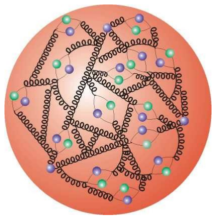
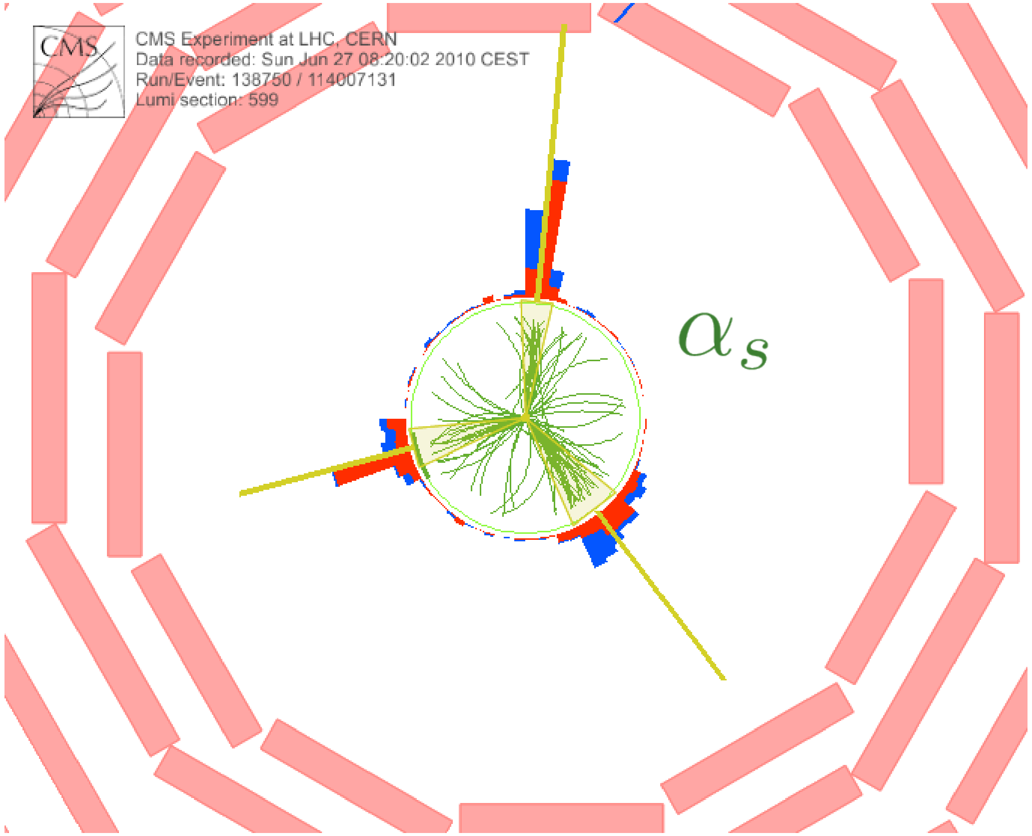
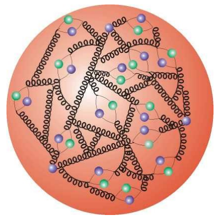
Jet Physics and Precision Tests of QCD



Proton Structure (PDF)





Proton Structure (PDF)

Klaus Rabbertz, KIT

Karlsruhe Institute of Technology

Outline

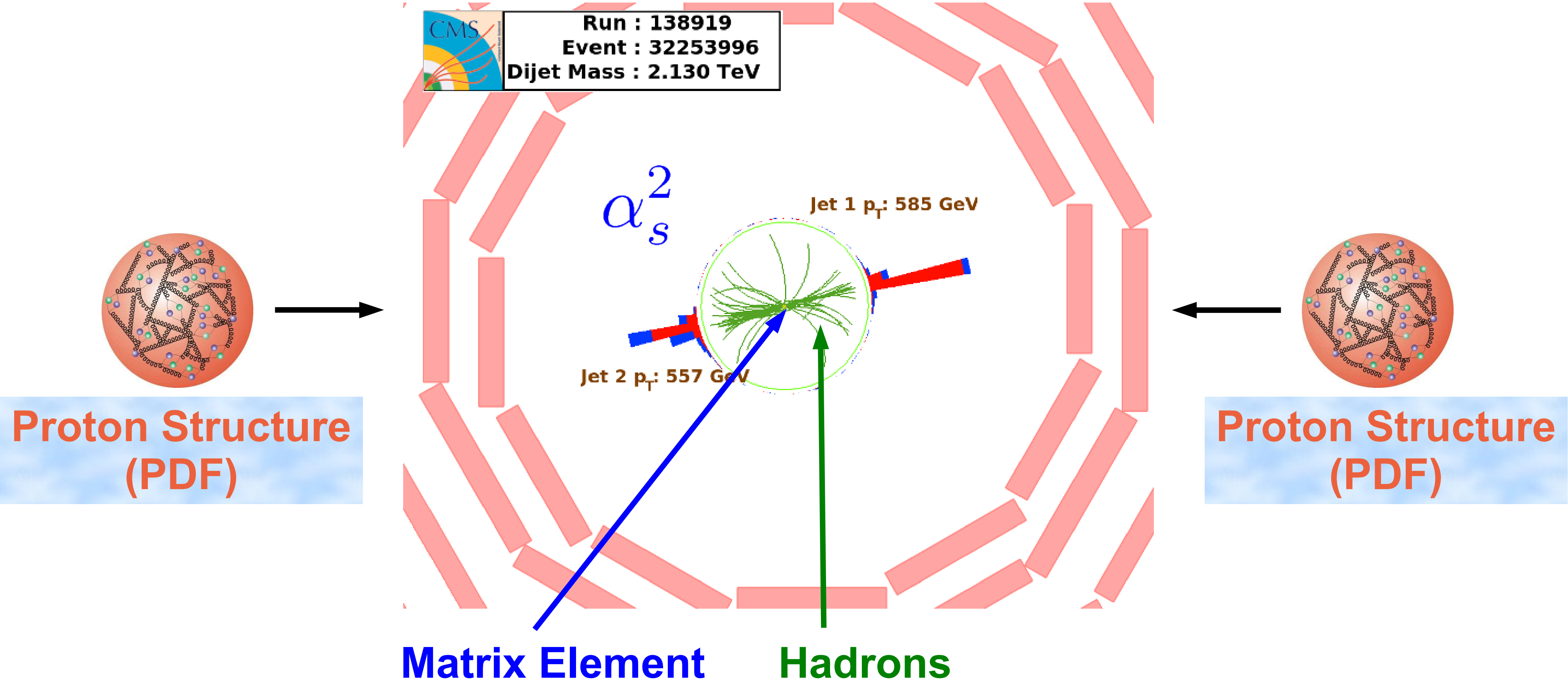
- Motivation
- Photons
- Boson + Jets
- Inclusive Jets
- Dijets
- Multi-Jets and the strong Coupling Constant α_s
- α_s Summary
- Perspectives at Future Colliders
- Summary

Many interesting jet measurements left out, concentrating on precision comparisons!
W, Z, top production covered by Manuella Vincter in the next talk.

(→ u valence, d valence, sea quark PDFs)

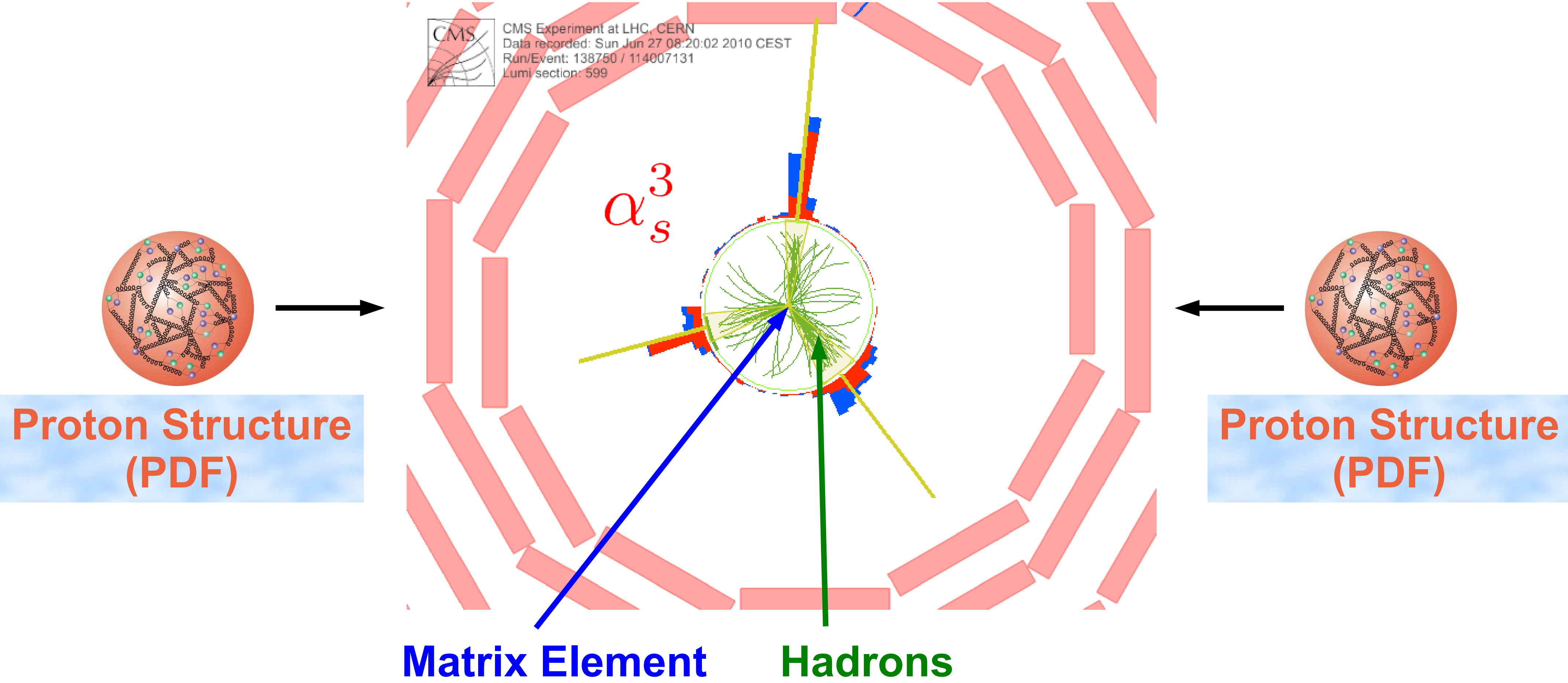
Jets at the LHC

Abundant production of jets → hadron colliders are “jet laboratories”
Learn about hard QCD, the proton structure, non-perturbative effects ...



Abundant production of jets → hadron colliders are "jet laboratories"

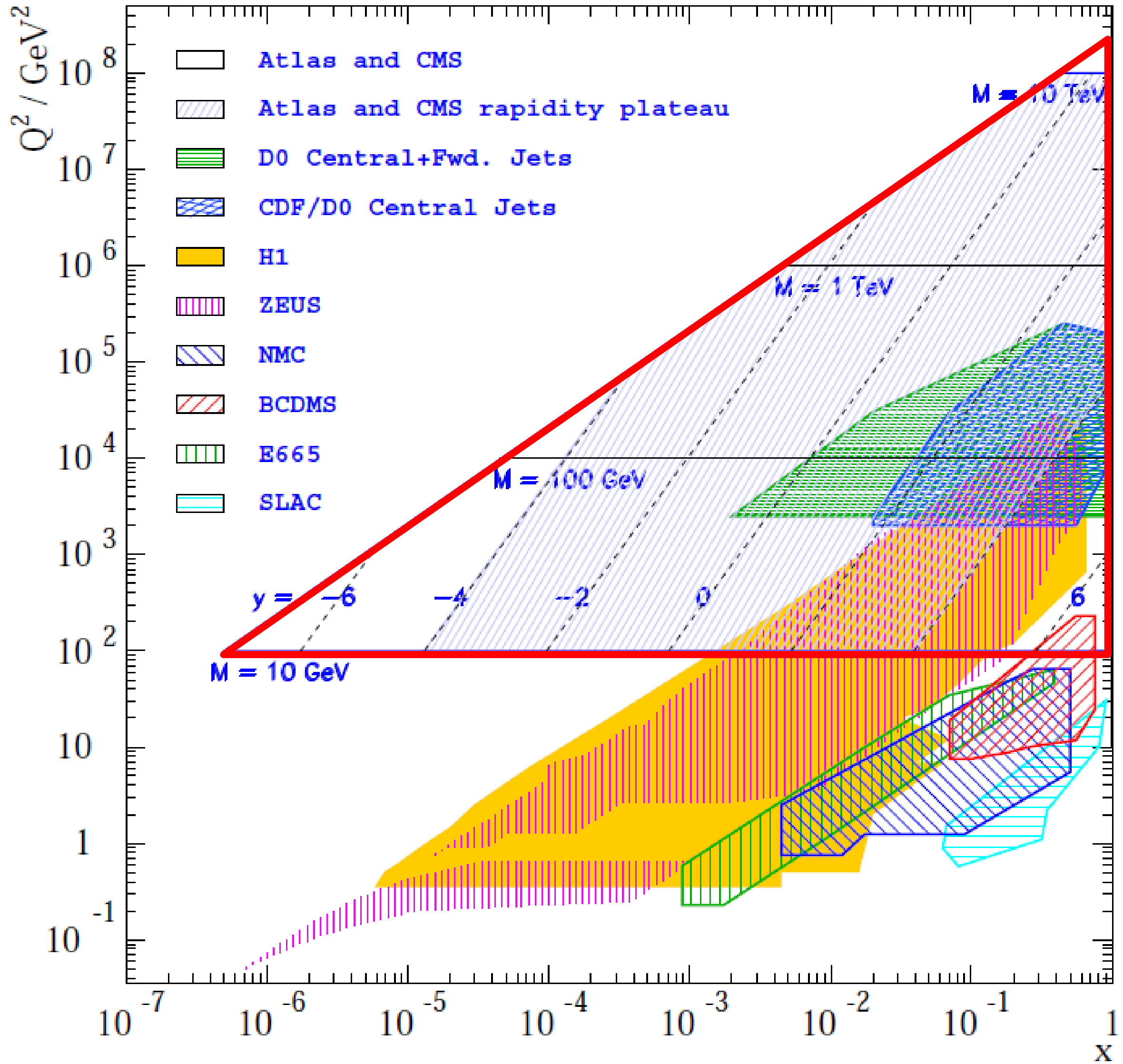
… and the strong coupling α_s . Least known fundamental constant!



QCD at the LHC

- **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

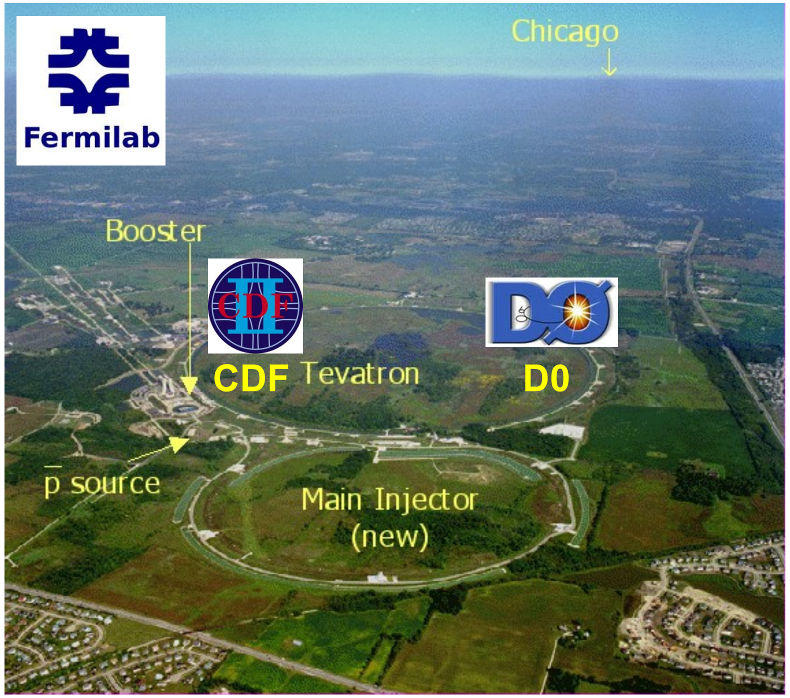
Huge accessible phase space



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

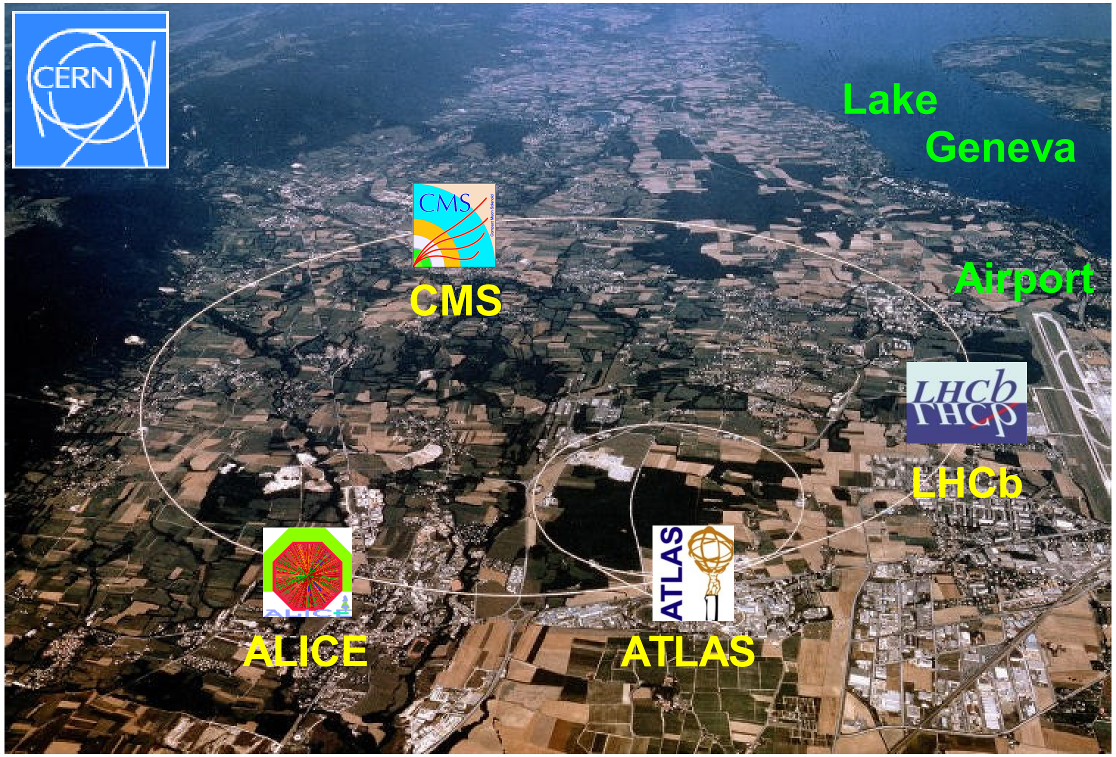
Past and Present Colliders

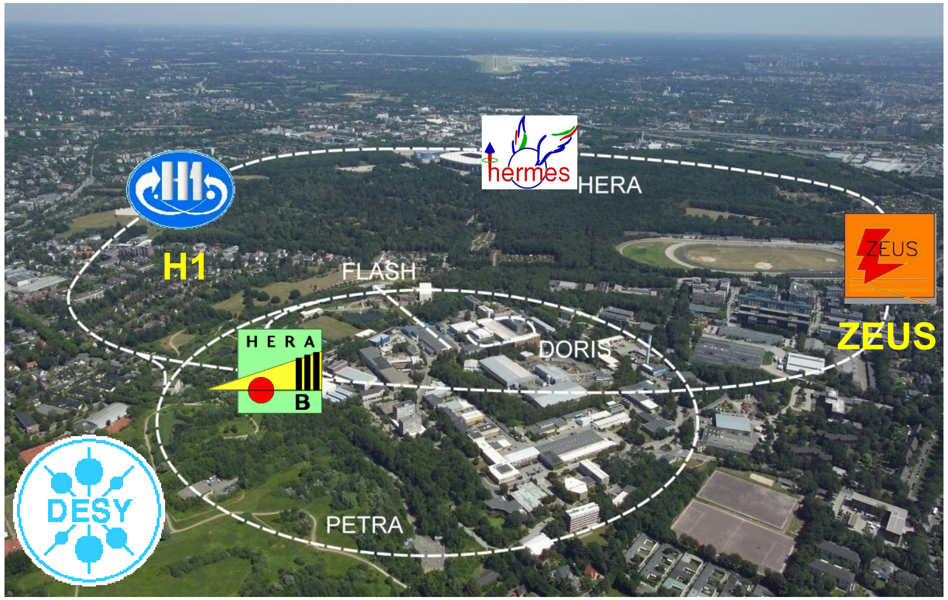
Tevatron: 1986 – 2011
Collisions of p anti-p
Run II: E_{cms} =1.96 TeV
Run II: Record luminosity: 4.3 x 10^{32} $cm^{-2}s^{-1}$



LHC: 2009 – present
Collisions of p-p, Pb-Pb, and p-Pb
E_{cms} = 0.9, 2.36, 2.76, 7, 8 TeV
Peak inst. Luminosity: ~ 8 x 10^{33} $cm^{-2}s^{-1}$

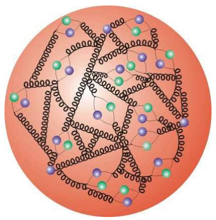
HERA: 1992 – 2007
Collisions of e^{+}-p, e^{-}-p
HERA II: E_{cms} = 319 GeV



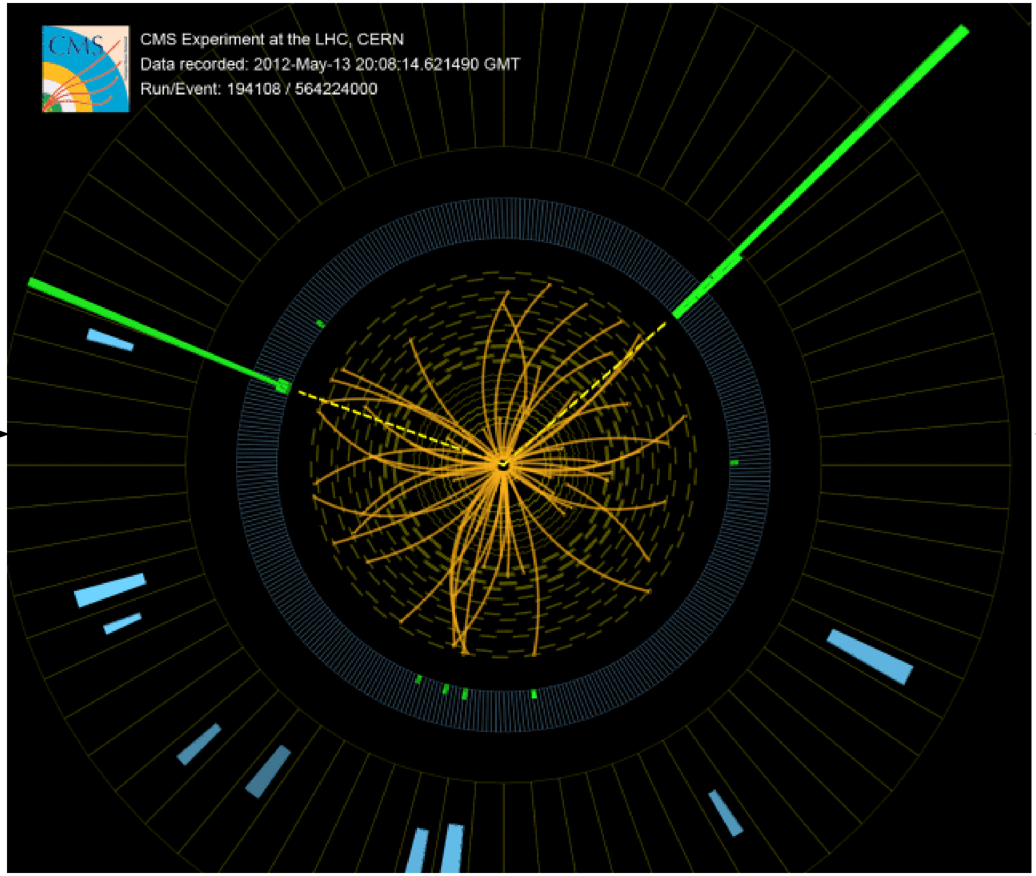


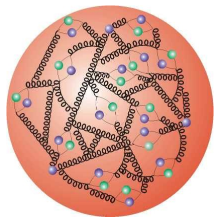
(Di-)Photons

Higgs or no Higgs?



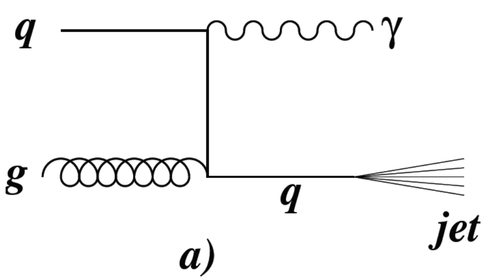
Proton

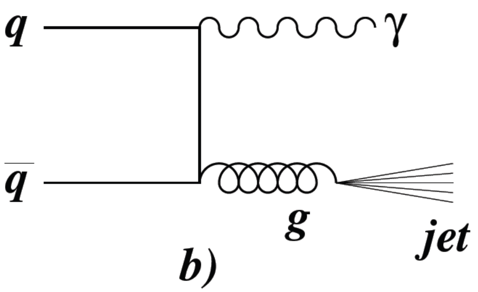




Proton

Photon Production





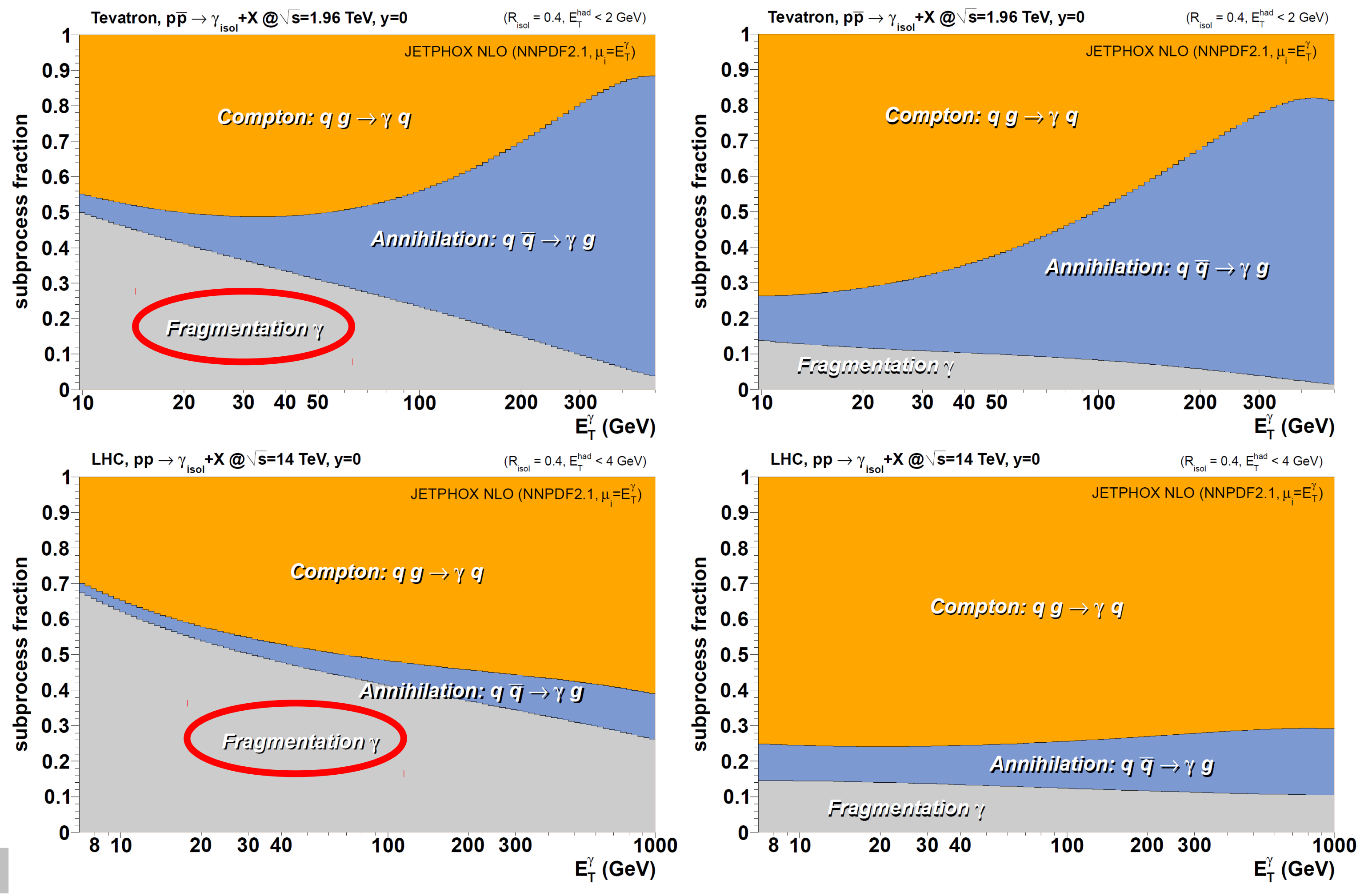
Formerly underexplored process:
- high fraction of fragmentation photons, cured by isolation
- theory available at NLO, sensitive to → gluon (PDF)

Tevatron

LHC 14 TeV

Background: Non-prompt Photons from Decays, e.g. π^0, η

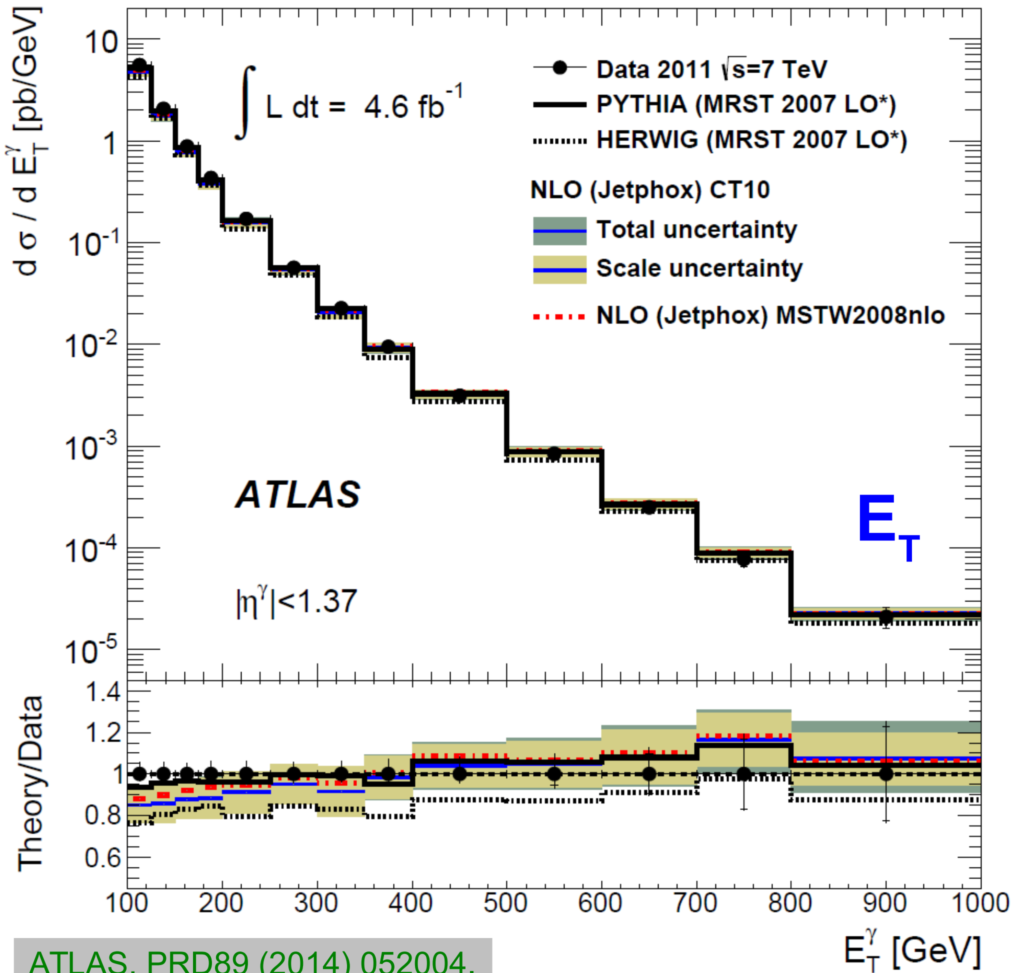
Inclusive | **Isolated**

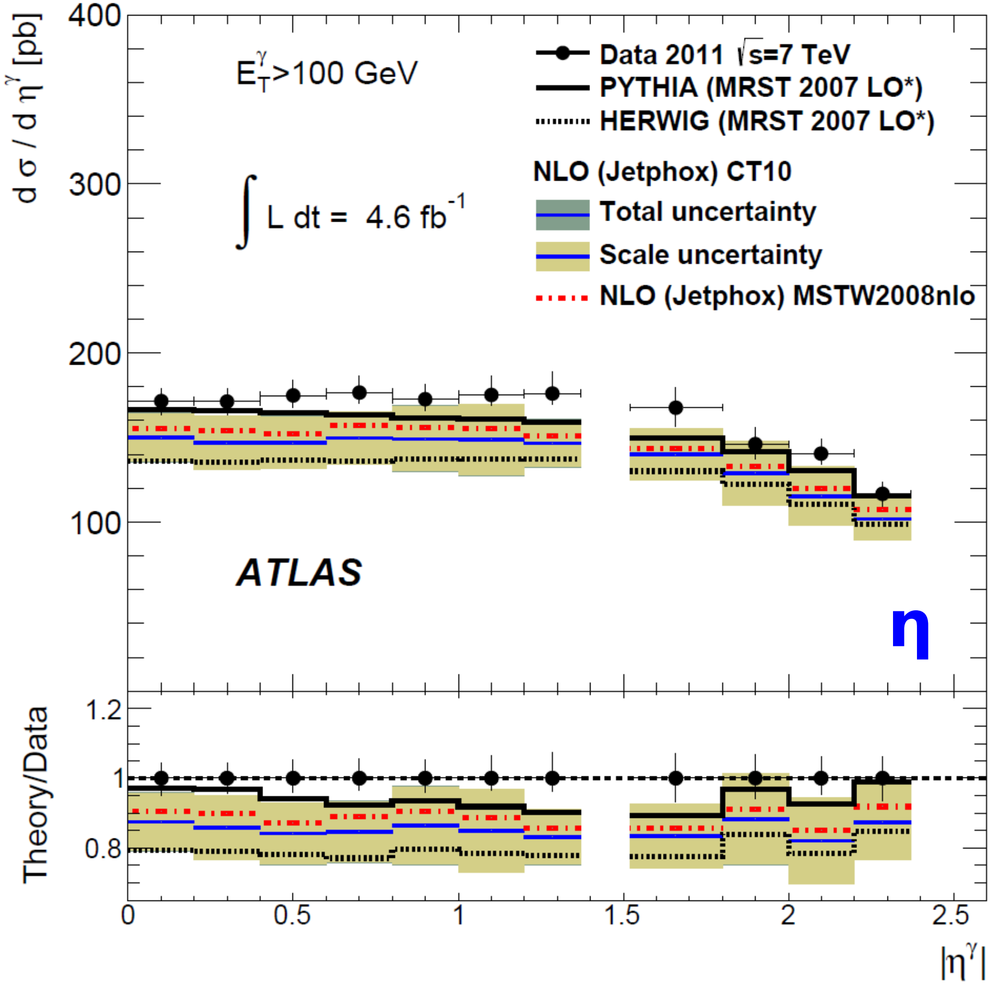


d'Enterria, Rojo, NPB860 (1202) 311.

Isolated Prompt Photons

- New ATLAS measurement extends to 1 TeV in photon transverse energy
- In agreement with NLO (JetPhox, incl. fragm. γ) over 5 orders of magnitude
- Limiting factor: Scale uncertainties in theory
- Some tension visible versus photon rapidity



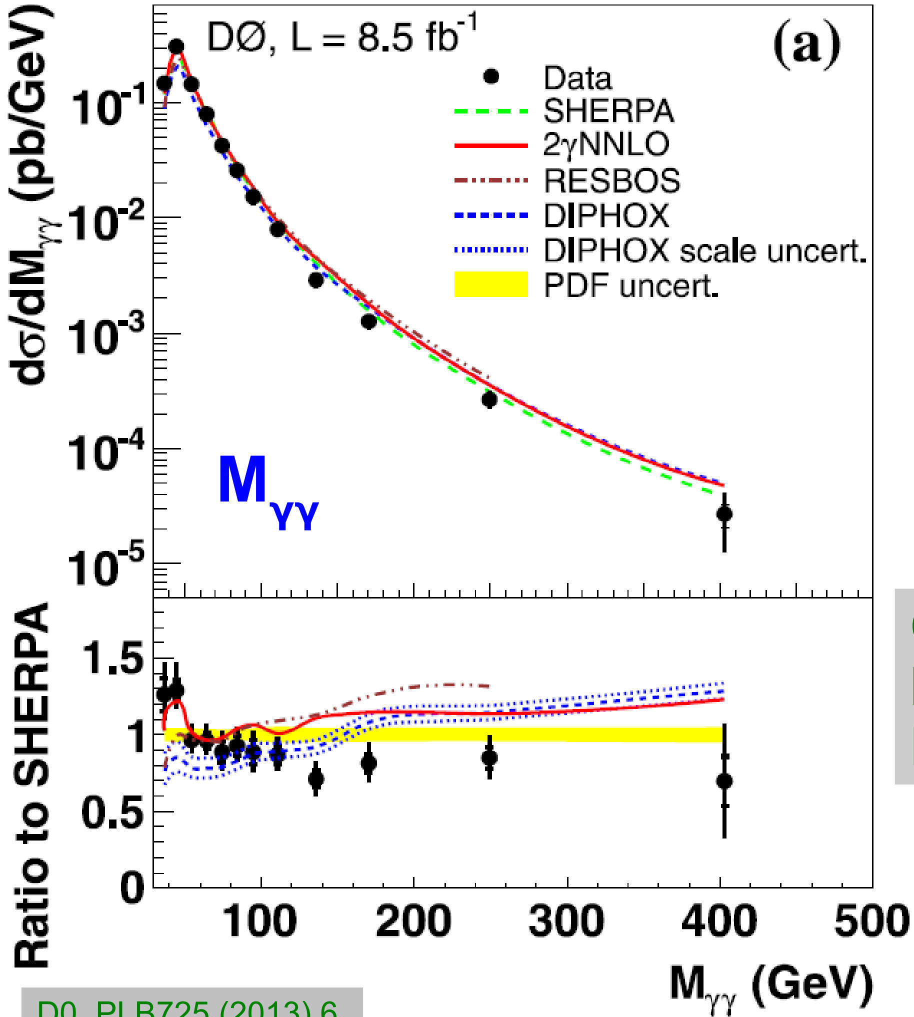


ATLAS, PRD89 (2014) 052004.

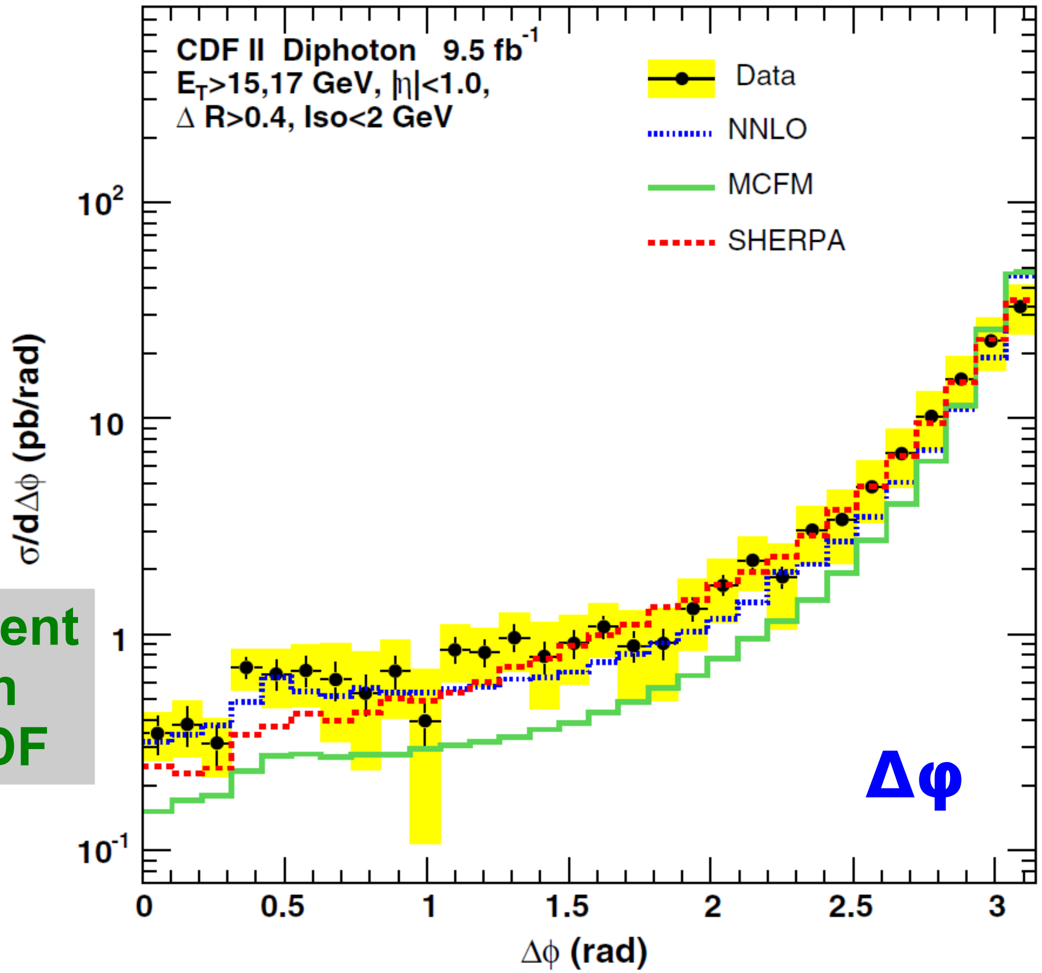
Di-Photons at 1.96 TeV

Final results from D0 and CDF for isolated photon pairs
Irreducible background in $M_{\gamma\gamma}$ for Higgs or other searches

Better agreement with NNLO (2γNNLO, direct γ only) than NLO (DiPhox including fragm. + gg box) or with improved photon treatment in parton showers (Sherpa)



Consistent between D0 & CDF

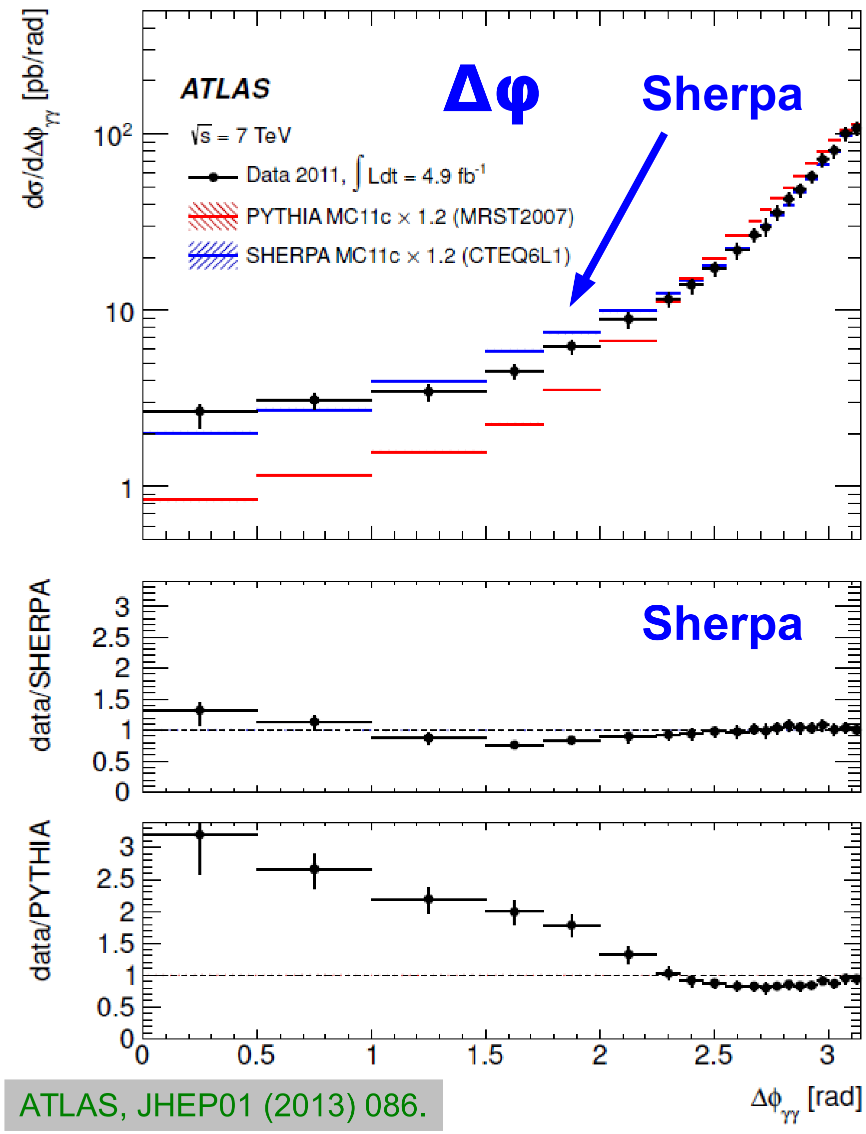


D0, PLB725 (2013) 6.

CDF, PRL110 (2013) 101801.

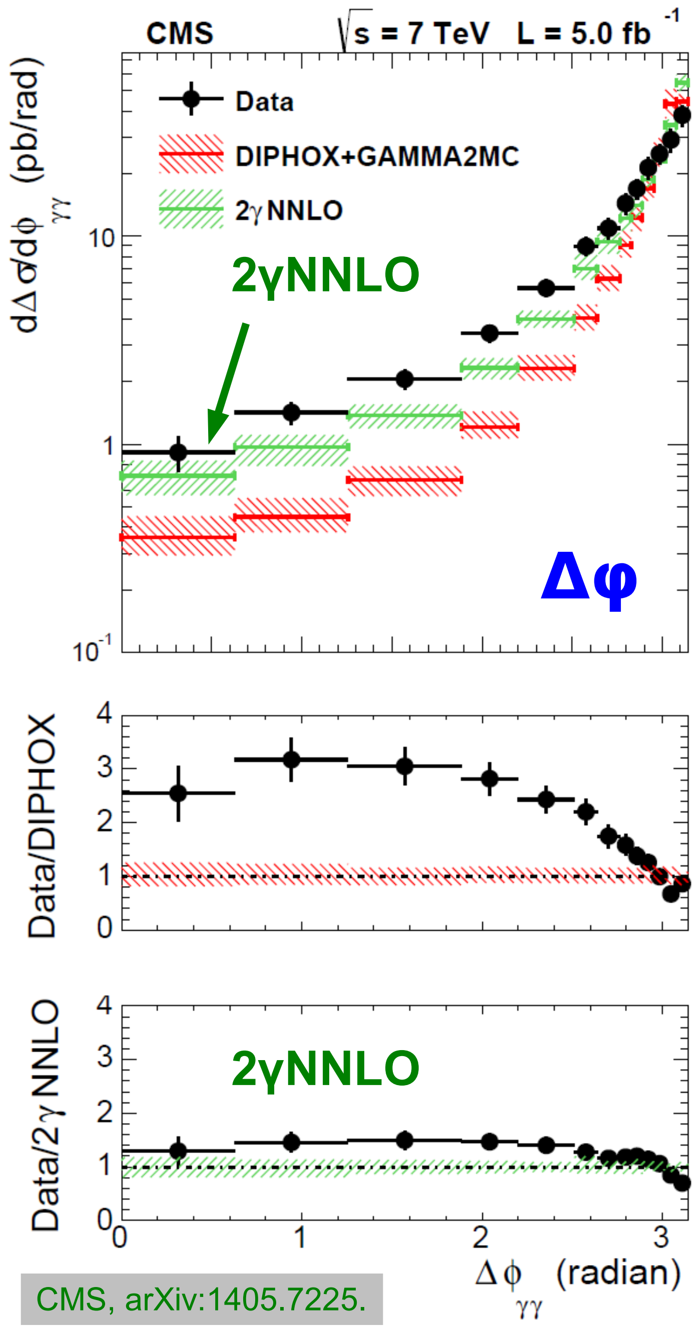
Di-Photons at 7 TeV

Significant improvement with NNLO (direct γ only!) at 7 TeV, some deviations visible in $\Delta\varphi_{\gamma\gamma}$ to 2γNNLO



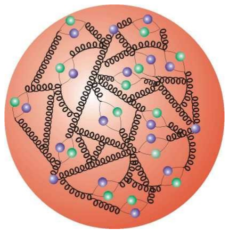
ATLAS, JHEP01 (2013) 086.

Consistent between ATLAS & CMS

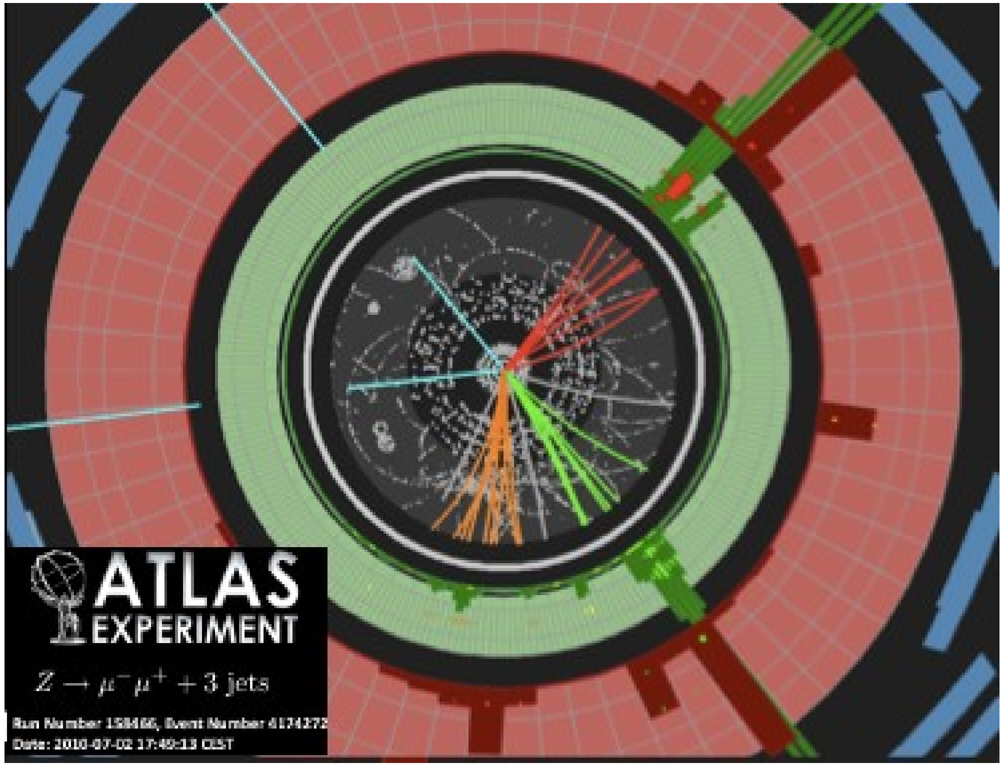


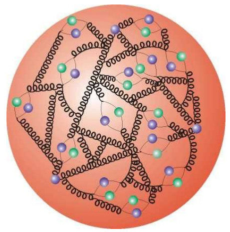
CMS, arXiv:1405.7225.

Standard Candles



Proton

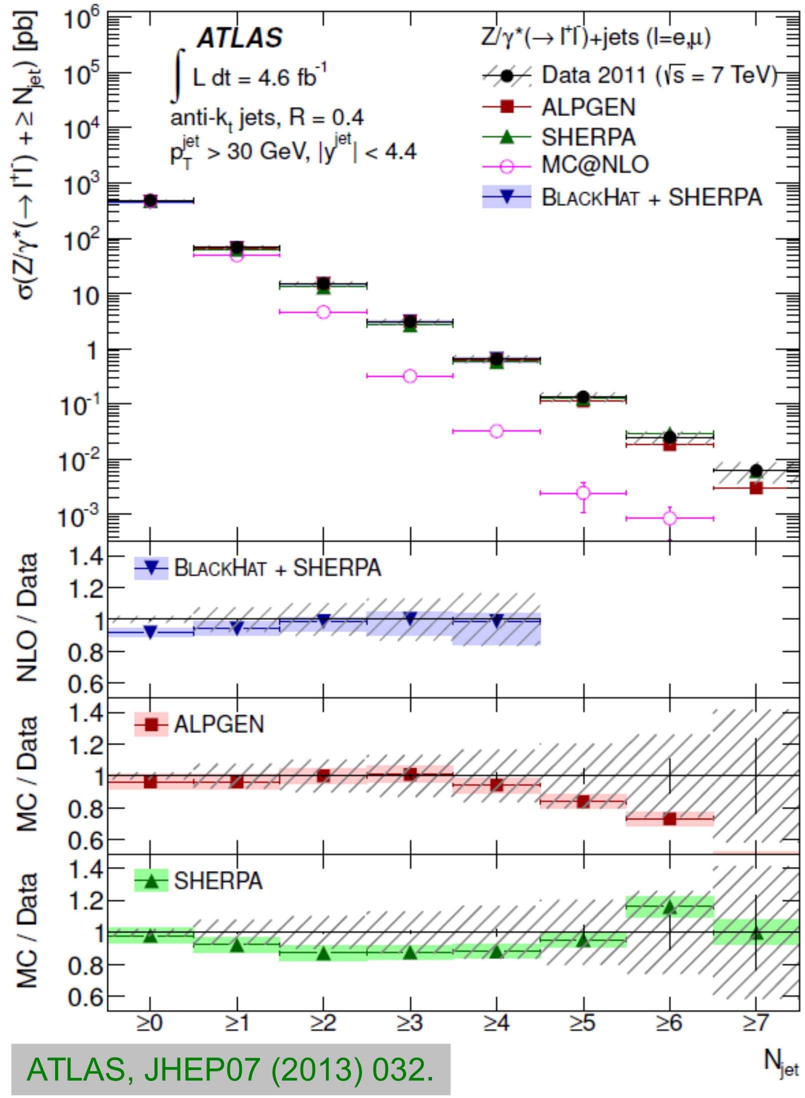




Proton

Z + Jets

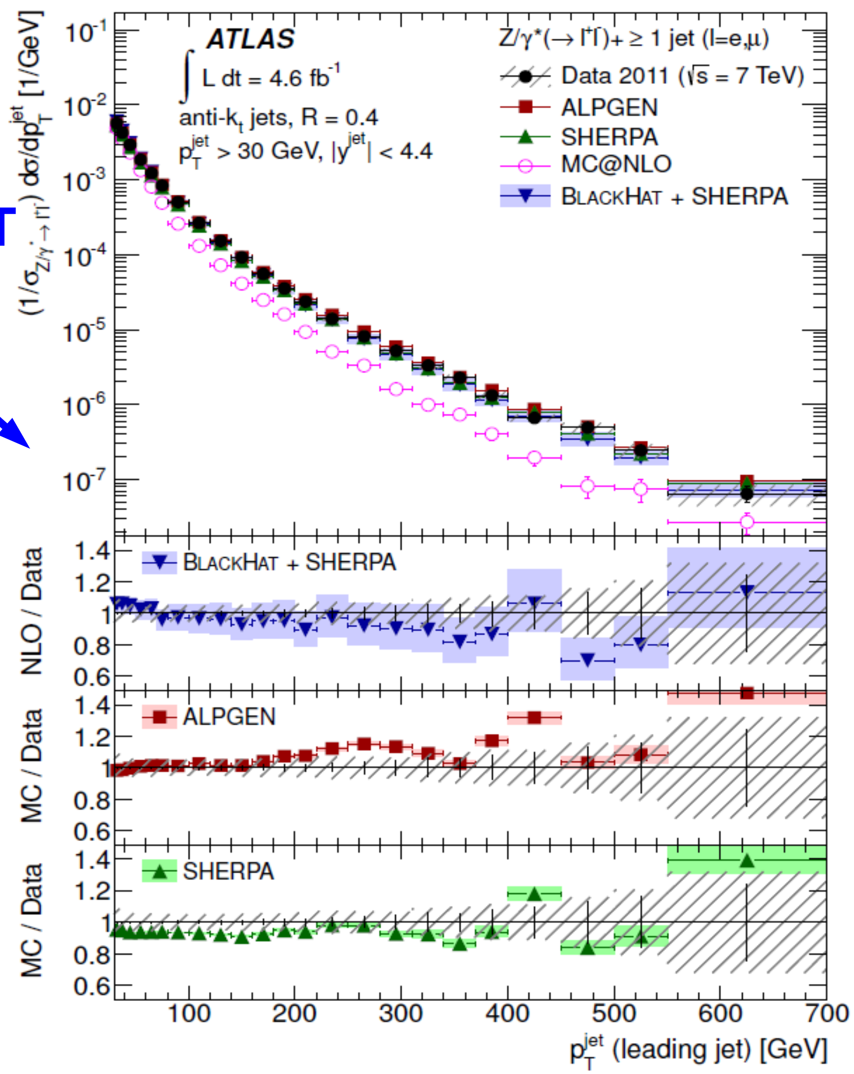
Z+jets by ATLAS with up to 7 jets inclusive!
Agreement with theory @ NLO up to 4 jets; from Z+jet → gluon (PDF)
OK: Sherpa; Alpgen, (MadGraph,Powheg) + Pythia; Severe discrepancies to MC@NLO



Jet multiplicity

Leading jet pT

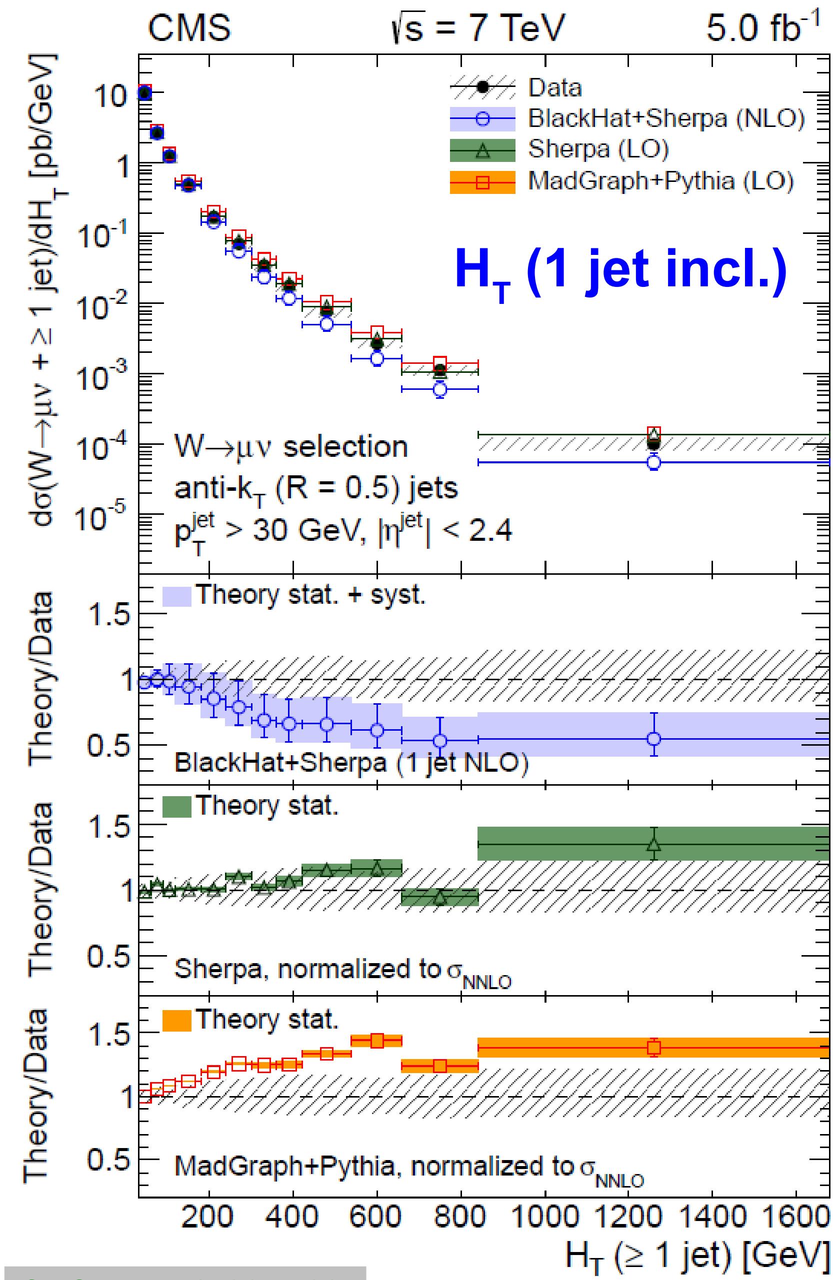
NLO



ATLAS, JHEP07 (2013) 032.

See also:
CMS 7 TeV, arXiv:1408.3104.
CMS 8 TeV, PAS-SMP-13-007.
CDF, arXiv:1409.4359.

W + Jets



CMS, arXiv:1406.7533.

Comprehensive studies by ATLAS and CMS

Multiplicities and rapidities well described

H_T problematic for W+1 jets incl. → no 3+ ME

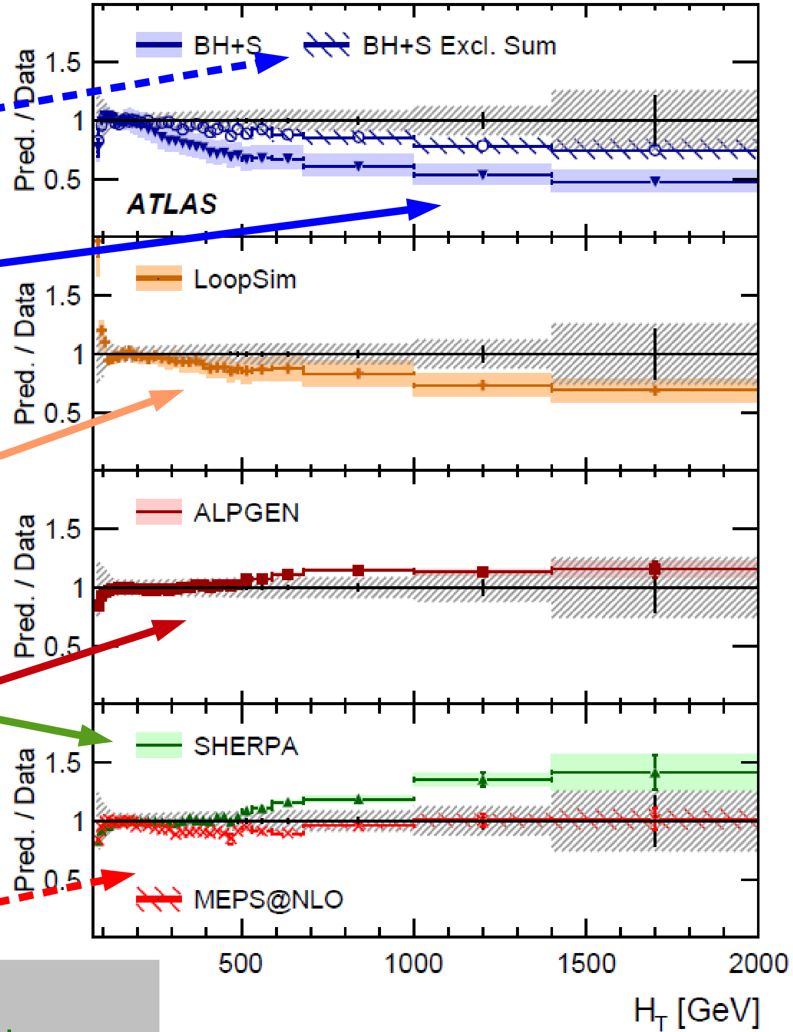
Sum of diff. jet multiplicities

No 3+jet ME

Approx. NNLO

Multi-leg + PS

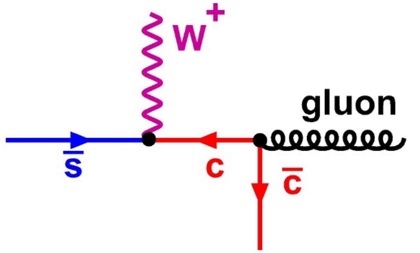
ME N+jet combined



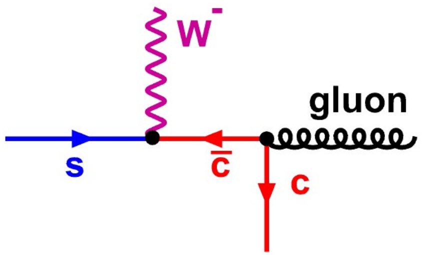
ATLAS, arXiv:1409.8639.

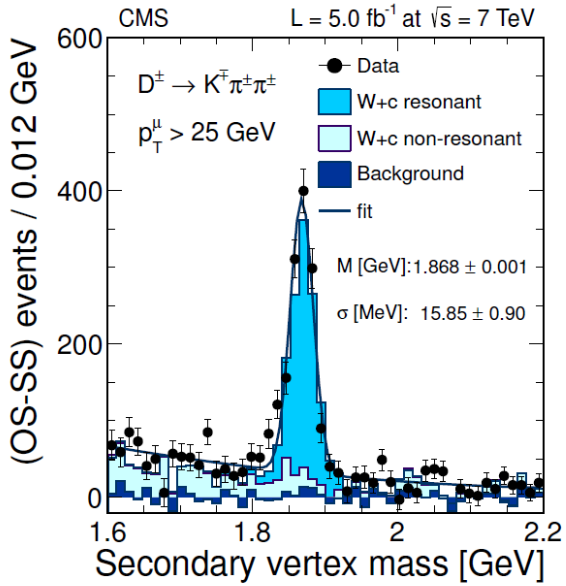
See also:
W+j: D0, PRD88 (2013) 092001.
W+j/Z+j ratios: ATLAS, arXiv:1408.6510.

W + charm

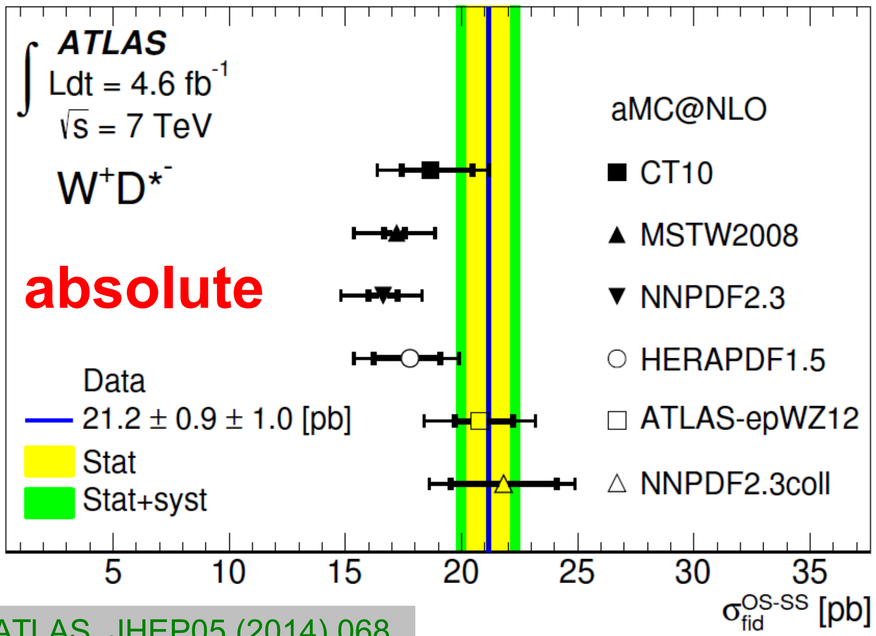


→ strange PDF

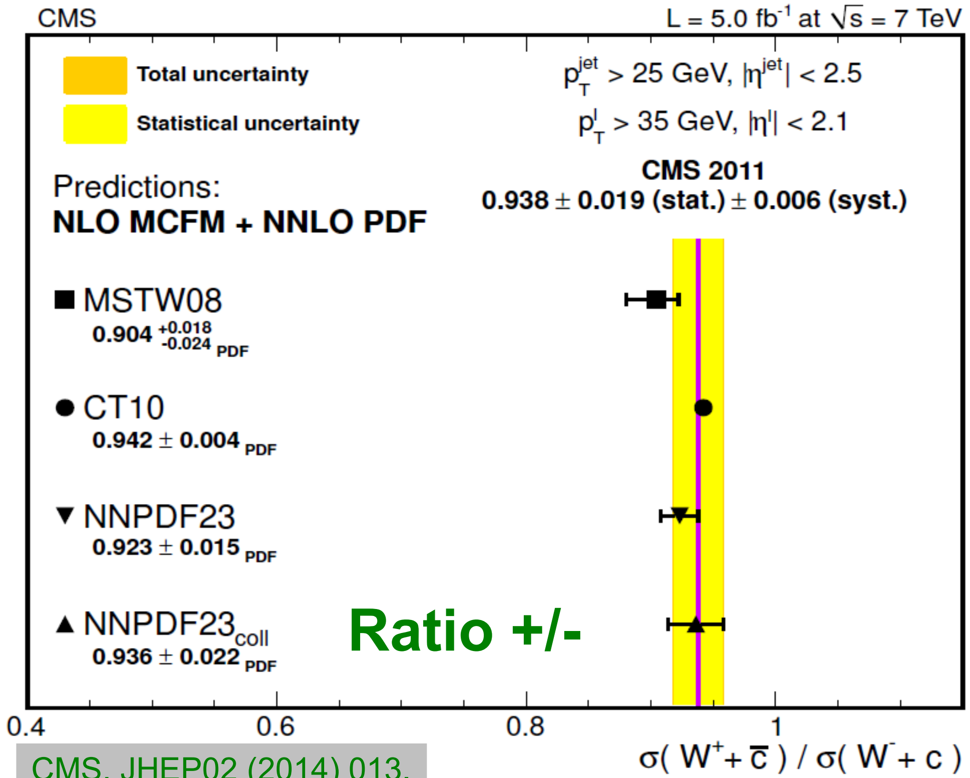




New measurements from ATLAS & CMS
Explicit reconstruction of charmed meson decays ($D^{\pm}$, $D^{\pm *}$) or incl. semileptonic
Different phase space ATLAS vs. CMS
ATLAS finds smaller abs. cross sections
Ratio W+/W- ok
CMS finds agreement within uncertainties for both

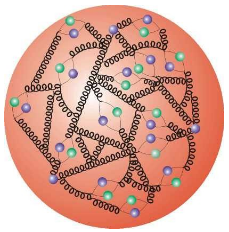


ATLAS, JHEP05 (2014) 068.

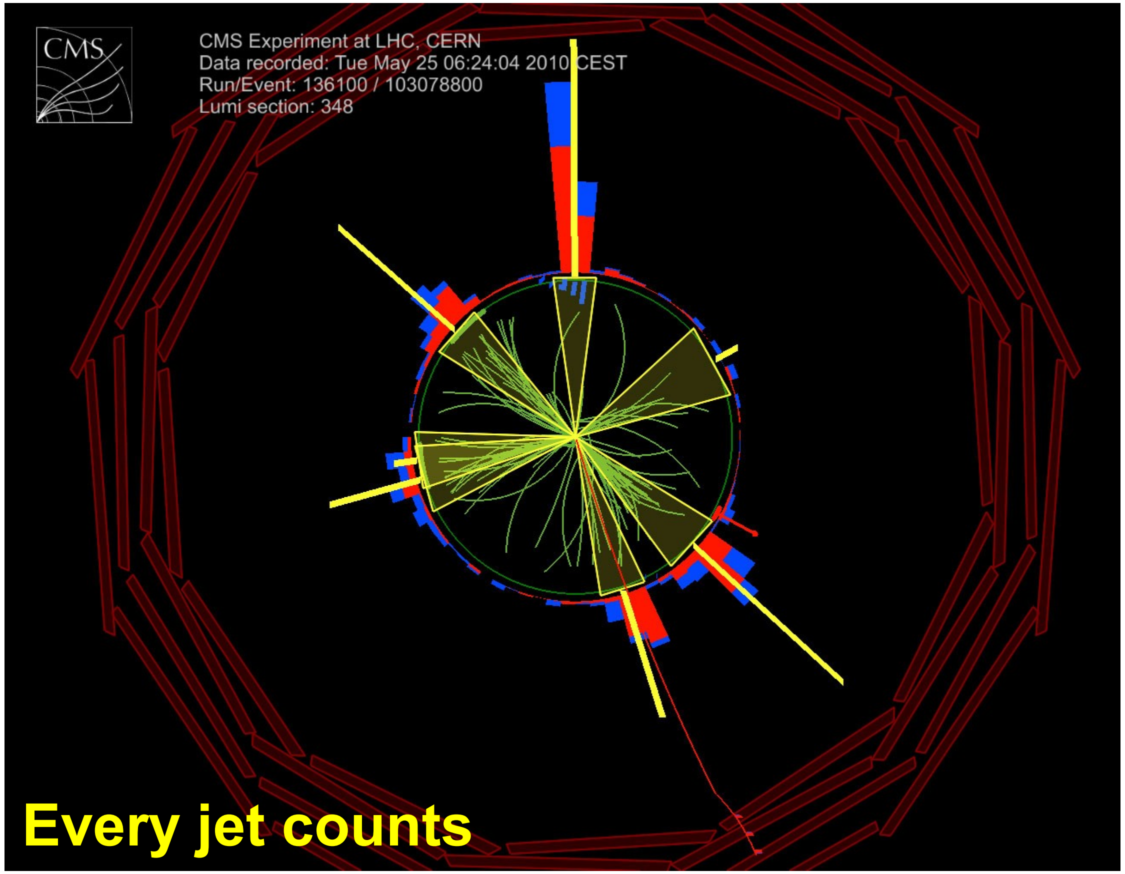


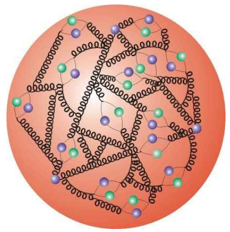
CMS, JHEP02 (2014) 013.

High transverse Momenta



Proton





Proton

Inclusive Jets

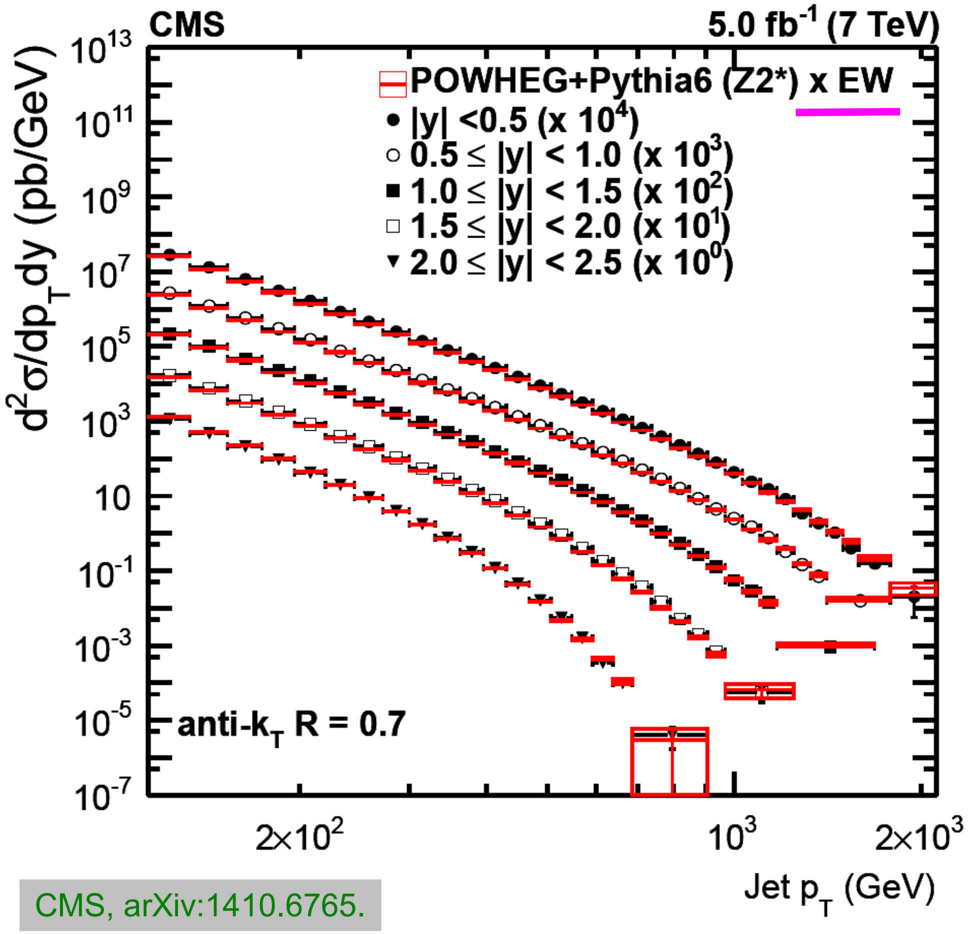
Agreement with predictions of QCD over many orders of magnitude in cross section and beyond 2 TeV in jet p_T

Constrains PDFs
"Harder" gluon at high x compared to DIS

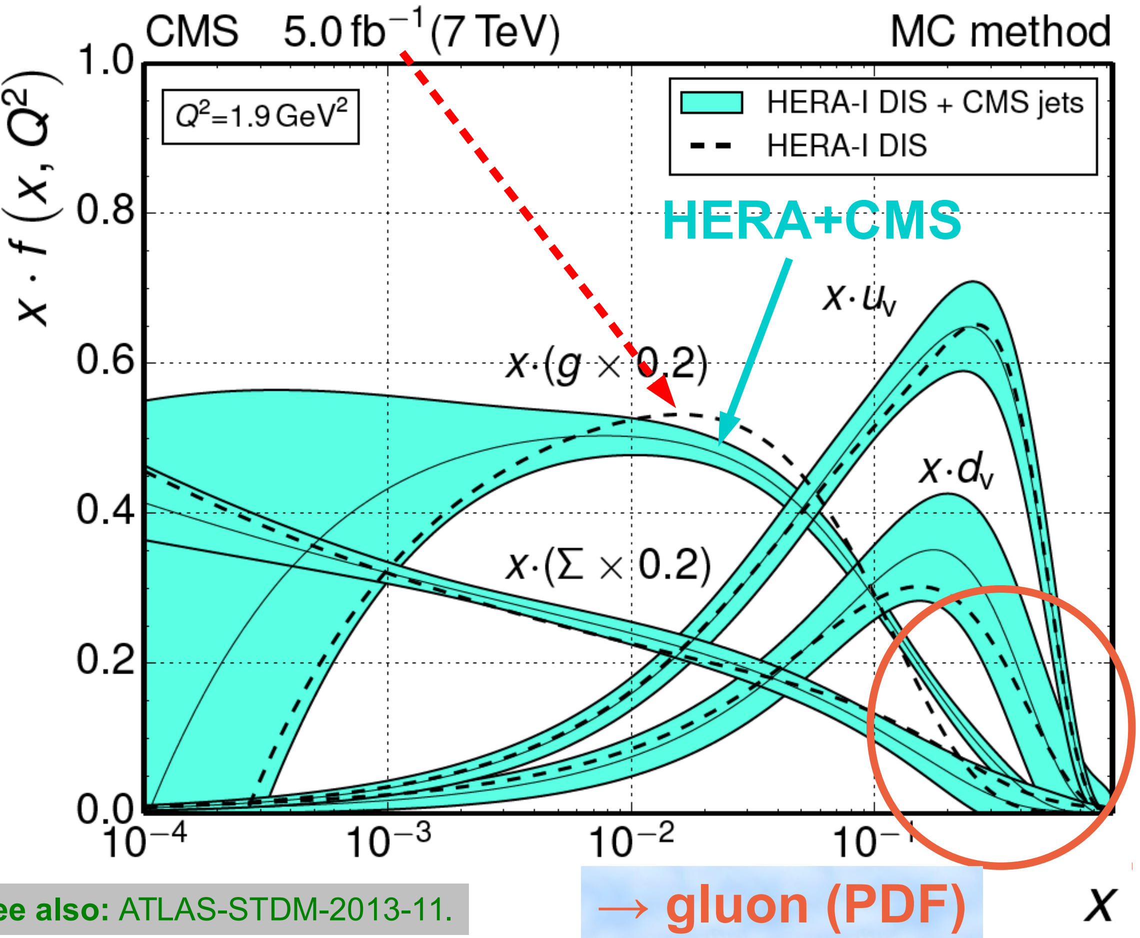
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

Data vs. NLO+PS ⊗electroweak corrections

anti-kT, R=0.7, 7 TeV, 2011



"HERA-I" gluon



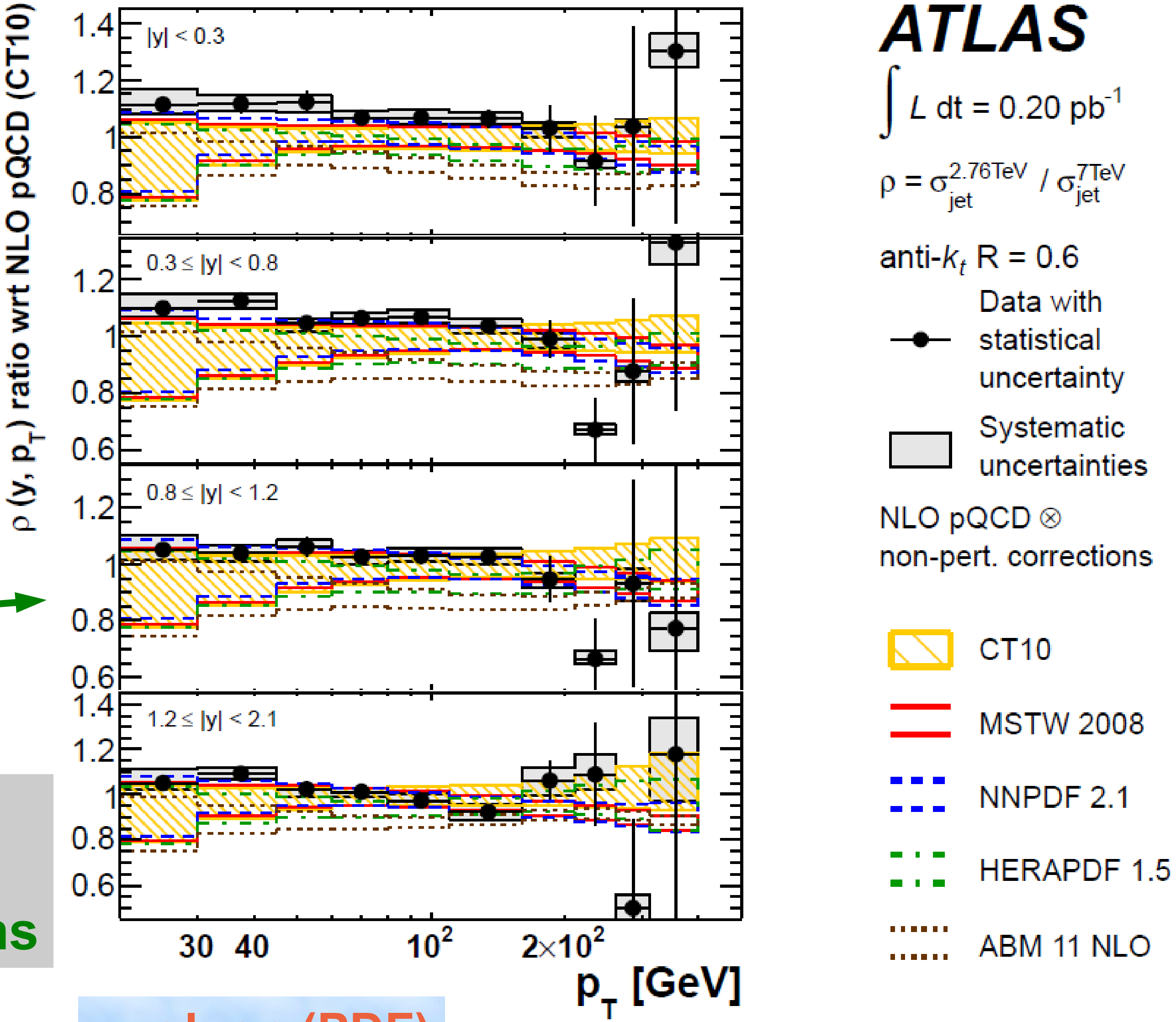
→ gluon (PDF)

CMS, arXiv:1410.6765.

See also: ATLAS-STDM-2013-11.

Here:
Ratio at different energies
E_{cms} = 2.76 and 7.0 TeV

Result from ATLAS:
- cross sections at 2.76 TeV
- ratios to 7 TeV
- ratio to 7 TeV divided by theory prediction (NLO, CT10, X NP)
  Shown
- study on PDF impact



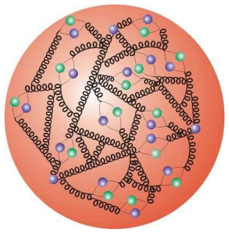
At least partial cancellation of uncertainties
→ more precise comparisons

→ gluon (PDF)

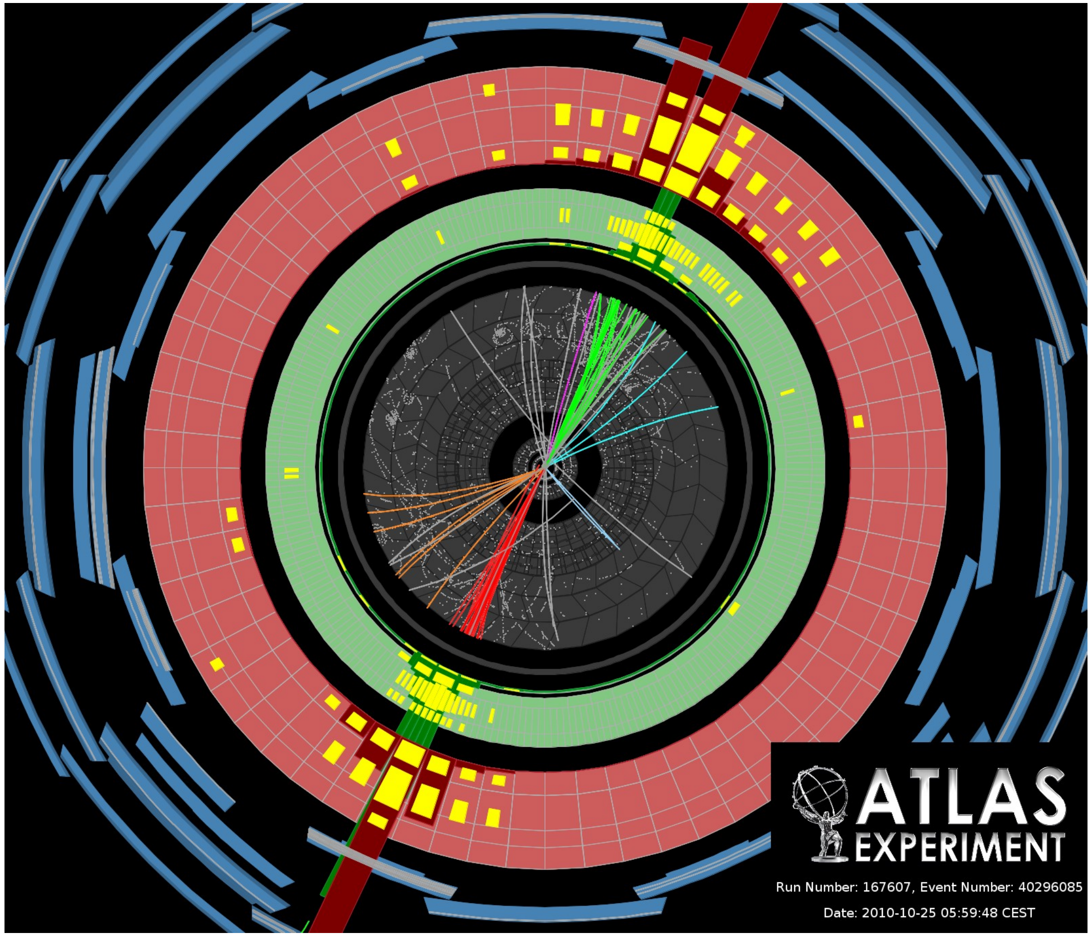
ATLAS, EPJC73 (2013) 2509.

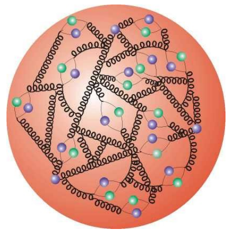
Dijets

High Masses



Proton



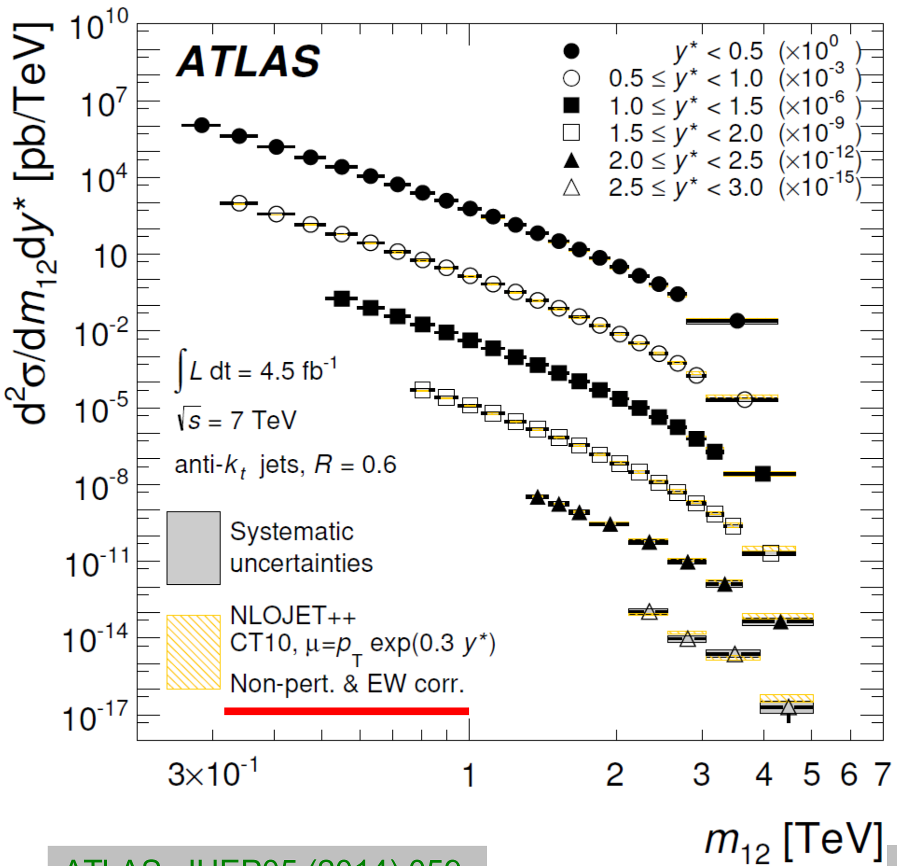


Proton

Dijet Mass

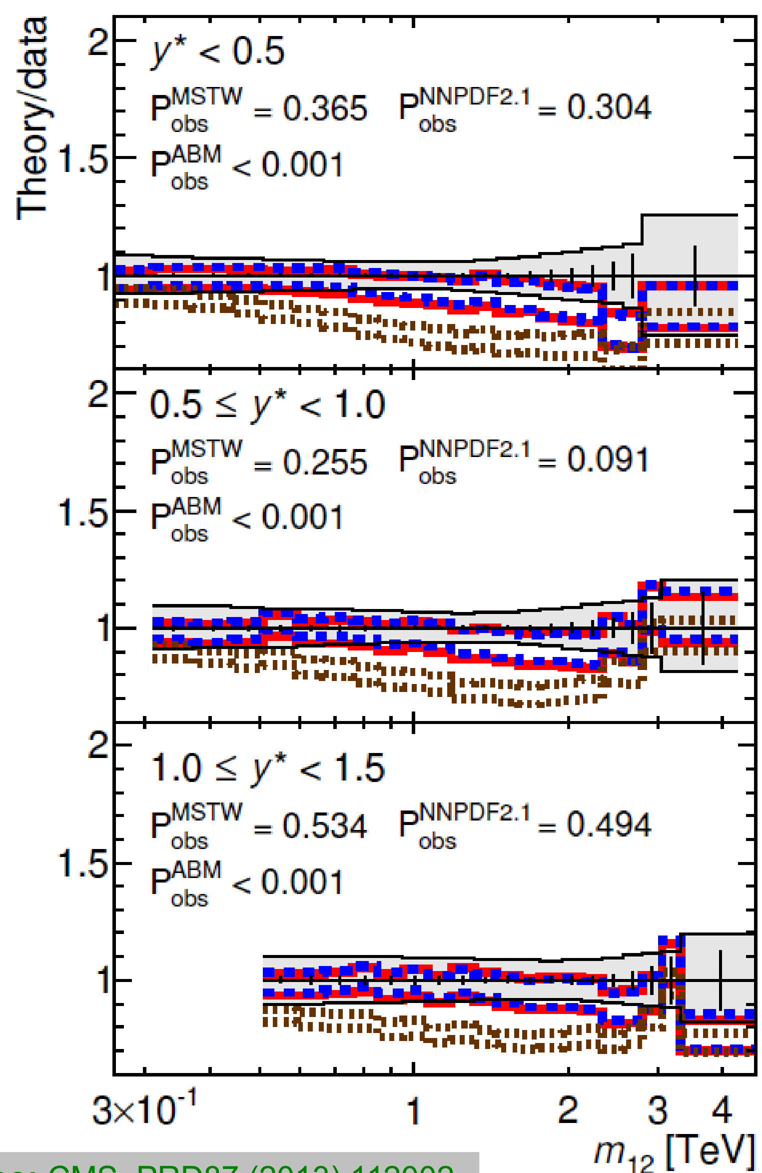
Compatible with QCD
- **over many orders of magnitude in σ**
- **over 2 orders of magnitude in M_{jj}**
- **up to rapidities of ~ 3**

anti-kT, R=0.6



$$y^* = |y_1 - y_2|/2$$

pQCD ⊗ nonperturbative and electroweak corrections



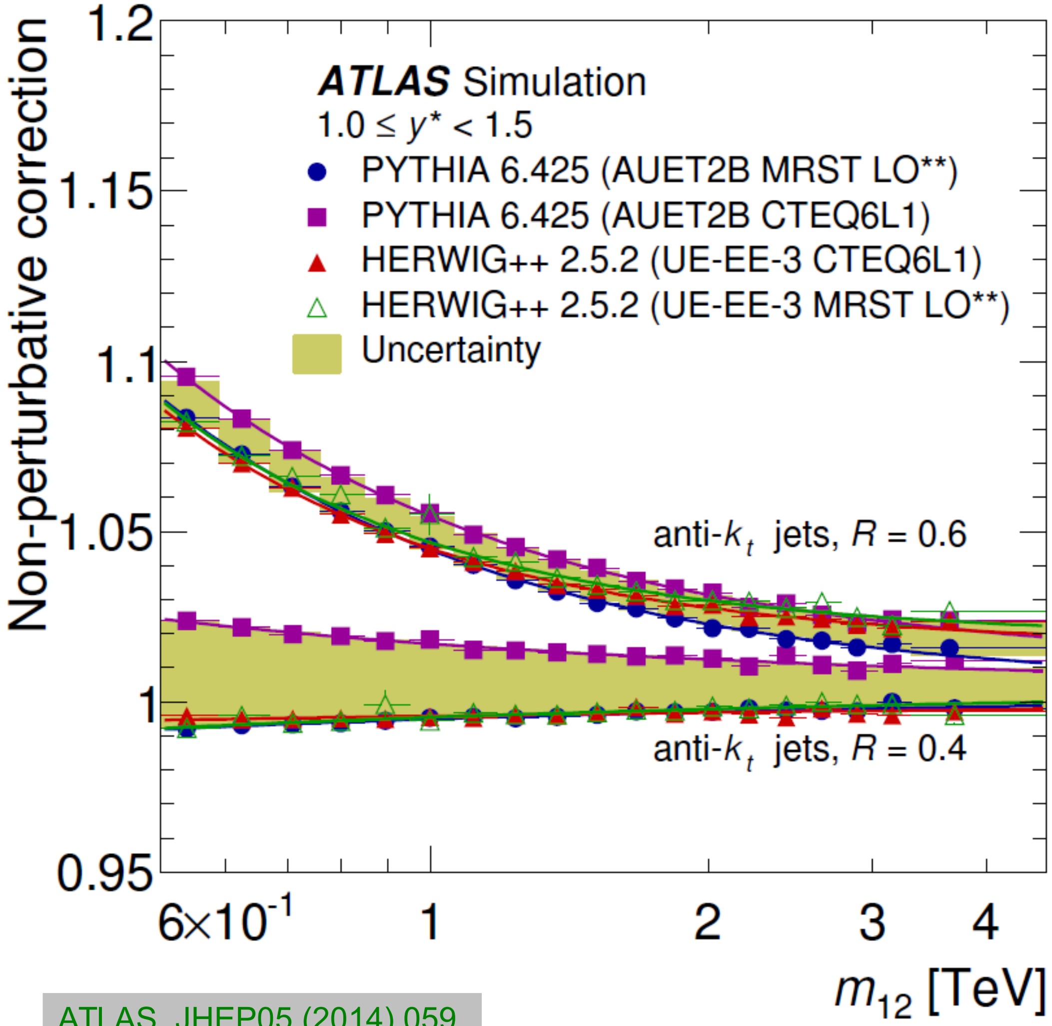
ATLAS, JHEP05 (2014) 059.

See also: CMS, PRD87 (2013) 112002.

ATLAS, JHEP05 (2014) 059.

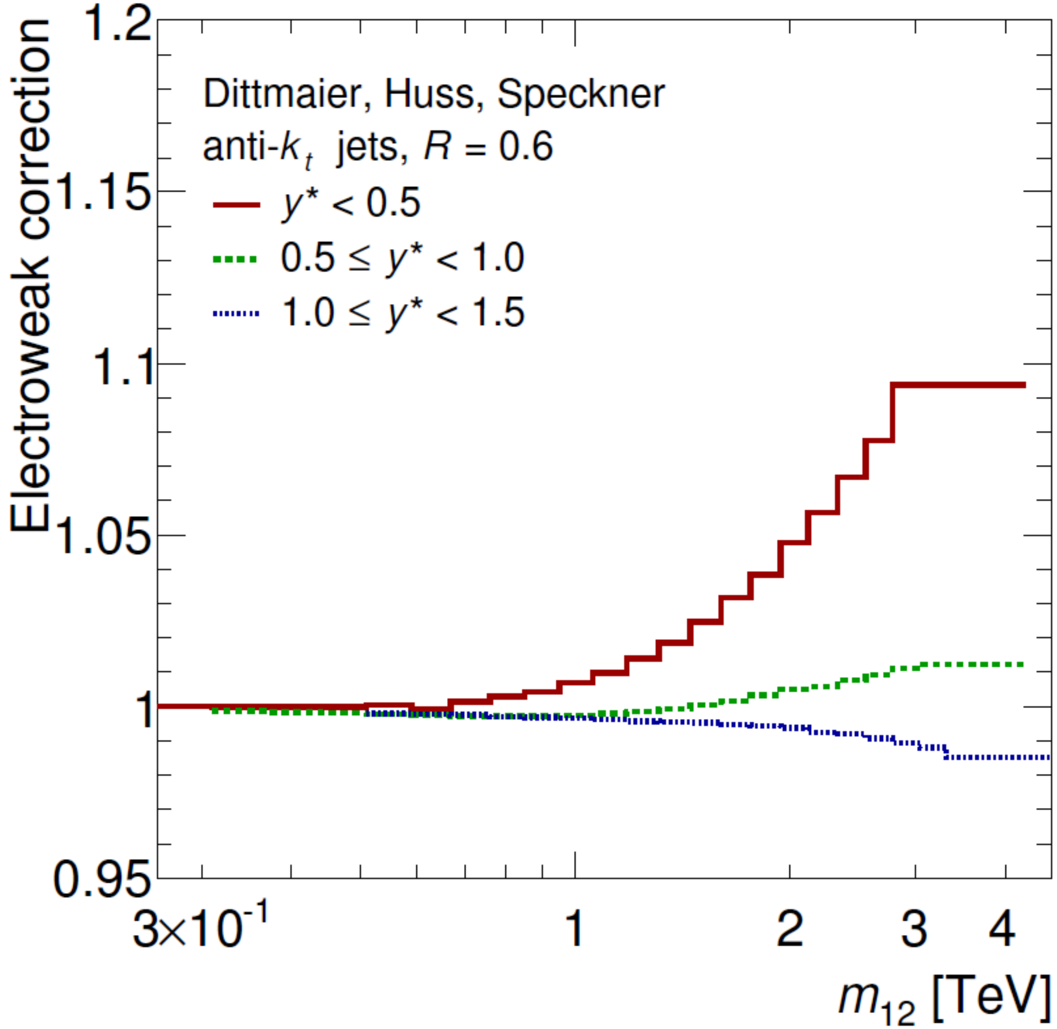
Dijet Mass

Non-perturbative corrections get small at high masses.
Size and uncertainty depend on jet size R.



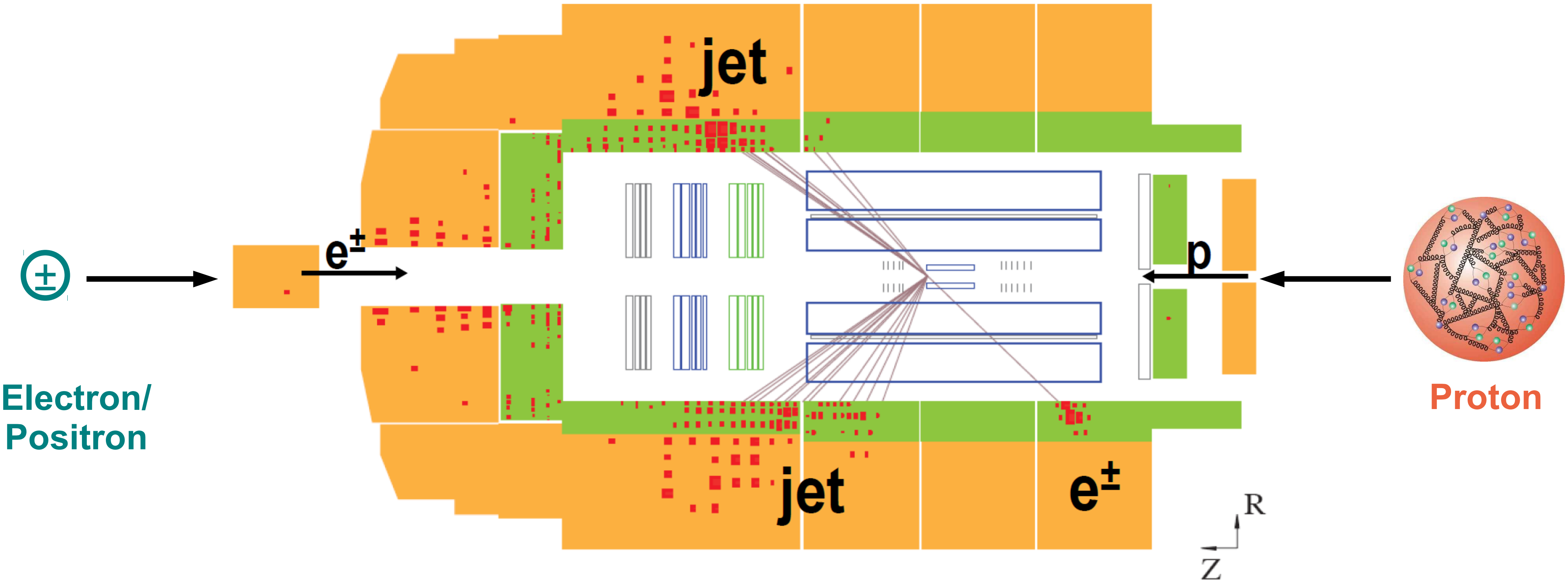
ATLAS, JHEP05 (2014) 059.

Electroweak corrections become sizeable at high masses!
Size depends on rapidity.



Multi-Jets and α_s

High Scales



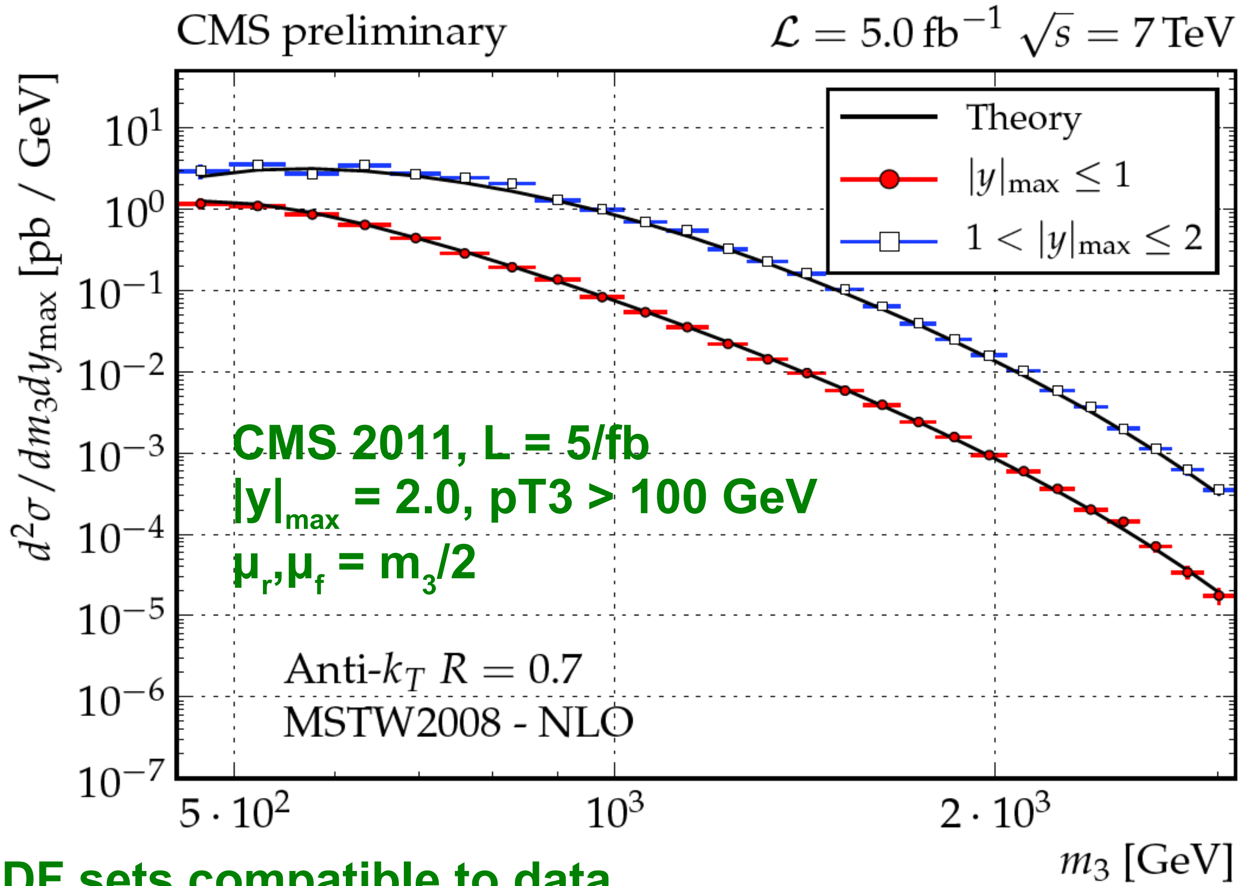
3-Jet Mass

Sensitive to α_s beyond 2→2 process

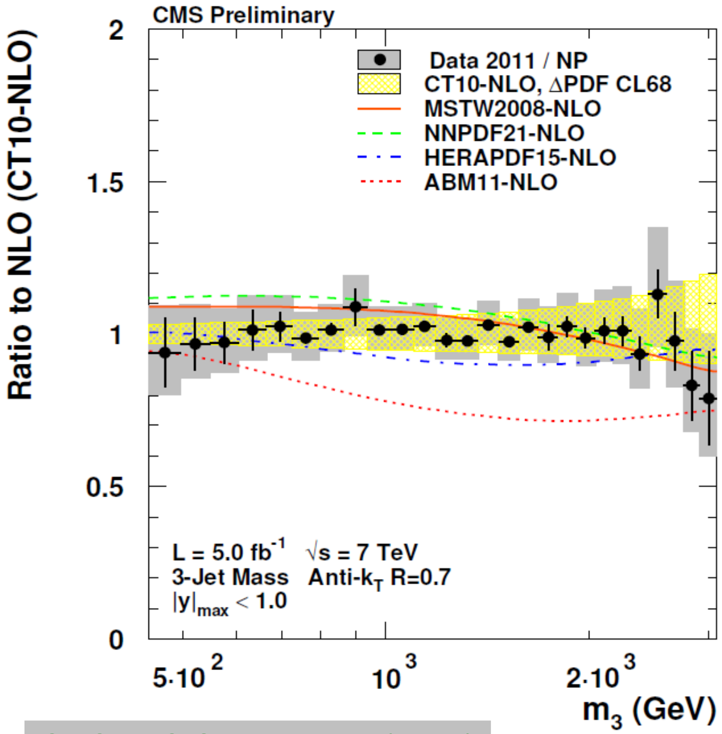
NLO with 3-4 partons (NLOJet++)

Sensitive to PDFs → gluon (PDF)

Involves additional "scale" $p_{T,3}$



CMS 2011, L = 5/fb
$|y|_{max}$ = 2.0, pT3 > 100 GeV
$\mu_r, \mu_f = m_3/2$



Most PDF sets compatible to data

$$\frac{d\sigma_{3jet}}{dm_{3jet}} \propto \alpha_s^3$$

Extraction of $\alpha_s(M_Z)$ from scales up to 1.4 TeV

Dominated by theory uncertainty! NLO only

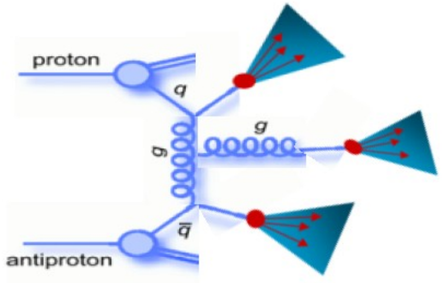
CMS-PAS-SMP-12-027 (2013)

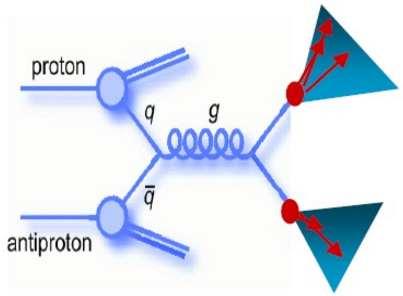
$$\alpha_S(M_Z) = 0.1160^{+0.0025}_{-0.0023}(\text{exp, PDF, NP})^{+0.0068}_{-0.0021}(\text{scale})$$

See also: ATLAS-CONF-2014-045.

3-Jet Ratios and α_s in hh

Again: Normalization or ratios for different multiplicity N_{jet} = 3 over 2:
- Similar as in H1 normalized cross Sections, see later!
- Reduced dependence on PDFs and the RGE
- Reduce exp. and scale uncertainties
- Eliminate luminosity dependence





⟷ α_s

M. Wobisch

Three observables investigated:

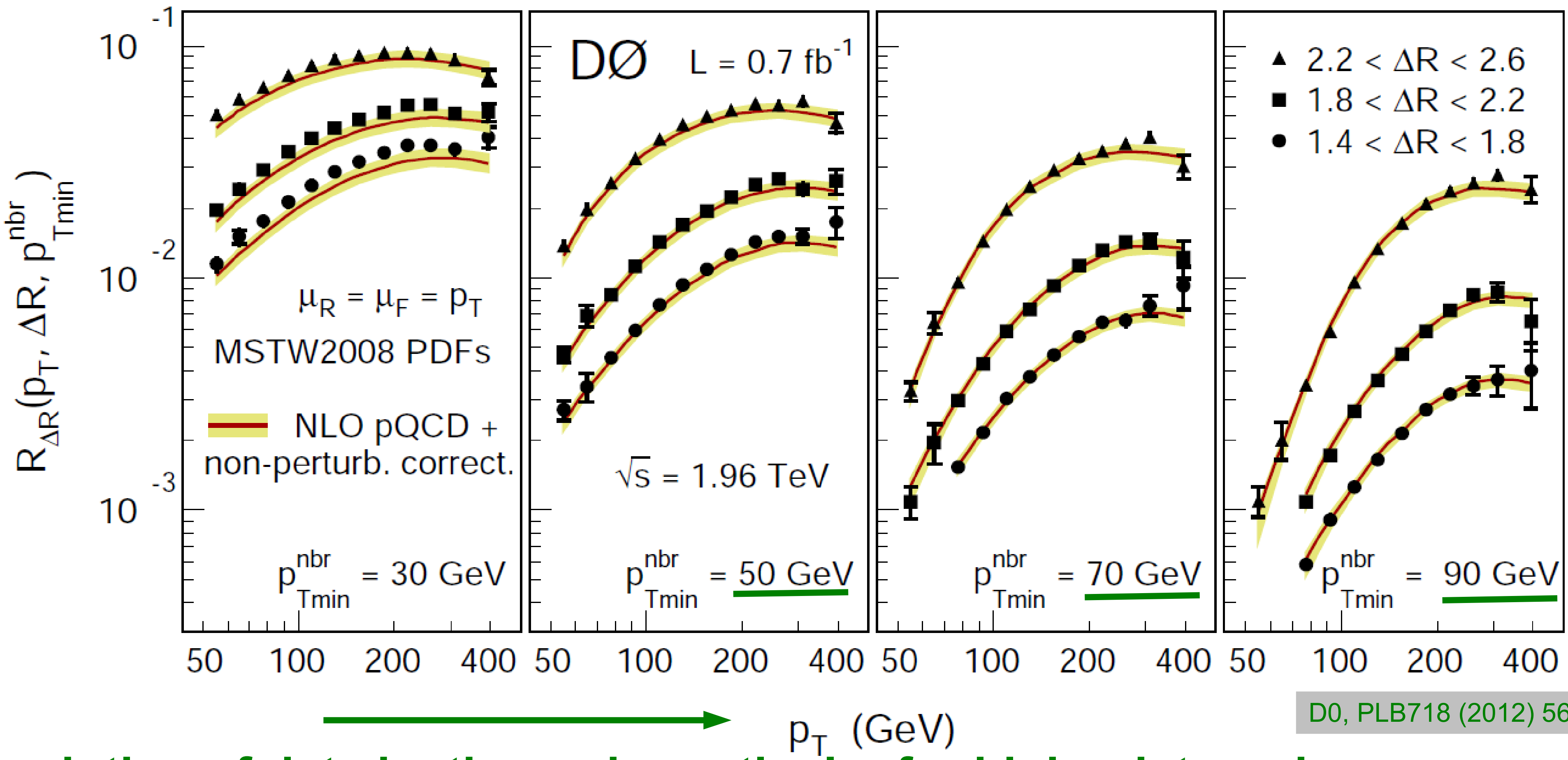
D0: $R_{\Delta R}$
- Average no. of neighbor jets within ΔR in incl. sample
- D0 midpoint cone R=0.7
- Min. jet pT: 50 GeV
- Max. rap.: |y| < 1.0
- Scale: Jet pT
- Data 0.7/fb

CMS: $R_{3/2}$
- Ratio of inclusive 3- to inclusive 2-jet events
- anti-kT R=0.7
- Min. jet pT: 150 GeV
- Max. rap.: |y| < 2.5
- Scale: Average dijet pT
- Data 2011, 5/fb

ATLAS: $N_{3/2}$
- Ratio of inclusive 3- to inclusive 2-jets
- anti-kT R=0.6
- Min. jet pT: 40 GeV
- Max. rap.: |y| < 2.8
- Scale: Jet pT
- Data 2010, 36/pb

Jet Angular Correlation

$R_{\Delta R}$



D0, PLB718 (2012) 56.

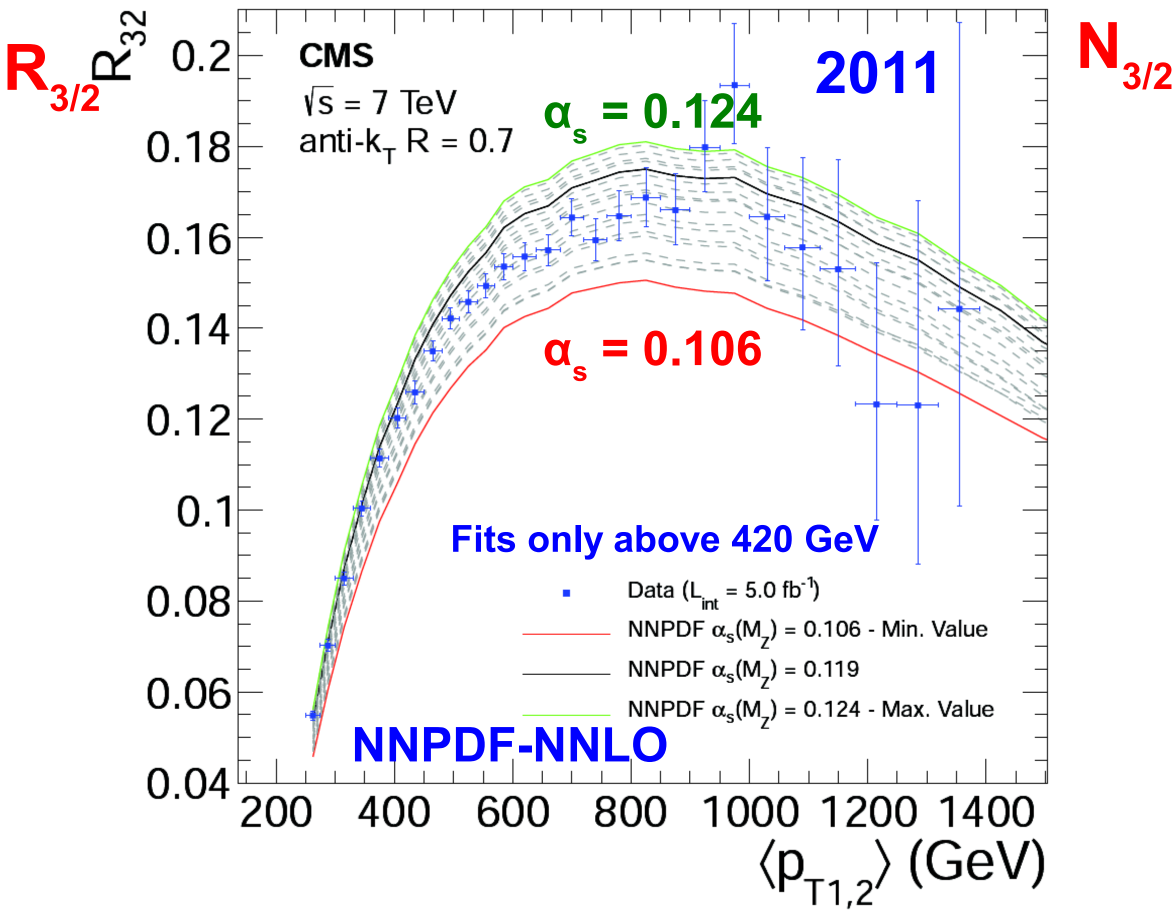
Good description of data by theory in particular for higher jet $p_T$min

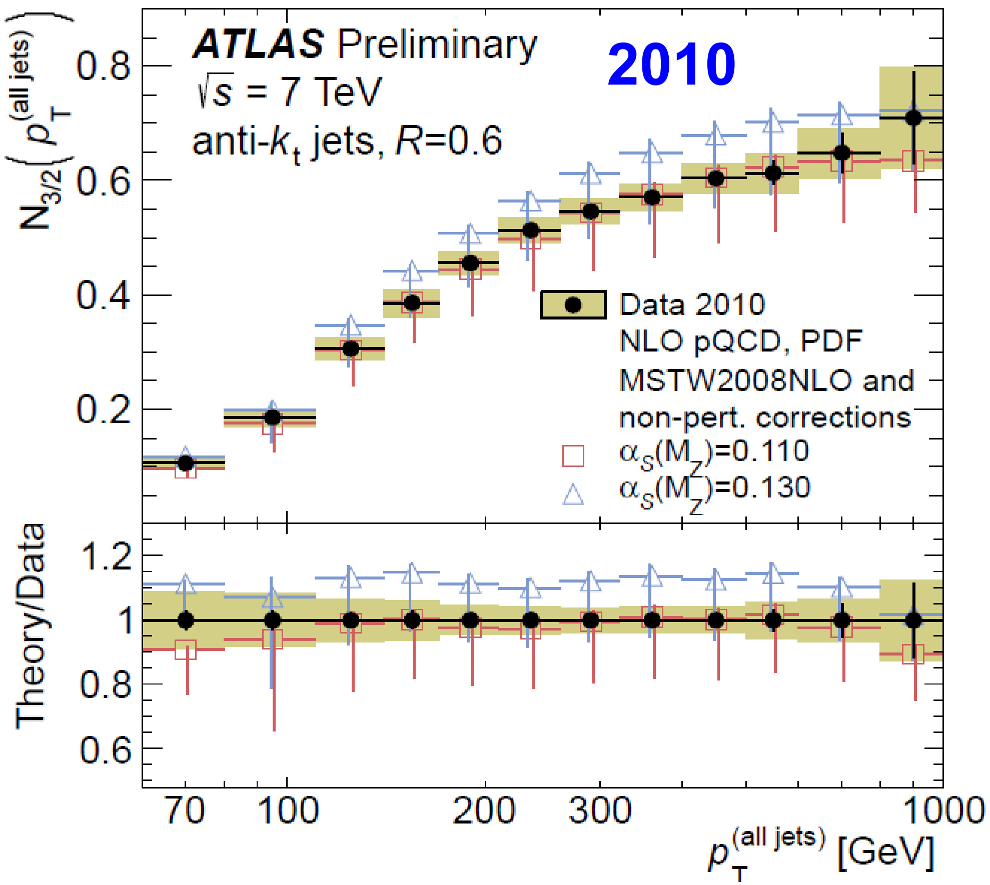
$$\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}(\text{total})$$

Dominated by theory uncertainty! NLO only

$$\pm 0.0003(\text{stat})^{+0.0007}_{-0.0009}(\text{exp.})^{+0.0002}_{-0.0001}(\text{NP})^{+0.0010}_{-0.0005}(\text{MSTW})^{+0.0000}_{-0.0024}(\text{PDFset})^{+0.0046}_{-0.0066}(\text{scale})$$

3- to 2-Jet Ratios





Similarly described by CT10 or MSTW2008

Discrepancies observed with ABM11

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\text{exp}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$$

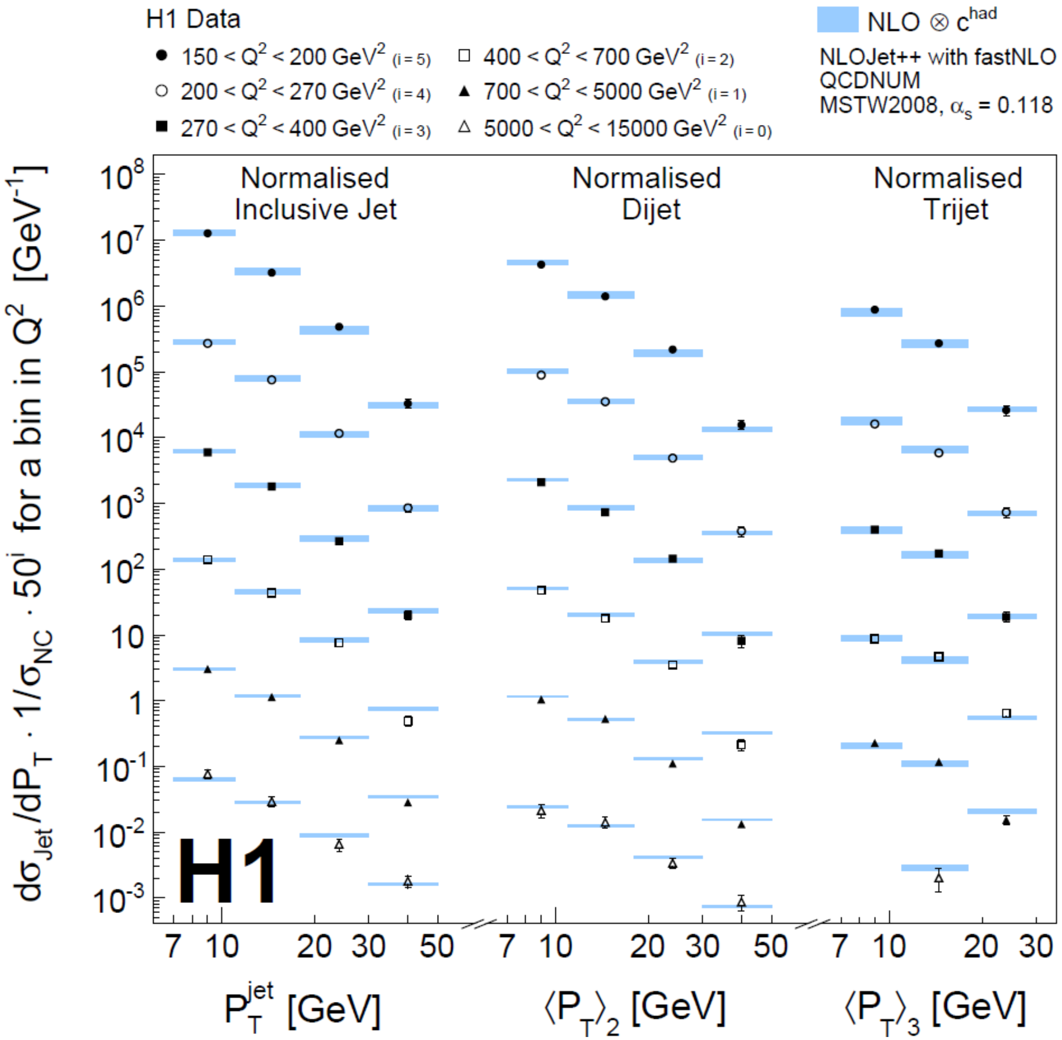
$$\alpha_s(M_Z) = 0.111 \pm 0.006\,(\text{exp}) \pm^{0.016}_{0.003}\,(\text{theory})$$

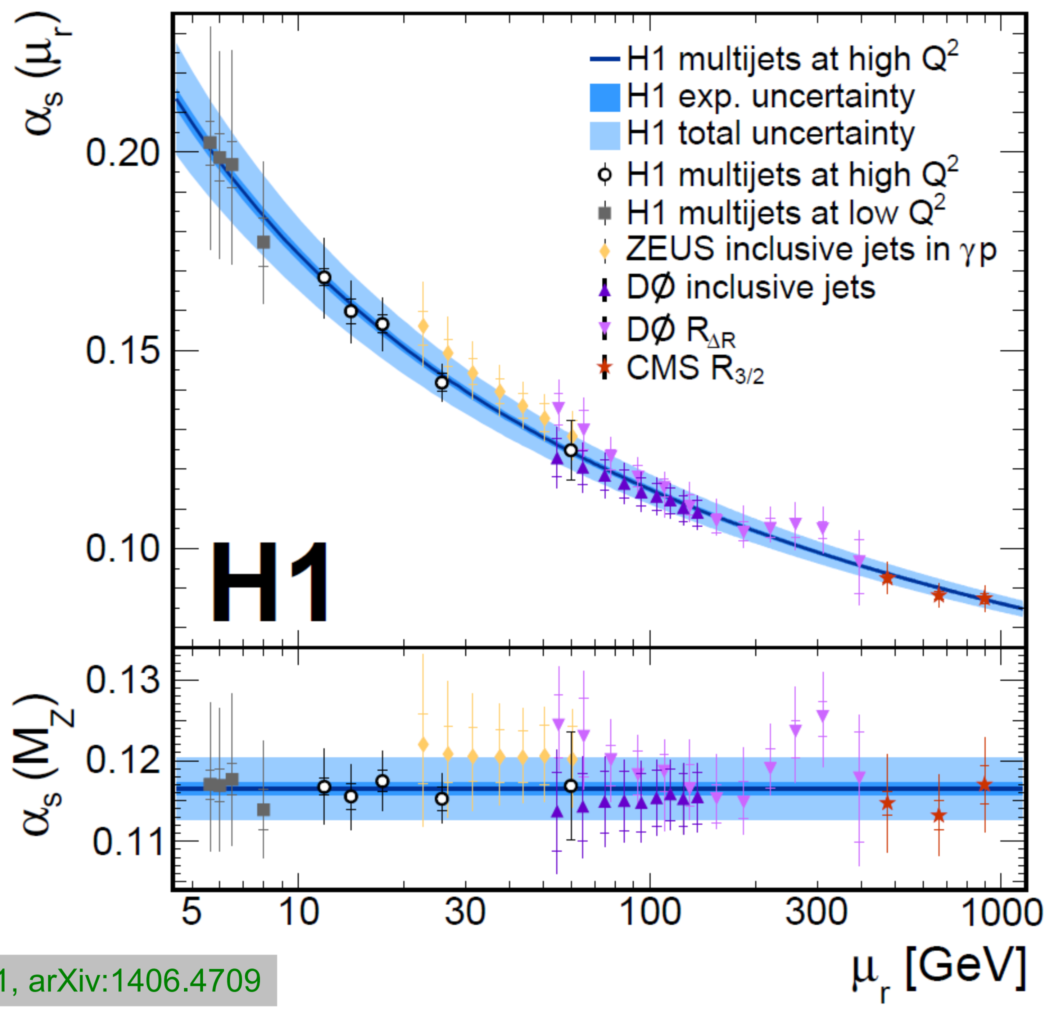
CMS, EPJC 73 (2013) 2604.

Dominated by theory uncertainty!

ATLAS-CONF-2013-041 (2013)

Normalized Multi-Jets in DIS





H1, arXiv:1406.4709

$$\alpha_s(M_Z) = 0.1165 \pm 0.0008(\text{exp.}) \pm 0.0038(\text{theor.})$$

NLO: Dominated by theory uncertainty!

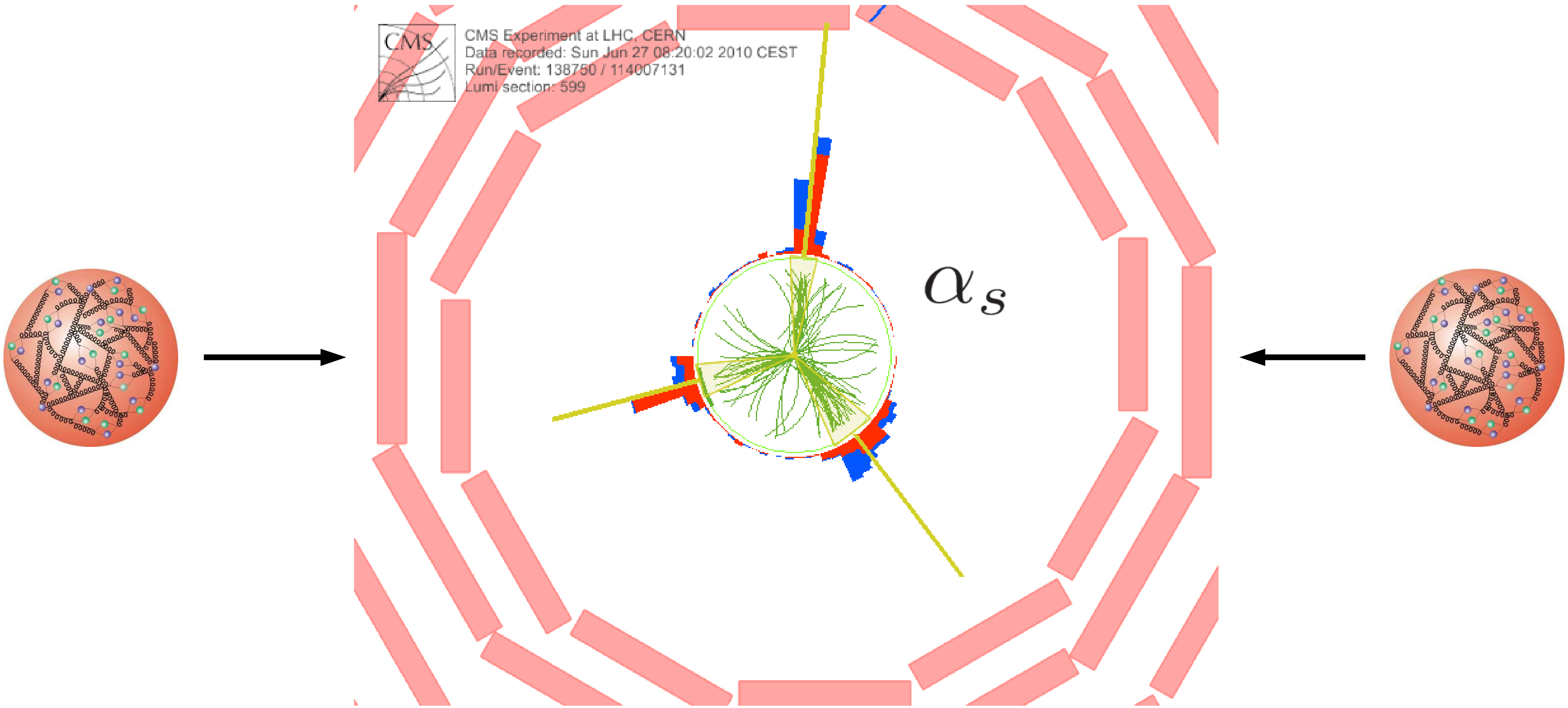
Jet phase space:

Jets incl.: $-1.0 < \eta_{lab} < 2.5$

$7 < pT < 50$ GeV

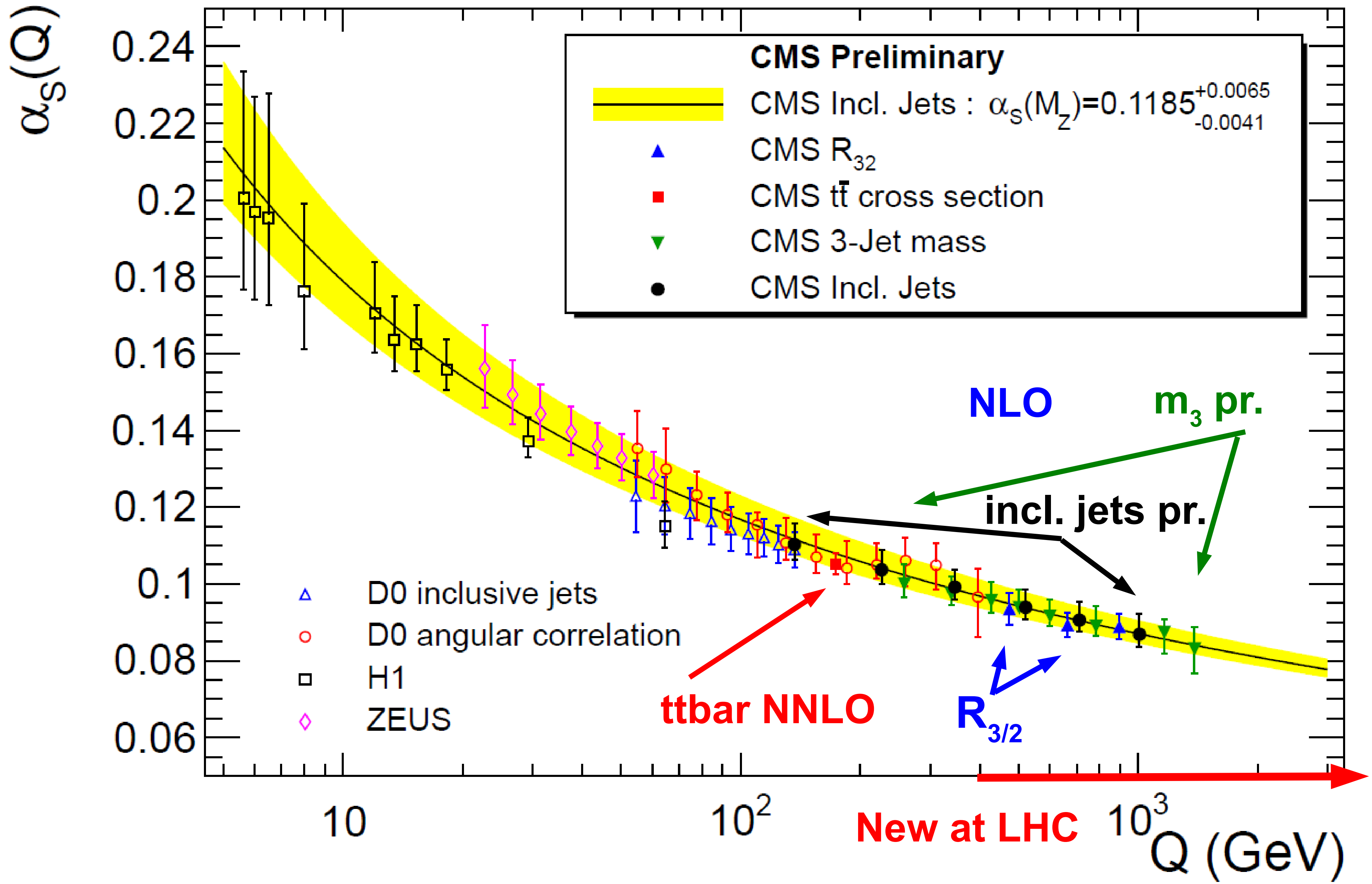
2-,3-Jets: $5 < pT < 50$ GeV

α_s (1 TeV) ?

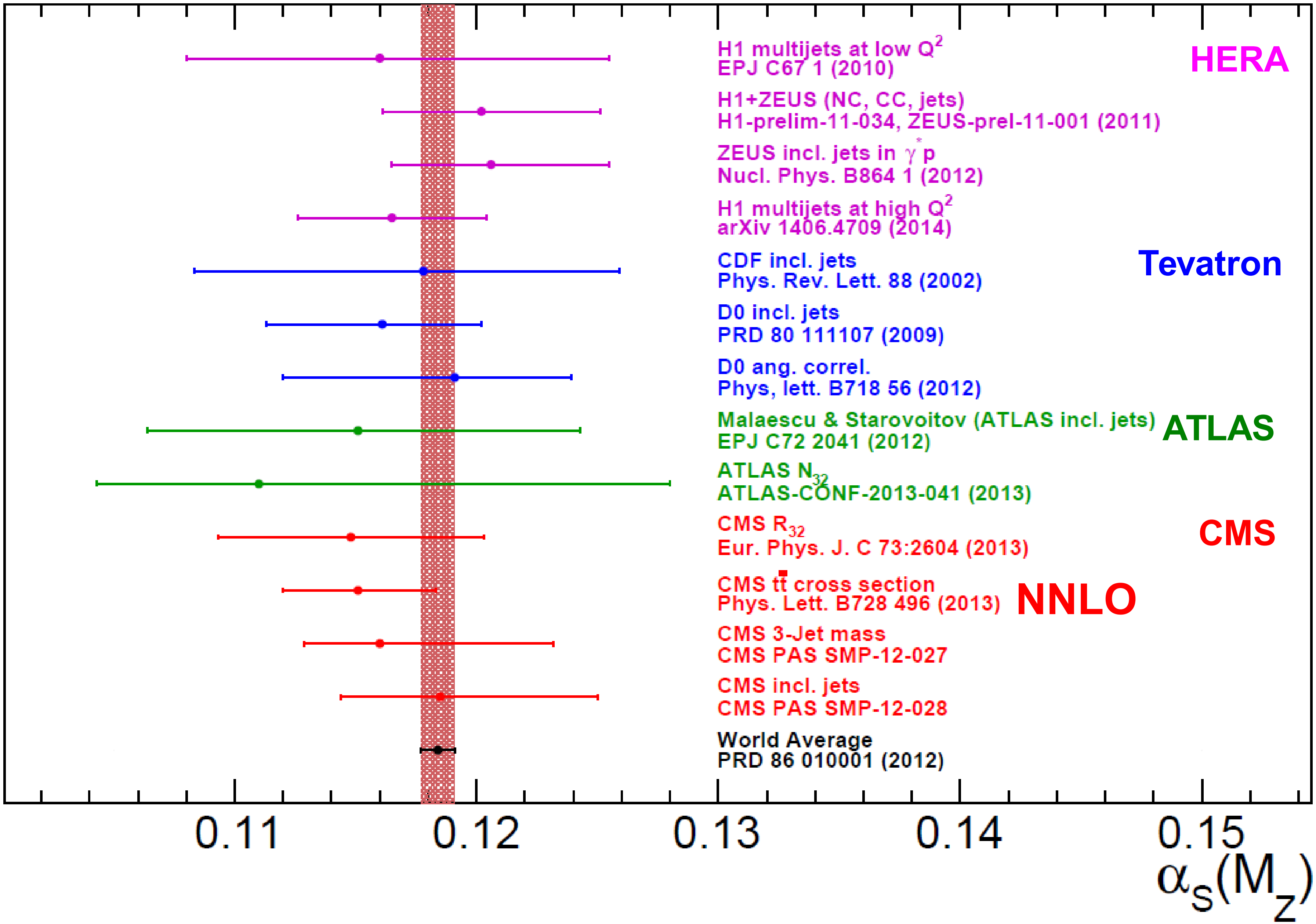


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 27 08:20:02 2010 CEST
Run/Event: 138750 / 114007131
Lumi section: 599
α_s

CMS α_s Summary



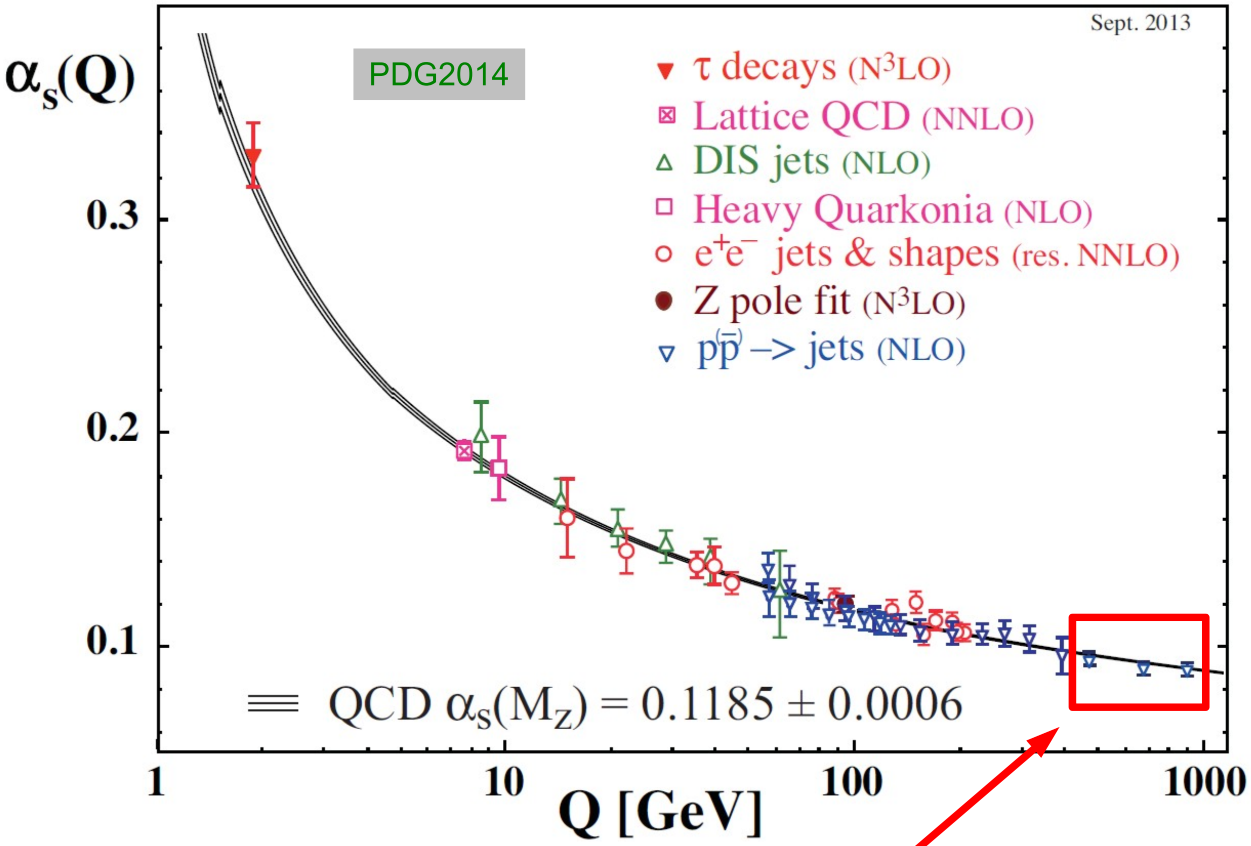
Jets (& ttbar) α_s Summary

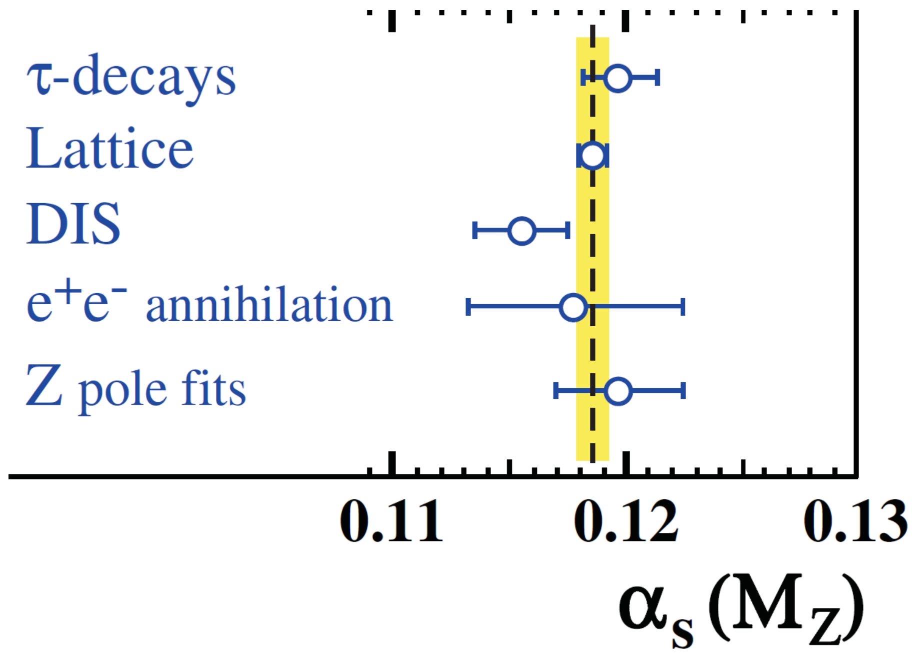


$\Delta\alpha_S/\alpha_S$

exp	theor
0.7%	3.3%
0.7%	4.9%
1.2%	4.6%
1.7%	1.3%
1.6%	4.1%

PDG α_s Summary





Dominated by Lattice Gauge Theory

CMS data, but not in average since only NLO theory!

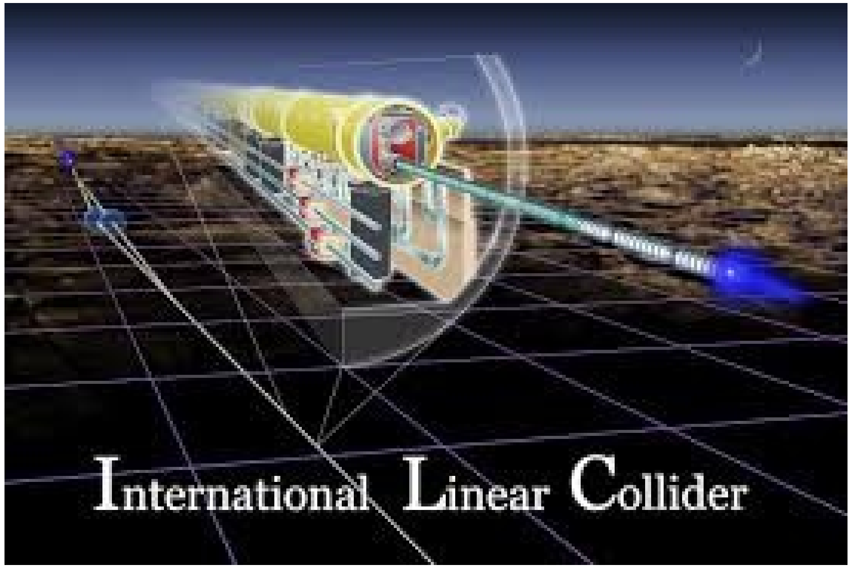
$$\alpha_s(M_Z) = 0.1185 \pm 0.0006$$

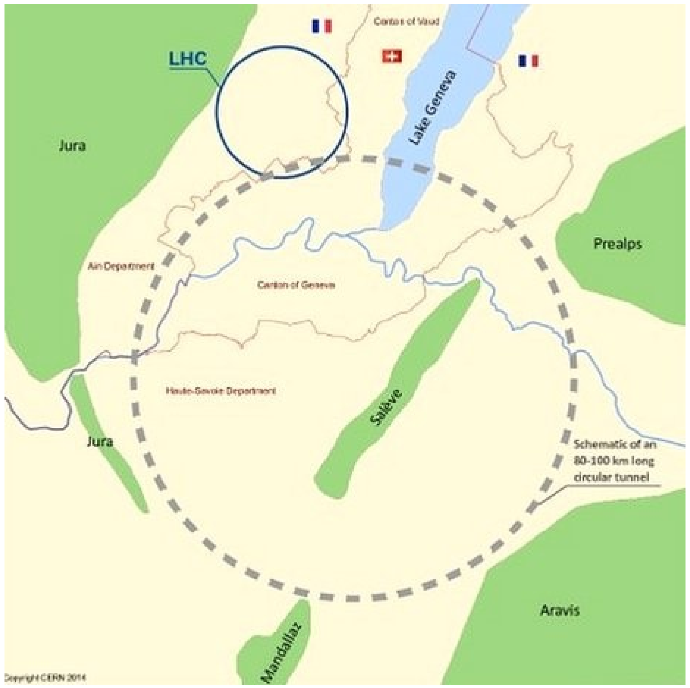
$$\frac{\Delta\alpha_S(M_Z)}{\alpha_S(M_Z)} = 0.5\%$$

PDG´92: 2.4%

PDG, Chin. Phys. C 38 (2014) 090001.

Perspectives at Future Colliders





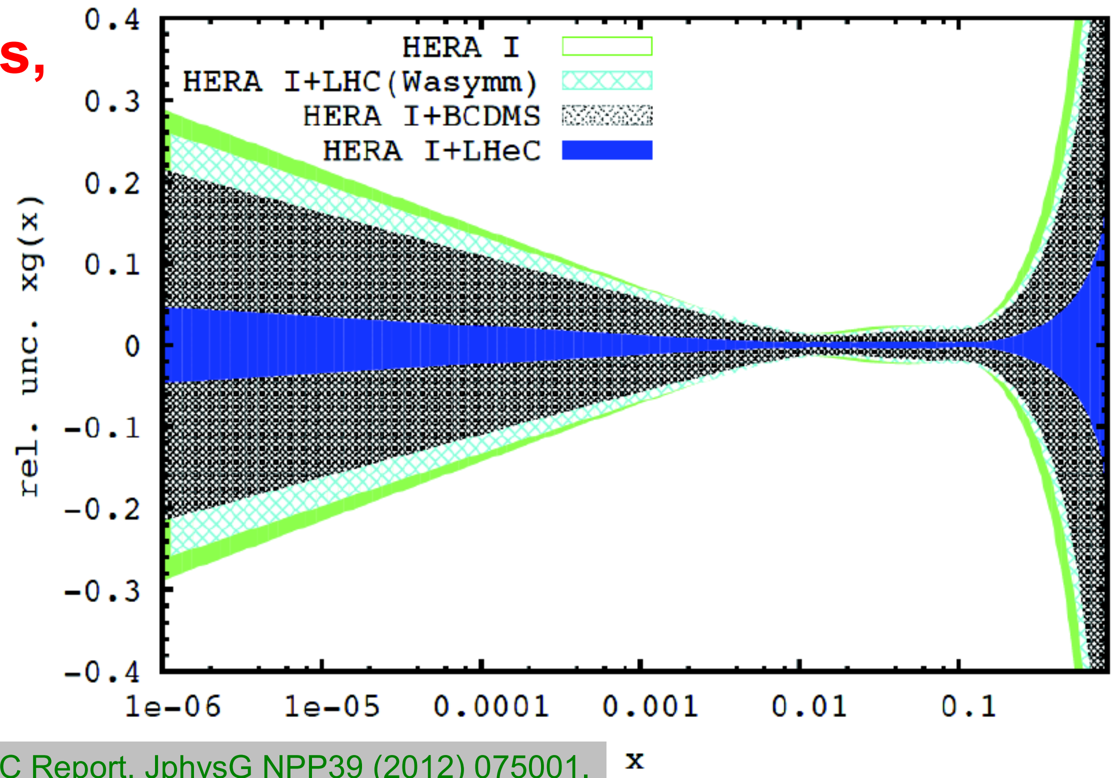
PDF Improvements

Important to reduce uncertainties on: M_W, $\sigma(gg \rightarrow H)$, α_s

Still at LHC:
Analysis of 7/8 TeV data still ongoing
Improve high mass regions, gluon, strange quark PDF, ...
Full impact still to be evaluated!

At high scales will need Photon PDFs, work ongoing; more experimental results needed!

Ultimate Tool for PDFs:
LHeC / FCC-he
→ low x, high x (luminosity!), high Q^2



LHeC Report, JphysG NPP39 (2012) 075001.

α_s Projections

Still at LHC:

Only jets probe running α_s at highest scales

1% uncertainty at M_Z challenging, but not impossible

Need NNLO and improved PDFs (gluon) plus some experimental optimization

Method	Current relative precision	Future relative precision	
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)	~1%
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)	
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)	<1%
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)	
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)	<1%
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])	~1%
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ (~ 5 yrs [38])	<0.5%

Snowmass QCD Report, arXiv:1310.5189.

Summary

- Still new precise measurements from HERA and Tevatron
- LHC Results at 8 TeV still to be finalized … and 13 TeV is at the doorstep
- Data quality makes jet measurements PRECISION PHYSICS
- Theory definitely entered regime of NLO as Standard
- But still theory uncertainty dominant, NNLO required at least …!
- … and photon PDFs.
- Many PDF/α_s relevant measurements from LHC ongoing or in near future
  $\rightarrow$ reduction of uncertainties possible
- Opportunity for ultimate improvements with future colliders

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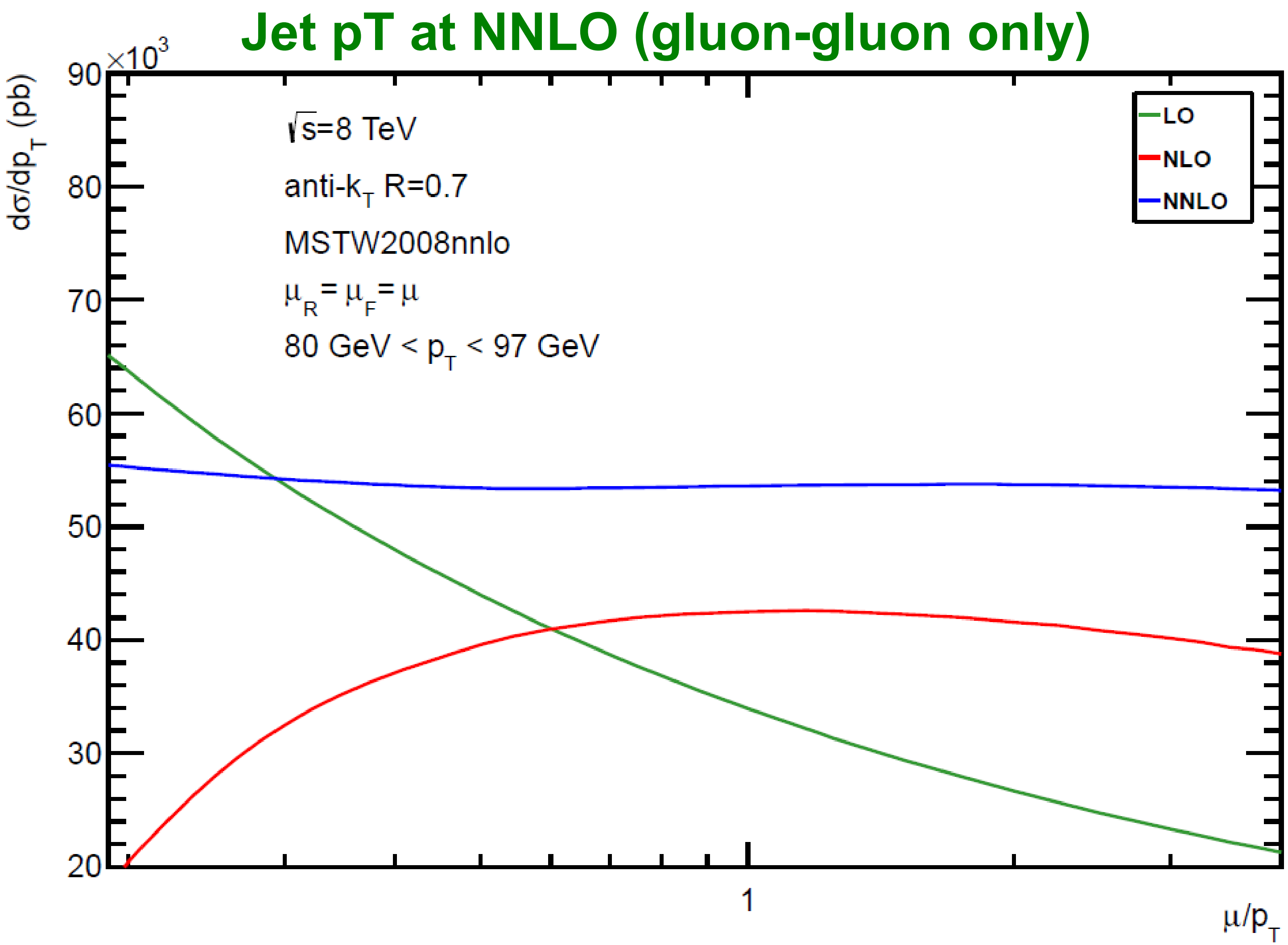
Thank you for your attention
and the invitation to speak here!

Backup Slides

NNLO Scale Dependence



Drastically reduced scale dependence!

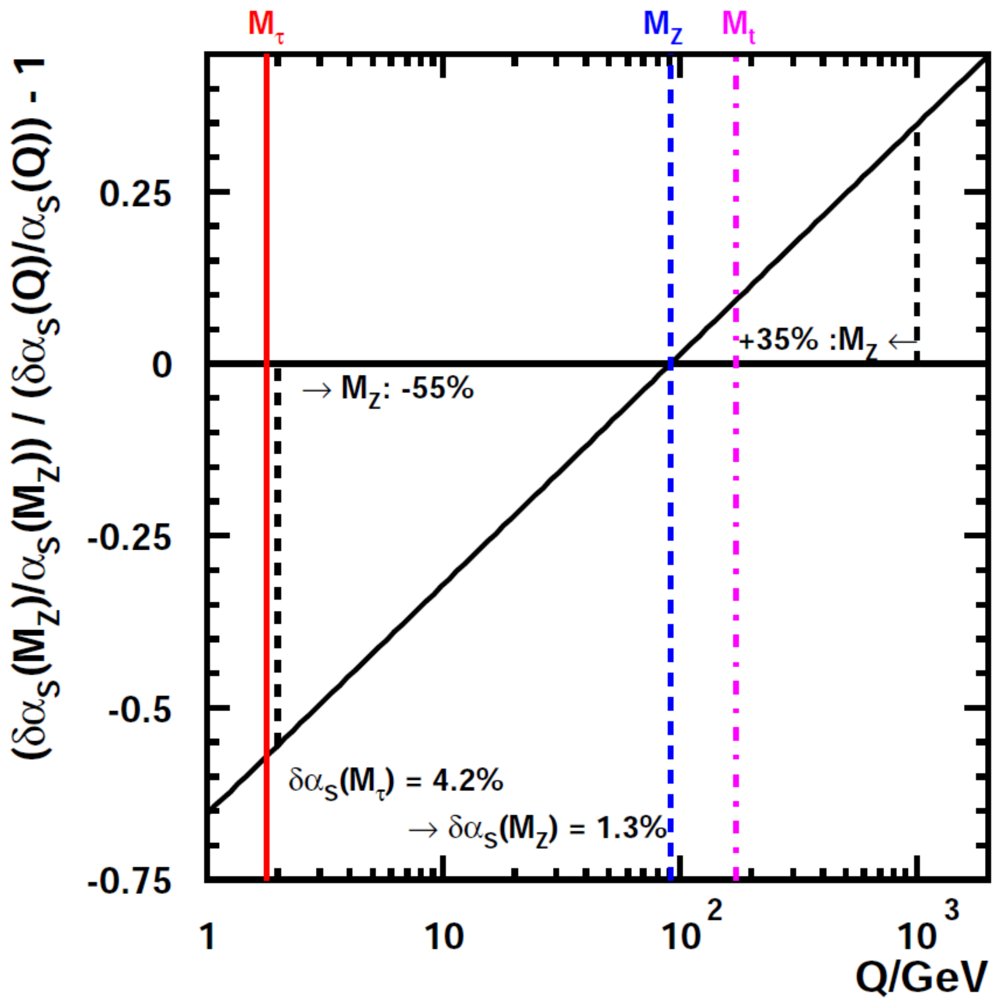
$|y| < 4.4$, 80 GeV $< p_T <$ 97 GeV

Gehrmann- de Ridder et al., PRL110 (2013), JHEP1302 (2013).

Evolving $\Delta\alpha_s$

Incredibly shrinking error →

← Uncomfortably growing error

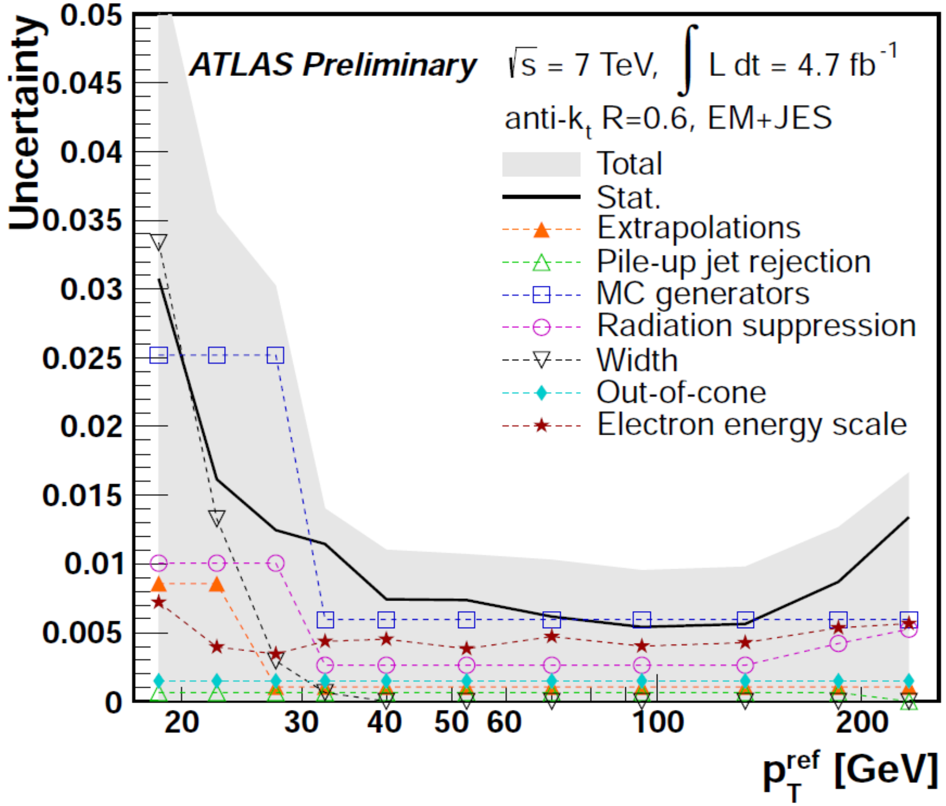


Jet Energy Scale

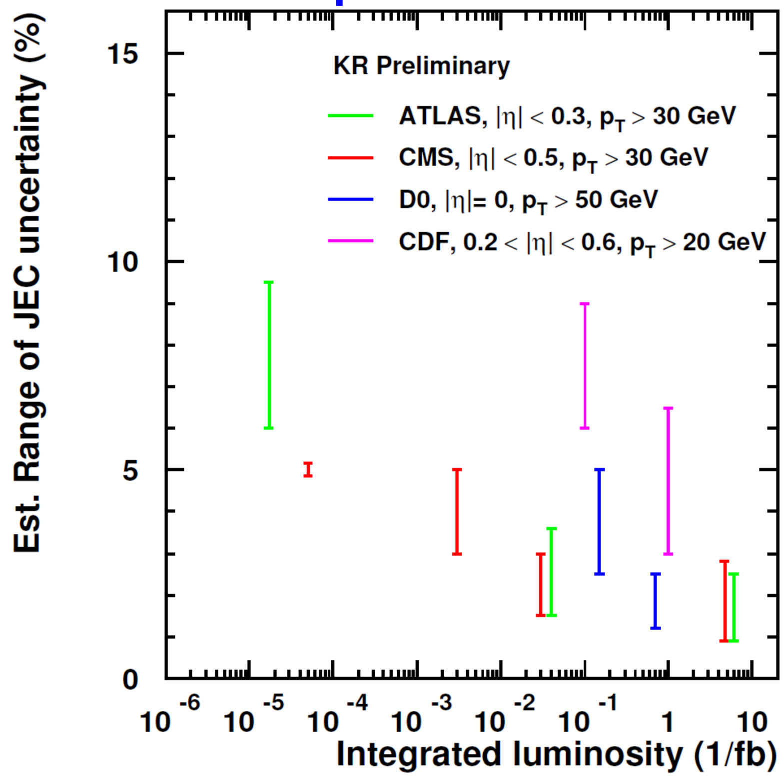
Dominant experimental uncertainties for jets!
Enormous progress in just three years.

- Jet Energy Scale (JES)
  - Noise Treatment
  - Pile-Up Treatment
- Luminosity
- Jet Energy Resolution (JER)
- ...

ATLAS from 5/fb (2011)
(Z+jet channel)



Approximate development of JEC precision

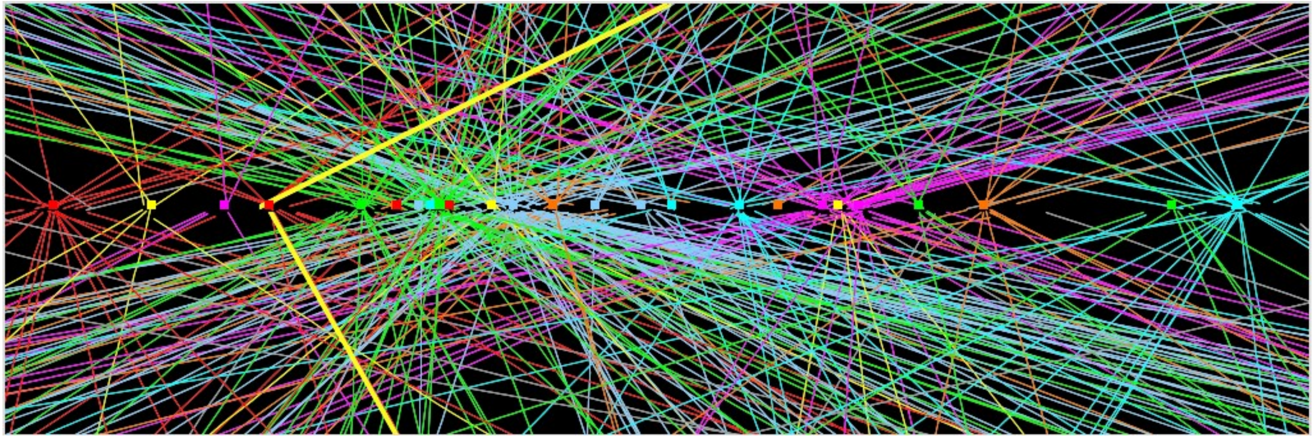


ATLAS, EPJC 71 2011; arXiv:1112.6297; CONF-2012-053; CONF-2012-063
CMS, JME-10-003; JME-10-010; JINST 6 2011; DP2012-006; DP2012-012
D0, arXiv:1110.3771; D0 prel. 2006

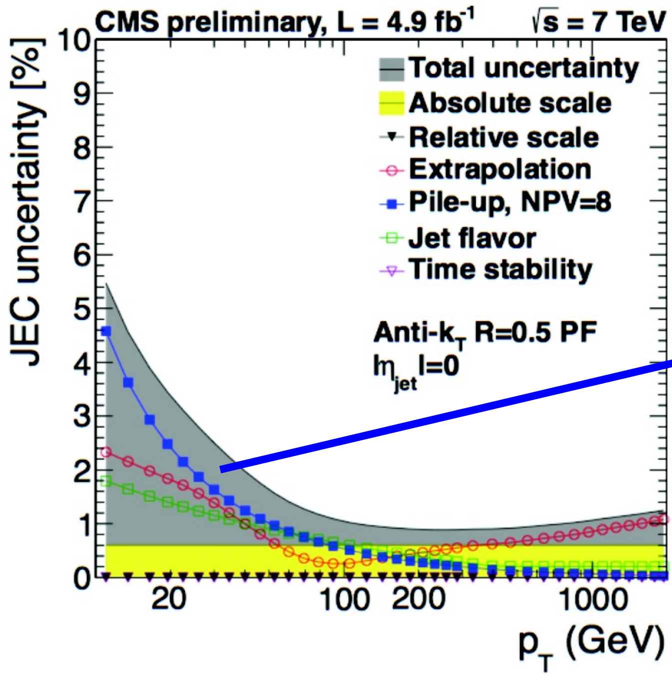
Jet Energy Scale and Pile Up

But:
New situation in 2012 at 8 TeV with many pile-up collisions!

ATLAS Z → μμ candidate with 25 reconstructed primary vertices:
(Record beyond 70!)

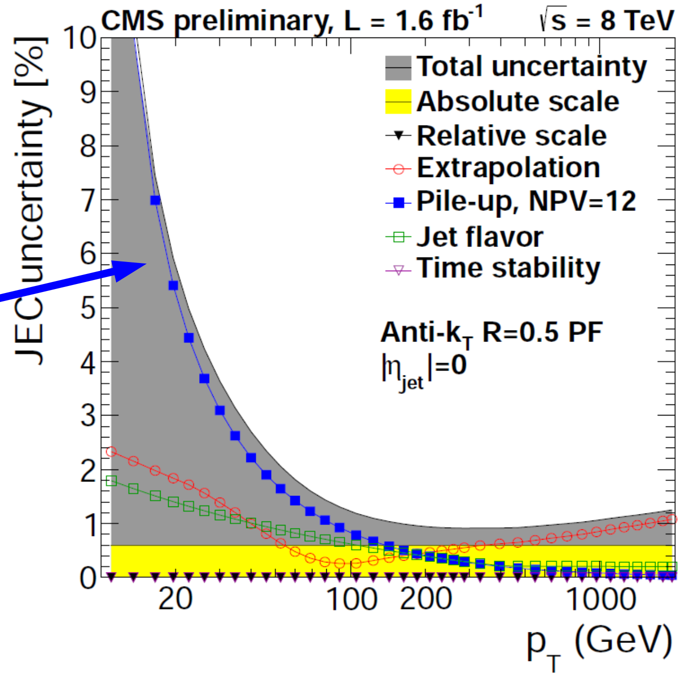


CMS from 5/fb (7 TeV, 2011)



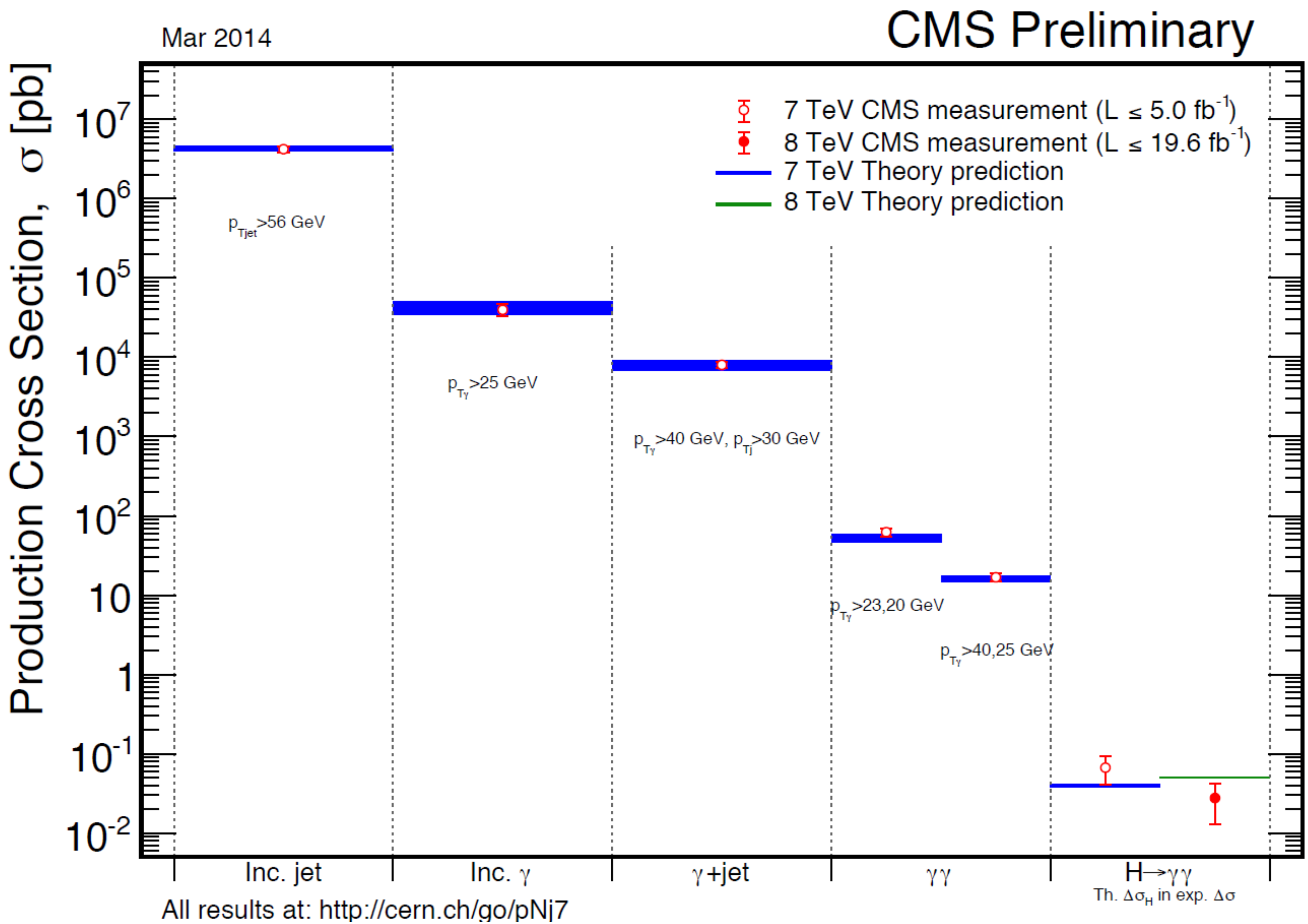
Pile-up effect

CMS from 1.6/fb (8 TeV, 2011)

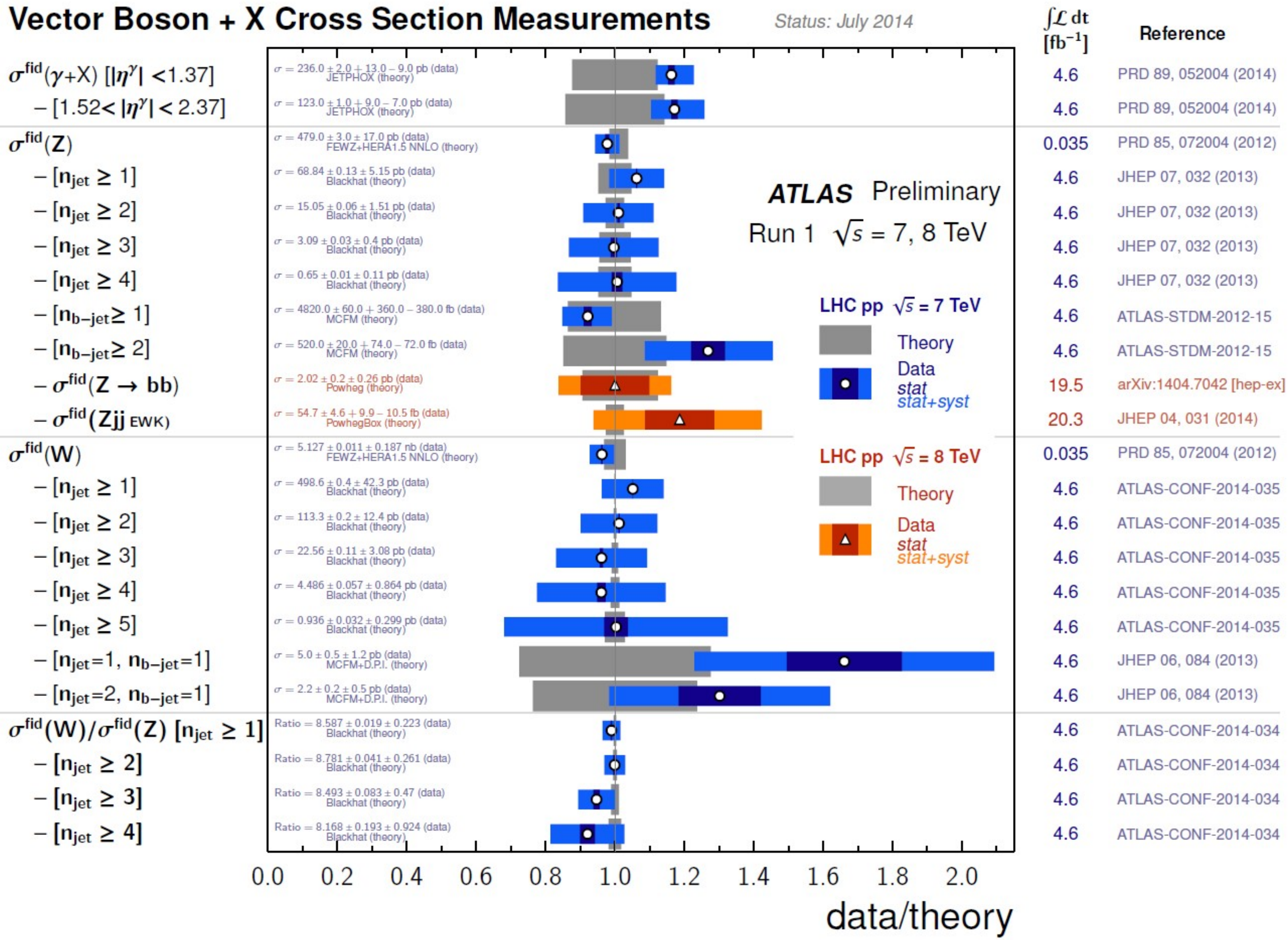


CMS, DP2012-006
CMS, DP2012-012

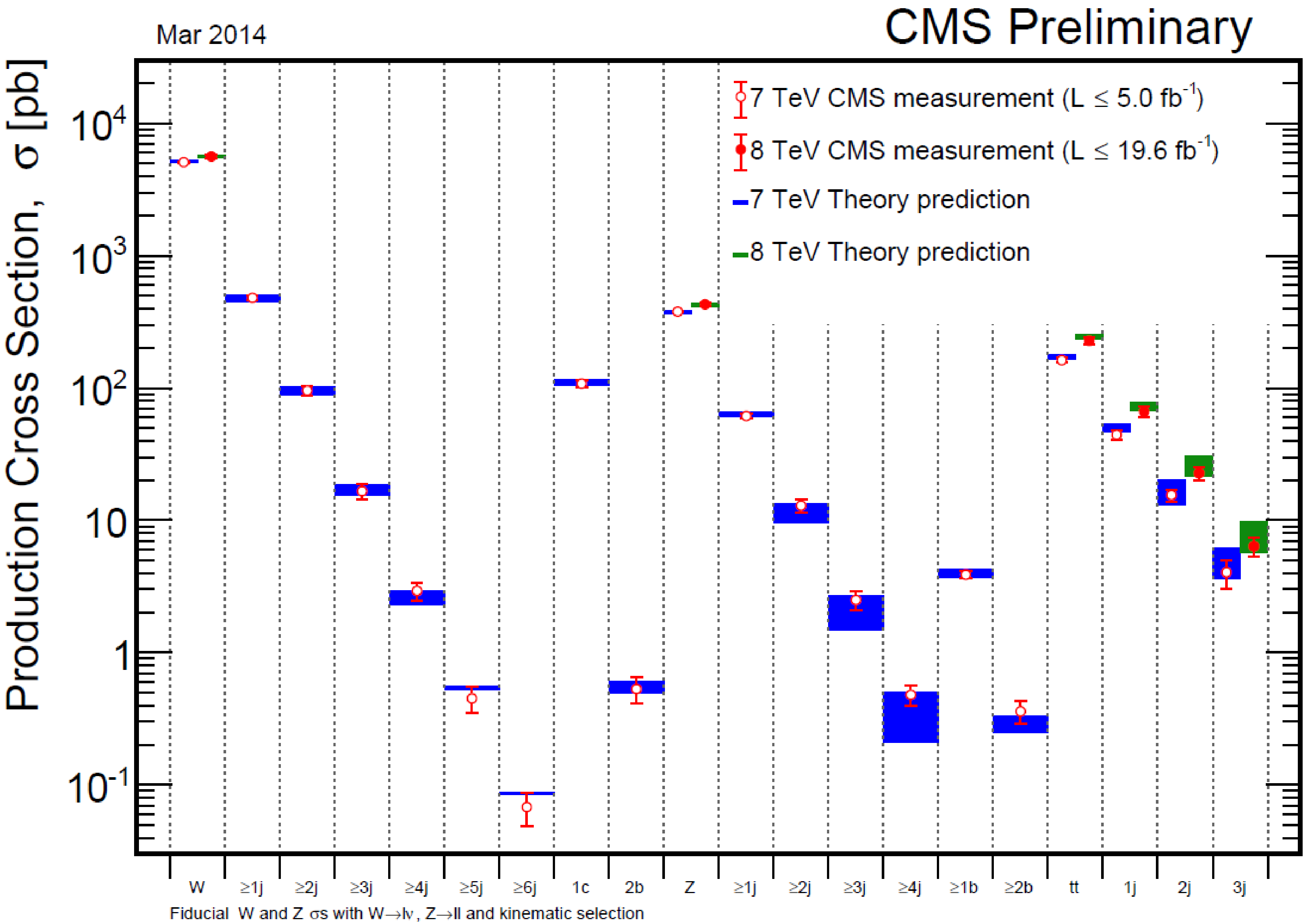
CMS Jet + Photon Summary



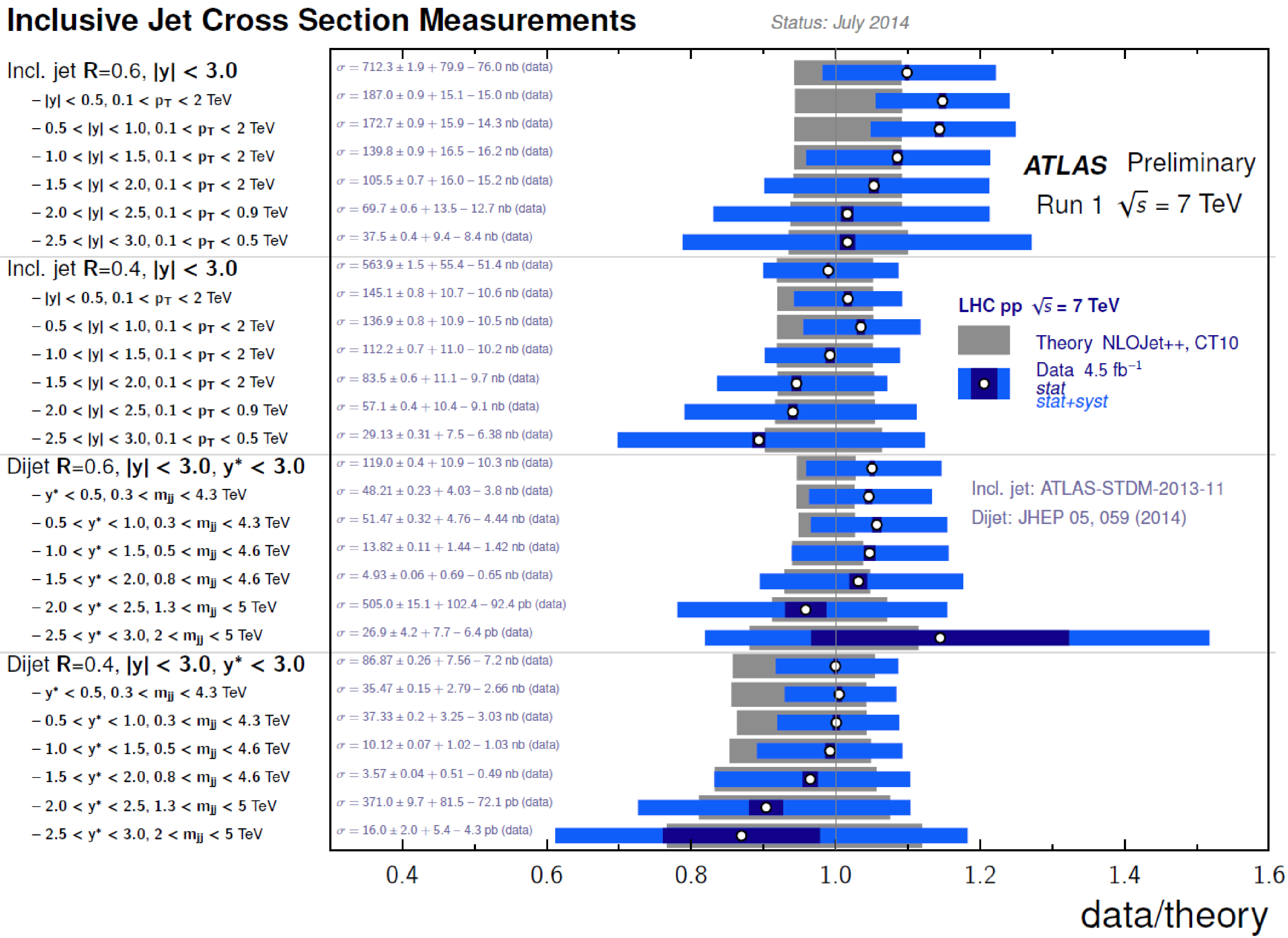
ATLAS V + X Summary (Ratio)



CMS W, Z, ttbar Summary



ATLAS Jets Summary (Ratios)



Inclusive Jet Ratios: "0.5 / 0.7"

Cross section ratio for R = 0.5/0.7

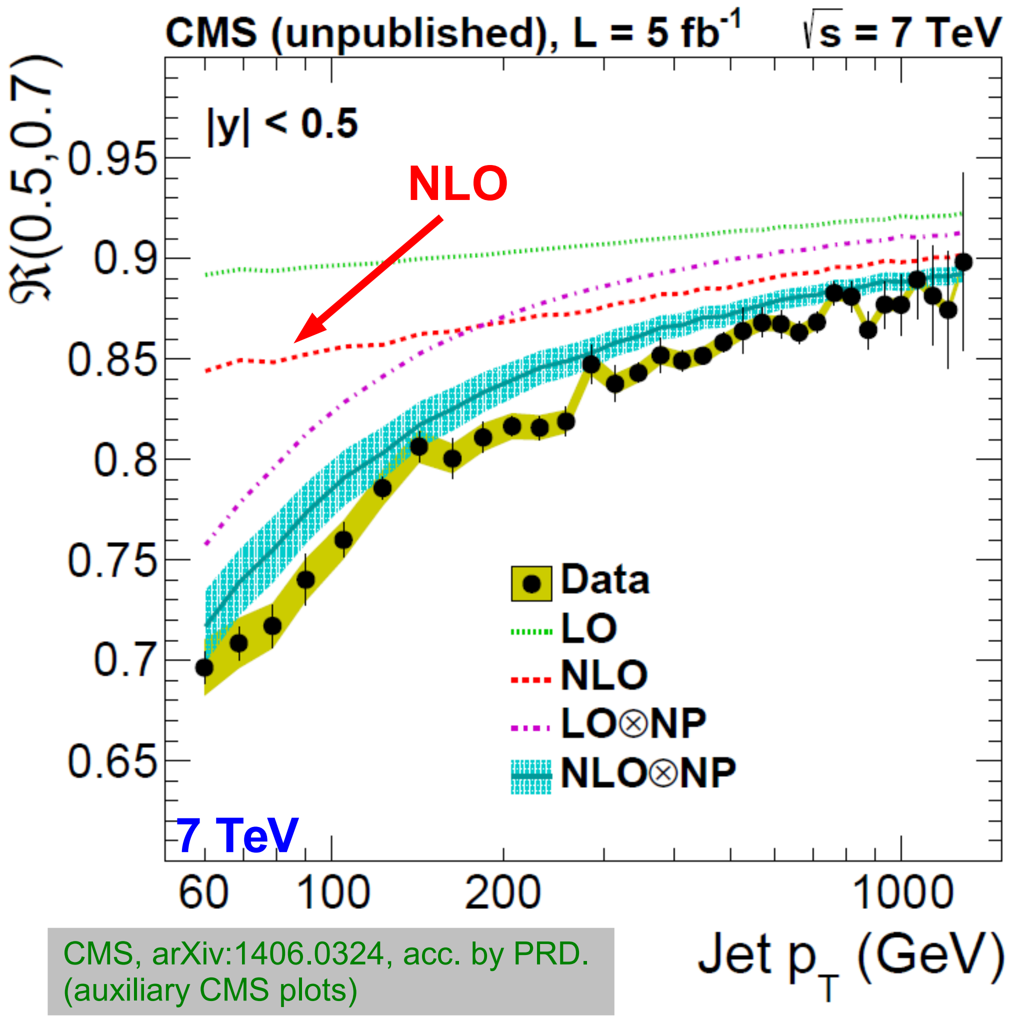
Emphasizes effects of showering and hadronization → NLO insufficient to describe data!

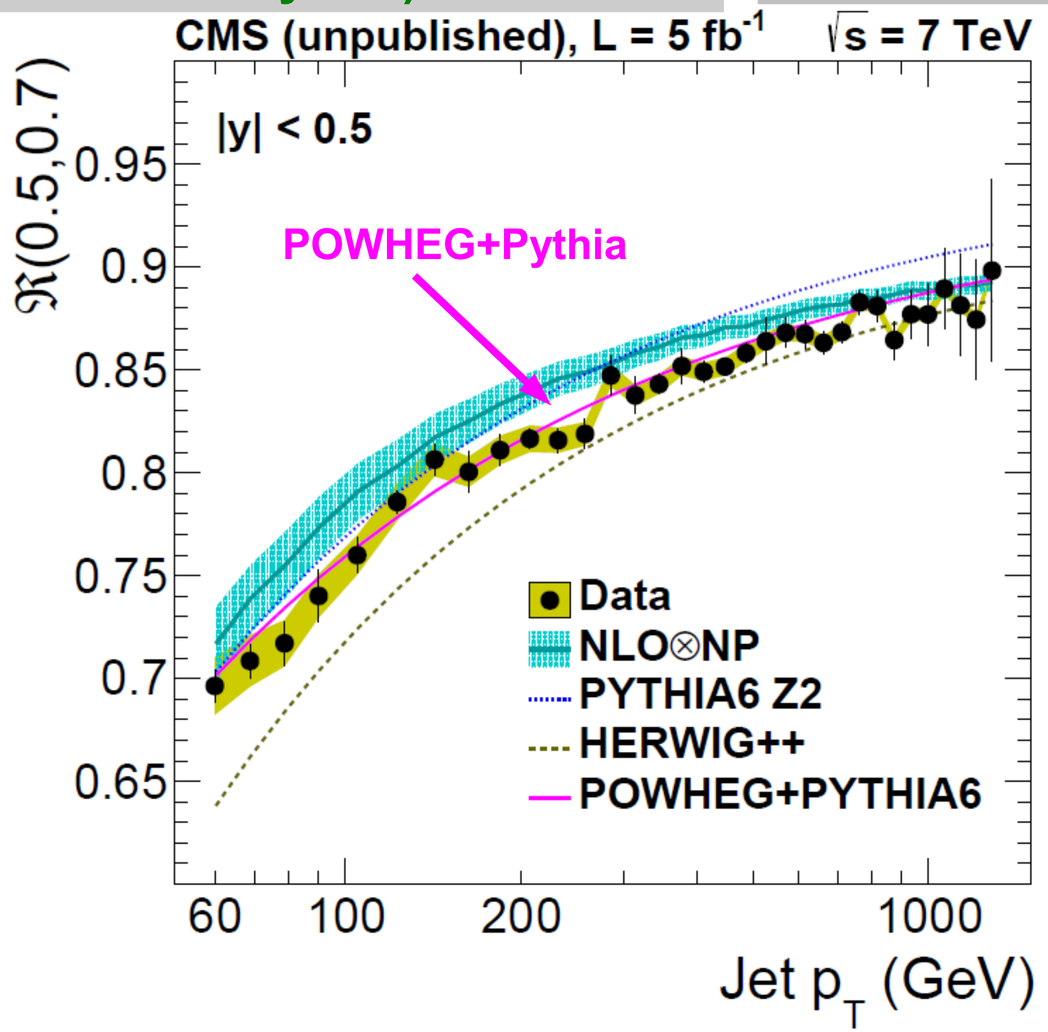
Requires event generators:
LO+PS+HAD → better (Pythia6,Herwig++)
NLO+PS+HAD → best (POWHEG+Pythia)

G. Soyez, PLB698 (2011).

ALICE study R=0.2 / R=0.4

See also: ALICE, PLB722 (2013) 262.

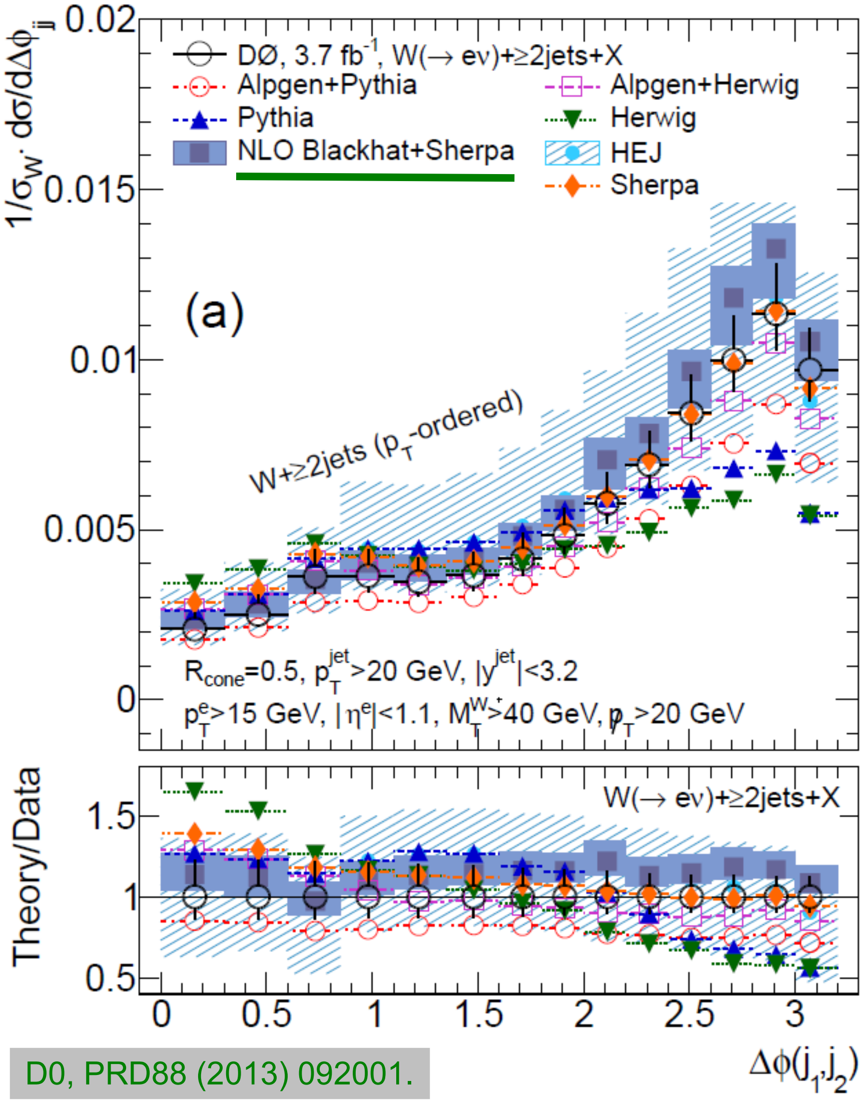




CMS, arXiv:1406.0324, acc. by PRD. (auxiliary CMS plots)

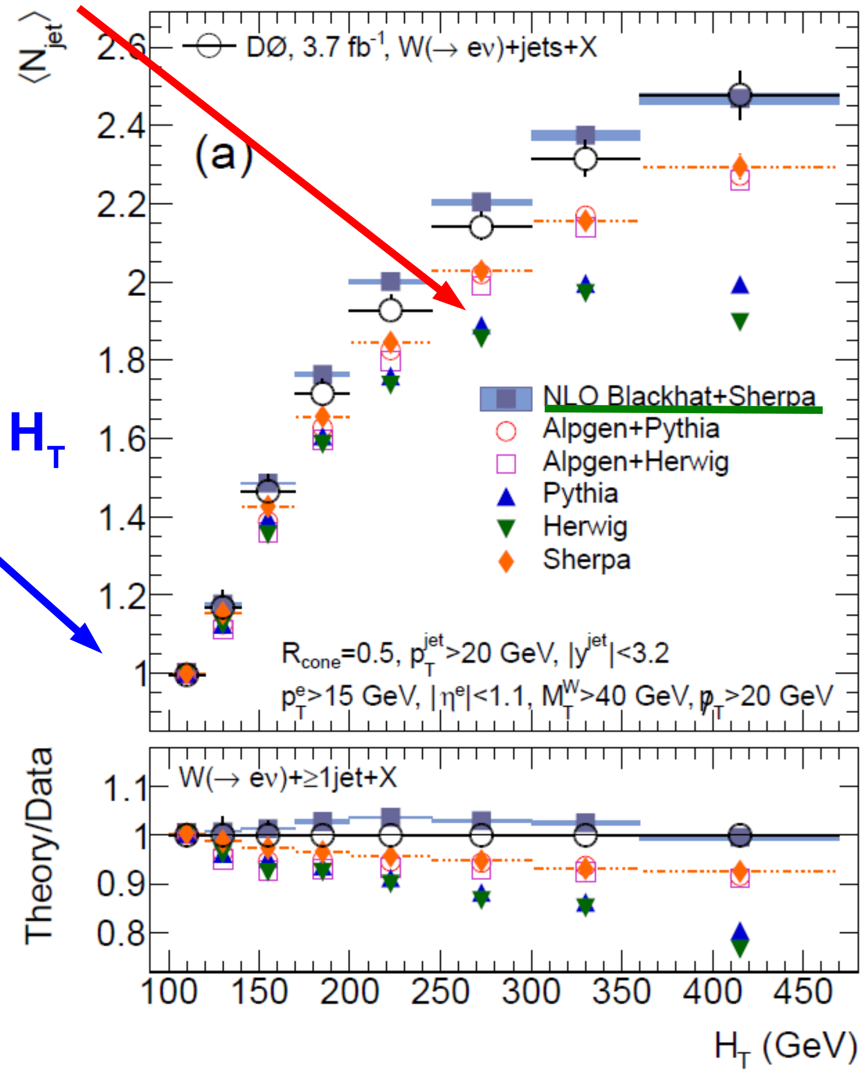
W + Jets

Comprehensive study by D0
Data well described by NLO
LO generators run into problems at high multiplicity



$\Delta\varphi_{j1,j2}$

$<N_{jet}>$ vs. H_T

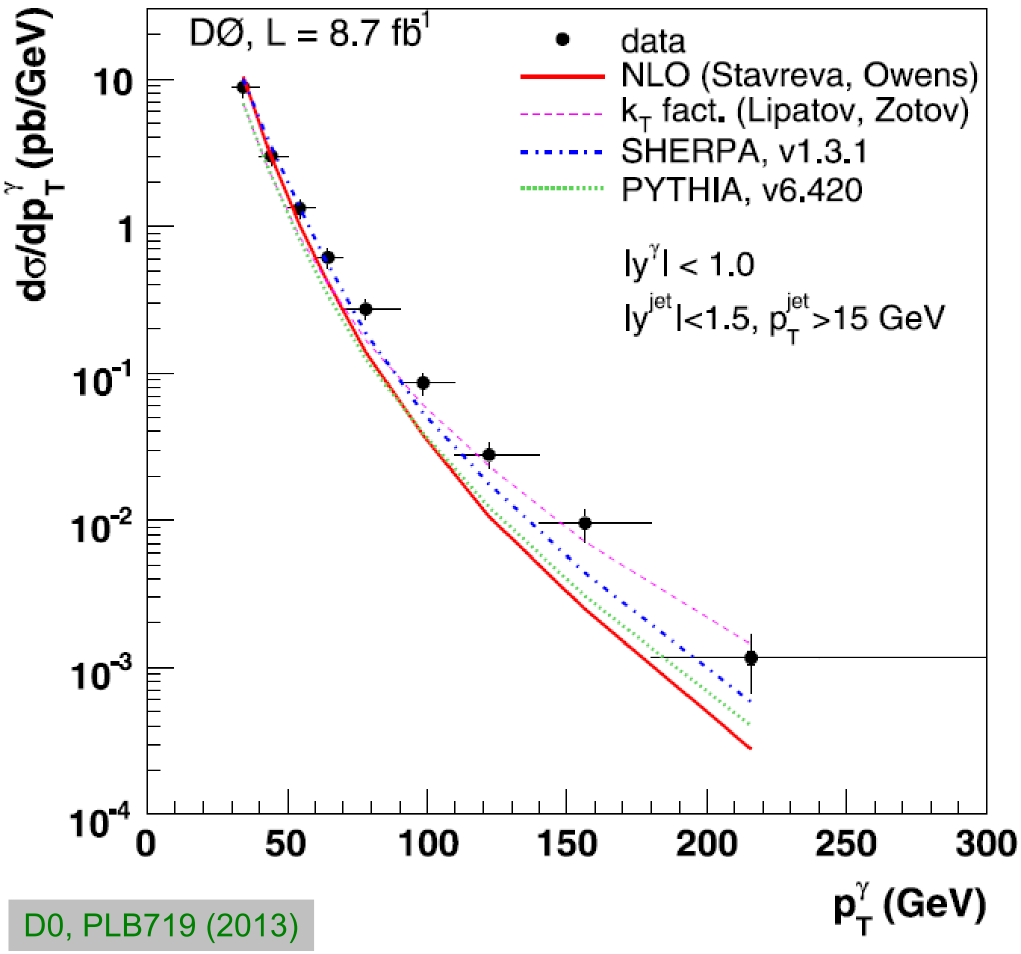


D0, PRD88 (2013) 092001.

Photon + HF Jet

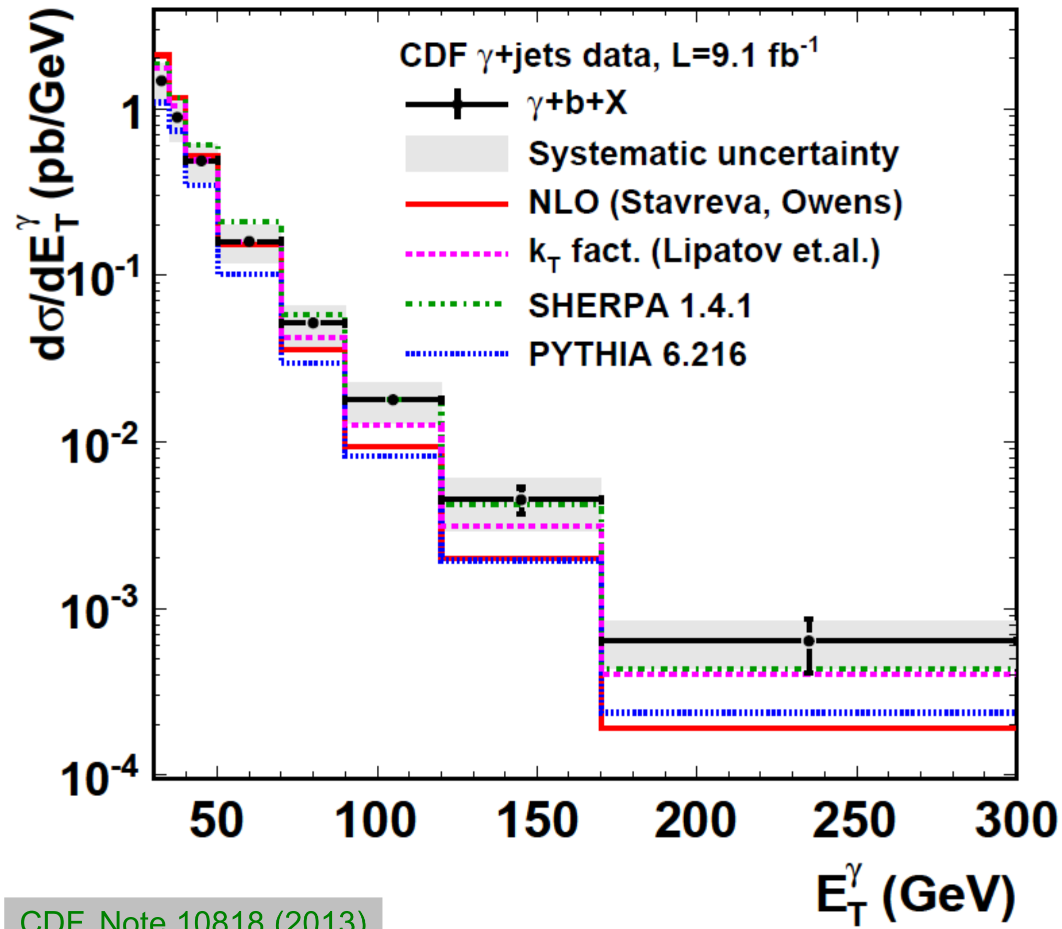
- New results from D0 and CDF for photon+heavy flavour (b,c) production
- At low pT probes HF PDF; at high pT produced by gluon splitting
- NLO insufficient
- Better described by e.g. Sherpa

D0: γ + c +X



D0, PLB719 (2013)

CDF: γ + b +X



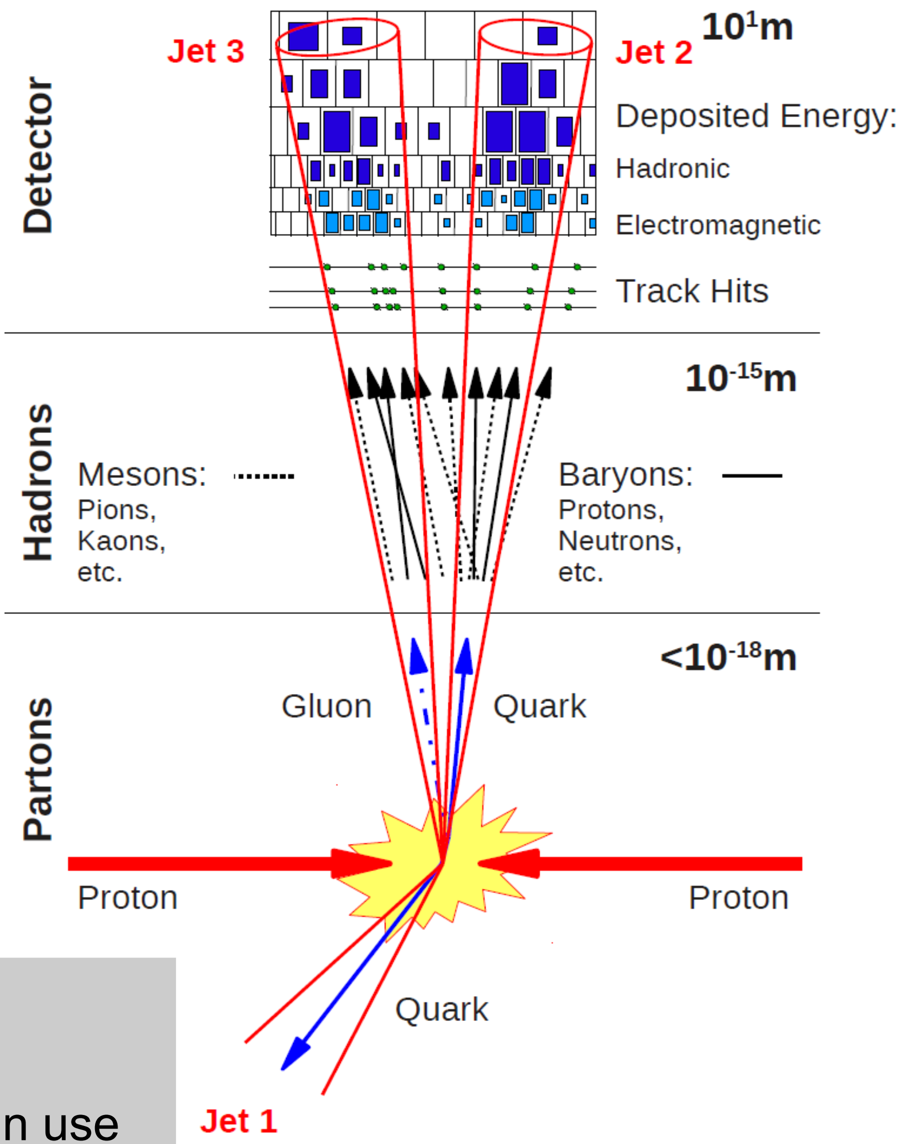
CDF, Note 10818 (2013)

Jet Algorithms

Primary Goal:

Establish a good correspondence between:
- detector measurements
- final state particles and
- hard partons

Two classes of algorithms:
1. Cone algorithms: "Geometrically" assign objects to the leading energy flow objects in an event (favorite choice at hadron colliders)
2. Sequential recombination: Repeatedly combine closest pairs of objects (favorite choice at e^+e^- & ep colliders)



Standard at Tevatron: MidPoint Cone
Standard at LHC: anti-kT
CDF also looked at kT; at LHC also kT, Cam/AC, SISCone in use

Achievements

30 years ago ...

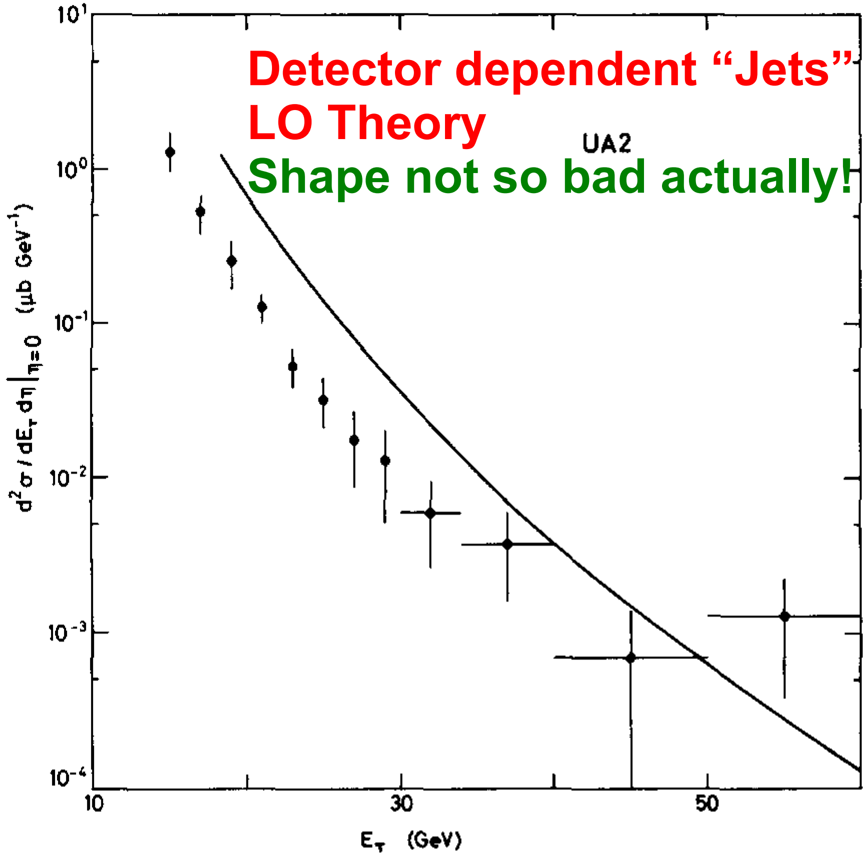
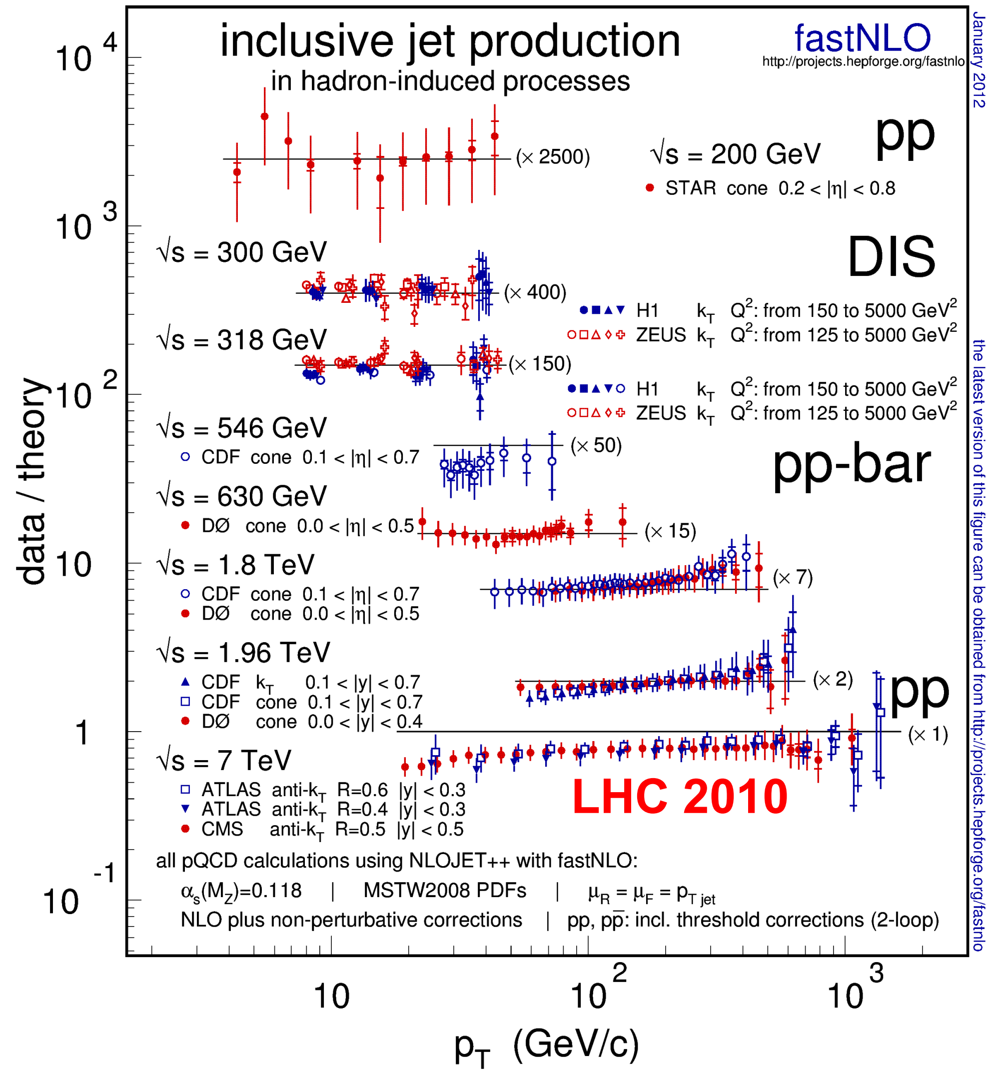


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

... and today !



fastNLO

LHC and Experiments

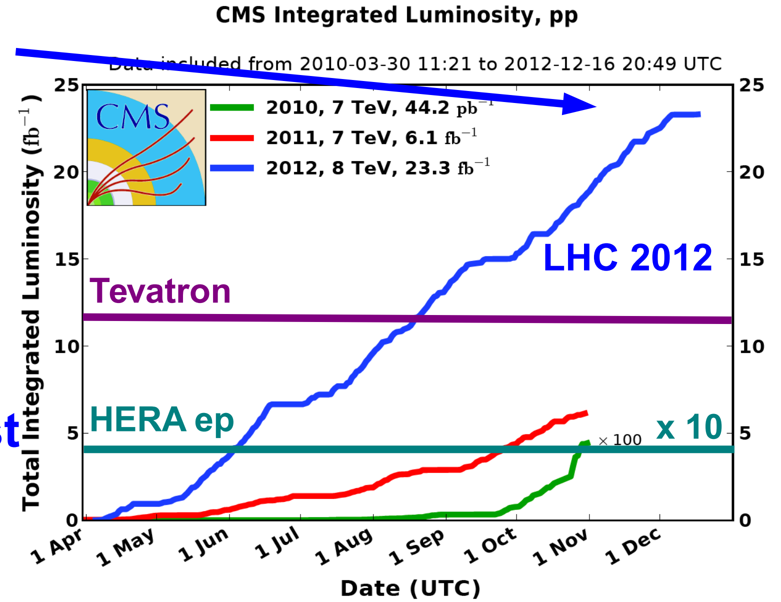
LHC: p-p collisions 2012: 23/fb

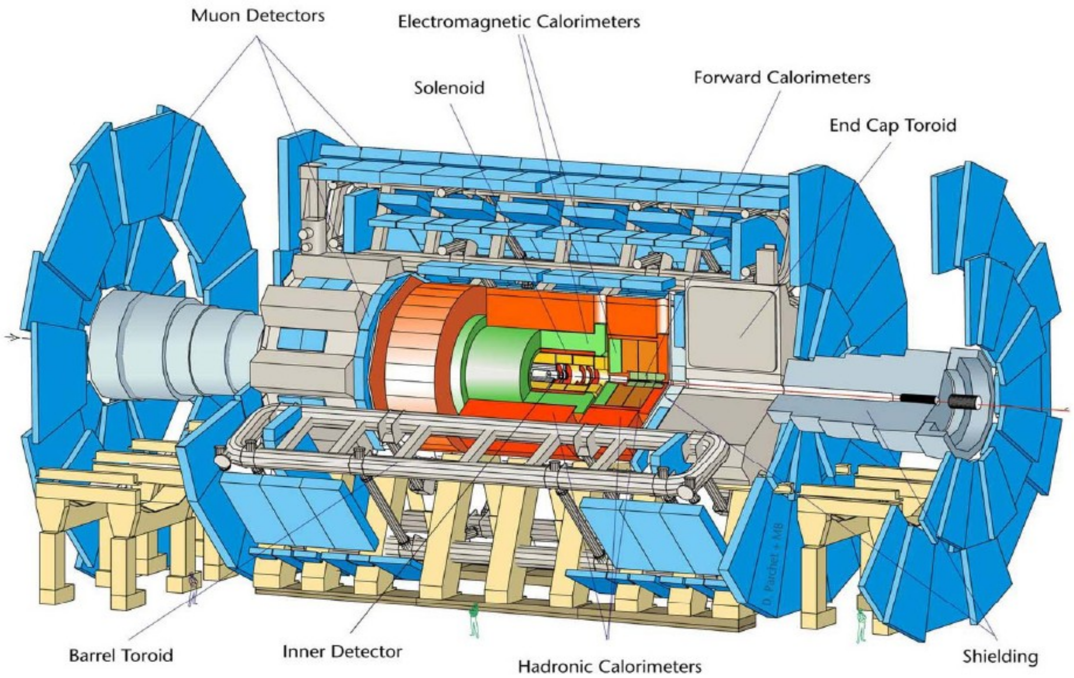
ATLAS/CMS global features:

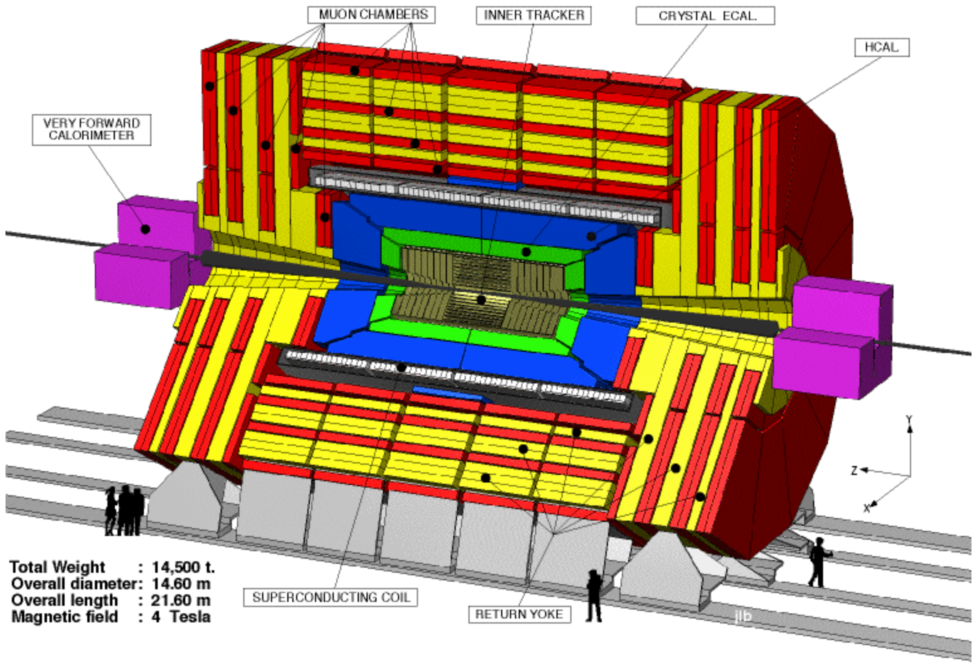
- **Silicon trackers:** Up to |η| = 2.5
- **Calorimetry:** Up to |η| ~ 5.0
- **Muon chambers:** Up to |η| = 2.4-2.7
- **Jet energy scale:** 1 – 3 % prec.

ALICE — Specialist for heavy ions

LHCb — Specialist for b quarks



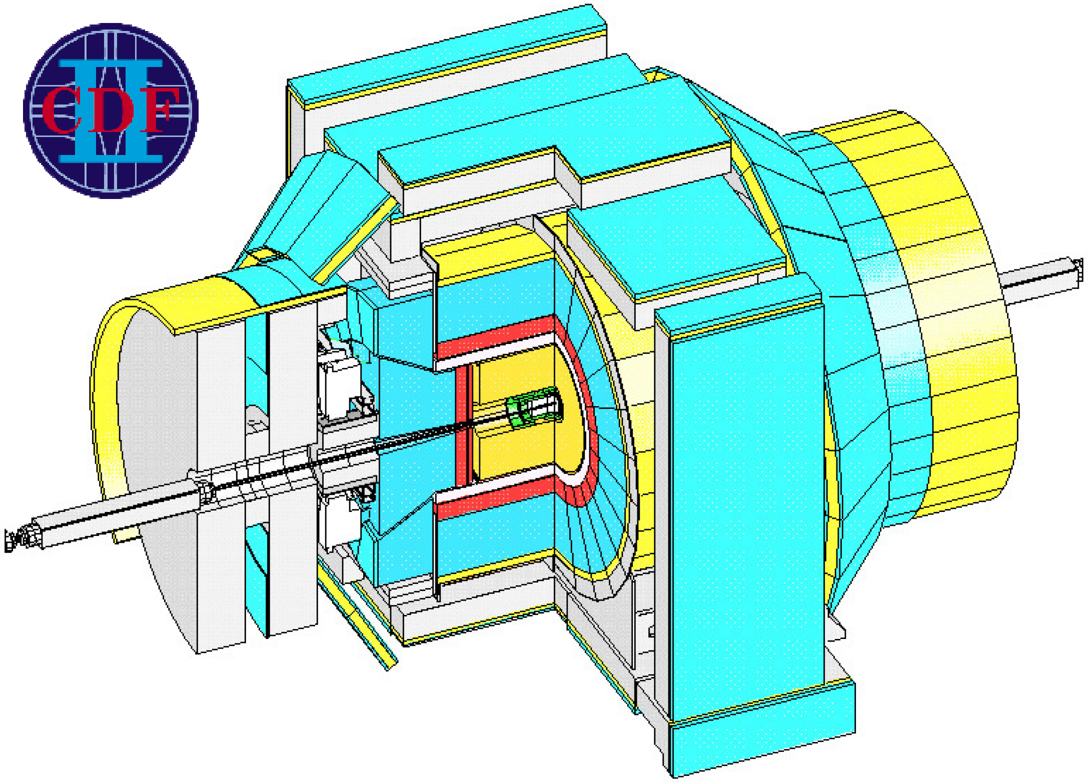


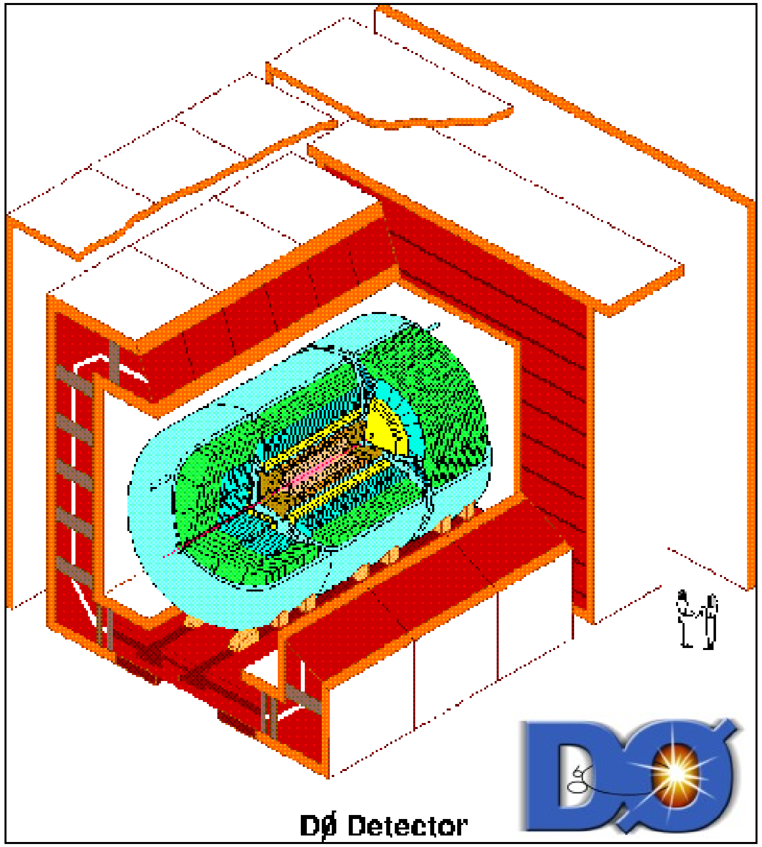


CDF and D0

Silicon tracker:	Up to $|\eta|$ = 2.0 – 2.5
Drift cell tracker:	Up to $|\eta|$ = 1.1
Calorimetry:	Up to $|\eta|$ = 3.2
Muon chambers:	Up to $|\eta|$ = 1.5
Jet energy scale:	2 – 3 % prec.

Silicon tracker:	Up to $|\eta|$ = 3.0
Fiber tracker:	Up to $|\eta|$ = 1.7
Calorimetry:	Up to $|\eta|$ = 4.0
Muon chambers:	Up to $|\eta|$ = 2.0
Jet energy scale:	1 – 2 % prec.





Process Decomposition