Experimental Summary

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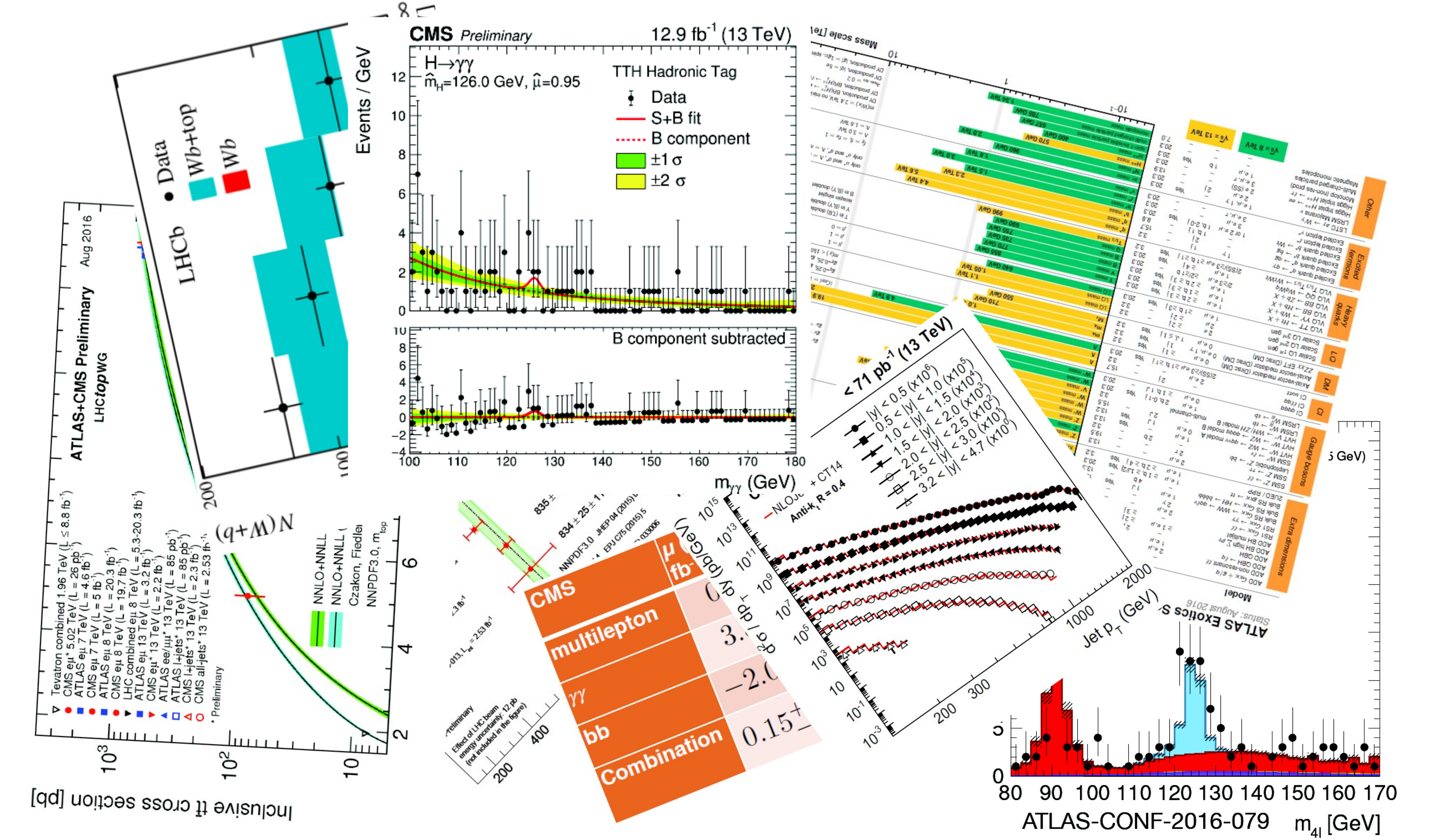
Karlsruhe Institute of Technology

Start with blank Sheet ...

coming from there to ...

here. So despite beautiful Weather ...

try to check all presented Results



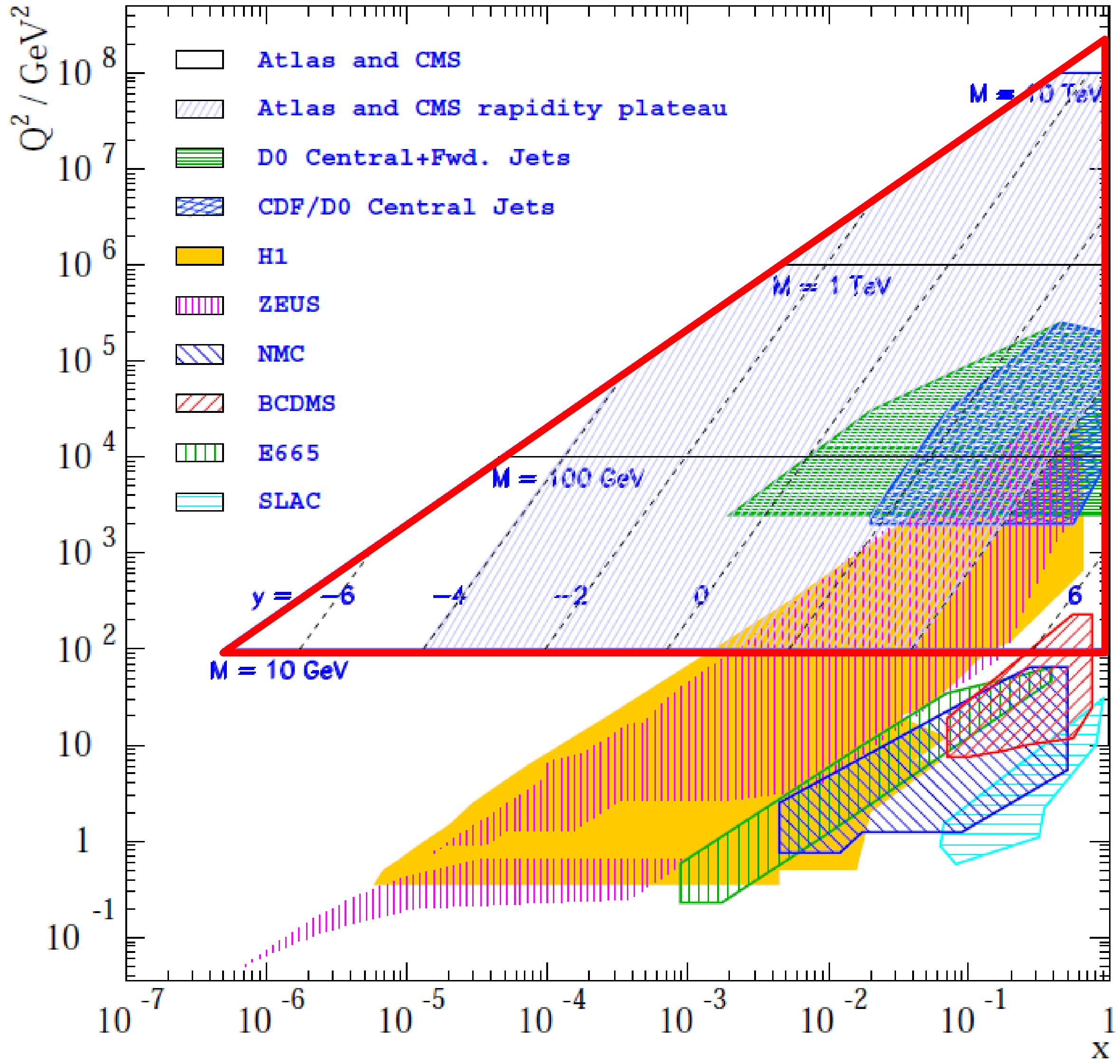
QCD at the LHC

My QCD advertisement slide

- **Fascinating –**
  comprises a huge variety of phenomena
- **Unavoidable –**
  hadrons are “made of QCD”
- **Indispensable –**
  linking piece between many processes
- **Demanding –**
  enormous background to searches for new physics
- **Uncharted –**
  dominating uncertainty for Higgs cross sections

➡ **Many analyses :-)**

Huge accessible phase space



S. Glazov, Braz.J.Ph. 37 (2007) 793.

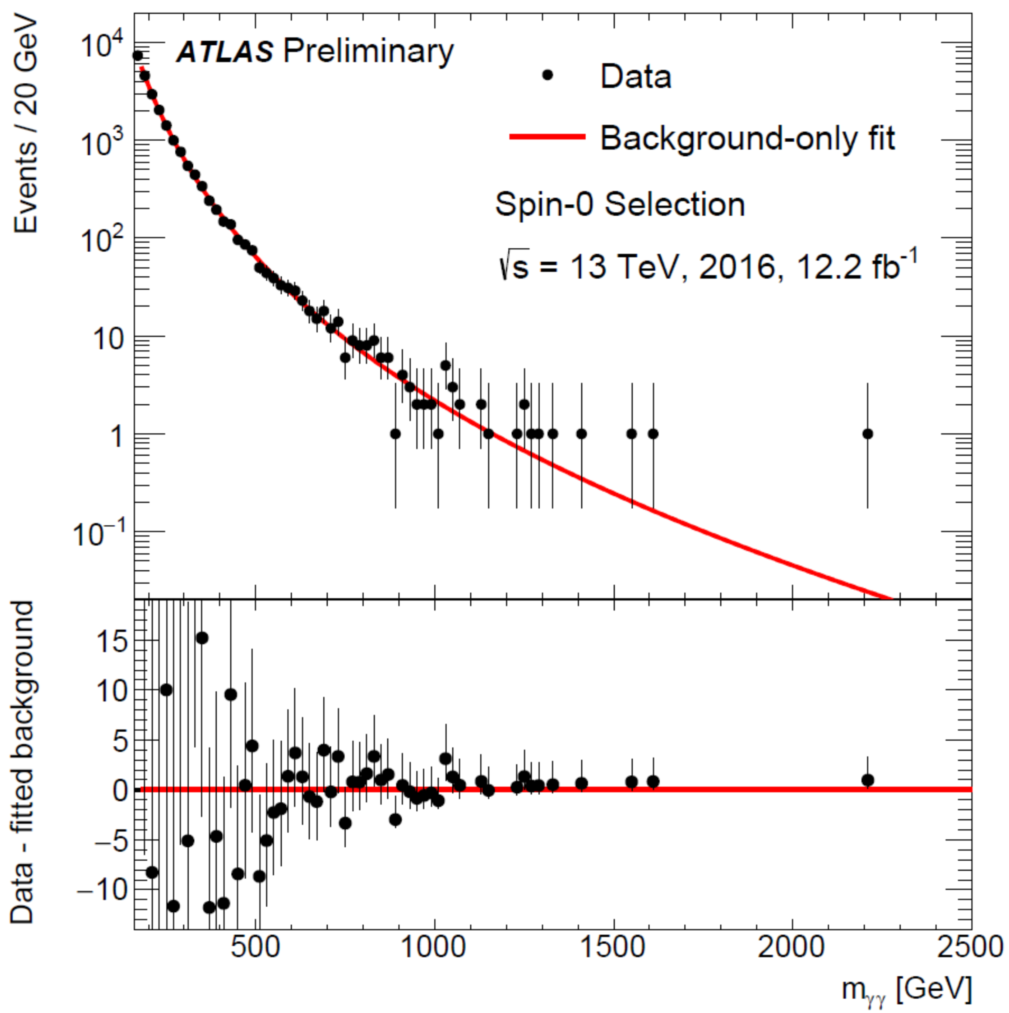
Selection Mandatory

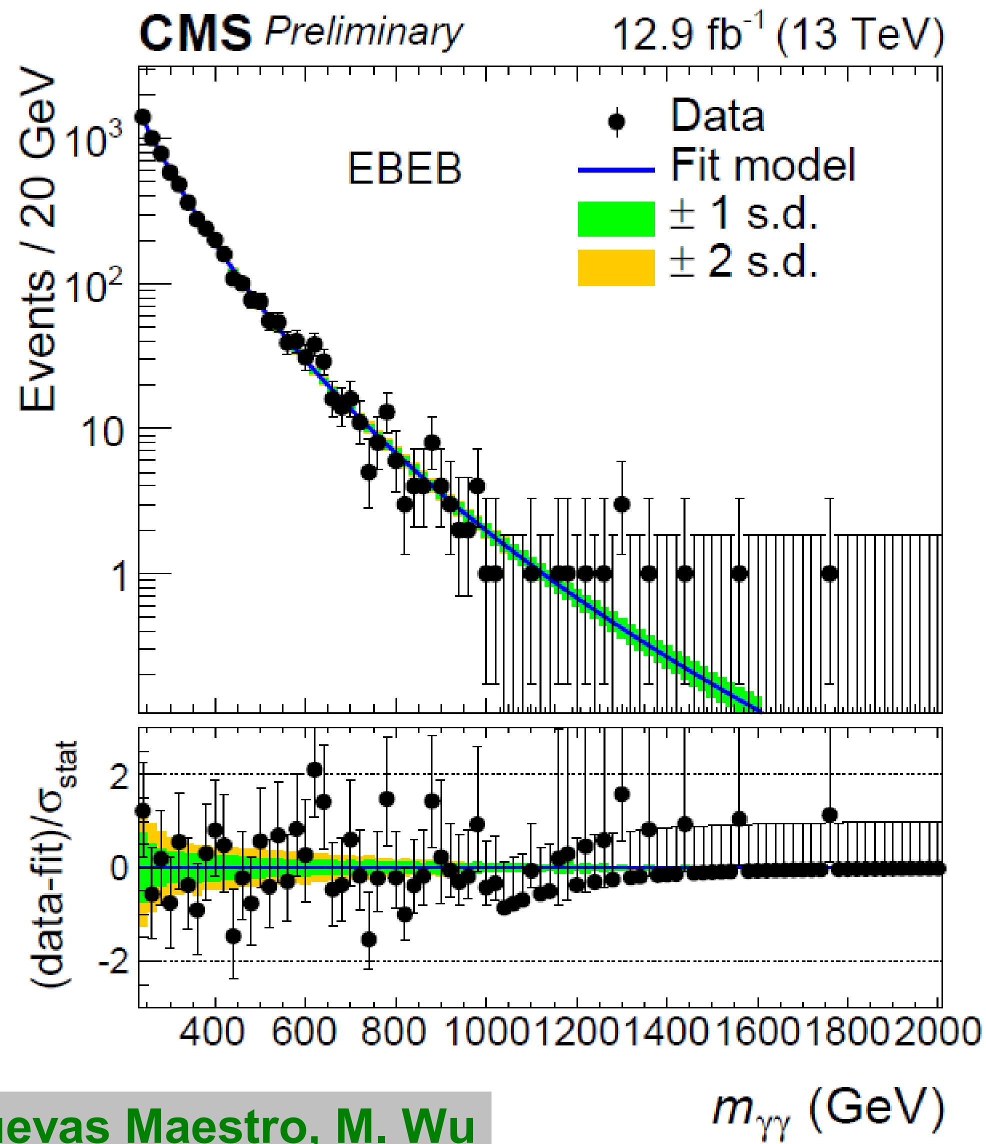
- **Disclaimer:**
  - **Impossible to cover all the nice measurements**
  - **Personal and biased selection from roughly 45 experimental Talks in the five subgroups**
  - **Some results appear multiple times, e.g. when used for PDFs and in the summary plenaries**
  - **Prioritized newer/13 TeV results**
  - **Apologies for omissions :-(**

750 GeV Excess "flatlined"

Diphoton mass spectrum re-measured in 2016

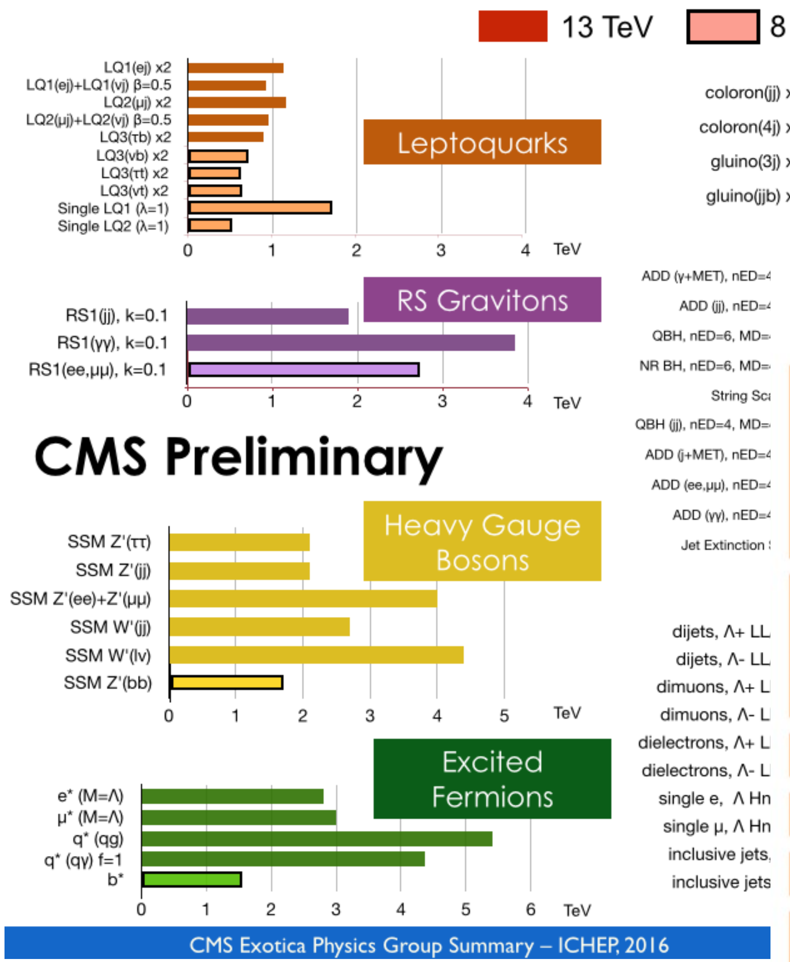
Much discussed anomaly not confirmed with 4 times more data than in 2015



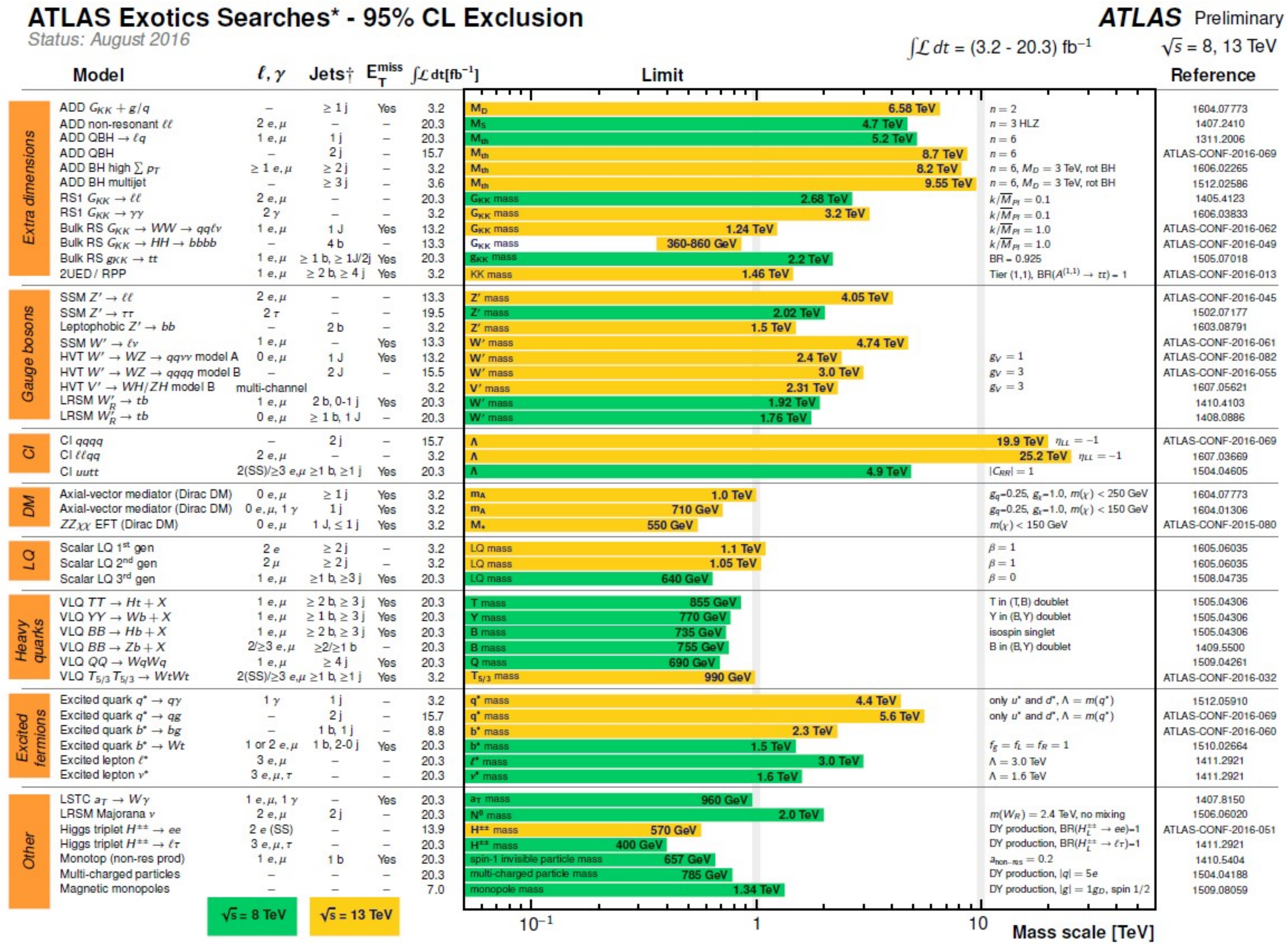


J. Cuevas Maestro, M. Wu

Updated Exclusion Limits

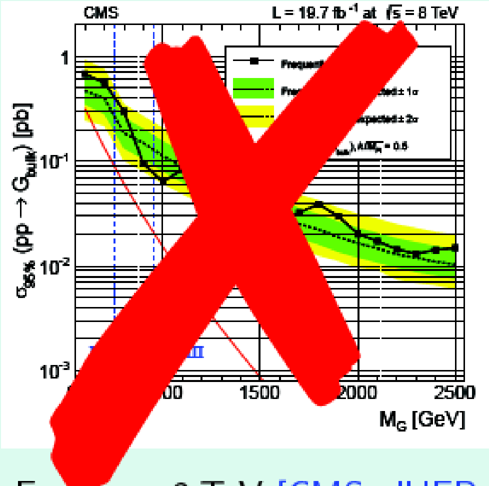


Exotica Searches from ATLAS & CMS
Similar for SUSY

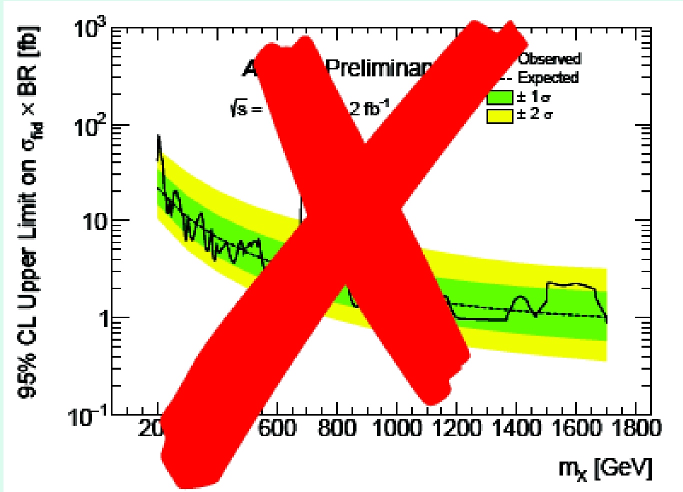


No Hint towards new Physics at the Horizon :-(

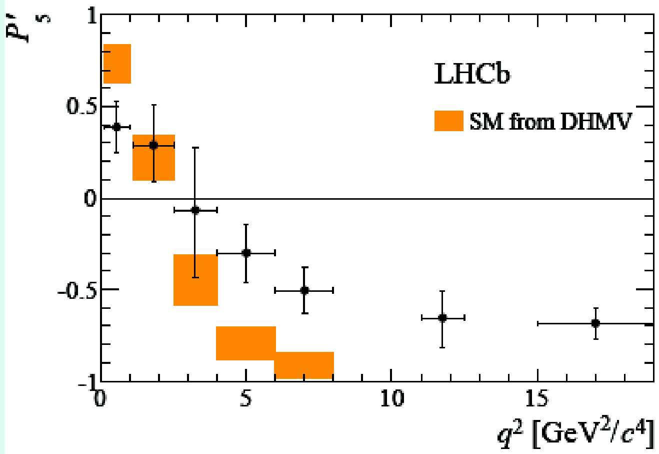
Smoking Gun in Flavor Physics?



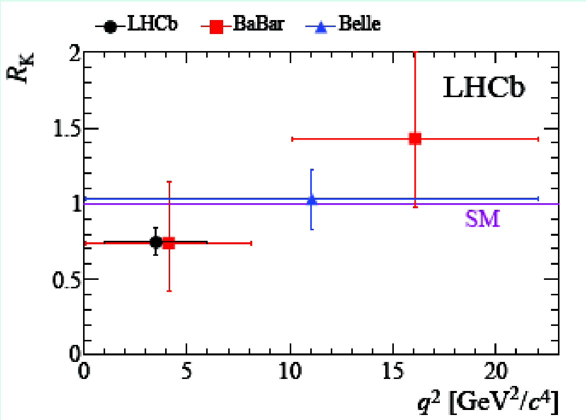
Excess at 2 TeV [CMS, JHEP 08 (2014) 174]



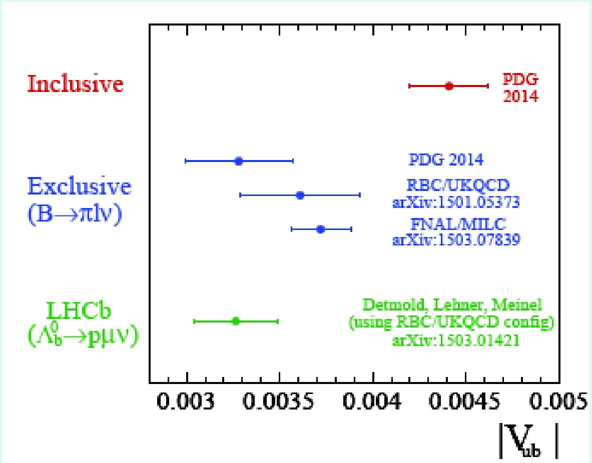
Excess at 750 GeV [ATLAS-CONF-2015-081]



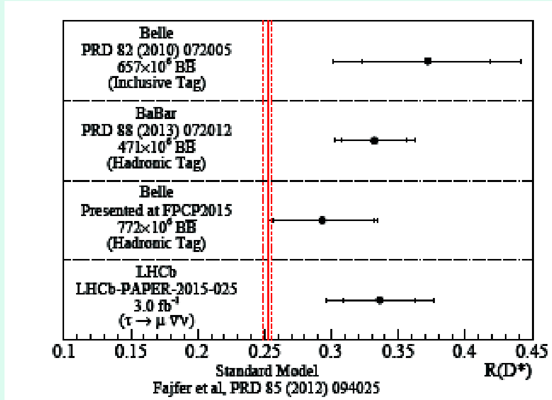
P'_5 in $B \to K^* \mu^+ \mu^-$ [JHEP 02 (2016) 104]



Lepton universality [PRL 113 (2014) 151601]



V_{ub} puzzle [Nature Physics 11 (2015) 743]



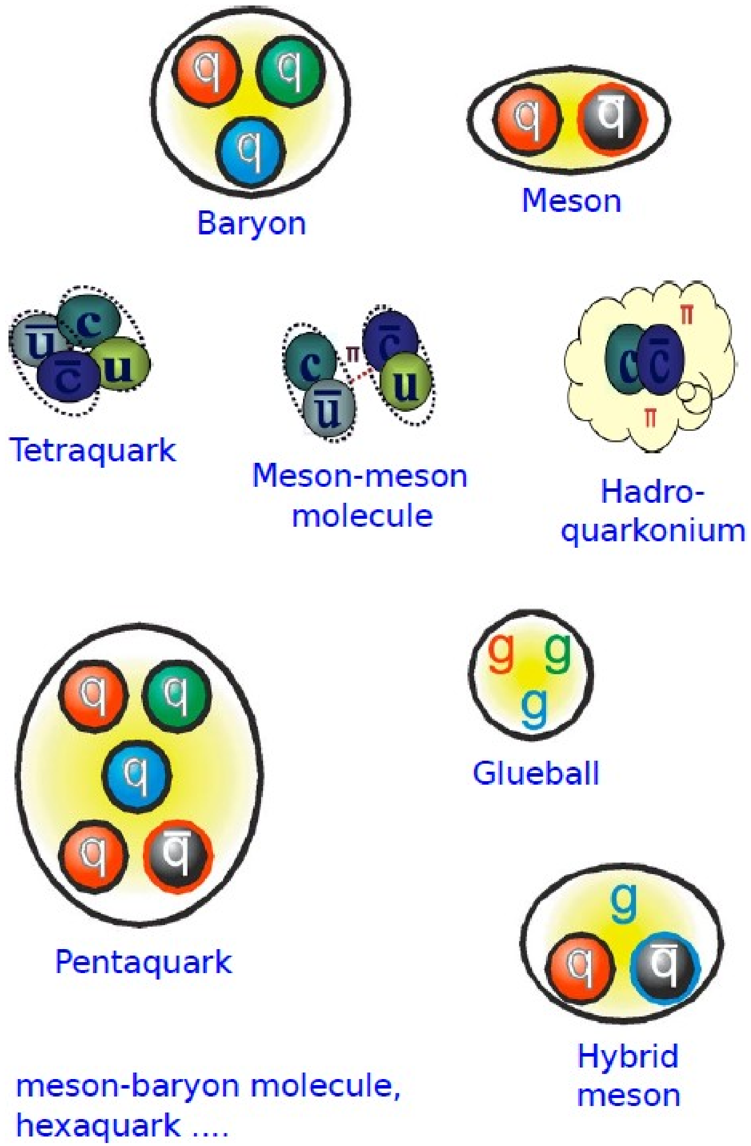
$B \to D^* \tau \nu$ [PRD 92 (2015) 011102(R)]

P. Koppenburg

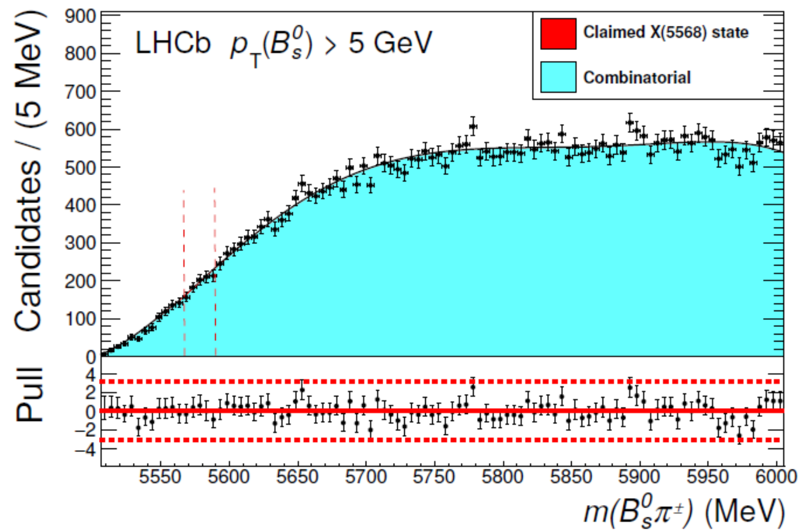
There's a handful of intriguing 3–4σ anomalies

Exotic (anti-)Quark Compounds

G. Cavallero



No confirmation for Tetraquark $B_s^0\pi$, X(5568) state of D0



4 J/ψΦ structures observed confirming X(4140) reported by CDF

State	M_0 [MeV]	Γ_0 [MeV]	J^{PC}
$X(4140)$ @ 8.4 σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{21}_{-14}$	1^{++} @ 5.7 σ

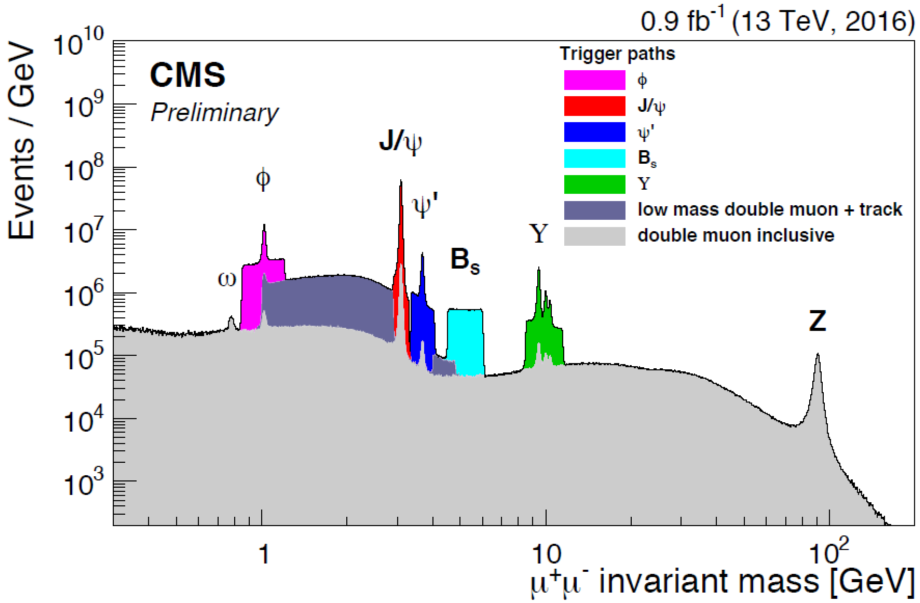
LHCb Pentaquark Candidates (uudccbar)

State	M_0 [MeV]	Γ_0 [MeV]	J^P
$P_c(4380)^+$ @ 9 σ	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$\frac{3}{2}^-$ $(\frac{3}{2}^+, \frac{5}{2}^+)$
$P_c(4450)^+$ @ 12 σ	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$\frac{5}{2}^+$ $(\frac{5}{2}^-, \frac{3}{2}^-)$

More LHCb results → D. Craik, C. Voss

D. Britzger: ZEUS pentaquark claim (uuddsbar) in pK^0_s not confirmed

Onium Production at 13 TeV

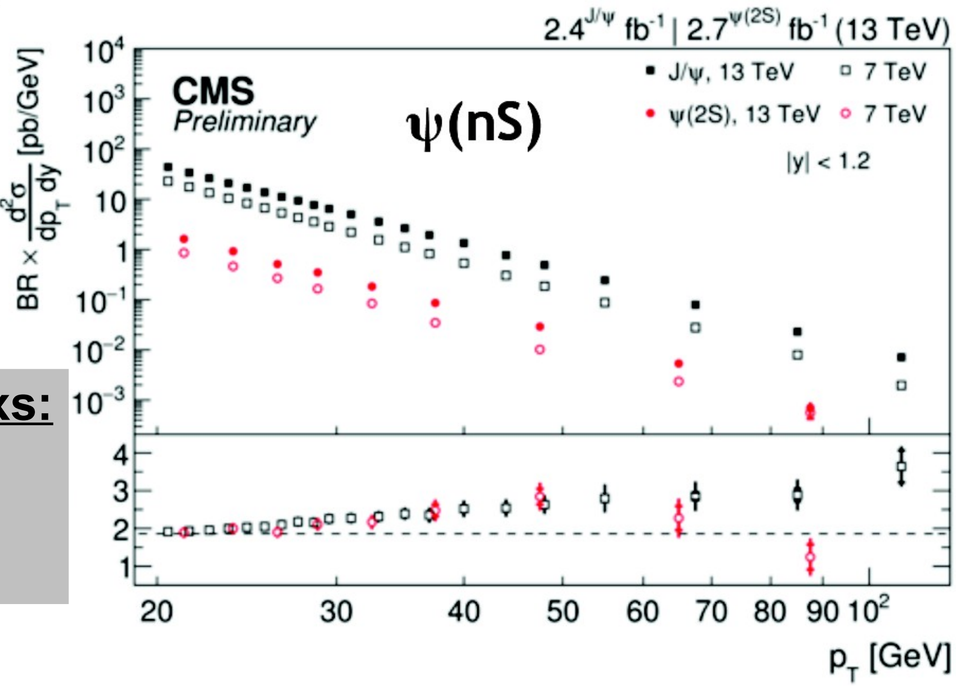


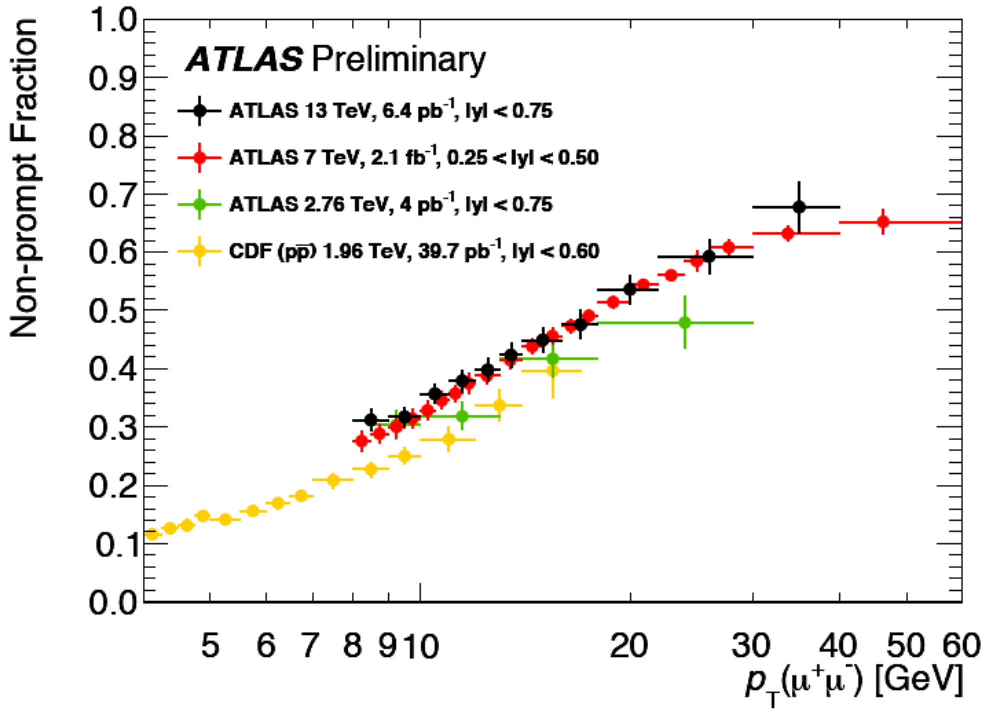
μ+μ- mass spectrum

I. Kratschmer, R. Jones

LHCb → R. Coutinho
J/Ψ and DPS → R. Bertsche, I. Belyaev

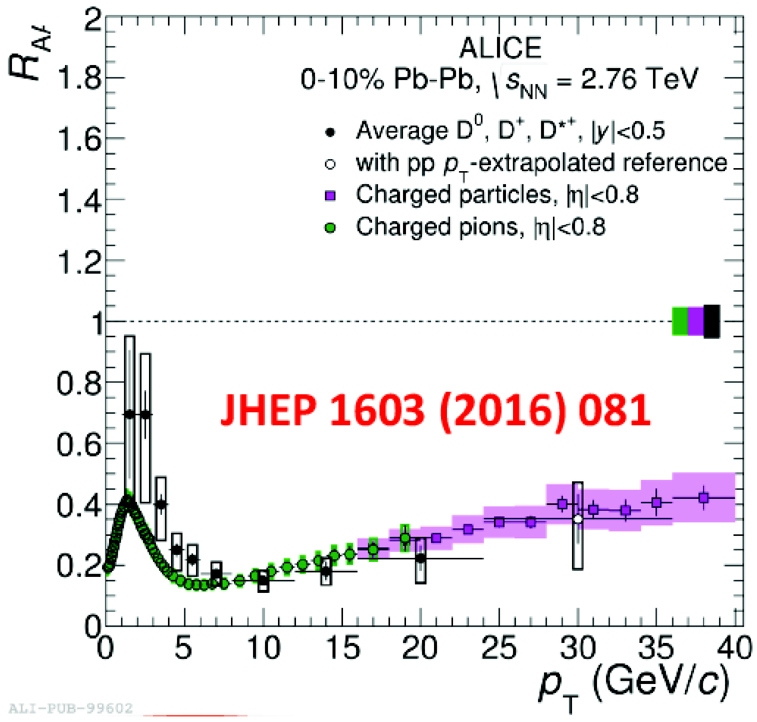
<u>J/Ψ non-prompt production fraction:</u>
- strong pT dependence
- no |y| dependence
- similar as at 7 TeV

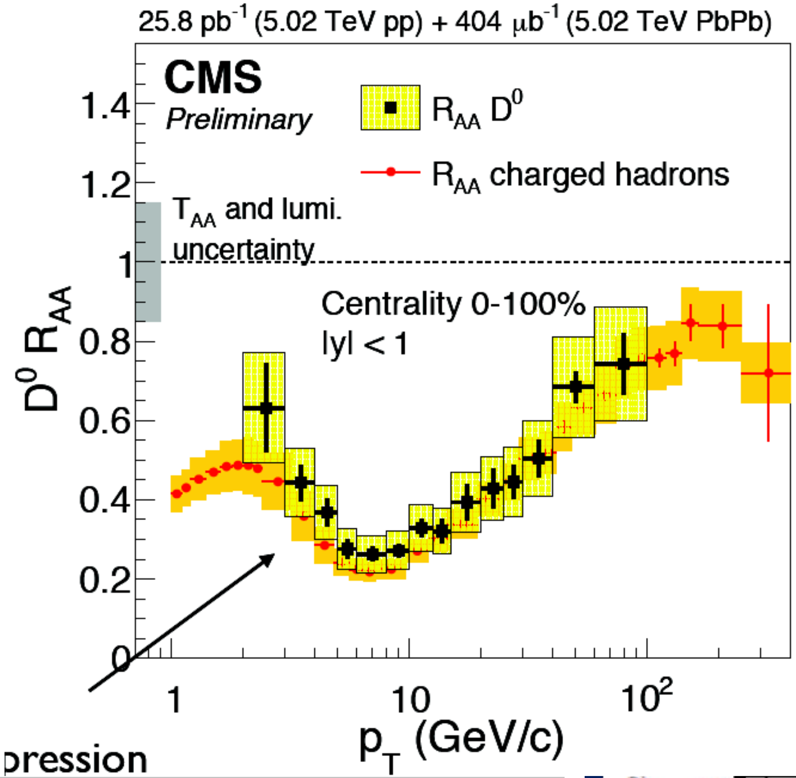




<u>J/Ψ 13/7 xs:</u>
2-3 times larger

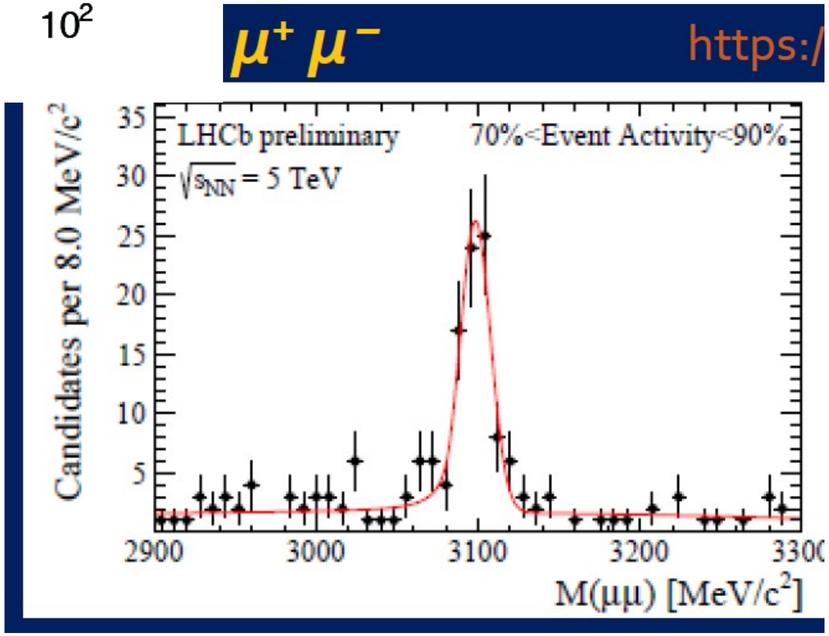
Heavy Ion Collisions





PbPb at 5.02 TeV

First participation of LHCb in HI running December 2015



ALICE & CMS:
Strong interaction of charm mesons with QGP
Nuclear suppression R_{AA} very similar between charm and light quarks

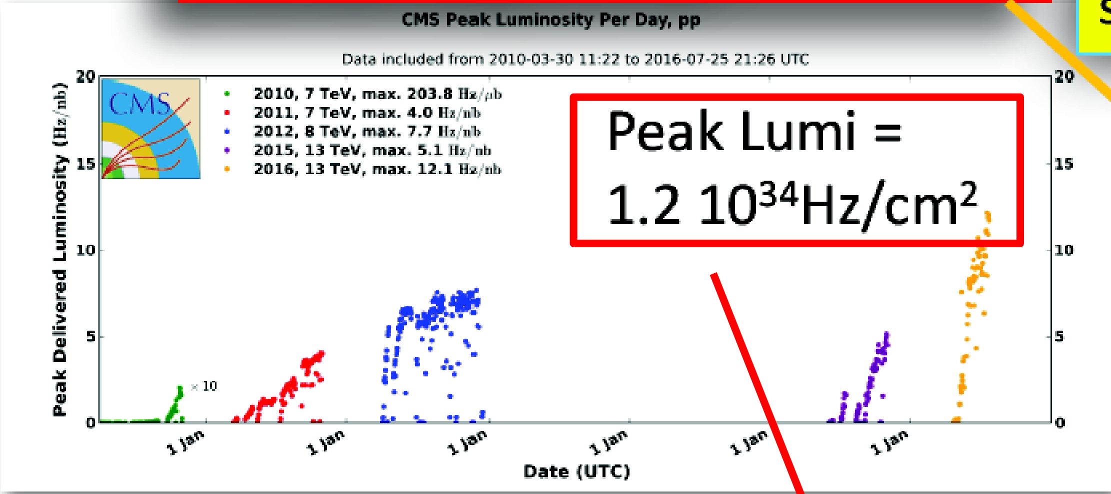
C. Jahnke, G. Innocenti, B. Schmidt

More HI results → E. Chapon

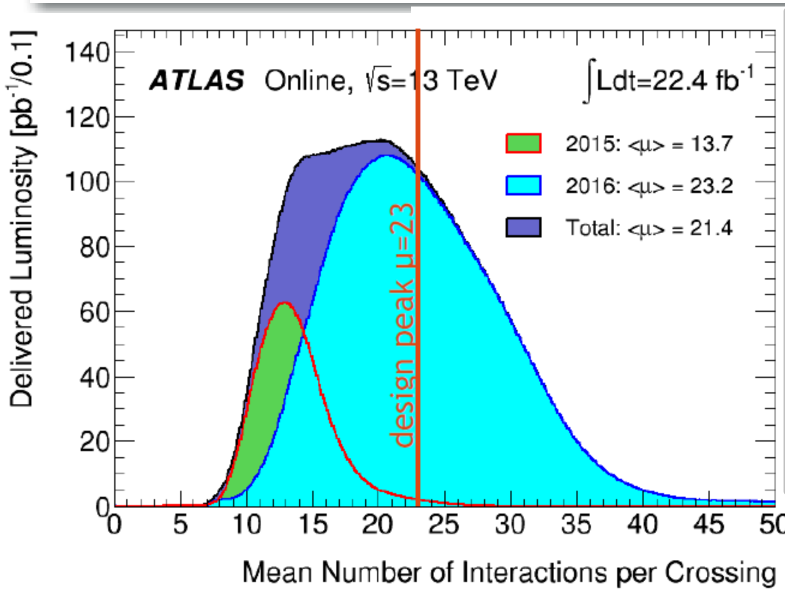
Excellent LHC Performance

Luminosity used for the results presented today 12.9 fb^{-1}

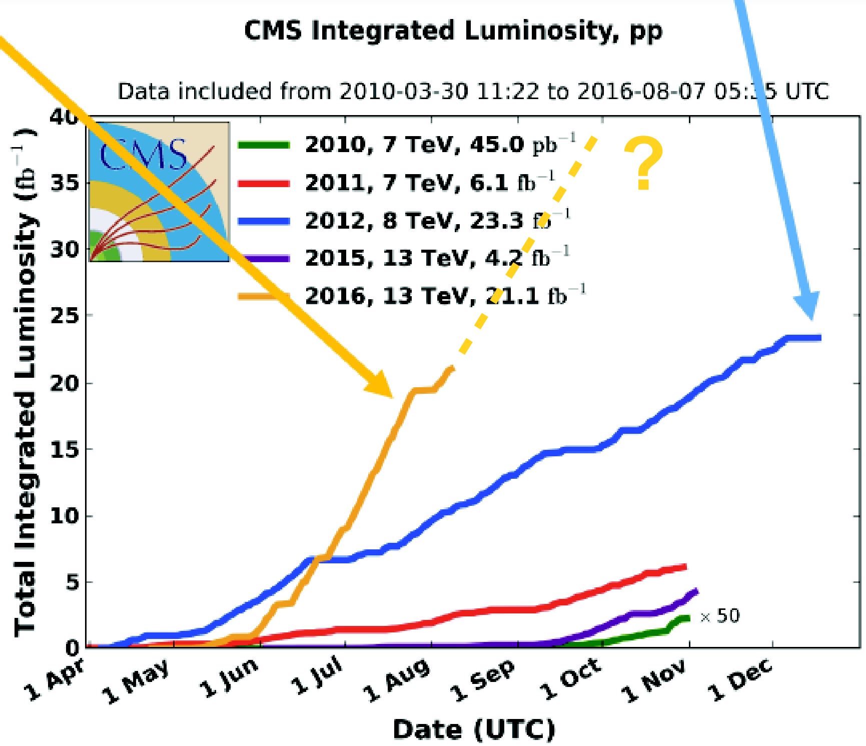
The estimate prior to the start of the 2016 campaign were to achieve something similar to the previous best (2012)



Peak Lumi = $1.2\ 10^{34} Hz/cm^2$



Beyond original design goals!

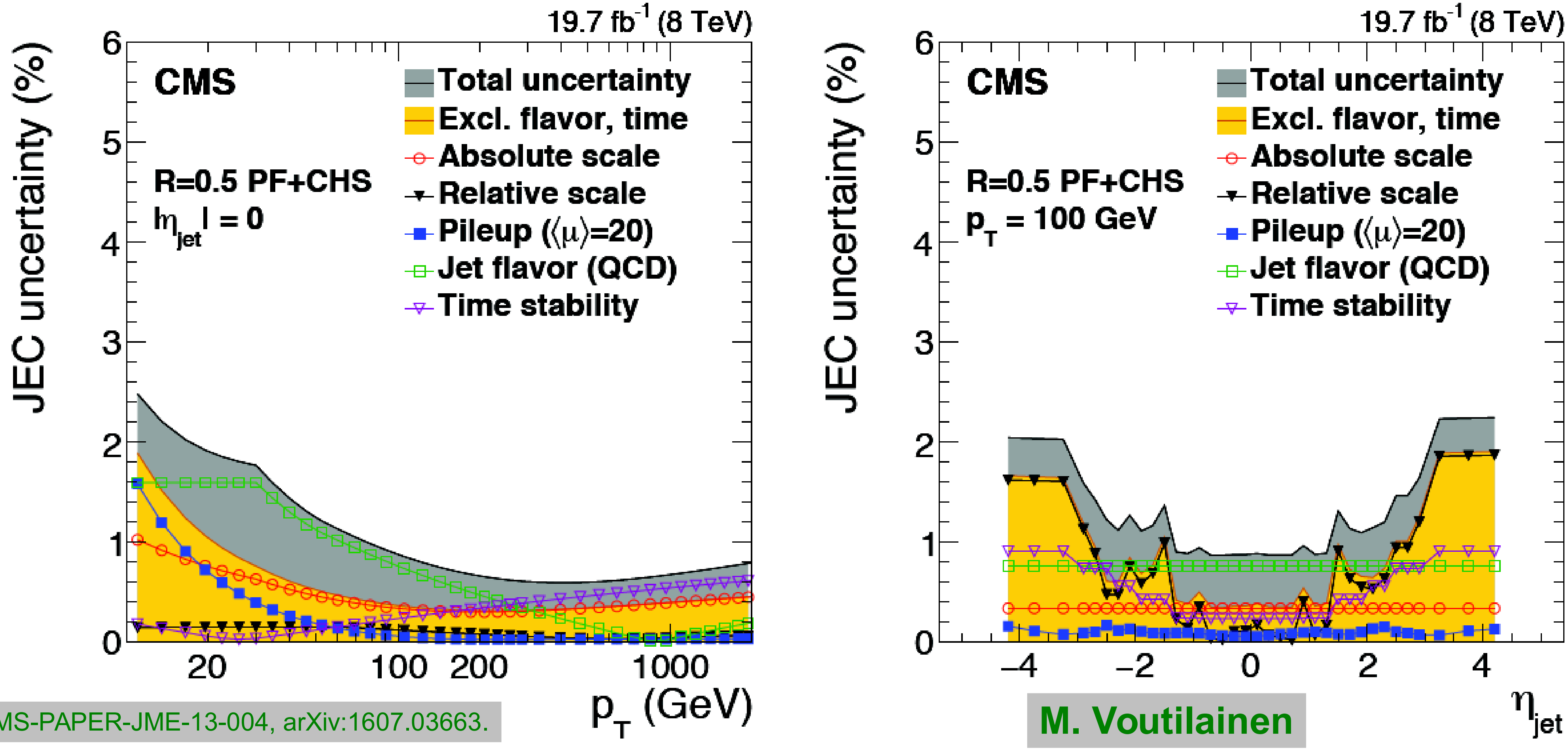


Pileup often above LHC design in 2016

Adapted from T. Camporesi & D. Charlton, ICHEP2016

CMS Run 1 Jet Energy Calibration

- Lowest uncertainty at y~0, p_T~200 GeV is **0.32%** (excluding flavor and time dependence)
- Well below 1% across much of the kinematic range
- For jet physics, the relevant uncertainty is golden band + green curve, "Jet flavor (QCD)"
  - this is entirely driven by MC-based uncertainty on gluon jet response



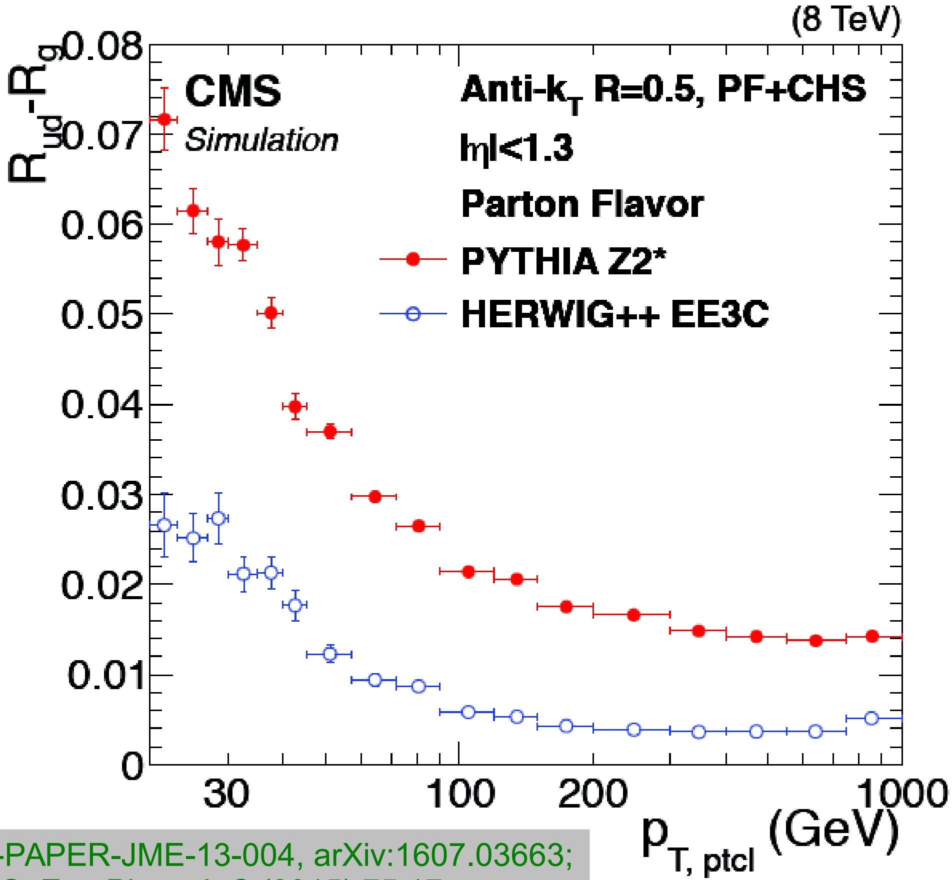
CMS-PAPER-JME-13-004, arXiv:1607.03663.

M. Voutilainen

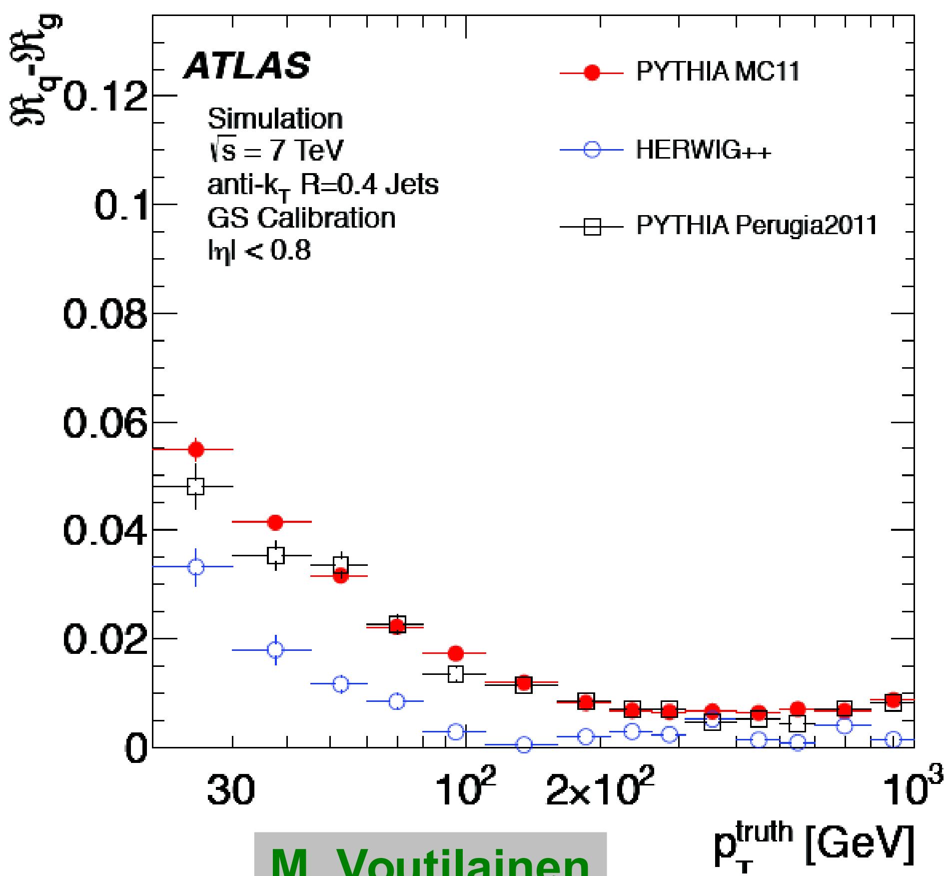
Gluon Jet Response from MC

Significant portion of JEC uncertainty common to ATLAS and CMS!

- "Jet flavor (QCD)" uncertainty mostly from gluon jets
- Not a feature unique to CMS: parton shower (or fragmentation) in Pythia6 and Herwig++, affects ATLAS response in a very similar fashion (GS vs PF, EM+JES vs Calo)



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2012-01/



CMS-PAPER-JME-13-004, arXiv:1607.03663;
ATLAS, Eur. Phys. J. C (2015) 75:17.

M. Voutilainen

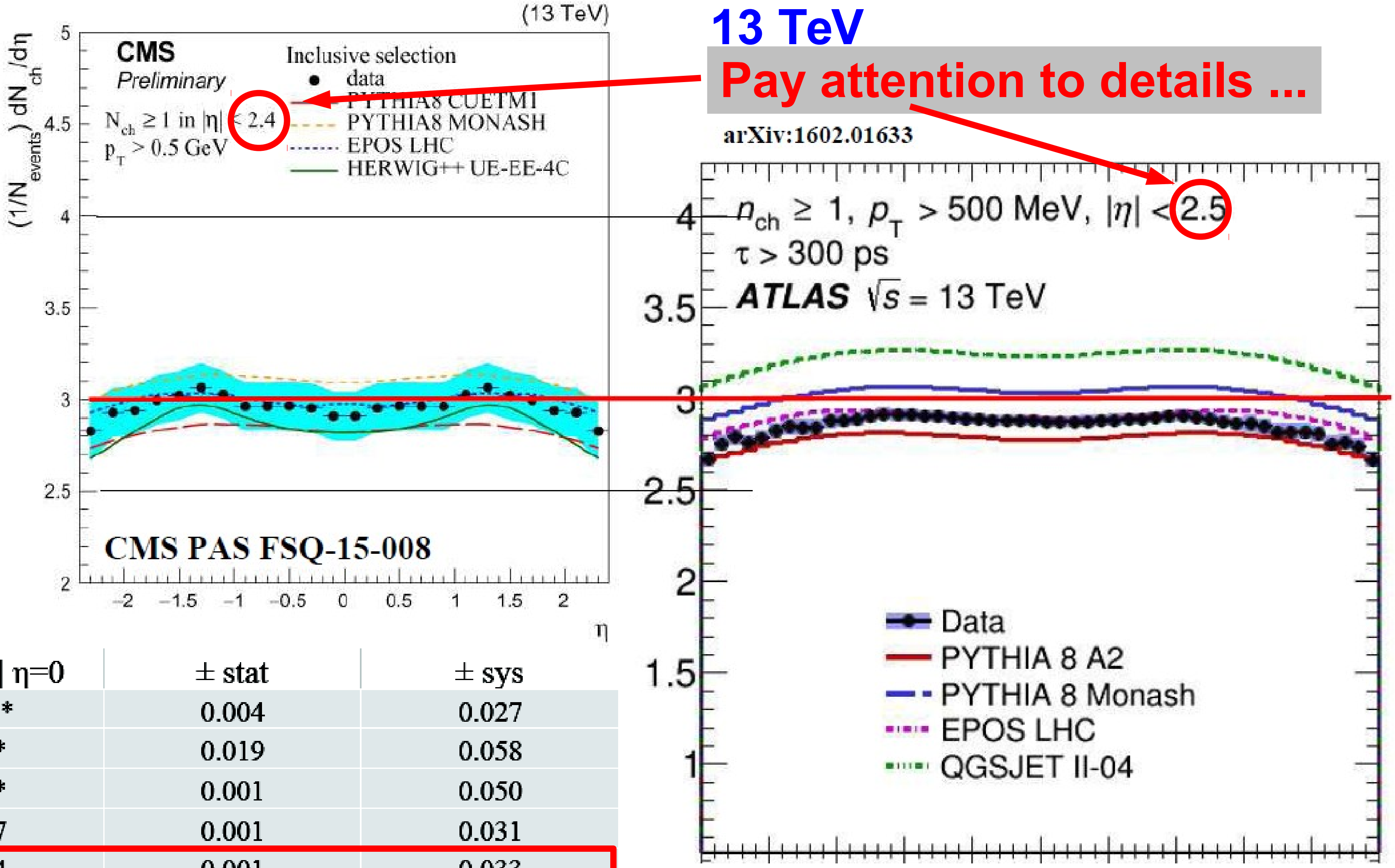
MC Tuning

A. Salzburger,
A. Mehta, R. Field

New E_{cms} to tune
E-dependence
→ improve
- simulation
- UE & pile up
- jet calibration

13 TeV

Pay attention to details ...



√s [TeV]	$dN_{ch}/d\eta$ | η=0	± stat	± sys
0.9	1.343*	0.004	0.027
2.36	1.74*	0.019	0.058
7	2.43*	0.001	0.050
8	2.477	0.001	0.031
13	2.874	0.001	0.033

Input from unique LHCb phase space → A. Grecu
UE in ttbar events → E. Yazgan
Total x section → K. Hiller

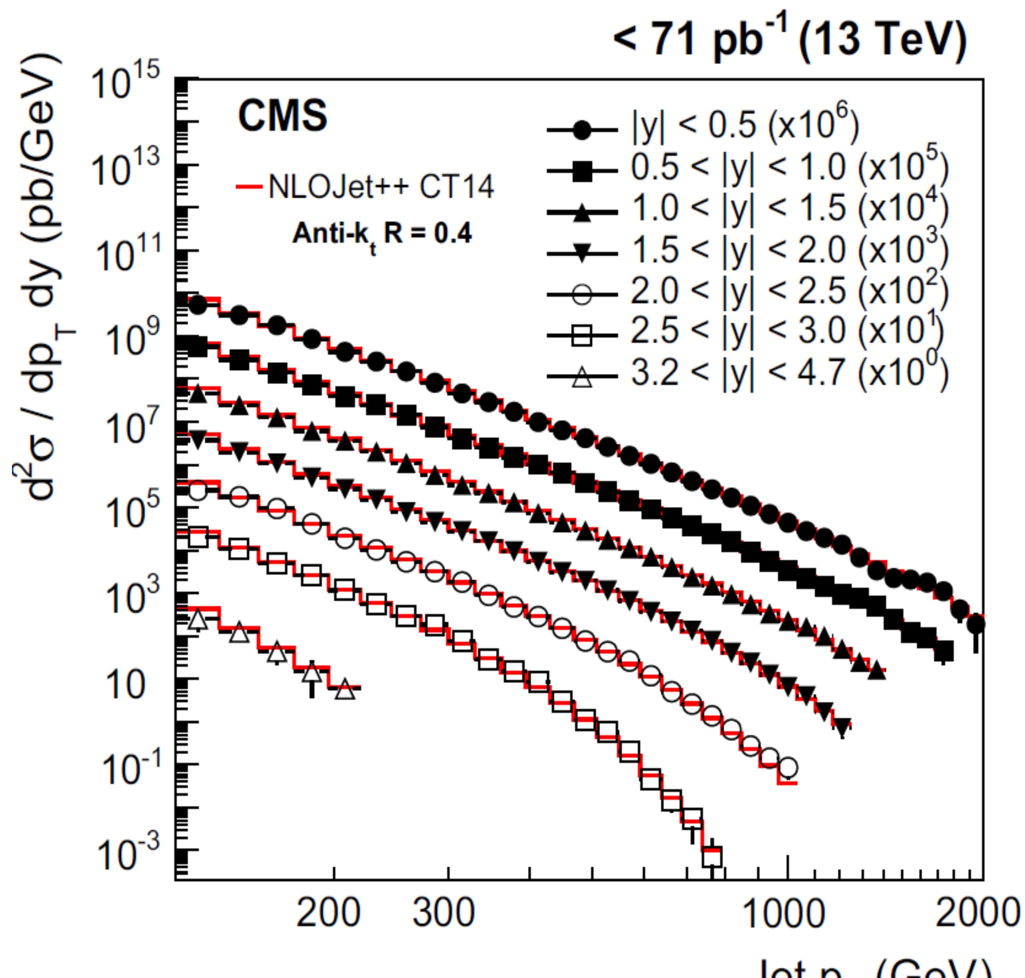
MC Tunes, preferably simultaneously for
MBias, UE, and DPS → R. Field

Inclusive Jets at 13 TeV

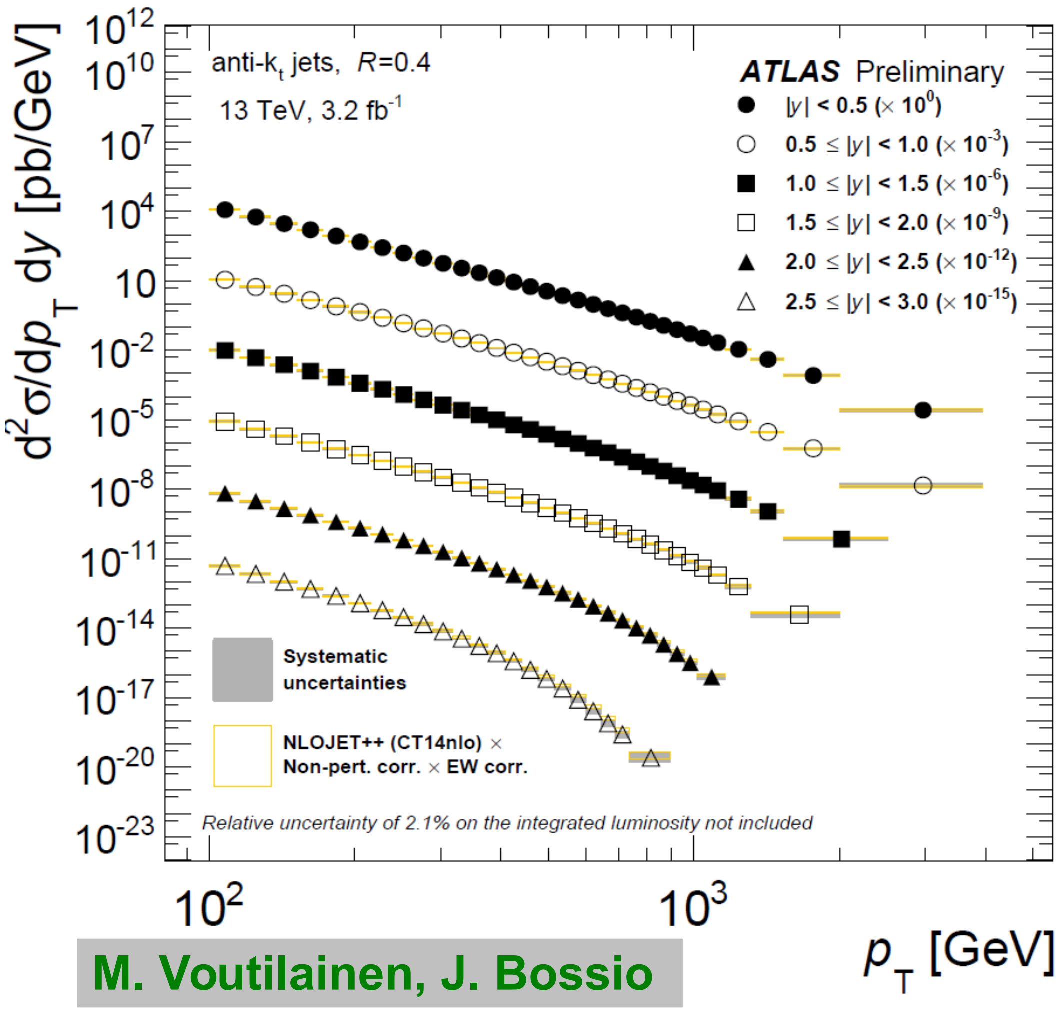
New publication from CMS, < 71/pb, jets up to 2 TeV,
New preliminary from ATLAS, 3.2/fb, jets up to 4 TeV.

$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

anti-kT, R=0.4, 13 TeV, 2015



anti-kT, R=0.4, 13 TeV, 2015



CMS EPJC 76 (2016) 415, ATLAS-CONF-2016-092.

M. Voutilainen, J. Bossio

DIS Jets versus NNLO

First comparison of jets in DIS to NNLO predictions
→ fully include jet data with NNLO theory into future fits of gluon PDF & α_s!

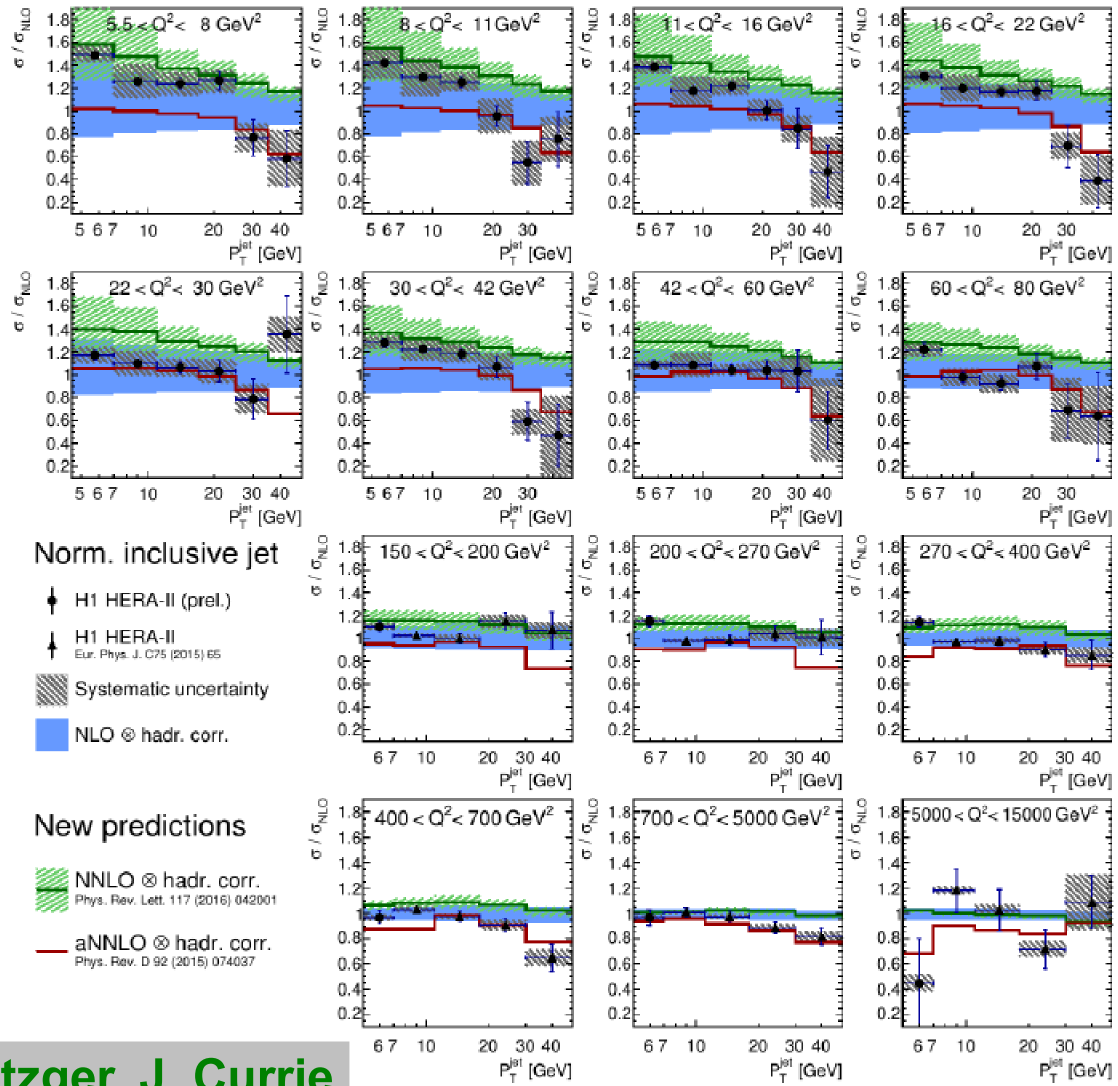
Detailed ratio to NLO prediction
- Data reasonably described by NLO theory, but NLO scale uncertainty large

New predictions: NNLO from NNLOJET
- NNLO predictions for inclusive jet and dijet production in NC DIS (*PRL 117 (2016) 042001*)
- Normalised with NC DIS predictions from APFEL using FONLL-C

NNLO
- Improved description of data by NNLO
- Significantly reduced scale uncertainty (particularly for higher scales)

aNNLO from JetViP
- Approximate NNLO using threshold resummation *PR D 92 (2015) 074037*
- Improved data description at high-pT

High-Q2 inclusive jets
- New datapoints for $5<p_T<7$ GeV plus *EPJ C75 (2015) 65*



H1prelim-16-062.

D. Britzger, J. Currie

Data Sets for PDF Extraction

V. Radescu.	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ12(15)	JR14
HERA data	HERA I+ charm	HERA I charm jets	HERA I+ H1 and ZEUS II charm	HERA I+II	HERA I charm	HERA I	HERA I charm jets
Fix. Target DIS	✓	✓	✓	✗	✓	JLAB, high x ✓	JLAB, high x ✓
Tevatron W,Z	✓	✓	✓	✗	✗/✓	✓	✗
Tevatron Jets	✓	✓	✓	✗	✗	✗	✓
Fix. Target DY	✓	✓	✓	✗	✓	✓	✓
LHC WZ	✓	✓	✓	✗	✓	✗	✗
LHC jets	✓	✓	✓	✗	✗	✗	✗
LHC top	✗	✓	✓	✗	✓	✗	✗
LHC charm	✗	✗	✓	✗	✗/✓	✗	✗
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

Type of processes:

- inclusive / purely leptonic
- processes with jets
- current precision of data ~<5%

see: E. Rizvi, R. Placakyte, K. Lohwasser, S. Glazov, K. Mueller S. Camarda, J. Bossio …

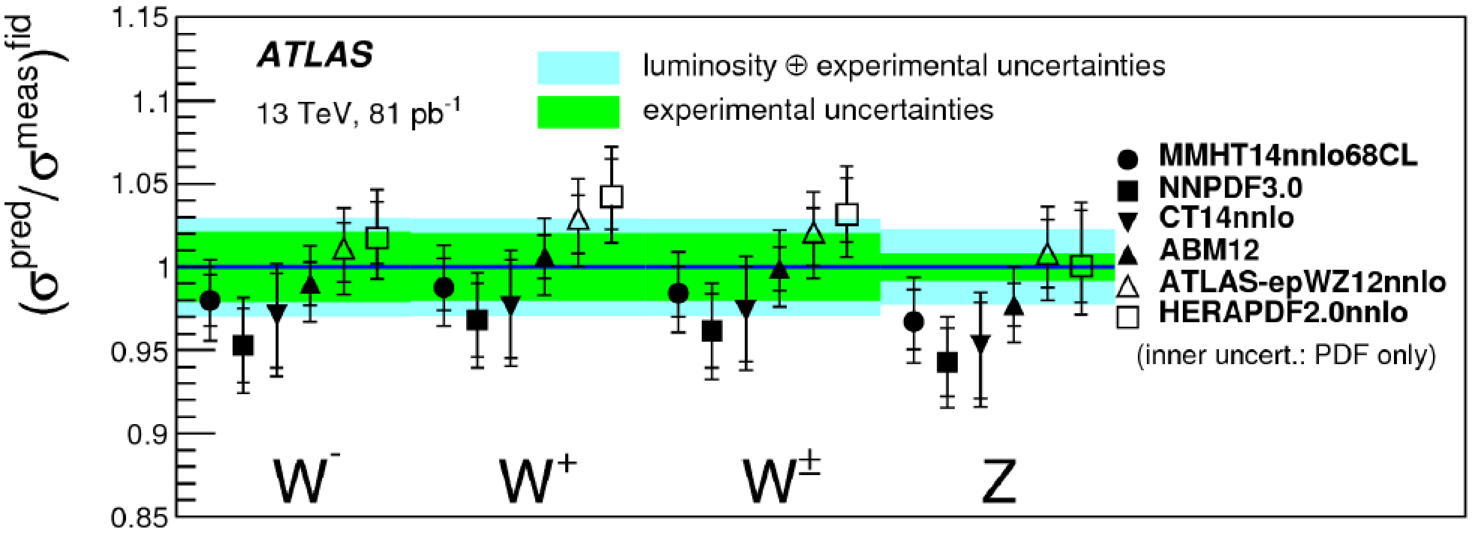
EW effects become more and more important → need Photon PDF → need sensitive measurements:

High mass DY production → E. Rizvi

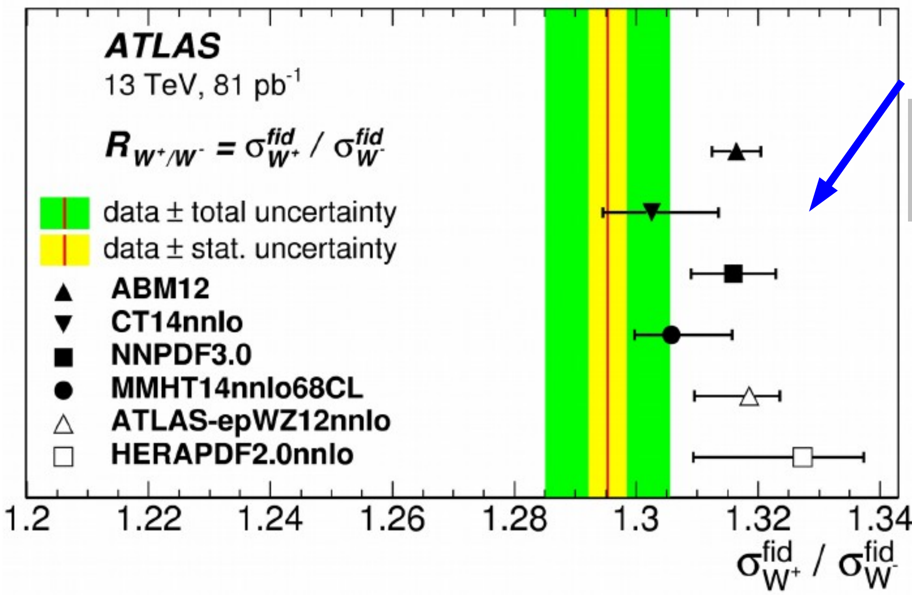
Inclusive W±,Z Production & Ratios

13 TeV data compared to NNLO

Uncertainties:
exp W: ~2%
exp. Z: ~1%
Lumi: 2.1%
→ Ratios

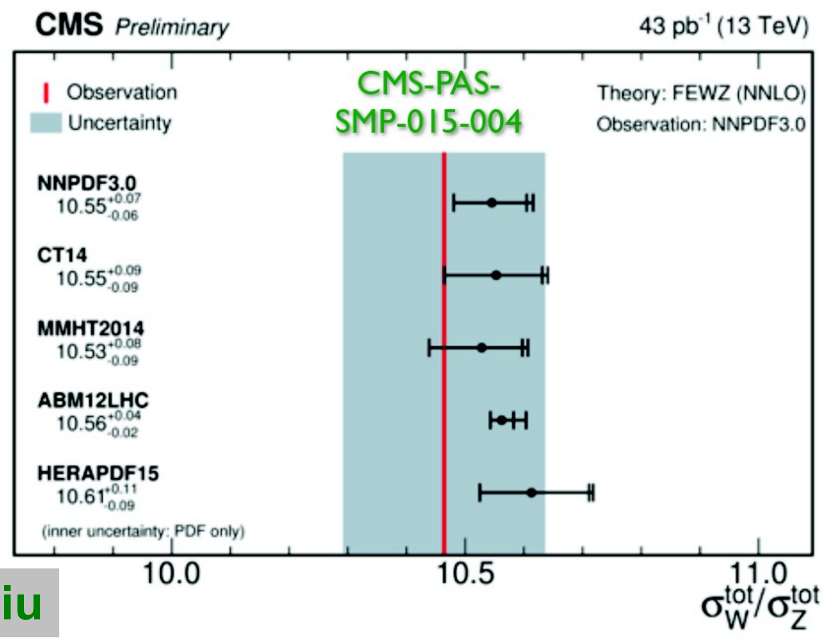


W+/W- sensitive to u_v/d_v PDF



similar behavior in ATLAS & CMS

W/Z sensitive to strange PDF



S. Camarda, X. Niu

Differential W,Z Production

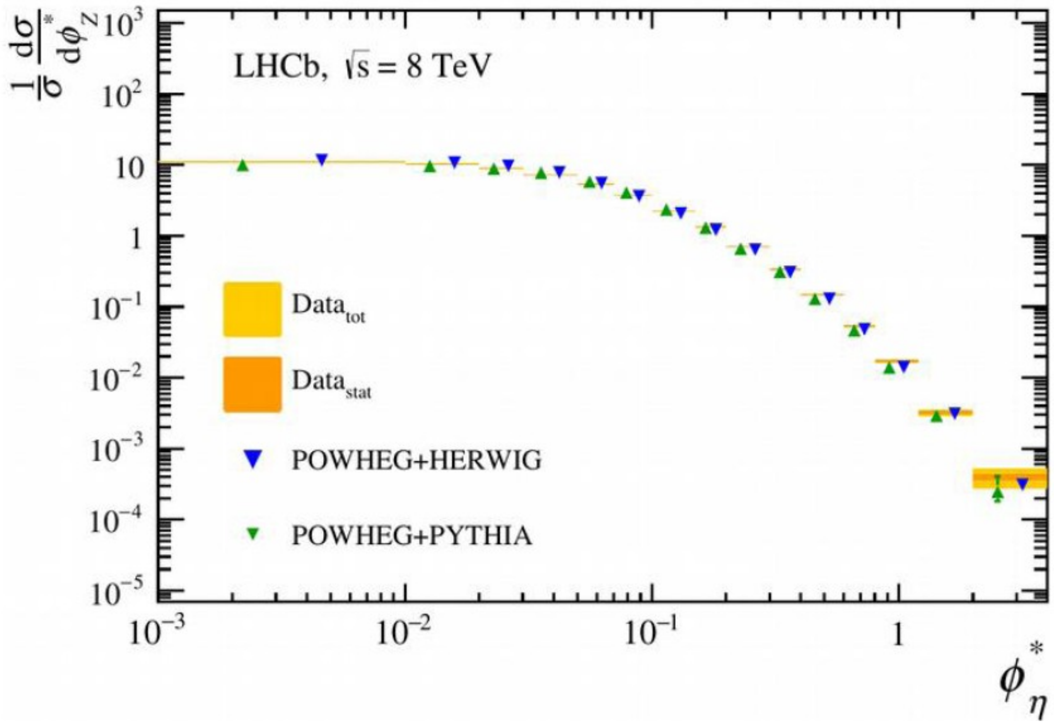
Differential in φ^*_η instead of $p_{T,Z}$:
roughly ~ $p_{T,Z}/M_Z$ but only angular → smaller uncertainties

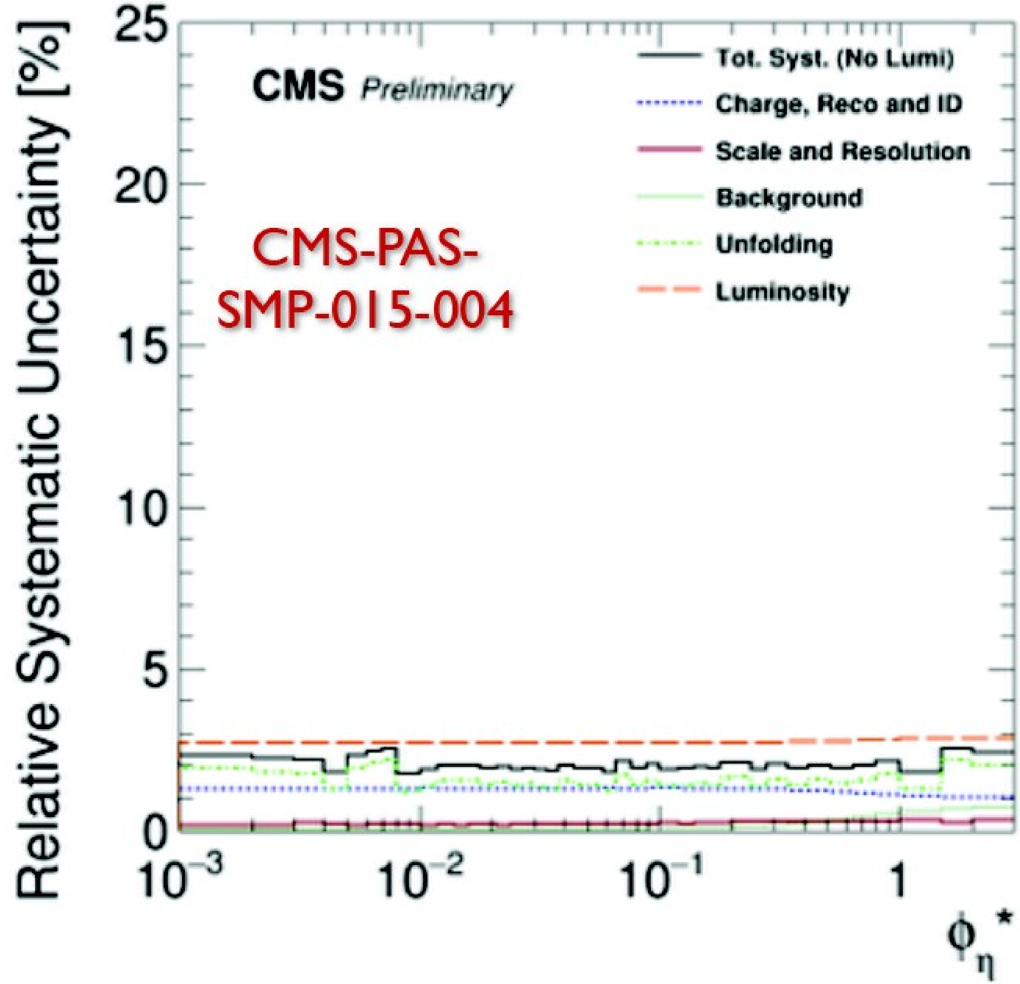
S. Camarda, X. Niu, A. Grecu

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right),$$

LHCb Forward Region

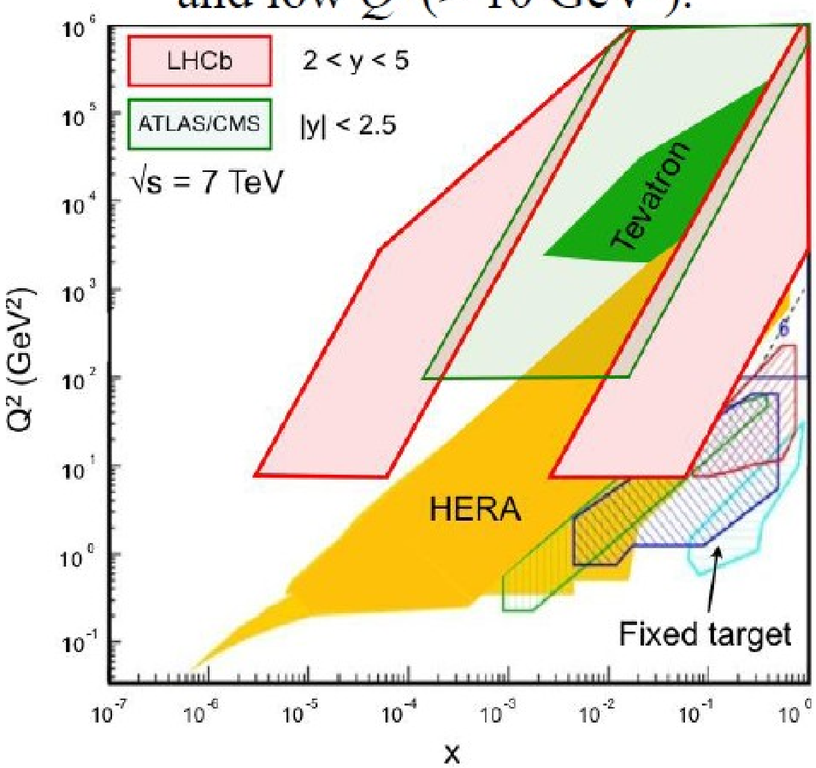




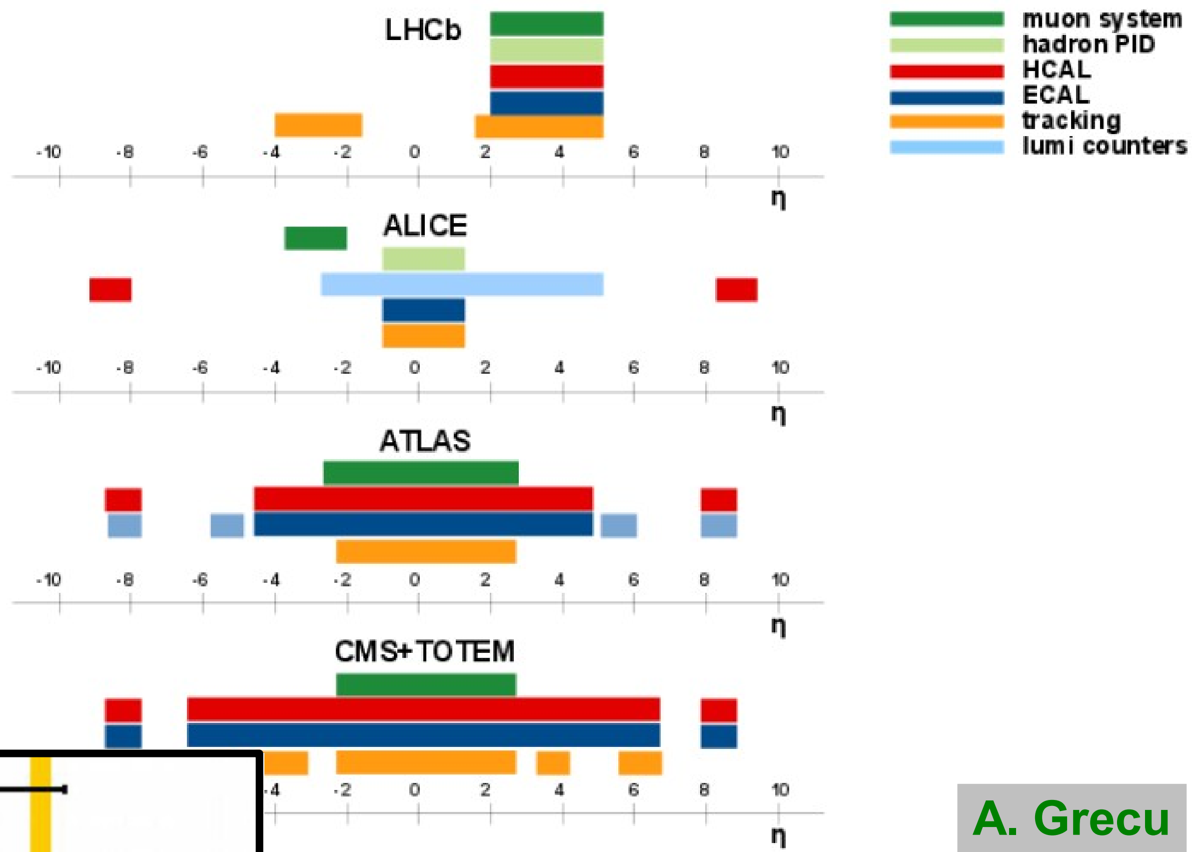
PDF constraints → V. Radescu, R. Placakyte
V+HF → R. Gold, R. Silva, G. Chiodini

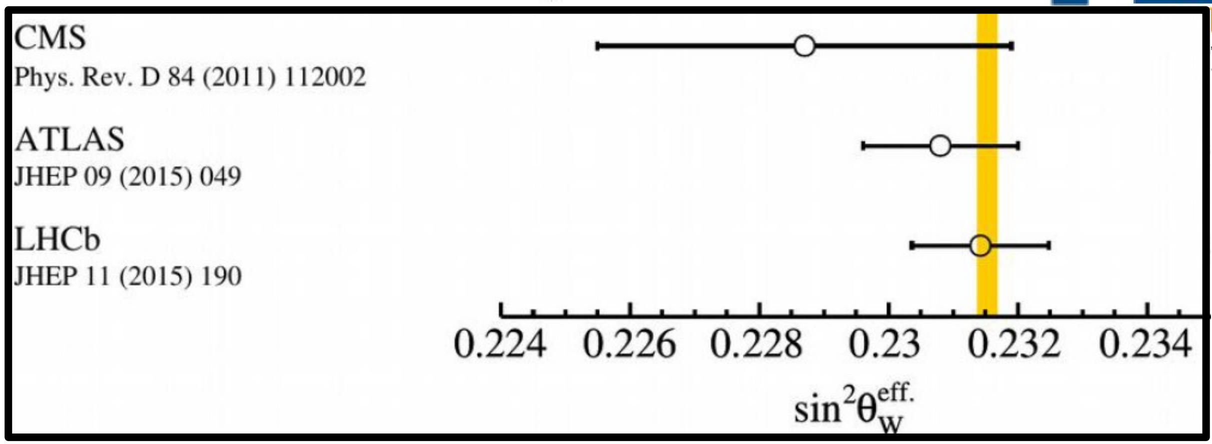
LHC Phase Spaces, $sin^2\Theta_W$

Also access low x_{Bj} (~ 10^{-6}) and low Q^2 (> 10 GeV²).



LHCb covered phase-space region complementary to other detectors at LHC





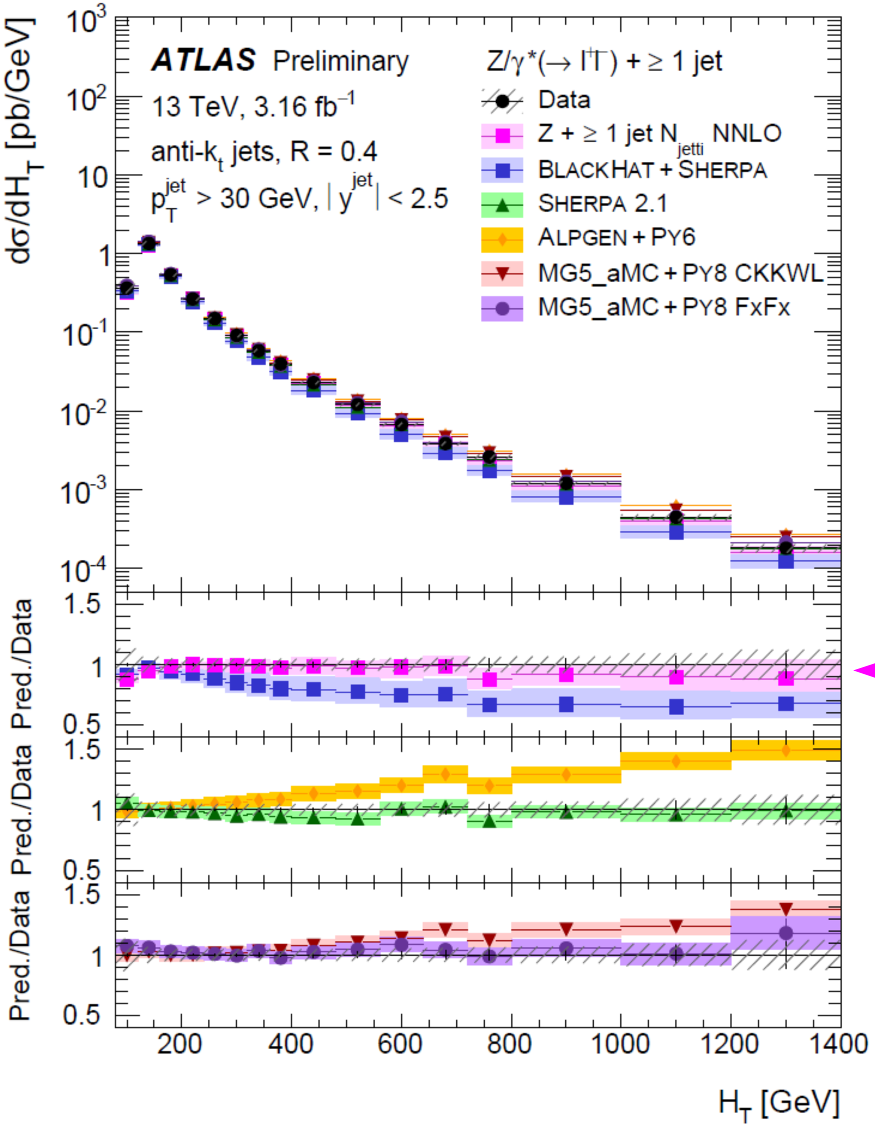
A. Grecu

Also use Z asymmetry A_{FB} to determine $sin^2\Theta_W$

Z+jets at 13 TeV

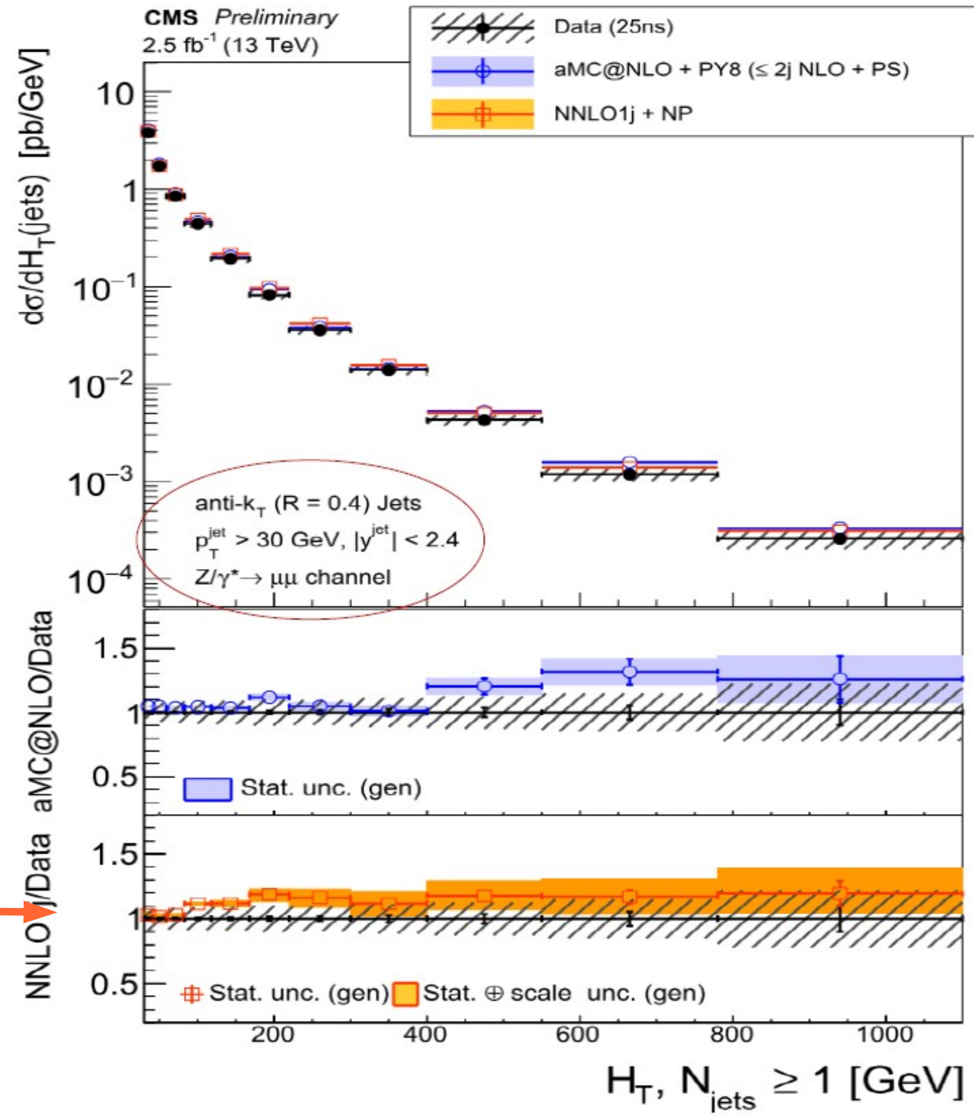
Agreement with new NNLO Calculations
Also: Run 1 data for W/γ+jets and Z/W + b/c jets

J.Bossio, F. Zang



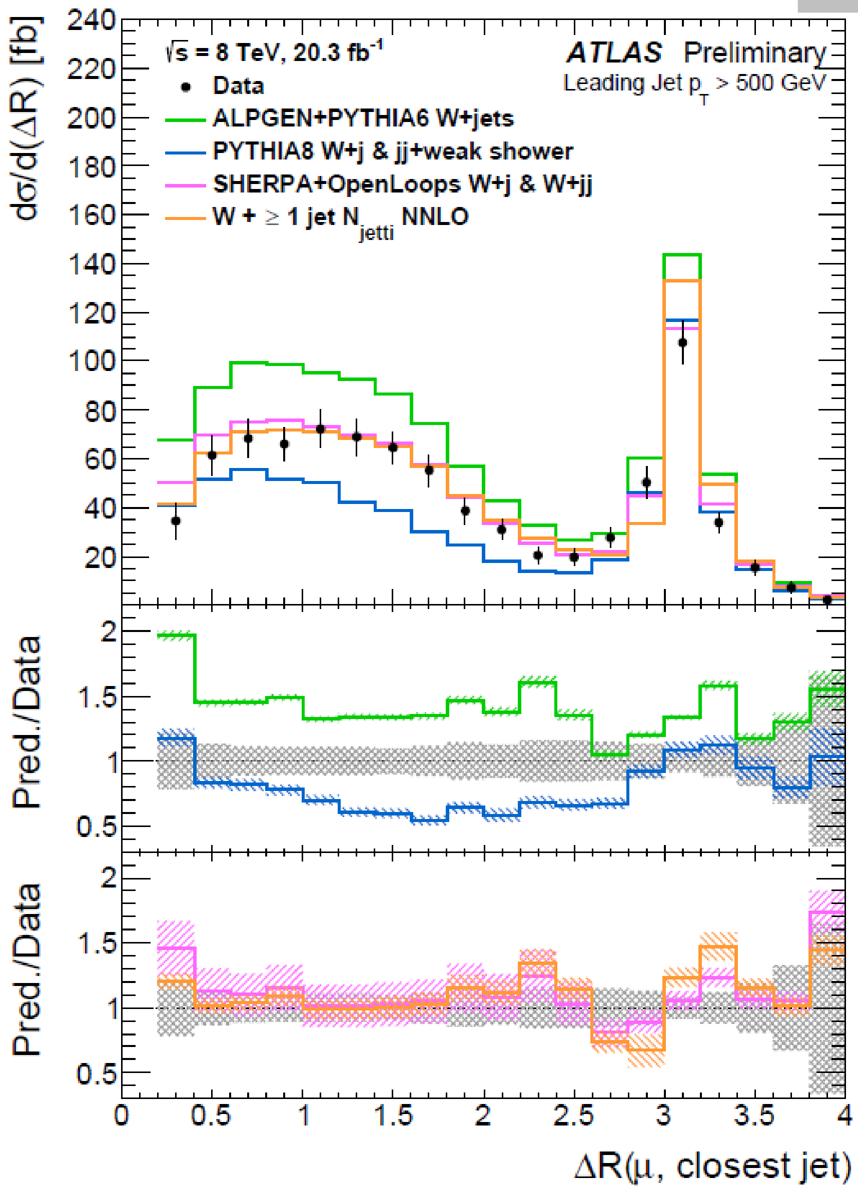
NNLO

NNLO



W+jet at high p_T low ΔR

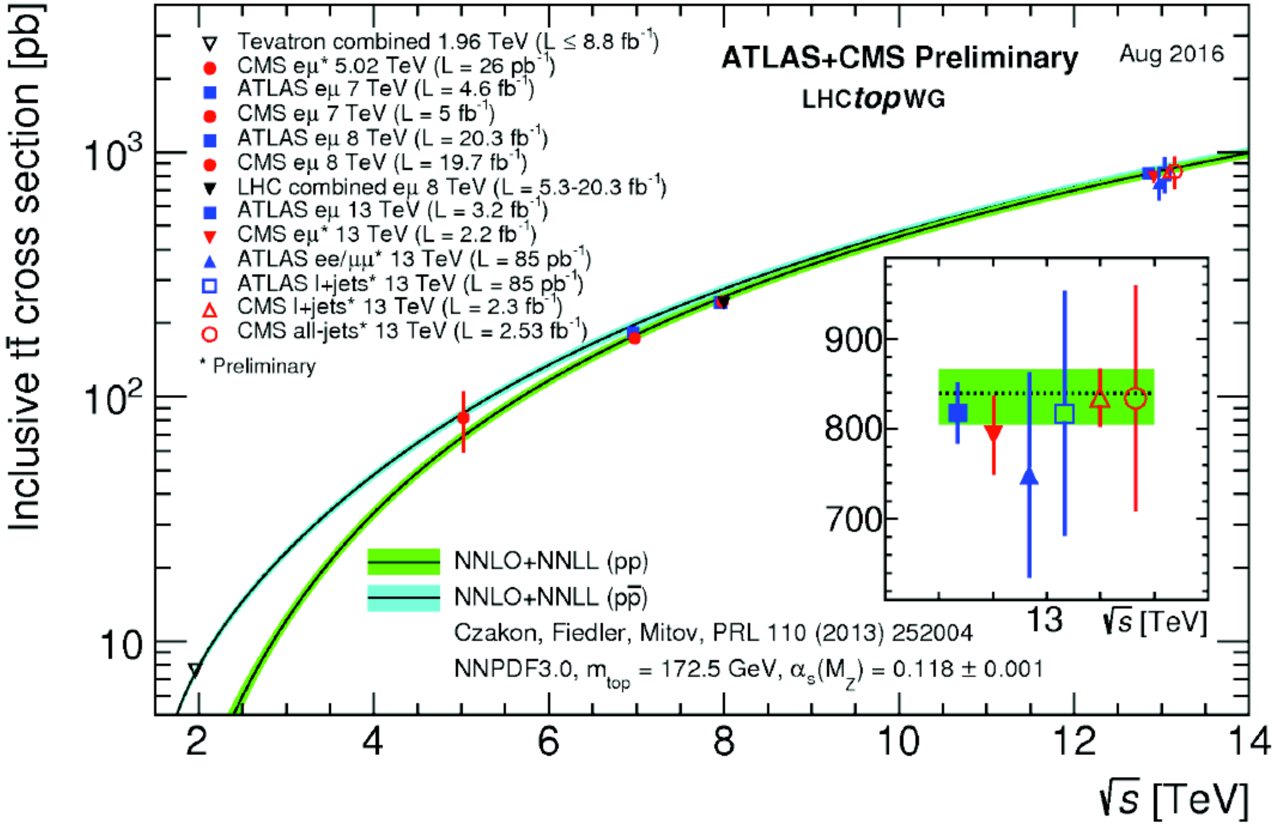
Test of real W emission process
Well described by NNLO or Sherpa+OpenLoops



- Unfolded data
- Reasonably small data uncertainties:
  - Dominant systematic uncertainties: jet energy scale (5%) and b-tagging efficiency (3%)
- Substantial differences between theory predictions
- New theory calculations (SHERPA+OpenLoops and NNLO) perform well

J. Bossio

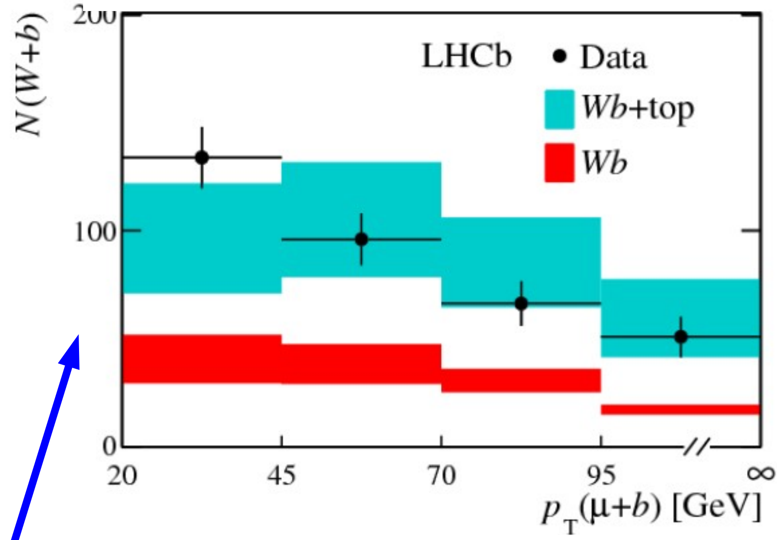
top Quark Production



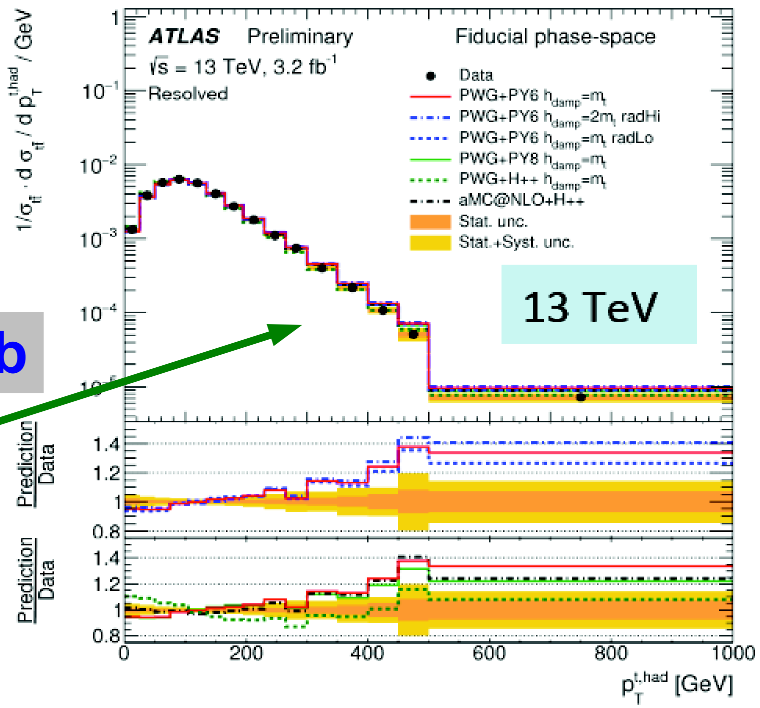
G. Krintiras, K. Lie, N. Castro, W. Hulsbergen, R. Coutinho

New x sections at 13 TeV & 5 TeV (CMS)

☞ First observation (5.4σ)



top in forward region: LHCb



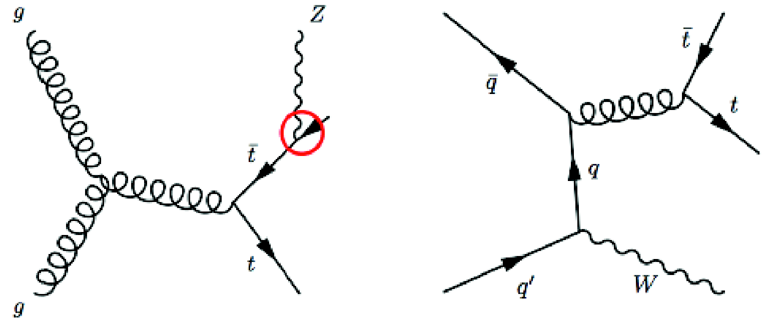
Differential fiducial cross sections at 13 TeV: top p_T

For single-top → S. Stamm, M. Komm

ttbar + (jets, W, Z) at 13 TeV

K. Lie

$t\bar{t}$+W/Z: 13 TeV

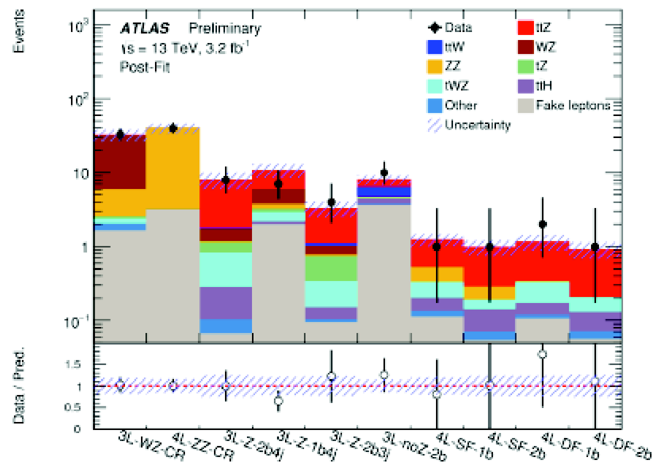


Motivation

- $t\bar{t}$Z: probe tZ coupling
- $t\bar{t}$W: background to many searches

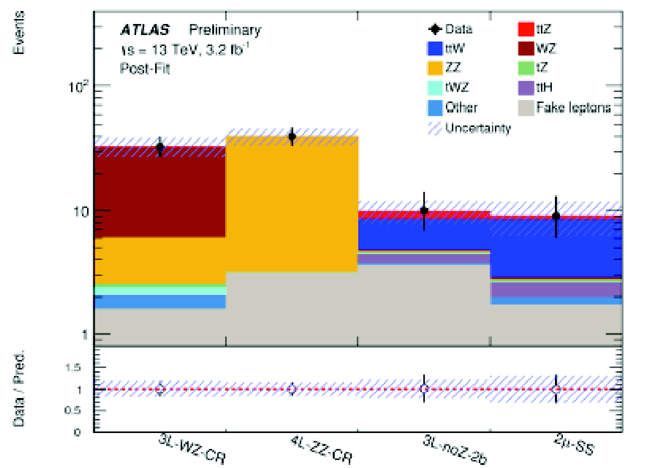
Main features

- Use 2(SS), 3 or 4 leptons
- Separate fit for $t\bar{t}$Z and $t\bar{t}$W



Results

- $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ pb
- $\Sigma_{t\bar{t}W} = 1.4 \pm 0.8$ pb
  - Still statistically limited
- NLO prediction (JHEP 07 (2014) 079)
  - $\sigma_{t\bar{t}Z} = 0.76$ pb ± 11% pb
  - $\sigma_{t\bar{t}W} = 0.57$ pb ± 11% pb

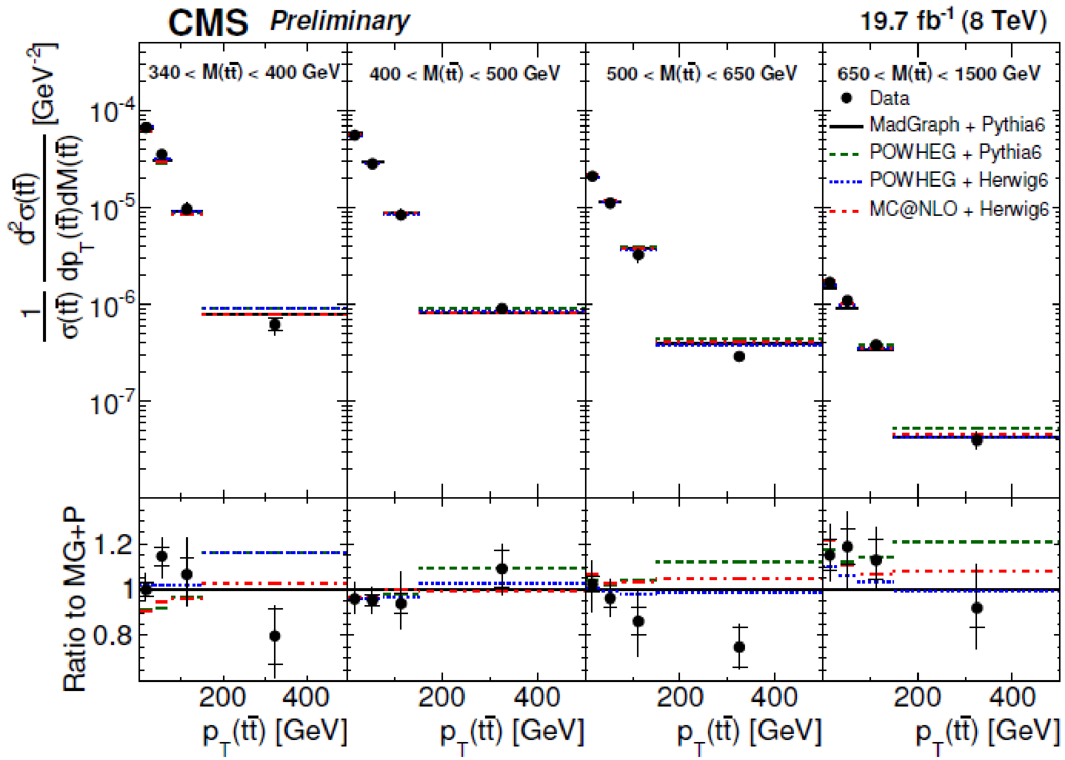


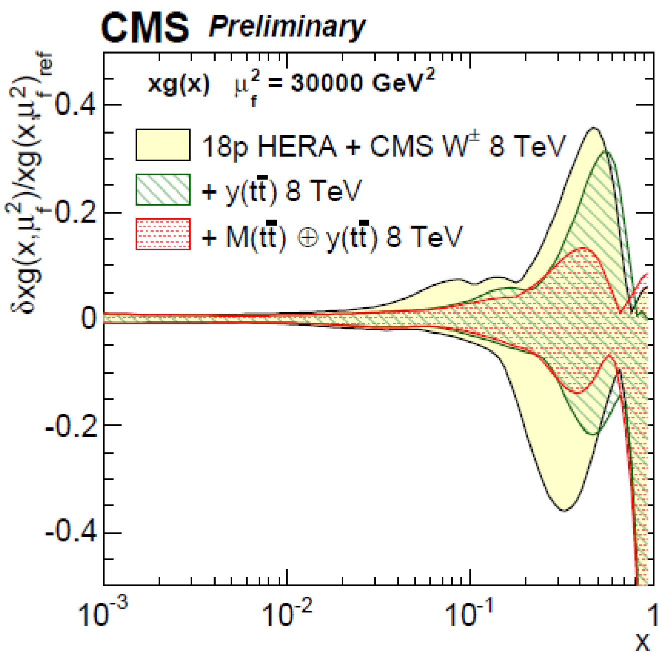
top & PDFs

$\sqrt{s} = 8$ TeV [CMS PAS TOP-14-013]

1. Use of differential top measurements for PDFs
2. Even double-differential → better constraints

- Double differential cross sections: bin $t\bar{t}$ events e.g. $p_T(t\bar{t})$ vs. $y(t\bar{t})$, $p_T(y)$ vs. $y(t\bar{t})$, etc



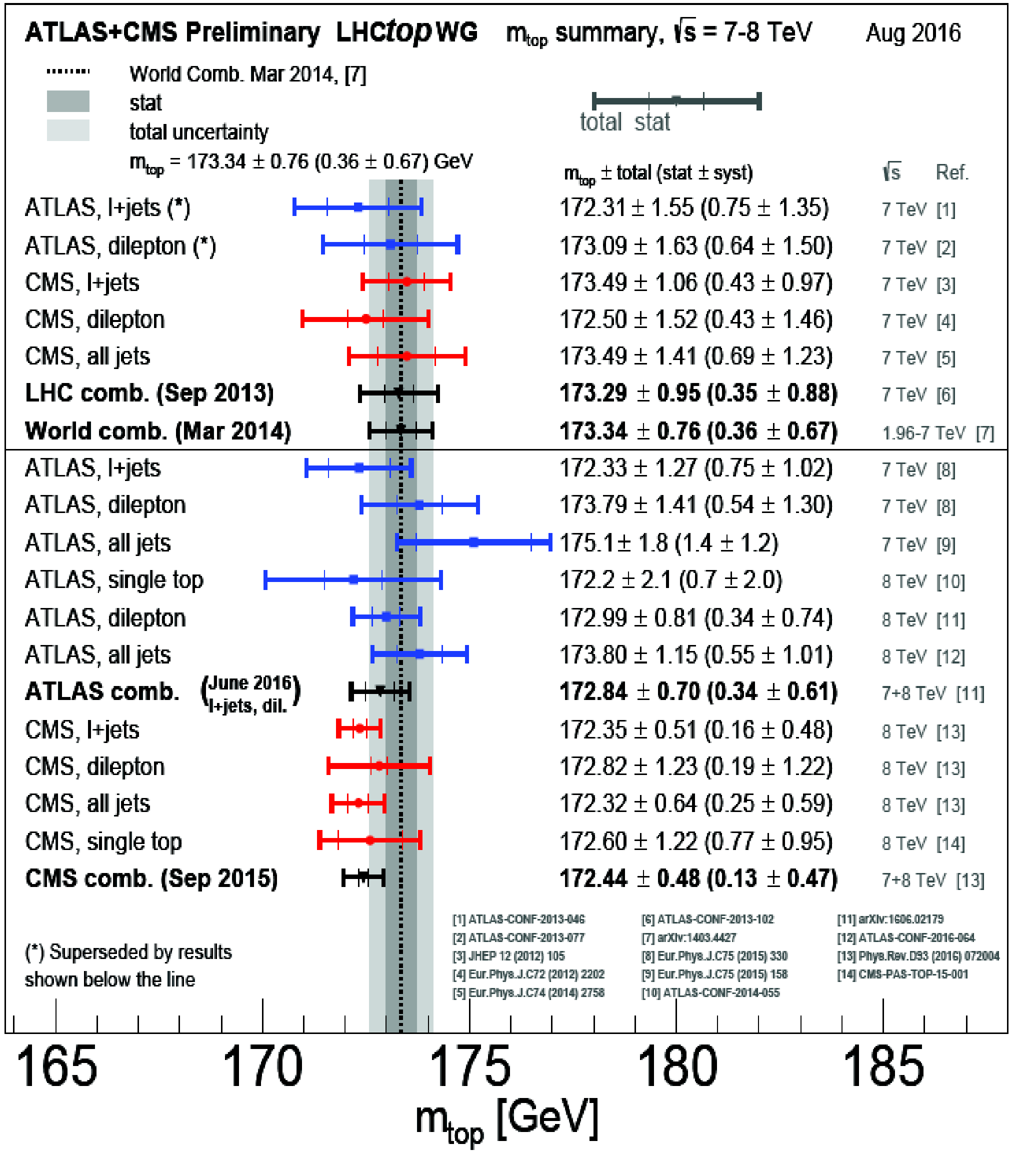


- $m(t\bar{t})$ vs. $y(t\bar{t})$ especially sensitive to PDFs (2D distributions provide stronger constraints than 1D)
- Significant reduction of the uncertainty at high-x

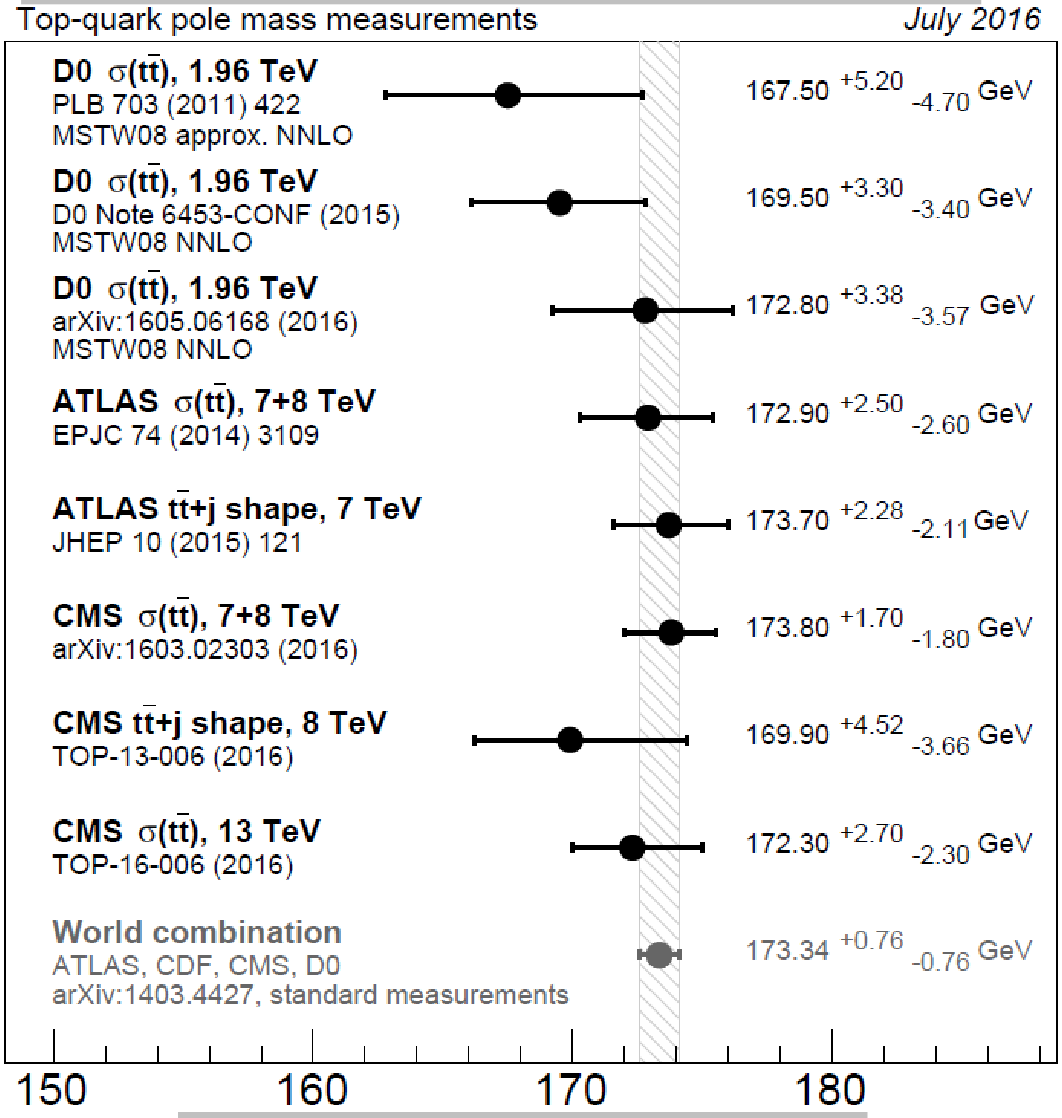
N. Castro, G. Krintiras

top Mass

Updated combinations
→ O(0.5 GeV) uncertainty on "MC mass"



Advanced precision of M_{top} demands theory-safe definition

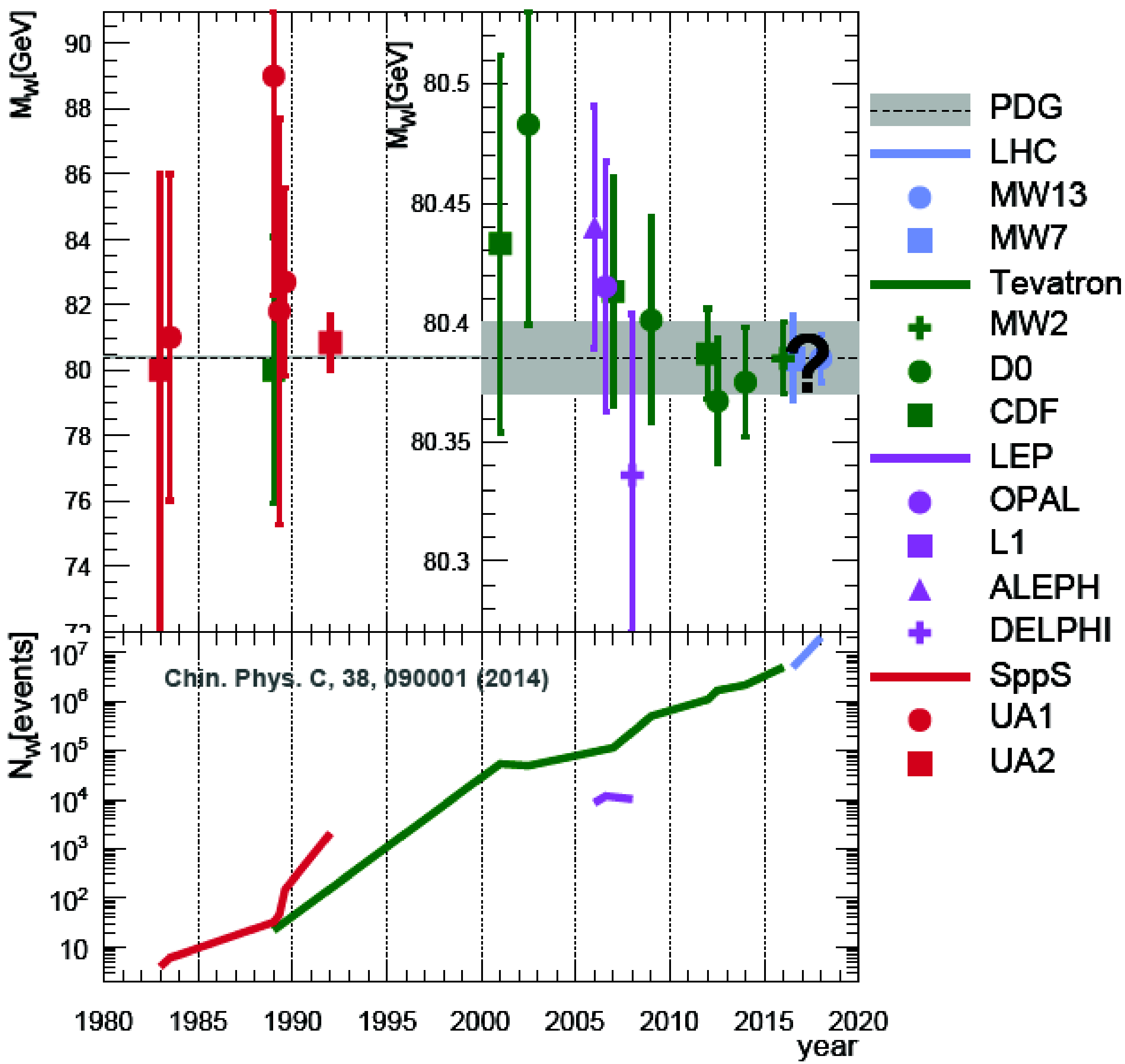


N. Castro, G. Krintiras, K. Lie

Challenge: W Mass

Highly untrivial, long-term combined effort required to improve precision

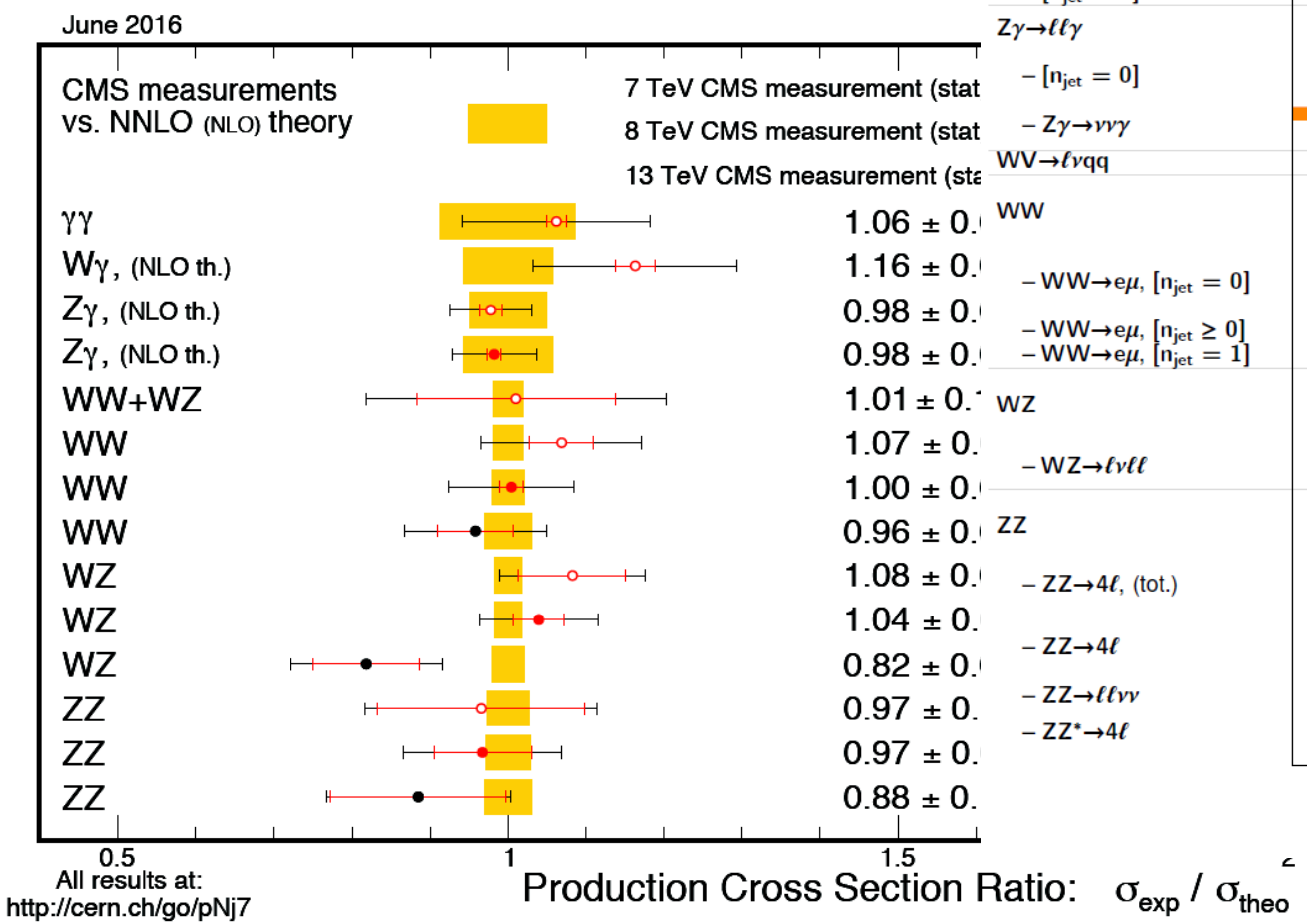
- Long term effort to M_W measurement from many teams and experiments.
- Theoretical predictions more precise then measurement.
- With CMS we showed proof of concept for detector performance and fit methodology.
- Very close cooperation between theoretical and experimental groups

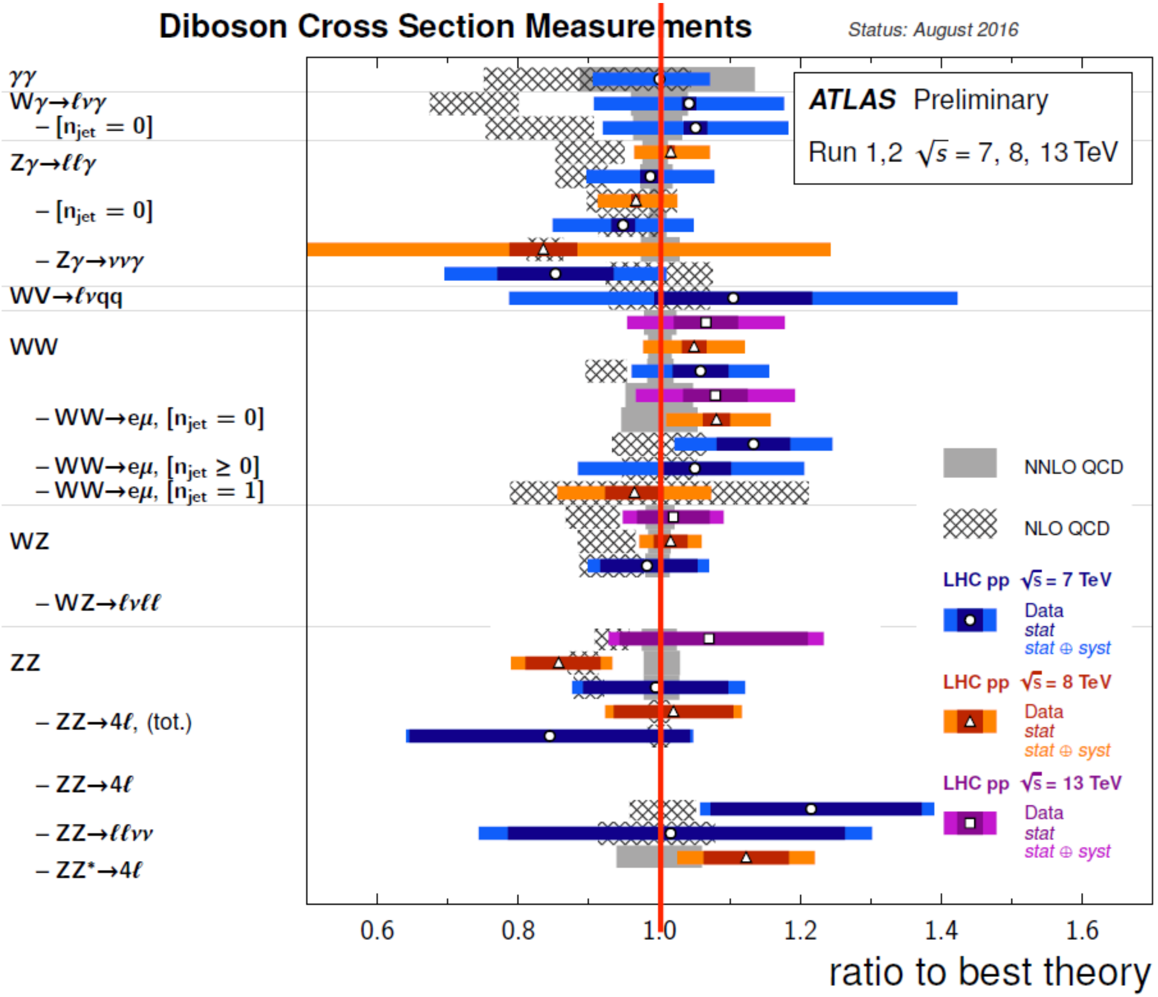


J. Cuth

Multiboson Production

Despite minute x sections many multiboson processes measured
No deviations from SM observed, no anomalous gauge couplings so far
Statistically limited → need more data.

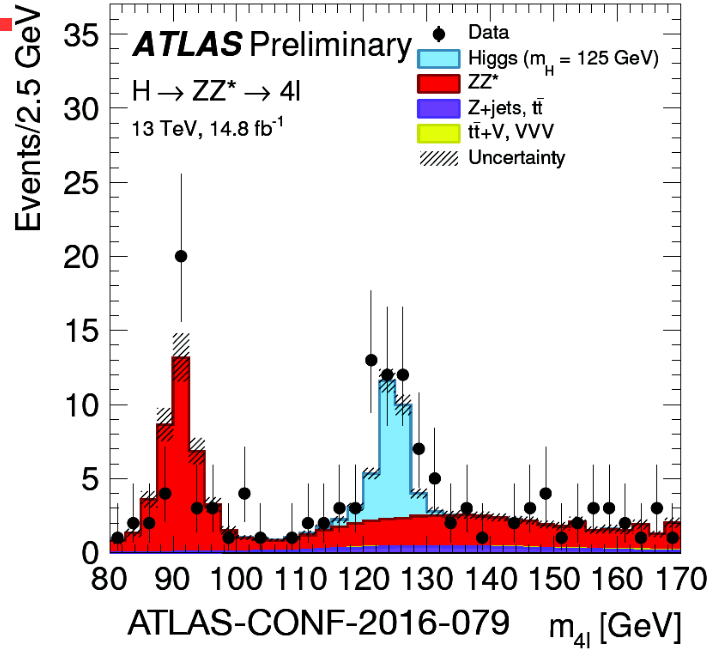




L. Di Caccio, I. Shvetsov, R. Zhang

Higgs rediscovered at 13 TeV

New 13 TeV H → ZZ* → 4l

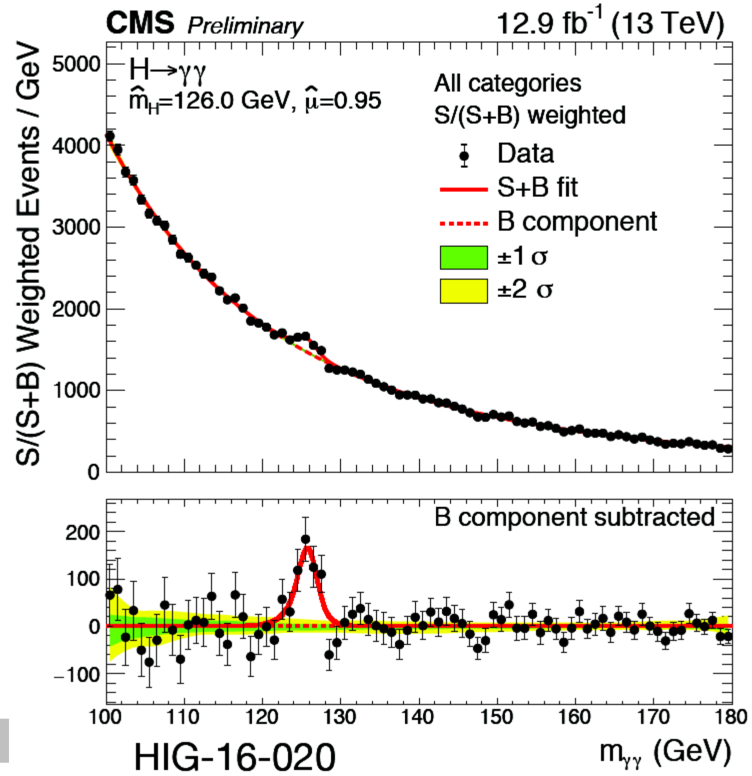


Run 1:

- Higgs mass determined to 0.2%
- Higgs signal strength ~1, determined to 10%
- Higgs couplings tested for many scenarios and assumptions (consistent with SM).
- Higgs spin-parity is compatible with SM from all studies
- Fiducial/Differential cross-section measurement at 8TeV

Higgs boson is very consistent with SM predictions, but measurements are still statistically limited.

New 13 TeV H → γγ

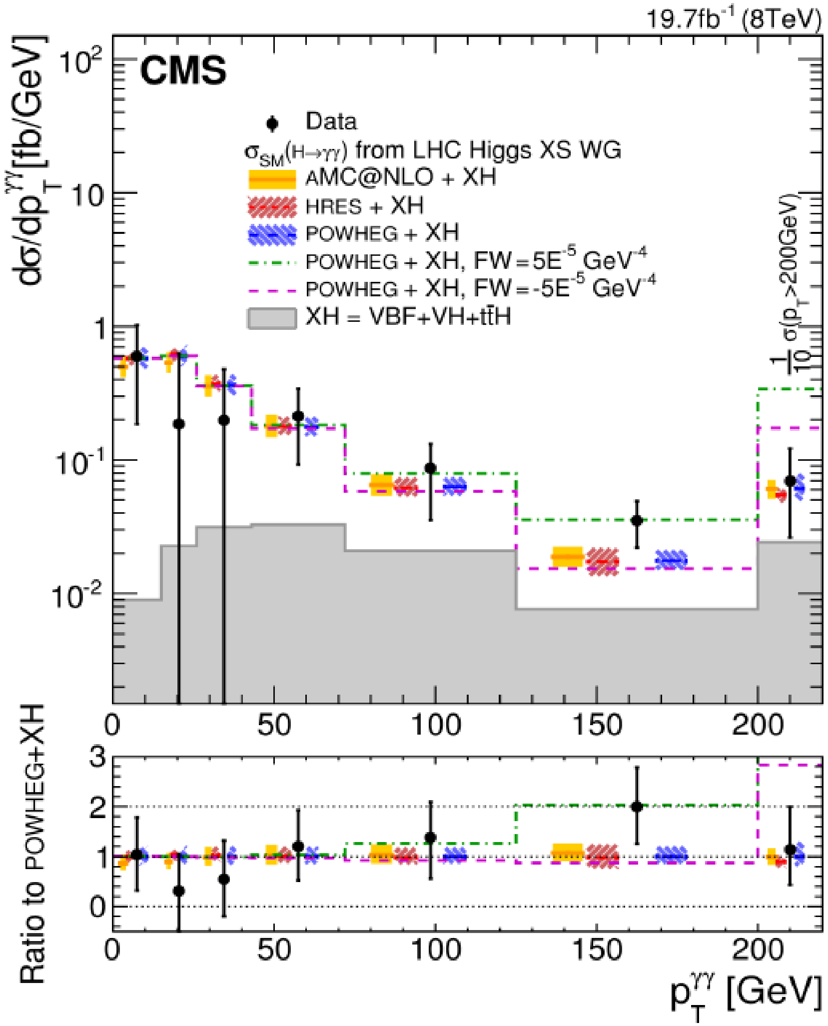


Y. Huang
Fermionic decay modes → N. Chernyavskaya

"Differential" Higgs

Move from discovery mode towards precision mode
→ measure Higgs differentially, e.g. $p_T^{\gamma\gamma}$

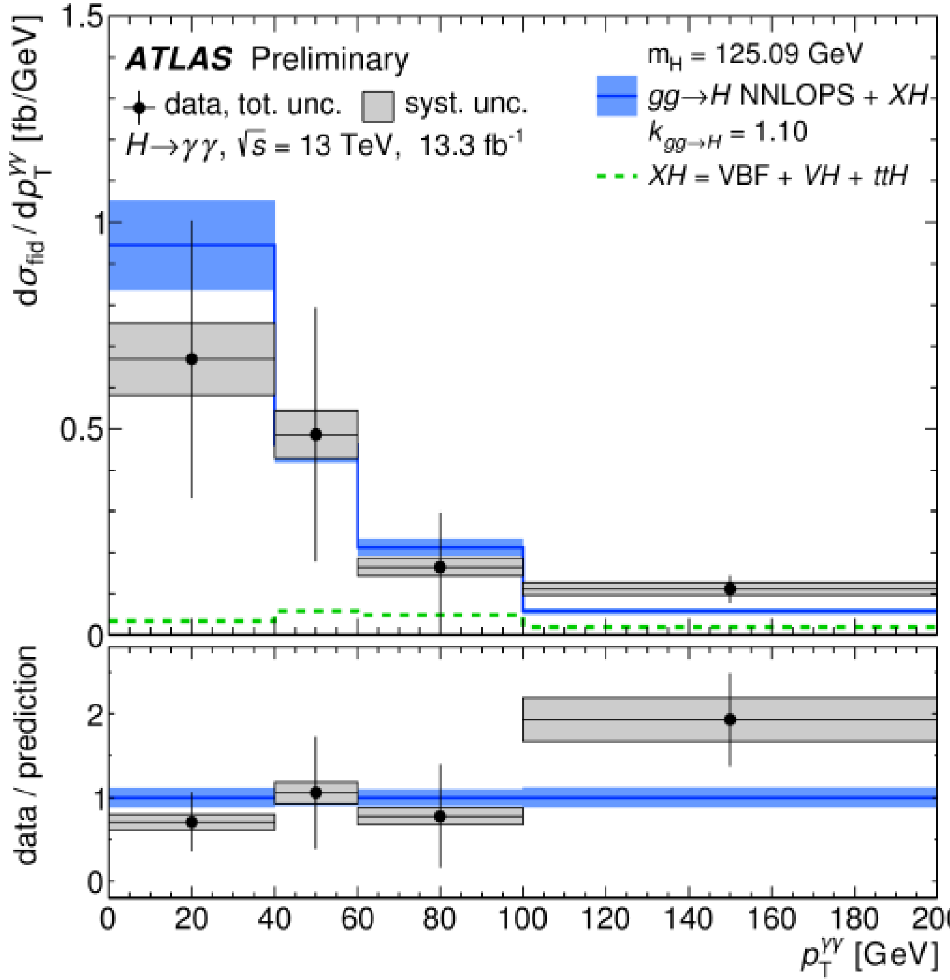
8 TeV



CMS: spectrum as SM exp.

ATLAS: spectrum slightly harder

13 TeV

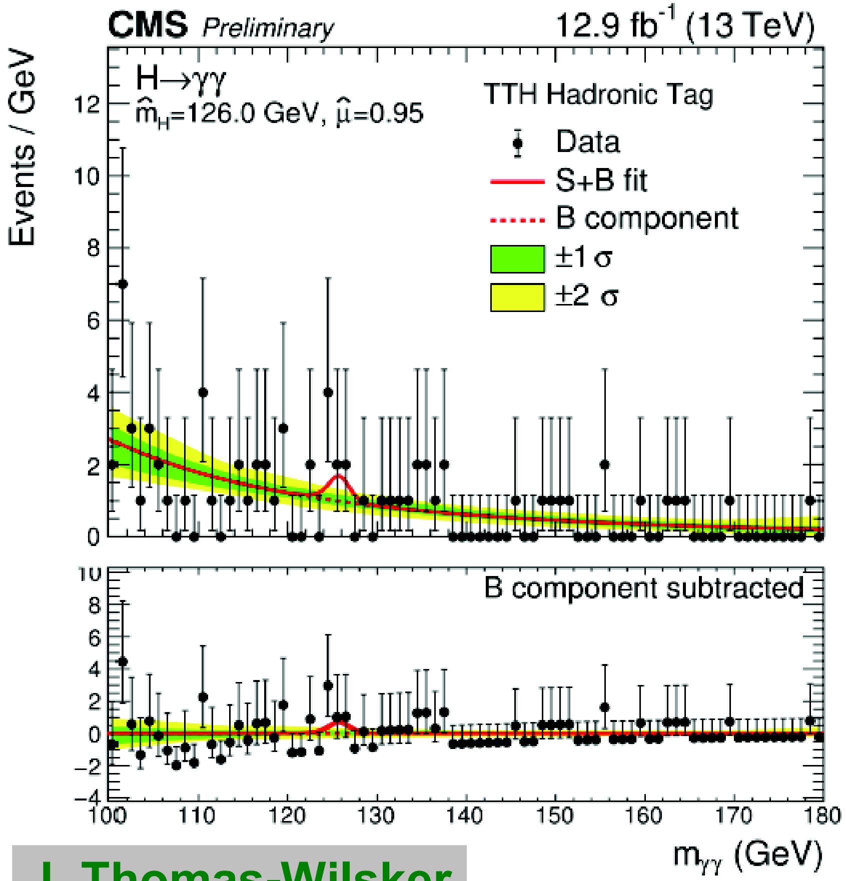


L. Viliani

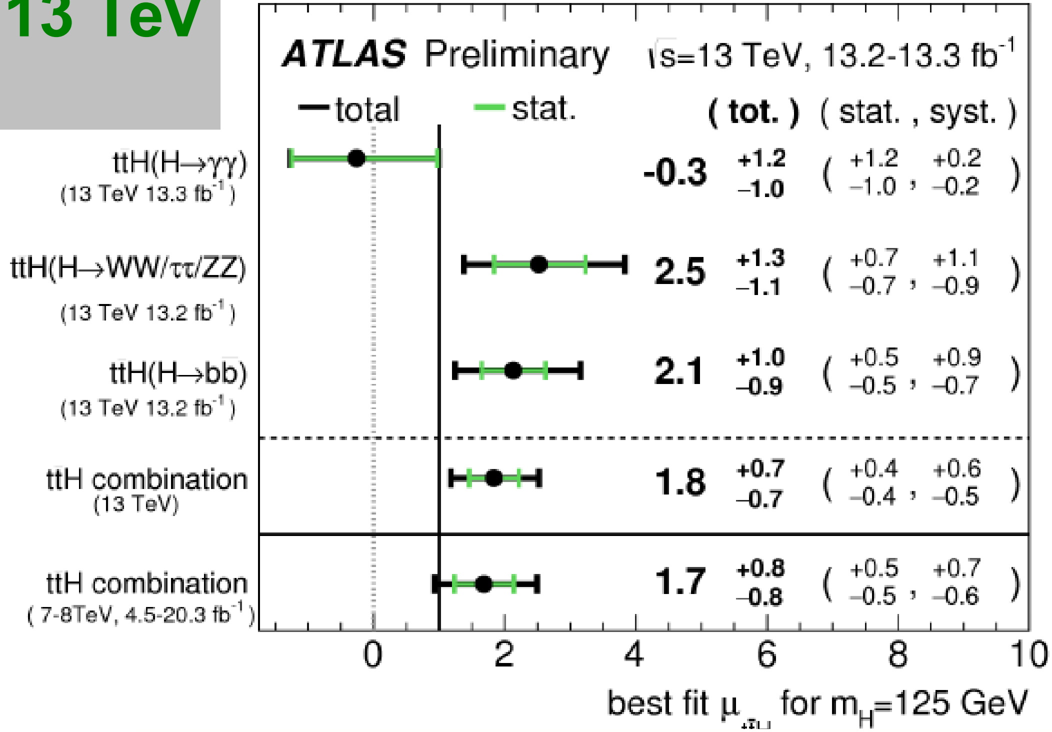
ttbar Production Mode of H

x section enhanced by factor ~4 at 13 TeV
still huge statistical uncertainties

E.g.: γγ decay mode

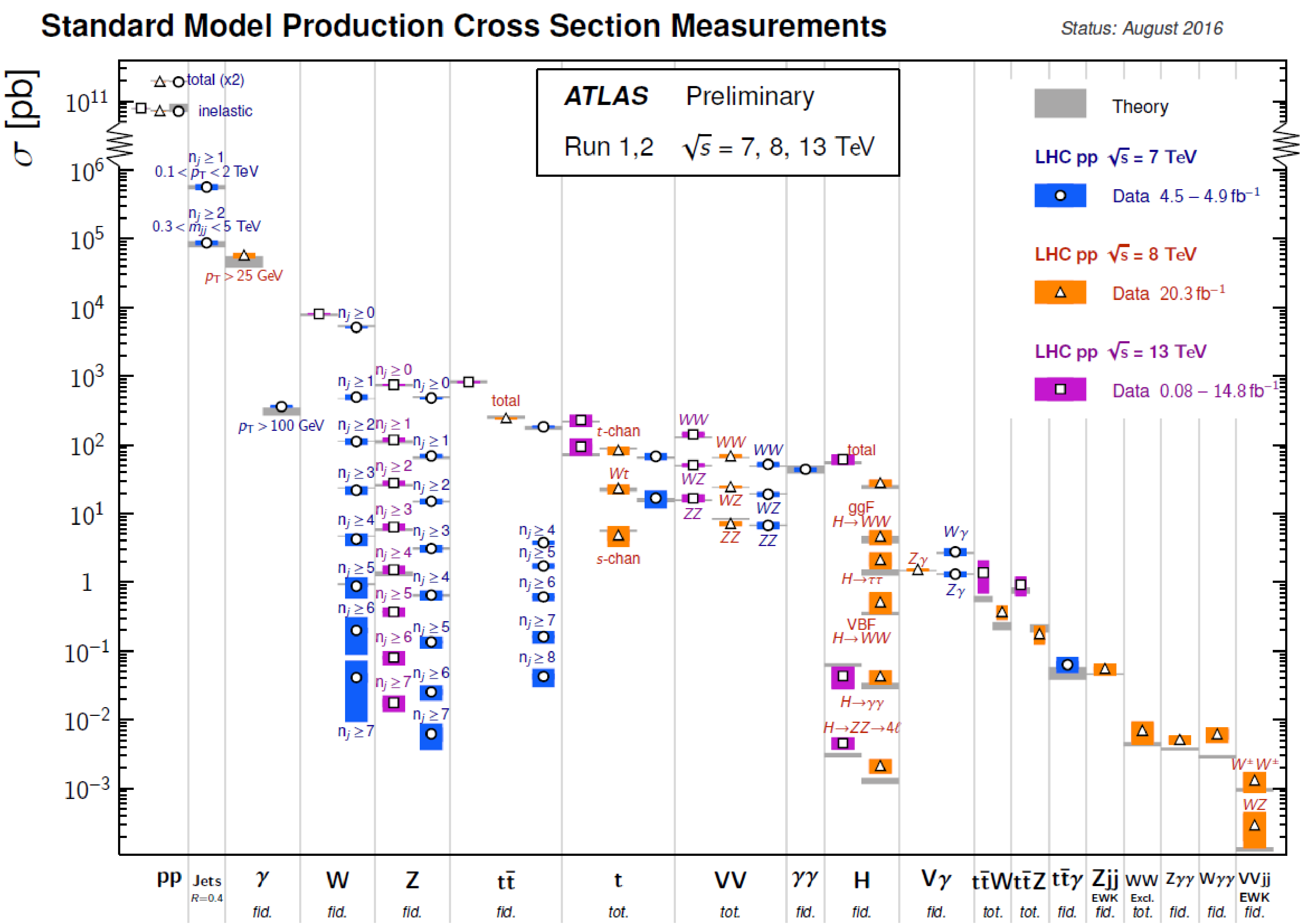


J. Thomas-Wilsker

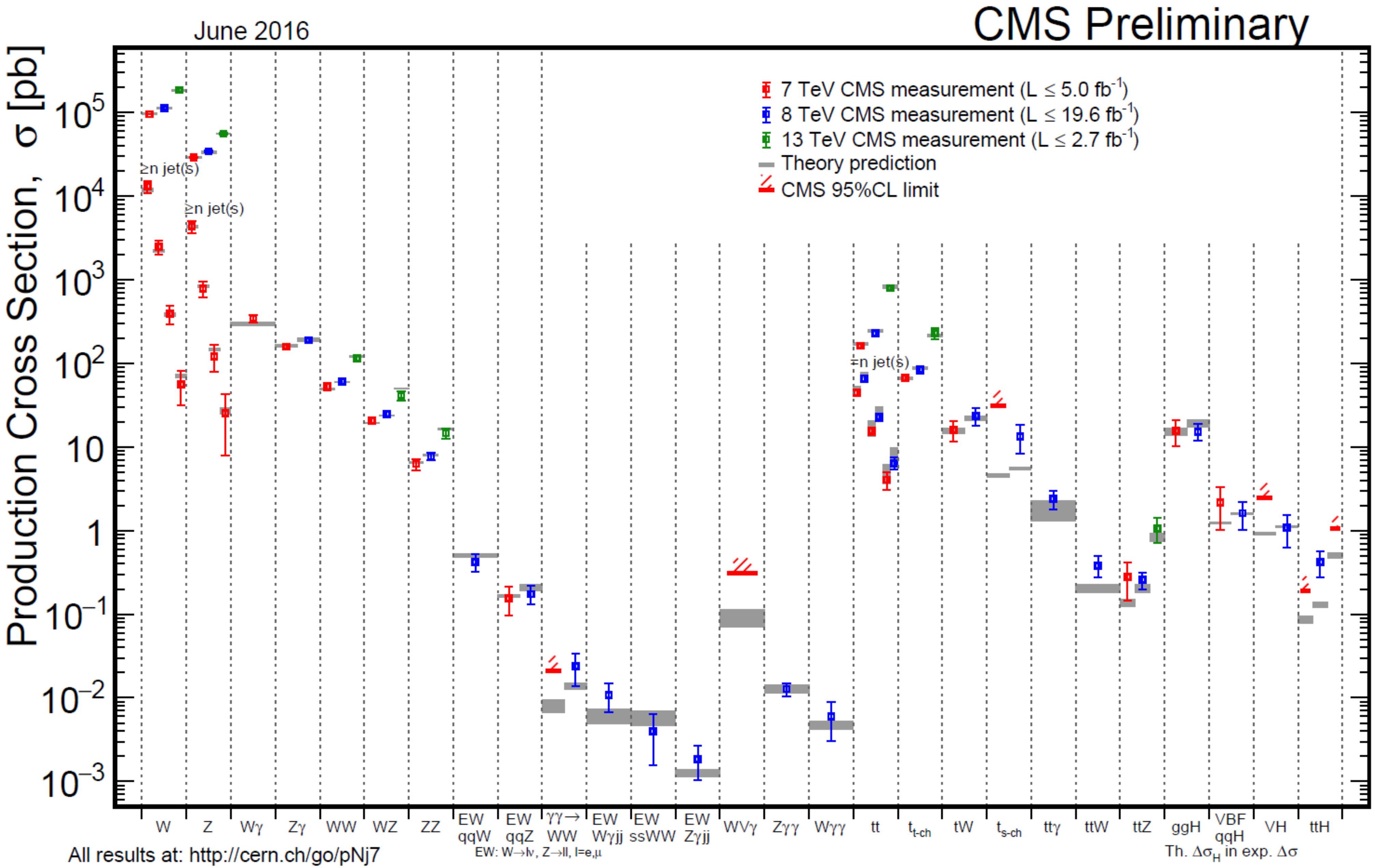


CMS	*μ* (2.3 - 2.7 fb^{-1})	*μ* (12.9 fb^{-1})
multilepton	$0.6^{+1.4}_{-1.1}$	$2.0^{+0.8}_{-0.7}$
$\gamma\gamma$	$3.8^{+4.5}_{-3.6}$	$1.91^{+1.5}_{-1.2}$
bb	$-2.0^{+1.8}_{-1.8}$	
Combination	$0.15^{+0.95}_{-0.81}$	

Latest ATLAS Summary



Latest CMS Summary

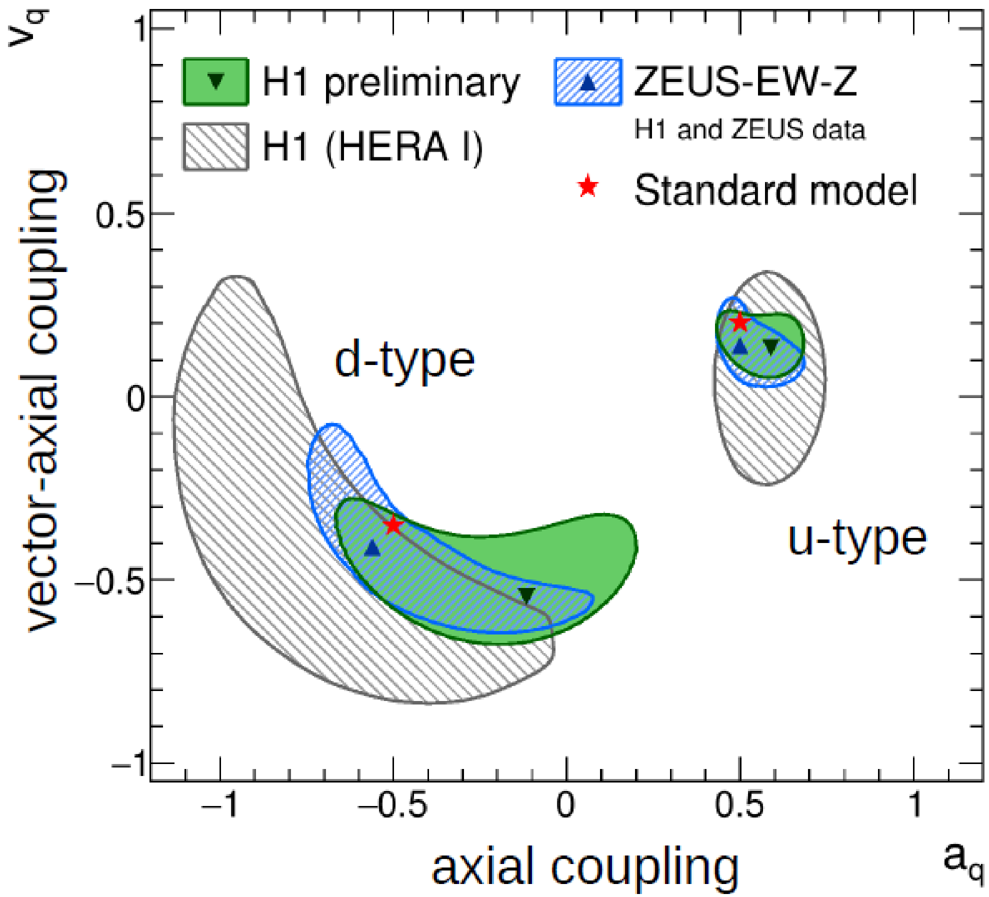


HERA EW Fit: q-Z Couplings

Exploit final HERA datasets to constrain electroweak parameters: light quark couplings, M_W, $\sin^2\theta_W$

Results from H1 and ZEUS collaborations

- χ^2/ndf typically around 1
  - ZEUS: 2946 datapoints
  - H1: 1388 datapoints
- *u*-type coupling better constrained than *d*-type coupling
  -> sensitivity from valence quarks
- *d-type* coupling:
  -> benefit from polarisation



Results from H1 and ZEUS compatible

- Results compatible with SM expectation

Comparison to H1 HERA-I

Phys.Lett.B 632 (2006) 35

- Considerably improved sensitivity using polarised HERA-II data
- Polarisation in HERA-II important for axial-vector couplings

D. Britzger

Tools needed for Fits

APPLfast-NNLO → M. Sutton

xFitter → V. Radescu

Simultaneous fit to jet data from multiple experiments

Avoids simple α_s averaging!

Input to combined fit

- choose H1, DØ (pure NLO) and CMS
  - no correlations assumed for exp. uncertainties across experiments
- PDF choice: MMHT2014nlo (others very similar)

Result

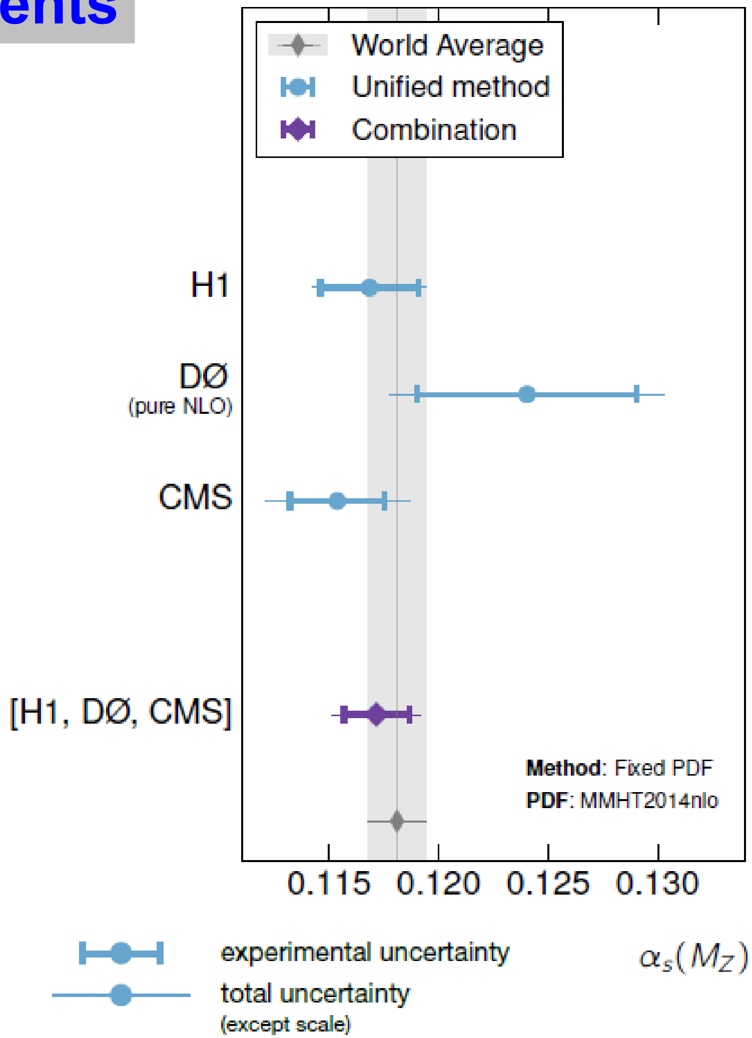
$$\alpha_s(M_Z) = 0.1172\,(15)_{\text{exp}}\,(5)_{\text{NP}}\,(9)_{\text{PDF, MMHT}}\,(8)_{\text{PDF set}}\,(5)_{\text{PDF}\,\alpha_s}\,(50)_{\text{scale}}$$

$$= 0.1172\,(15)_{\text{exp}}\,(14)_{\text{theo (except scale)}}\,(50)_{\text{scale}}$$

$$\chi^2_{\text{min}}/\text{ndf} = 152.2/178 = 0.855$$

Conclusions

- combined fit shows reasonable χ^2/ndf
- combined result compatible with individual fits
- uncertainties reduced



D. Savoiu

Summary & Outlook

- Beyond design performance of the LHC and the experiments
- But no sign of new physics so far :-(
- A plethora of new measurements, many at 13 TeV
- Sometimes limited in precision already by syst. effects and/or luminosity
  - Ratios of cross sections
  - Improve on PDFs and MC models
- Numerous (multi-)differential measurements and in fiducial volume!
- MC simulations use NLO+PS as a default and in almost all cases theory at least at NNLO is at hand
- Go find the odd-looking deviation from the SM
- Excellent playground for studies with more data, more ideas, and more precision in the future

Thank you for your attention!

Backup Slides

Input to HERA EW Fits

Input data to ZEUS fit

HERA-I: NC and CC
- All H1 and ZEUS HERA-I datasets
  - e^+ and e^-
  - NC and CC; low and high-Q^2
  - unpolarised

HERA-II: NC and CC
- ZEUS high-Q^2 polarised data
- H1 high-Q^2 unpolarised data
- ZEUS Reduced-E_p (unpolarised)
- H1 Reduced-E_p (unpolarised)

Correlations as in HERAPDF2.0
- More than 2900 data points

ZEUS-Fitter as fitting framework

Input data to H1 fit

H1 Low-Q^2 data
- NC and CC, e^+ and e^-
- All H1 HERA-I and HERA-II data are combined into one dataset

H1 High-Q^2 data
- NC and CC, e^+ and e^-
- HERA-I
  - H1 unpolarised data
- HERA-II
  - H1 polarised data

Polarisation measurements
- treated as measurement on its own

Alpos used as fitting framework

D. Britzger