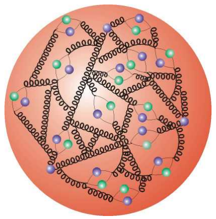
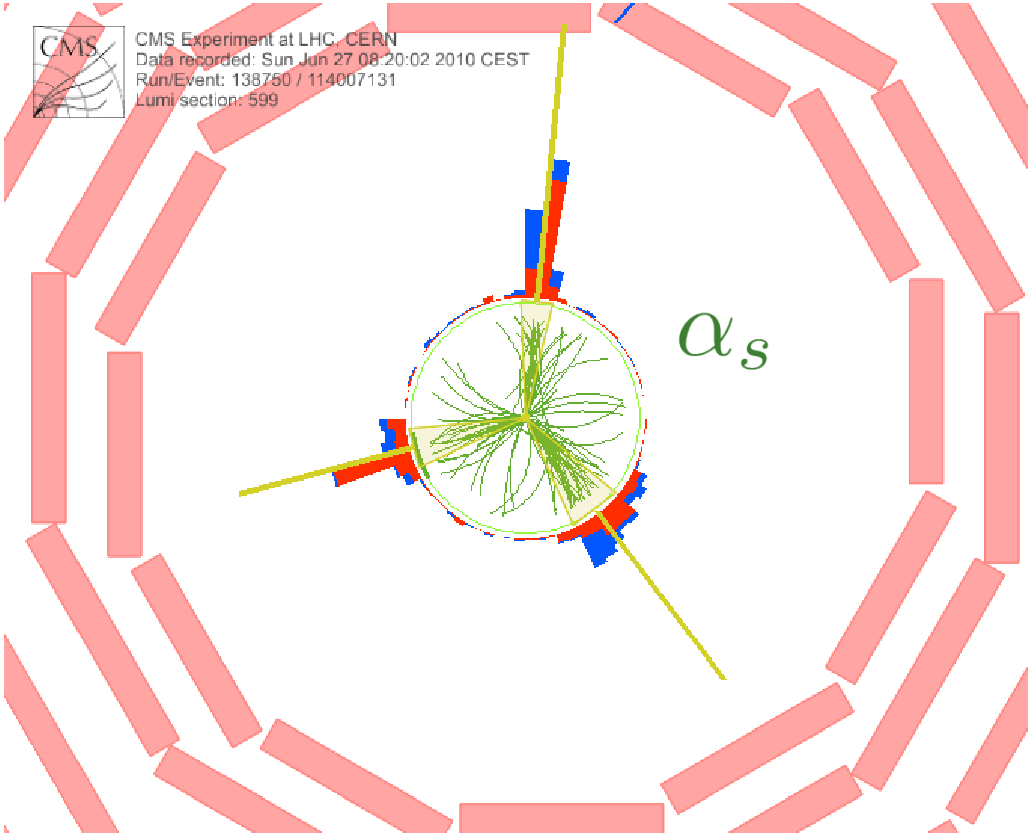
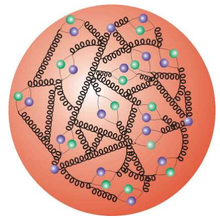
Experimental Tests of QCD



Proton Structure
(PDF)





Proton Structure
(PDF)

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Klaus Rabbertz, KIT

Karlsruhe Institute of Technology

Outline

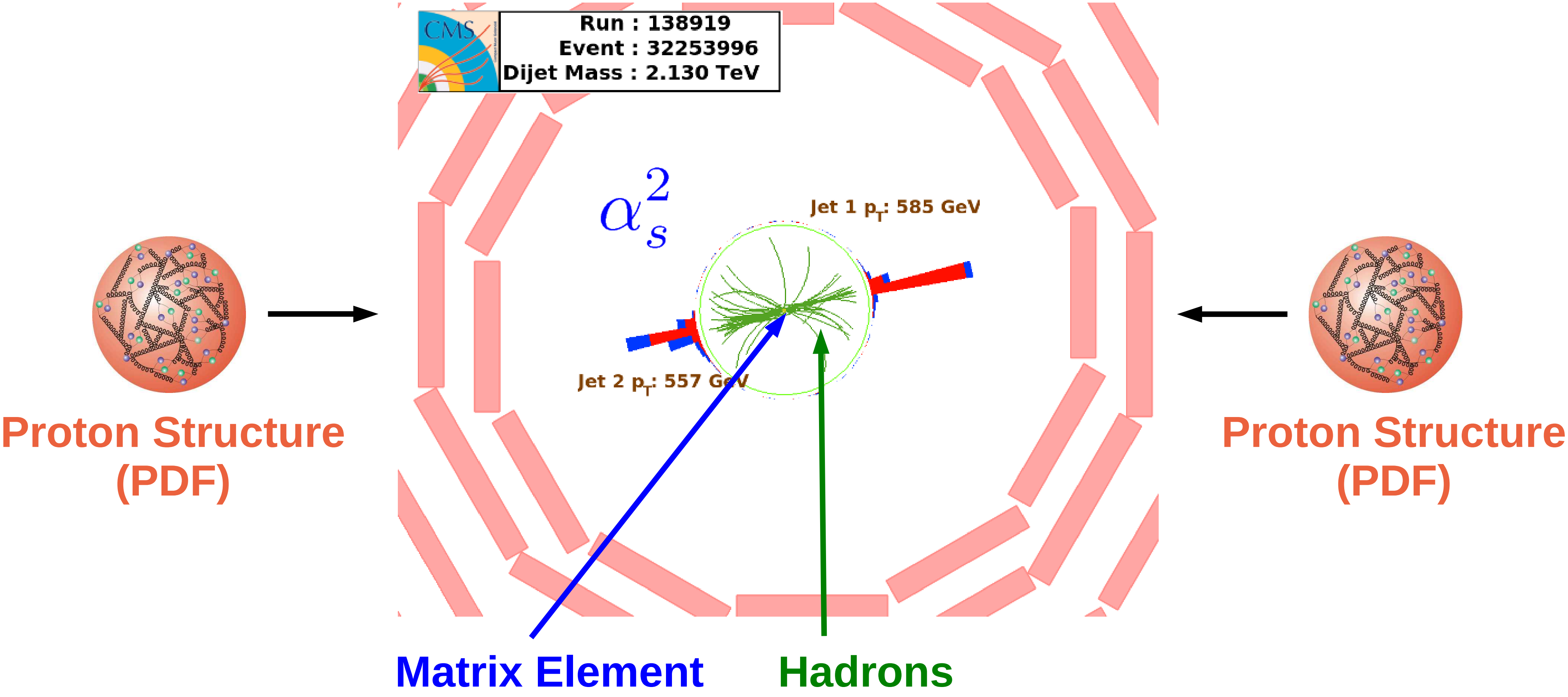
- Motivation
- Colliders and Detectors
- Photons
- Boson + Jets
- Inclusive Jets
- Dijets and 3-Jets
- Normalized Multi-Jets and the strong Coupling Constant α_s
- Outlook

W/Z production will be covered by João Guimarães da Costa in the next talk.
For more details on W/Z/γ or jet production at the LHC see also the
talks of Massimo Casarsa and Rolf Seuster in the parallel session room A.

Obviously I still had to leave out numerous interesting topics :-(
Priority was given to latest results.

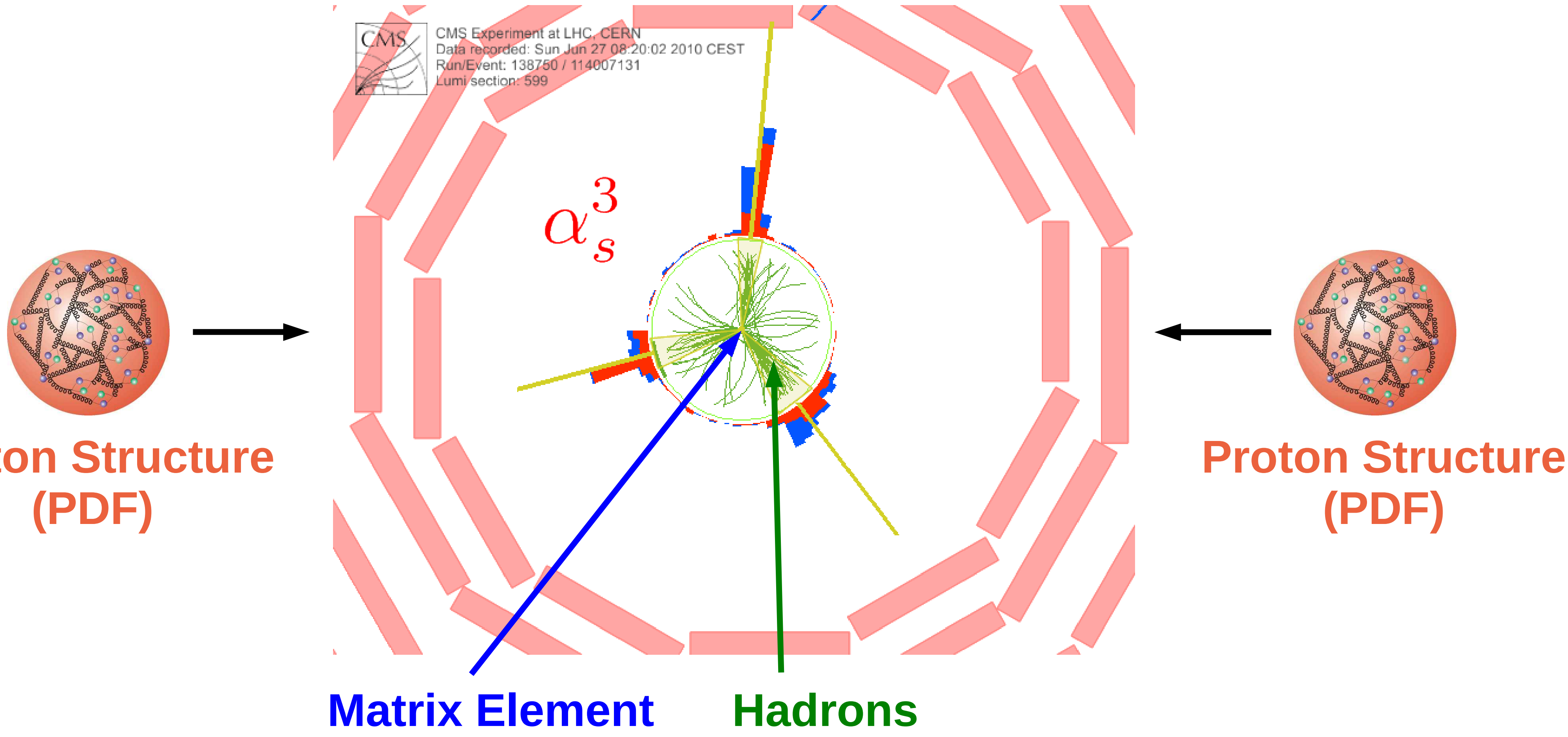
Why QCD?

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



Why QCD?

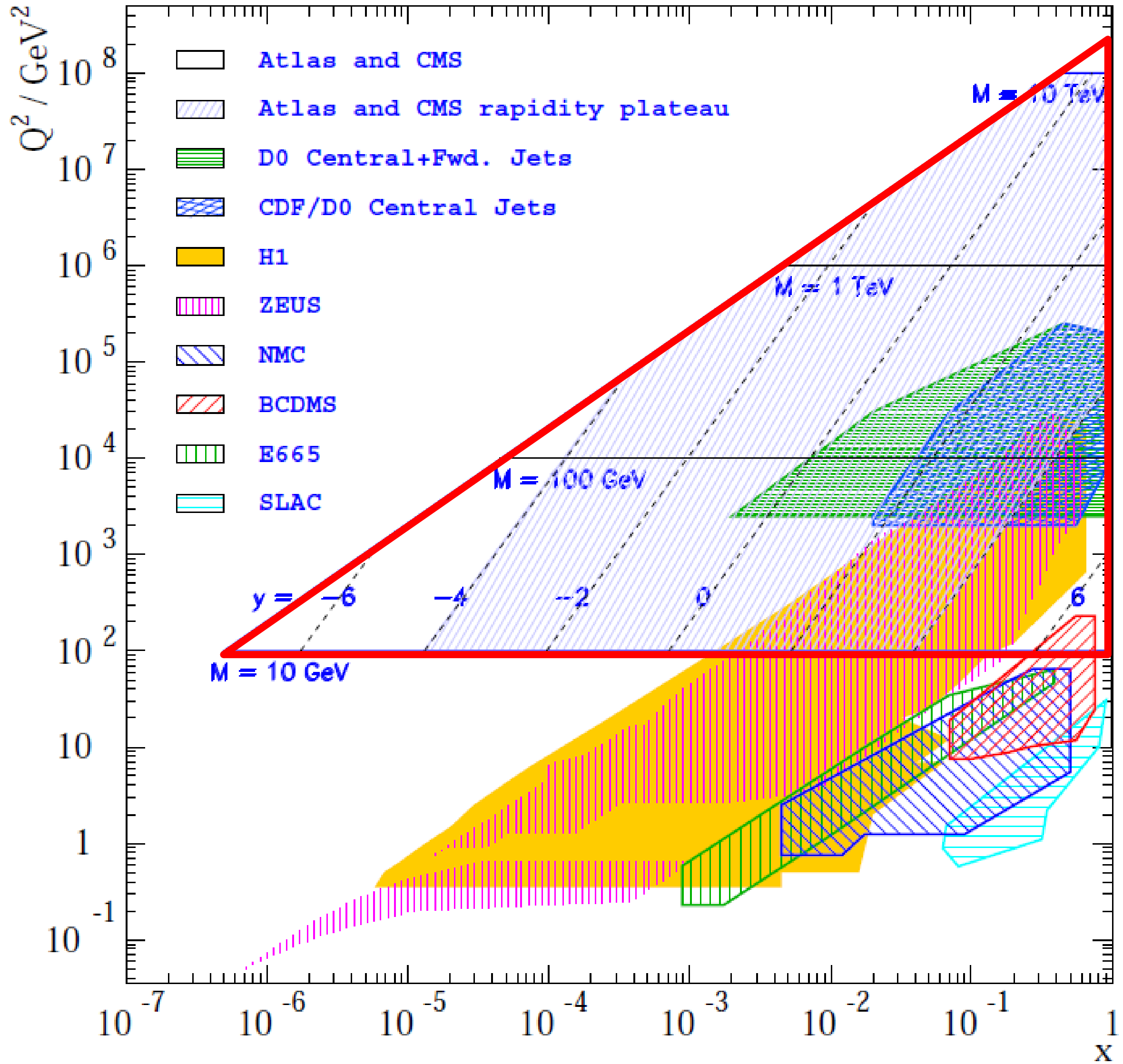
Abundant production of jets → hadron colliders are "jet laboratories"
… and the strong coupling alpha_s !



Why QCD?

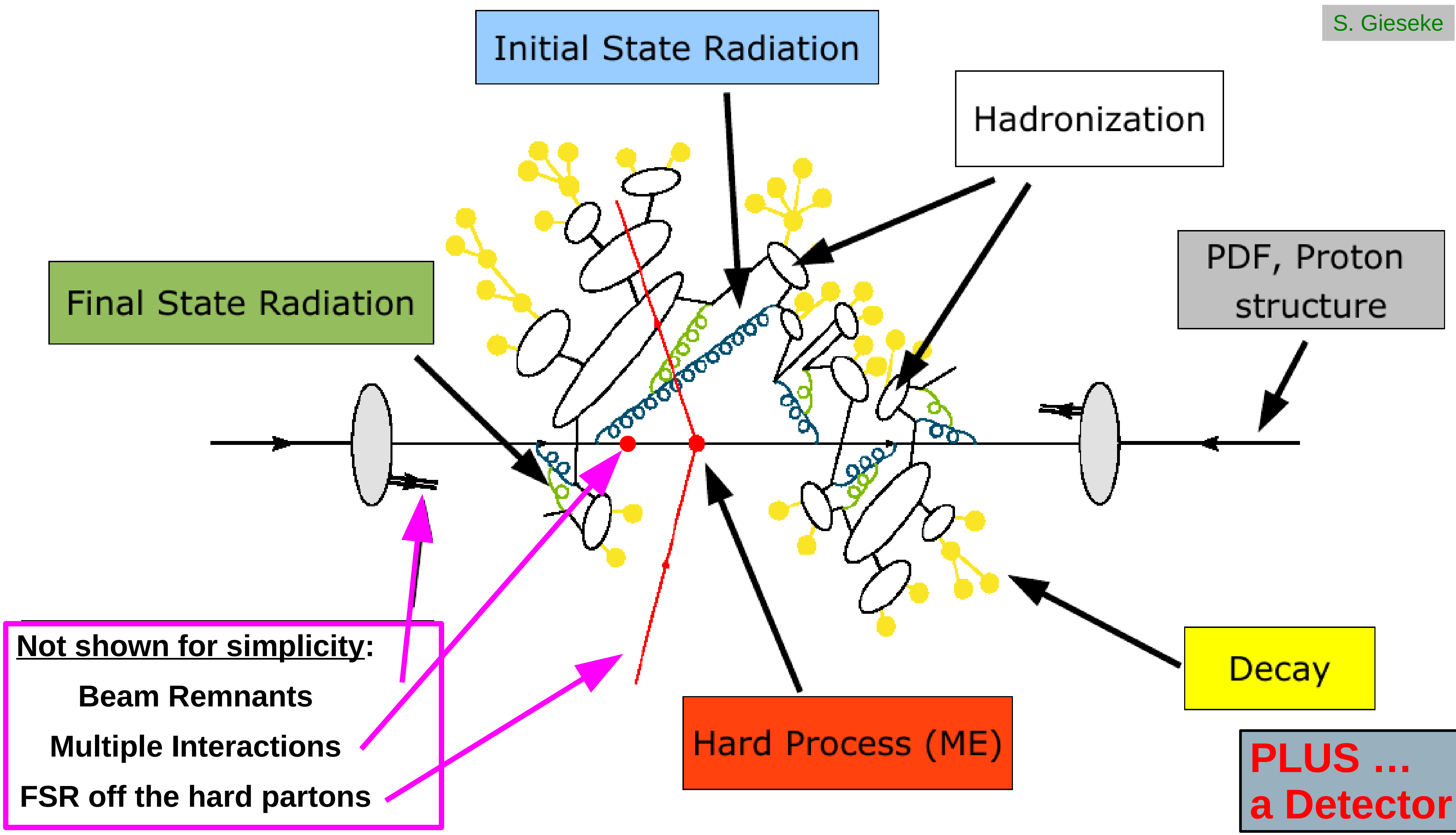
- **Fascinating –**
  comprises a huge variety of phenomena
- **Unavoidable –**
  hadrons are "made of QCD"
- **Indispensable –**
  linking piece between many processes
- **Demanding –**
  enormous background to searches for new physics
- **Uncharted –**
  dominating uncertainty for Higgs cross sections

Huge accessible phase space



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

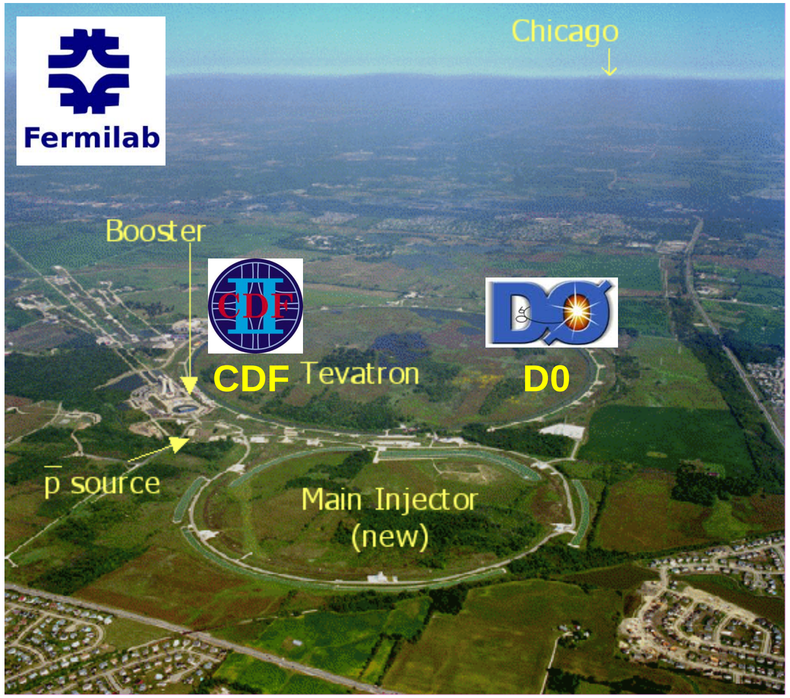
The Complexity of QCD



PLUS … a Detector!

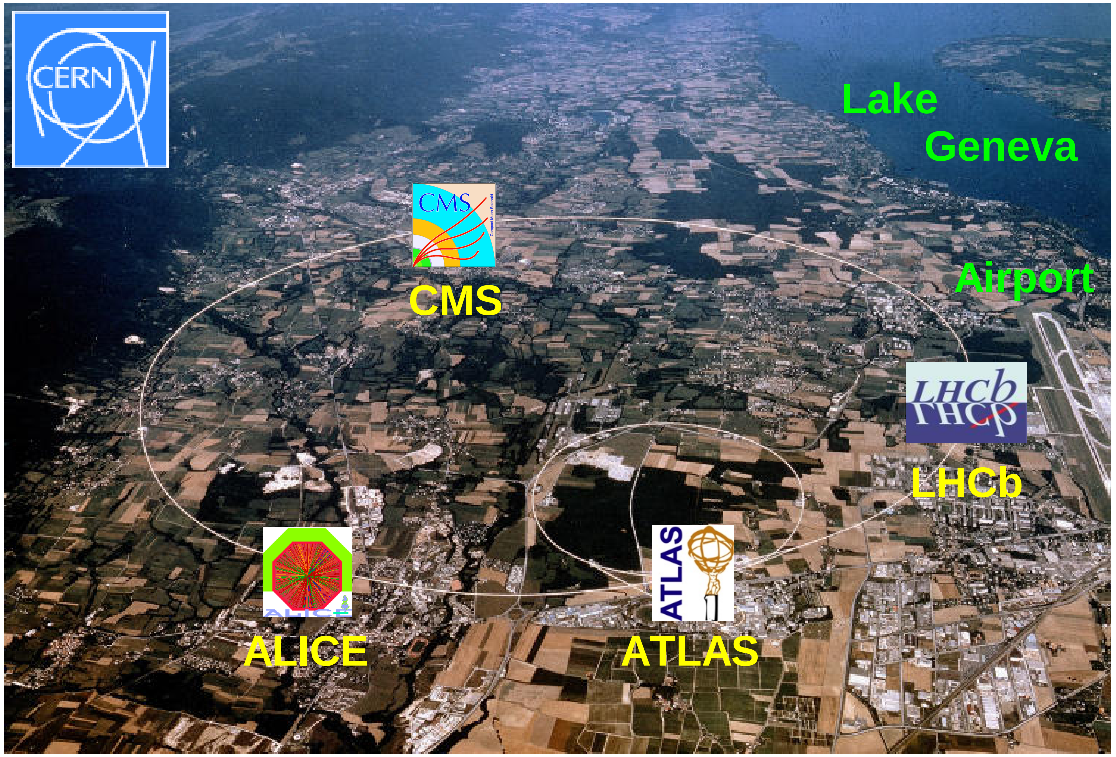
The Colliders

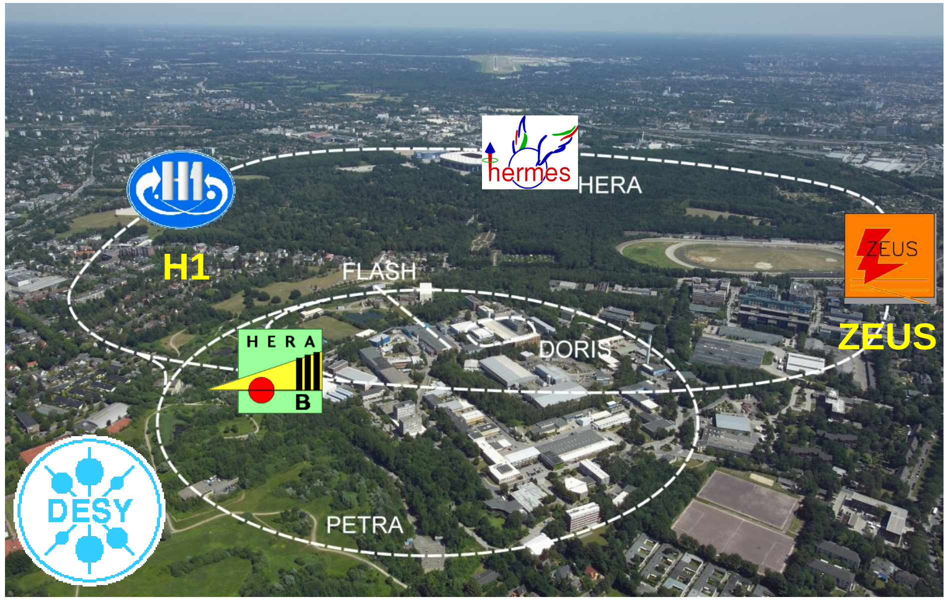
Tevatron: 1986 – 2011
Collisions of p anti-p
Run II: E_{cms} =1.96 TeV
Run II: Record luminosity: 4.3 x 10^{32} $cm^{-2}s^{-1}$



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} $cm^{-2}s^{-1}$

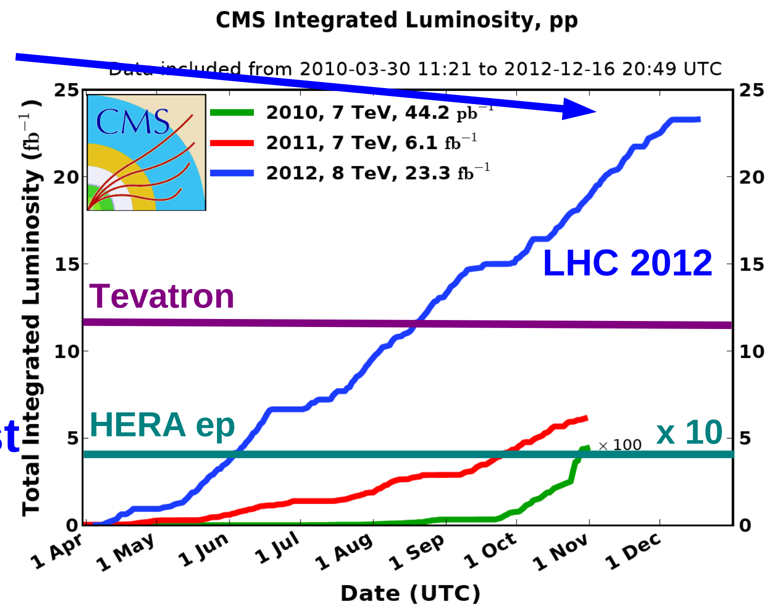
HERA: 1992 – 2007
Collisions of e^+-p, e^--p
HERA II: E_{cms} = 319 GeV





LHC and Experiments

LHC: p-p collisions 2012: 23/fb

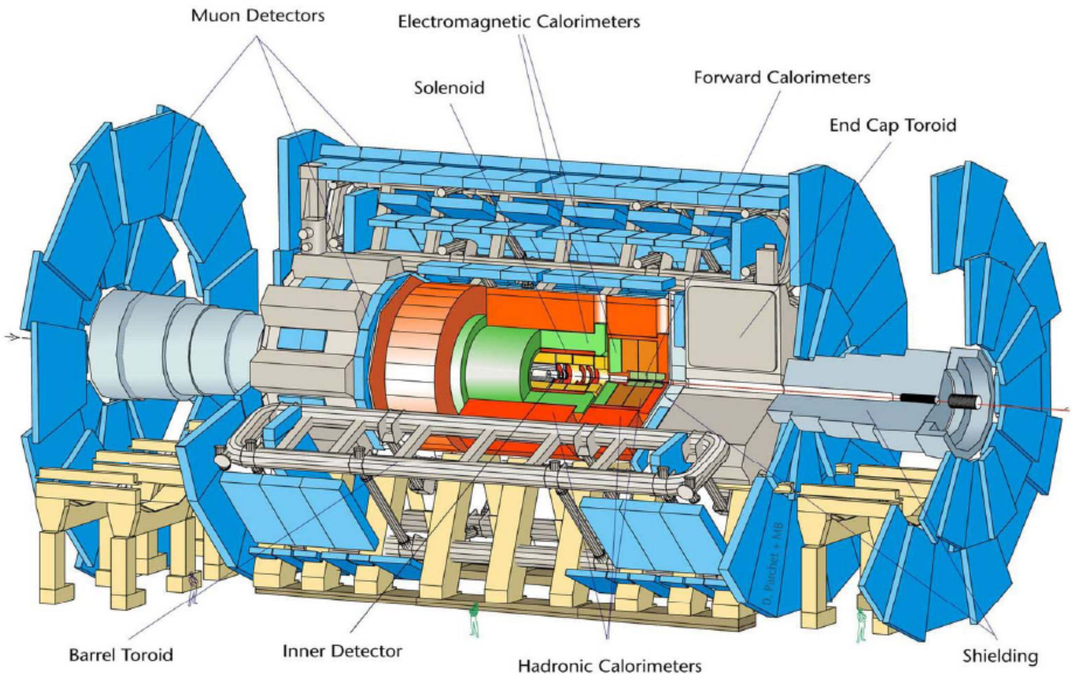


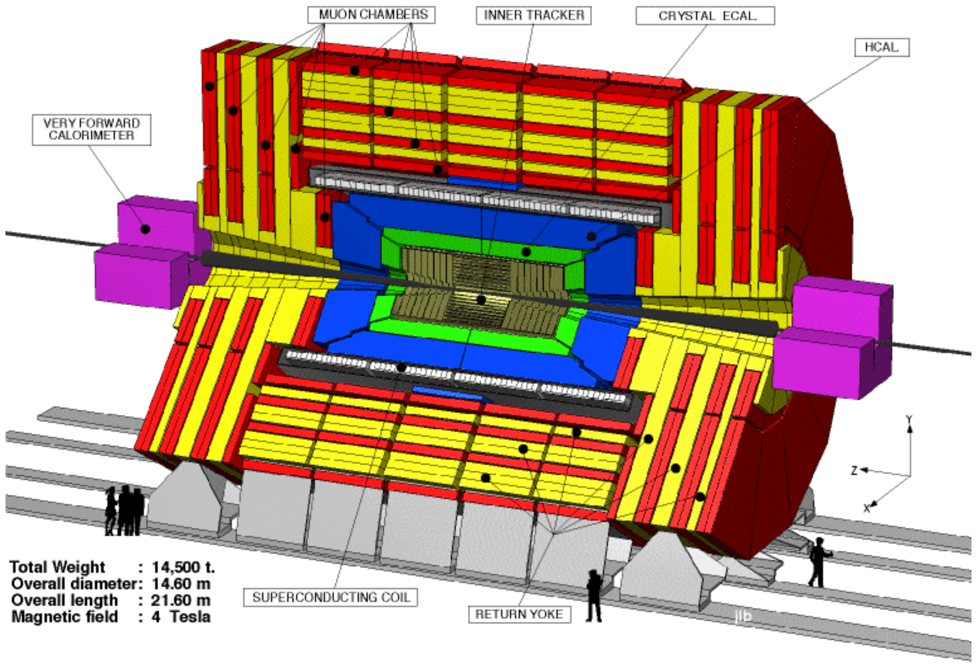
ALICE: **Specialist for heavy ions**

LHCb: **Specialist for b quarks**

ATLAS/CMS global features:

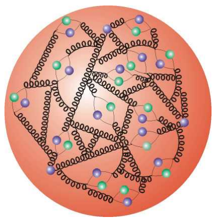
Silicon trackers:	Up to |η| = 2.5
Calorimetry:	Up to |η| ~ 5.0
Muon chambers:	Up to |η| = 2.4-2.7
Jet energy scale:	1 – 3 % prec.



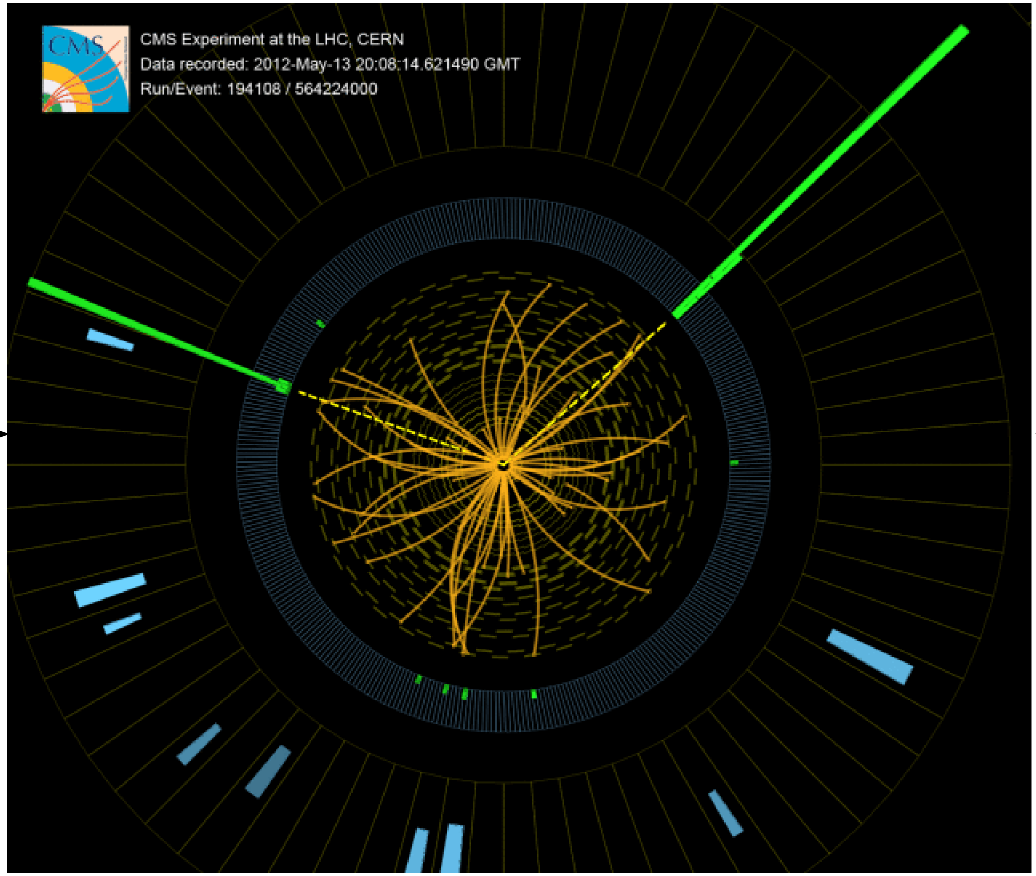


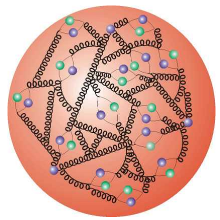
(Di-)Photons

Higgs or no Higgs?



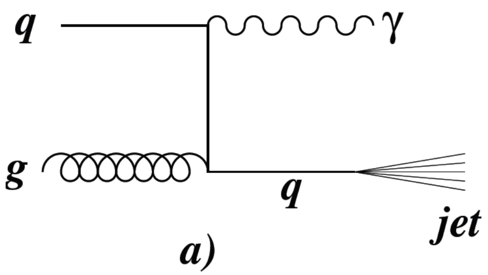
Proton

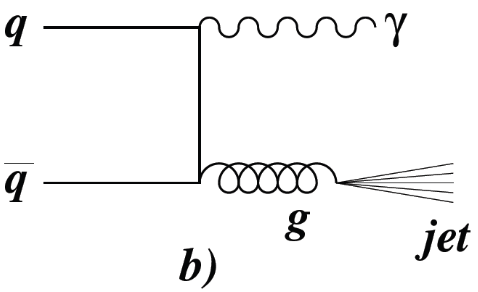




Proton

Photon Production



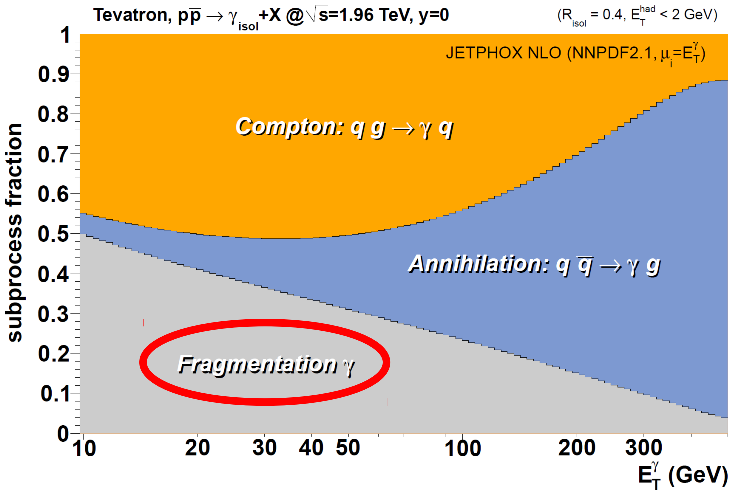


Formerly underexplored process:

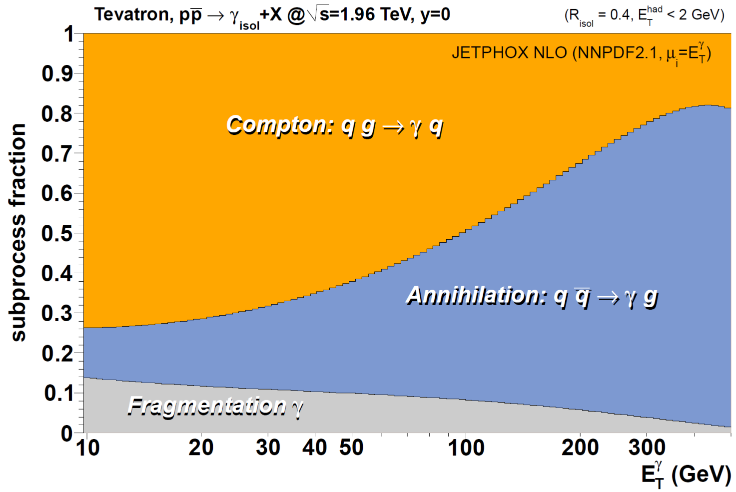
– high fraction of fragmentation photons, cured by isolation
– theory available at NLO, sensitive to gluon PDF

Tevatron

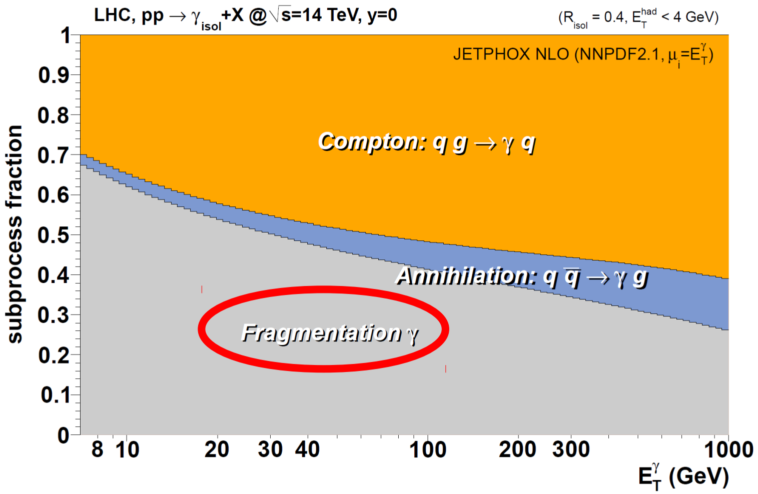
Inclusive

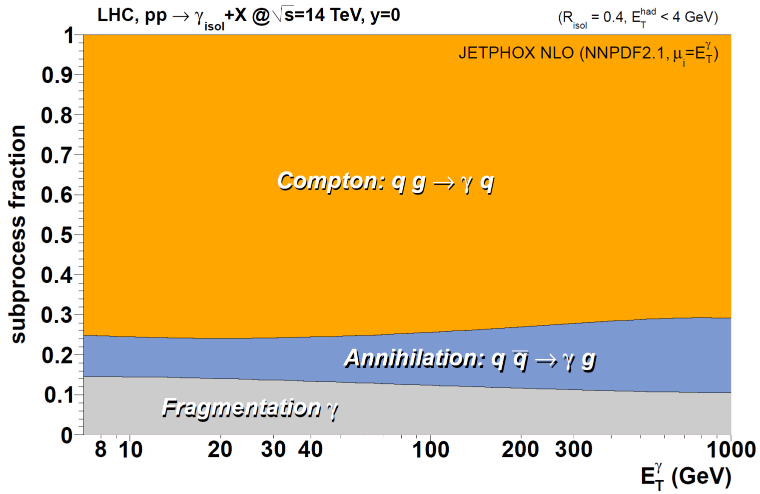


Isolated



LHC 14 TeV



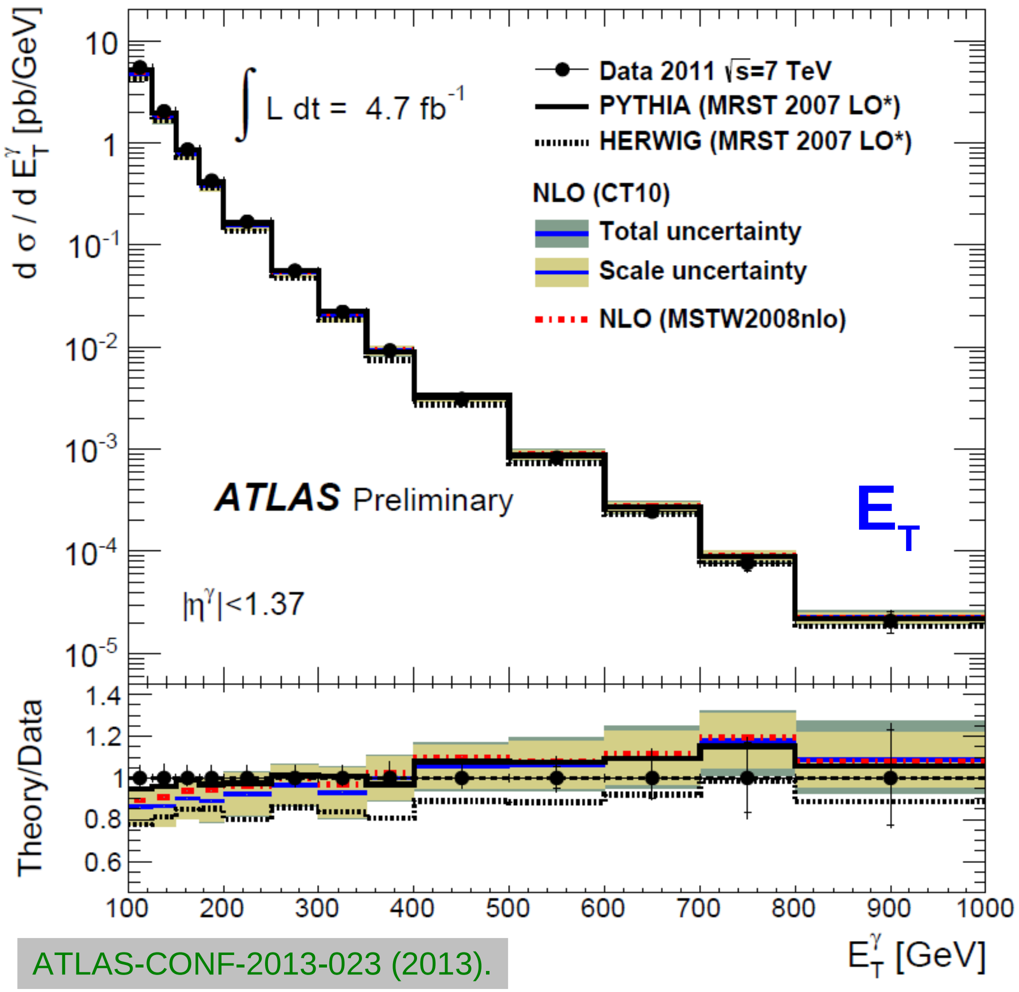


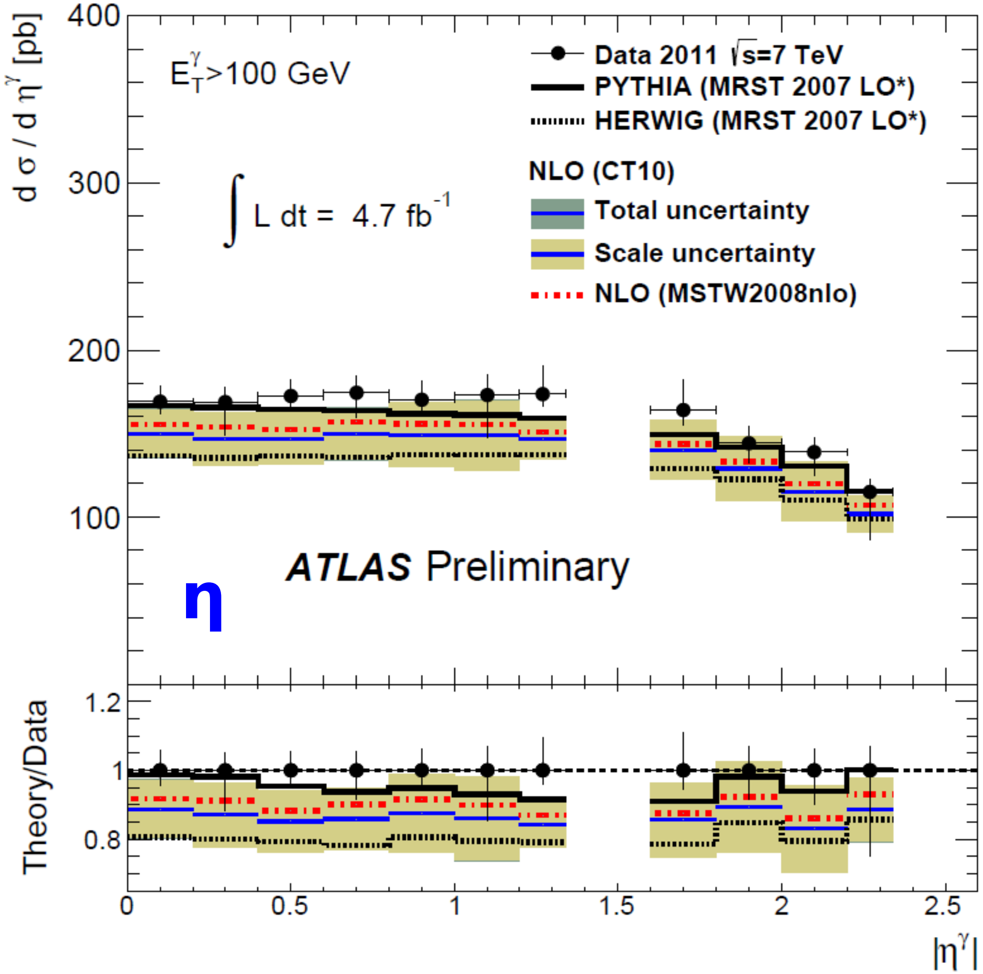
Background: Non-prompt Photons from Decays, e.g. π^0, η

d'Enterria, Rojo, arXiv:1202.1762

Isolated Prompt Photons

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

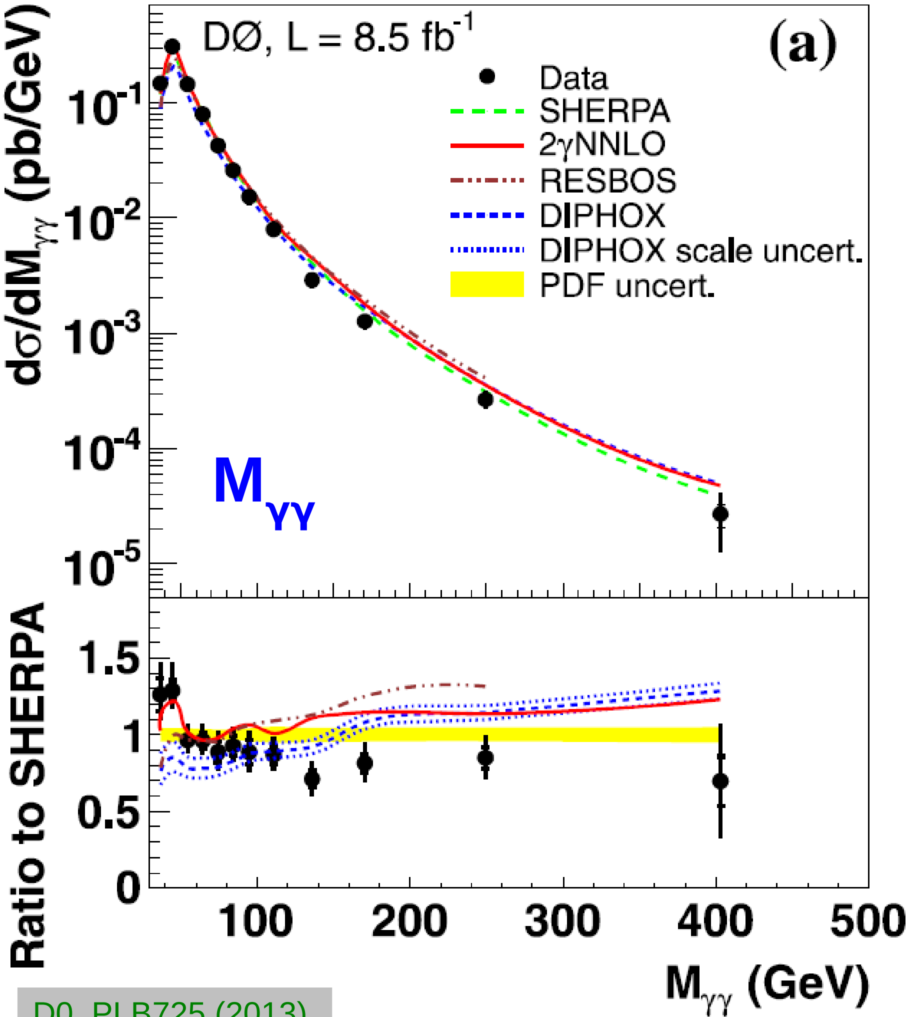


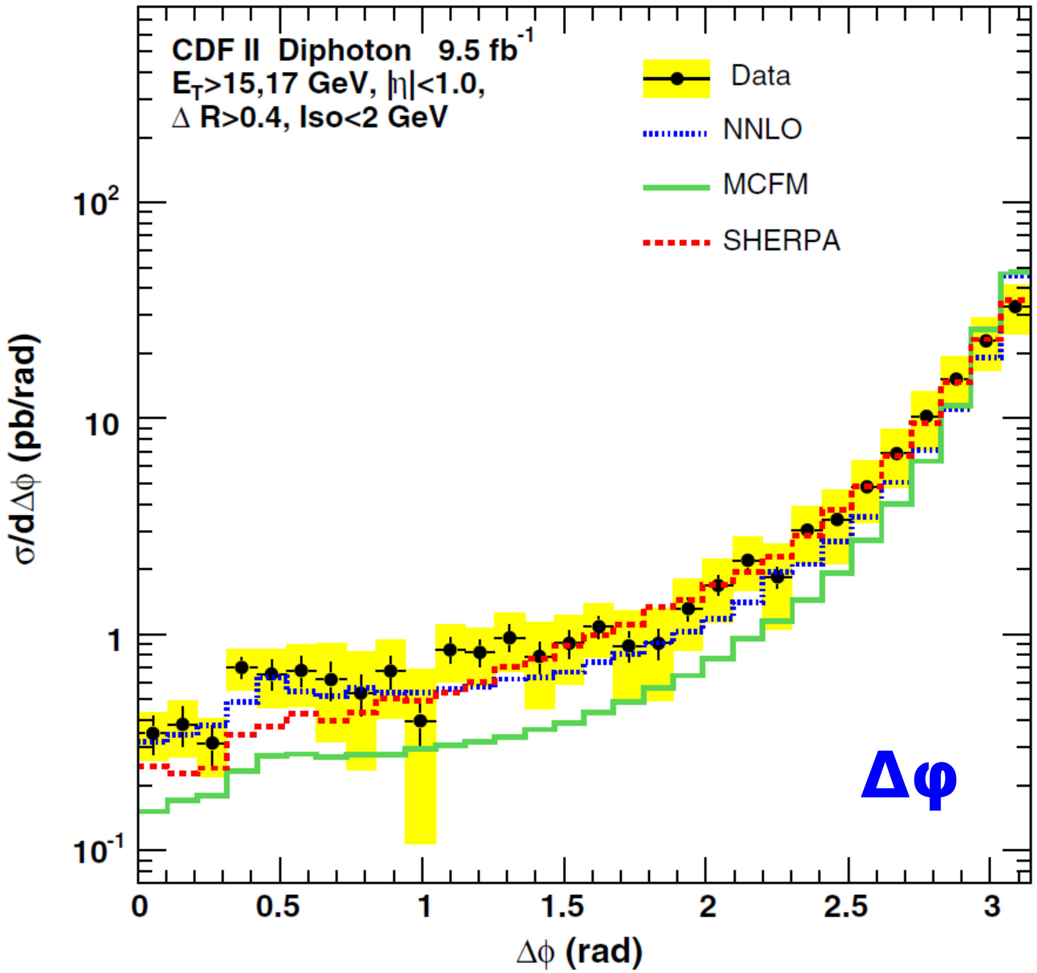


ATLAS-CONF-2013-023 (2013).

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
- Somewhat better agreement with NNLO (2γNNLO) than previous NLO (DiPhox) or with improved photon treatment in parton showers (Sherpa)



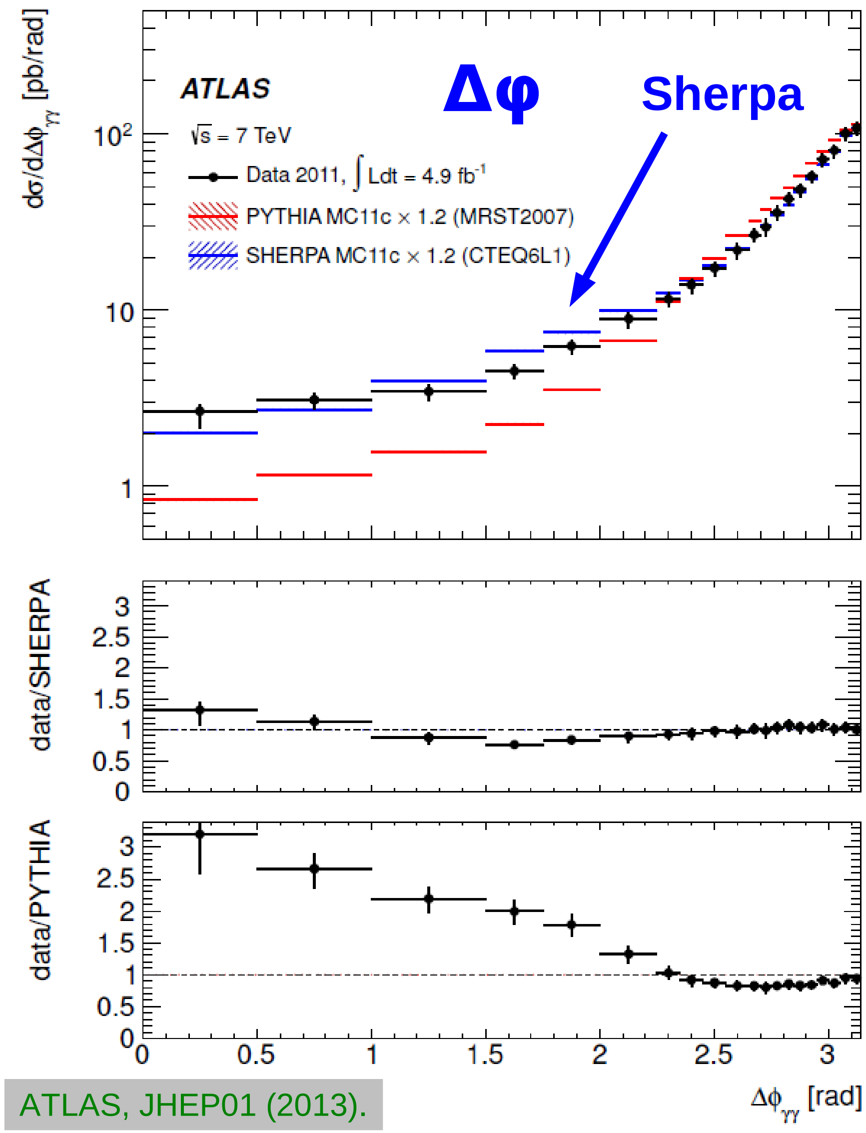


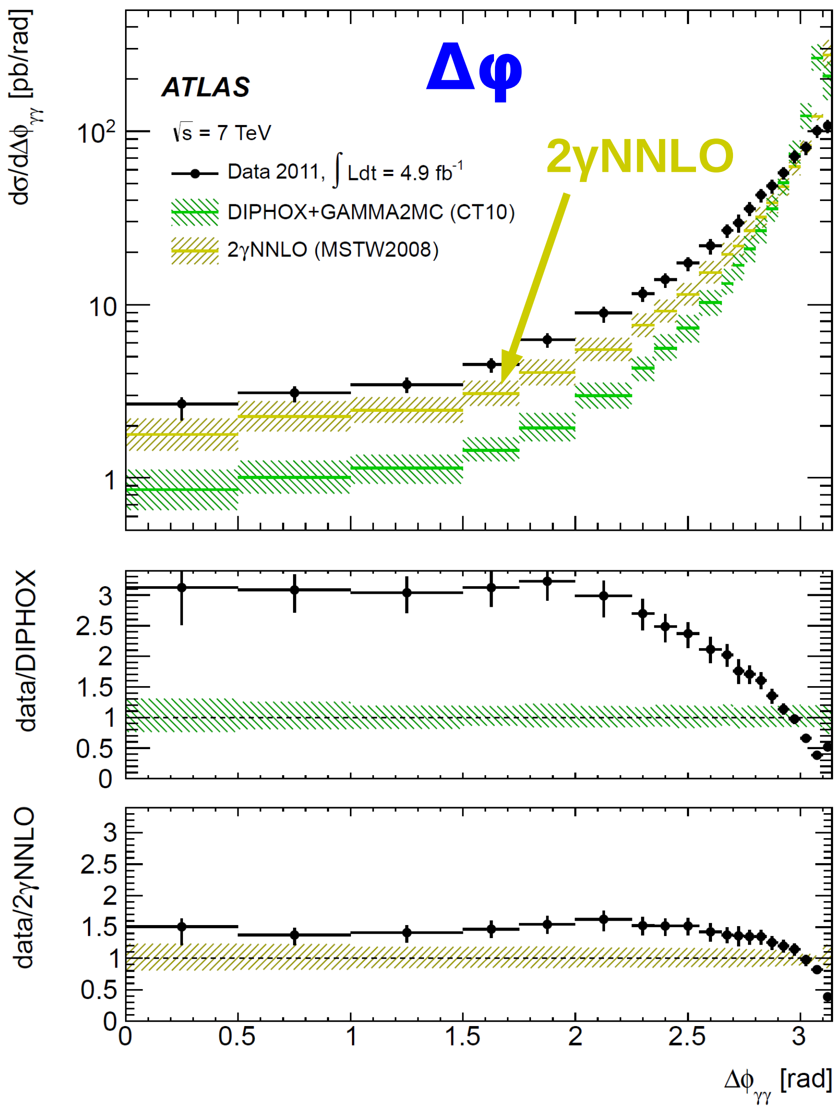
D0, PLB725 (2013).

CDF, PRL110 (2013).

Di-Photons at 7 TeV

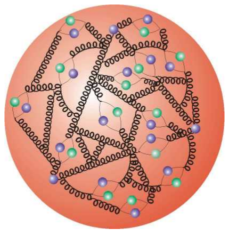
– **Significant improvement confirmed by ATLAS at 7 TeV**
– **Still some deviations visible in $\Delta\varphi_{\gamma\gamma}$ even to 2γNNLO**



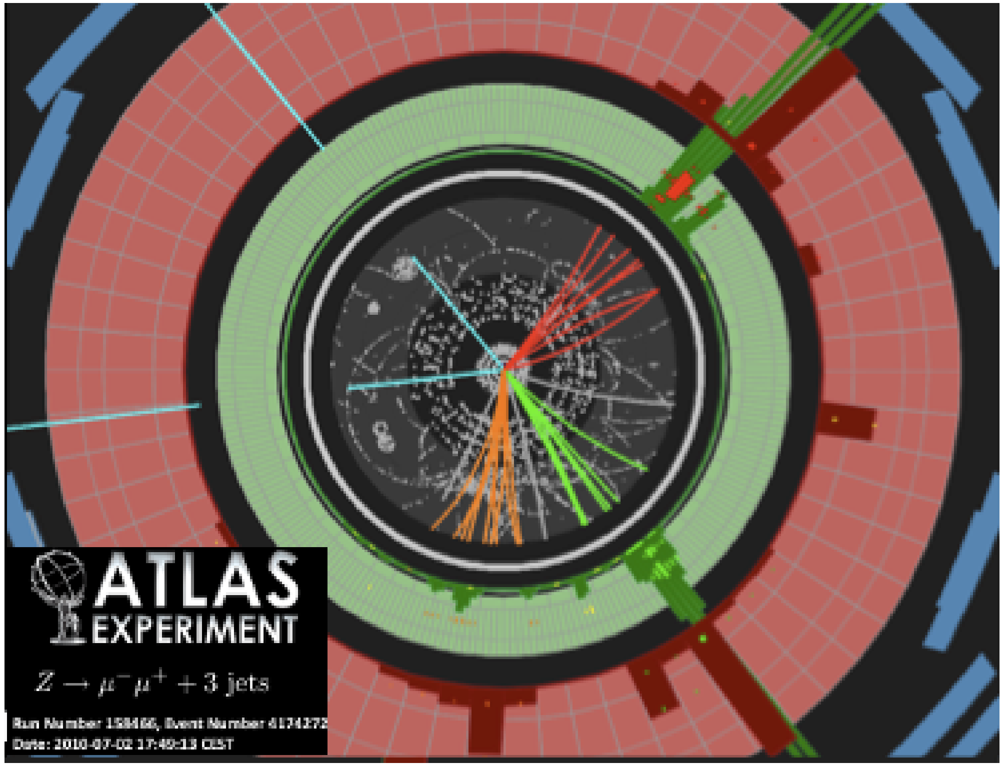


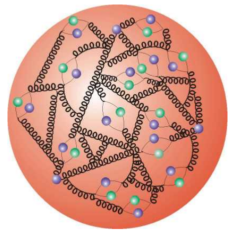
ATLAS, JHEP01 (2013).

Standard Candles



Proton

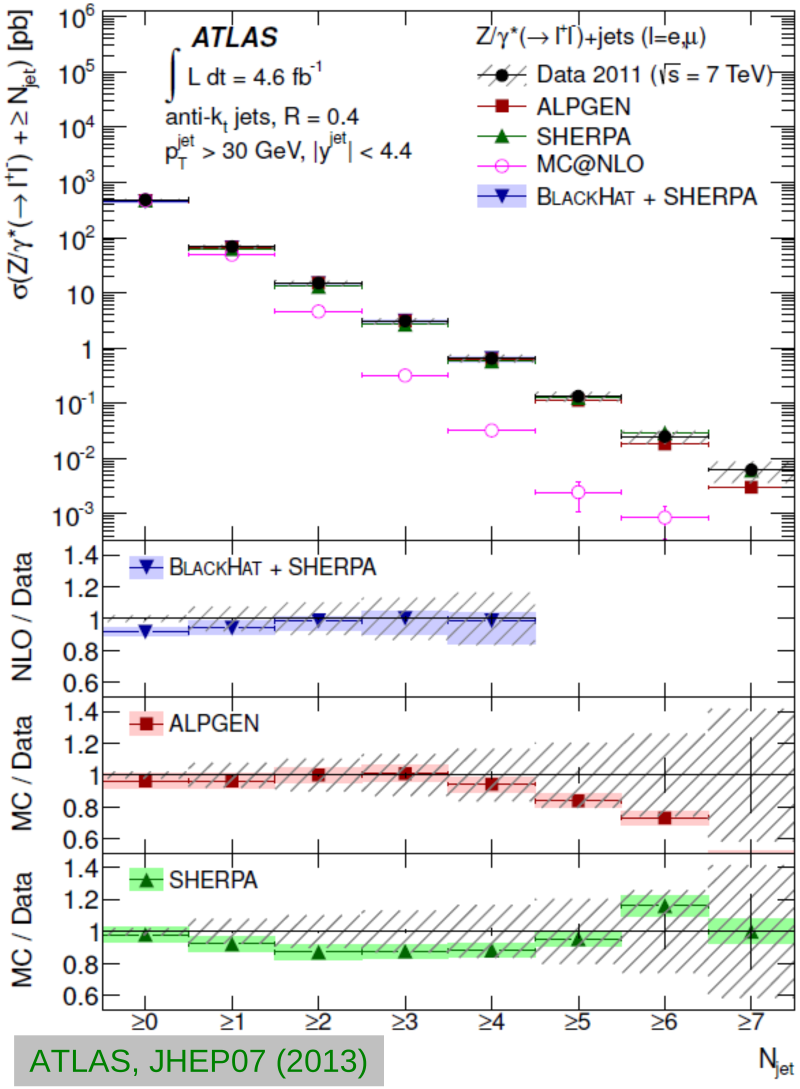




Proton

Z + Jets

- No newer result on γ+jets, but on Z+jets (ATLAS) with up to 7 jets or more!
- In general, agreement with theory @ NLO up to 4 jets, Alpgen and Sherpa OK
- Severe discrepancies to MC@NLO

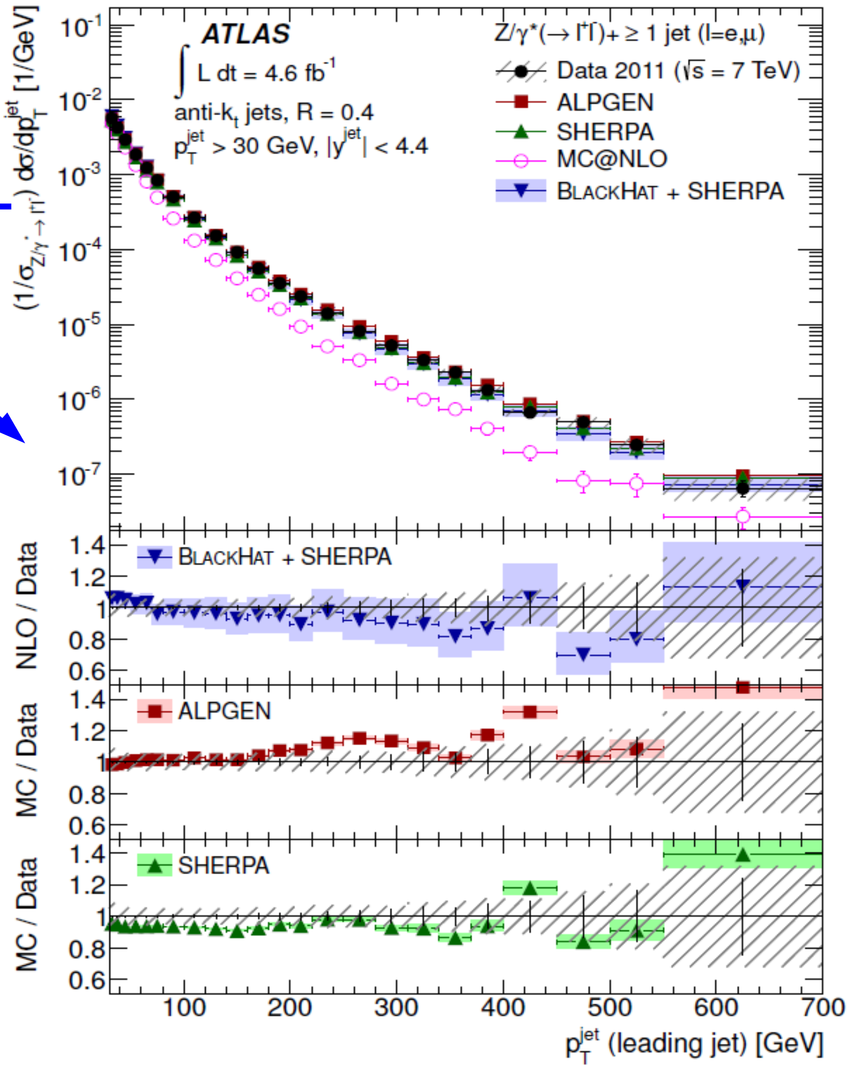


ATLAS, JHEP07 (2013)

Jet multiplicity

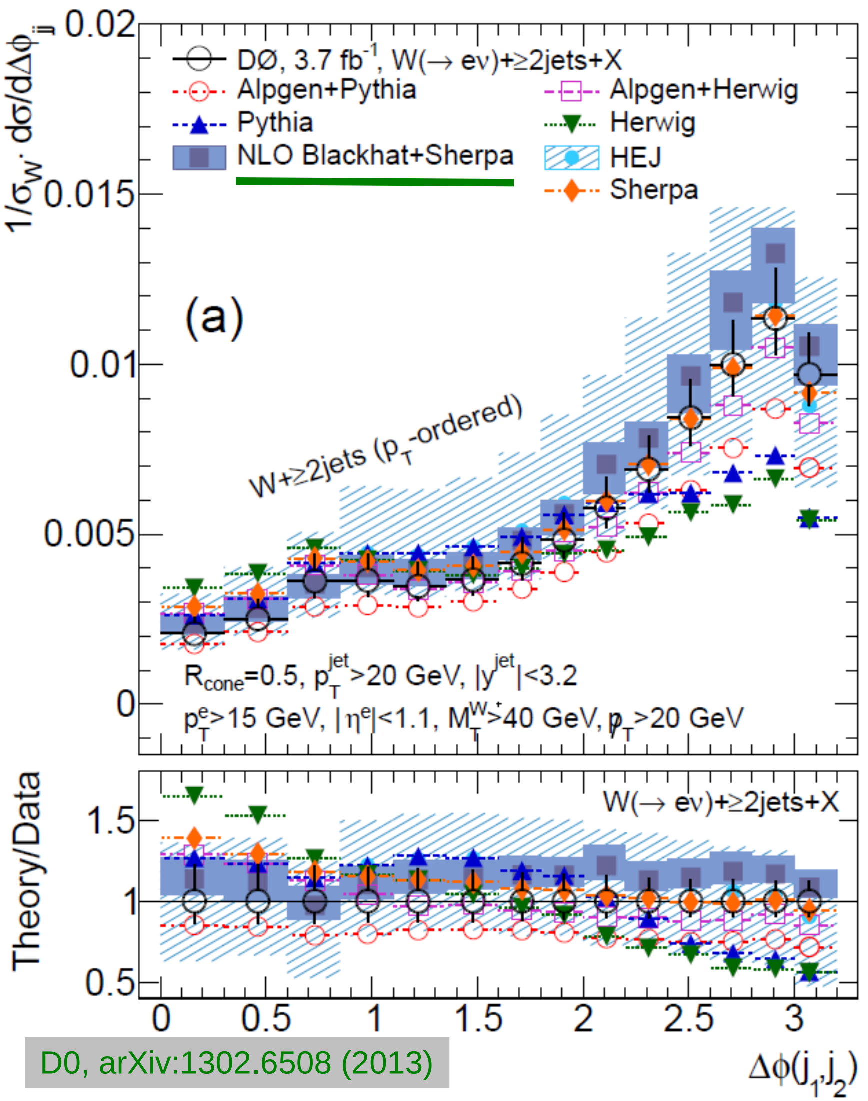
Leading jet pT

NLO



W + Jets

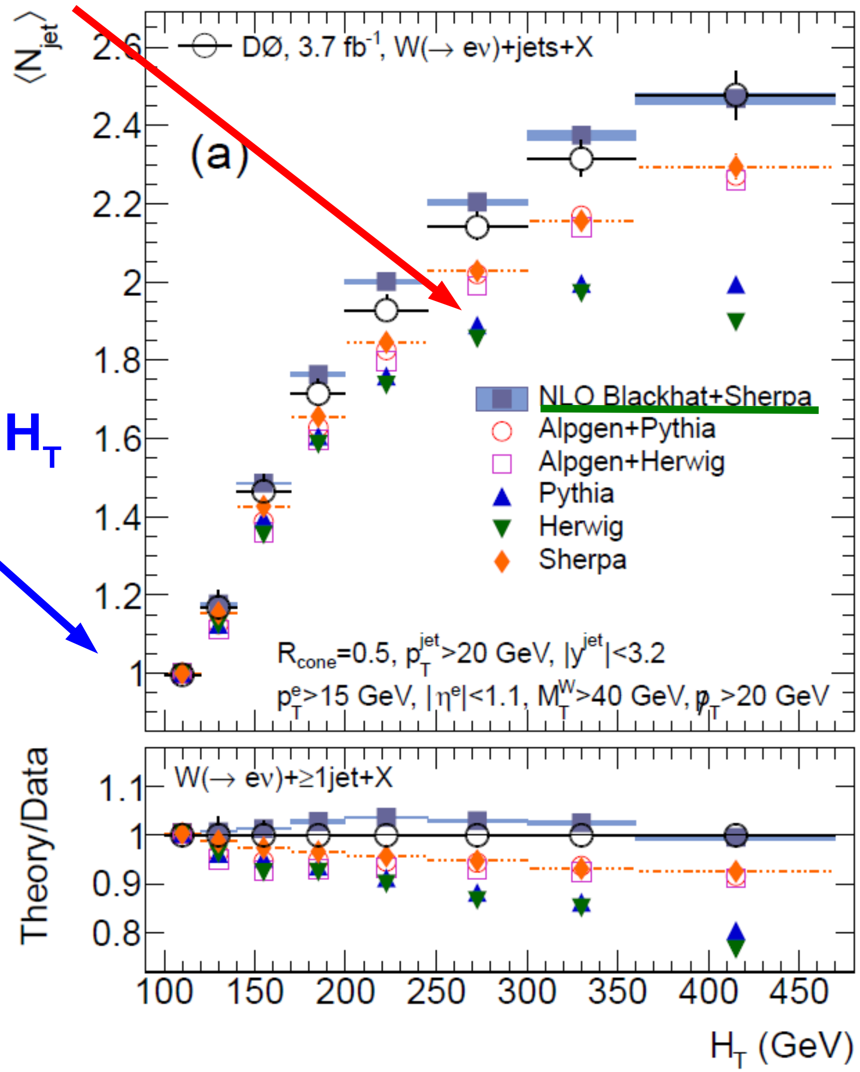
- New comprehensive study by D0
- Data well described by NLO
- LO generators run into problems at high multiplicity



D0, arXiv:1302.6508 (2013)

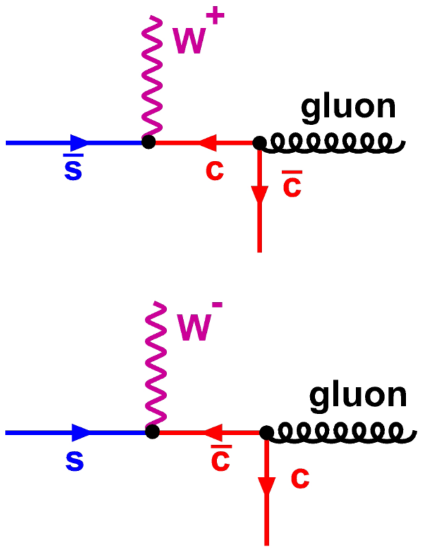
$\Delta\varphi_{j1,j2}$

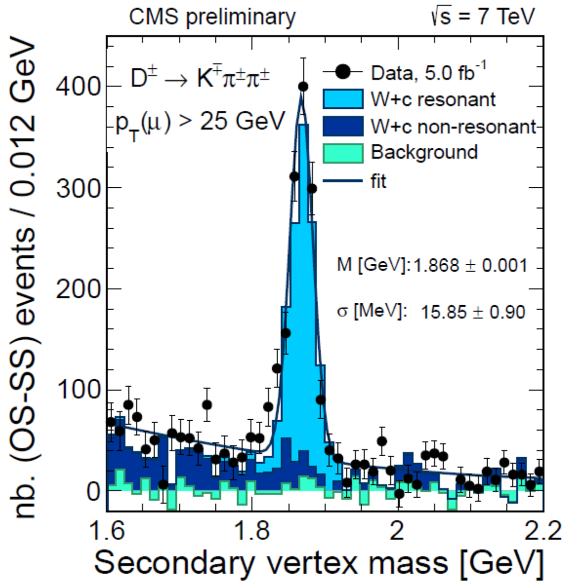
$<N_{jet}>$ vs. H_T

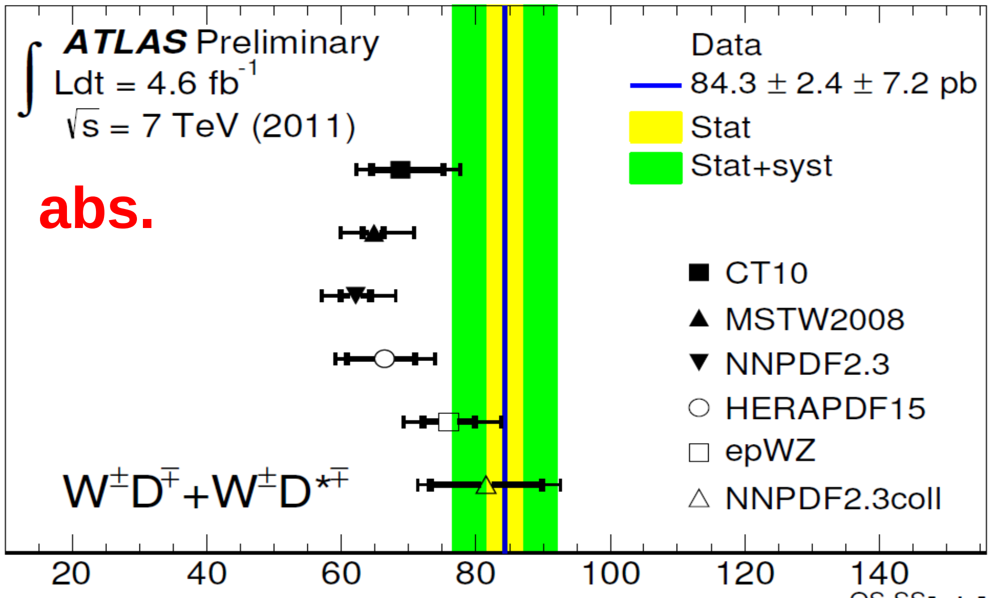


W + c

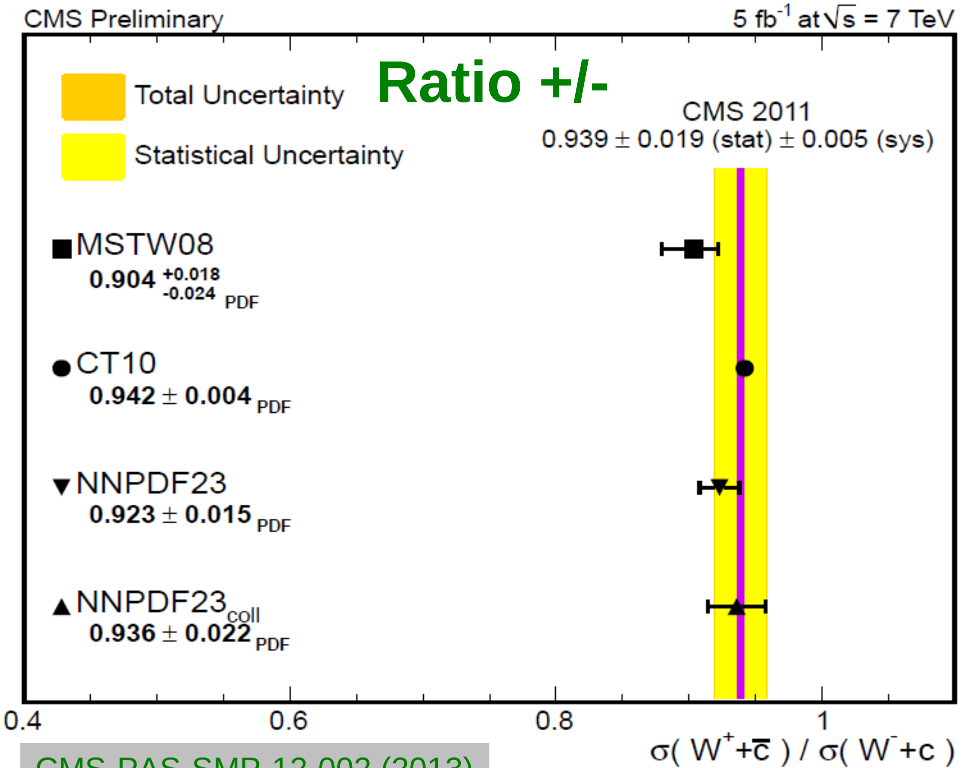
– New measurements from ATLAS & CMS
– Explicit reconstruction of charmed meson decays ($D^{\pm}$, $D^{*\pm}$) or incl. semileptonic (CMS)
– Different phase space ATLAS vs. CMS
– ATLAS finds smaller abs. cross sections ratio W+/W- ok
– CMS finds agreement within uncertainties for both





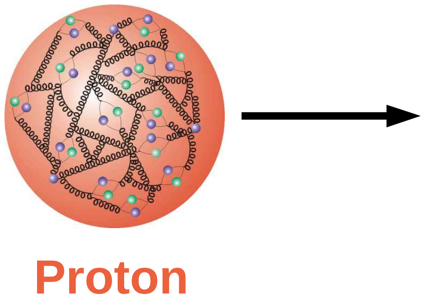


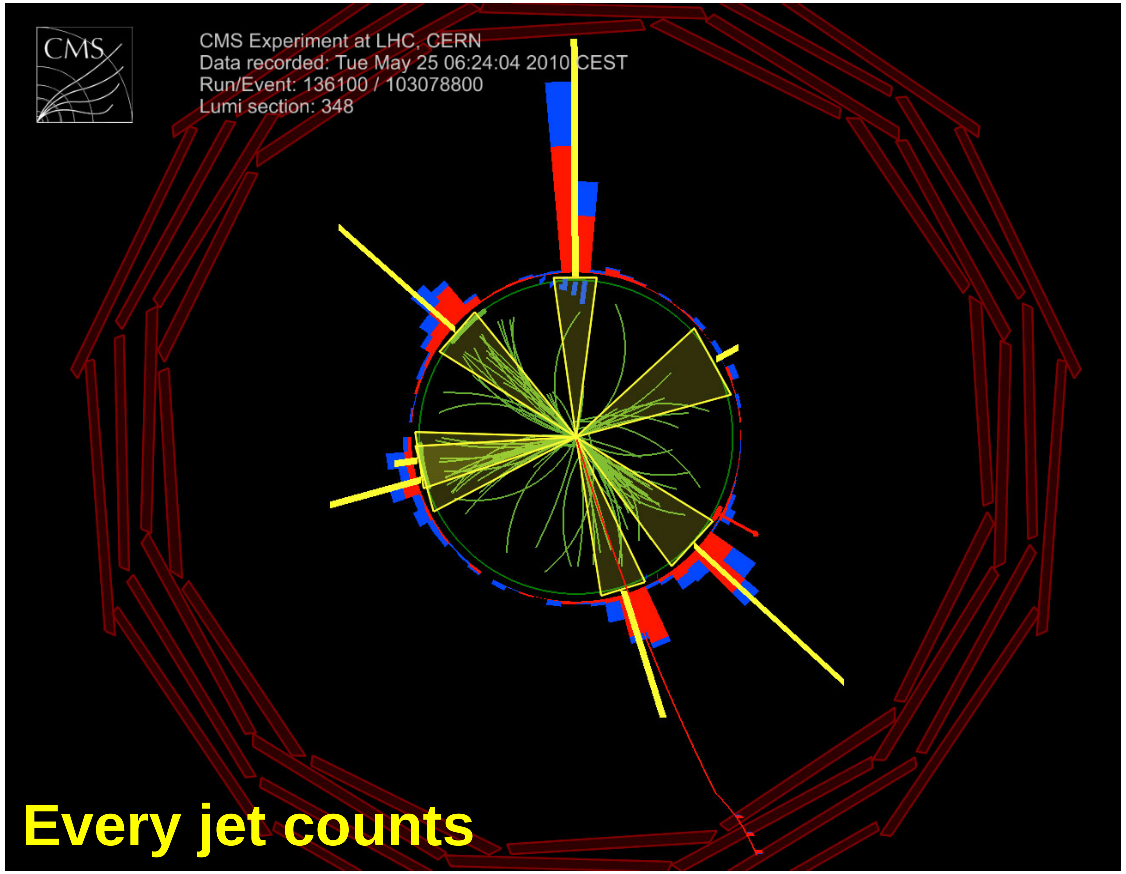
ATLAS-CONF-NOTE-2013-045 (2013)

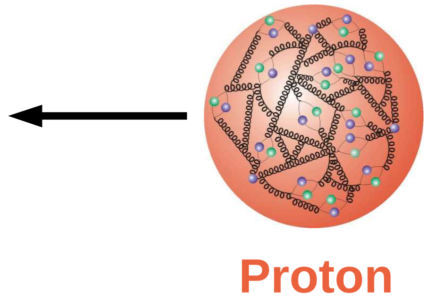


CMS-PAS-SMP-12-002 (2013)

High transverse Momenta







Inclusive Jets

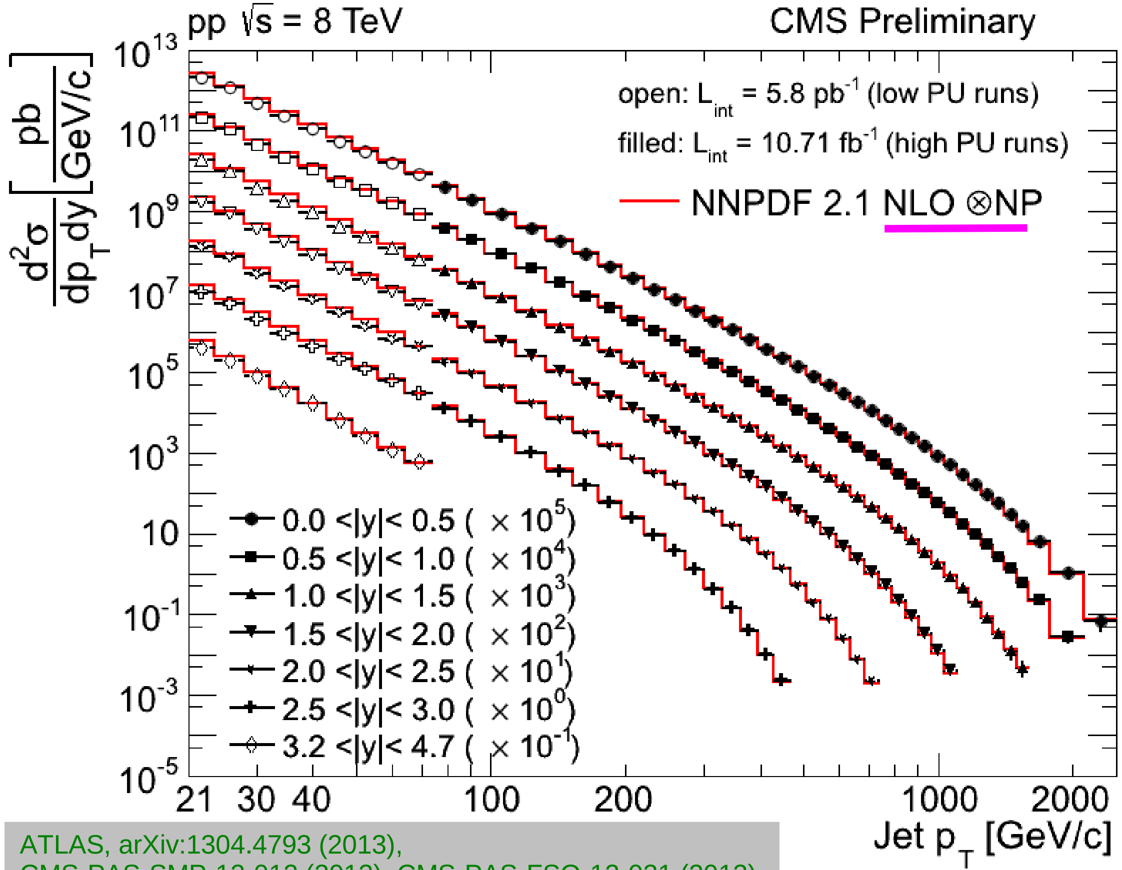
Agreement with predictions of QCD at NLO over many orders of magnitude in cross section and even beyond 2 TeV in jet p_T and for rapidities |y| up to ~ 5 → constrain gluon PDF!

Similar picture at 7 TeV, 8 TeV (CMS left) or 2.76 TeV (ATLAS right)

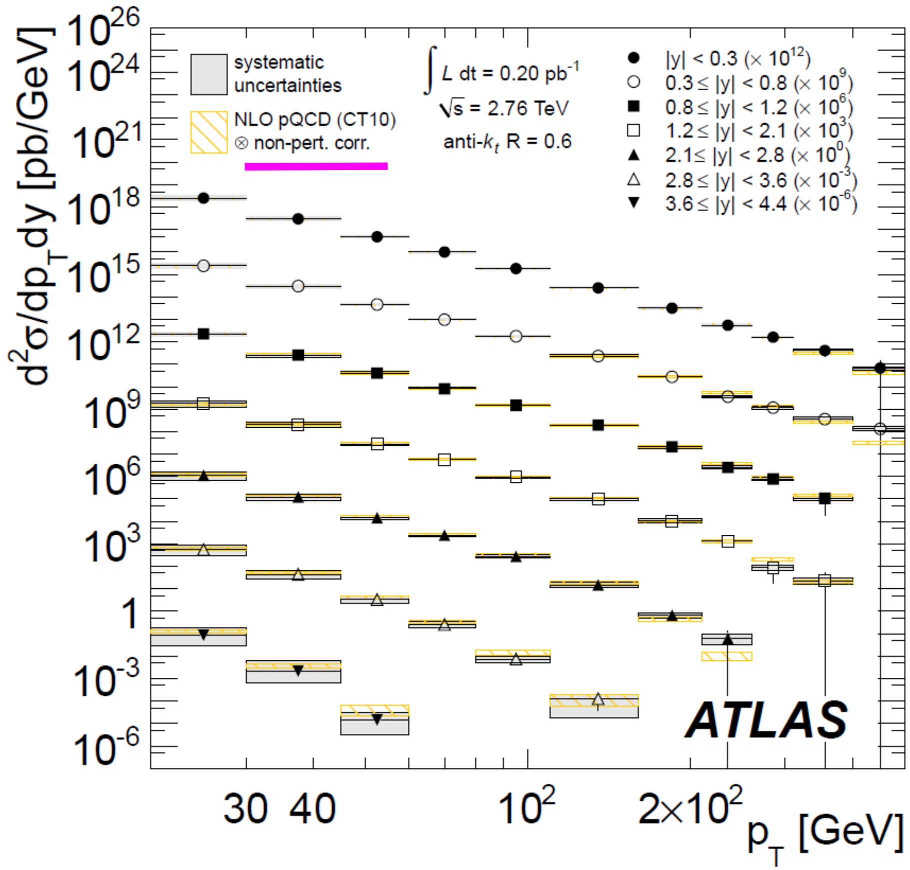
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

Data vs. NLO pQCD ⊗non-perturbative corrections

anti-kT, R=0.7, 8 TeV, 2012



anti-kT, R=0.6, 2.76 TeV, 2012



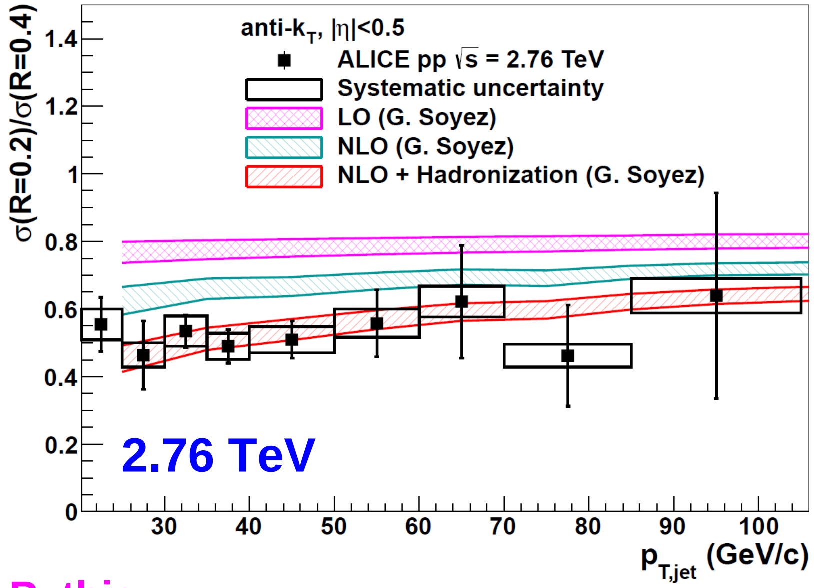
ATLAS, arXiv:1304.4793 (2013), CMS-PAS-SMP-12-012 (2013), CMS-PAS-FSQ-12-031 (2013).

Inclusive Jet Ratios: Jet Size R

Ratio with different jet sizes
R = 0.5/0.7 and 0.2/0.4

G. Soyez, PLB698 (2011).

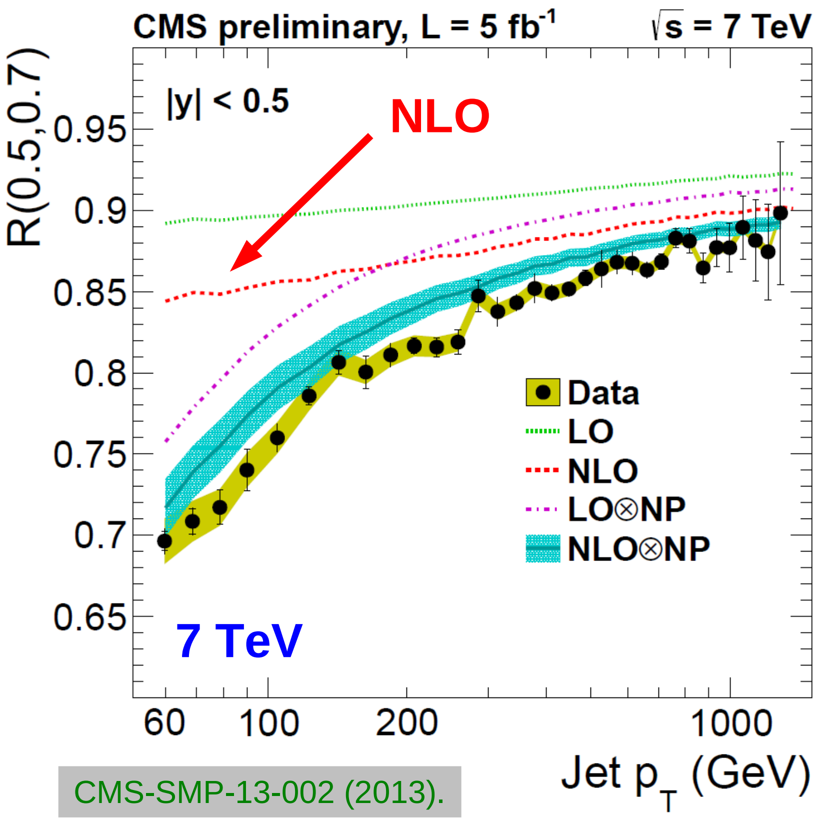
ALICE study
R=0.2 / R=0.4



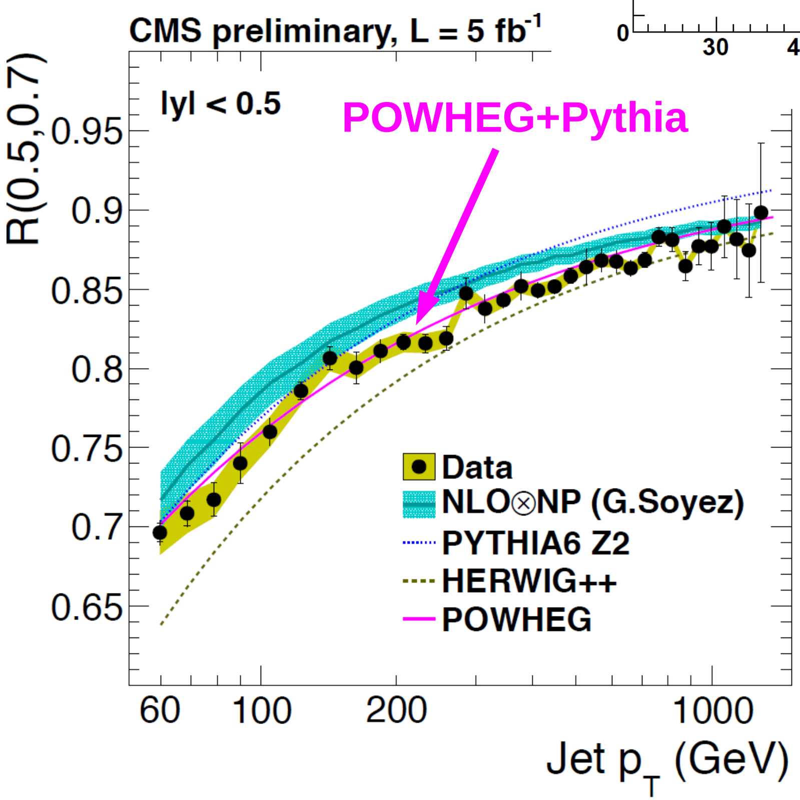
ALICE, PLB722 (2013).

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

New CMS study: R=0.5 / R=0.7



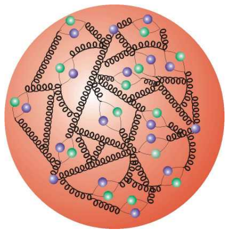
CMS-SMP-13-002 (2013).



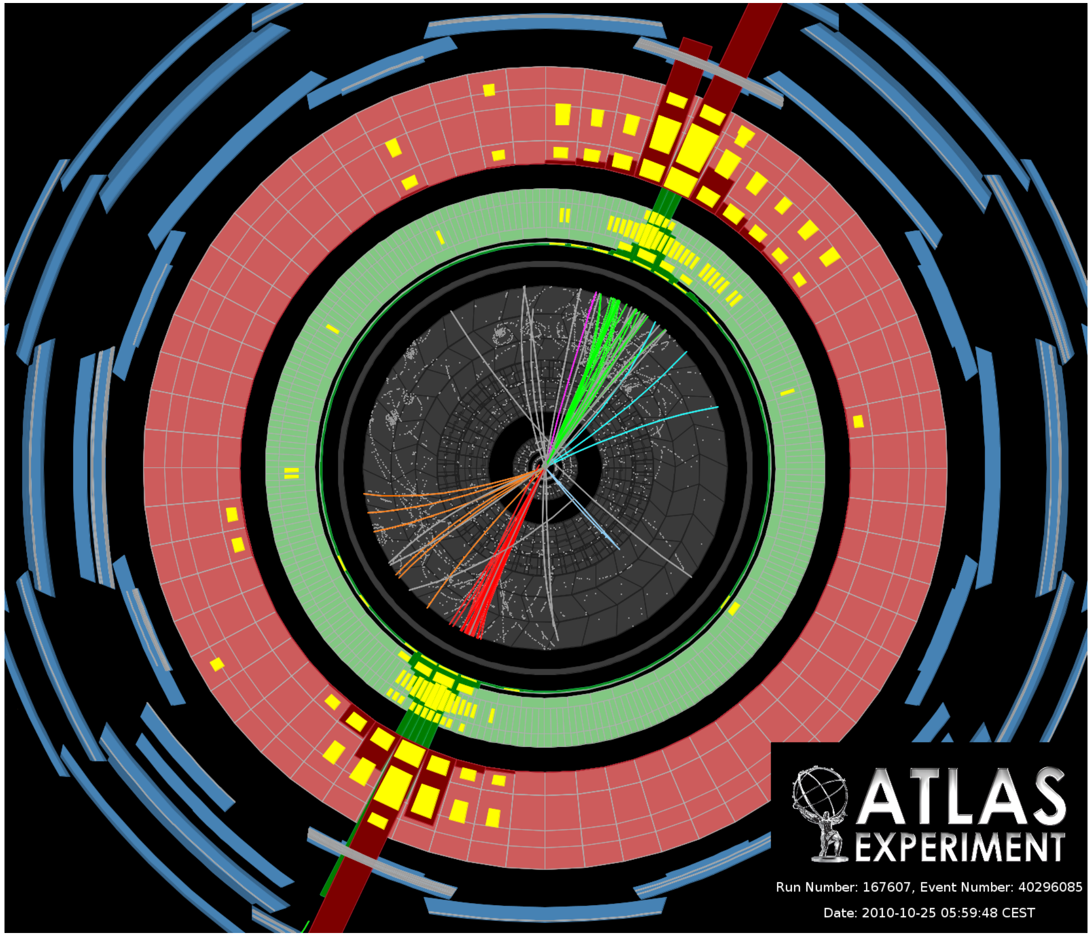
Requires event generators:
LO+PS+HAD → better (Pythia6,Herwig++)

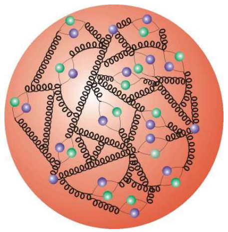
NLO+PS+HAD → best (POWHEG+Pythia)

High Masses



Proton





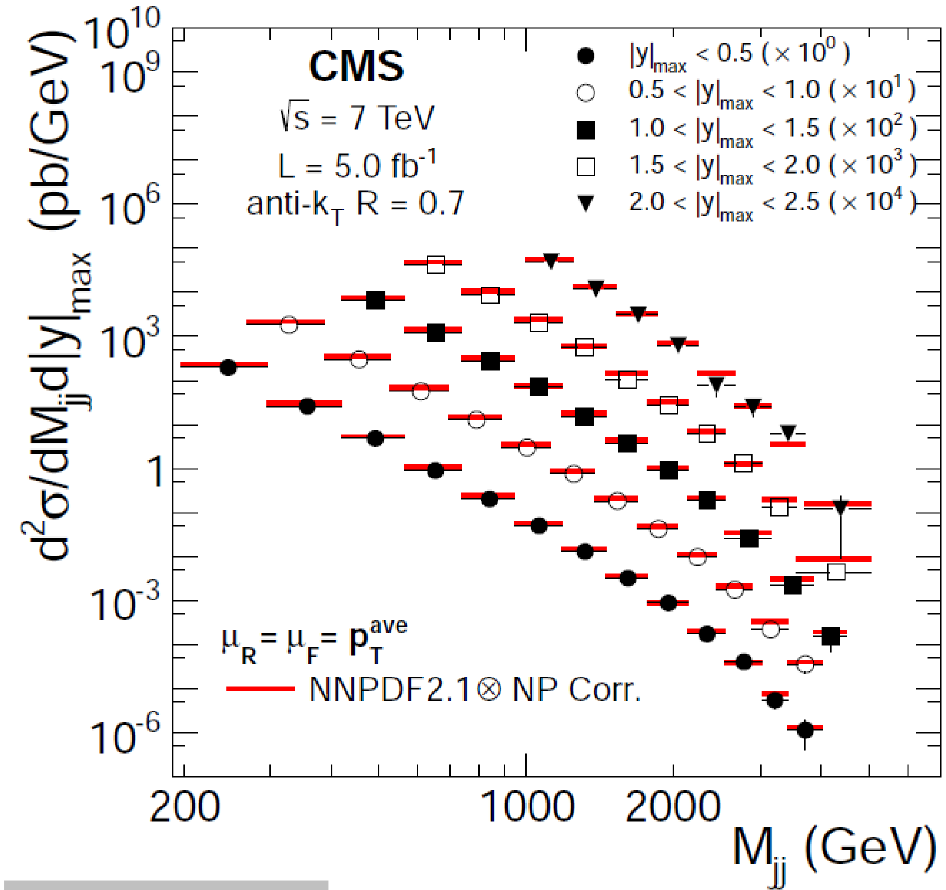
Proton

Dijet Mass

Again agreement with predictions of QCD over many orders of magnitude!
QCD works too well :-)

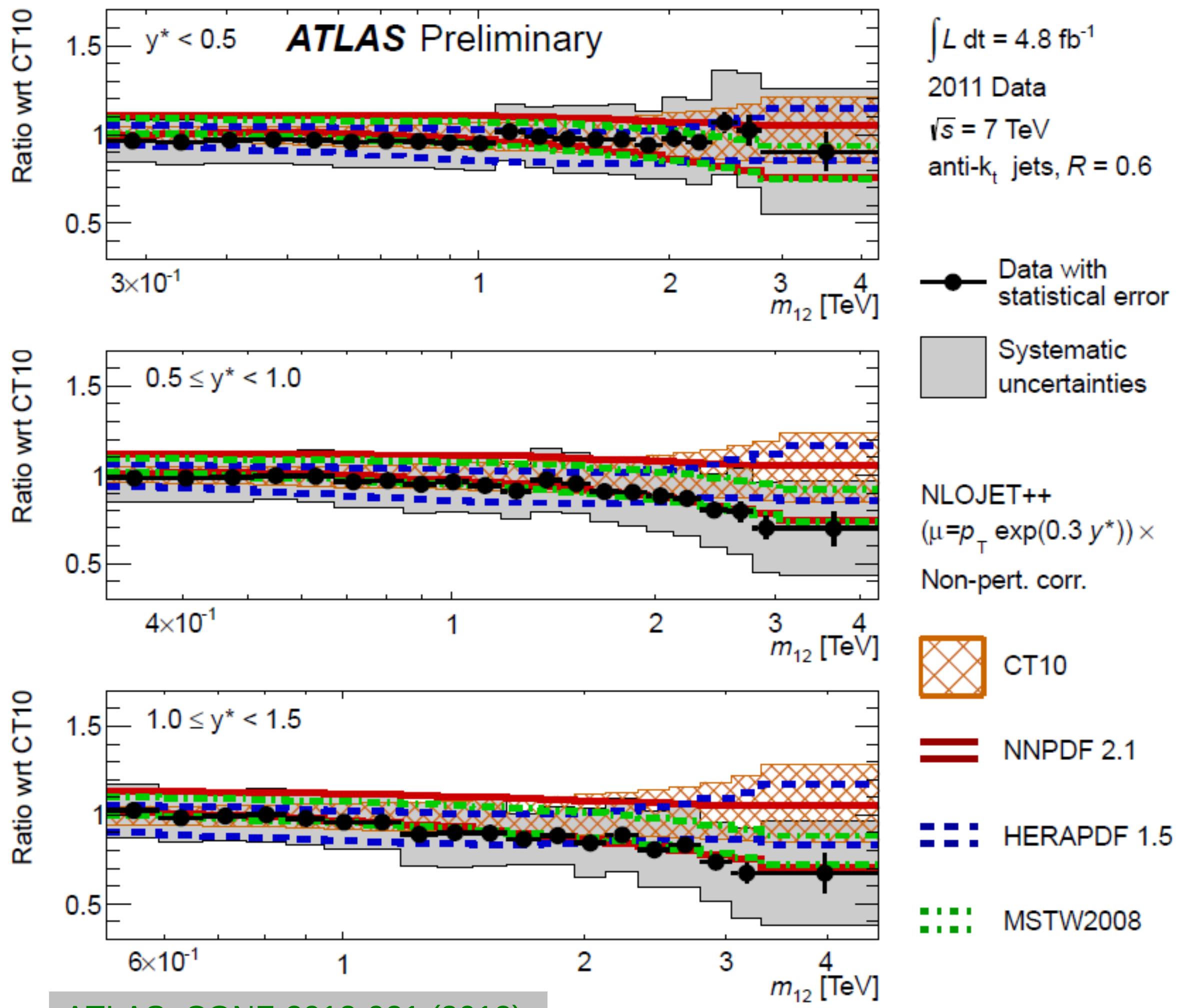
$$\frac{d^2\sigma}{dM_{JJ}d[|y|_{max}, y^*]} \propto \alpha_s^2$$

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



CMS, PRD87 (2013)

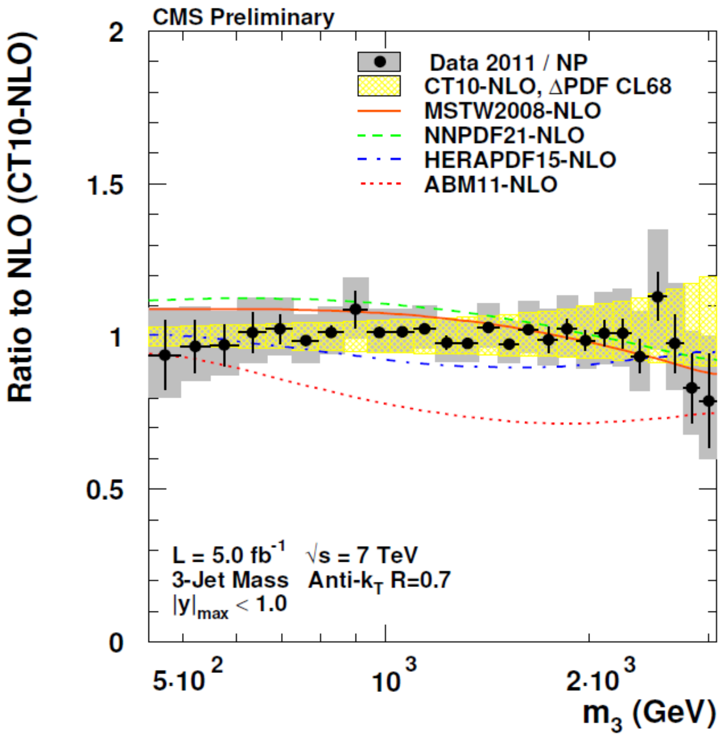
anti-kT, R=0.6, 7 TeV, 2011

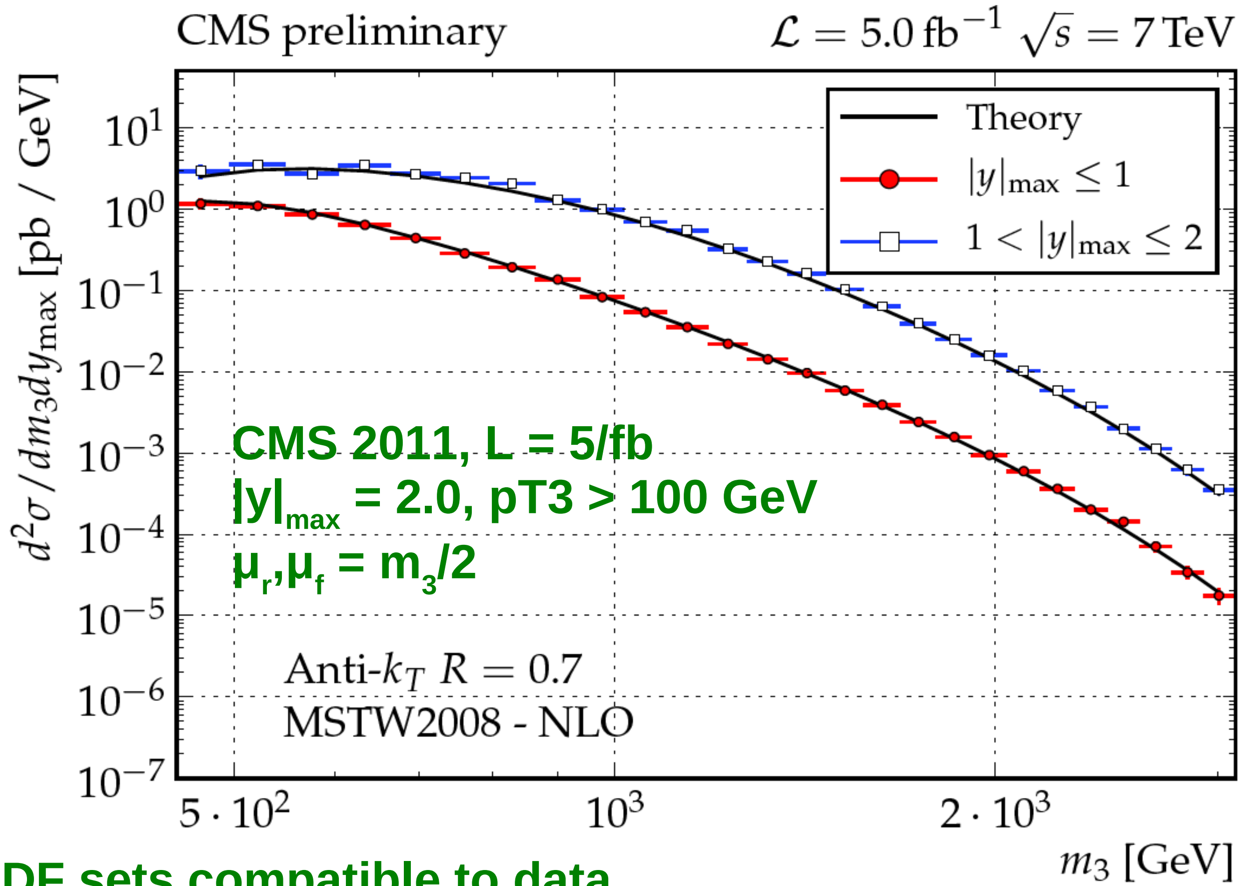


ATLAS, CONF-2012-021 (2012).

3-Jet Mass

- Sensitive to α_s beyond 2→2 process
- Known at NLO (NLOJet++)
- Sensitive to PDFs
- Involves additional "scale" $p_{T,3}$





Most PDF sets compatible to data

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

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

Dominated by theory uncertainty! NLO only

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

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

Color Coherence

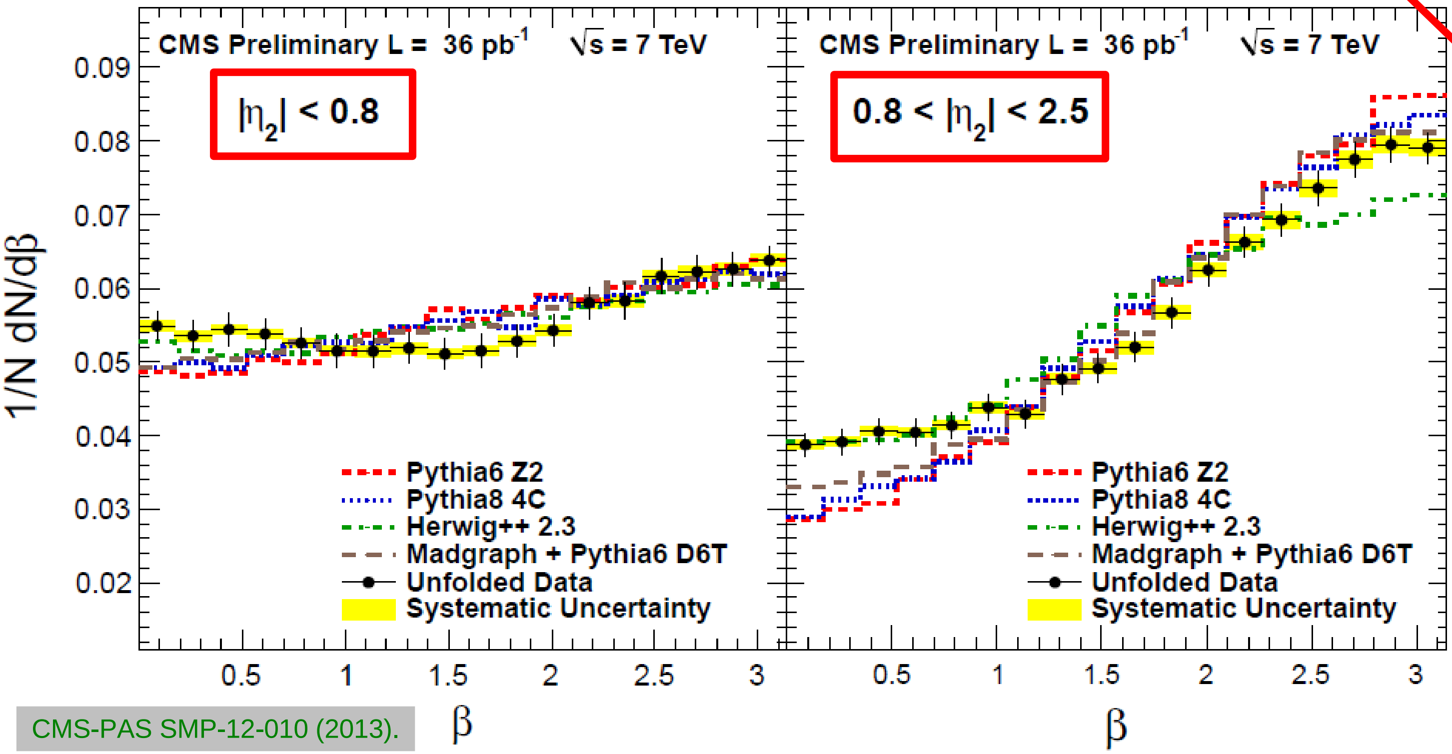
Study orientation of 3rd jet emission near 2nd → test interference in parton emissions

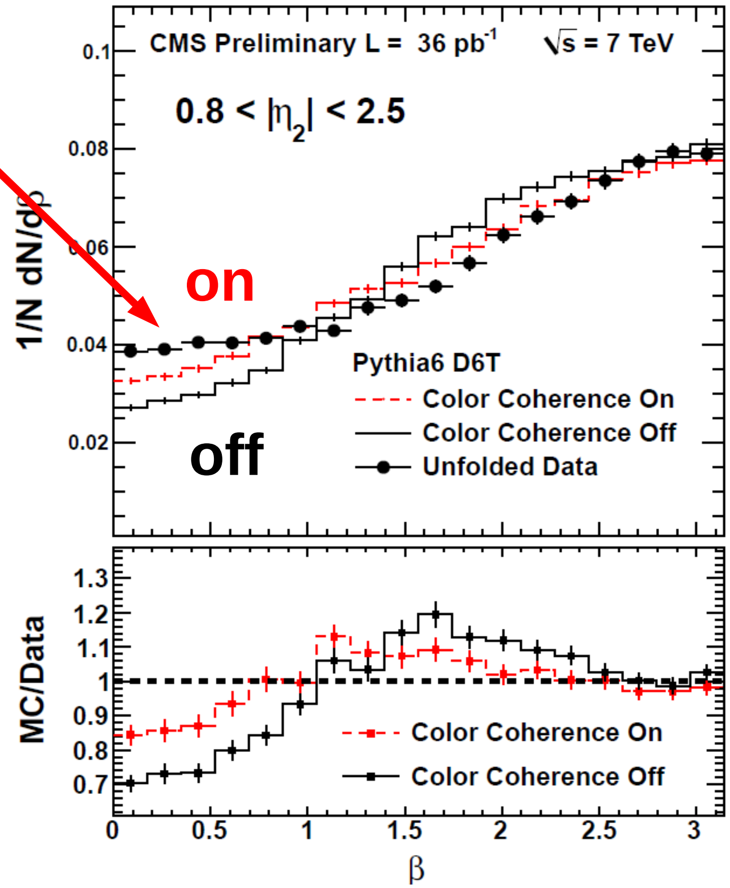
$$\beta = \left| \tan^{-1} \frac{\Delta\phi_{32}}{\mathrm{sign}(\eta_2)\Delta\eta_{32}} \right|$$

In MC approximated by angular ordering → improves description
still not perfect

β ~ 0 → emission between jet 2 and beam

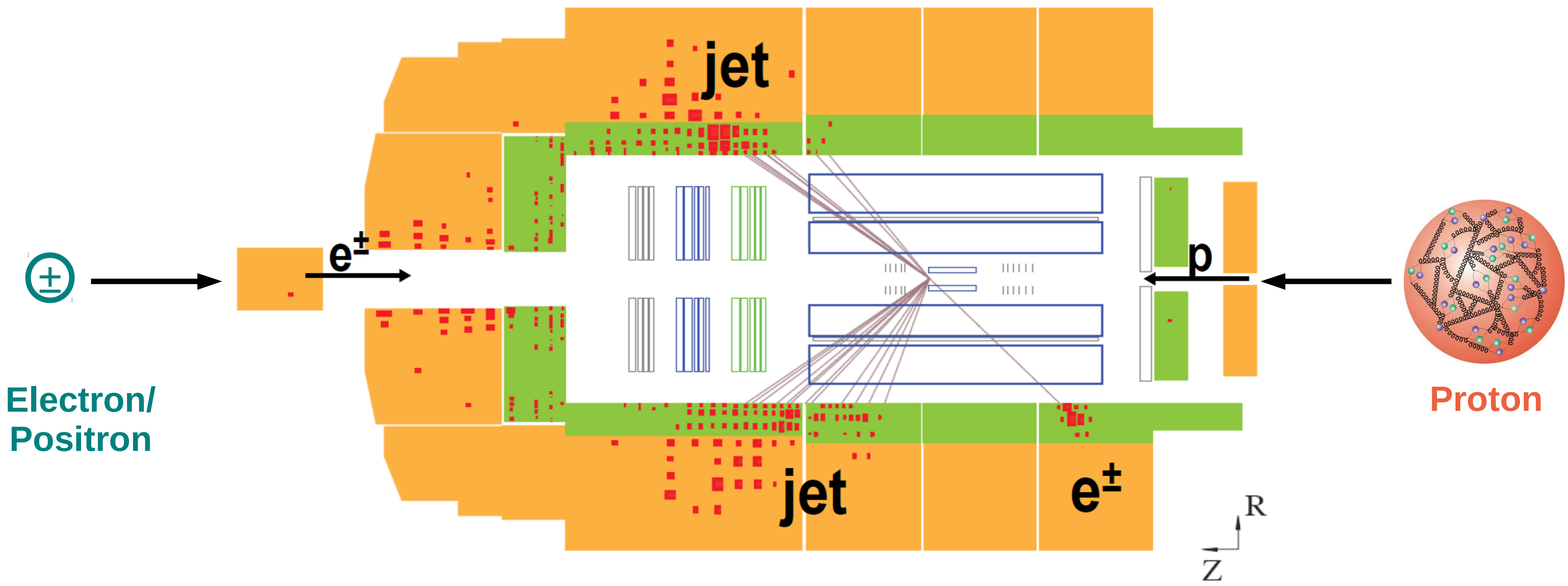
No MC really good, better tunes required



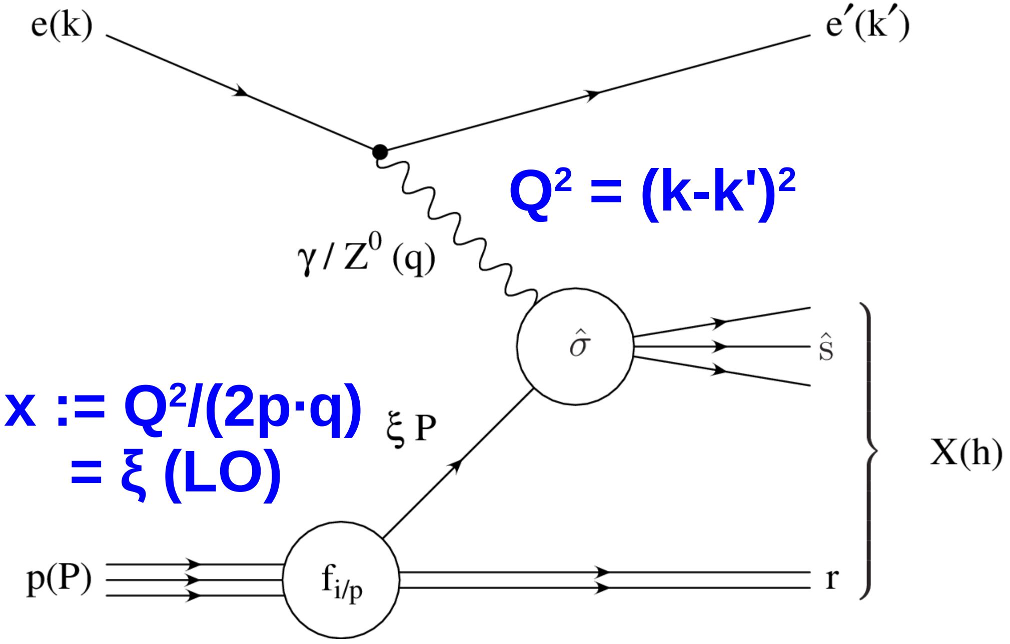


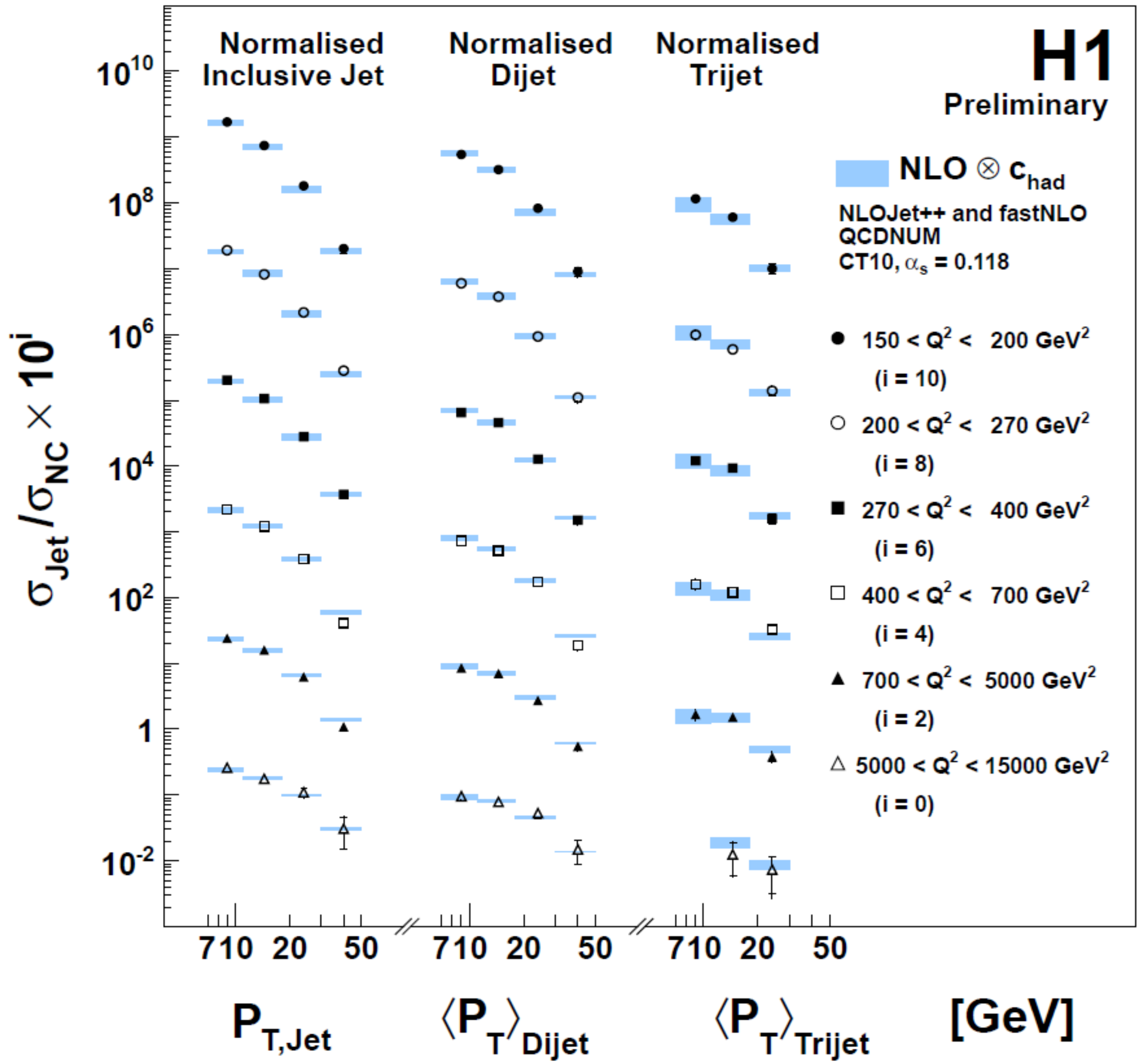
CMS-PAS SMP-12-010 (2013).

High Scales



Normalized Multi-Jets in DIS





Jet phase space:

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

$7 < pT < 50$ GeV

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

Scales: $\mu_r^2 = (Q^2+E_T^2)/2$

$\mu_f^2 = Q^2$

Normalization: NC DIS

Normalized Multijet (k < 1.3)

NLO only

$\alpha_s(M_Z) = 0.1163 \pm 0.0011(\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0008\ (\text{had}) \pm 0.0040\ (\text{theo})$

H1prelim-12-031

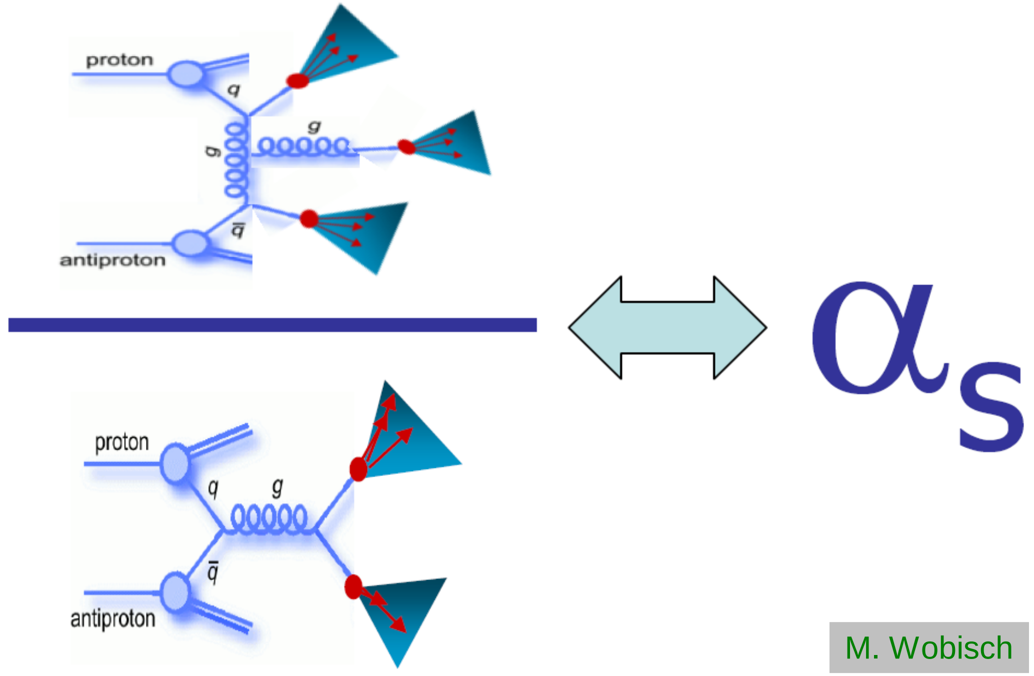
χ^2 / ndf = 53.3 / 41 = 1.30

Dominated by theory uncertainty!

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!
- Avoid direct dependence on PDFs and the RGE
- Reduce exp. and scale uncertainties
- Eliminate luminosity dependence



Three observables investigated:

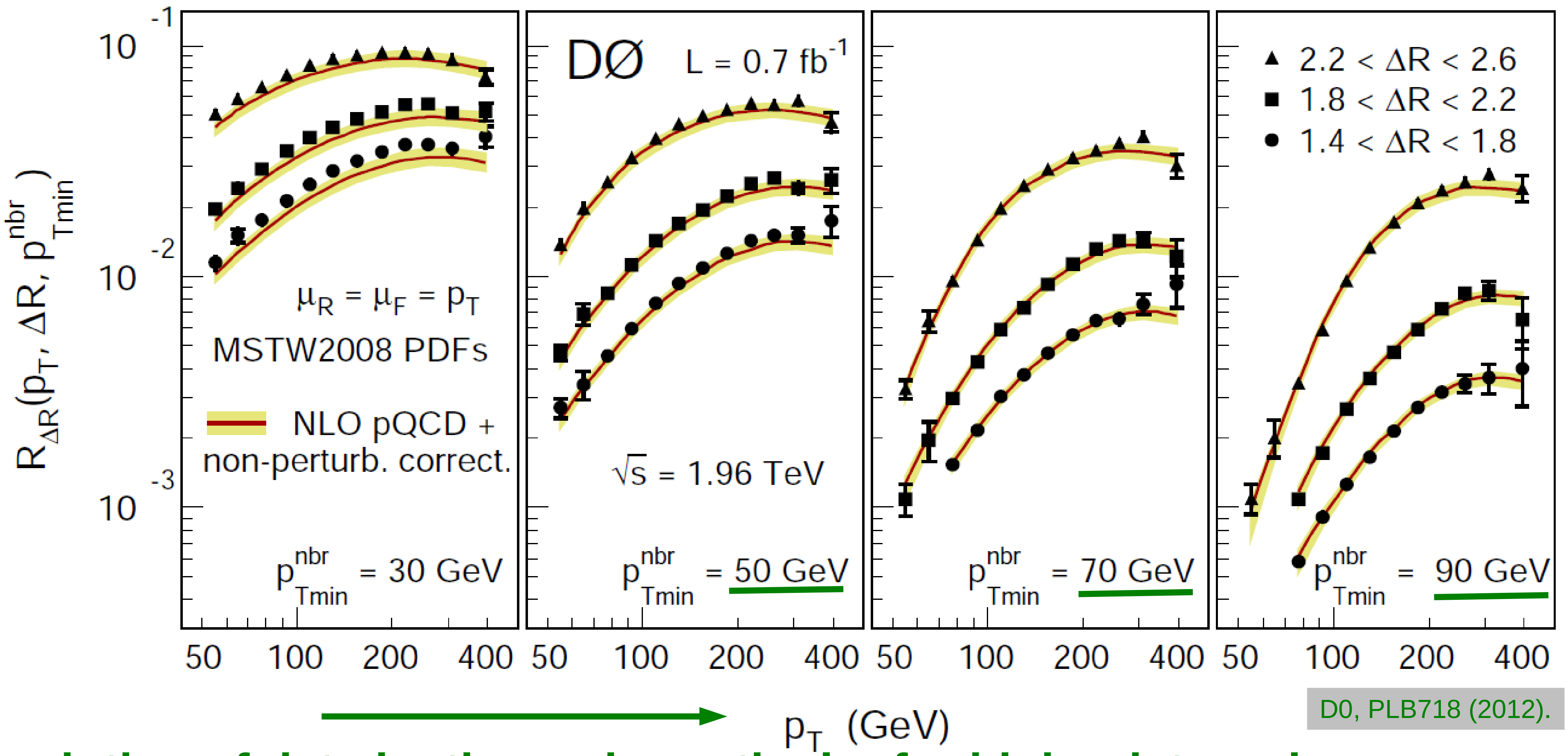
D0: $R_{\Delta R}$
- Average no. of neighbor jets within ΔR in incl. sample
- D0 midpoint cone R=0.7
- Min. jet pT: 50 GeV
- Max. rap.: |y| < 1.0
- Scale: Jet pT
- Data 0.7/fb

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).

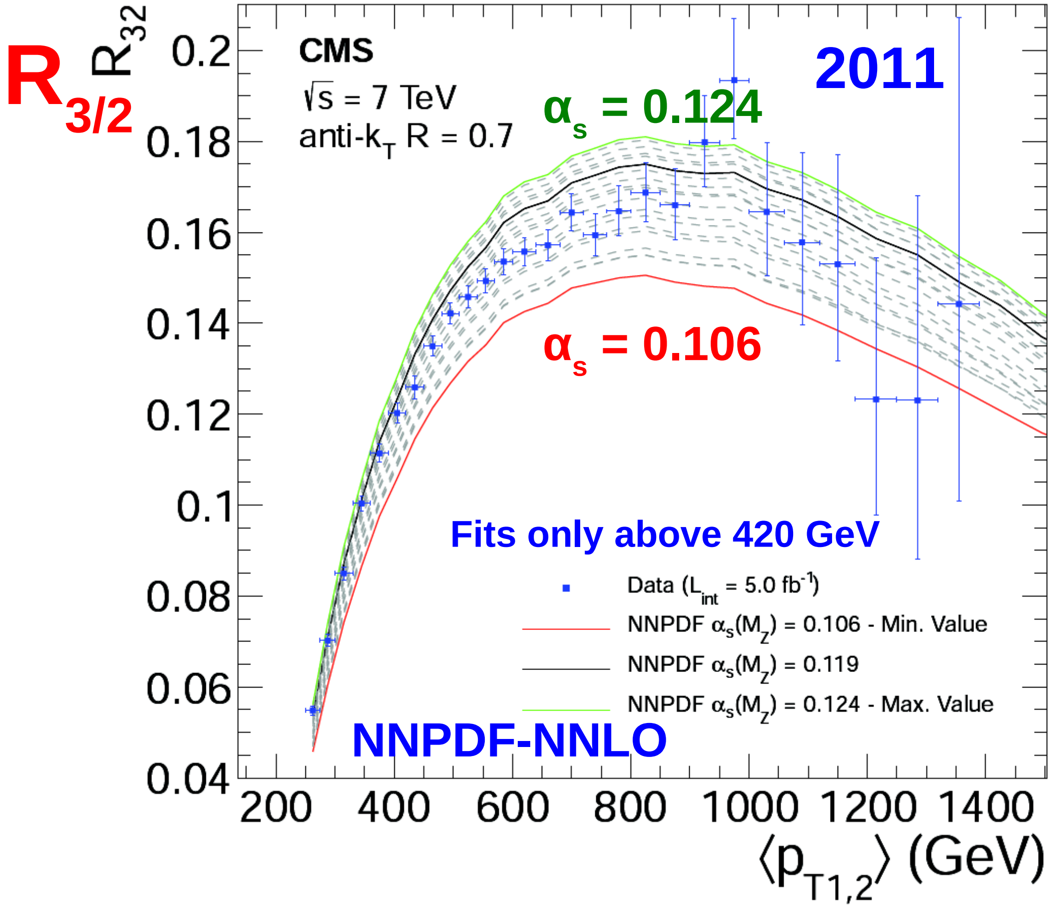
Good description of data by theory in particular for higher jet $p_T$min

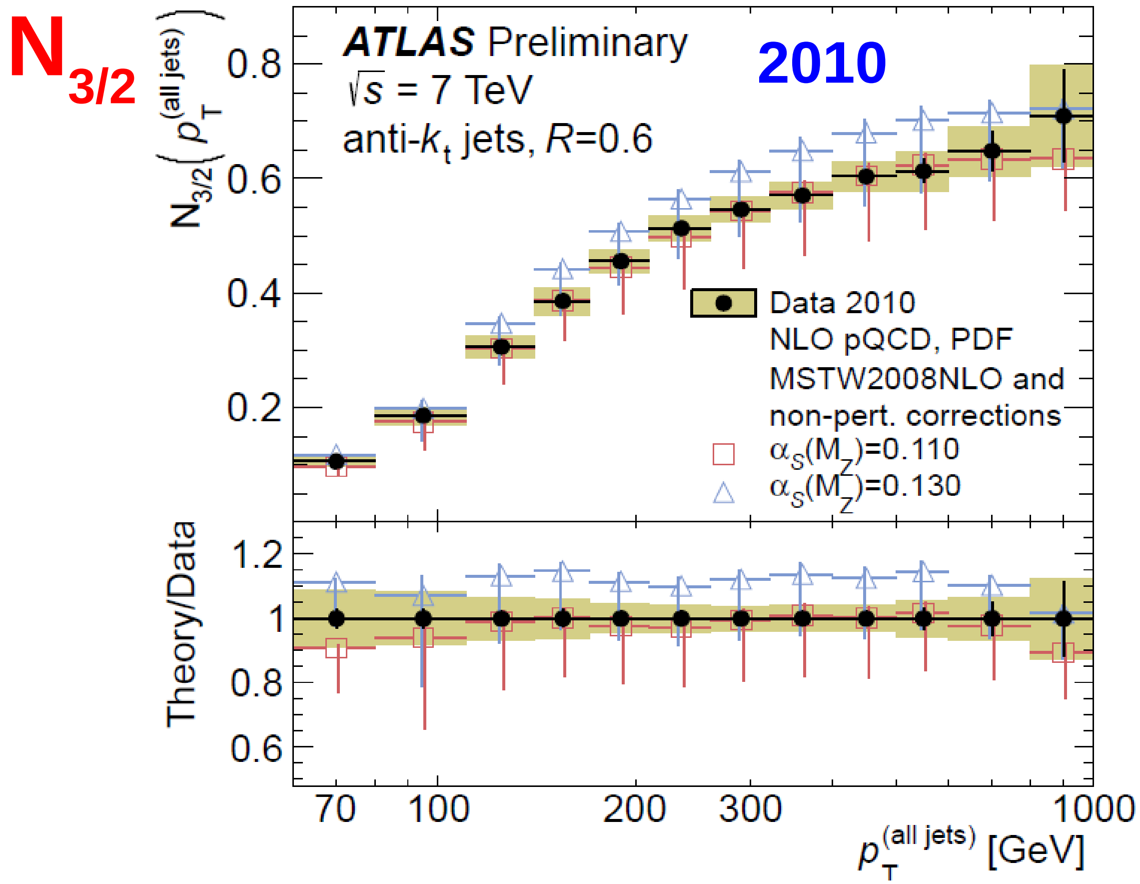
$$\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}(\text{total})$$

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

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\text{exp}) \pm 0.0018\,(\text{PDF}) \pm^{0.0050}_{0.0000}\,(\text{scale})$$

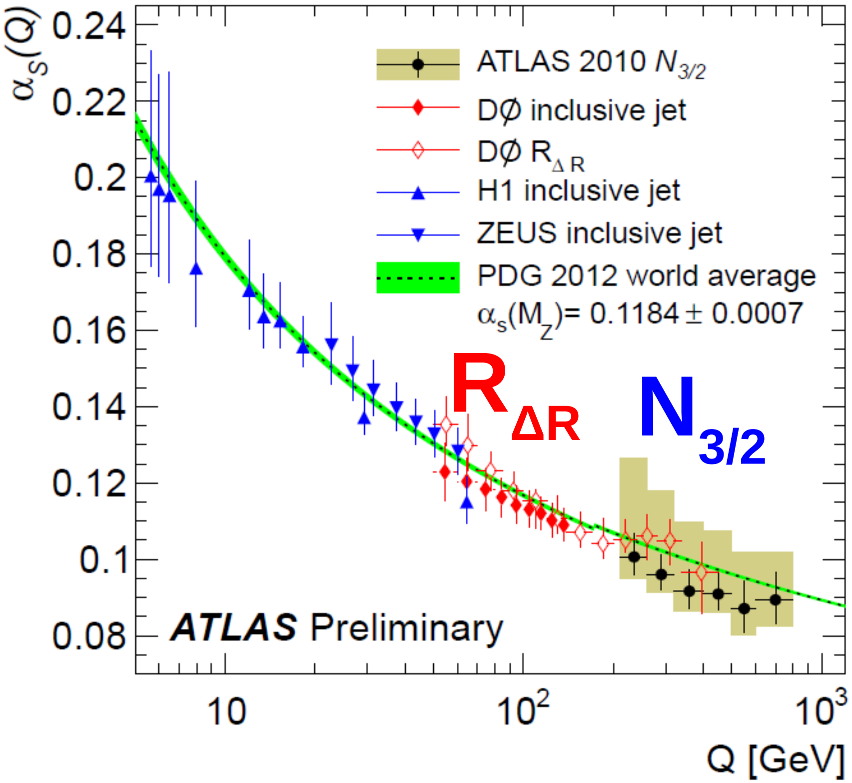
$$\alpha_s(M_Z) = 0.111 \pm 0.006\,(\text{exp}) \pm^{0.016}_{0.003}\,(\text{theory})$$

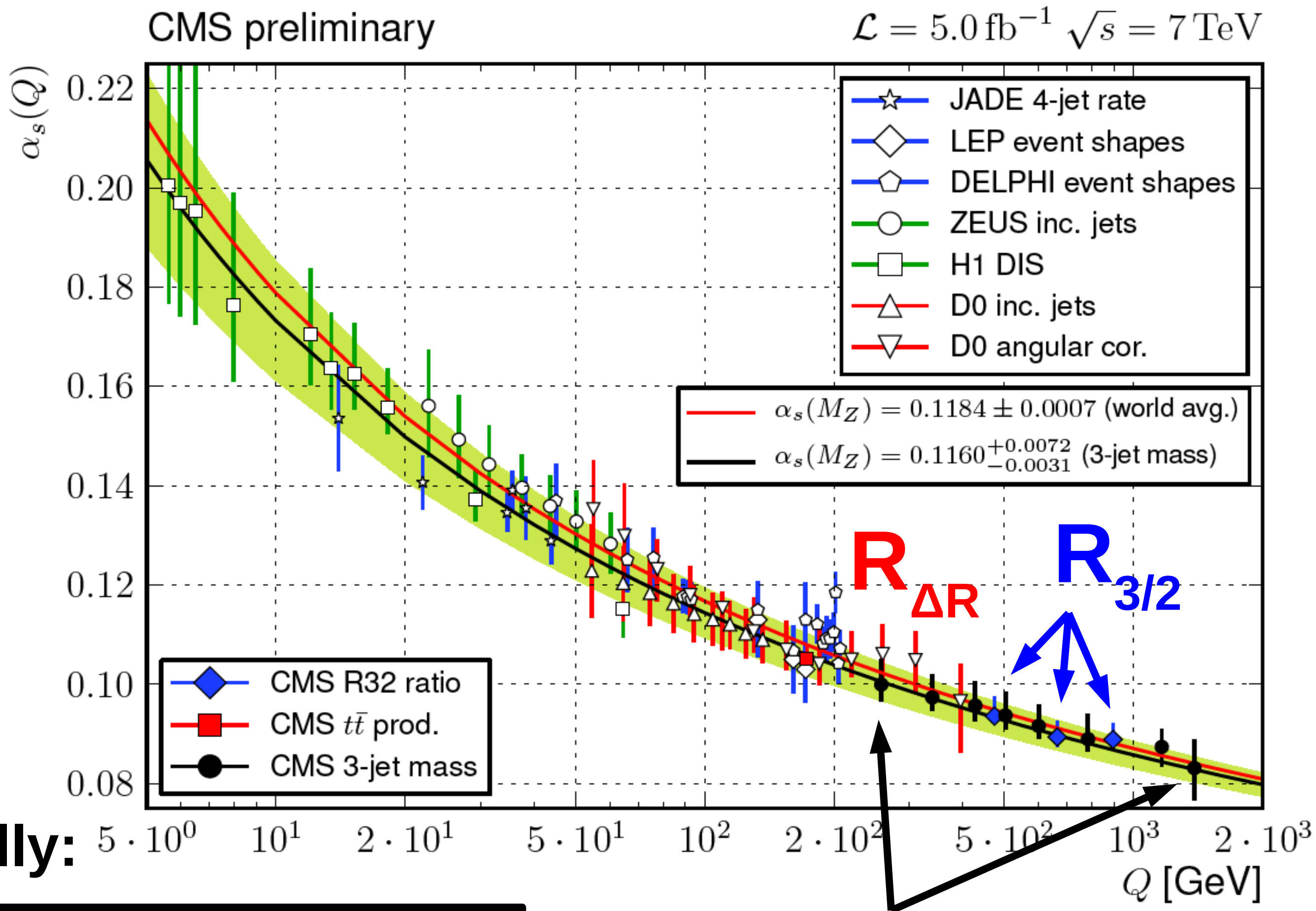
CMS, arXiv:1304.7498 (2013)

Dominated by theory uncertainty!

ATLAS-CONF-2013-041 (2013)

Determination of α_s (NLO)





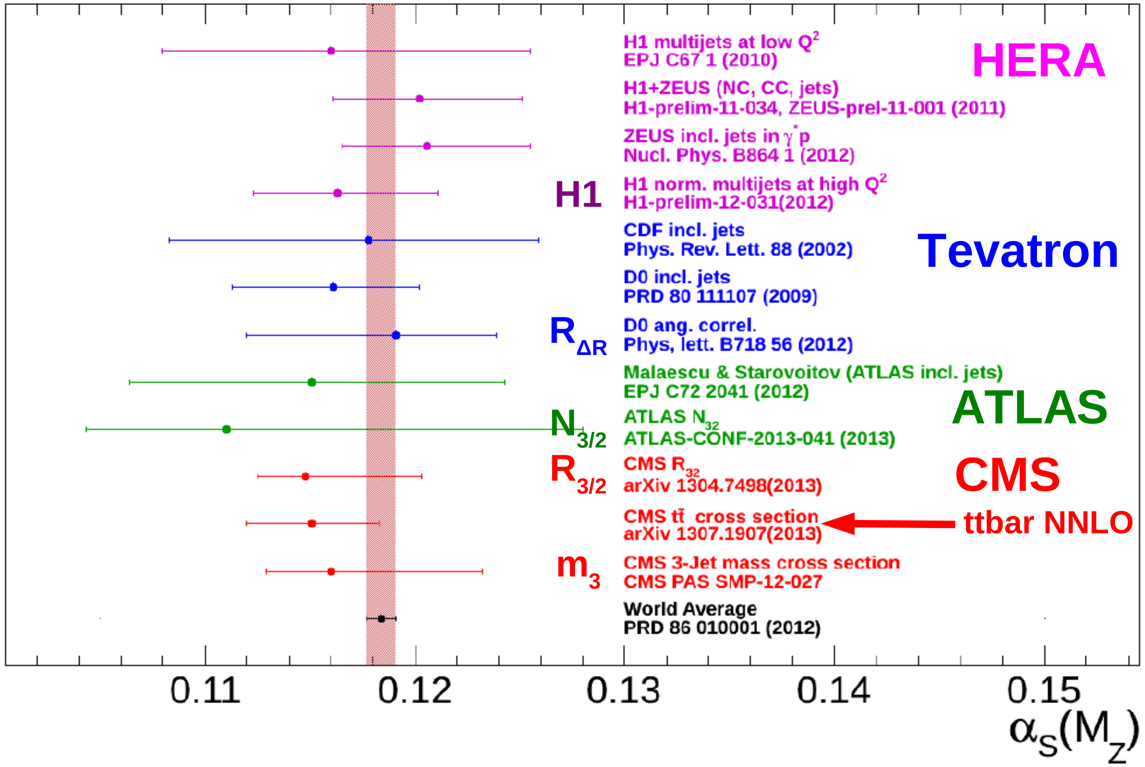
Uncertainties added quadratically:

3-Jet Mass

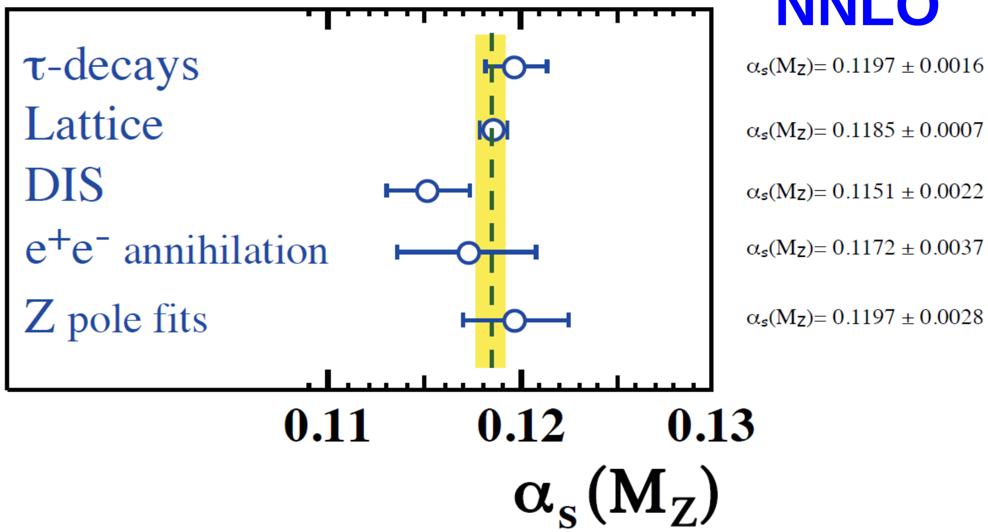
H1 preliminary	$\alpha_s(M_Z) = 0.1163 \pm 0.0045(\mathrm{total})$
D0 $R_{\Delta R}$	$\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}(\mathrm{total})$
ATLAS $N_{3/2}$ prel.	$\alpha_s(M_Z) = 0.111^{+0.017}_{-0.007}(\mathrm{total})$
CMS m_3 prel.	$\alpha_s(M_Z) = 0.1148^{+0.0055}_{-0.0023}(\mathrm{total})$
CMS $R_{3/2}$	$\alpha_s(M_Z) = 0.1160^{+0.0072}_{-0.0031}(\mathrm{total})$

α_s Summary

P. Kokkas, EPSHEP 2012: **NLO**



S. Bethke, 2012: **NNLO**



$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

PDG2012

Jet data from hadron colliders measure up to scales of 1.4 TeV (2011 data)!

Uncertainties dominated by theory →
- **need jets at NNLO for inclusion into world summary**
- **→ inclusive jets in progress by Gehrmann-de Ridder et al.**
- **and electroweak corrections**
- **→ done by Dittmaier et al.**

Outlook

- Still new precise measurements from HERA and Tevatron
- Already at 7 TeV LHC opened up new regimes in phase space, more results for 8 TeV to come … and for 13/14 TeV of course
- Data quality makes jet measurements PRECISION PHYSICS
- Theory definitely entered regime of NLO as Standard
- But still more precise theory required, partially to come this year
- New ideas for analyses are explored
- Didn´t even mention other exciting topics like jet substructure, gap fractions, ...

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Thank you for your attention!

Backup Slides

Achievements

30 years ago ...

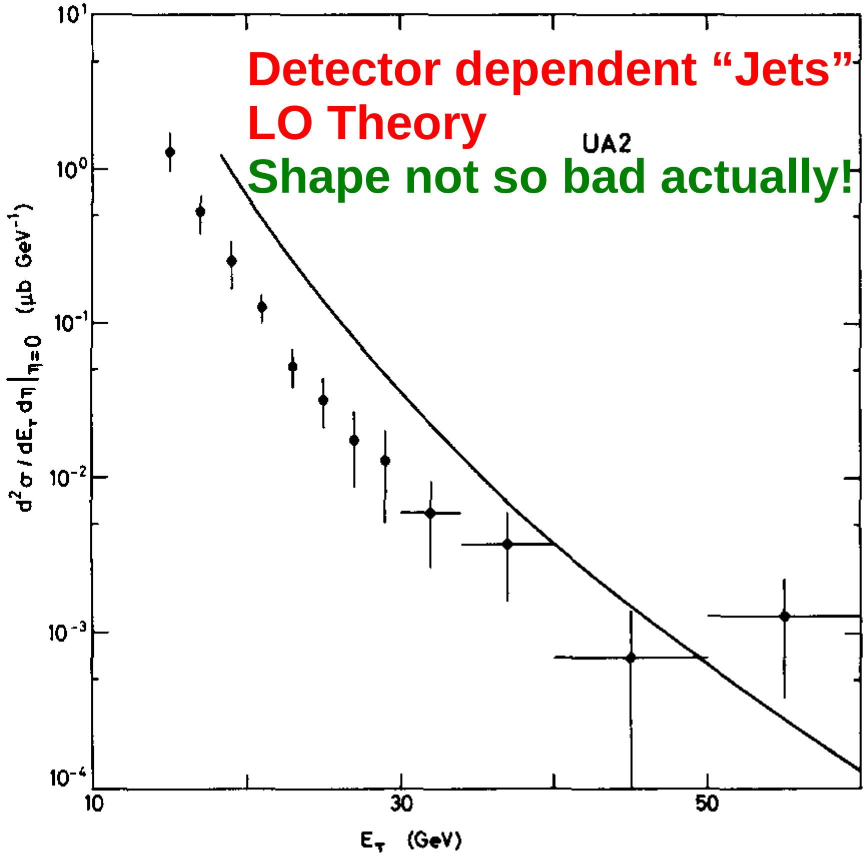
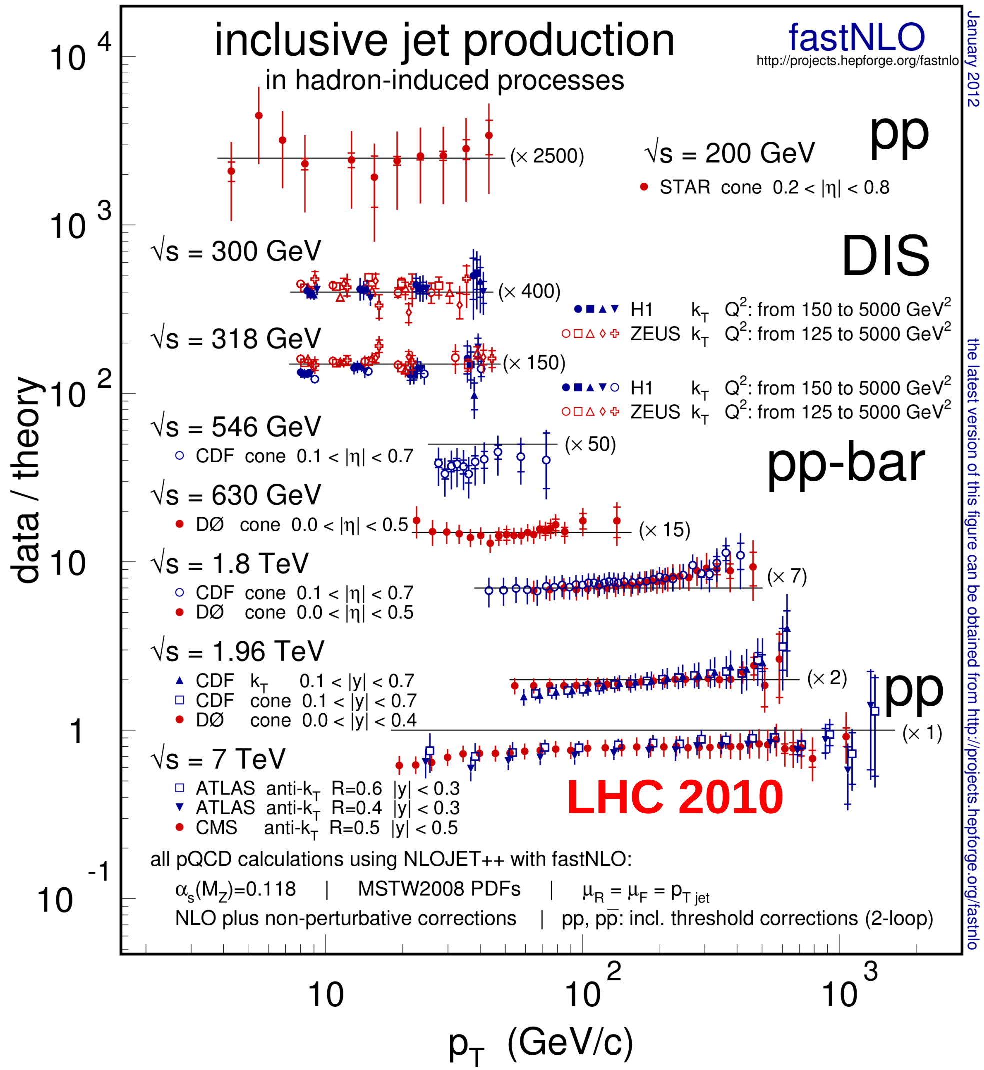


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

... and today !



fastNLO

Jet Algorithms

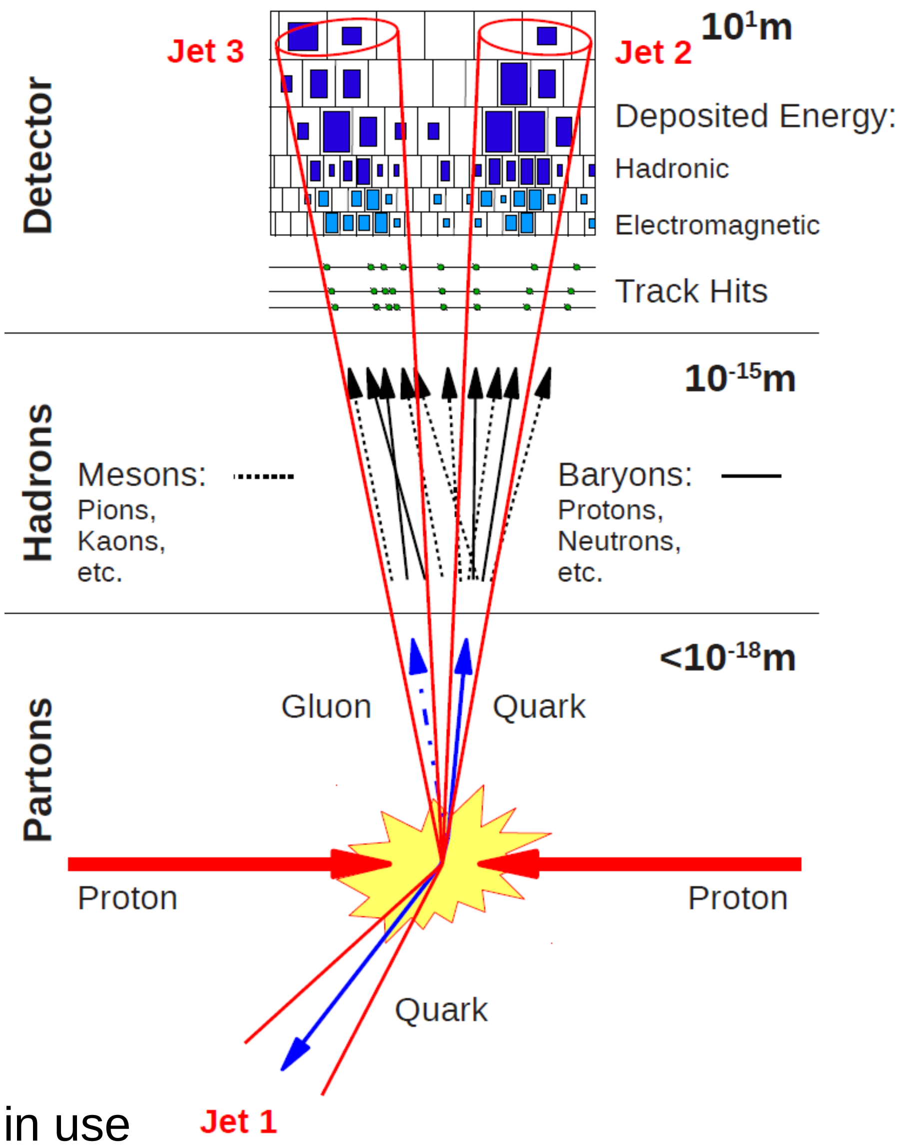
Primary Goal:

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

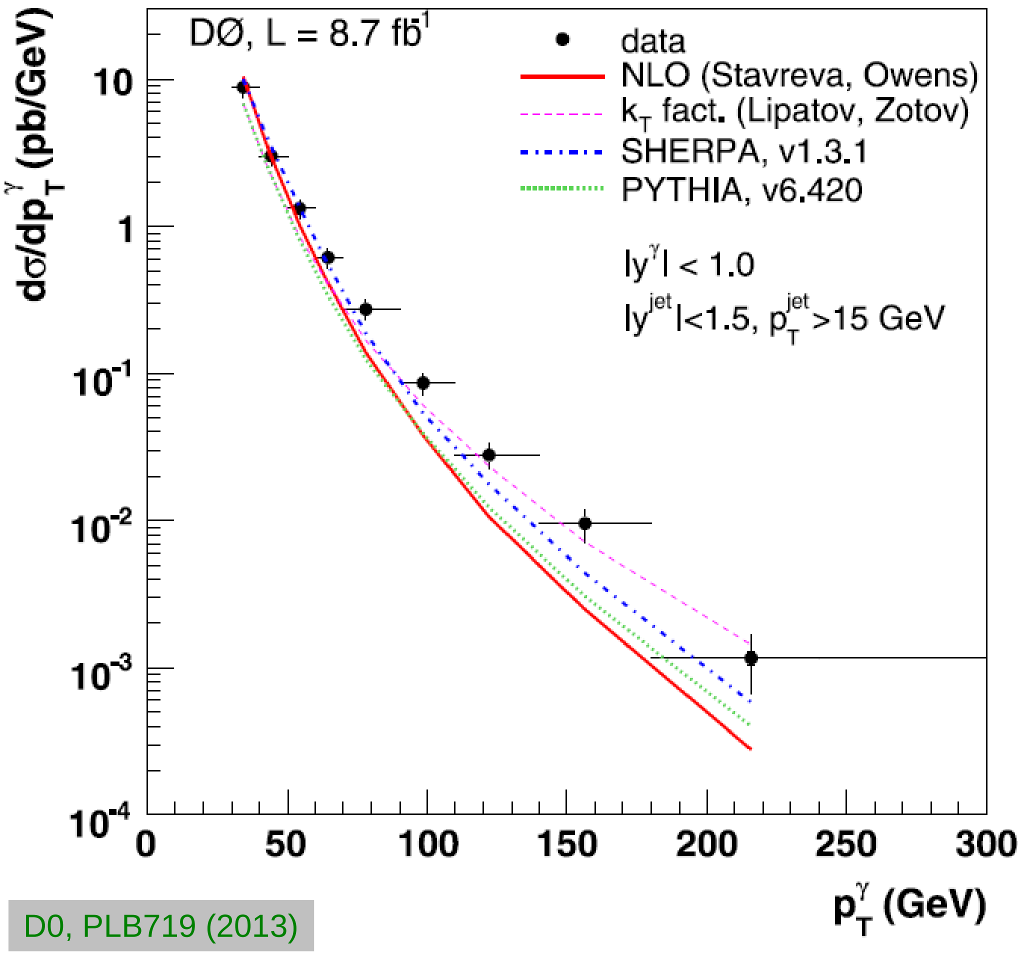
Standard at LHC: anti-kT

CDF also looked at kT; at LHC also kT, Cam/AC, SISCone in use

Photon + HF Jet

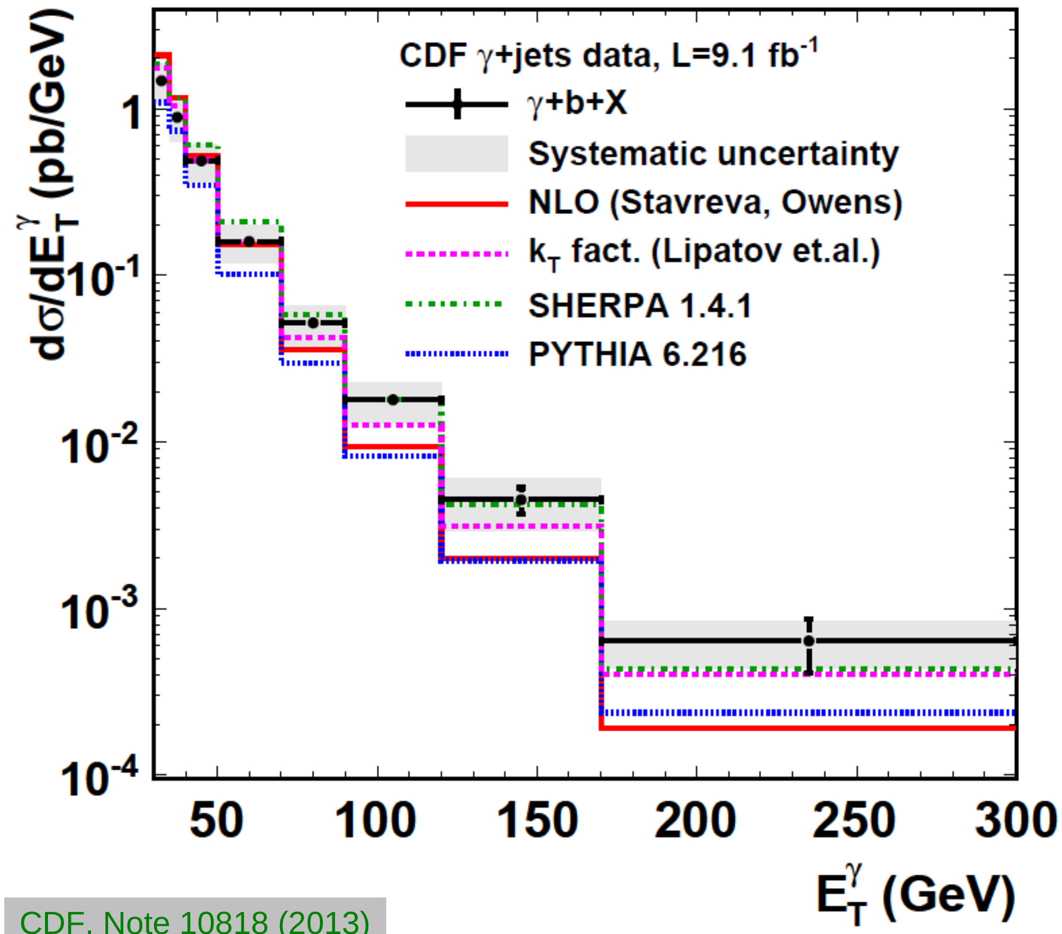
- New results from D0 and CDF for photon+heavy flavour (b,c) production
- At low pT probes HF PDF; at high pT produced by gluon splitting
- NLO insufficient
- Better described by e.g. Sherpa

D0: γ + c +X



D0, PLB719 (2013)

CDF: γ + b +X



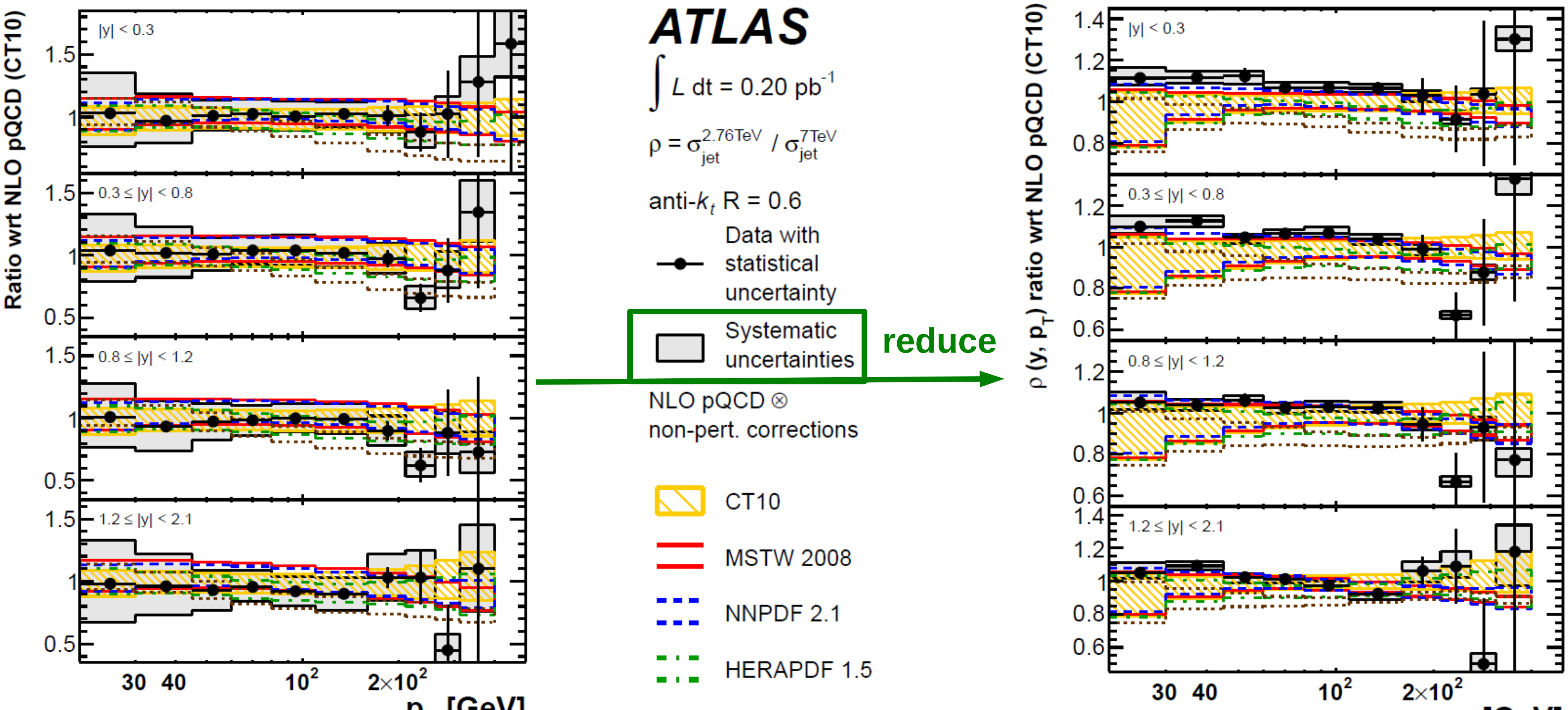
CDF, Note 10818 (2013)

Inclusive Jet Ratios: E_{cms}

Ratio to NLO (CT10) at E_{cms} = 2.76 TeV

At least partial cancellation of uncertainties → more precise comparisons

"Ratio of ratios to NLO" at two different energies E_{cms} = 2.76 and 7.0 TeV

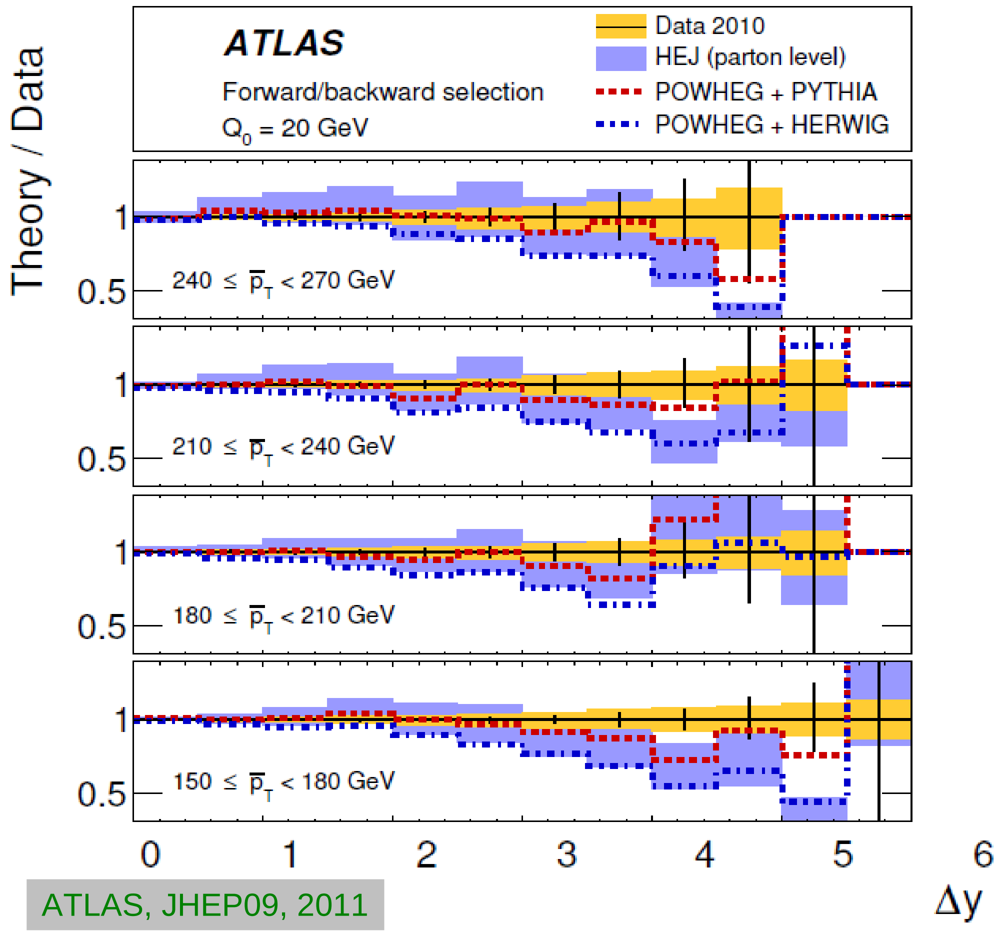


ATLAS, arXiv:1304.4793 (2013).

Dijets separated in Rapidity

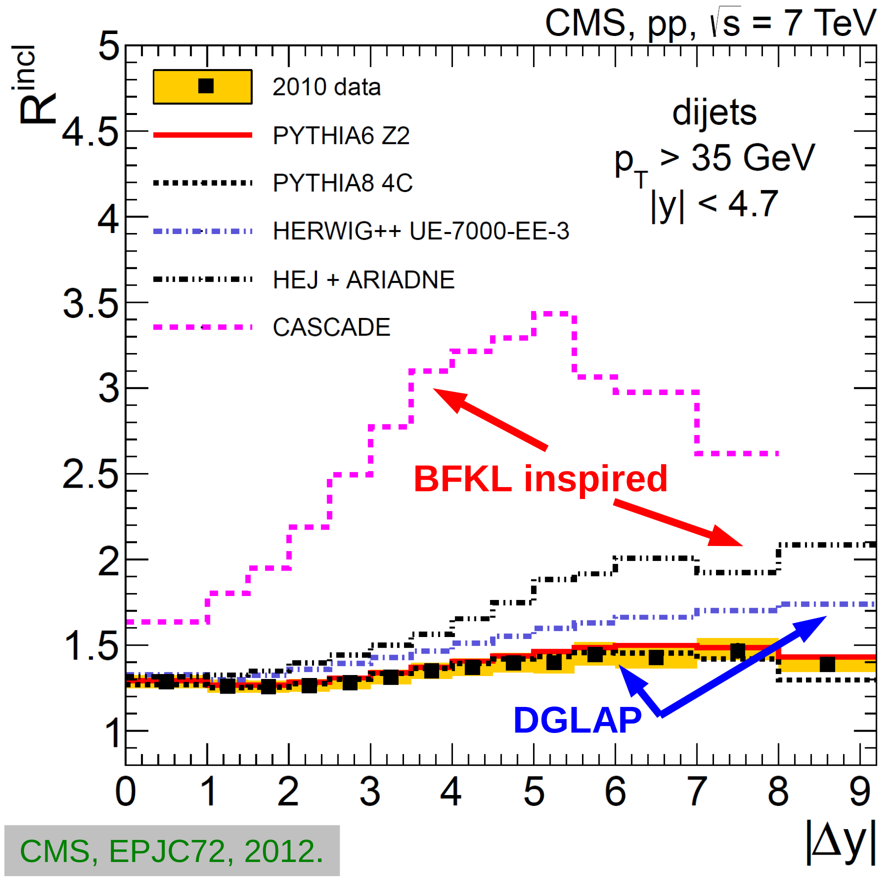
Quantities sensitive to potential deviations from DGLAP evolution at small x
Some MC event generators run into problems … but also BFKL inspired ones!
Large y coverage needed, also useful for WBF tagging jets.

Most forward-backward dijet selection



ATLAS, JHEP09, 2011

All possible dijet pair distances over leading dijet pair distance

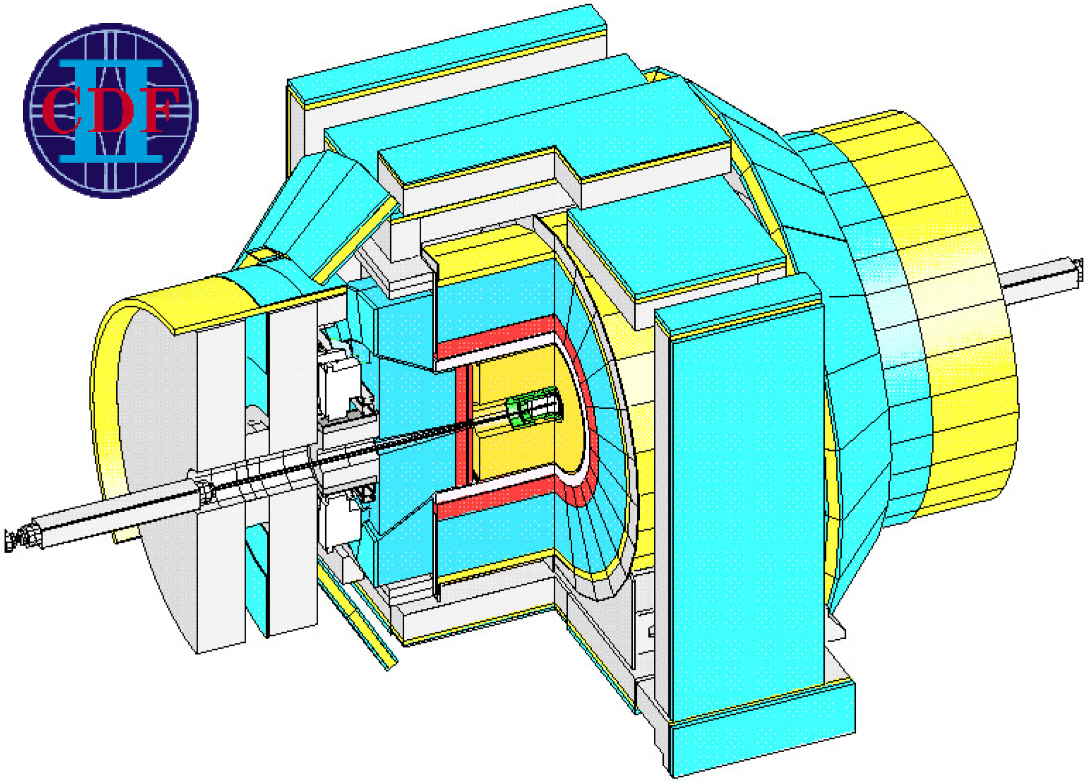


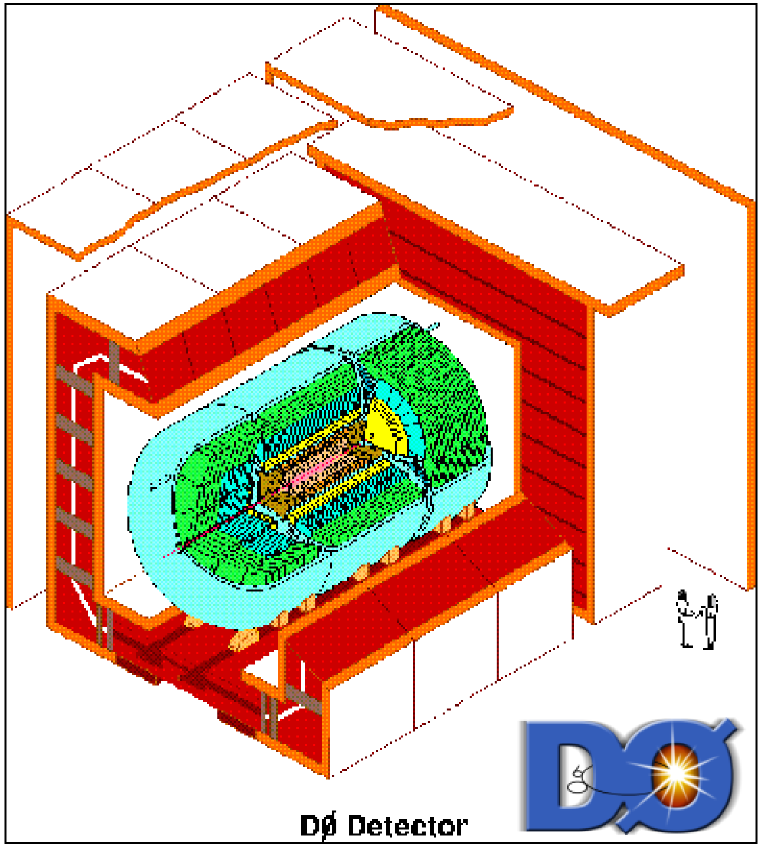
CMS, EPJC72, 2012.

CDF and D0

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

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

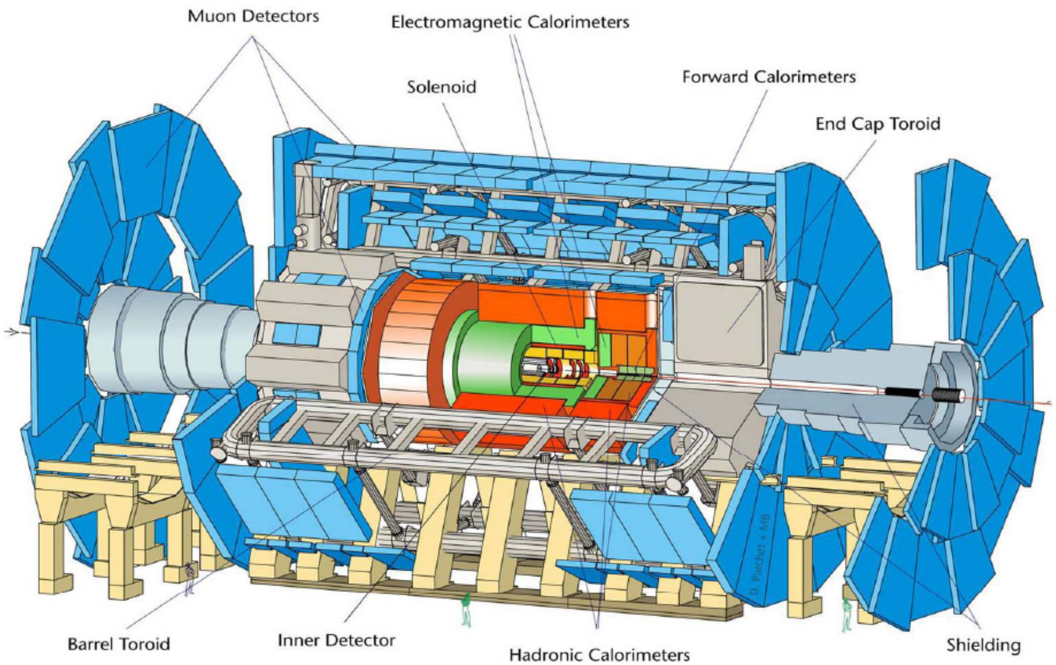


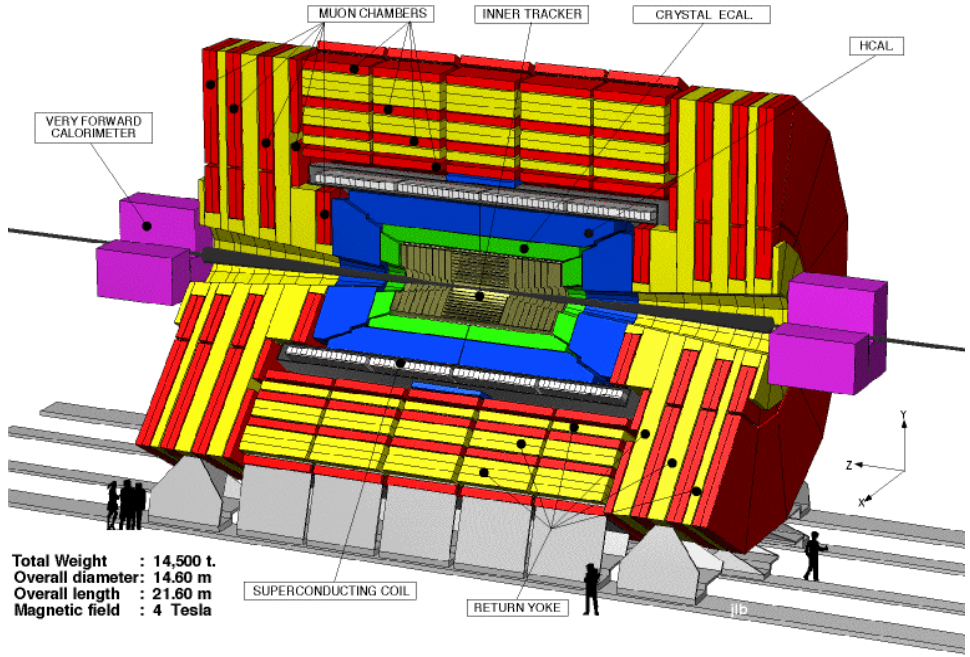


ATLAS and CMS

	ATLAS		CMS
Silicon trackers:	Up to $|\eta|$ = 2.5	Silicon trackers:	Up to $|\eta|$ = 2.5
Calorimetry:	Up to $|\eta|$ = 4.9	Calorimetry:	Up to $|\eta|$ = 5.0
Muon chambers:	Up to $|\eta|$ = 2.7	Muon chambers:	Up to $|\eta|$ = 2.4
Jet energy scale:	1 – 3 % prec.	Jet energy scale:	1 – 3 % prec.

Both detectors are/will be complemented by further instrumentation at larger rapidities.



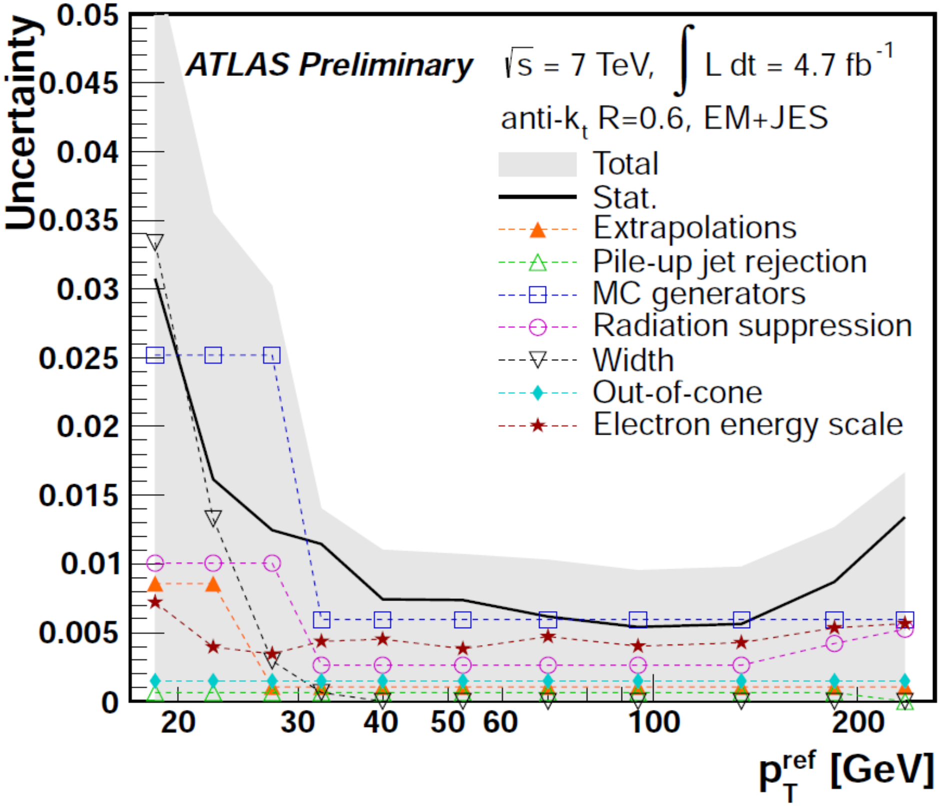


Jet Energy Scale

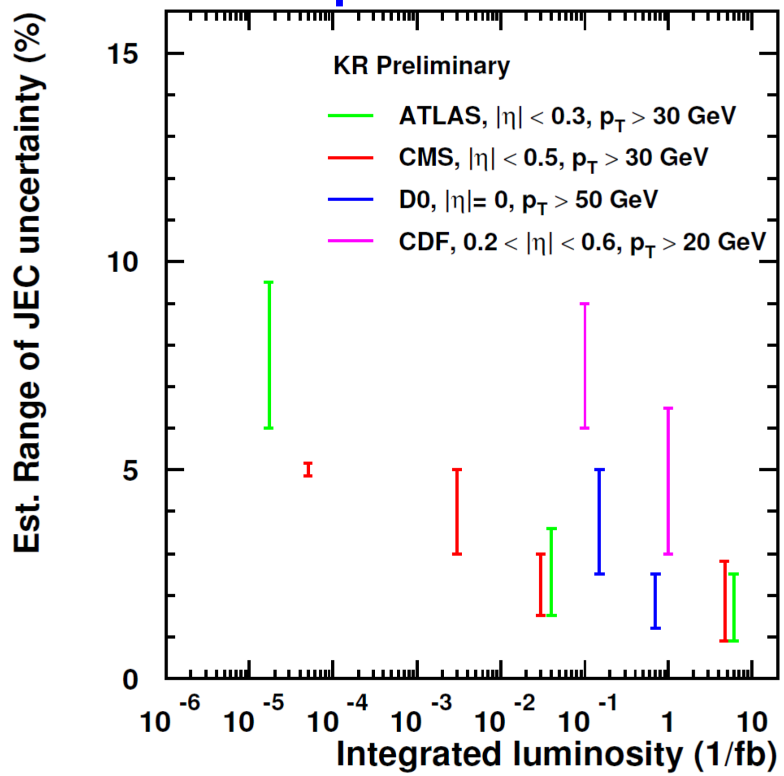
Dominant experimental uncertainties for jets!
Enormous progress in just three years.

- 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



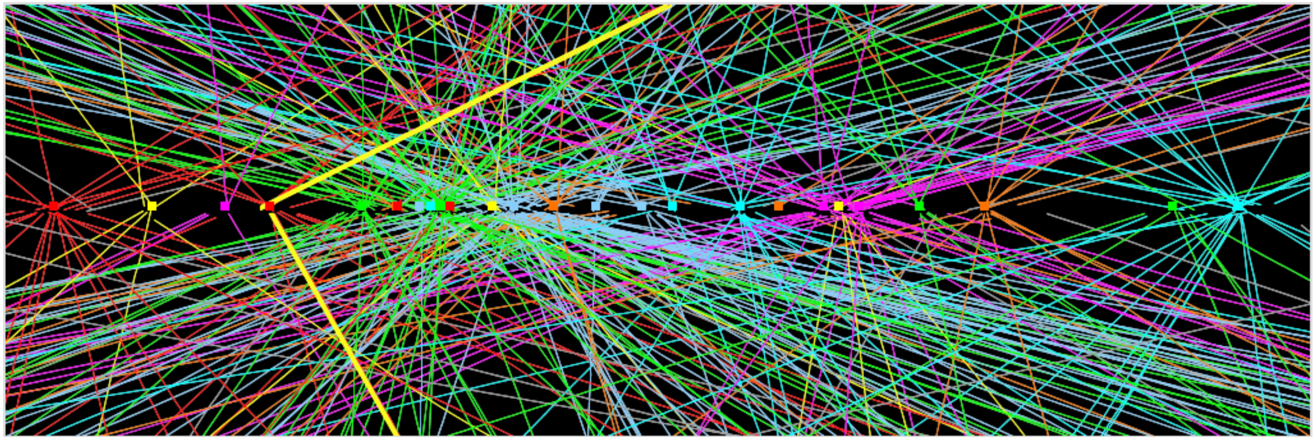
ATLAS, EPJC 71 2011; arXiv:1112.6297; CONF-2012-053; CONF-2012-063
CMS, JME-10-003; JME-10-010; JINST 6 2011; DP2012-006; DP2012-012
D0, arXiv:1110.3771; D0 prel. 2006

Jet Energy Scale and Pile Up

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

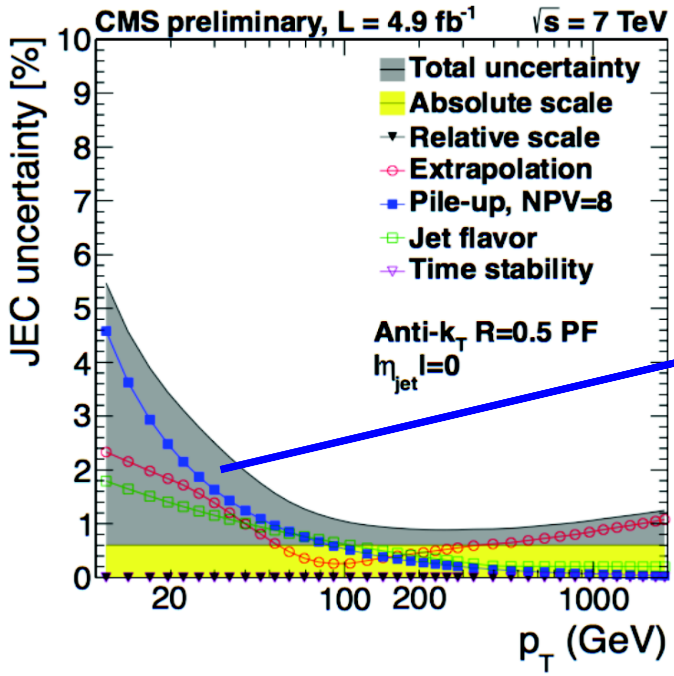
ATLAS Z → μμ candidate
with 25 reconstructed primary vertices:
(Record beyond 70!)

μ



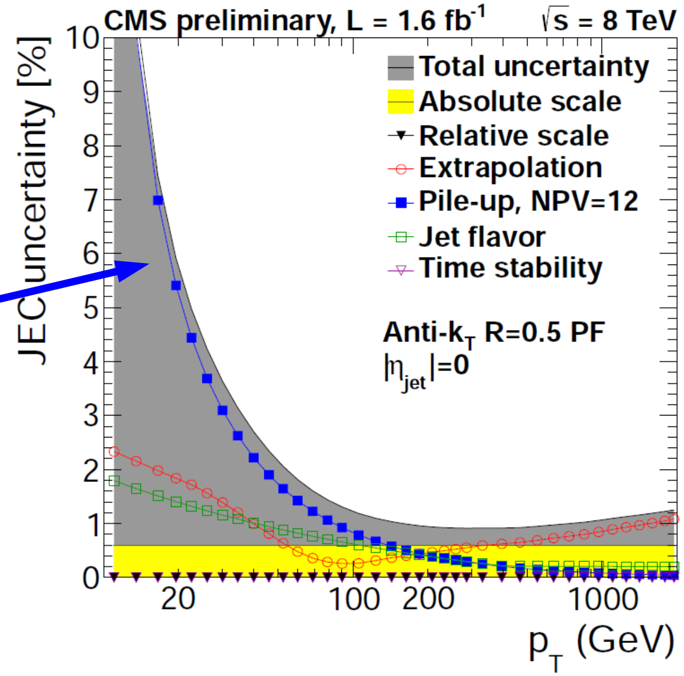
μ

CMS from 5/fb (7 TeV, 2011)



Pile-up effect

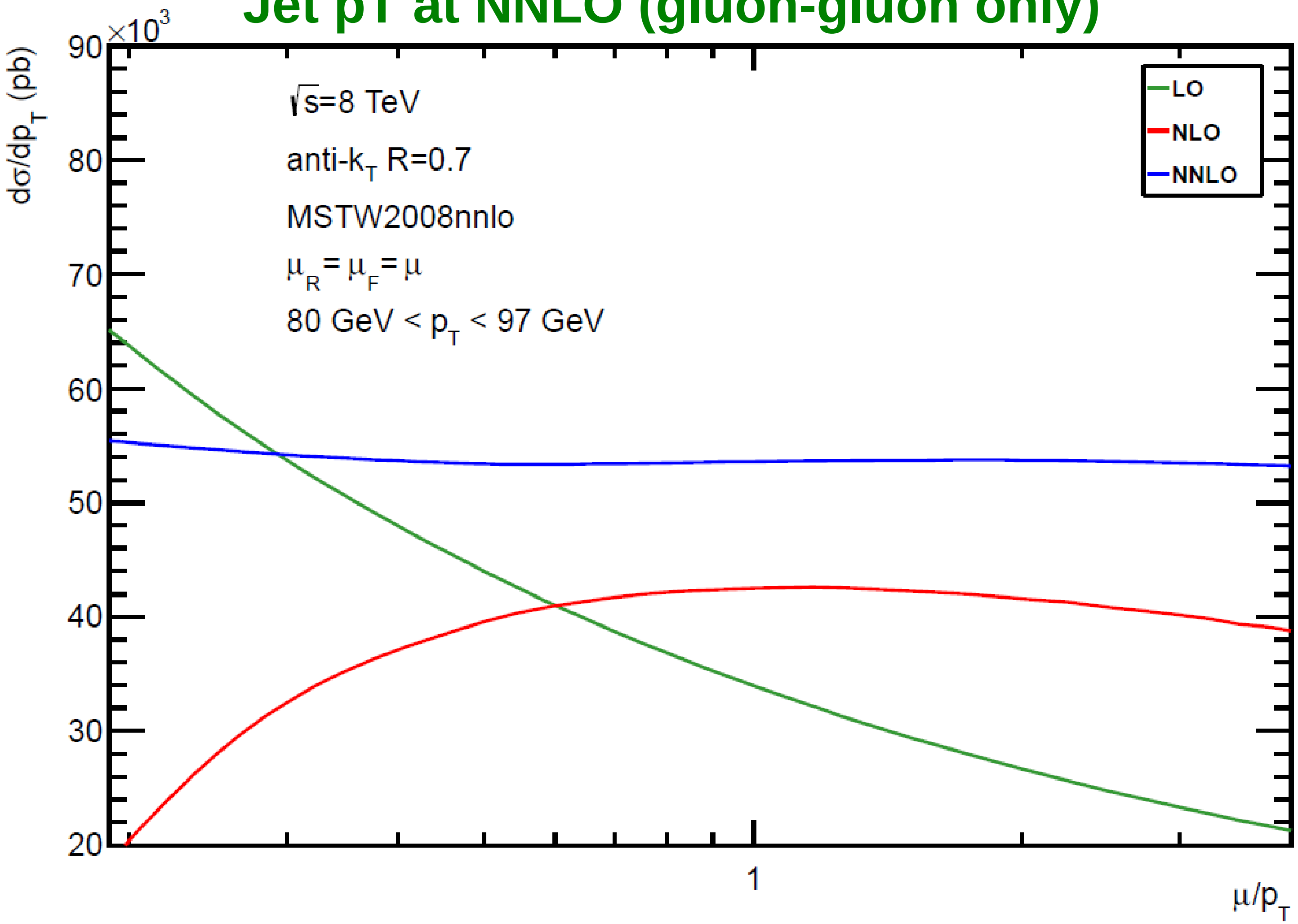
CMS from 1.6/fb (8 TeV, 2011)



CMS, DP2012-006
CMS, DP2012-012

NNLO Scale Dependence

Jet pT at NNLO (gluon-gluon only)



New

Drastically reduced scale dependence!

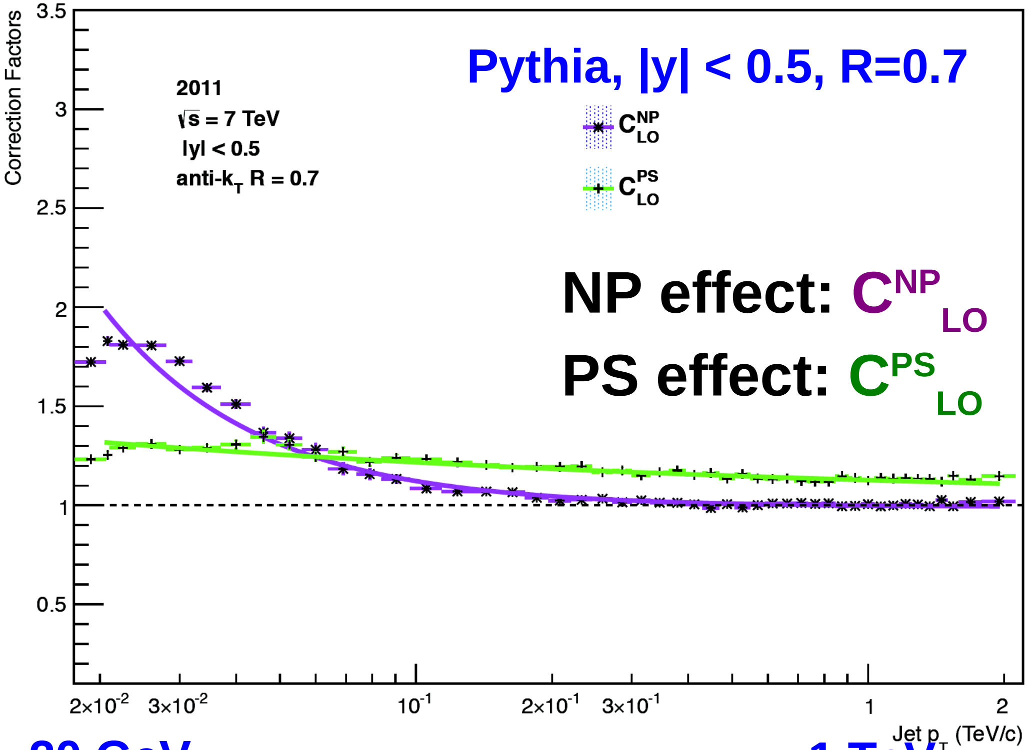
$|y| < 4.4$, 80 GeV $< p_T <$ 97 GeV

From talk by N. Glover, see also: Gehrmann- de Ridder et al., PRL110 (2013), JHEP1302 (2013).

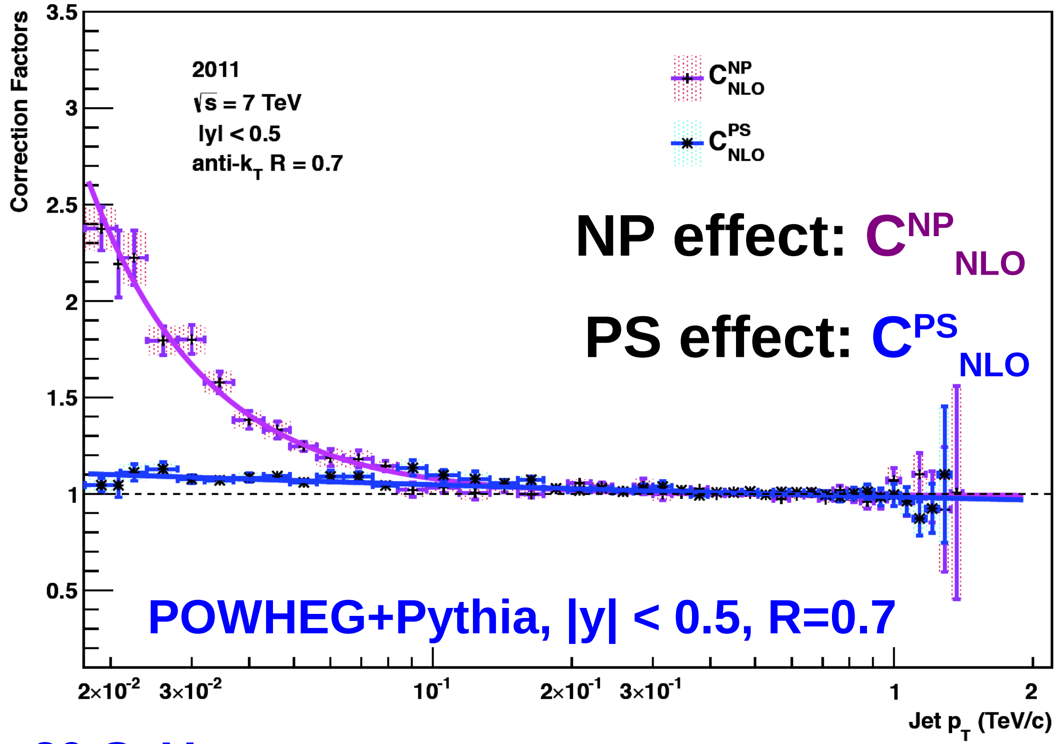
Non-perturbative Corrections

Recipe used at Tevatron & LHC:
- take LO parton shower (PS) MC
- derive corr. for non-pert. (NP) effects, i.e. multiple parton interactions and hadronization

→ assume PS effect small on NLO
→ assume NP effects similar for LO,NLO



20 GeV 1 TeV



20 GeV 1 TeV

Observations:
- assumptions fine at central rapidity (not shown here)
- NP corrections larger for R=0.7 than 0.5
- for |y| > 2 PS effects visible

Figures courtesy of S.Dooling, H.Jung, P.Gunnellini, P.Katsas, A.Knutsson (s. also arXiv:1212.6164)

Process Decomposition

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