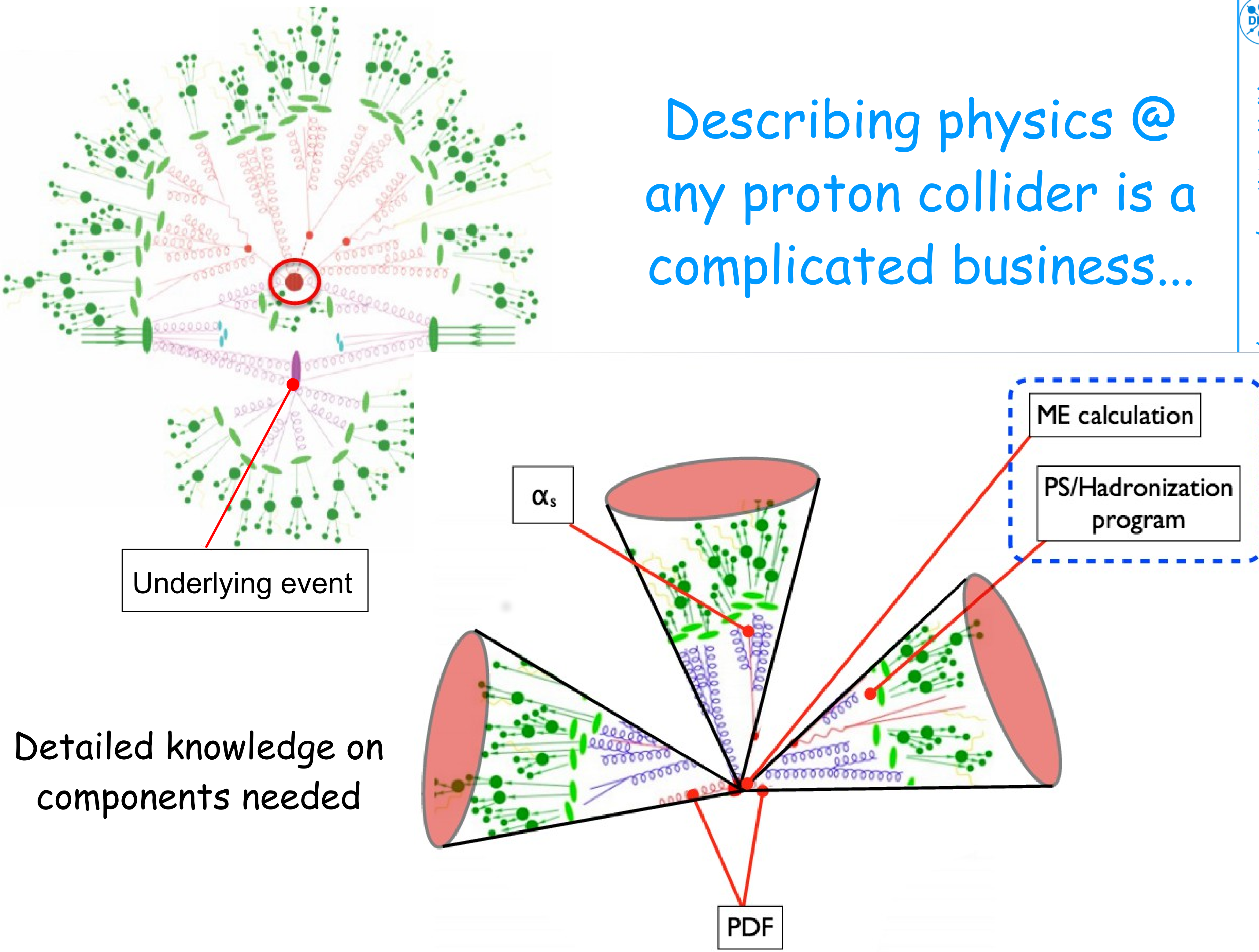
John Ellis @ LP2015

The basis for everything at the LHC

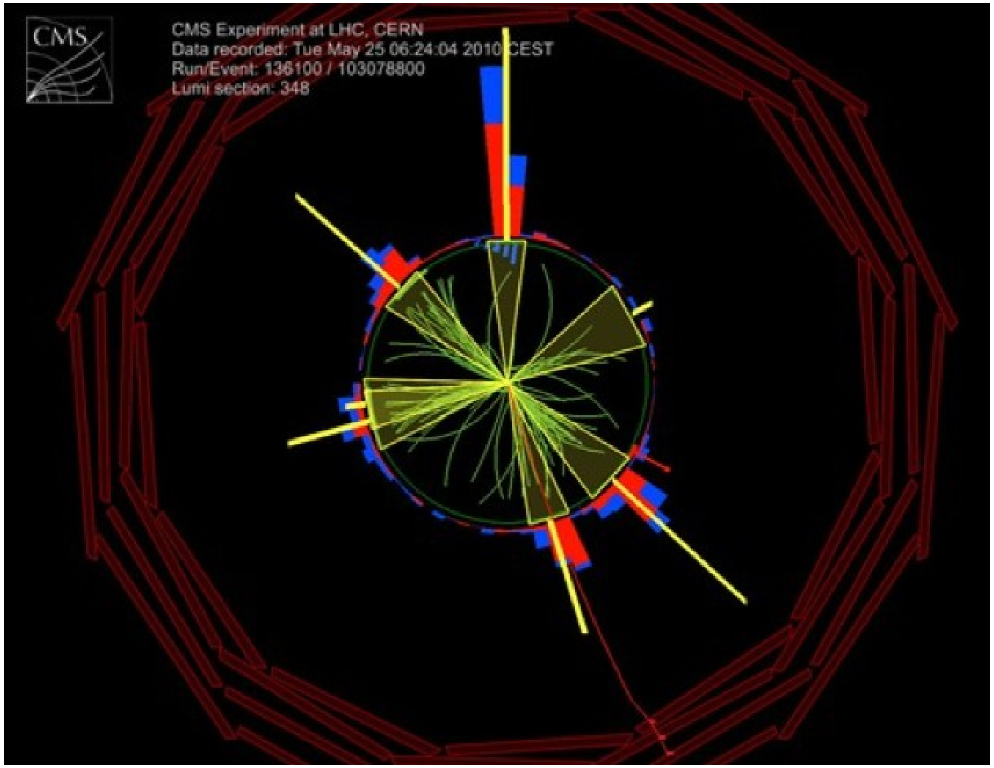
… end essentially everywhere else

Describing physics @ any proton collider is a complicated business...



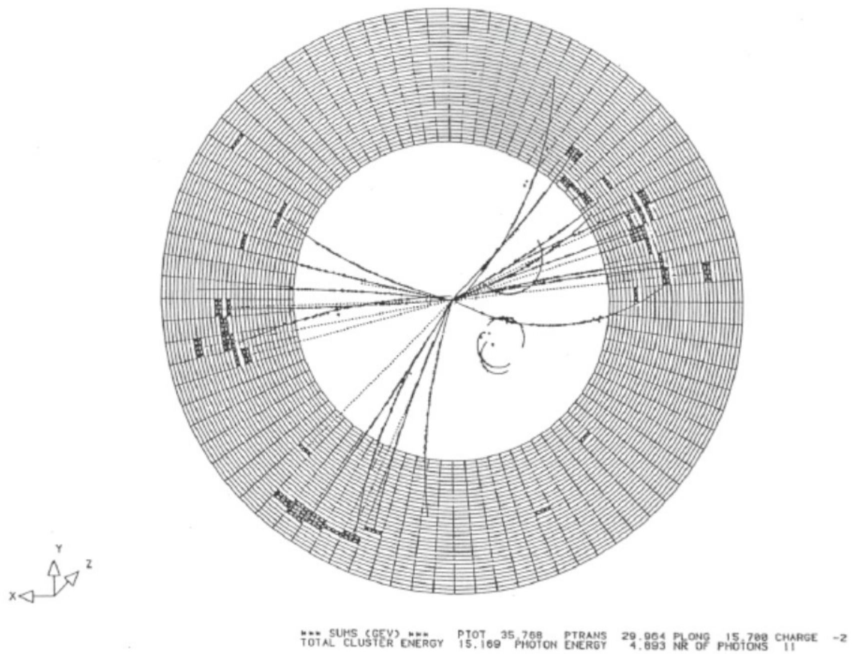
Detailed knowledge on components needed

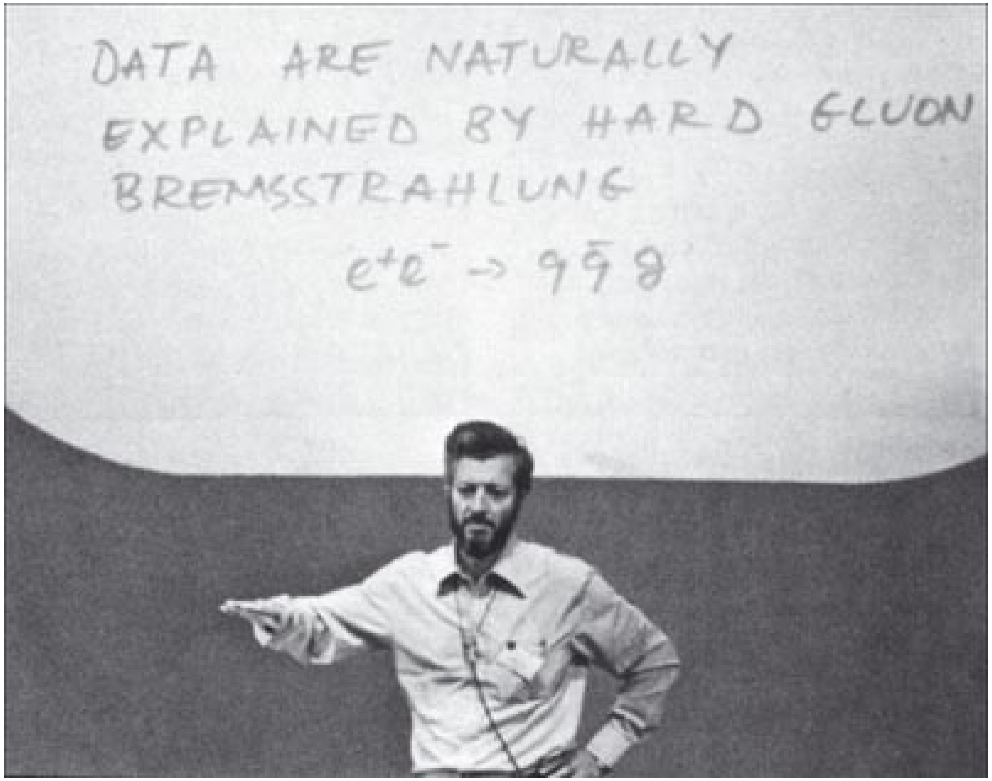
Jets in hard QCD



Jet production is excellent probes of QCD dynamics and modeling over many orders of magnitude

- Plenty of reasons to study jets !
  - pQCD calculations
  - α_s determination
  - Constraining PDFs
  - Understanding non-pQCD
  - MC tuning
  - New particle searches with jets in final states
- Many experimental results from HERA, Tevatron & LHC at different CME





36th anniversary of GLUON

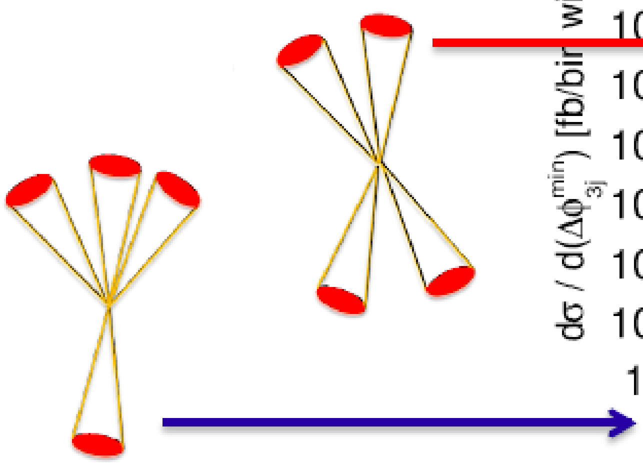
- PETRA, 1979
  - → 1st observation of 3-jet events
- LHC, 2015
  - → jet factory

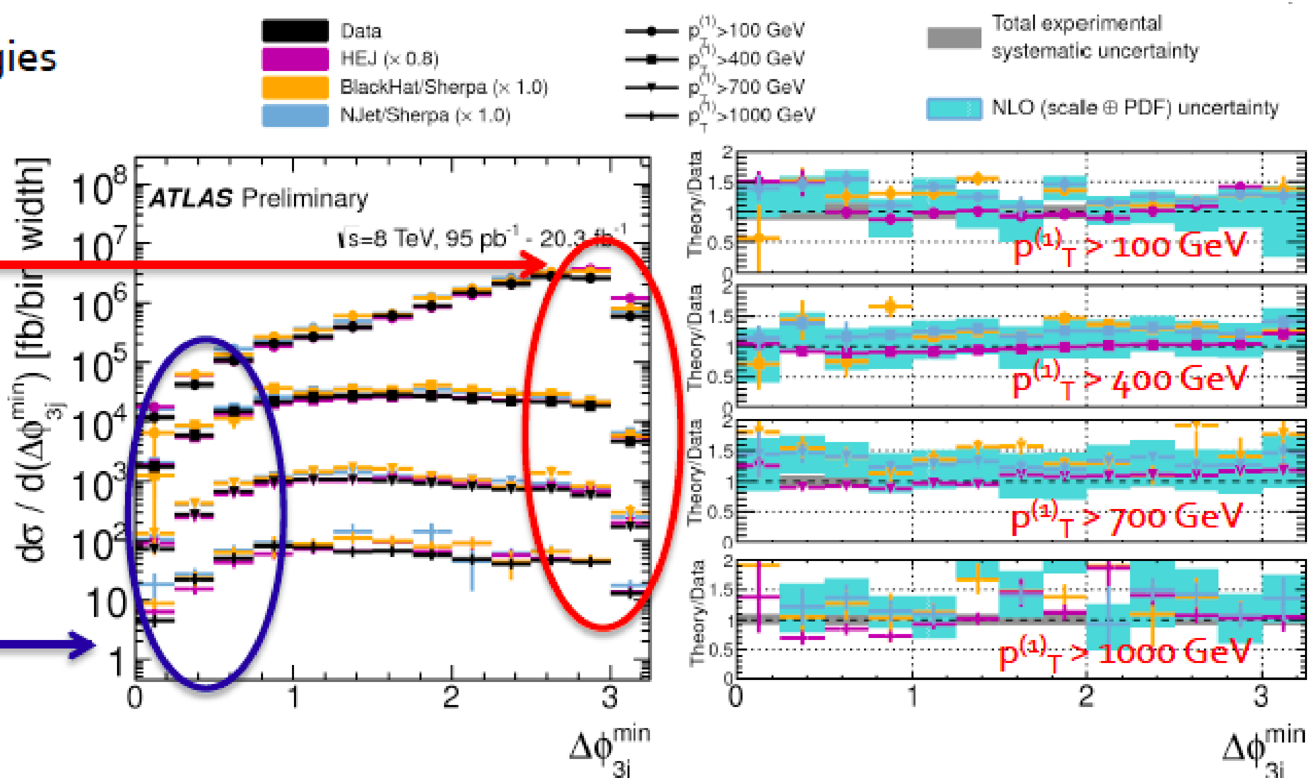
Hard QCD: jet cross-sections

- **ATLAS 4-jets cross-sections at 8 TeV**, differentially in several variables depending on the jet momenta and angular distributions, in various event topologies
  - **Test of LO (PS and ME+PS) and NLO predictions up to multi-TeV scales**

➢ $\Delta\phi^{min}_{3j}$: 2-vs-2 from 1-vs-3 topologies

$$\Delta\phi^{min}_{ijk} = min_{\substack{i,j,k\in[1,4] \\ i\neq j\neq k}} \left(|\Delta\phi_{ij}| + |\Delta\phi_{jk}|\right)$$





➢ NLO predictions `BlackHat/Sherpa` and `NJet/Sherpa`: compatible with data within large theoretical uncertainties (O(30%) at low momenta)

➢ HEJ (all-order resummation) provides a good description of angular variables

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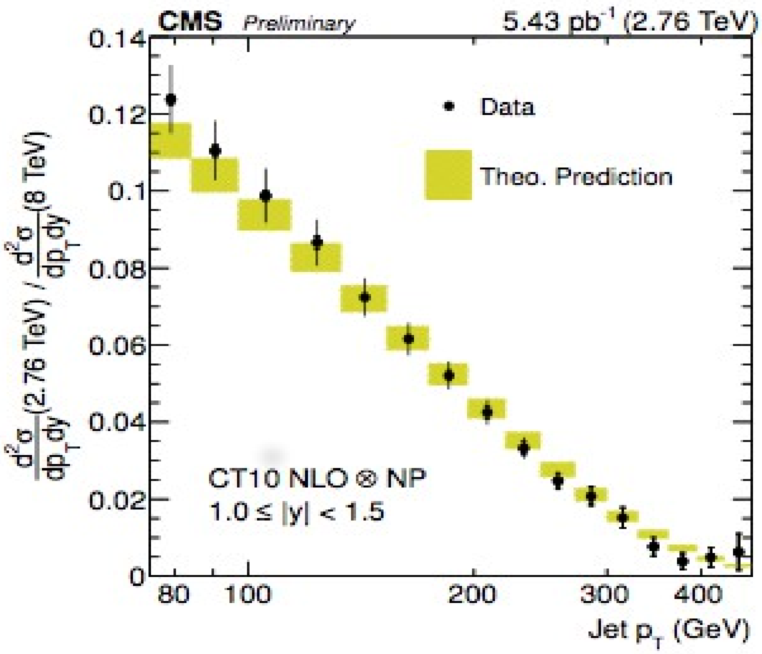
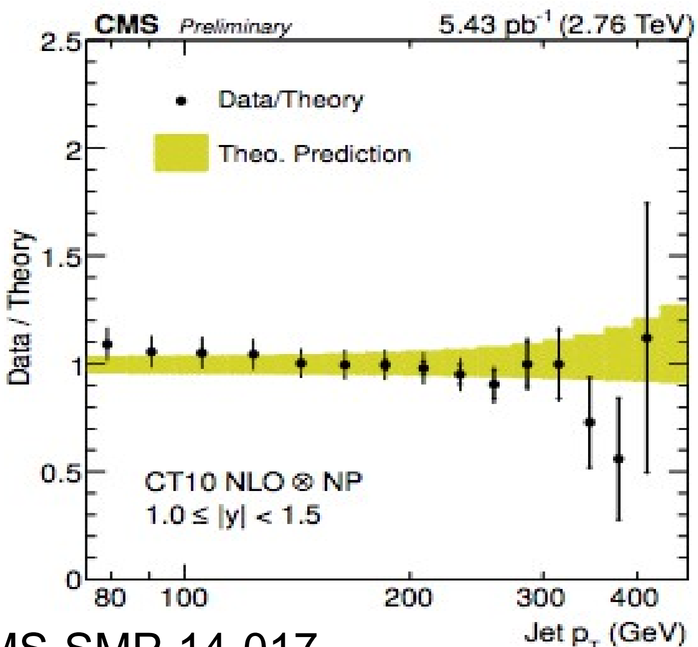
Ratio of jets @ 2.76 and 8 TeV





CMS-SMP-14-017

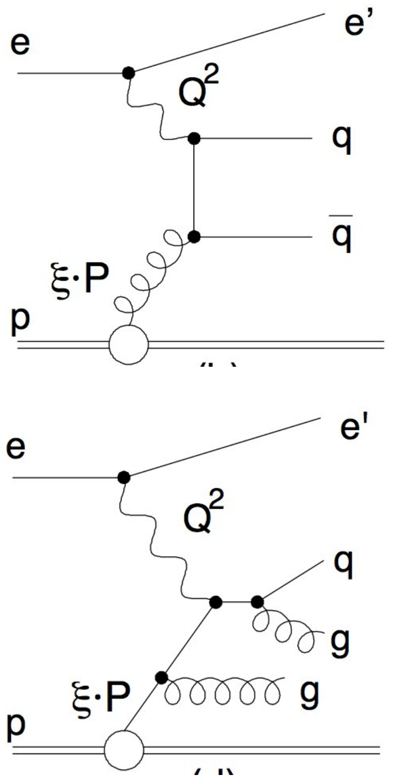
- Ratios of jet cross–sections at different $\sqrt{s}$ measured
  - Proper taking into account correlated uncertainties necessary
  - Some uncertainties cancel
  - Precise test of QCD at different $\sqrt{s}$
  - input to global QCD fits (EPJC(2013)73 2509)

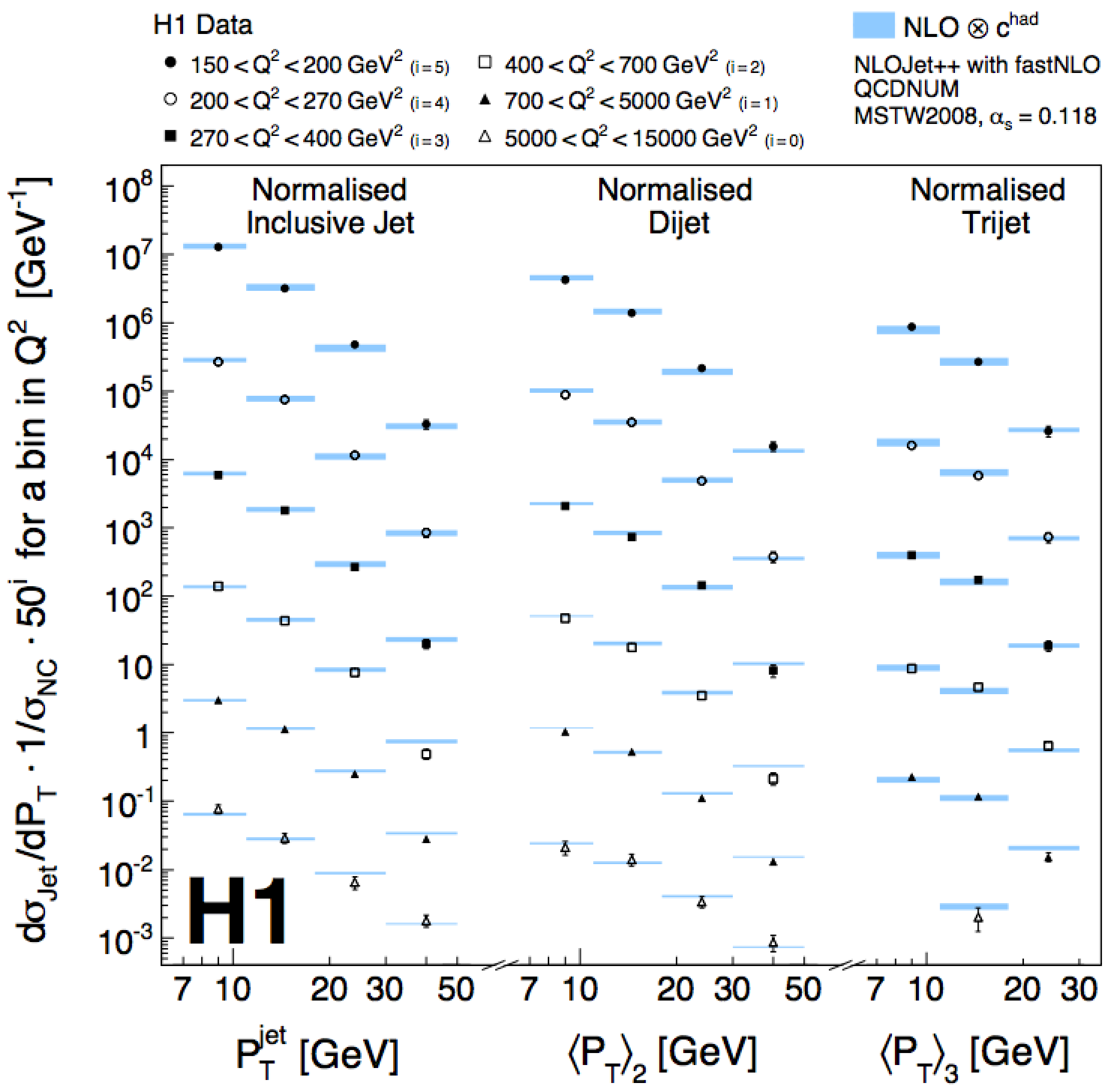
- CMS 2.76 TeV / 8 TeV ratio in range 0.1–14%
  - decreases with increasing jet p_T

good agreement with NLO theory

Multi-jet production @ HERA

- Complementary measurements of multi−jet cross sections at HERA and LHC
- Different sensitivity to underlying sub−processes and parton densities, e.g. gluon & quarks at high x



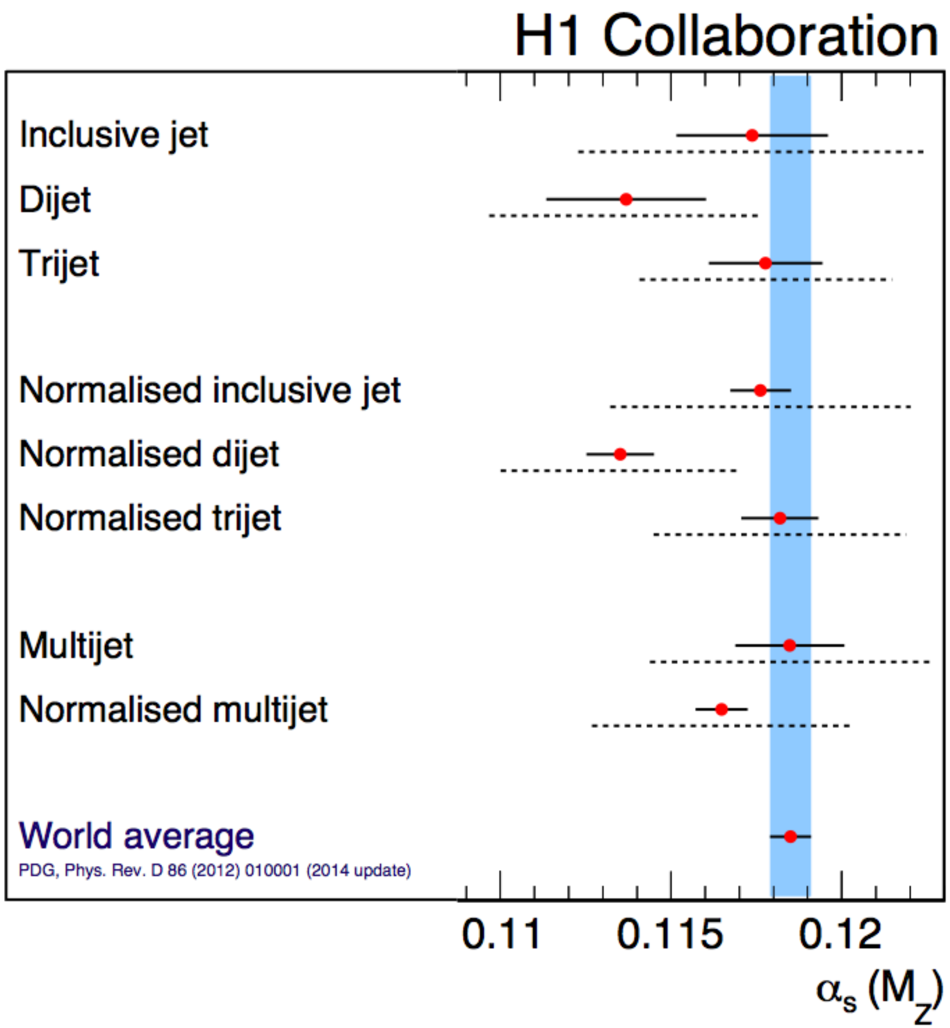


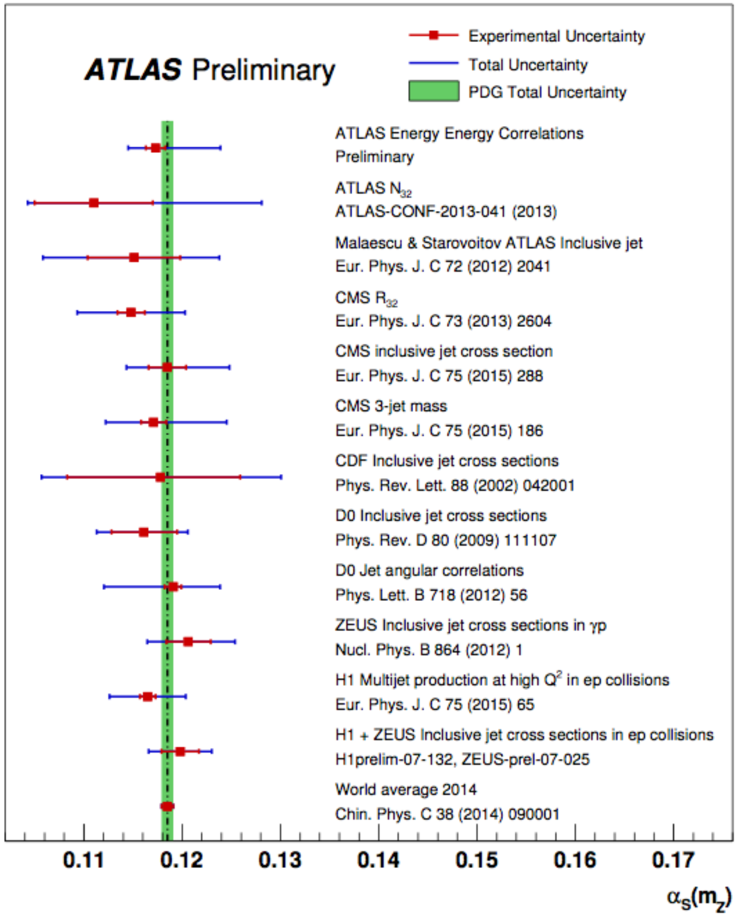
- H1 also measures $\sigma_{JET}/\sigma_{DIS}$
- Good description by NLO

Eur. Phys. J. C75 (2015) 2, 65

α_s measurements

α_s: fundamental QCD quantity which many measurements are sensitive to



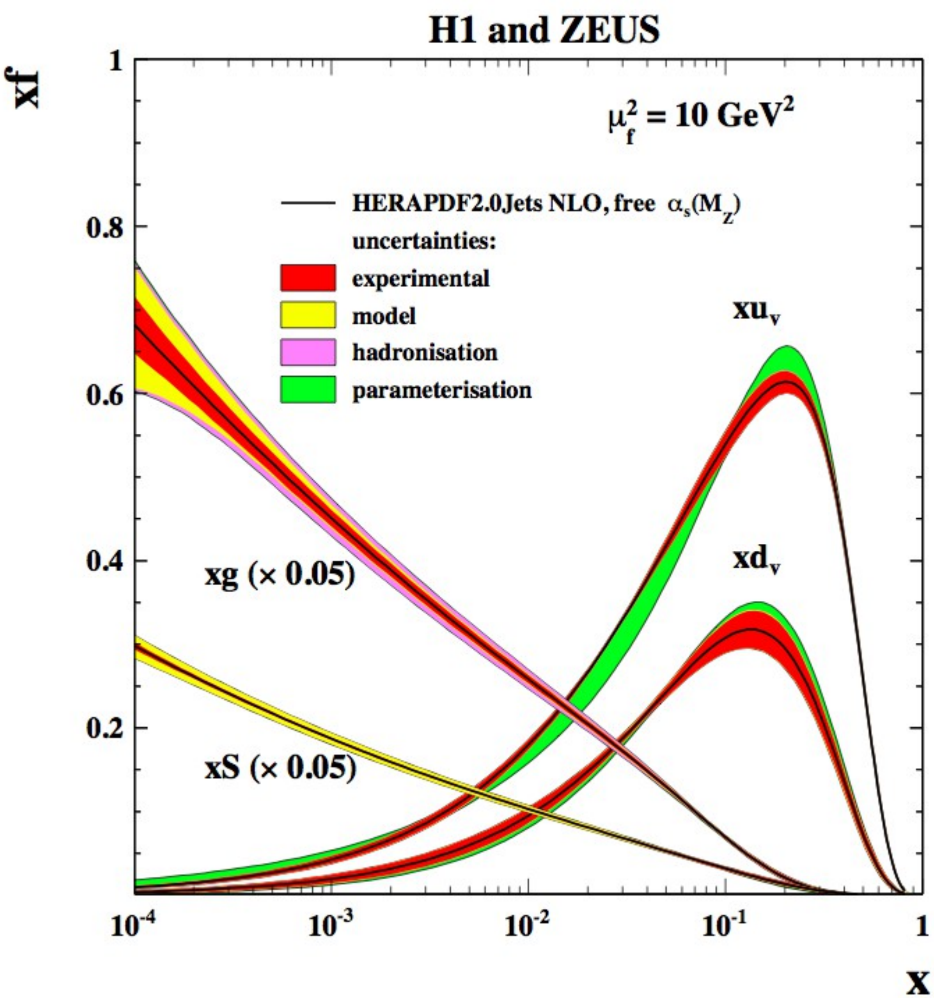


Theory uncertainty dominates

- experimental even < 1%!

Excellent compatibility with World Average of jet–based measurements at hadron and ep colliders

α_s from global QCD fits



$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\mathrm{exp})$$

Experimental uncertainty below 1%

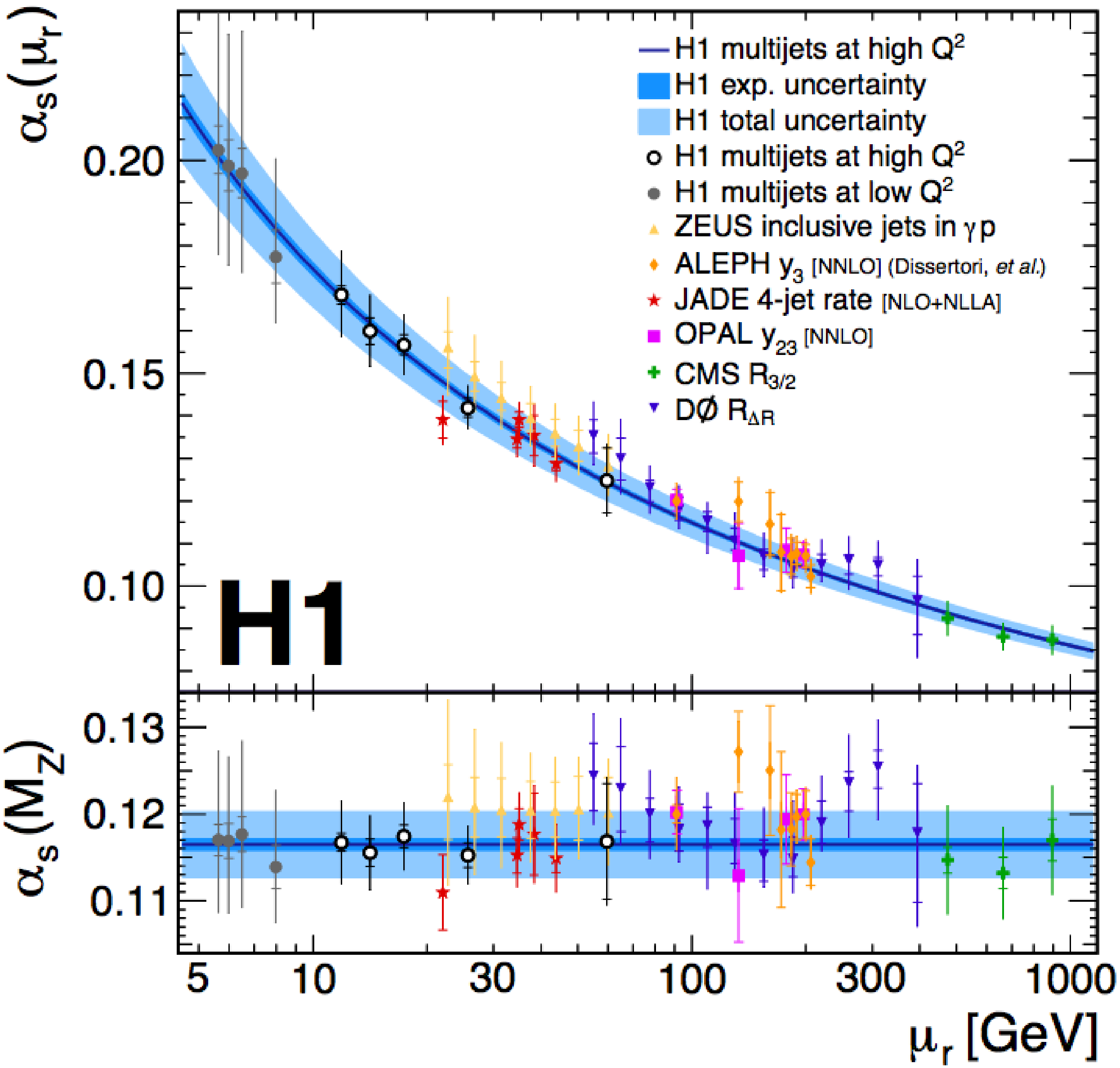
$$\pm 0.0005(\mathrm{model/parameterisation})$$

$$\pm 0.0012(\mathrm{hadronisation})$$

$$^{+0.0037}_{-0.0030}(\mathrm{scale})$$

Uncertainty dominated by theory, NNLO ep jet calculations needed

α_s running



- α_s sensitive to new physics
- Running of α_s measured to unprecedented scales in many different processes at LHC & HERA

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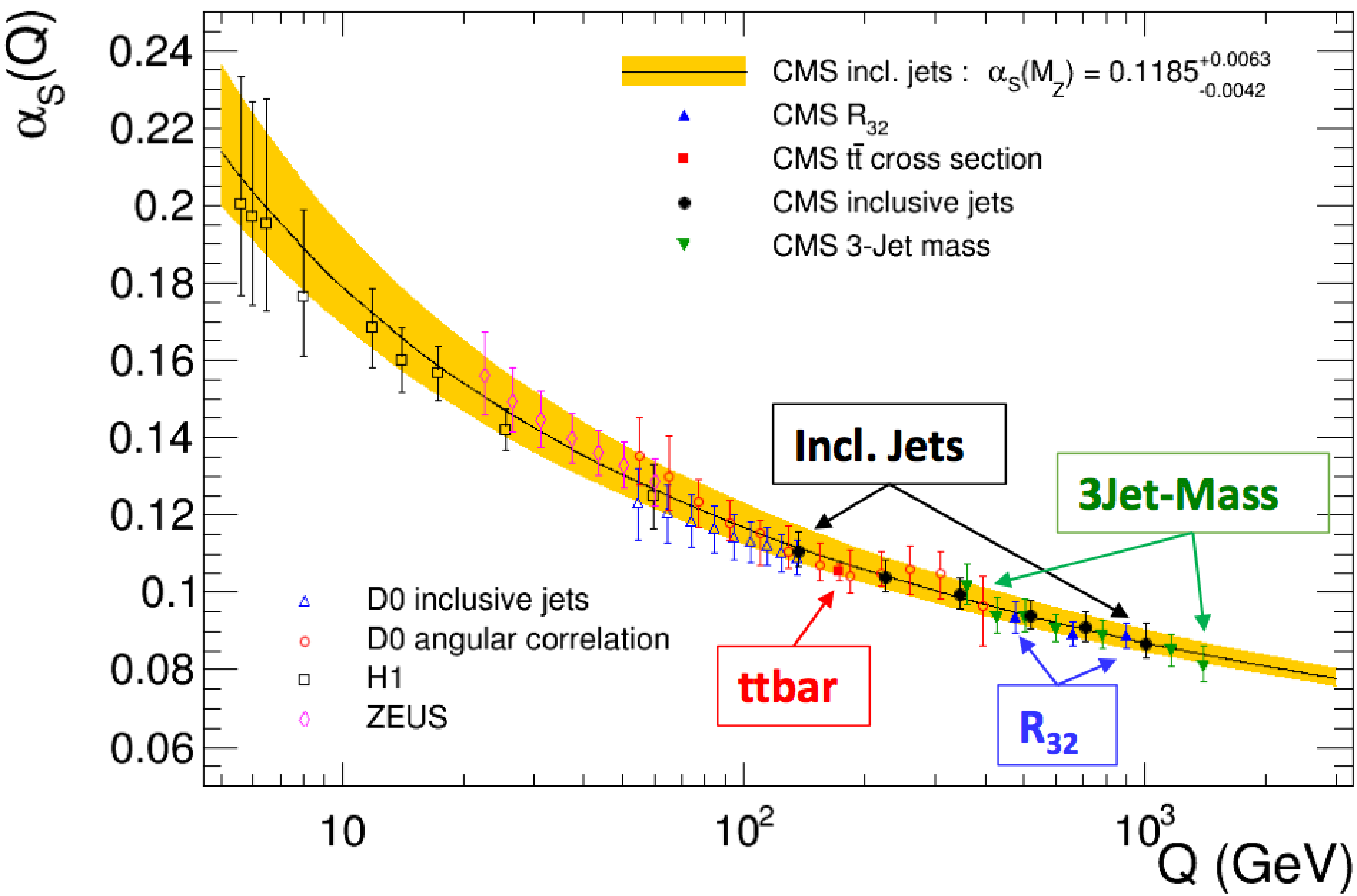
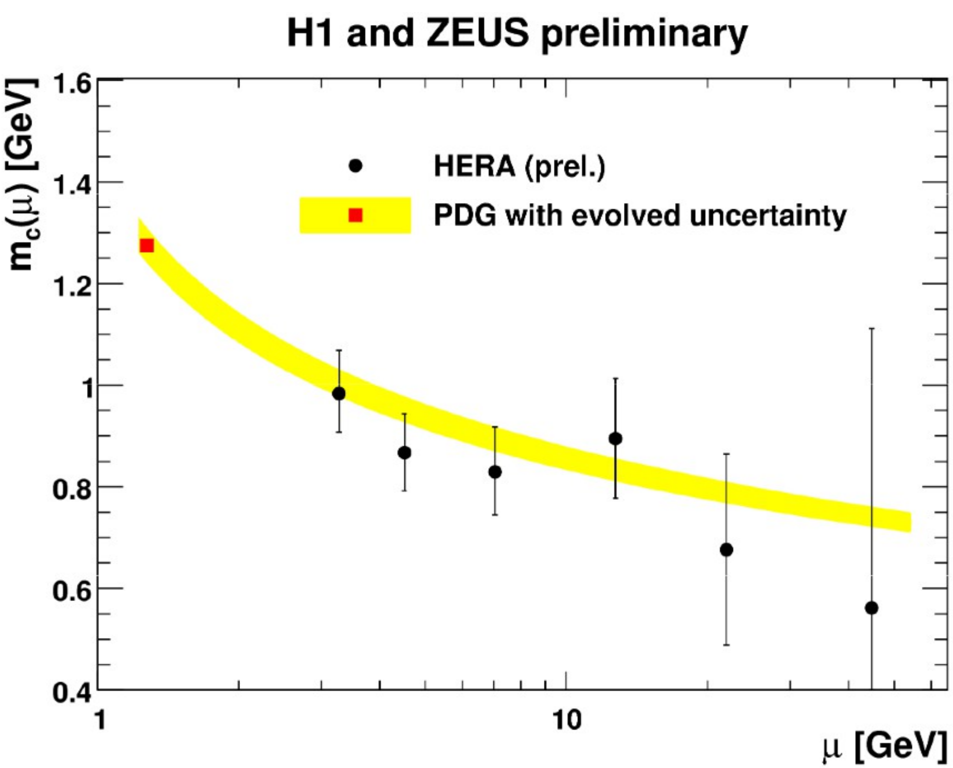
α_s running

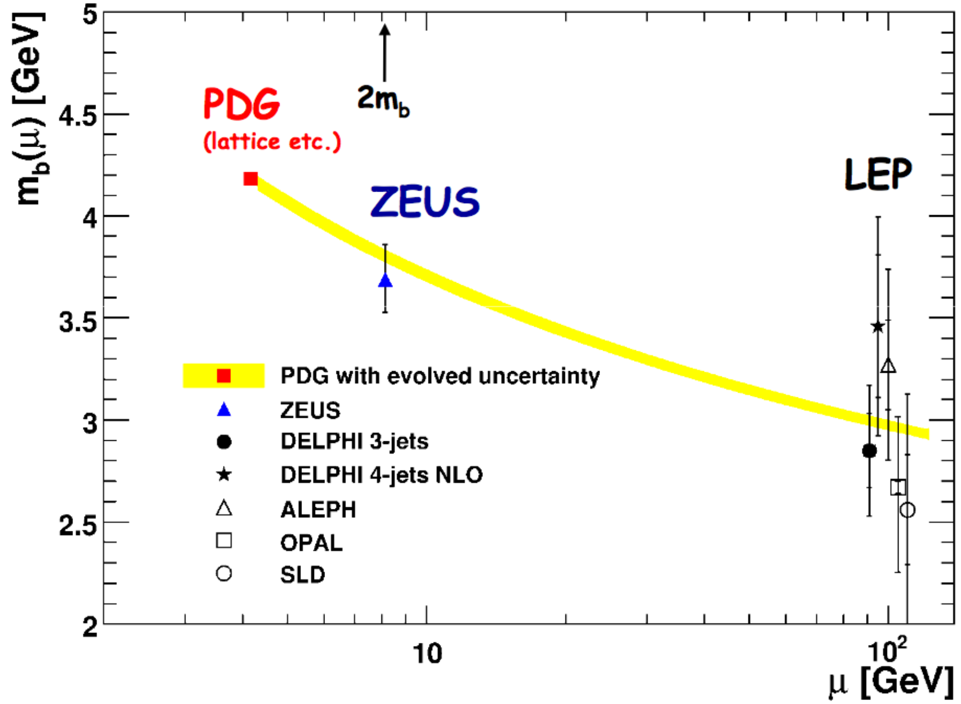


K. Wichmann, PIC2015, Everything you want to know about QCD…

Charm & beauty mass running

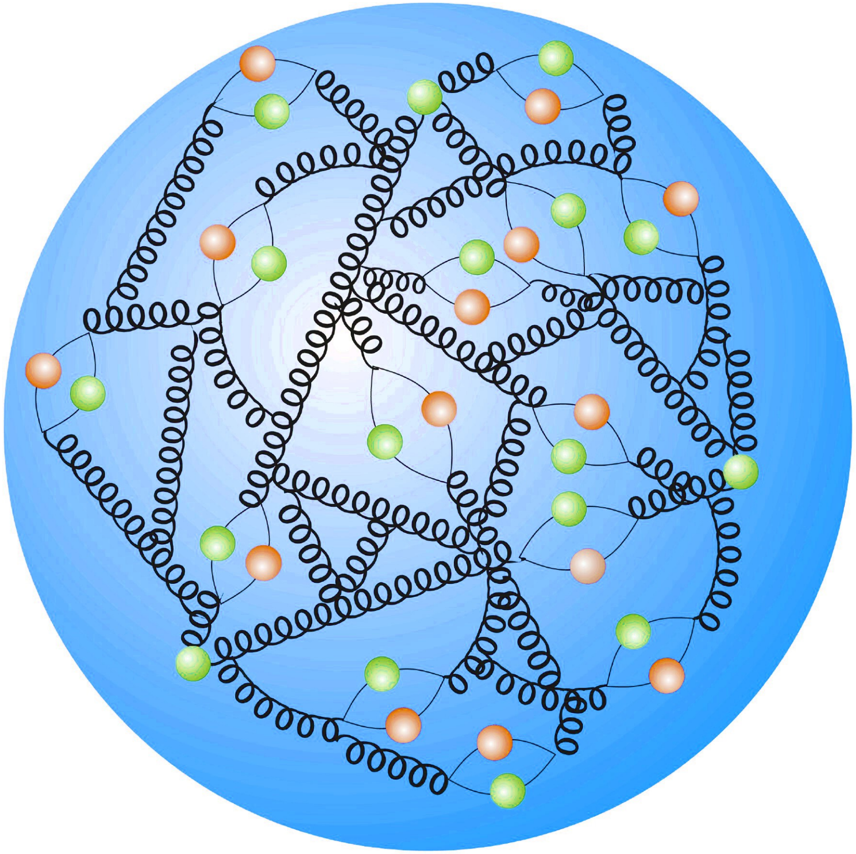
- HERA combined charm data well described by QCD in FFNS
  - Measure mass running
- ZEUS beauty data well described by NLO QCD
  - Measure mass running





- Charm and beauty mass running consistent with QCD

Global QCD fits



Global analysis of parton distributions

Goal: determination of the ***input distributions*** (for light quarks and gluons):

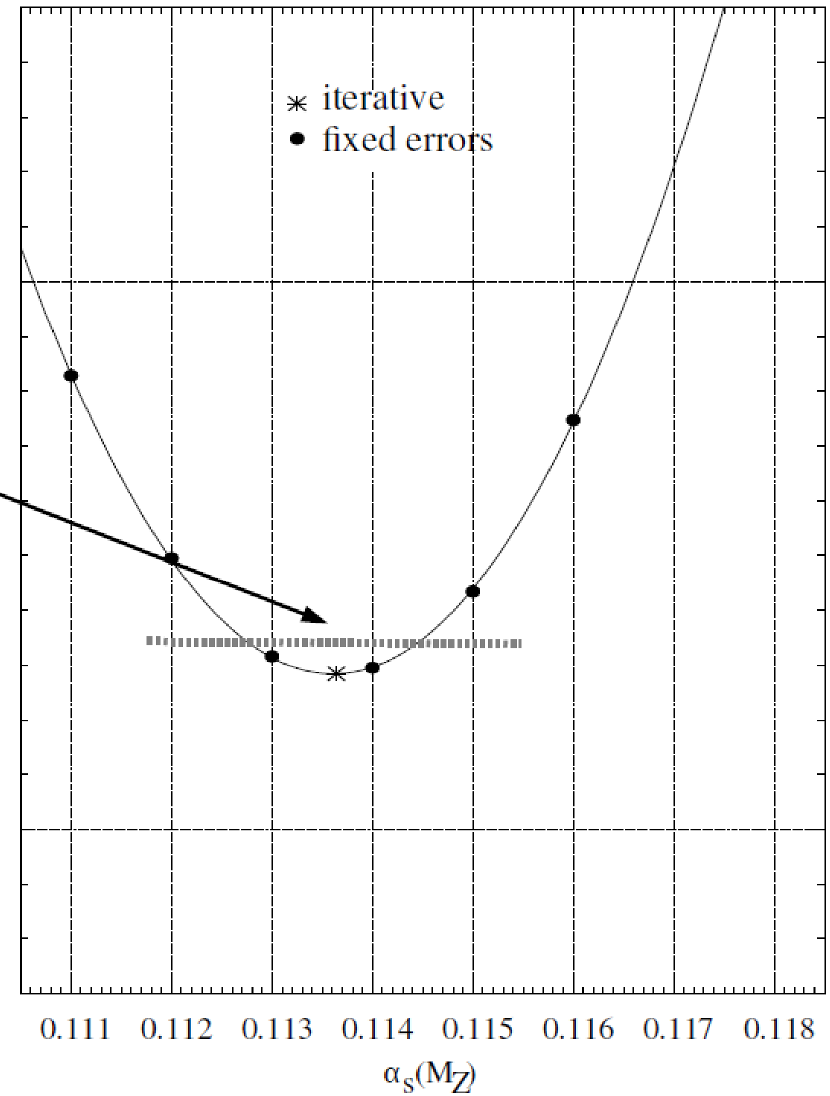
Method: Parametrizations $xf(x, Q_0^2) = Nx^a(1-x)^b \, \text{function}(x)$
and usual *statistical estimation* (fits):

$$\chi^2(p) = \sum_{i=1}^{N} \left(\frac{\text{data}(i) - \text{theory}(i,p)}{\text{error}(i)} \right)^2$$

Position of minimum gives the value and curvature gives the error (region within a certain "tolerance" $\Delta\chi^2 = 1$)

(Monte Carlo methods can also be used)

Usually the chi-square definition is more sophisticated, experimental correlations are also treated, etc.

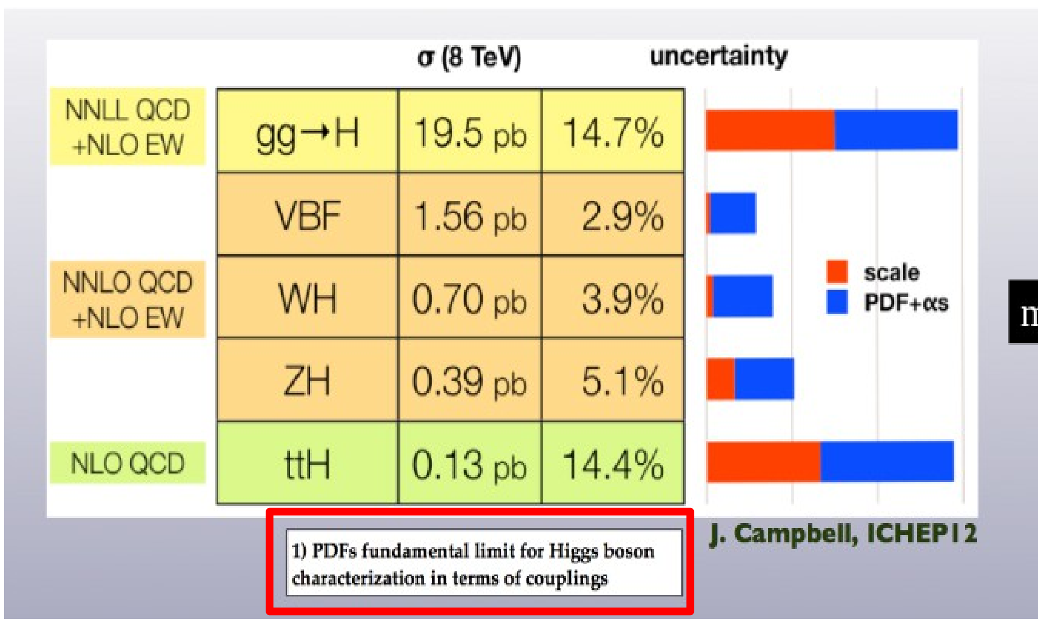


PDF uncertainties important

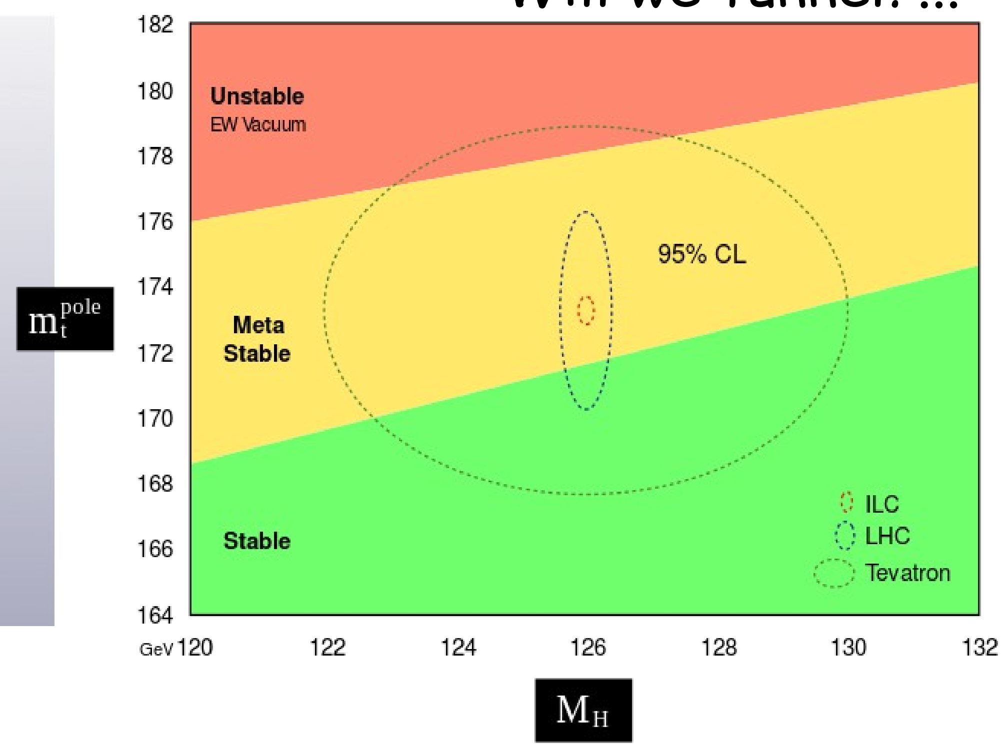
- Parton densities necessary for every process with scattering proton
- <u>Uncertainties of many variables often dominated by PDF uncertainties</u>

- PDFs necessary for background estimate BSM searches and SM tests
- Important for global electroweak fit parameters like m_W

Will we tunnel?...

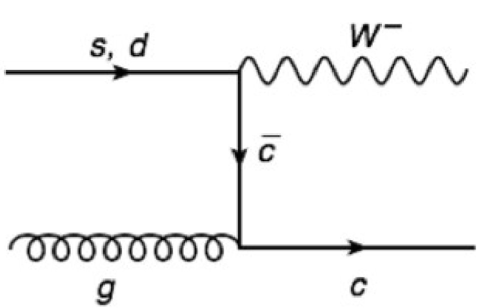


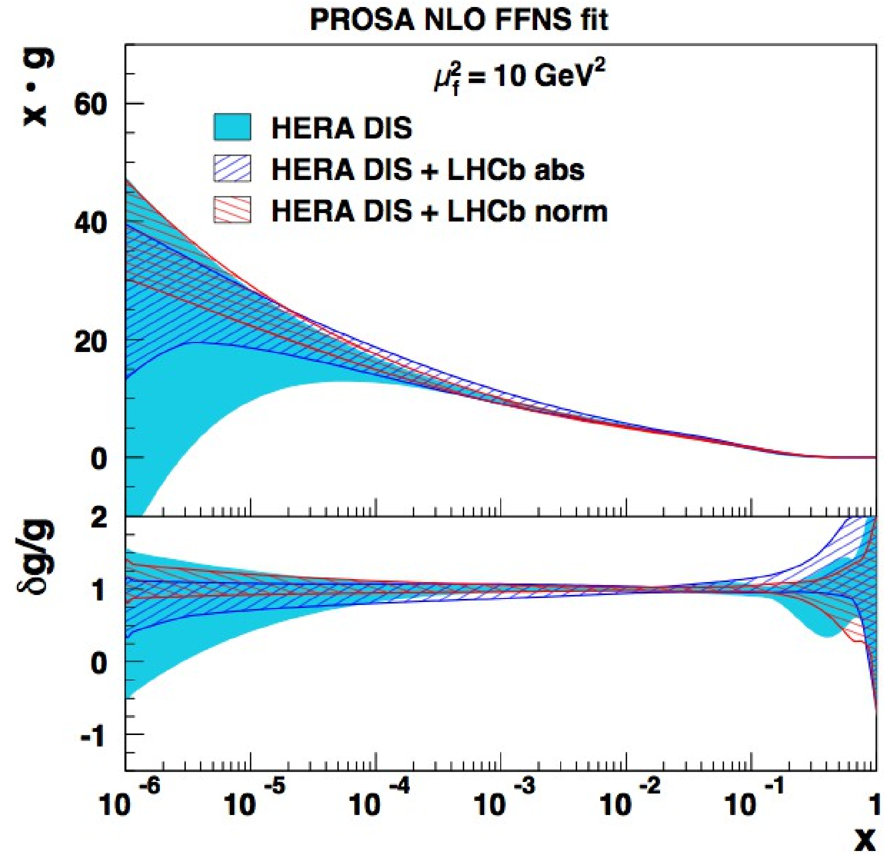
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%

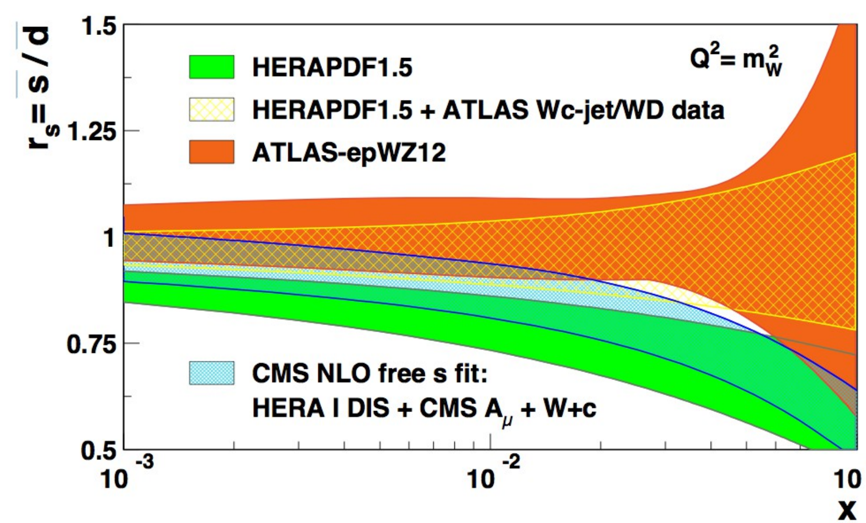


Adding LHC & Tevatron data to PDFs

- LHC and Tevatron data gives additional constrains for PDFs
  - Jets → gluon, quarks
  - Heavy flavors → gluon
  - Drell-Yan and W assymmetry → quarks & antiquarks
  - W + charm → strange sea!

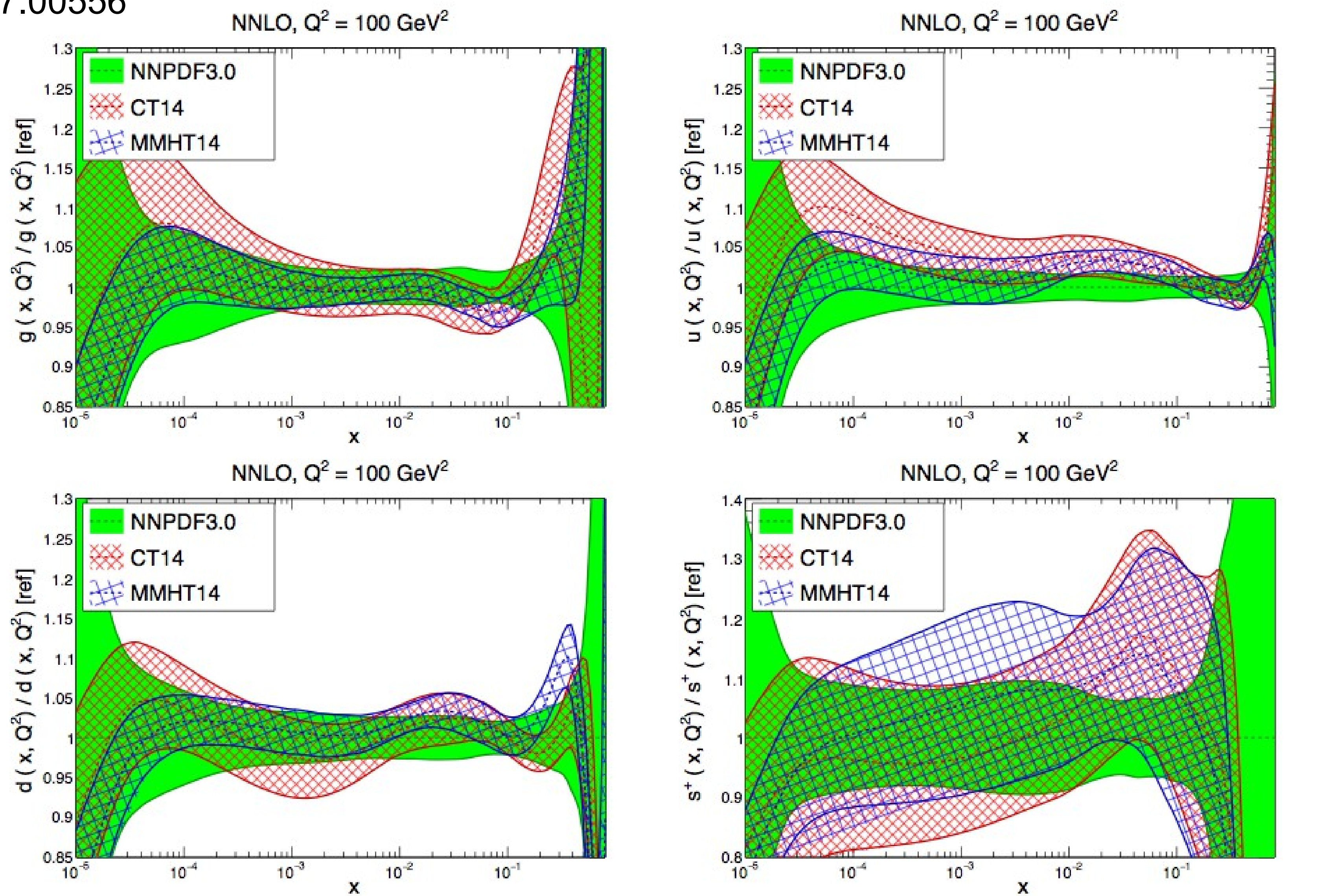






Present picture of PDFs

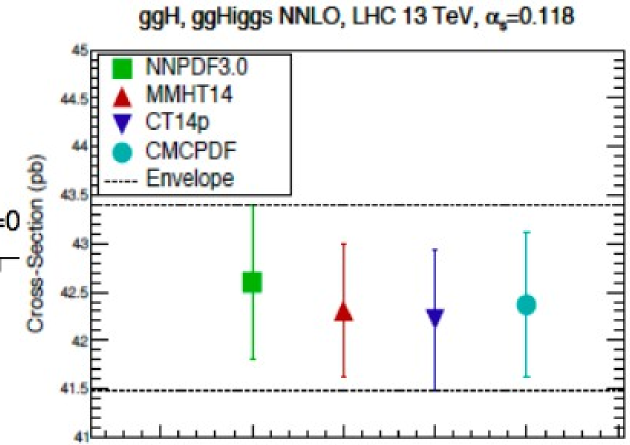
arXiv:1507.00556

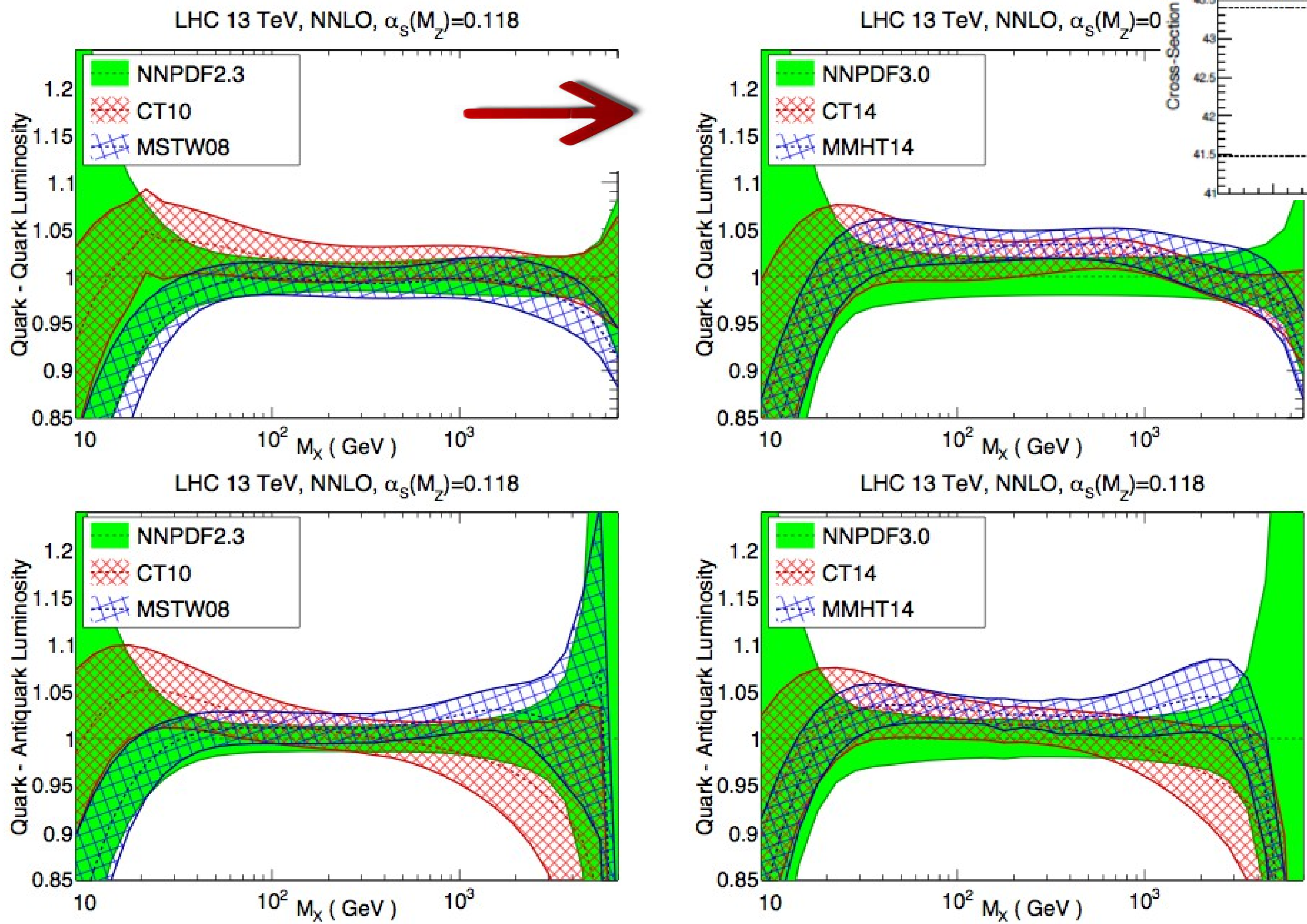


PDFs still differ but present ones closer together and more precise

Alexander von Humboldt
Stiftung/Foundation

PDFs @ 13 TeV



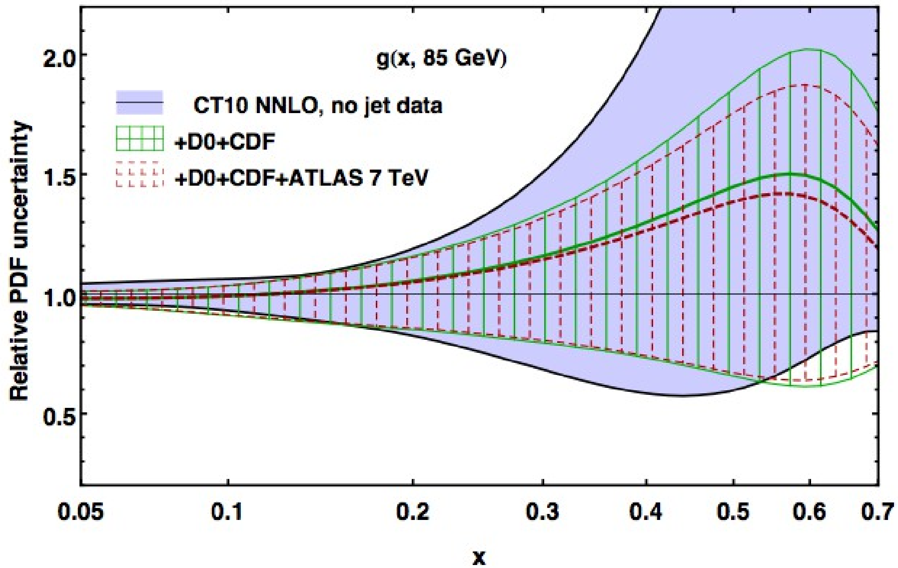


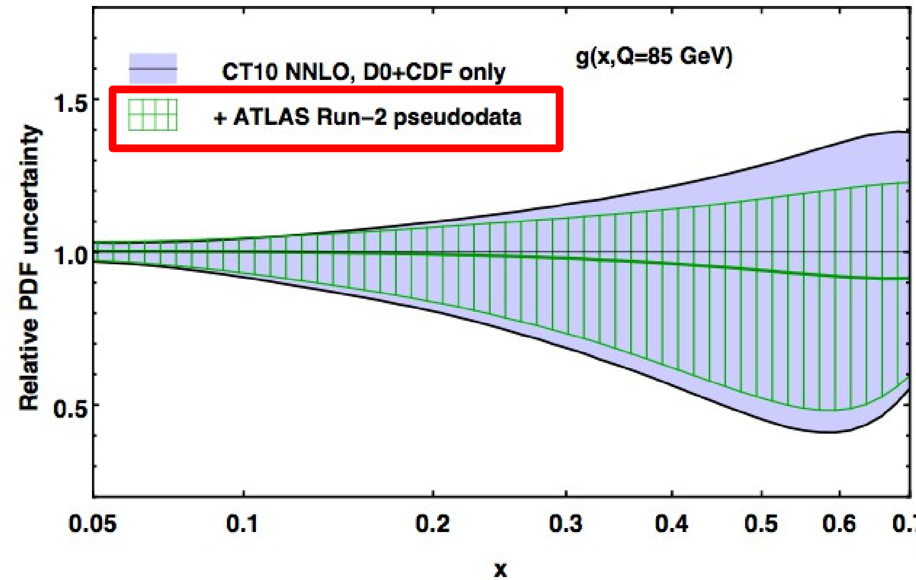
Clear improvements in PDFs with LHC and Tevatron data added

C2015, Everything you want to know about QCD...

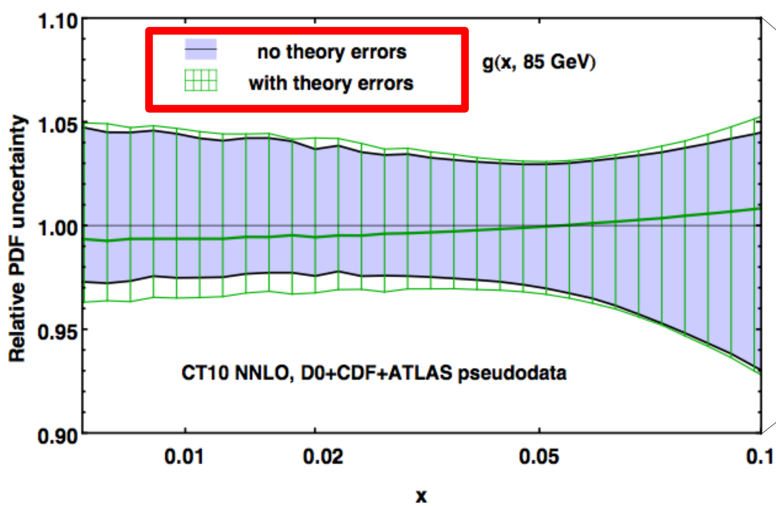
Back to the future...

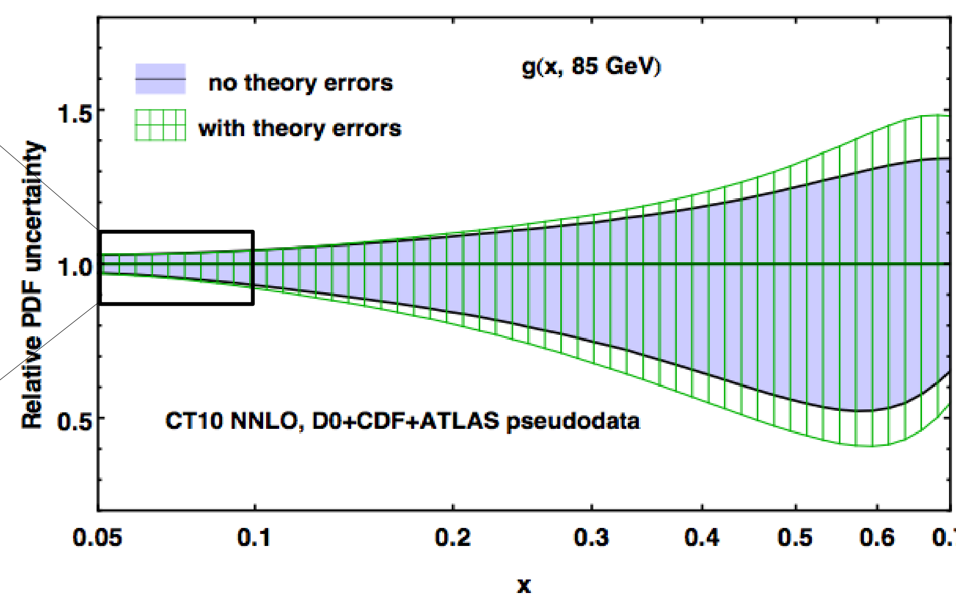
Run-2 data important





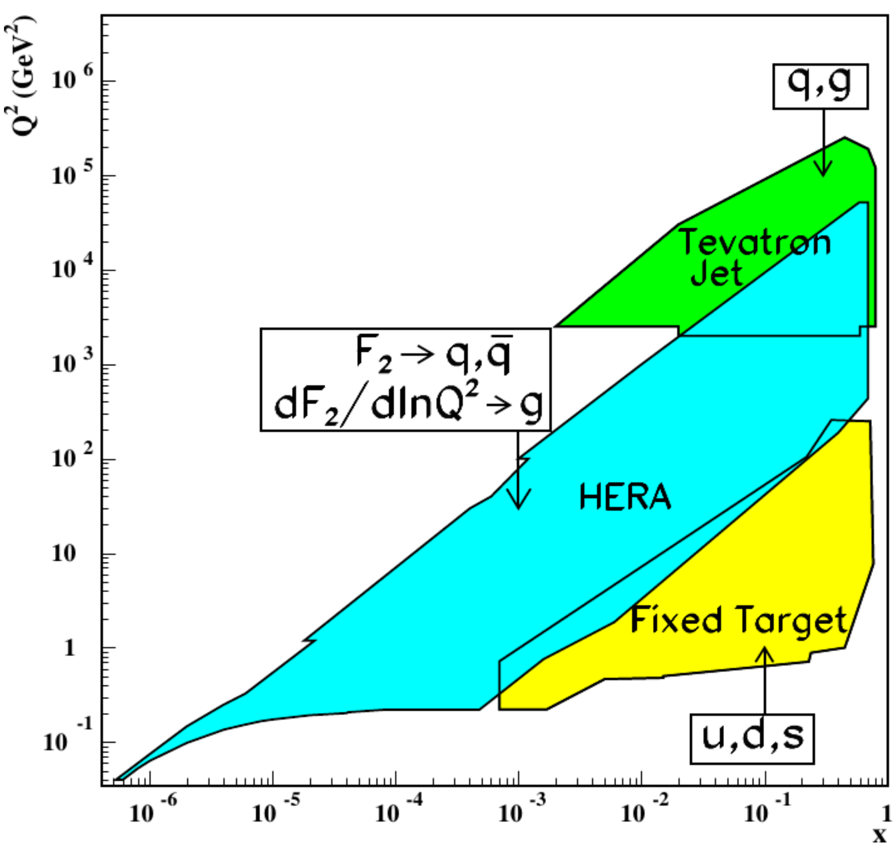
Theory uncertainty important



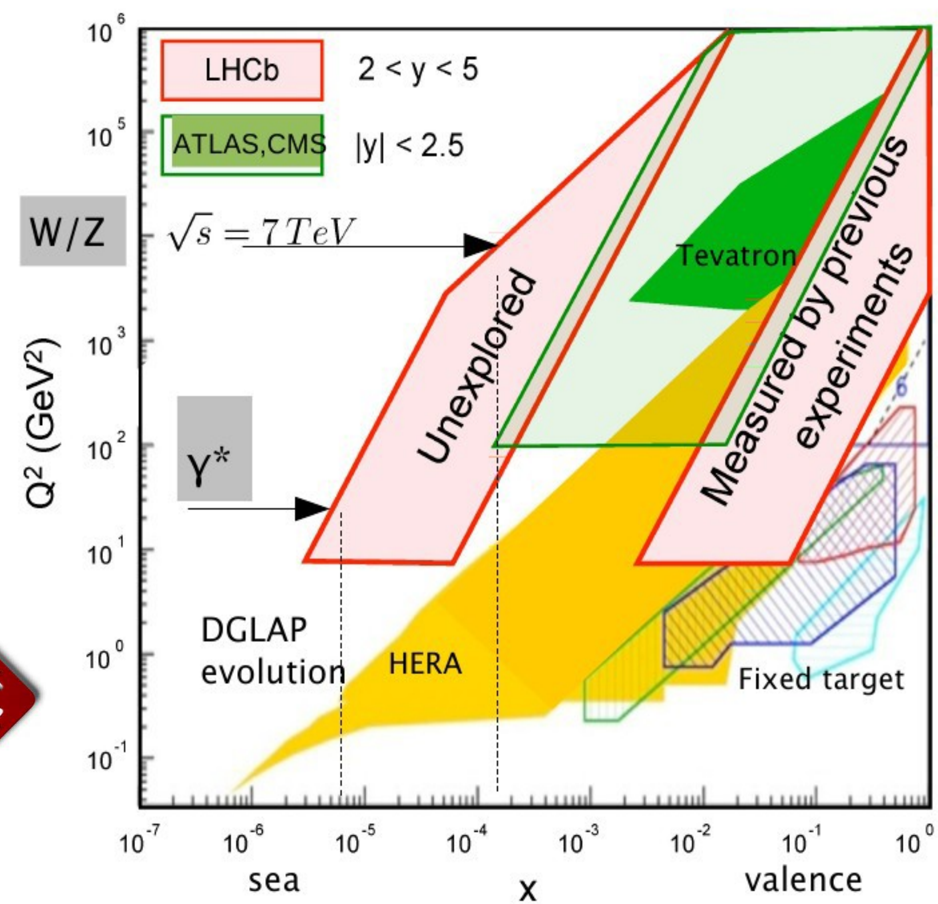


Present PDF landscape

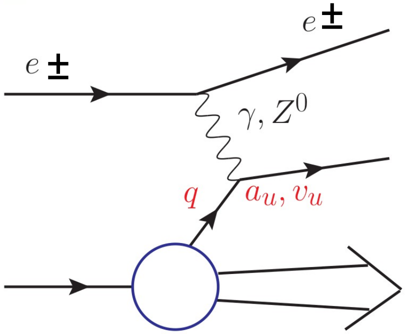
Data for parton distributions: preLHC

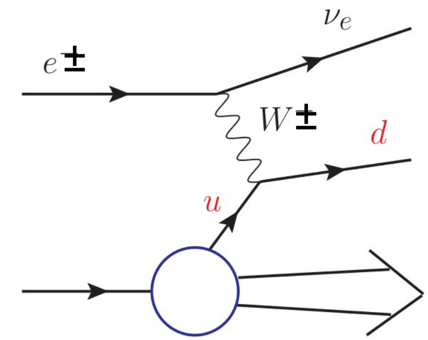


Now:from predicting LHC measurements to using them to constraining parton distributions

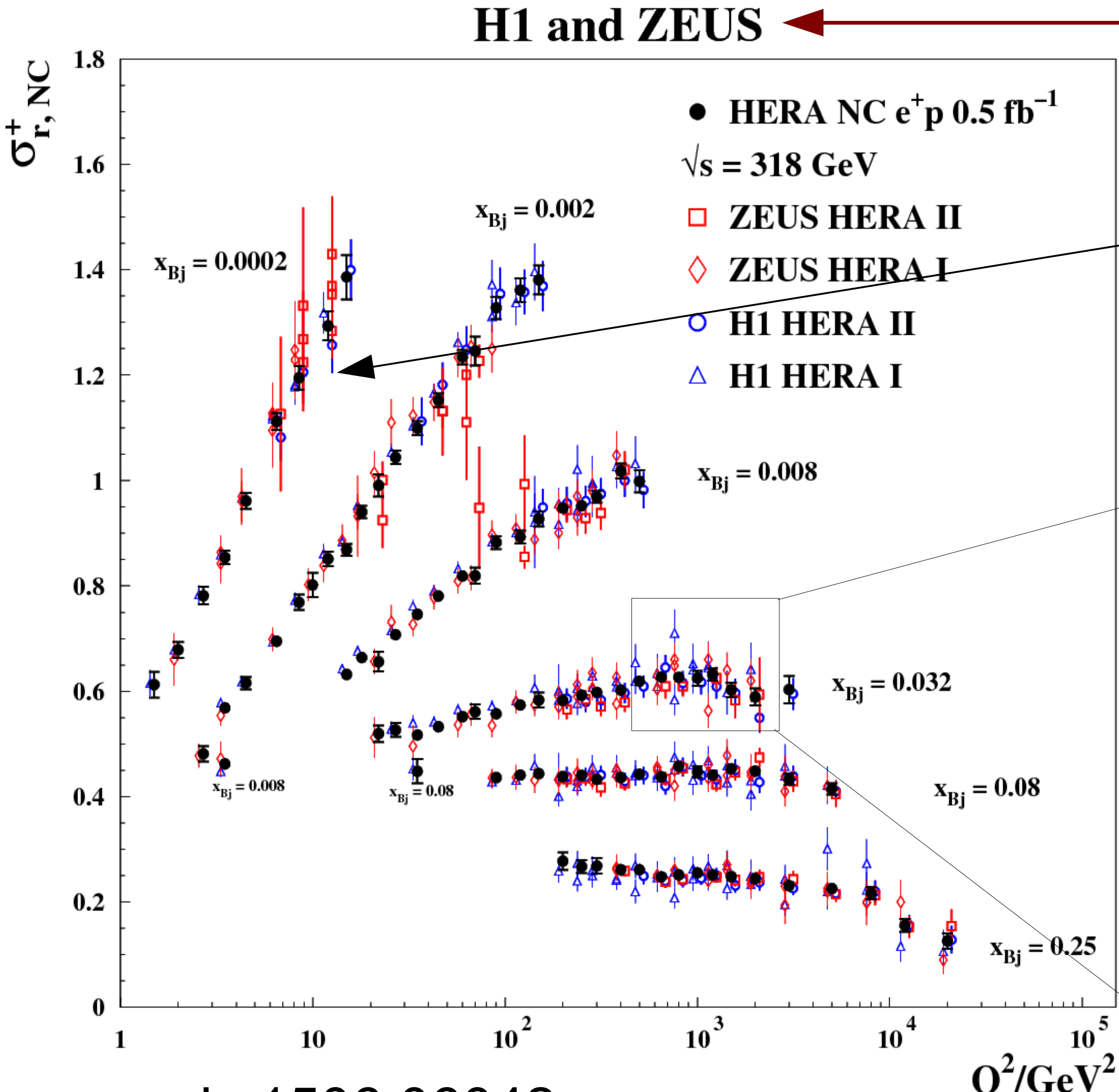


DIS @ HERA: core of ever PDF extraction

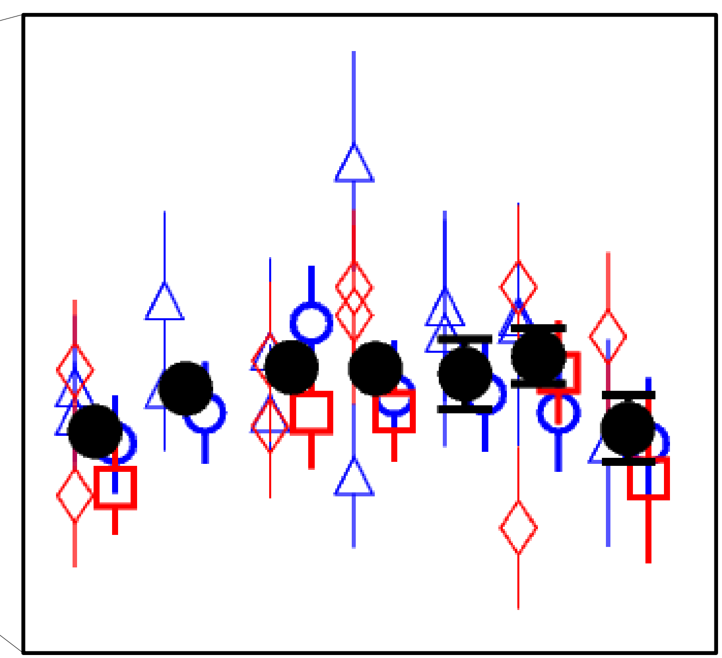




Combined cross sections



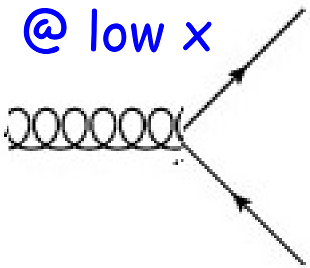
- 2927 data points combined to 1307
- 162 correlated systematic uncertainties accounted for

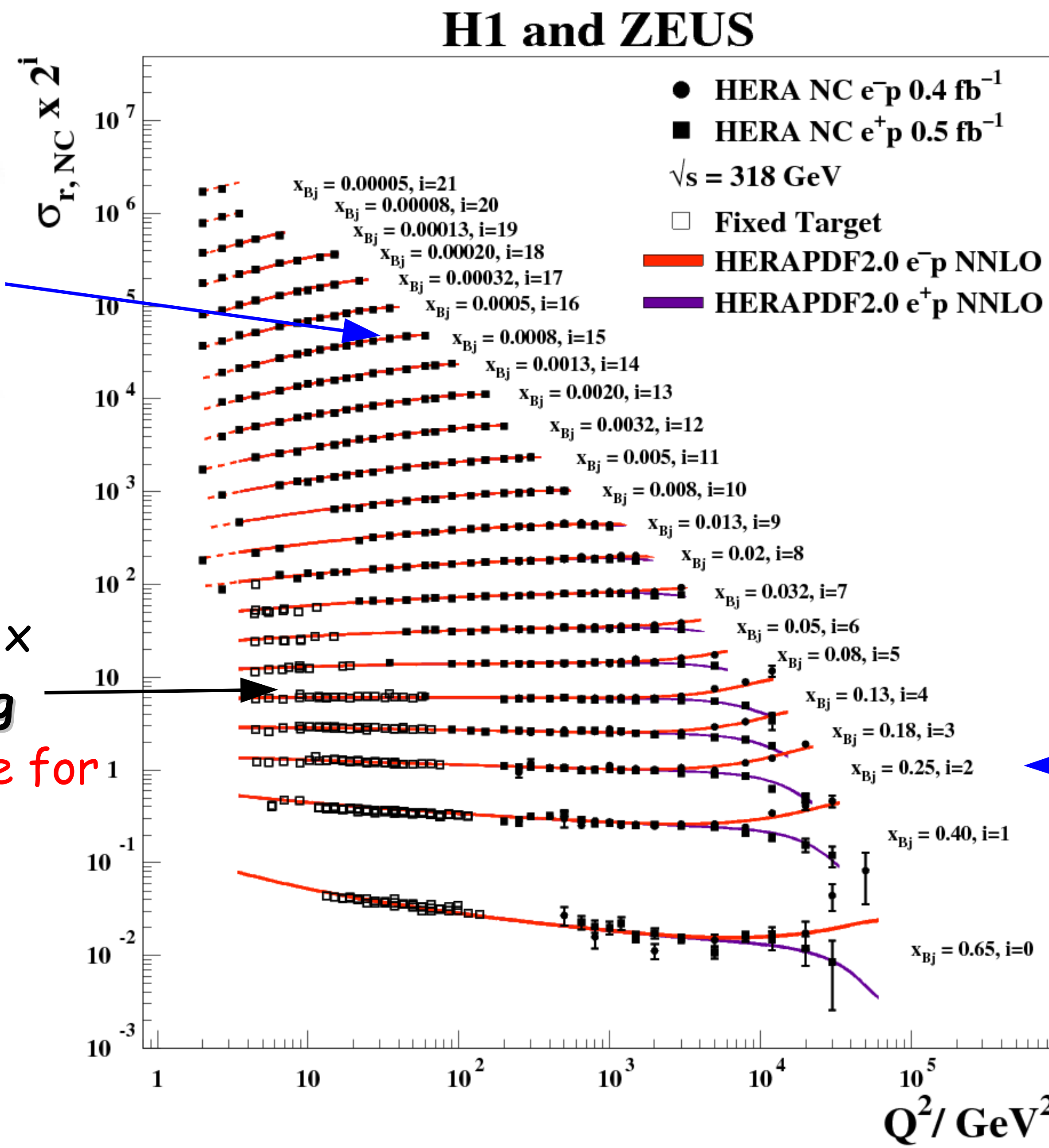


arxiv:1506.06042

QCD scaling and scaling violation

@ low x

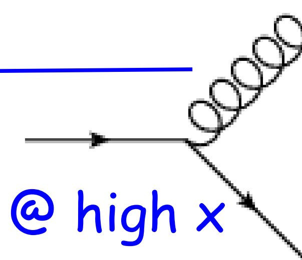




@ moderate x

QCD scaling

2015 Wolf prize for J. Bjorken!

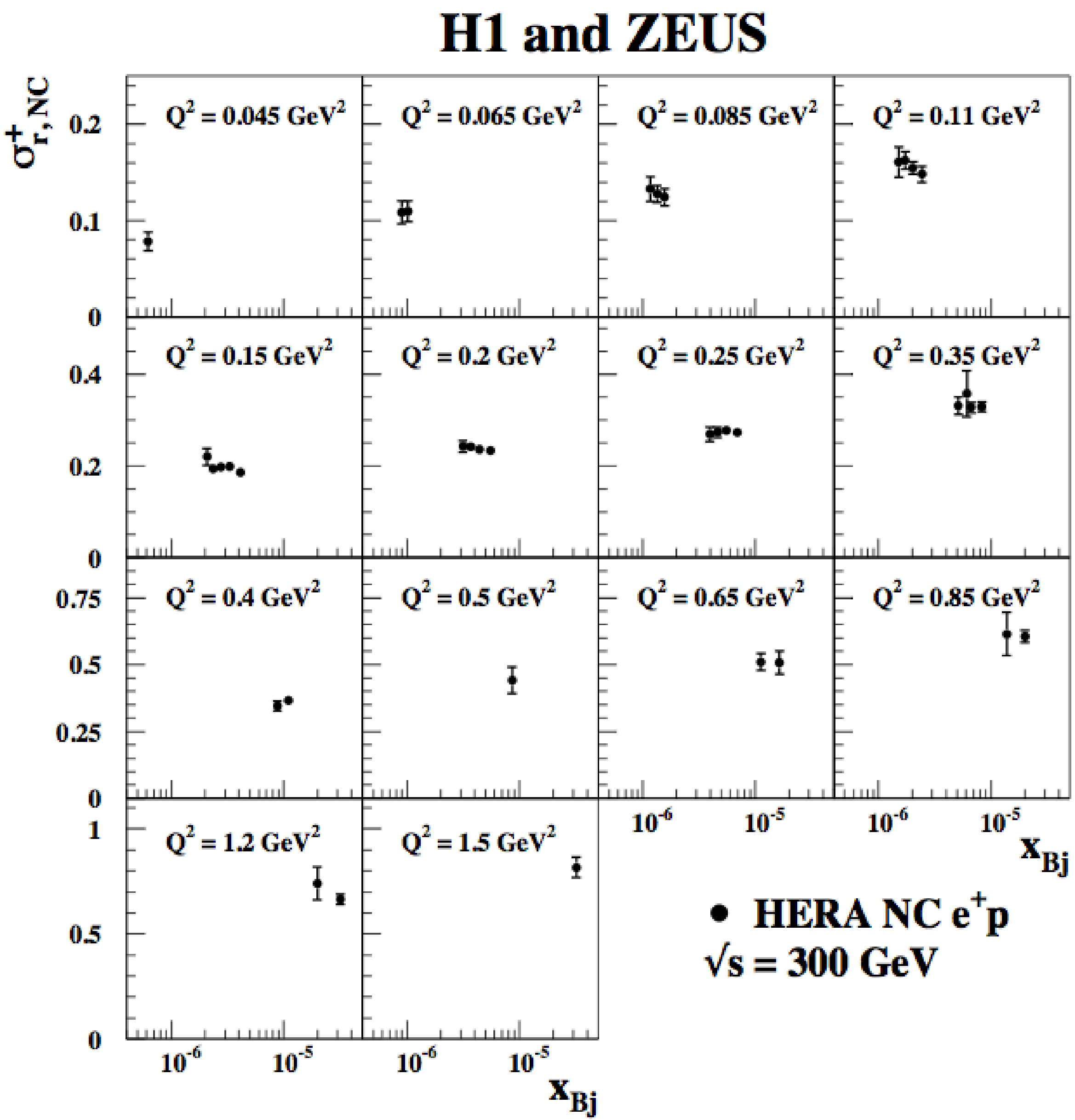


@ high x

Text book plot of fundamental properties of particle interactions

K. Wichmann, PIC2015, Everything you want to know about QCD...

Low Q^2 combined data



- Combined inclusive cross sections for low Q^2
- Available for two CMEs
- Interesting for
  - Studying applicability of pQCD
  - dipole/saturation models
  - higher twists

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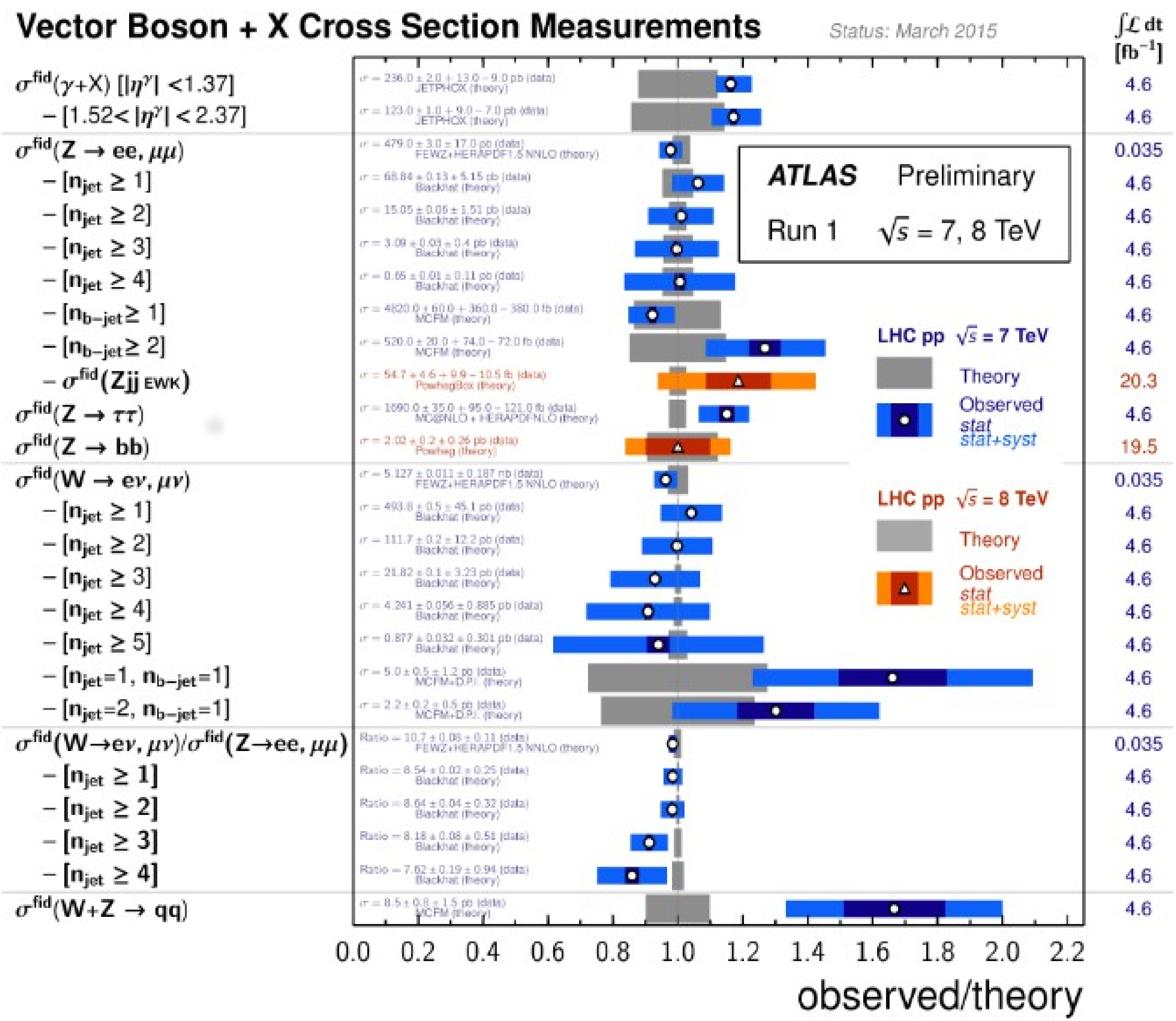
Back to jets:

V + jets

V + heavy flavor jets

V+jets



- V+jets sensitive to various aspects of QCD calculations (and EWK)
- Stress test of event generators/calculations

- Good data-theory agreement over 5 orders of magnitude in cross-sections
- Experimental accuracy high enough to expose discrepancies with predictions

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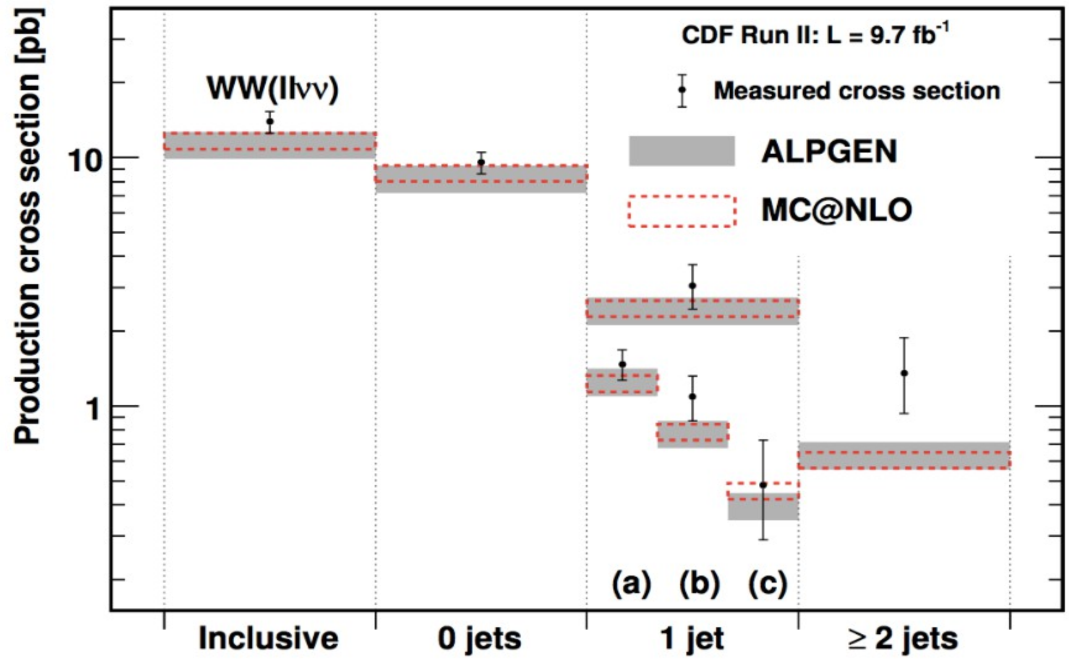
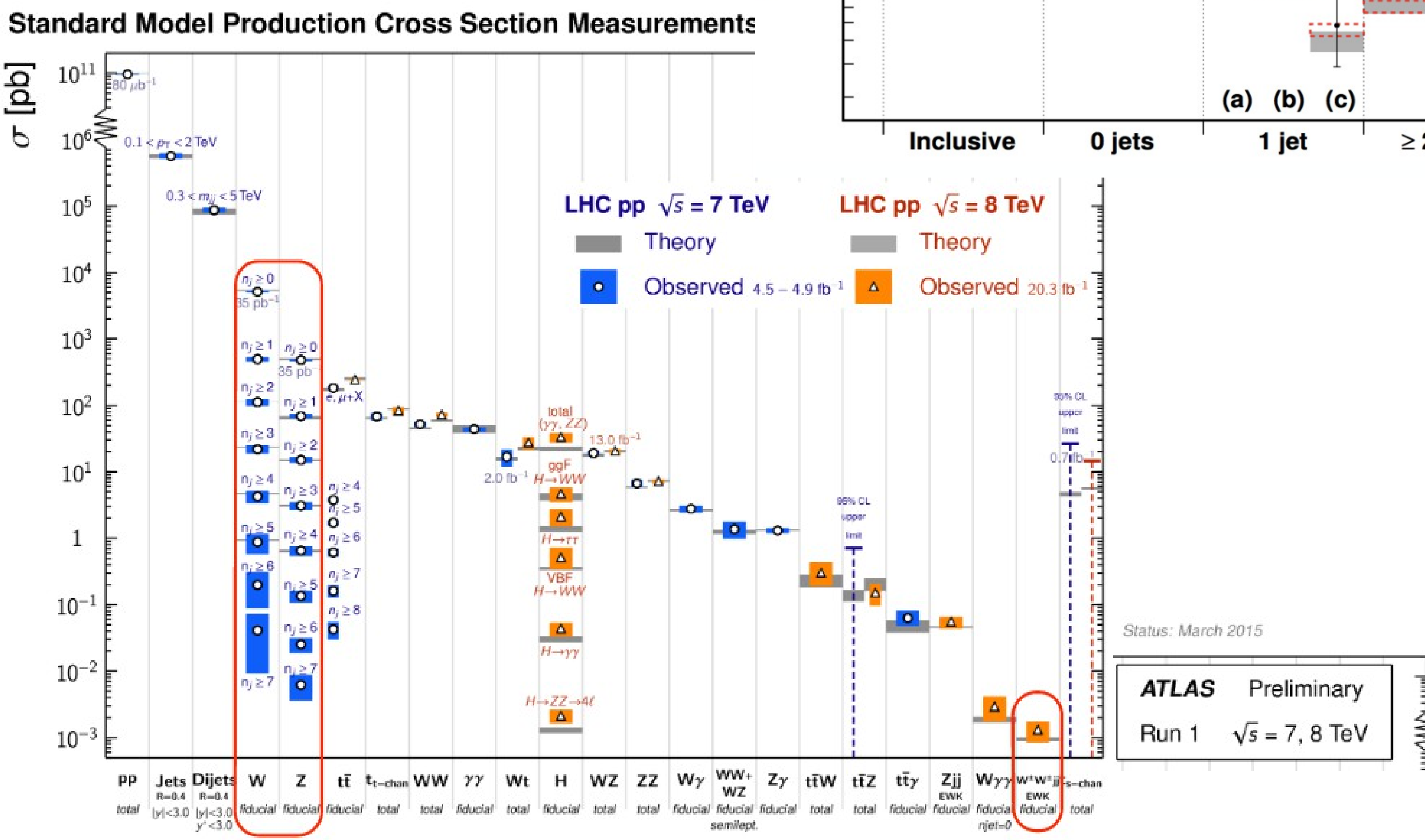
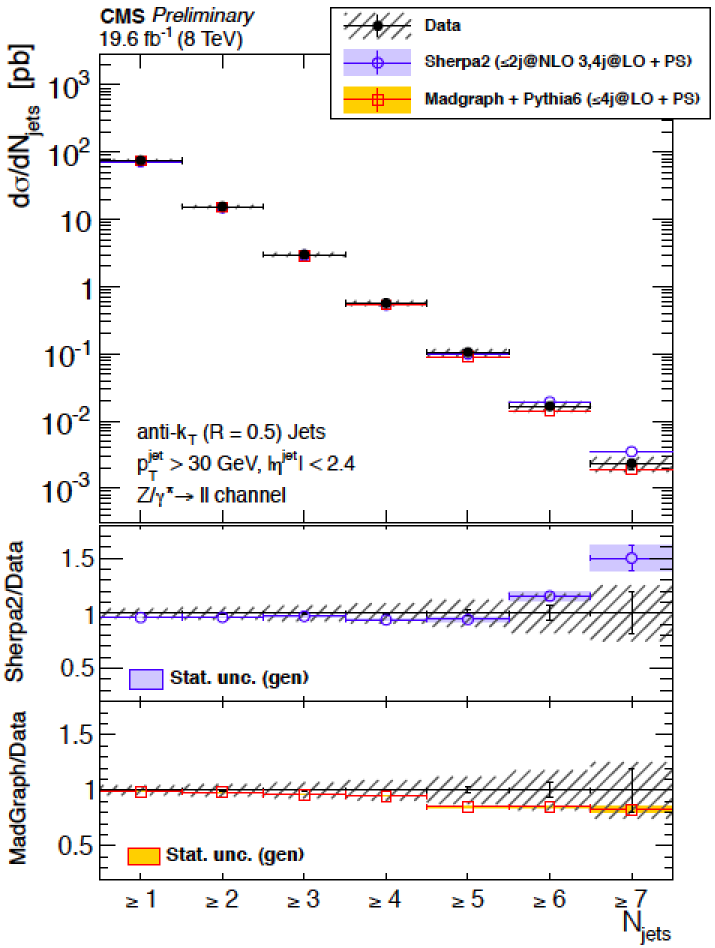
- Started at Tevatron → legacy
- New measurements coming
  - LHC joined in



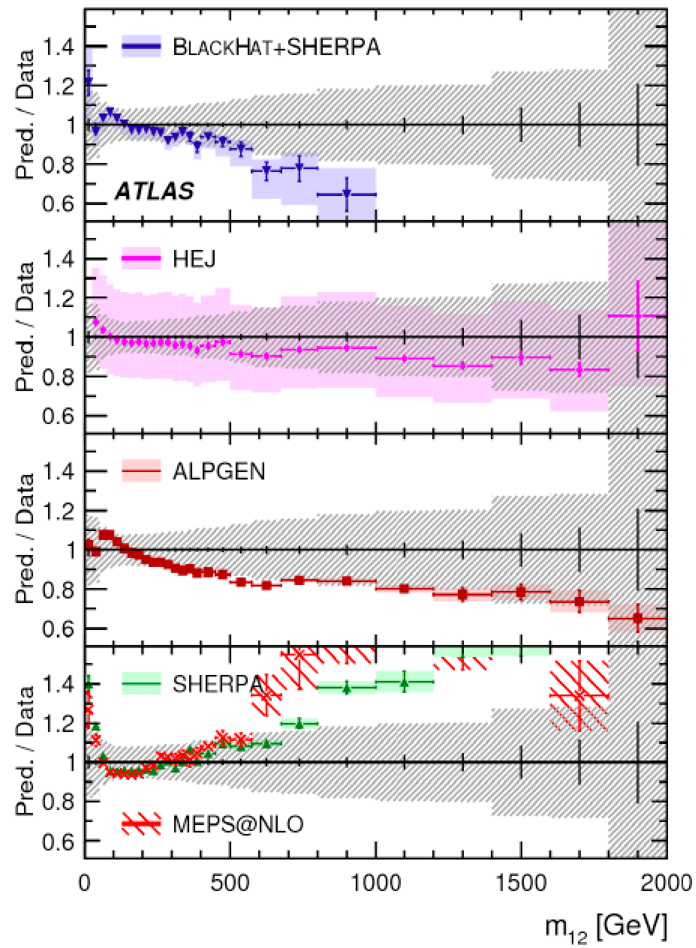


thing you want to know about QCD...

V + jets @ LHC



CMS-PAS-SMP-13-007



Eur.Phys.J.C(2015)75:82

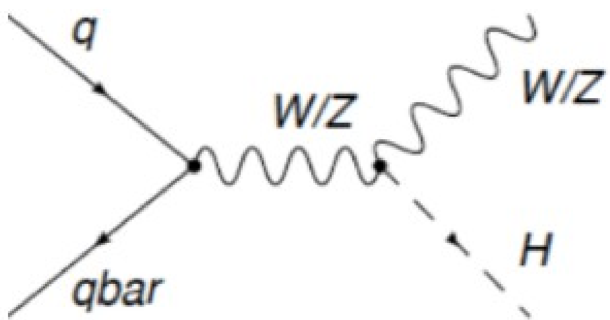
- Fantastic kinematic reach
- Predictions disagree

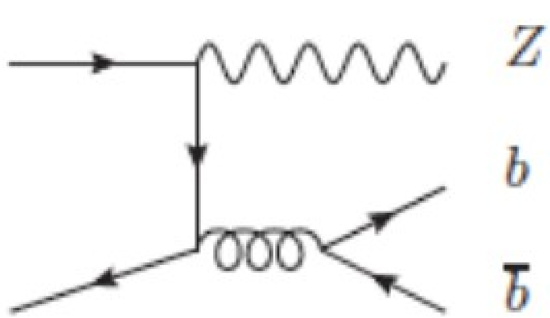
→ used to improve MC simulations

- *Great theoretical advances in recent years/months*
  - NLO calculations up to W+5 partons, NNLO for W/Z+1 parton, NLO MC matched to Parton Showering, resummed calculations

V + heavy flavor jets

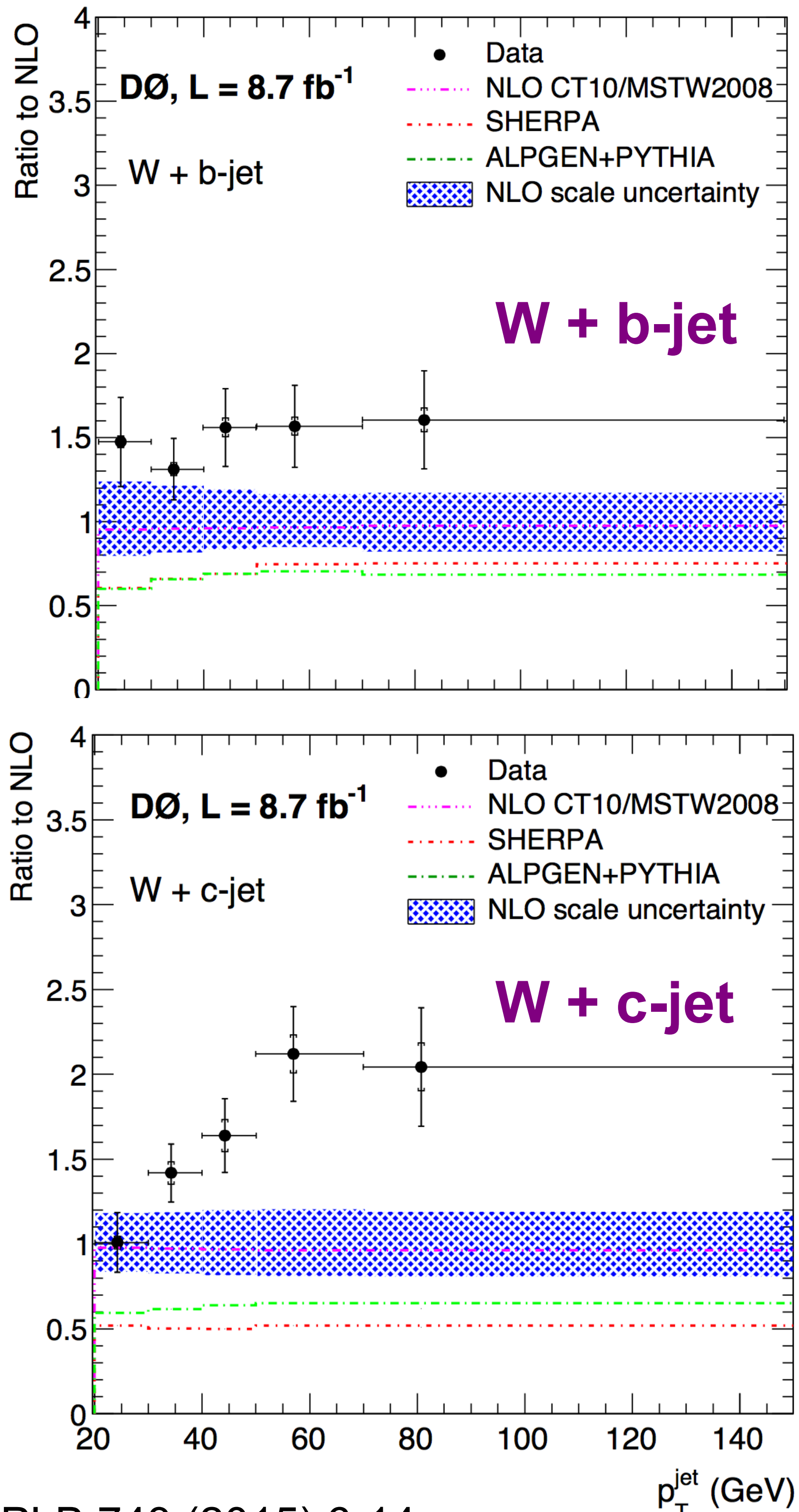
- Very important processes as background to Higgs and searches





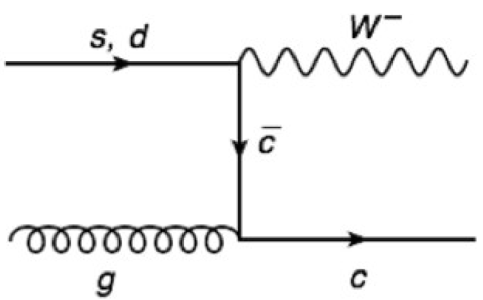
- Tevatron and LHC measurements complementary
  → Challenging experimentally
- Theoretical uncertainties larger than for light jets
  - heavy-quark content in proton
  - modeling of gluon splitting (initial state, final state)
  - massive vs massless b-quark in calculations
- Test of QCD predictions with various implementations (LO multileg+PS NLO, NLO+PS)

W +c/b at D0



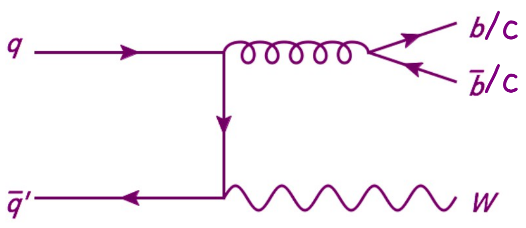
PLB 743 (2015) 6-14

- Generally poor description
  - Higher order corrections necessary?



- W + c-jet
  - Dominant contribution sensitive to strange PDF
  - Sea enhancement? (also seen @ LHC)
  - Underestimated gluon splitting?

At high p_T - unlike for W+b - gluon splitting more important



V + jets @ LHCb

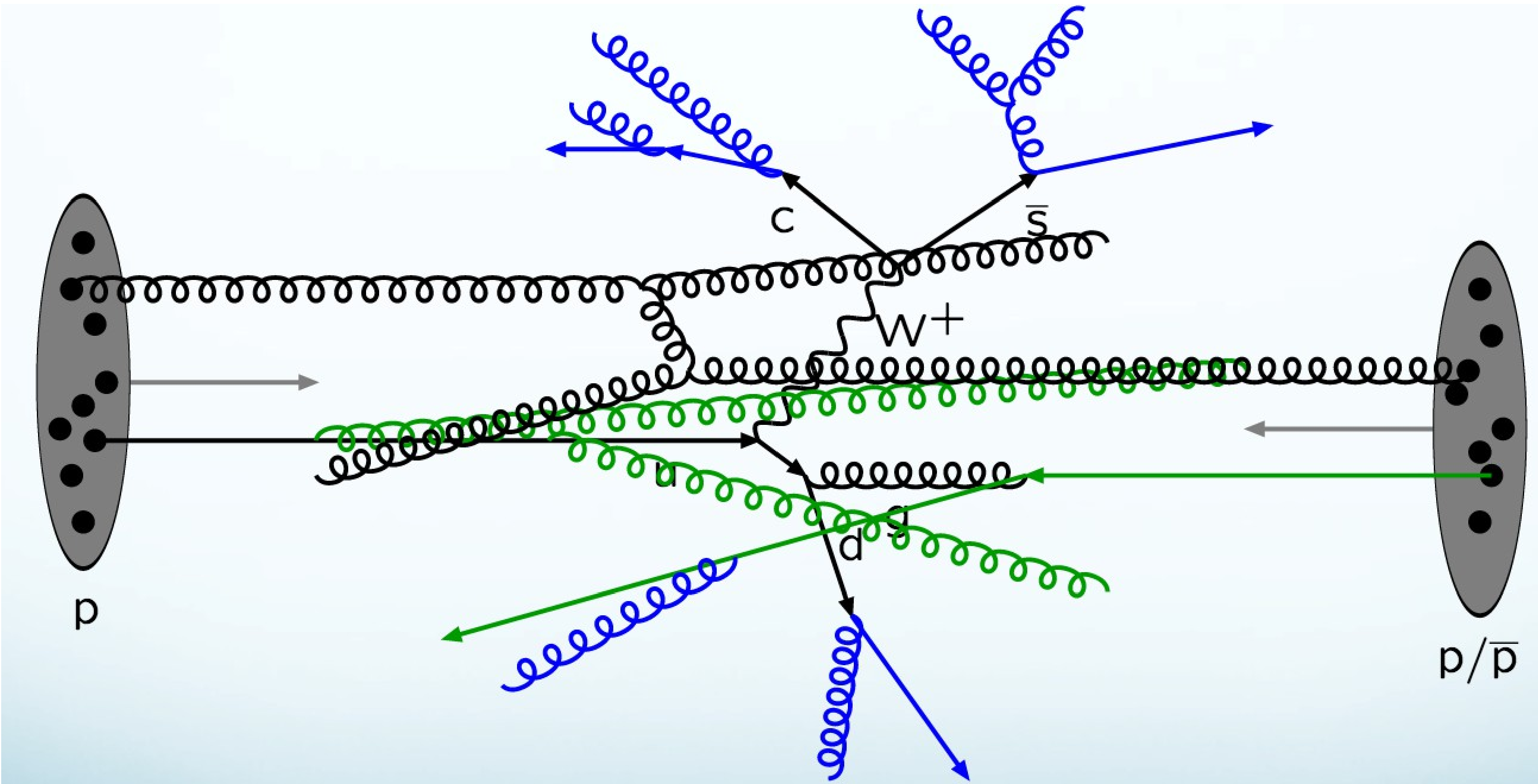
- LHCb forward: simultaneous analysis of W+light–jet, W+b and W+c
  - Comparison with with NLO QCD (4–flavor scheme MCFM with CT10)

	Results 7 TeV	Results 8 TeV	SM prediction 7 TeV	SM prediction 8 TeV
$\frac{\sigma(Wb)}{\sigma(Wj)} \times 10^2$	$0.66 \pm 0.13 \pm 0.13$	$0.78 \pm 0.08 \pm 0.16$	$0.74^{+0.17}_{-0.13}$	$0.77^{+0.18}_{-0.13}$
$\frac{\sigma(Wc)}{\sigma(Wj)} \times 10^2$	$5.80 \pm 0.44 \pm 0.75$	$5.62 \pm 0.28 \pm 0.73$	$5.02^{+0.80}_{-0.69}$	$5.31^{+0.87}_{-0.52}$
$\mathcal{A}(Wb)$	$0.51 \pm 0.20 \pm 0.09$	$0.27 \pm 0.13 \pm 0.09$	$0.27^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$
$\mathcal{A}(Wc)$	$-0.09 \pm 0.08 \pm 0.04$	$-0.01 \pm 0.05 \pm 0.04$	$-0.15^{+0.02}_{-0.04}$	$-0.14^{+0.02}_{-0.03}$
$\frac{\sigma(W^+j)}{\sigma(Zj)}$	$10.49 \pm 0.28 \pm 0.53$	$9.44 \pm 0.19 \pm 0.47$	$9.90^{+0.28}_{-0.24}$	$9.48^{+0.16}_{-0.33}$
$\frac{\sigma(W^-j)}{\sigma(Zj)}$	$6.61 \pm 0.19 \pm 0.33$	$6.02 \pm 0.13 \pm 0.30$	$5.79^{+0.21}_{-0.18}$	$5.52^{+0.13}_{-0.25}$

$$\mathcal{A}(Wq) \equiv \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}$$

- $\sigma(Wb)/\sigma(Wj)$ consistent with W+b from gluon splitting @ O(10%)
- $\sigma(Wc)/\sigma(Wj)$ consistent with W+c production from intrinsic s quark in p
- Charge asymmetry for W+c smaller then predicted
  - s-sea asymmetric?
  - larger than expected contribution from scattering off of strange quarks?

Amazing (crazy?) world of underlying events



UE comprises all particles from collision except those from hard process of interest

Pythia/Herwig Underlying Event Tunes

- hard 2-to-2 parton scattering in QCD MC models

$$1/\hat{p}_T^4 \rightarrow 1/(\hat{p}_T^2 + p_{T_0}^2)^2$$

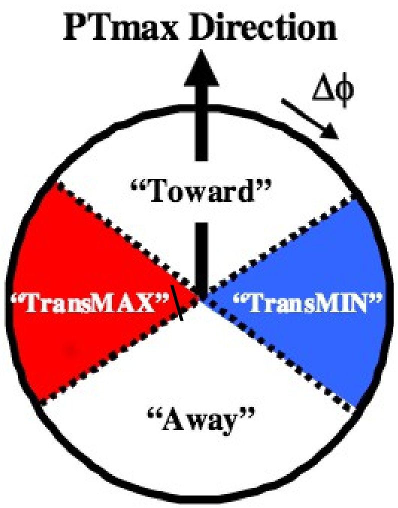
- Phenomenological cut-off p_{T0}^2 depends on E_{cm}

$$p_{T_0}(E_{cm}) = p_{T_0}^{REF} \times (E_{cm}/E_0)^{\epsilon}$$

→ use data @ various CM and tune parameters using UE observables
  - Check various PDFs

→ validate against UE sensitive variables

- Z Boson
- Leading Track
- Leading Jet



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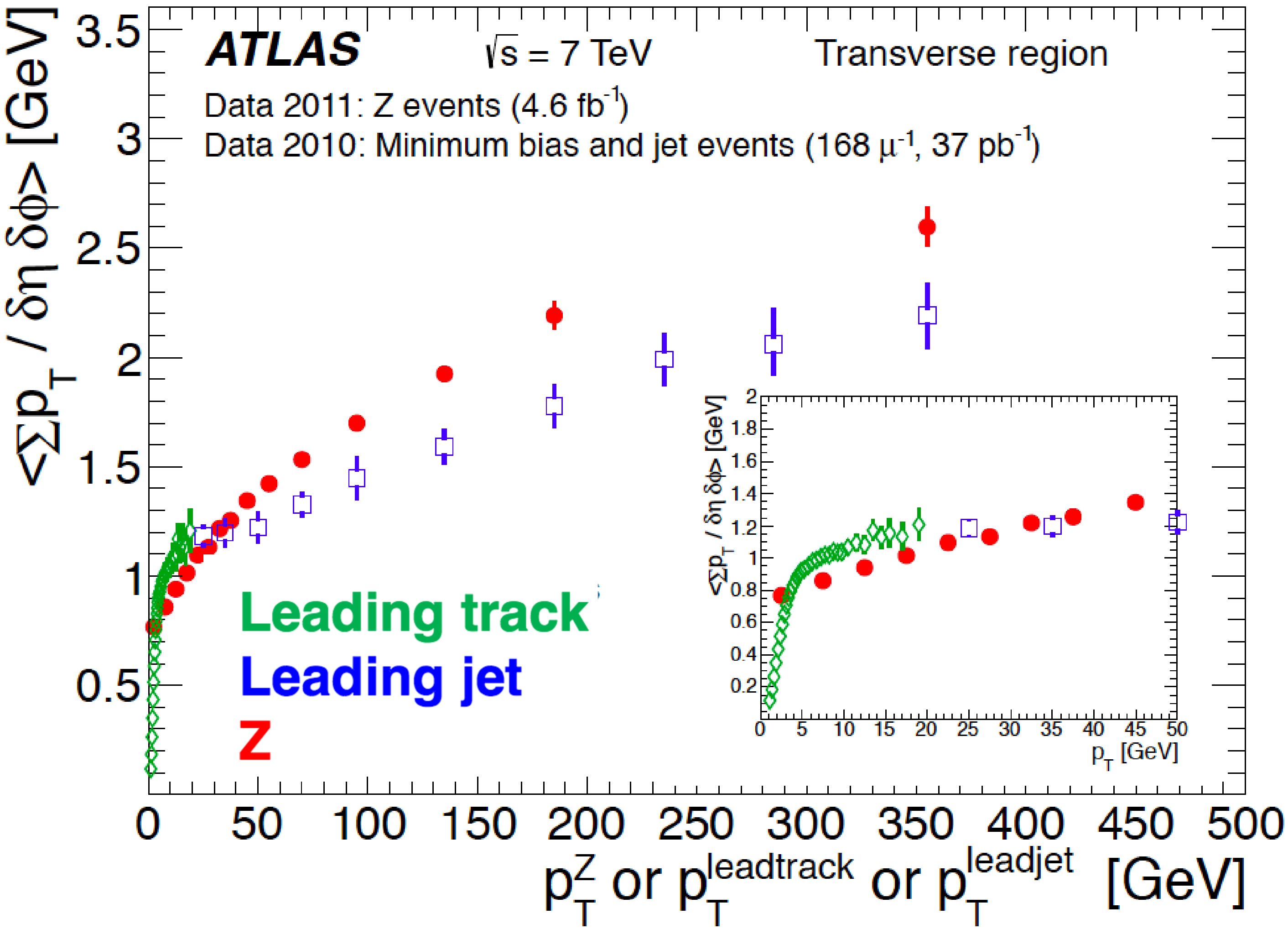
UE observables

EPJC (2014) 74,3195



- Typical observables
  - Number density, Σp_T , σp_T
- Leading track/jet complementary - mooth transition around 20 GeV
- Consistent UE activity across processes within known selection bias

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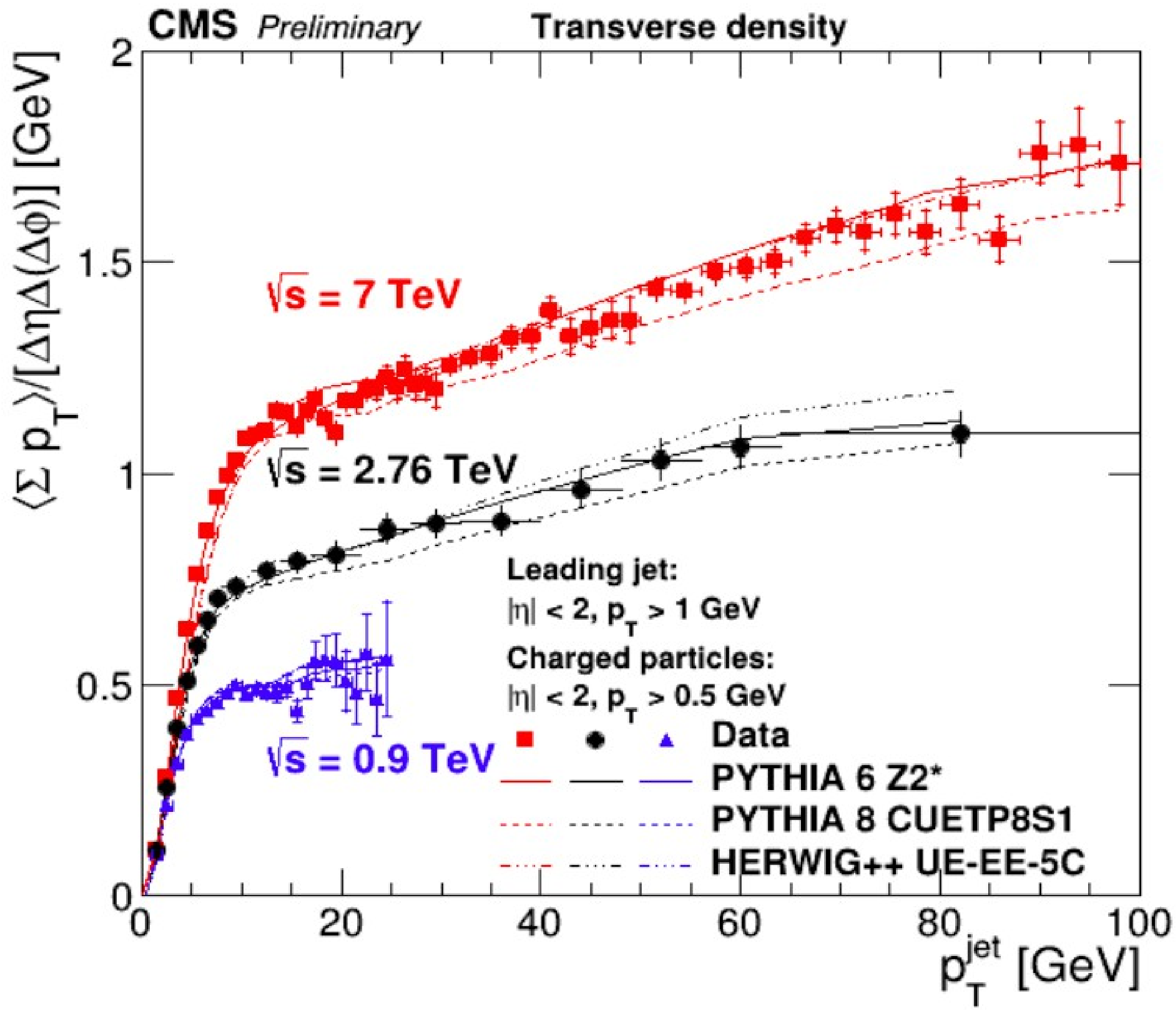
Dependence on CM

CERN-PH-EP-2015-176



B. Wynne's talk!

Modern tunes reproduce well energy dependence up to 13 TeV

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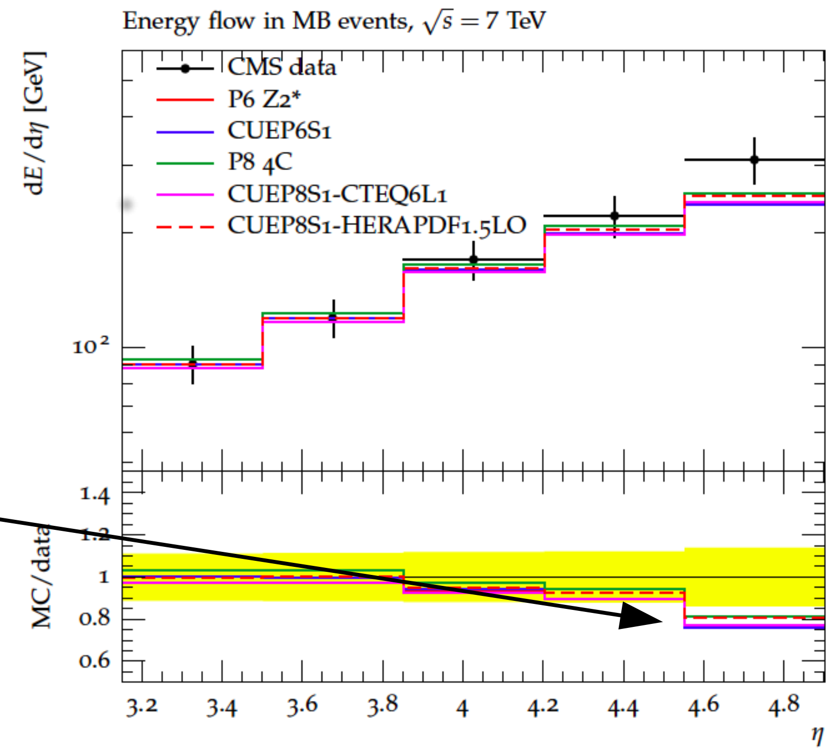
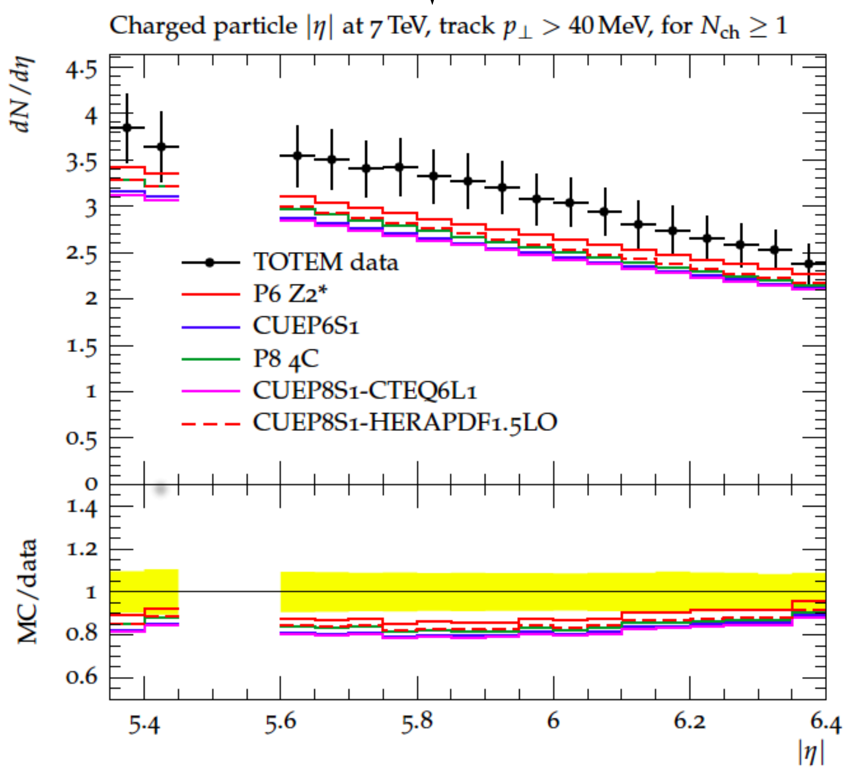
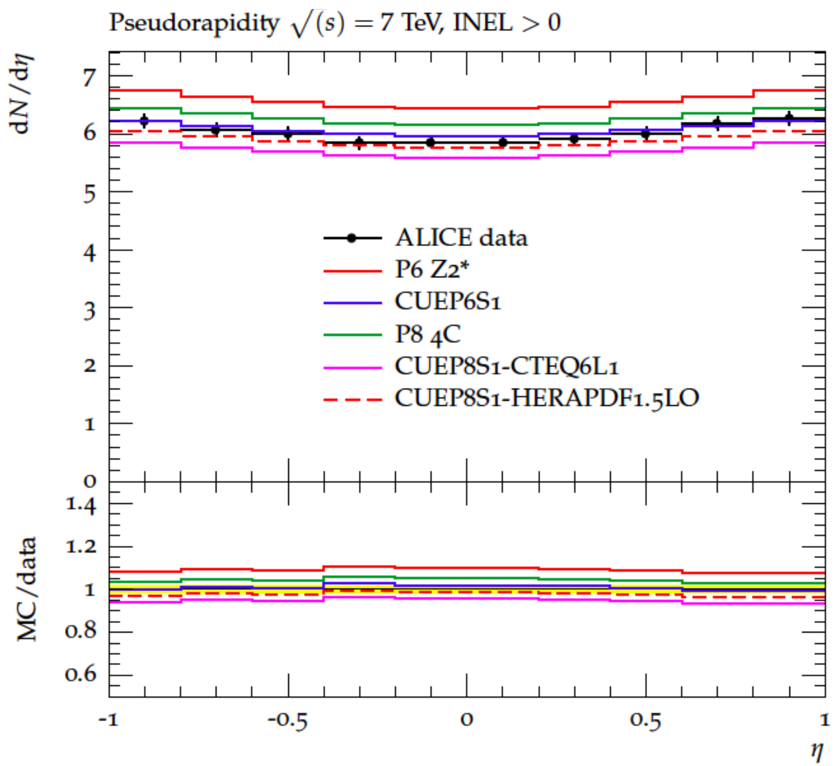
Validation of UE tunes

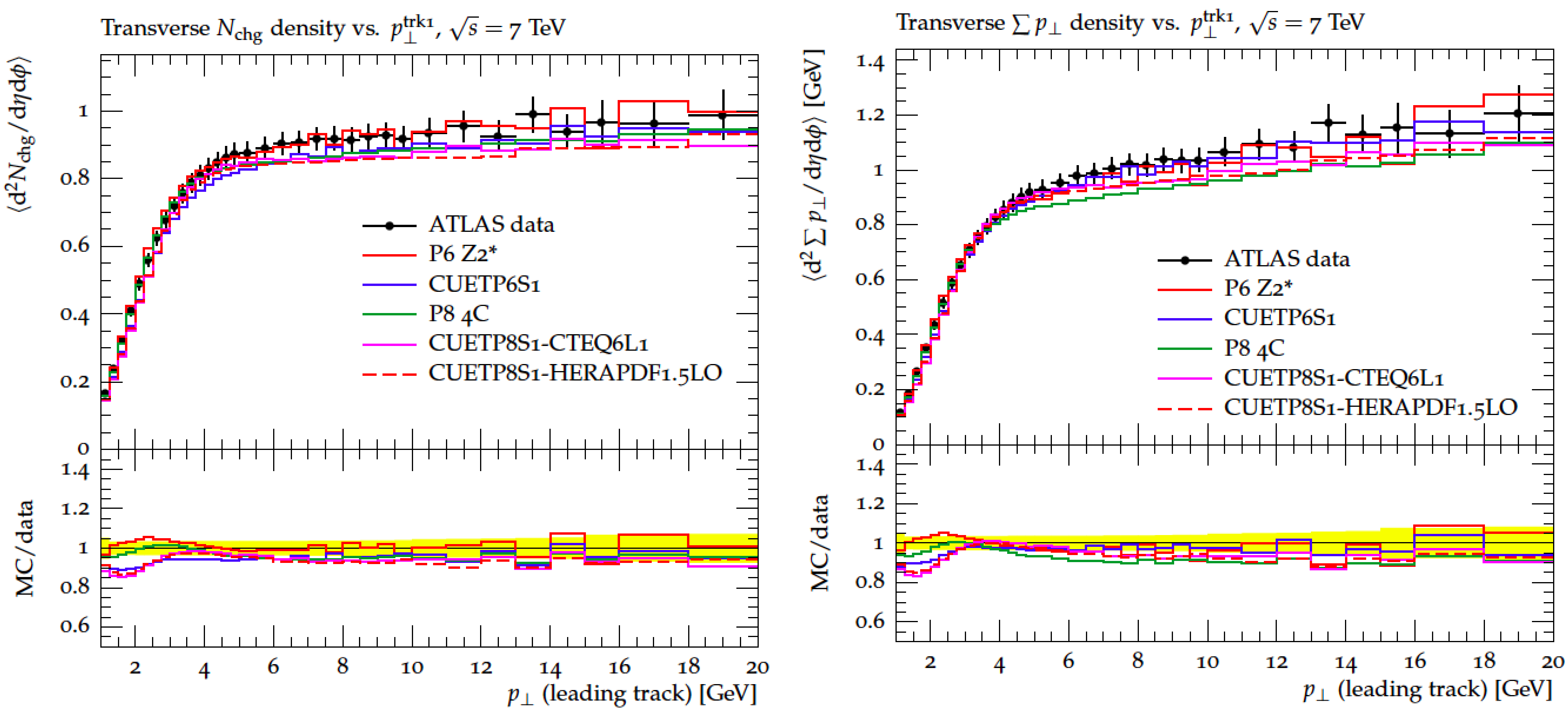
- In general good description
  - Except very forward region







CMS tunes against ATLAS data @ 7 TeV



- CMS tunes describe ATLAS data remarkably well

SUMMARY

- Understanding QCD plays crucial role in hadron collider physics
- Many new and more precise results from Hera, Tevatron and LHC

  → prompting further theoretical developments on QCD

  → still more precise calculations needed (e.g. NNLO jets)
- LHC kinematic reach at LHC allows to test SM validity to unprecedented phase spaces
- There are very interesting times ahead for us with Run II
  - further insight on QCD dynamics in new energy regime

Both experimentalists and theorists are striving to improve our knowledge of QCD further and further

Additional slides

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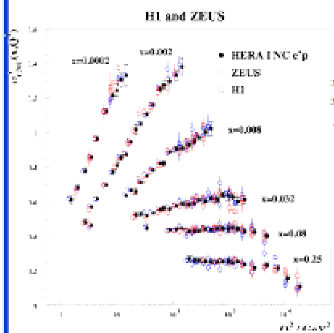
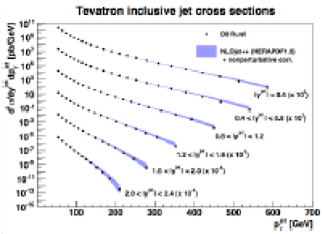
DESY

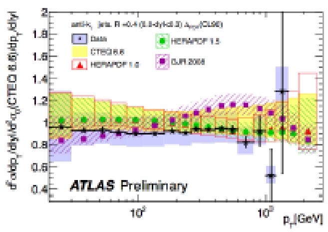
https://www.herafitter.org

experimental input





experiments:
HERA, Tevatron,
LHC, fixed target



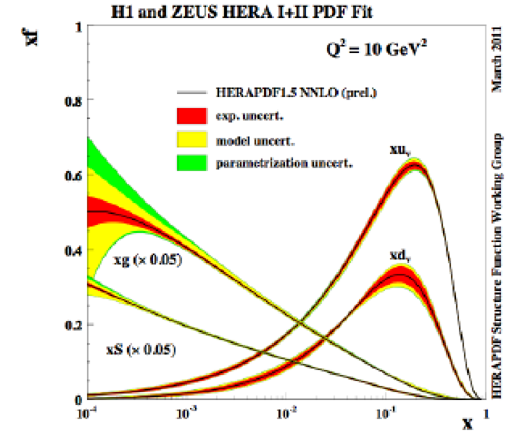
processes:
NC, CC DIS, jets, diffraction,
heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or uPDF or DPDF

$\alpha_S(M_Z), m_c, m_b, m_t, f_s, ..$

Theory predictions

Benchmarking

Comparison of schemes

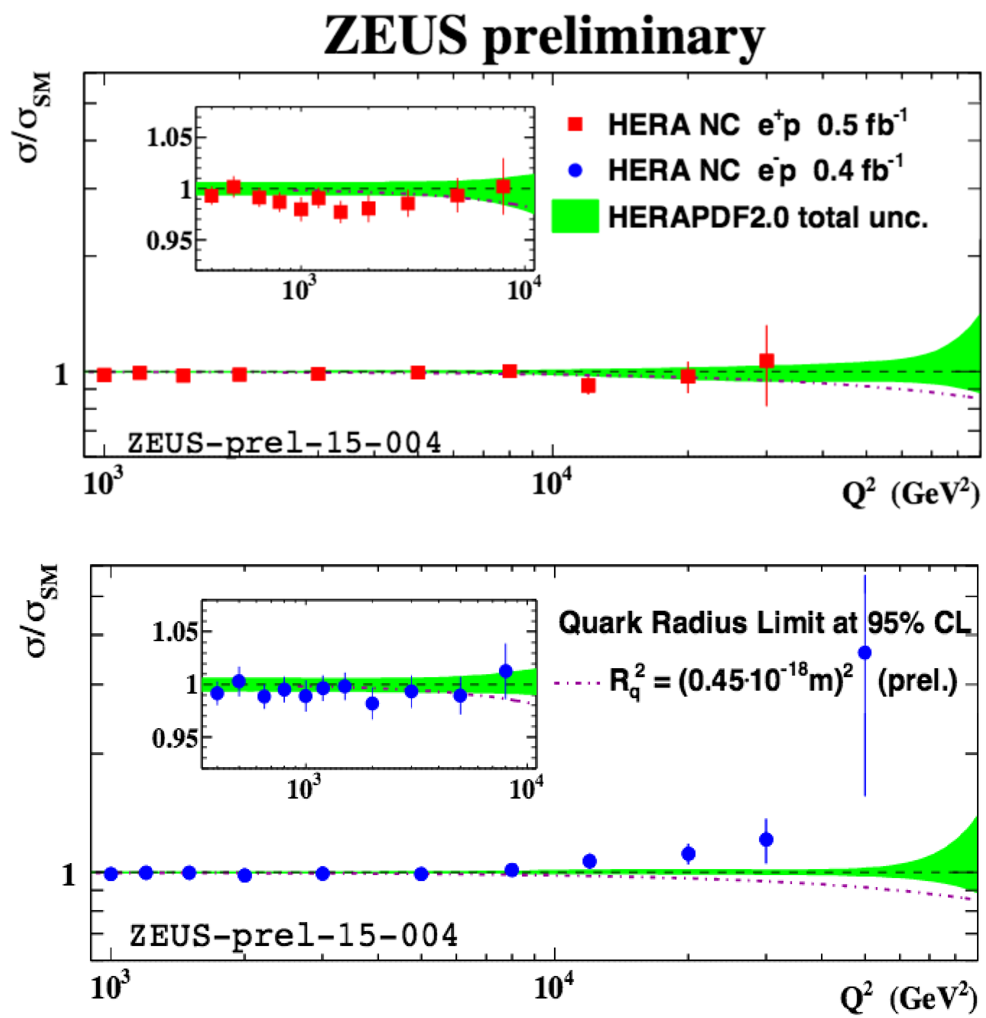
Search for BSM

Classical quark Form Factor approach:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_e^2}{6}Q^2\right)^2\left(1 - \frac{R_q^2}{6}Q^2\right)^2$$

$$R_q < 0.45 \cdot 10^{-16}\ \mathrm{cm}$$

Improvement wrt previous ZEUS and similar to L3 limit



- Inclusive DIS from HERA used to look for CI
  - Competitive limit for quark radius
- New method (strict)
  - CI fitted together with PDFs
  - Otherwise BSM might hide in PDFs