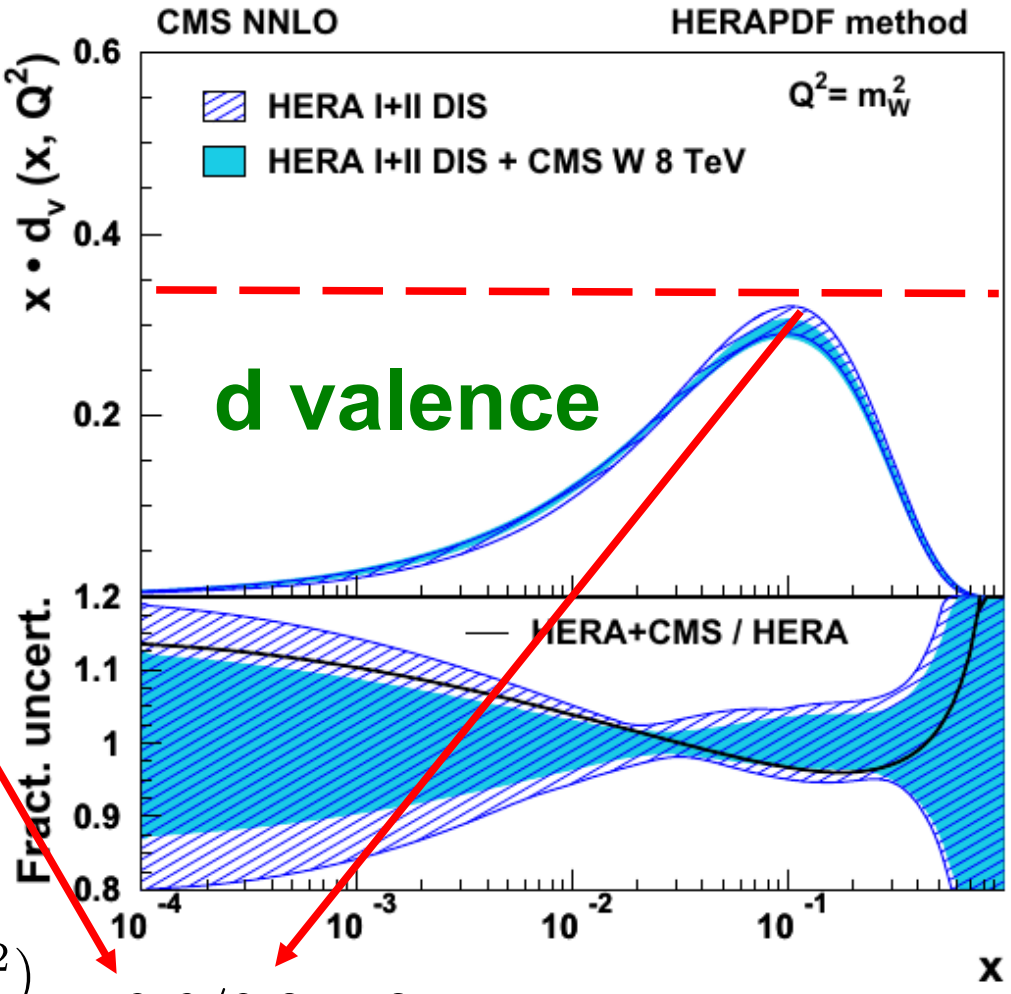
CMS, Eur. Phys. J. C76 (2016) 469.

Constraints on u and d valence

$$x \cdot u_v(x, Q^2)$$

$$x \cdot d_v(x, Q^2)$$

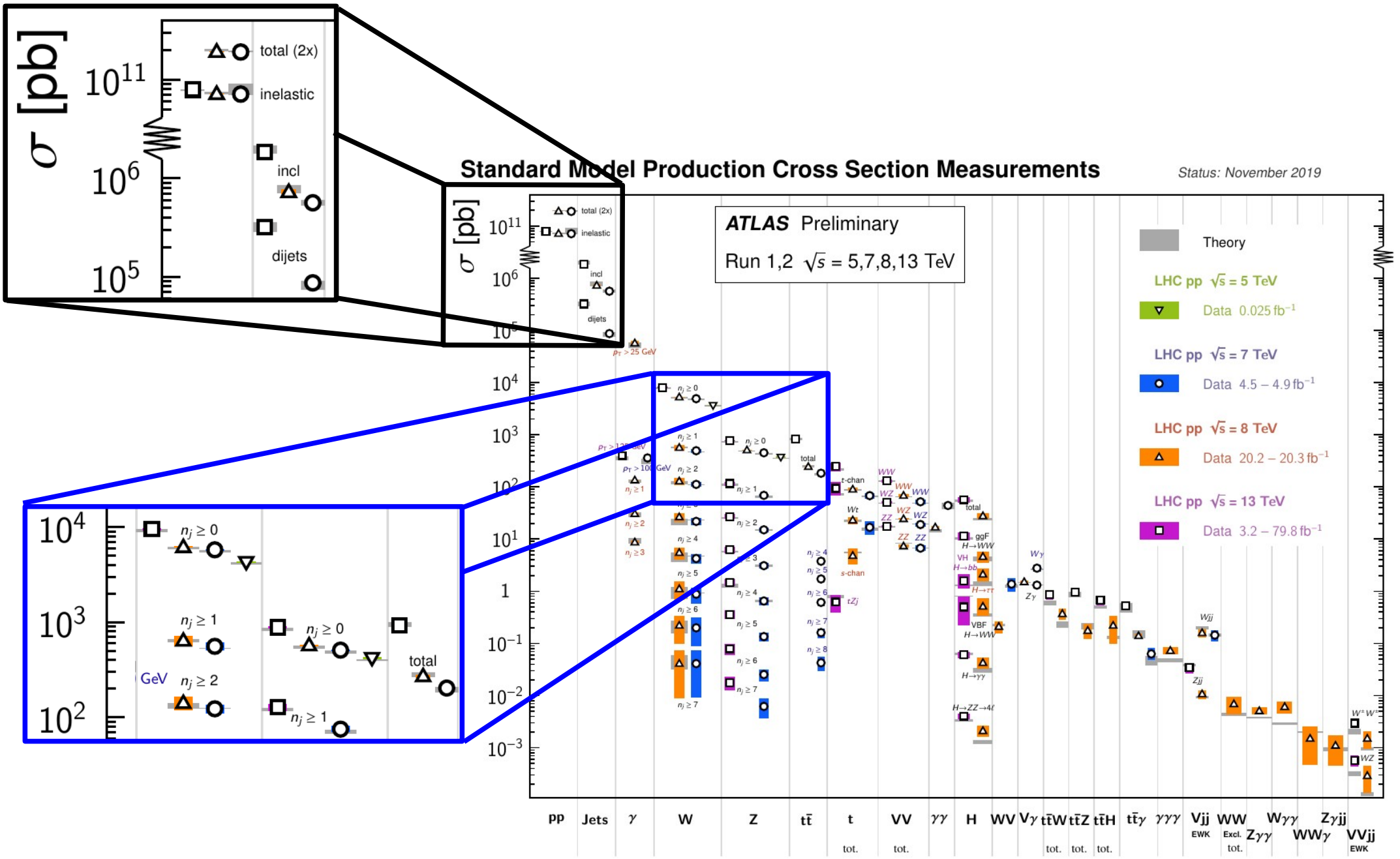




$$\frac{u_v(x, Q^2)}{d_v(x, Q^2)} \approx 0.6/0.3 = 2$$

CMS, Eur. Phys. J. C76 (2016) 469.

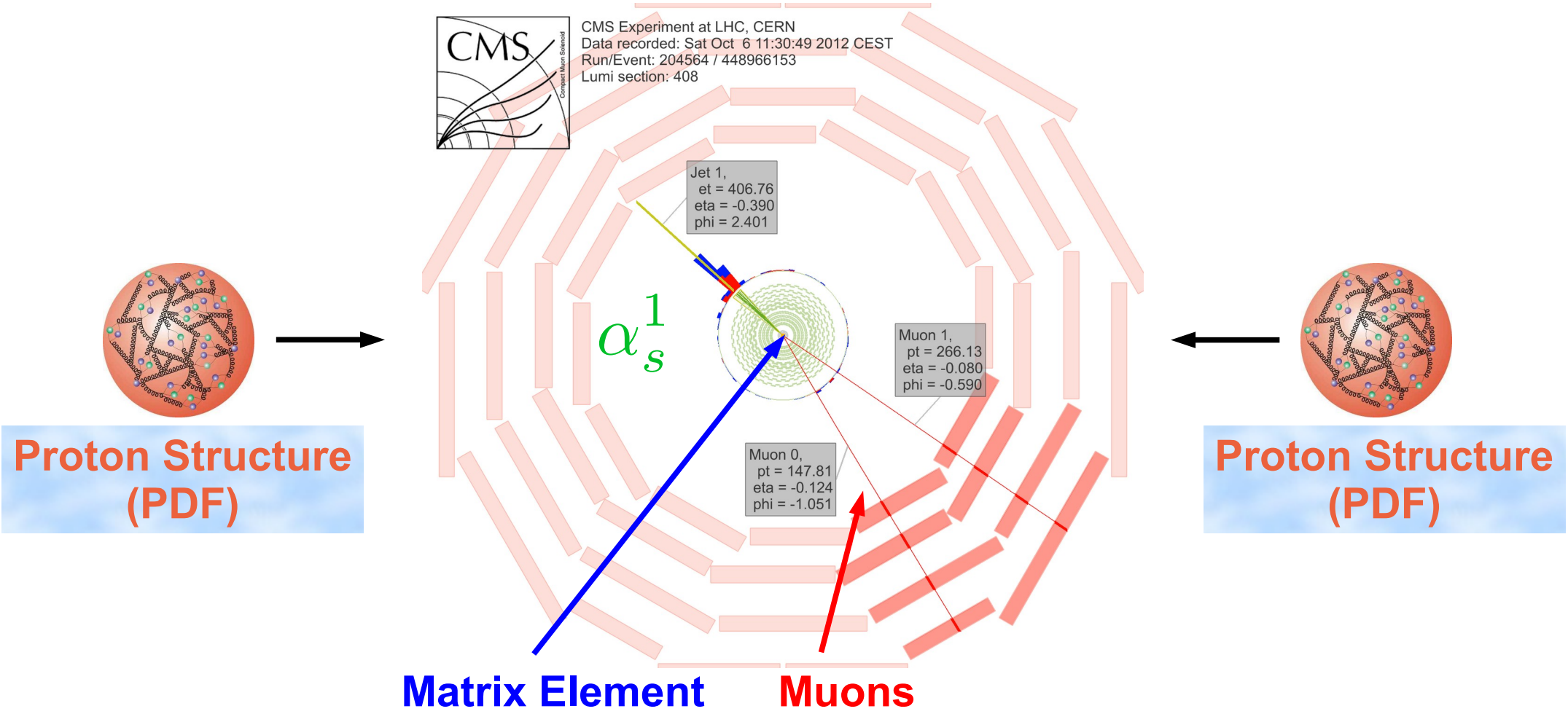
W & Z (+X) at the LHC



W & Z at the LHC

High-precision lepton measurements:

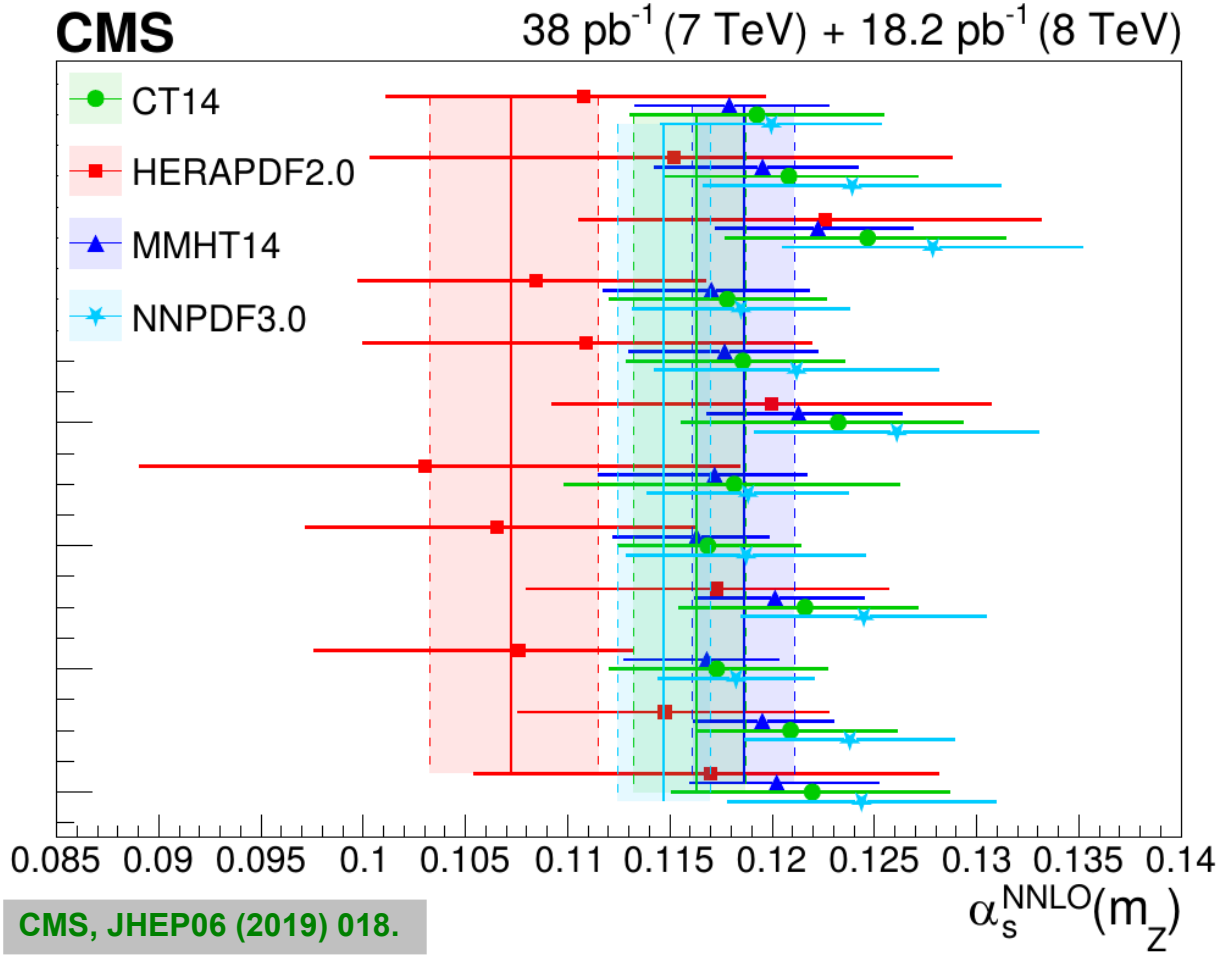
- W, Z, top measurements provide high-precision cross sections
- Also learn about electroweak parameters, the strong coupling and the proton structure



Inclusive W,Z production

Result from combined fit for set of inclusive W and Z cross section measurements, e and μ decay final states only.

$$\sigma_{\mathrm{LO}} \propto \alpha_s^0$$



CMS, JHEP06 (2019) 018.

Results using NNLO pQCD BUT at LO not sensitive to α_s!

→ Work with Z+jet events!

$$\alpha_s(M_Z) = 0.1186\,^{+0.0025}_{-0.0025}$$

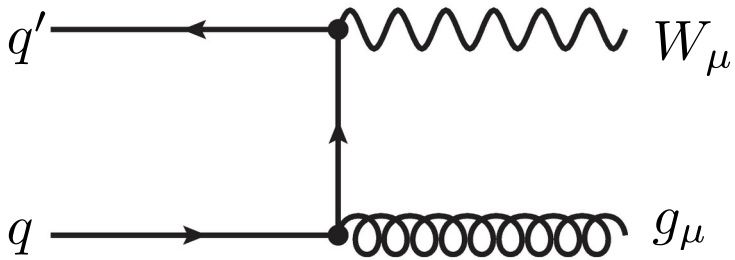
CMS only
MMHT14 PDF set

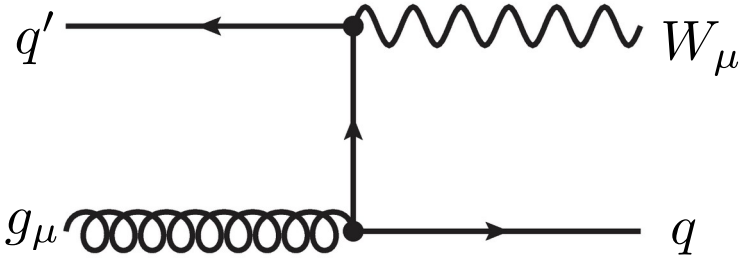
W + jets

- Precision test of QCD
- Important background to searches for new phenomena in Higgs, top, SUSY

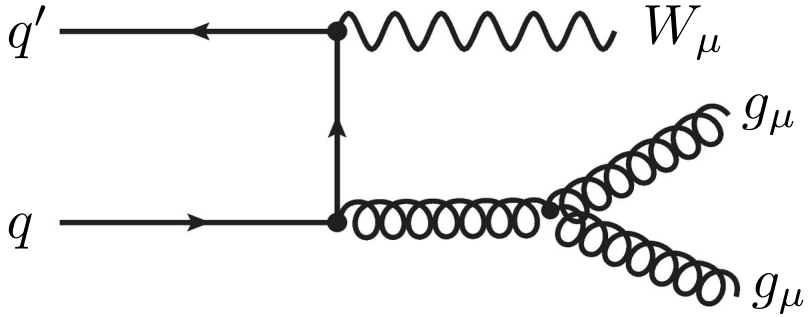
Leading-order process in QCD:

W+1 Jet





W+2 Jet



Naive expectation:
One order more in α_s for each additional parton/jet
(Berends-Giele scaling; similar Z+jets)

...

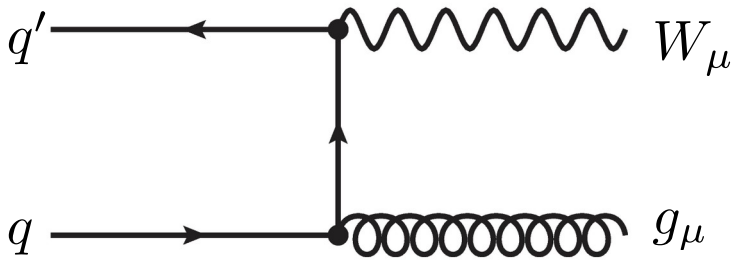
$$\frac{\sigma(W_\mu + (n+1)\text{ jets})}{\sigma(W_\mu + n\text{ jets})} = \frac{\sigma(W_\mu + 2\text{ jets})}{\sigma(W_\mu + 1\text{ jet})}$$

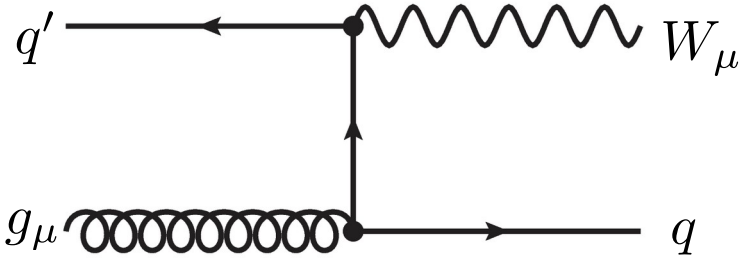
W + jets

- Precision test of QCD
- Important background to searches for new phenomena in Higgs, top, SUSY

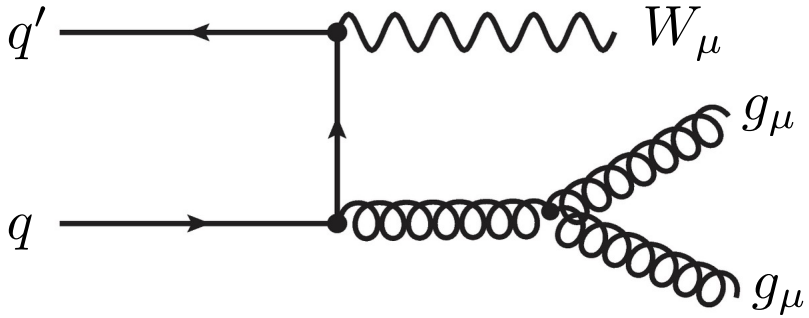
Leading-order process in QCD:

W+1 Jet





W+2 Jet



...

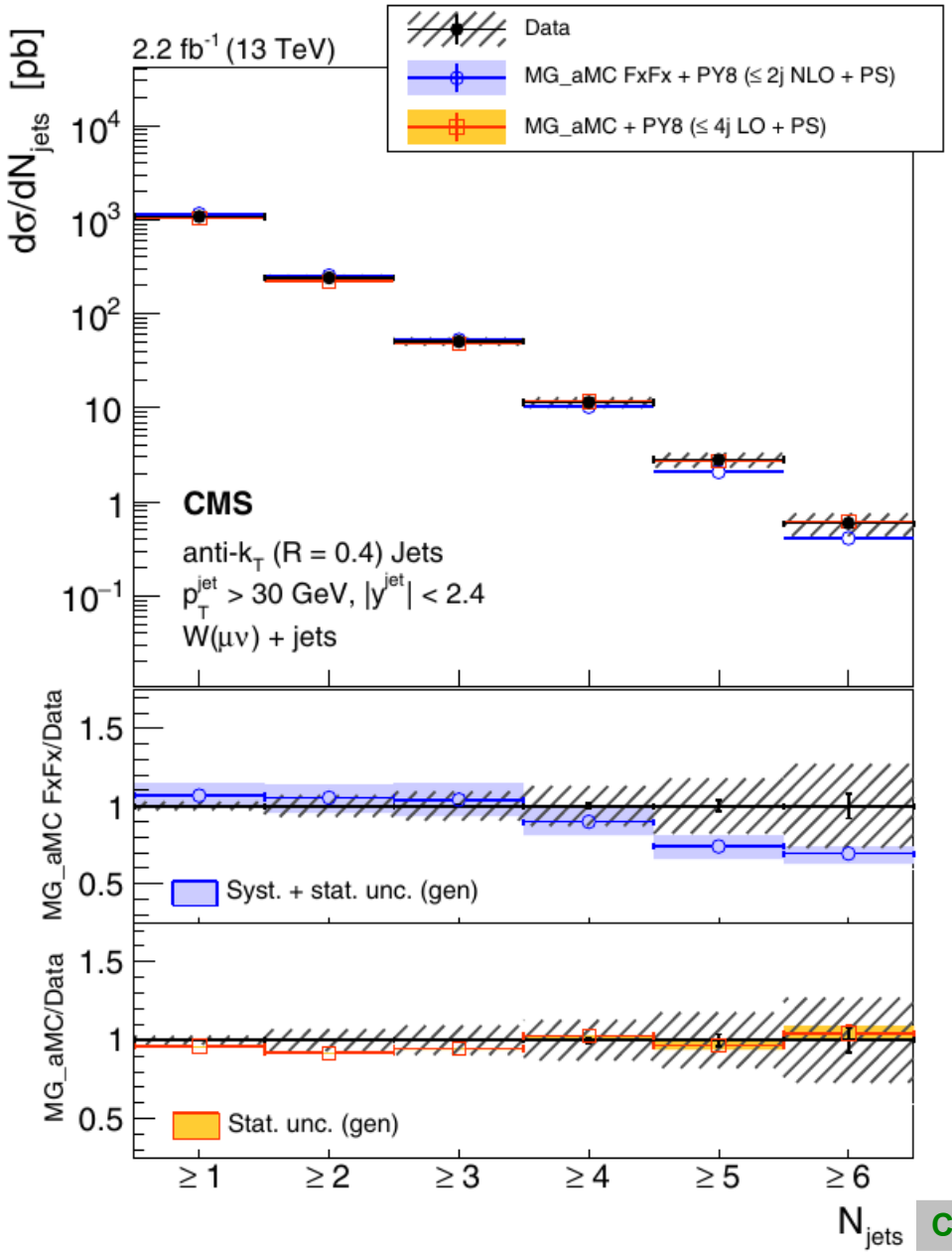
Fixed-order predictions:

- LO known up to $2 \to 10$ partons
- # of NLO diagrams per final state jet

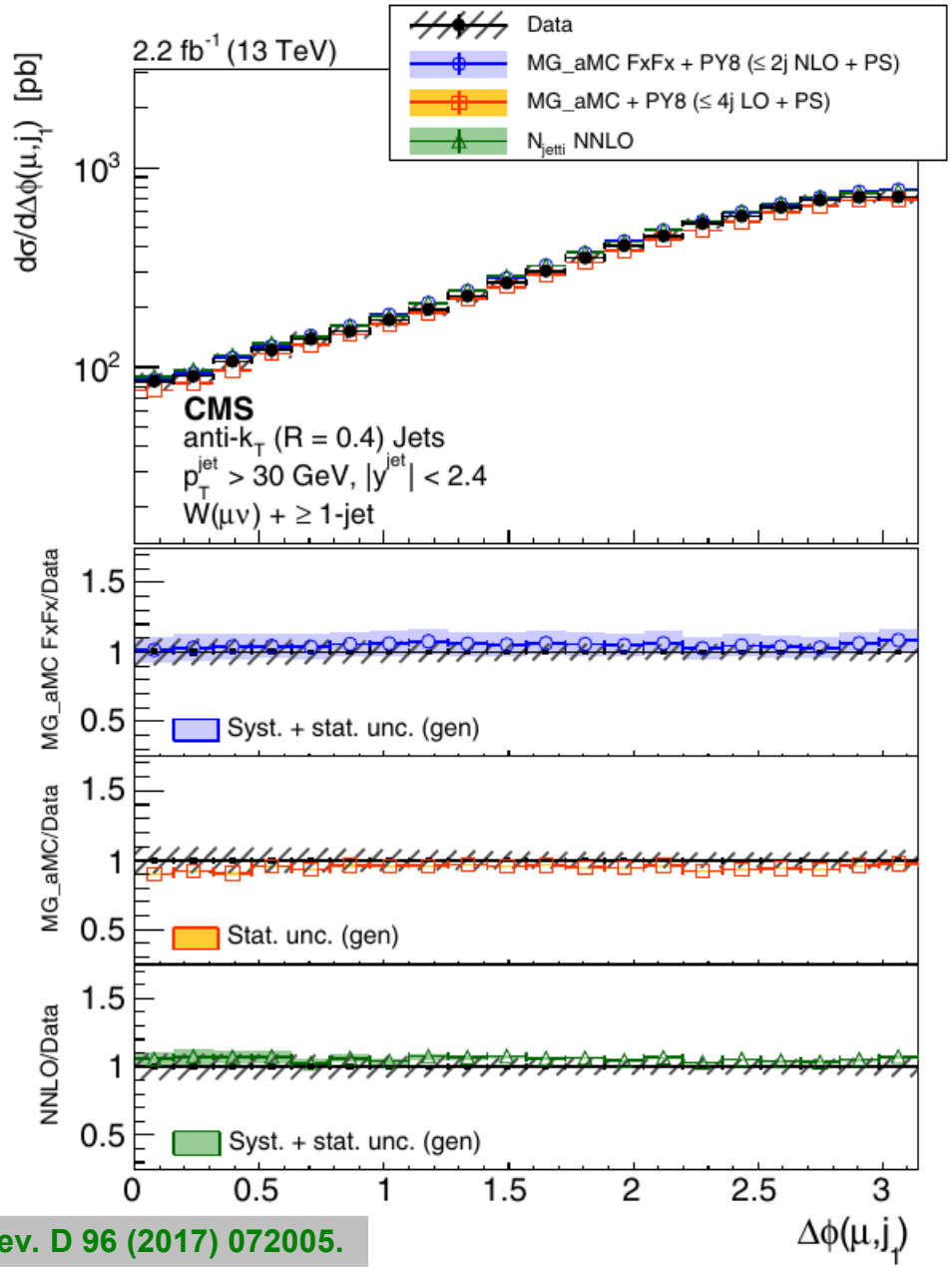
N_{Jets}	NLO Diagramme
1	11
2	110
3	1 253
4	16 648
5	256 265

W + jets

Inclusive # of jets → sensitive to α_s

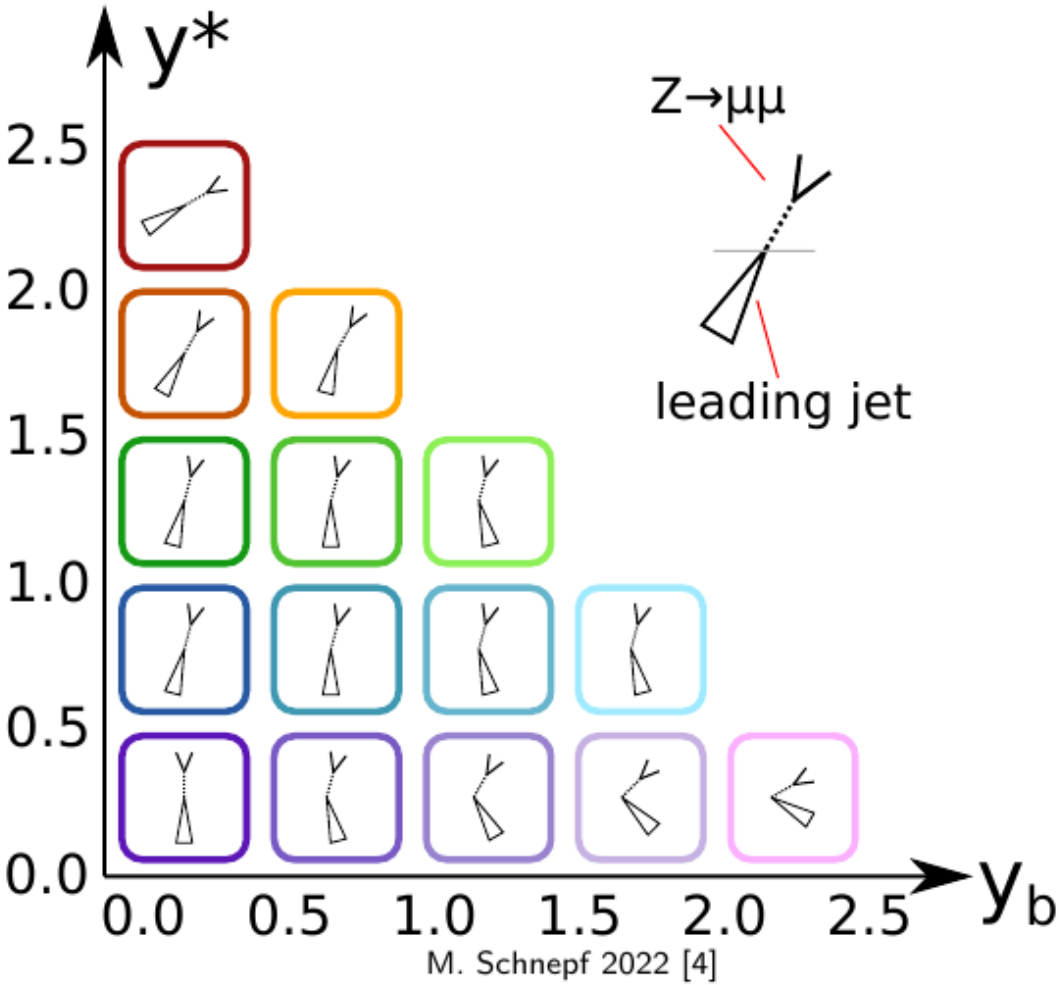


ΔΦ(jet,μ) → check parton shower



CMS, Phys. Rev. D 96 (2017) 072005.

Z + 1jet + X

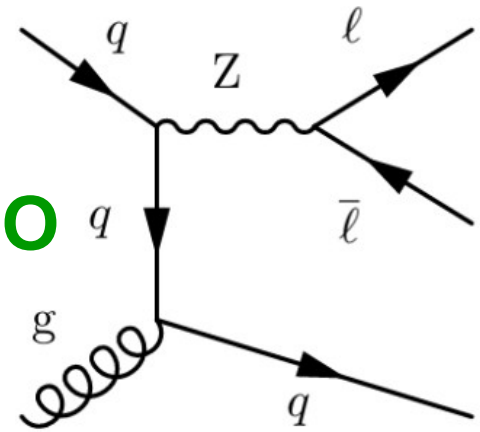


- Transverse momentum of di-muon
  - P_T^Z
  - Scale of hard interaction
- Boost of center-of-mass system
  - $y_b = ½ | y^Z + y^{jet} |$
  - Parton momentum fractions
- Rapidity separation
  - $y^* = ½ | y^Z - y^{jet} |$
  - Scattering angle in cms system

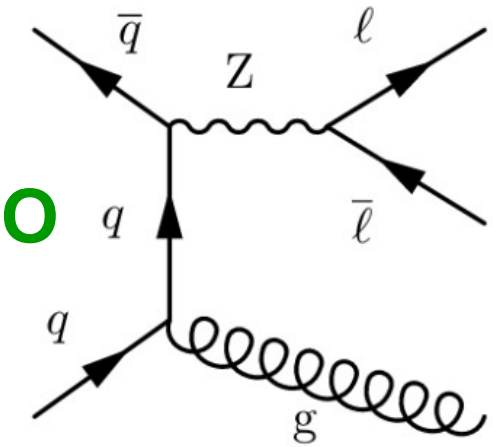
Sensitive to gluon PDF of proton

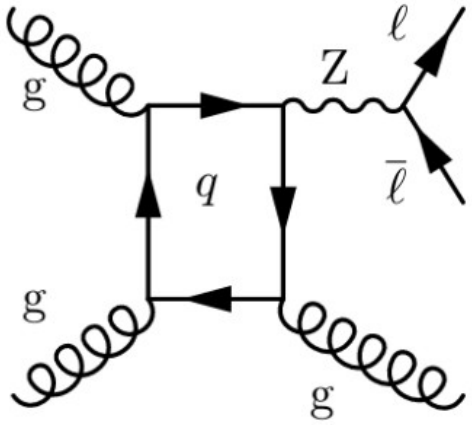
Z + 1jet + X

LO

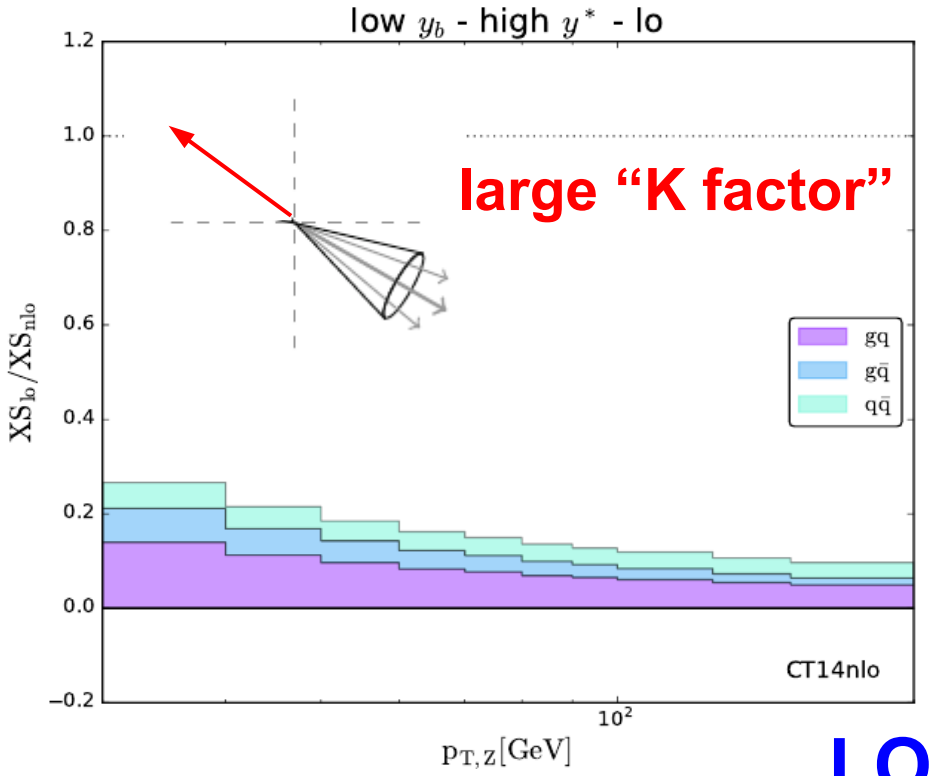


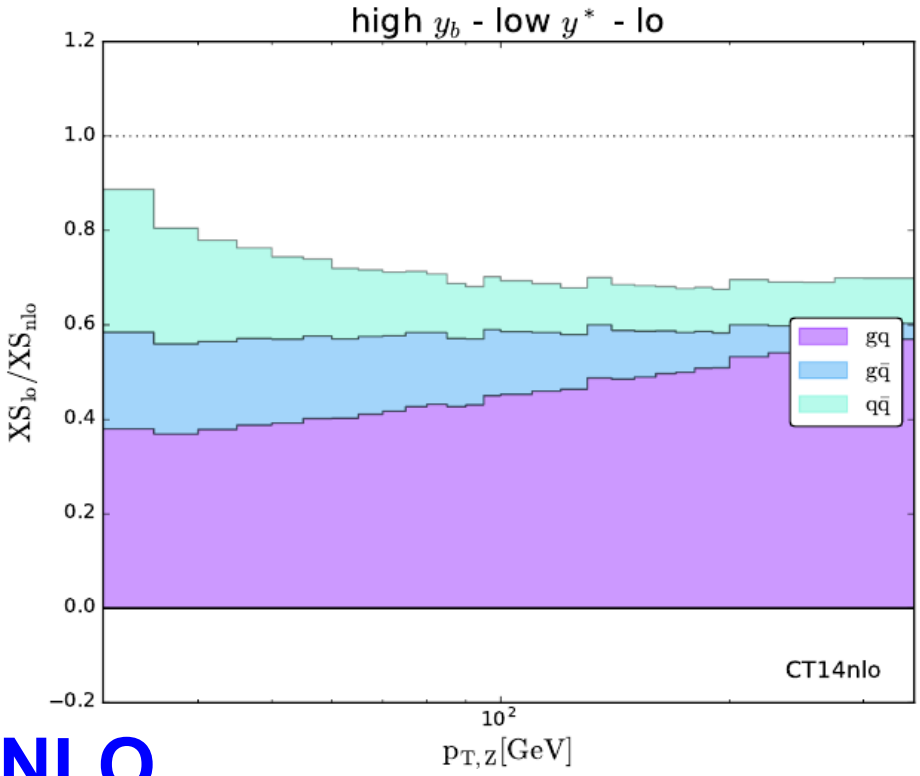
LO

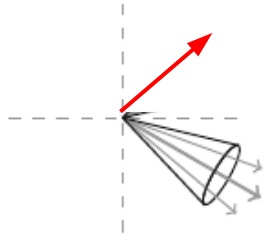




NLO



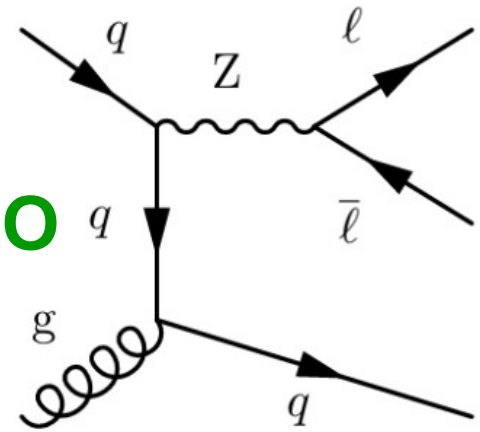




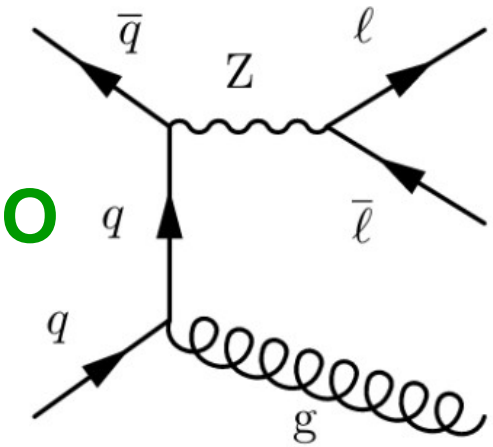
LO/NLO

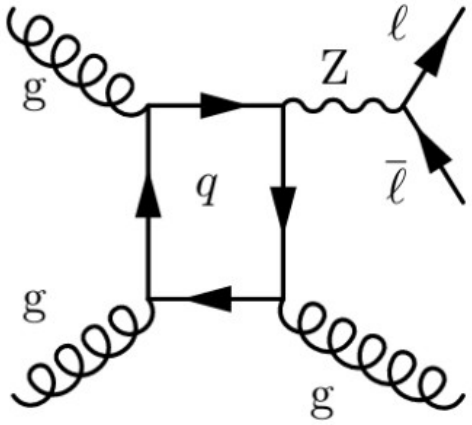
Z + 1jet + X

LO

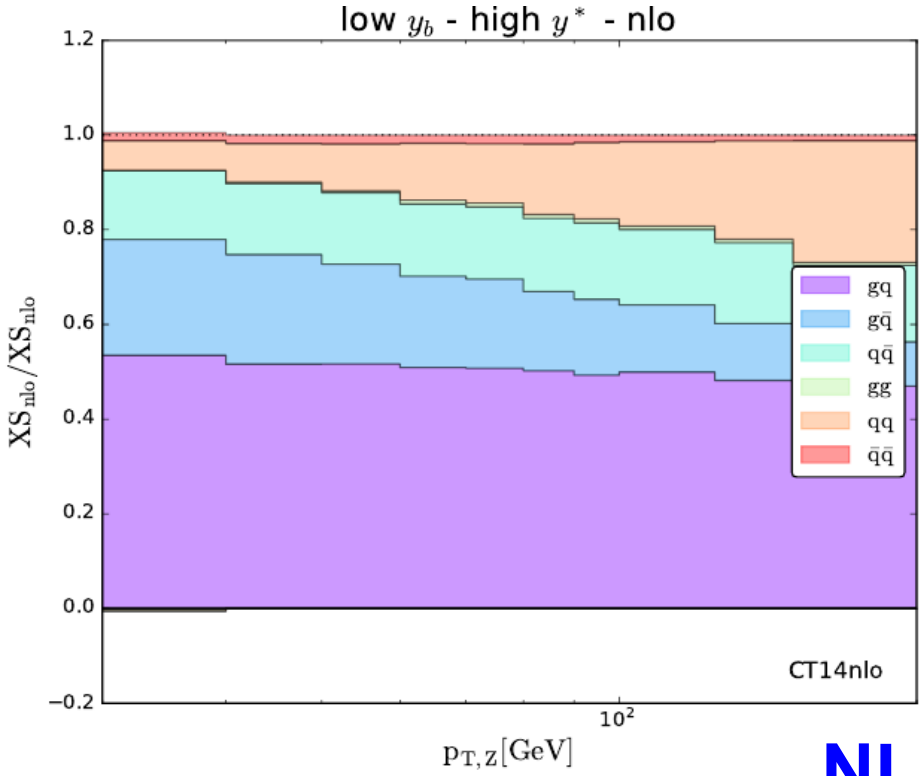


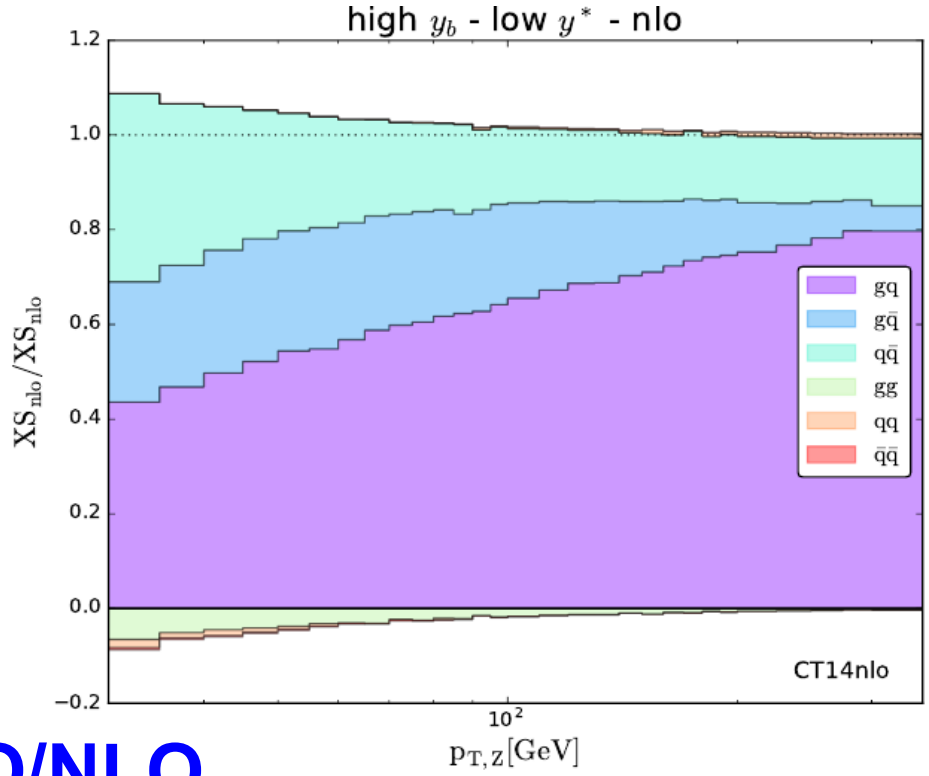
LO





NLO

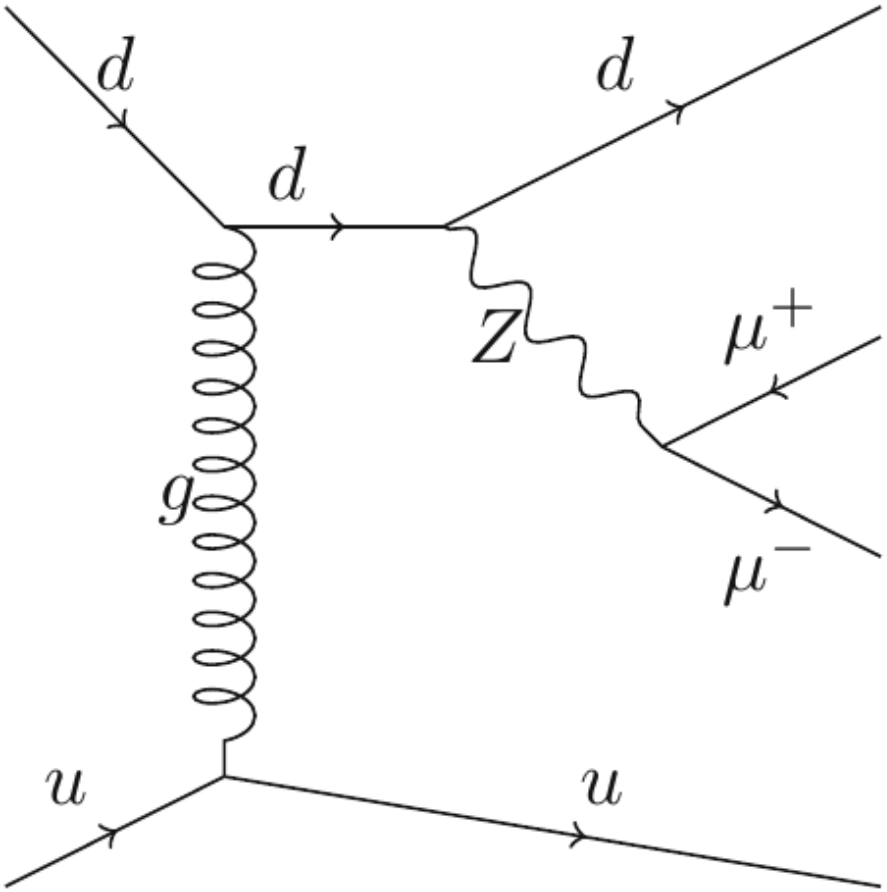


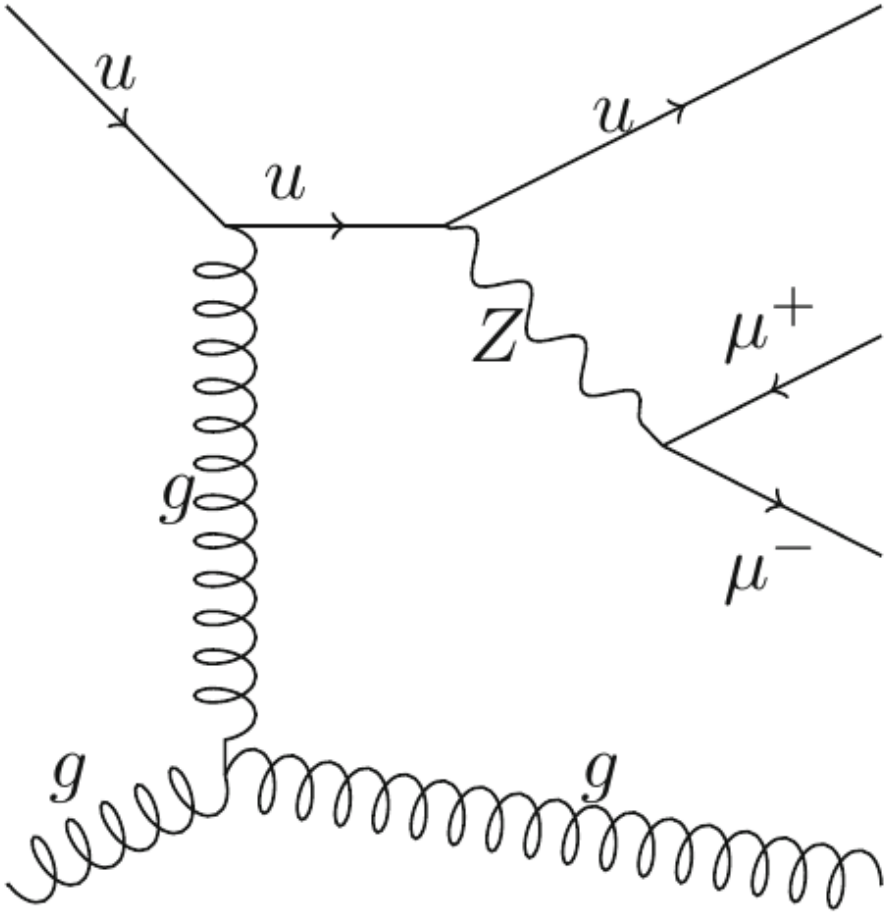


NLO/NLO

Z(W) + 2jets + X

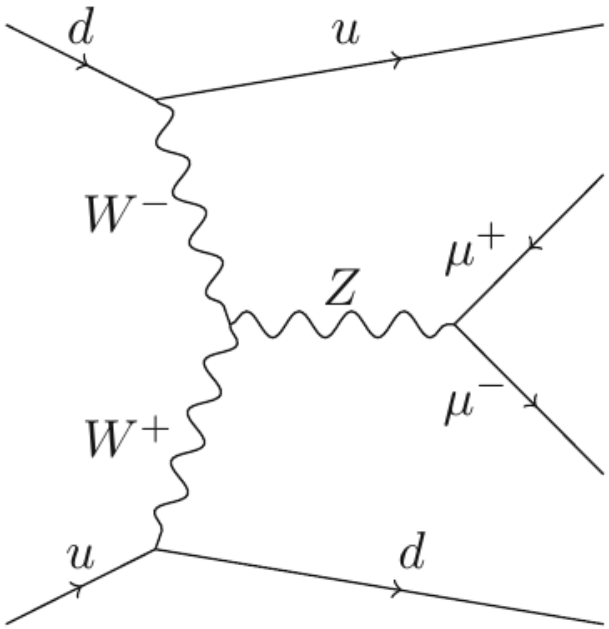
Examples of order α_s^2 corrections to Drell-Yan $pp \to l^+l^-$



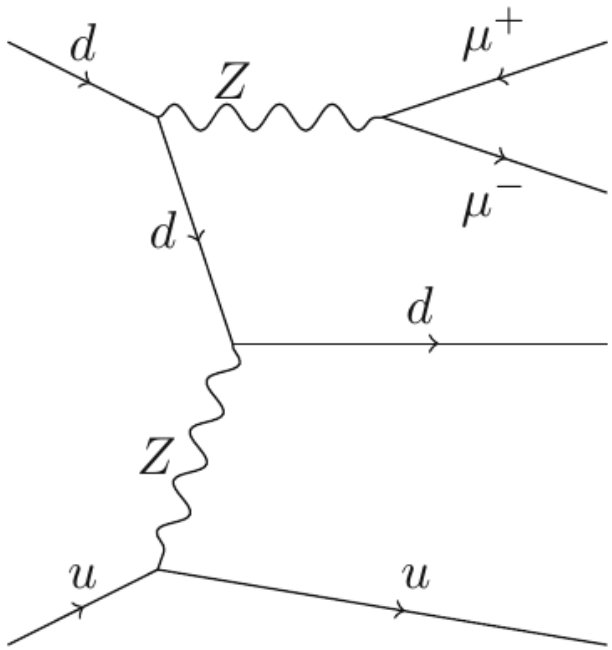


Z(W) + 2jets + X

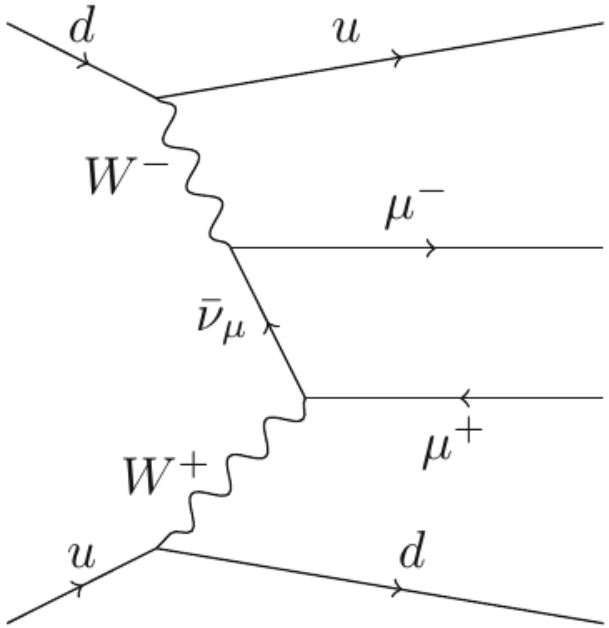
Electroweak production of Z + 2jets



Vector Boson Fusion (VBF)



bremsstrahlung-like



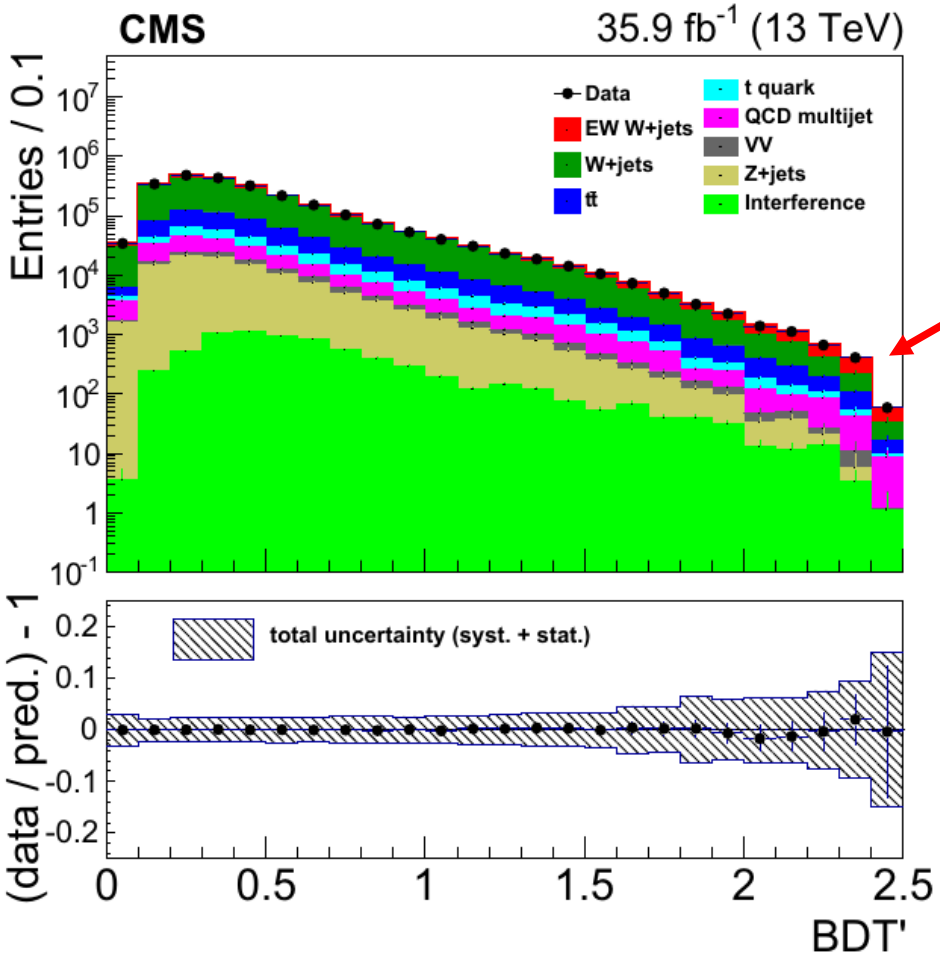
multiperipheral

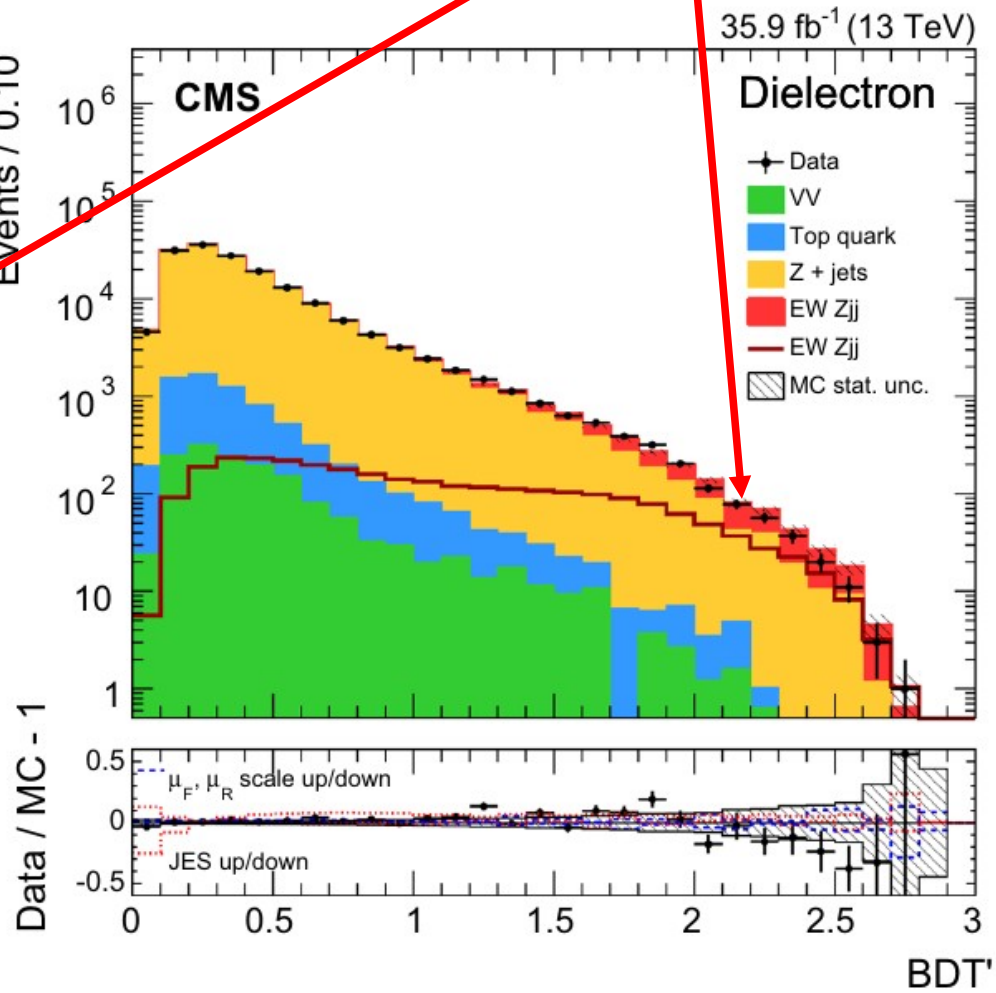
Characteristic: Two high-pT tagging jets with large Δy

Z/W + 2jets EWK

Requires advanced techniques (Boosted Decision Trees) to find small signal

Allows search for anomalous triple gauge couplings





CMS, Eur. Phys. J. C78 (2020) 589.

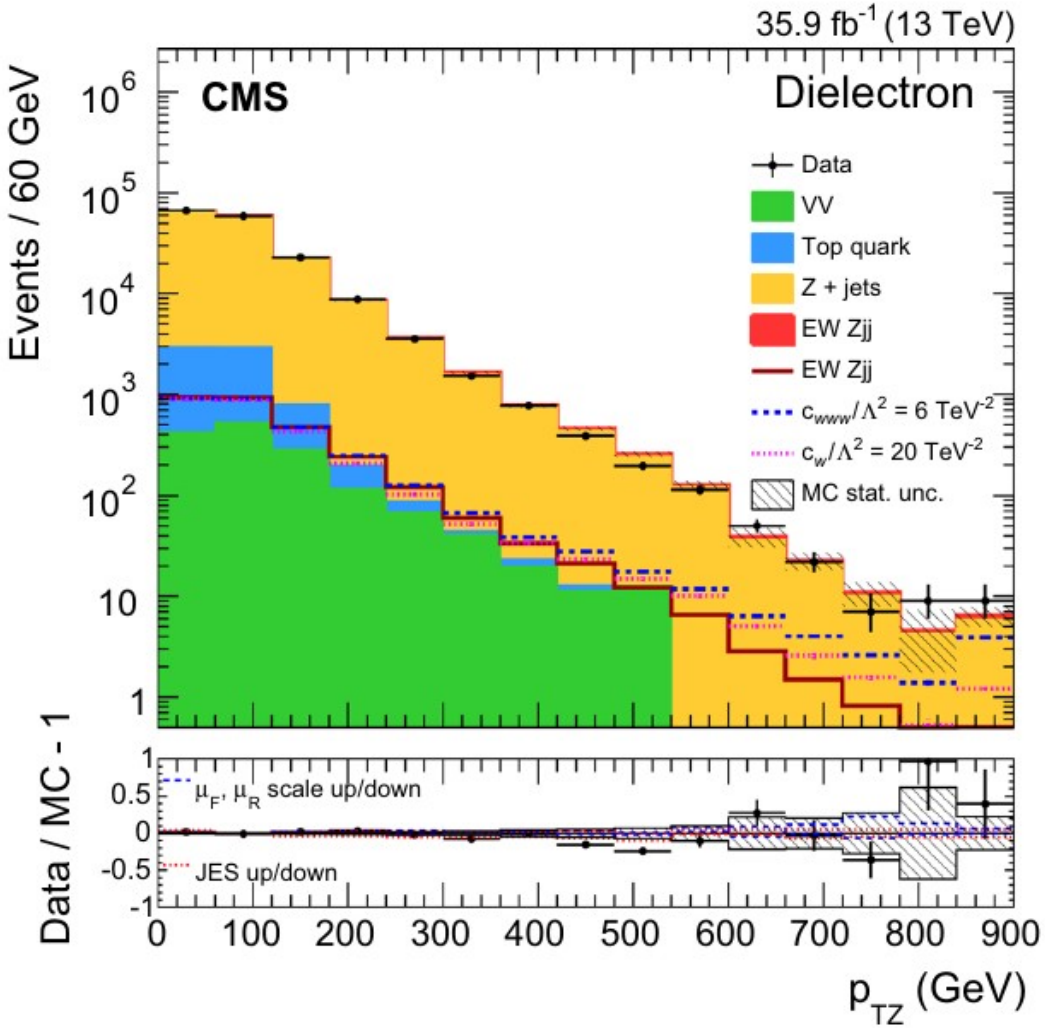
CMS, Eur. Phys. J. C80 (2018) 43.

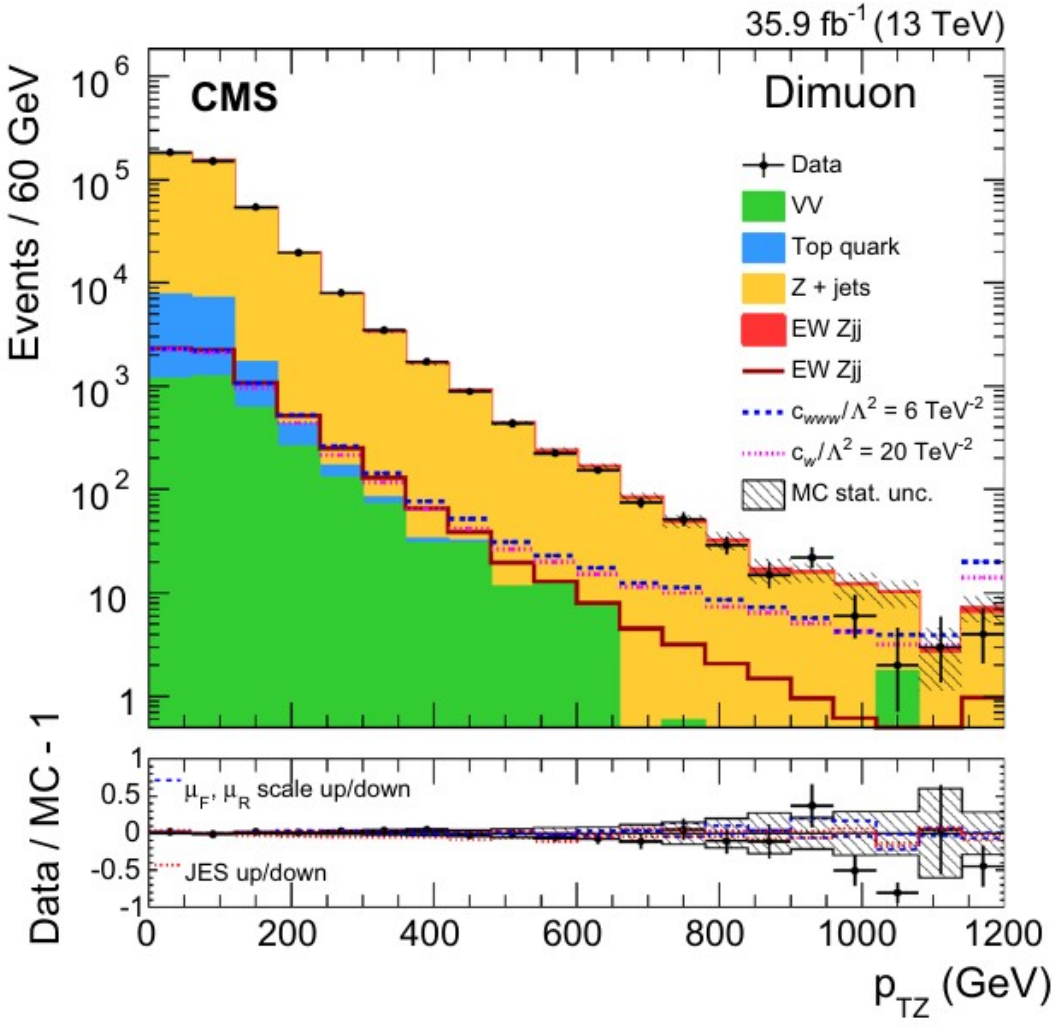
Signal compatibel with SM?

Signal strength:
ee & μμ combined

$$\mu = 0.98 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.98 \pm 0.11\,(\text{total}),$$

Compatibel with unity, i.e. the SM → set limits

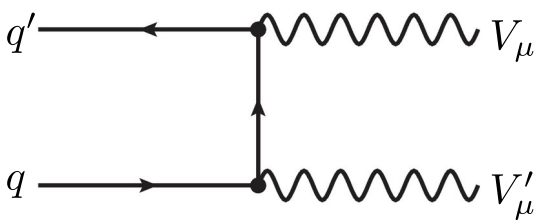




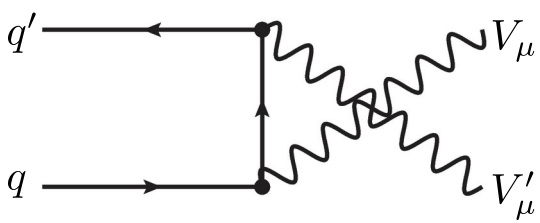
CMS, Eur. Phys. J. C80 (2018) 43.

Production of two V bosons

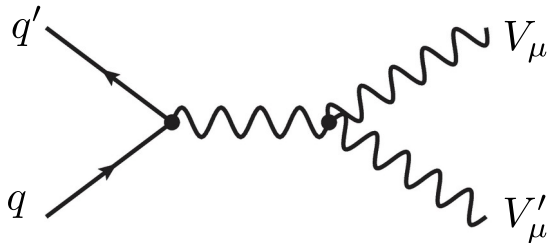
LO diagrams for production of two vector bosons



$V_\mu, V'_\mu = W_\mu, Z_\mu$



QGC

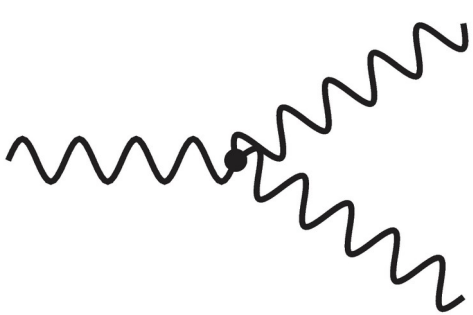


TGC

Important test of standard model

Triple gauge coupling not observable separately

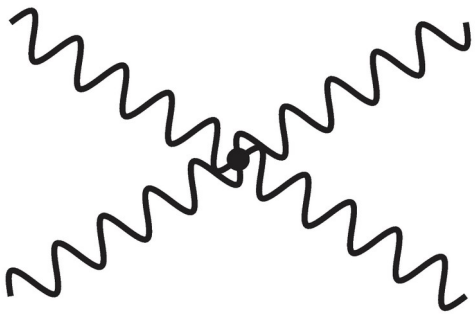
Which couplings are allowed?



$\gamma WW \quad ZZ\gamma$

$ZWW \quad Z\gamma\gamma$

ZZZ

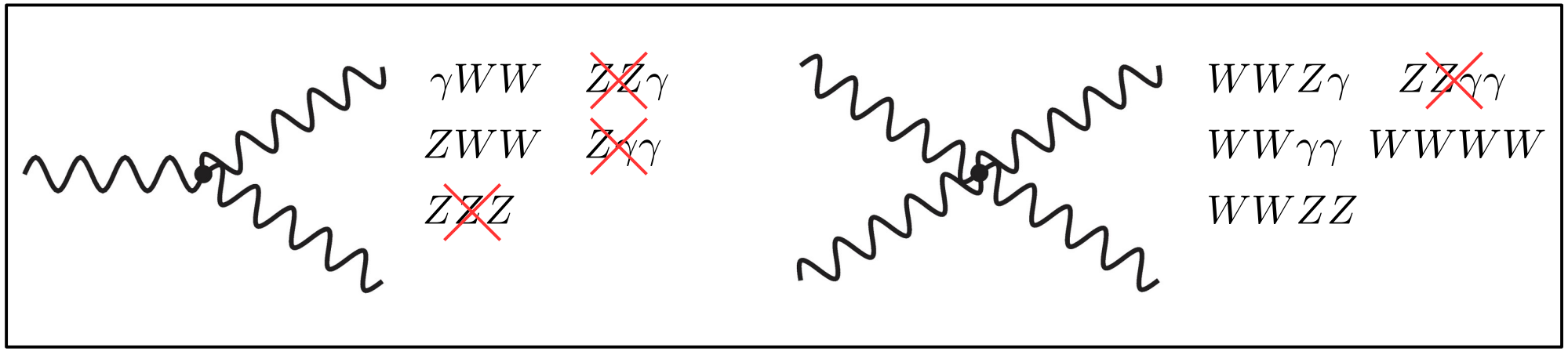


$WWZ\gamma \quad ZZ\gamma\gamma$

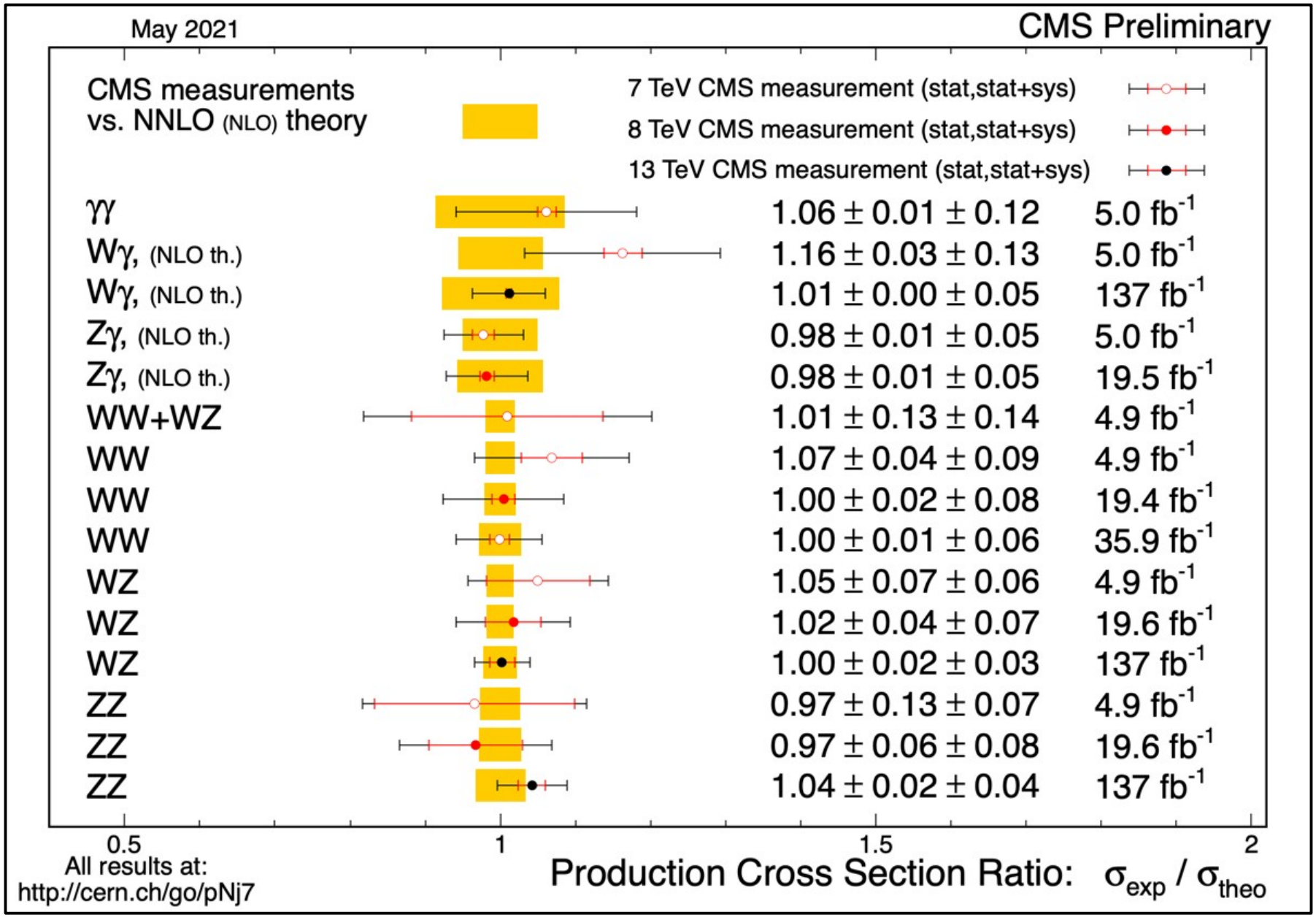
$WW\gamma\gamma \quad WWWW$

$WWZZ$

Which couplings are allowed?



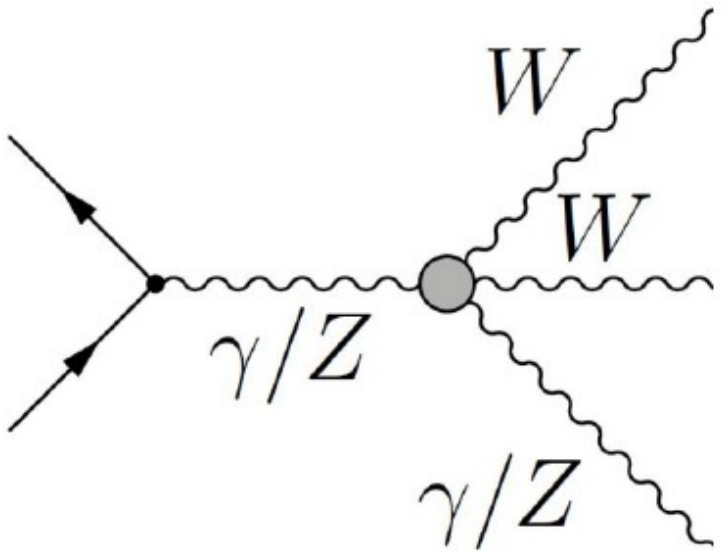
Production of two V bosons



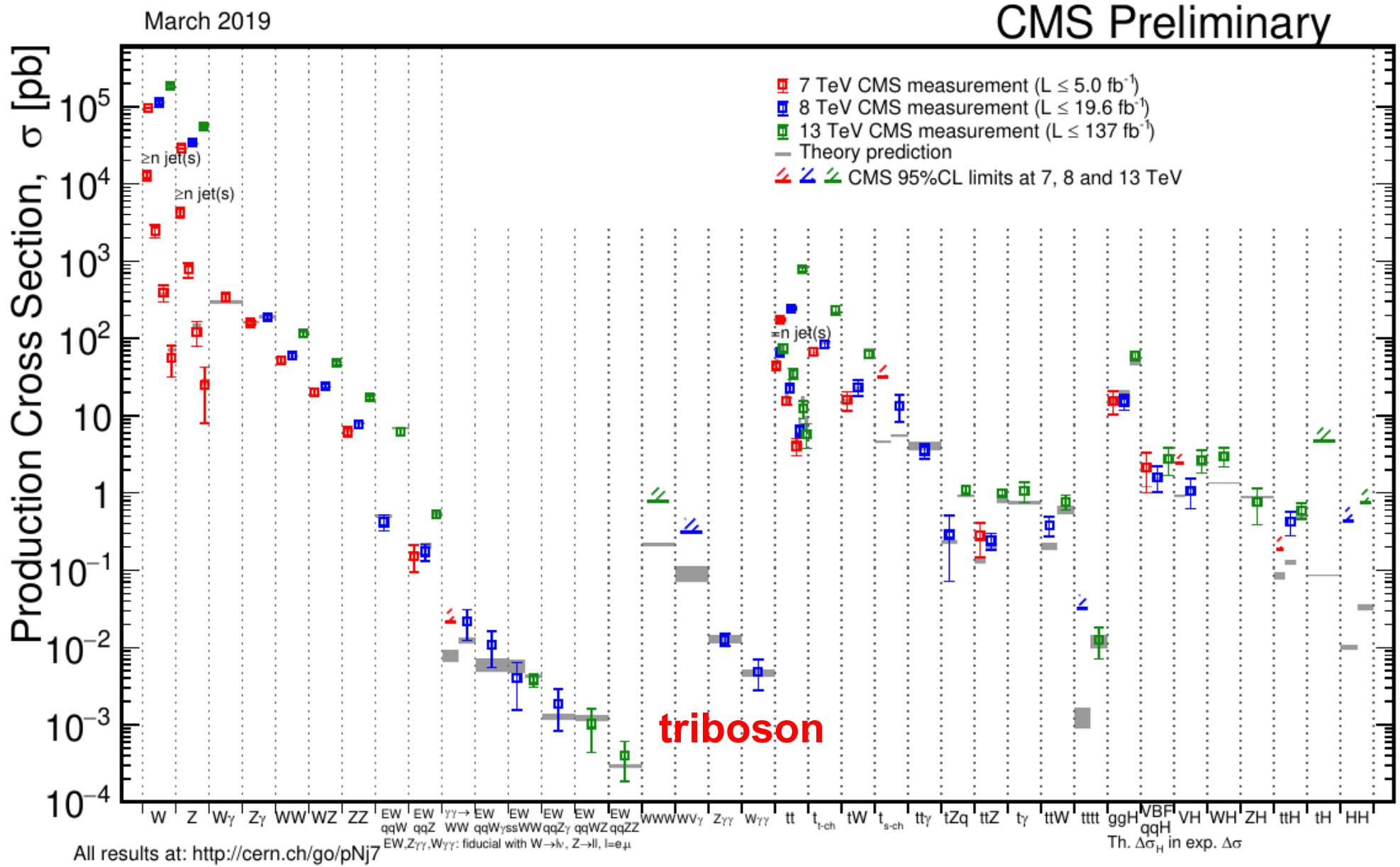
Triple boson production

- Mediated by **4-point V boson interaction vertex** (“quartic vertec”)
- In the Standard Model
  - WWWW
  - WWZZ
  - WWZγ
  - WW$\gamma\gamma$

  (4 neutral bosons forbidden)
- Problem: cross-section extremely small



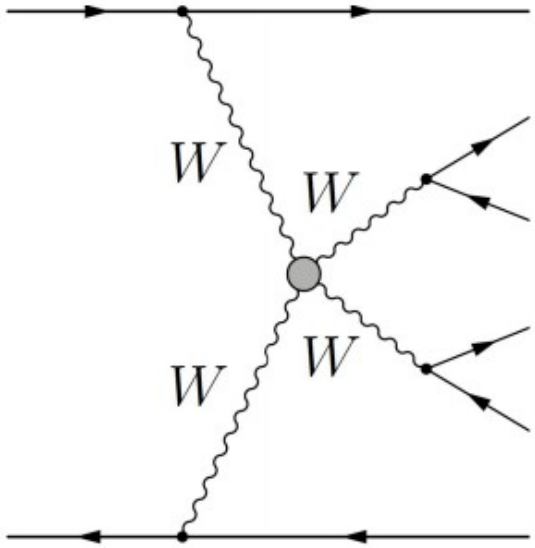
“Stairway to heaven” plot



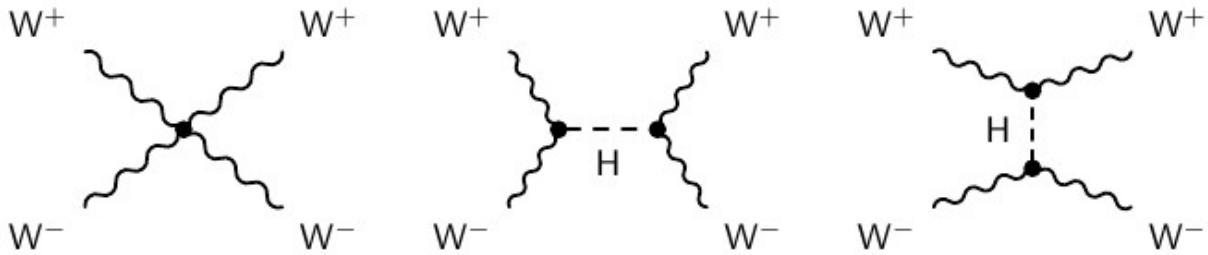
CMS TWiki

Vector boson scattering

- Study quartic vertex in V boson scattering (VBS)

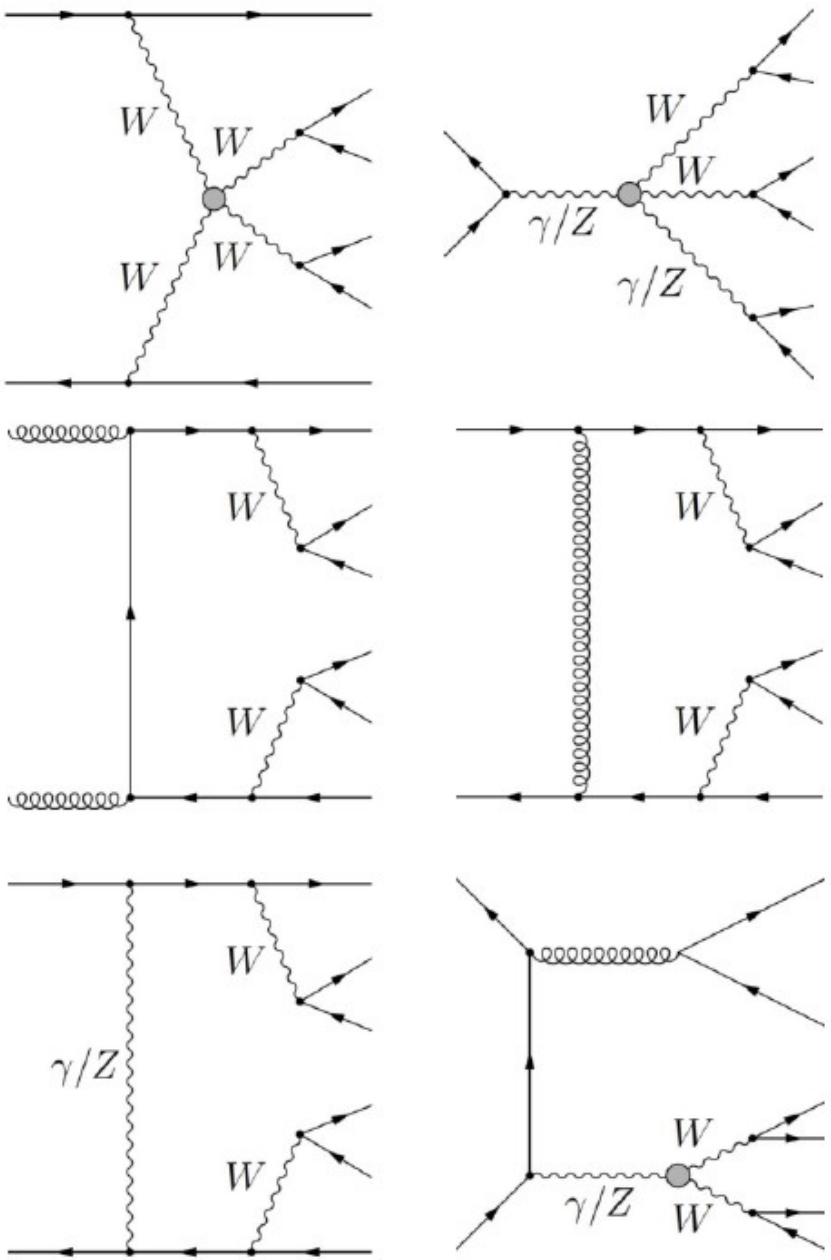


- Cross-section for longitudinally polarised states diverges at high energies: in SM cancelled by negative interference with Higgs diagrams



Vector boson scattering

- 2 W + 2 jets processes common
  - **Jets typically forward**
- Event selection: 2 jets with
  - **high dijet mass**
  - **large rapidity difference**
- Study $W^{\pm}W^{\pm}$
  - No gluon-induced initial states
  - Largely reduced backgrounds



Observation of VBS

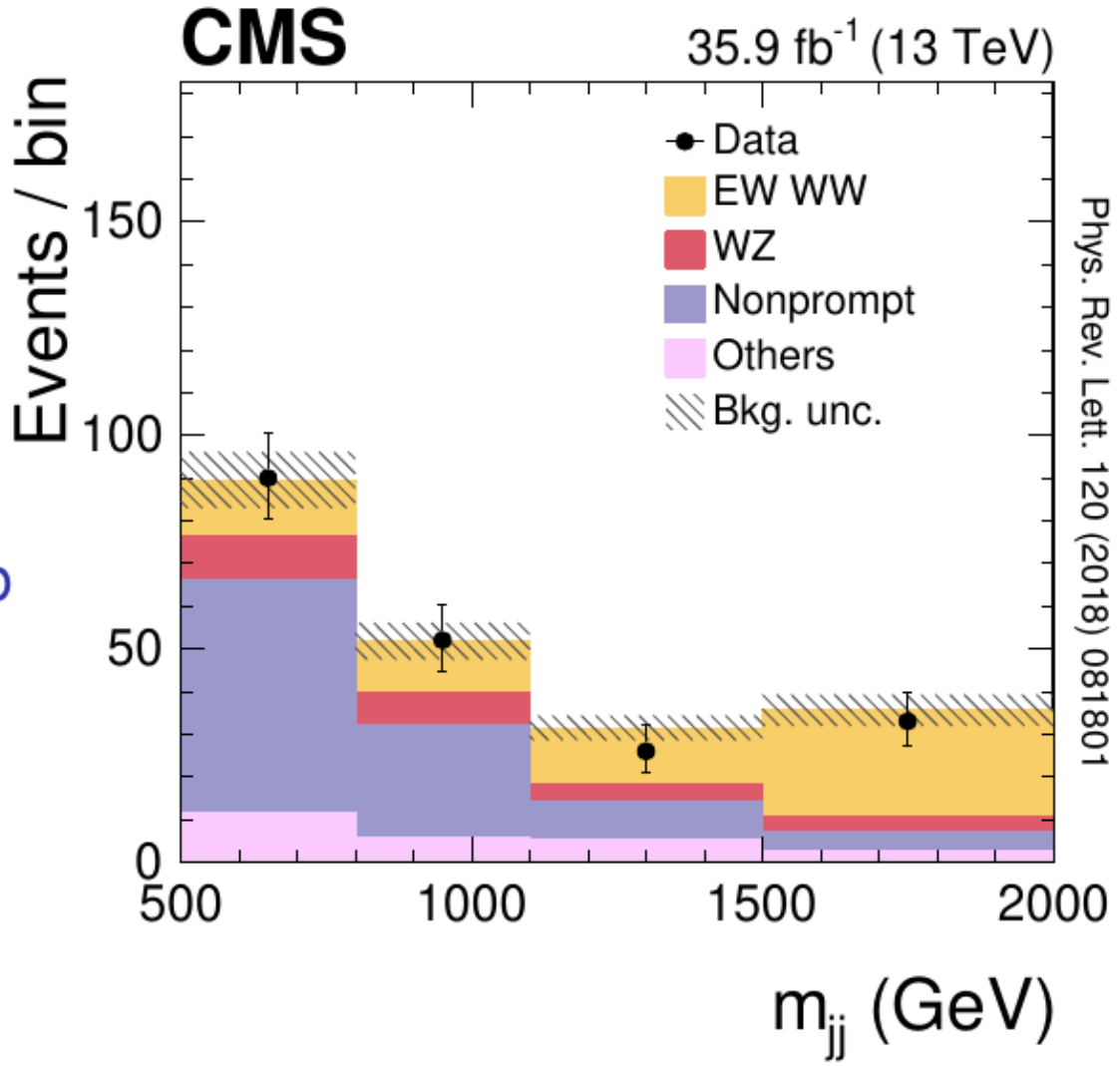
- First **observation in 2017**
  - EWK contribution detected at $5\,\sigma$ significance

$$\sigma(pp \to W^{\pm}W^{\pm}) = 3.83 \pm 0.66\,(stat) \pm 0.35\,(syst)\,fb$$

(SM prediction: 4.25 ± 0.2 fb)

- New evidence also in ZZ channel

[Phys. Lett. B774 (2017) 682]



Finish of W & Z

With this rare process I close my discussion of W & Z;

the remaining lectures are on Higgs.

A few slides with reminders on literature search ...

Publications in Particle Physics

Where to find publications in particle physics?

For example the Higgs discovery with CMS:

Chatrchyan, S. & others, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", Phys. Lett. B 2012, 716, 30.

- **If you're lucky there is also a Digital Object Identifier (DOI):**
  10.1016/j.physletb.2012.08.021 → type into mask at https://dx.doi.org/ → journal publication
  - **Access might be restricted**
  - **But not for LHC publications thanks to SCOAP³ Open Access initiative**
- **Frequently there are also pre-print versions of peer-reviewed articles:**
  arXiv:1207.7235 → type into mask at https://arxiv.org/ → version before peer-review
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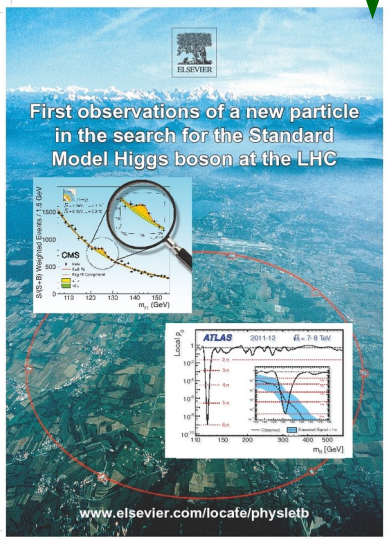
- **THE search engine for HEP:**

  https://inspirehep.net/



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High Energy Physics - Experiment

[Submitted on 31 Jul 2012 (v1), last revised 28 Jan 2013 (this version, v2)]

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at sqrt(s) = 7 and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 inverse femtobarns at 7 TeV and 5.3 inverse femtobarns at 8 TeV. The search is performed in five decay modes: gamma gamma, ZZ, WW, tau tau, and b b-bar. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, gamma gamma and ZZ; a fit to these signals gives a mass of 125.3 +/- 0.4 (stat.) +/- 0.5 (syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Comments:	Submitted to Phys. Lett. B
Subjects:	**High Energy Physics - Experiment (hep-ex)**
Journal reference:	Phys. Lett. B 716 (2012) 30
DOI:	10.1016/j.physletb.2012.08.021
Report number:	CMS-HIG-12-028; CERN-PH-EP-2012-220
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	(or arXiv:1207.7235v2 **[hep-ex]** for this version)

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[v1] Tue, 31 Jul 2012 13:27:18 UTC (2,076 KB)

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Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC #1

CMS Collaboration • Serguei Chatrchyan (Yerevan Phys. Inst.) et al. (Jul 31, 2012)

Published in: *Phys.Lett.B* 716 (2012) 30-61 • e-Print: 1207.7235 [hep-ex]

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The Black Book of Quantum Chromodynamics

a Primer for the LHC Era

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Author(s)
Campbell, John
Huston, Joey
Krauss, Frank

The LHC (Large Hadron Collider) will serve as the energy frontier for high-energy physics for the next 20 years. The highlight of the LHC running so far has been the discovery of the Higgs boson, but the LHC programme has also consisted of the measurement of a myriad of other Standard Model processes, as well as searches for Beyond-the-Standard-Model physics, and the discrimination between possible new physics signatures and their Standard Model backgrounds. Essentially all of the physics processes at the LHC depend on quantum chromodynamics, or QCD, in the production, or in the decay stages, or in both. This book has been written as an advanced primer for physics at the LHC, providing a pedagogical guide for the calculation of QCD and Standard Model predictions, using state-of-the-art theoretical frameworks. The predictions are compared to both the legacy data from the Tevatron, as well as the data obtained thus far from the LHC, with intuitive connections between data and theory supplied where possible. The book is written at a level suitable for advanced graduate students, and thus could be used in a graduate course, but is also intended for every physicist interested in physics at the LHC.

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Keywords
LHC, Tevatron, QCD, Standard Model, Higgs boson, W/Z bosons, jets, parton showers, resummation, parton distribution functions

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