QCD at high and highest scales

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

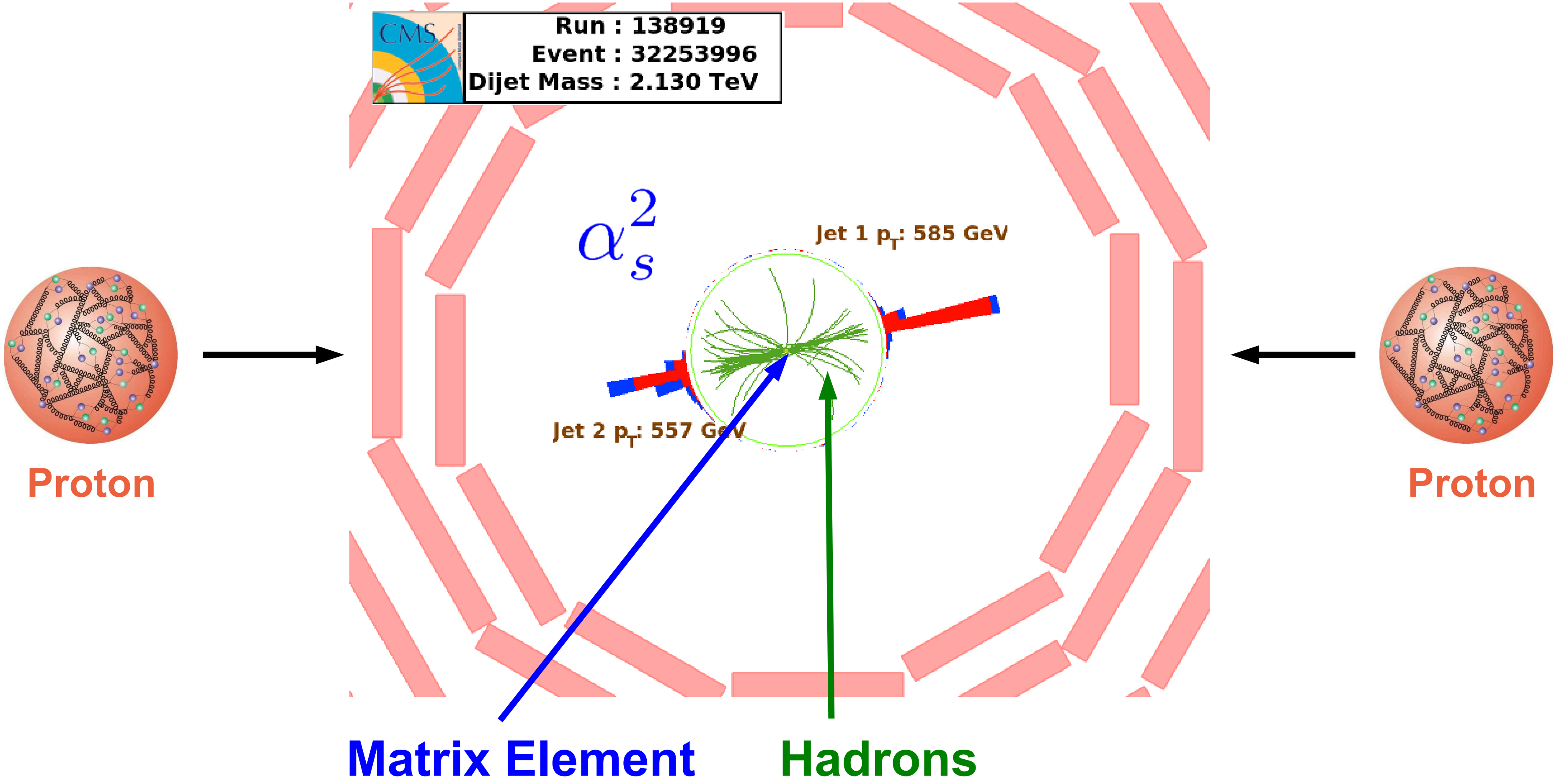
Klaus Rabbertz, KIT

Karlsruhe Institute of Technology

Today's Menu

- Introduction
- The Observables
  - Anything
  - Particles
  - Shapes
  - Jets
  - Accompanying Bosons
- The strong Coupling
- Summary and Outlook

Components of a Collision



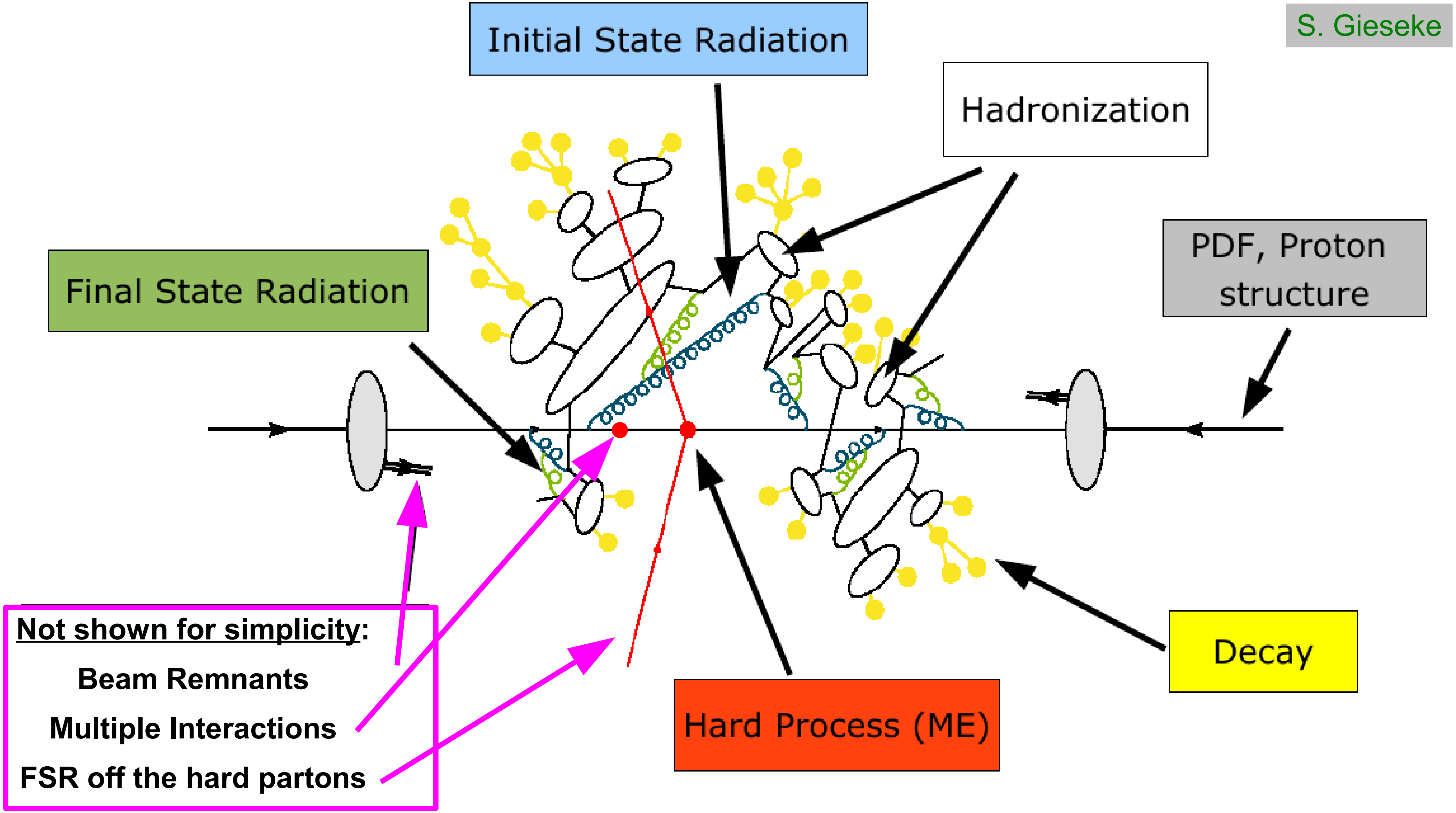
Proton

Proton

Matrix Element

Hadrons

The central Pixel resolved ...



S. Gieseke

Initial State Radiation

Hadronization

PDF, Proton structure

Final State Radiation

Hard Process (ME)

Decay

<u>Not shown for simplicity</u>:

Beam Remnants

Multiple Interactions

FSR off the hard partons

Event Rates at the LHC

Assuming here: L = 10^{33}cm^{-2}s^{-1}

Total cross section

Jets: $\sigma_{jet}(E_T^{jet} > 100\text{GeV})$ or

Photons: $\sigma_\gamma(E_T^\gamma > 20\text{GeV})$

~ 400 / s

W & Z bosons: σ_W, σ_Z

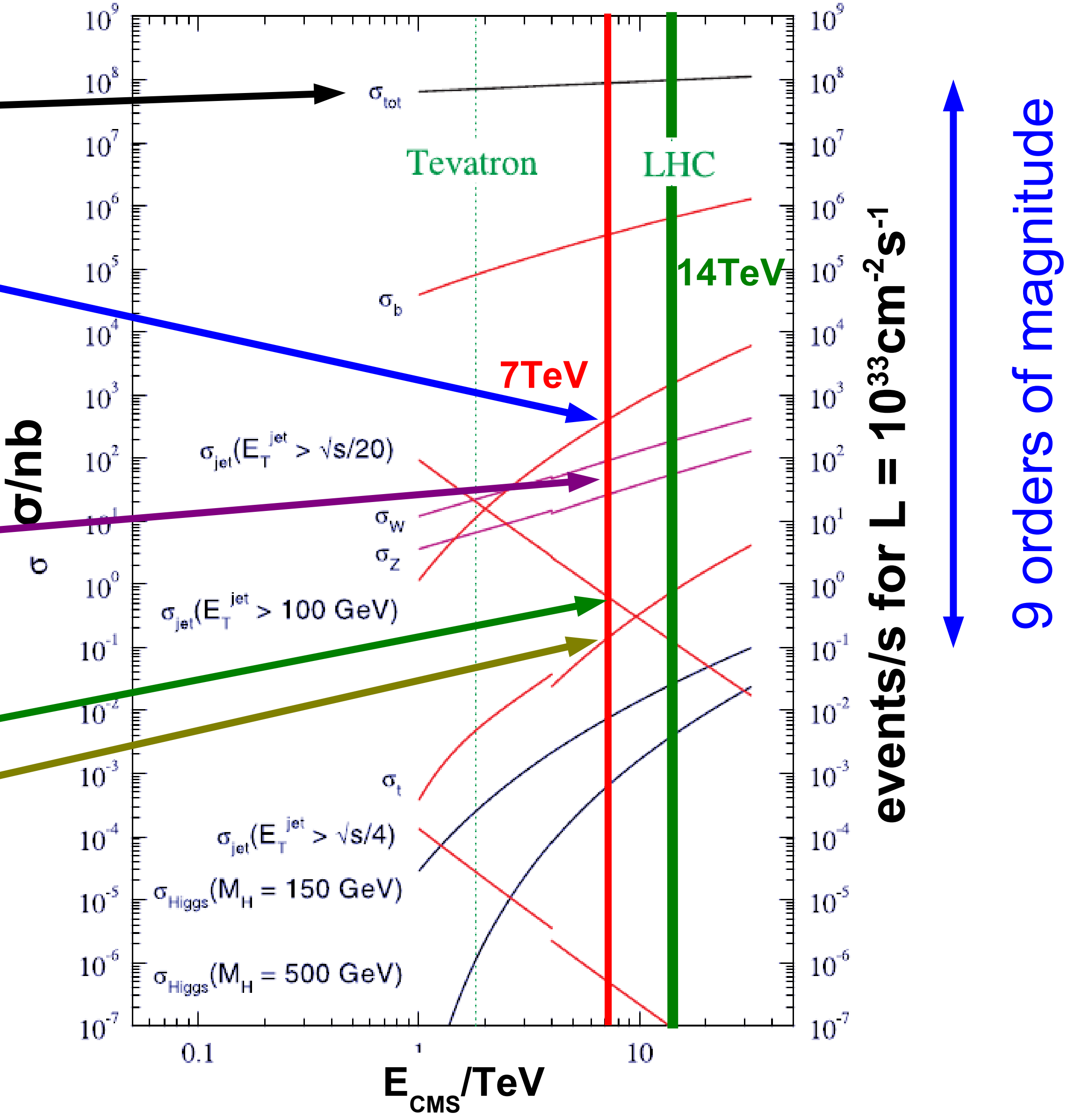
~ 100 / s, 33 / s

Jets: $\sigma_{jet}(E_T^{jet} > 350\text{GeV})$

~ 33 / min

Top quarks (σ_{tt})

~ 6 / min



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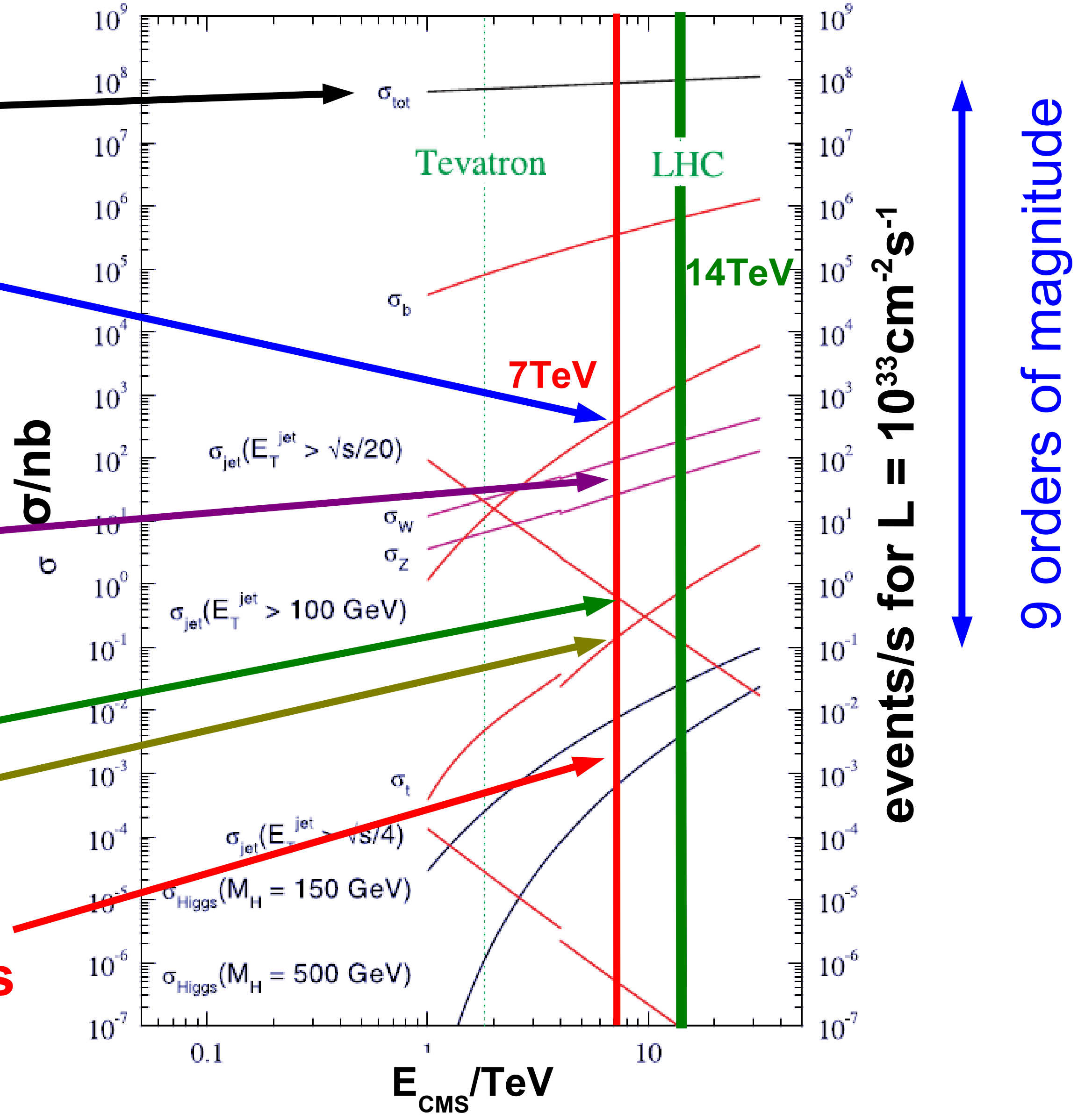
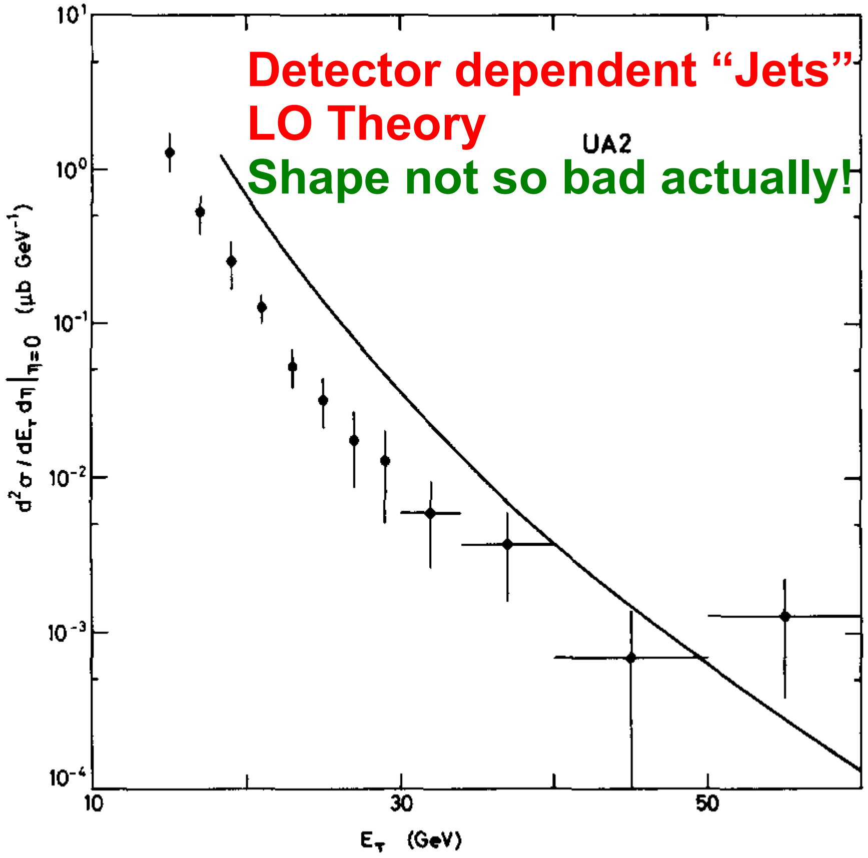
Higgs ??? Wrong mass



Older version of Stirling-Plot

Some Progress

30 years ago ...



Detector dependent “Jets”

LO Theory

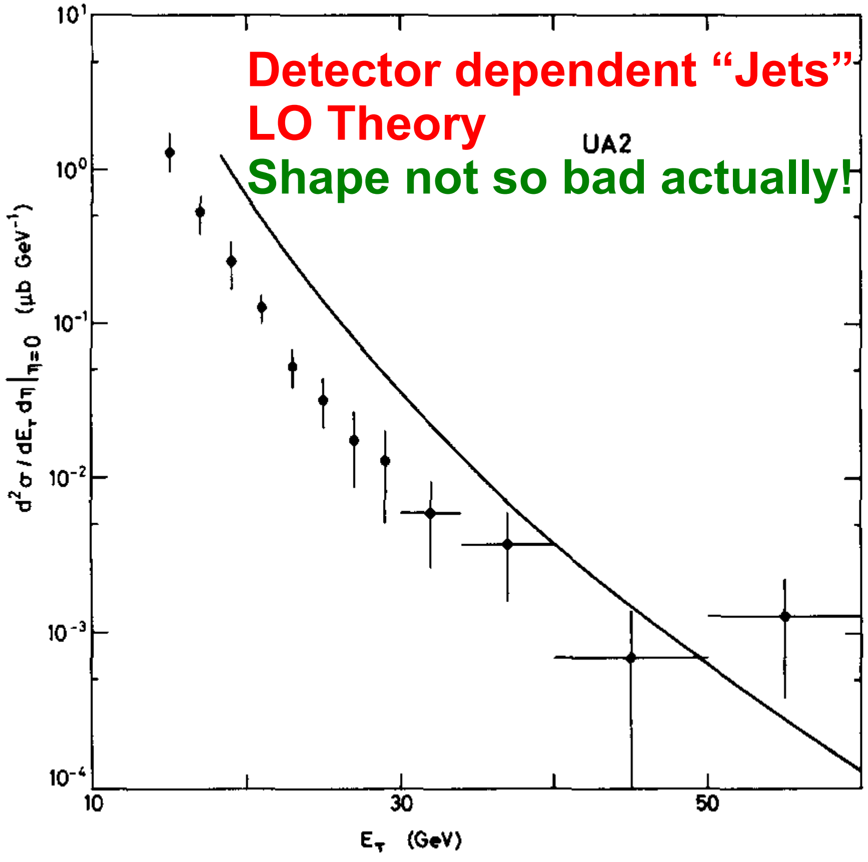
Shape not so bad actually!

Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses $\Lambda = 0.5$ GeV while $\Lambda = 0.15$ 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).

Some Progress

30 years ago ...



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LO Theory

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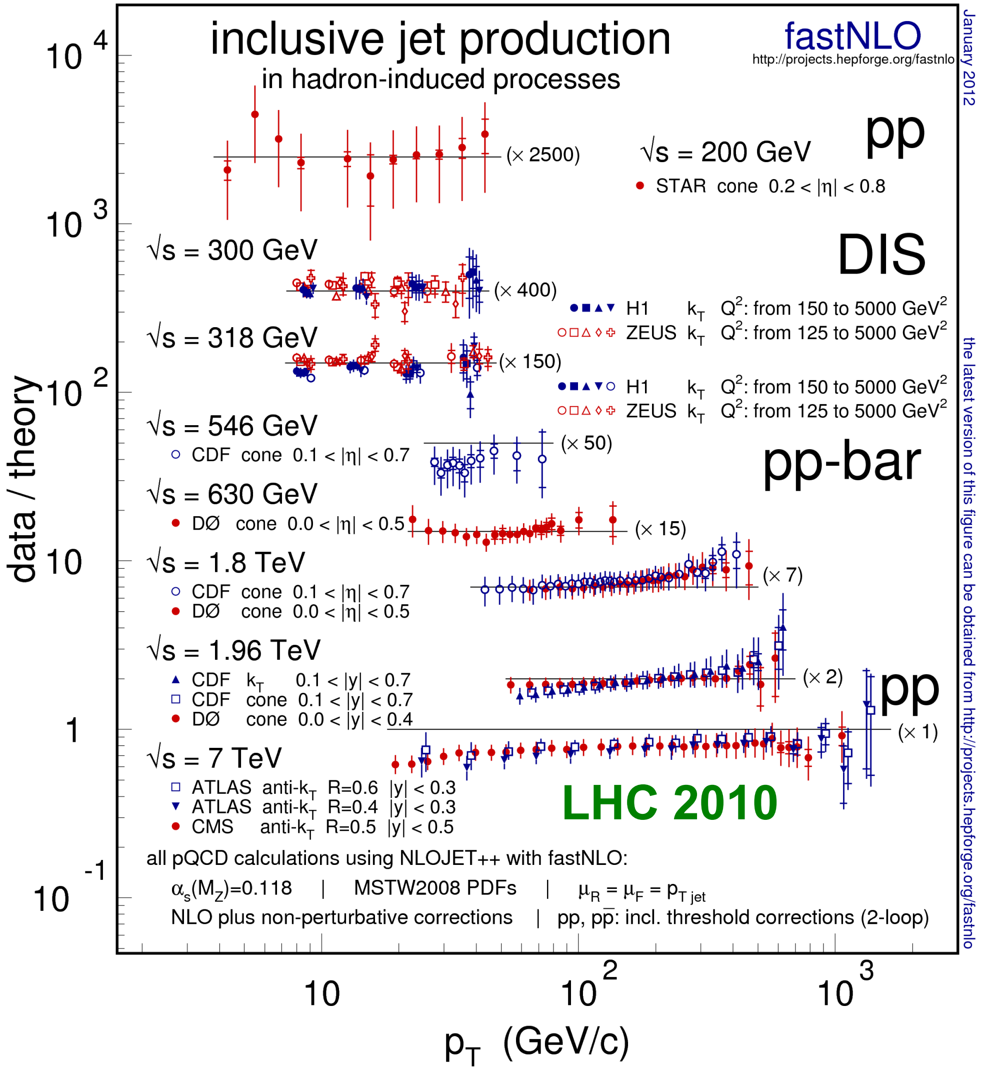
UA2, PLB 118 (1982).

... and today !



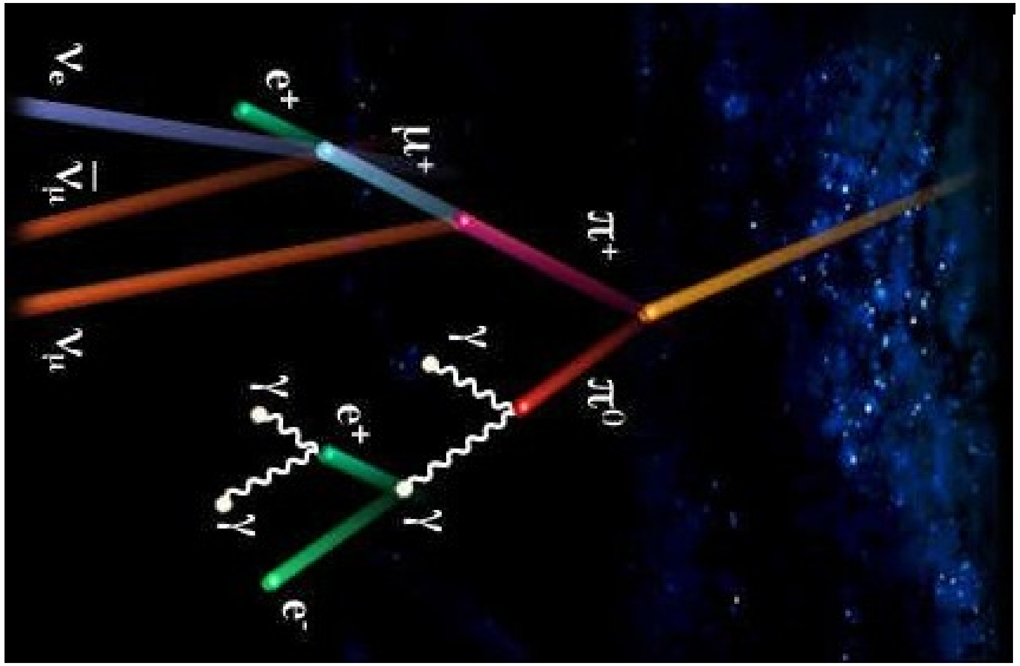
LHC 2010

Anything

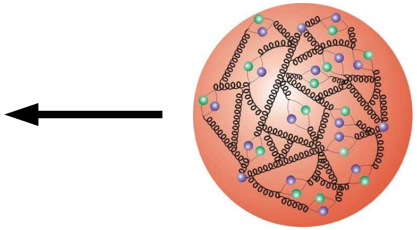
Happens elsewhere all the time

High Altitude & High Energy

Earth



Cosmic ray shower



Proton

NASA (Apollo17)

CERN

DESY

The total Cross Section

$$\sigma_{\mathrm{el}} = (25.1 \pm 1.1)\,\mathrm{mb}$$
$$\sigma_{\mathrm{inel}} = (72.9 \pm 1.5)\,\mathrm{mb}$$
$$\sigma_{\mathrm{tot}} = (98.0 \pm 2.5)\,\mathrm{mb}$$

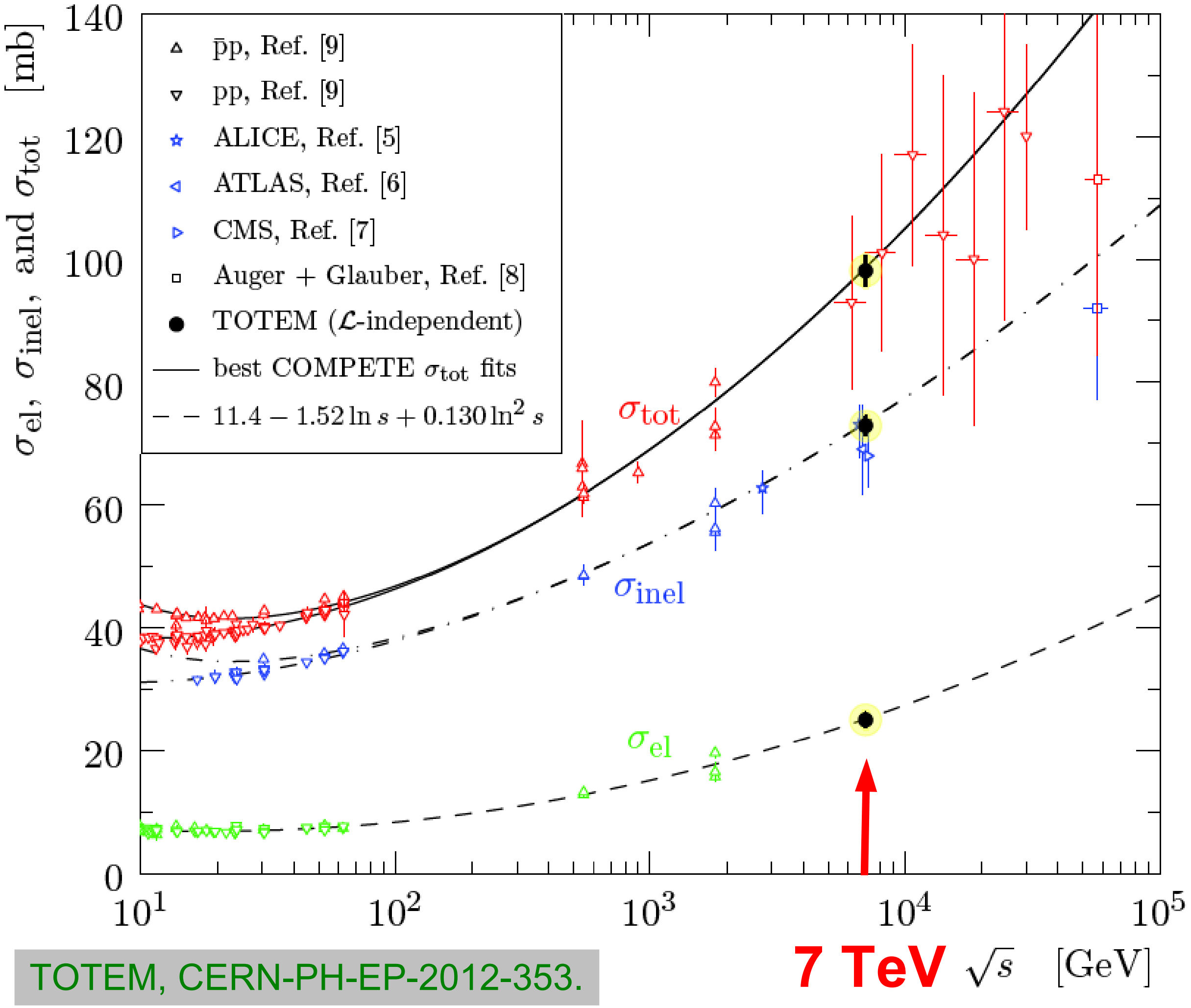
Related via optical theorem; independent of luminosity if el. and inel. can be measured for forward scattering

Helps clarifying source of so-called knee in energy spectrum of cosmic ray showers above 10^{15}eV

LHC: High energy → 2.5 10^{16}eV
No indication of change in fundamental cross sections
→ other origin

See also: R. Engel et al., AnnRevNPS (2011).

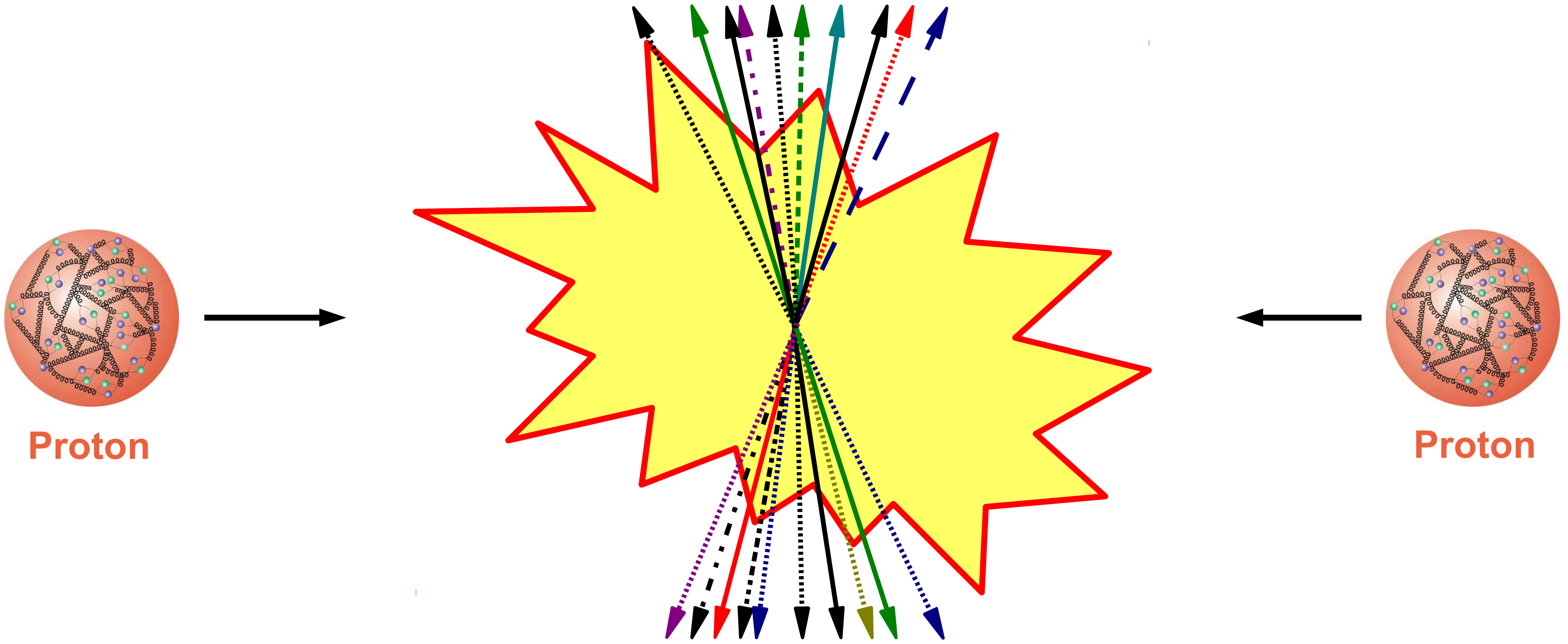
$$\sqrt{s} = 7\mathrm{TeV} \triangleq E_{\mathrm{p,lab}} = 2.5 \cdot 10^{16}\mathrm{eV}$$



TOTEM, CERN-PH-EP-2012-353.

Charged Particles (Tracks)

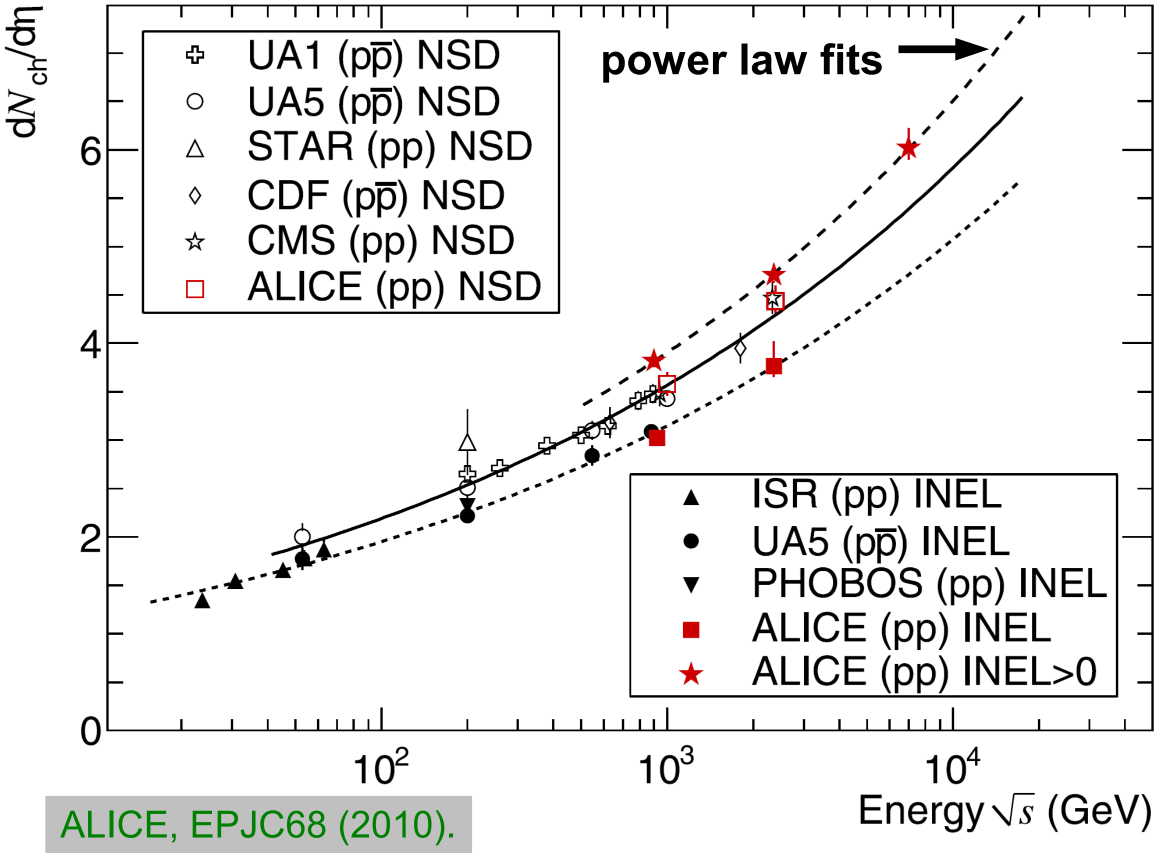
High Multiplicity



Charged Particle Density

Usually the first measurement performed, requires low to no pile up
Important to tune MC event generators!

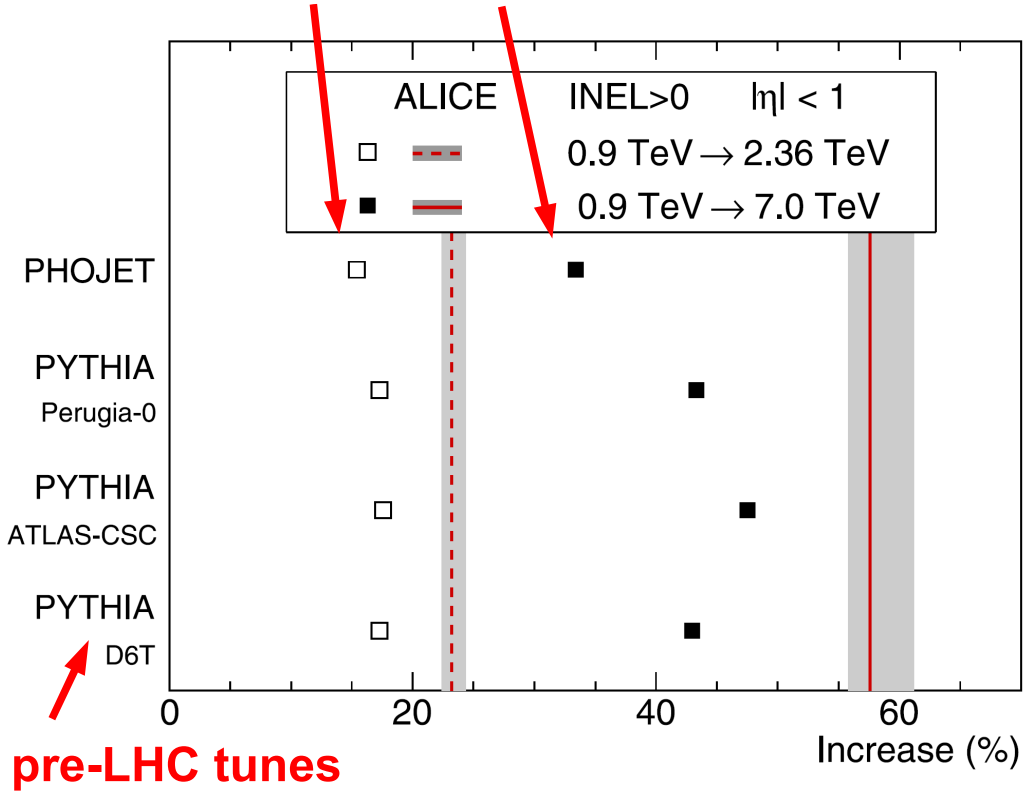
√s Dependence of particle density at central η



ALICE, EPJC68 (2010).

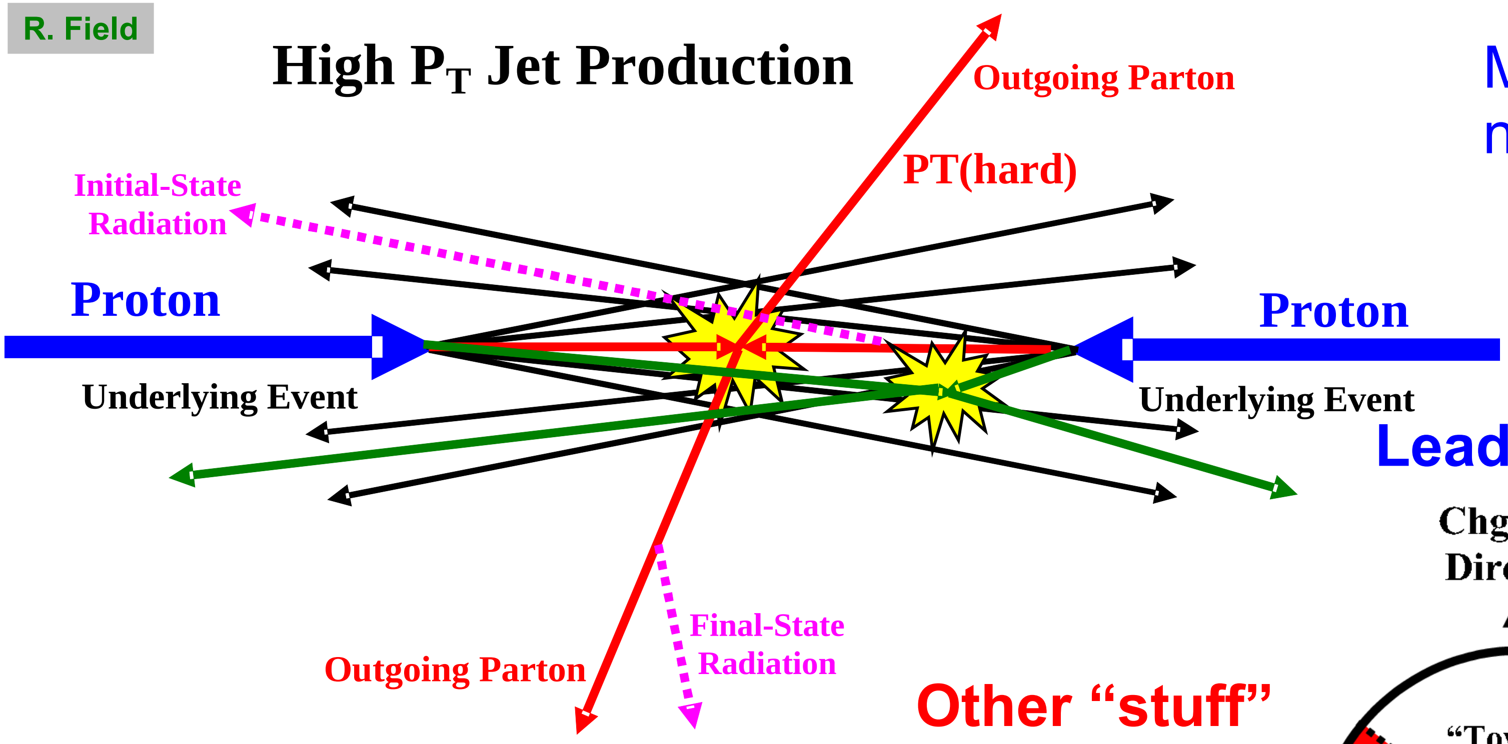
Ratios vs. 900 GeV

Extrapolation of tunes to higher √s give too low multiplicity



Underlying Event - Traditional Approach

R. Field



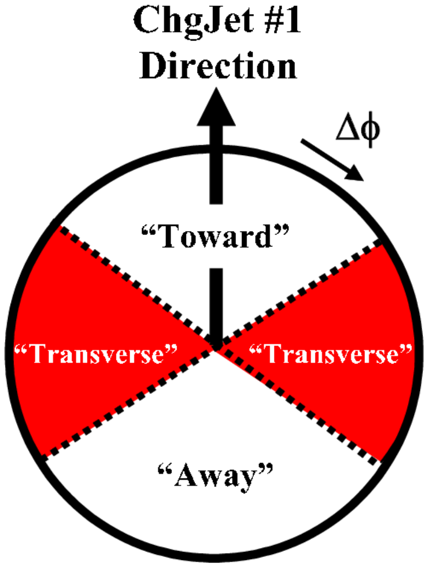
MPI, BBR, ISR and FSR
not uniquely differentiable

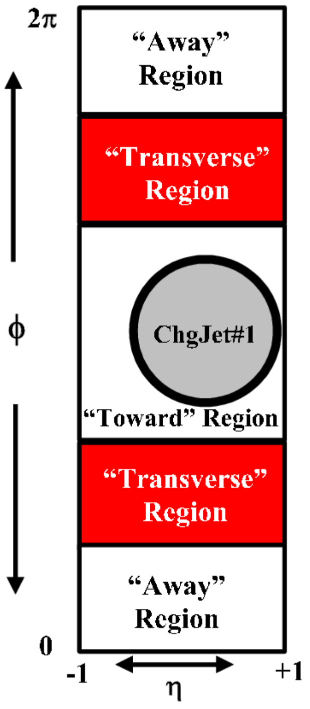
Measurement possibility:

- Charged particle and p_T sum densities in transverse region of leading jet of charged particles

Other "stuff" but the hard scatter

Leading jet



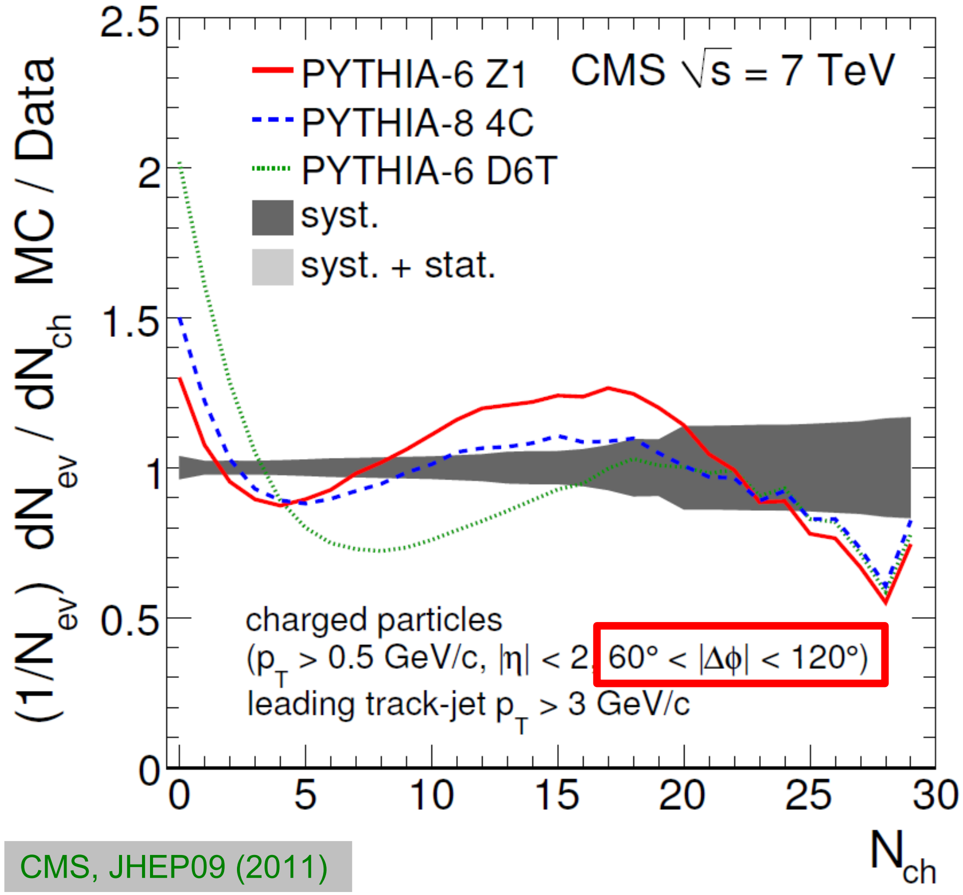


Balancing jet

Underlying Event - Traditional Approach

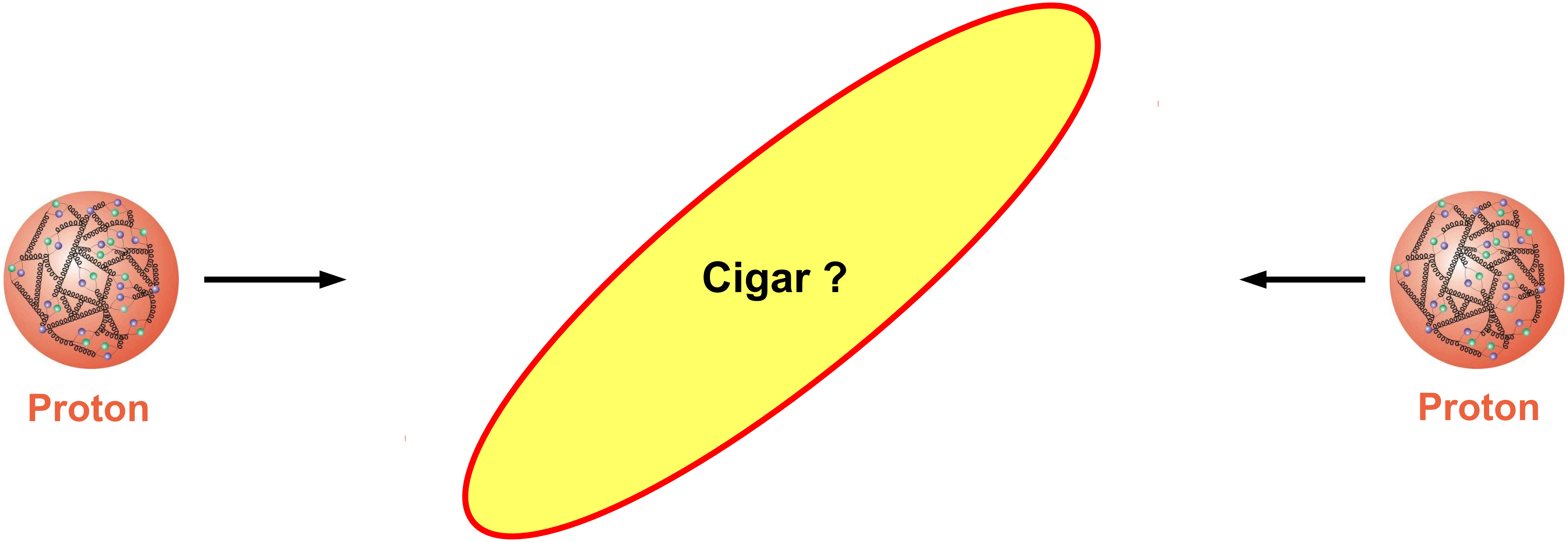
Ratio of MC to data, no MC worked really well!

Conventional UE analysis,
in the transverse plane.
Charged particle density



CMS, JHEP09 (2011)

Shapes



Proton

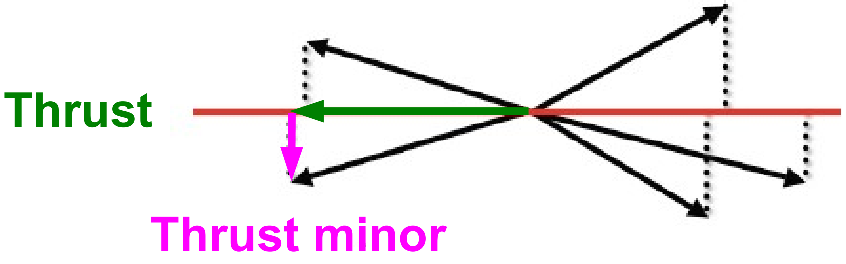
Cigar ?

Proton

Event Shapes

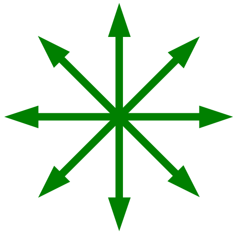
Definition:

Transverse global thrust



$$T_{\perp,g} = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

Redefine to get $\tau_{\perp,g} \equiv 1 - T_{\perp,g}$



linear ~ dijet $\tau_{\perp,g} \to 0$

spherical ~ multijet $\tau_{\perp,g} \to 1 - 2/\pi$

See also A. Banfi et al., JHEP06, 2010

Event Shapes

Originally:

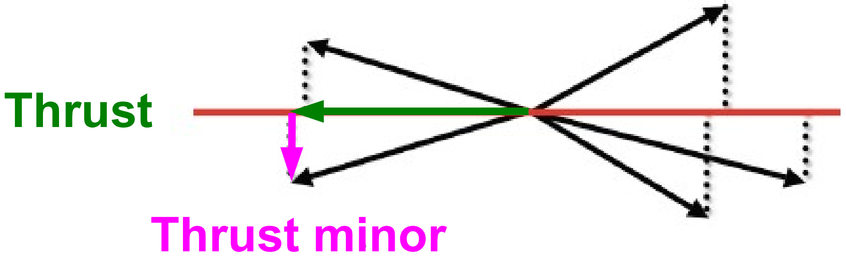
Event Shapes in e^+e^- (and ep)
Played a key role in the discovery of the gluon at DESY in 1978!

Old but still-used definition since collinear and infrared safe:
Thrust

S. Brandt et al., PL12 (1964),
E. Farhi, PRL39 (1977).

Definition:

Transverse global thrust



$$T_{\perp,g} = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

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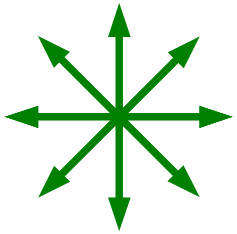
linear ~ dijet

$$\tau_{\perp,g} \to 0$$



spherical ~ multijet

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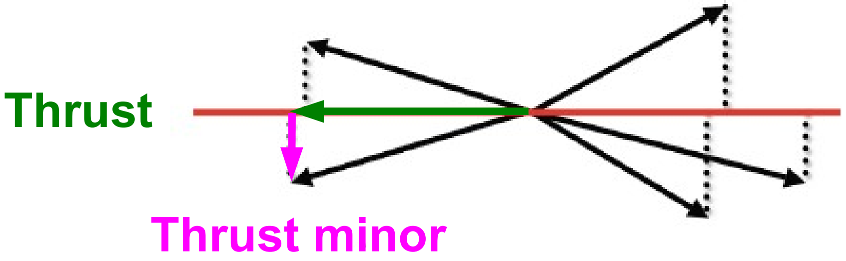
At LHC: Transverse global thrust
- **In praxis, need to restrict rapidity range: $|\eta| < \eta_{max}$ →**

Transverse central thrust

Definition:

Transverse global thrust



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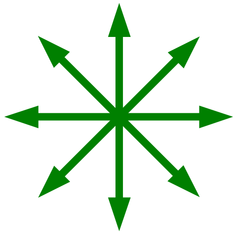
Redefine to get $\tau_{\perp,g} \equiv 1 - T_{\perp,g}$



linear ~ dijet
$\tau_{\perp,g} \to 0$

spherical ~ multijet
$\tau_{\perp,g} \to 1 - 2/\pi$

See also A. Banfi et al., JHEP06, 2010

Central Transverse Thrust

Basic description by MC ok

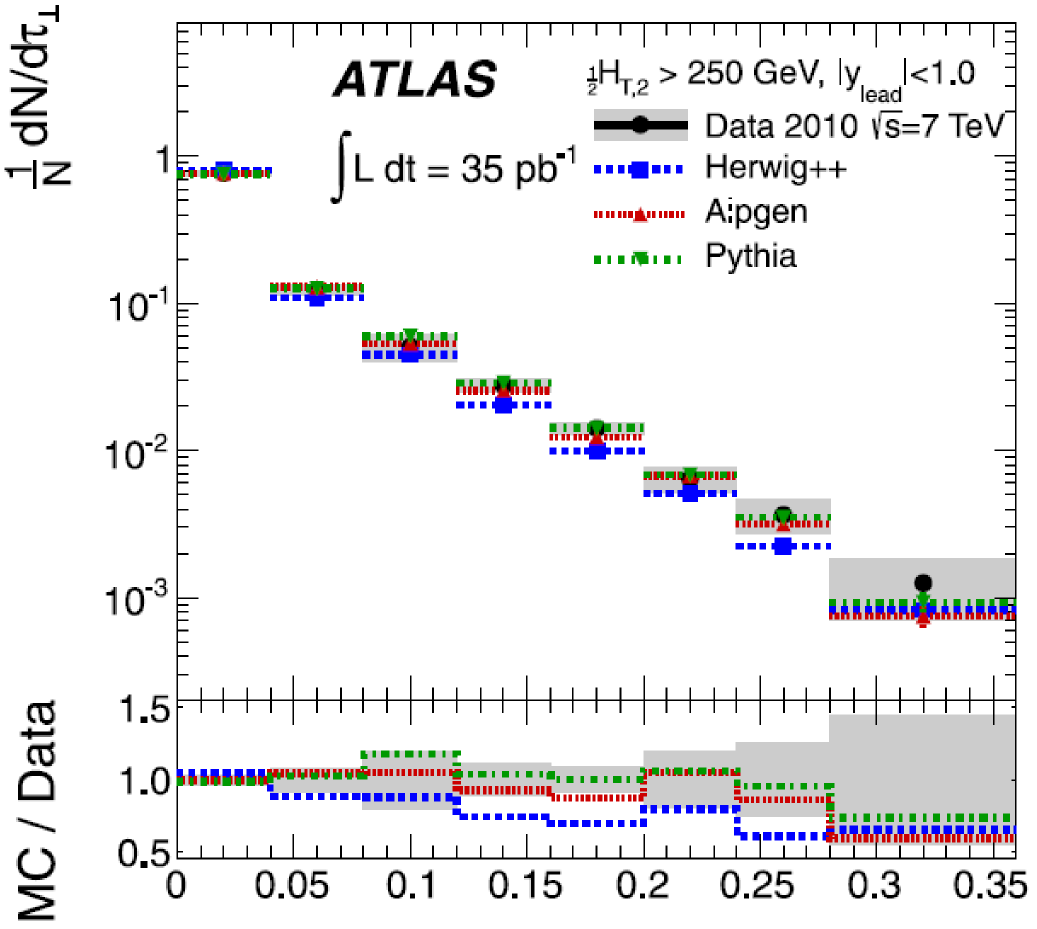
Some deviations visible
→ good for tuning!

$$\tau_{\perp,C} \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

Great tools in e+e-, known to NNLO+NLLA resummation
→ precise determination of α_s

Dissertori et al, JHEP0908 (2009).

Also used successfully in ep



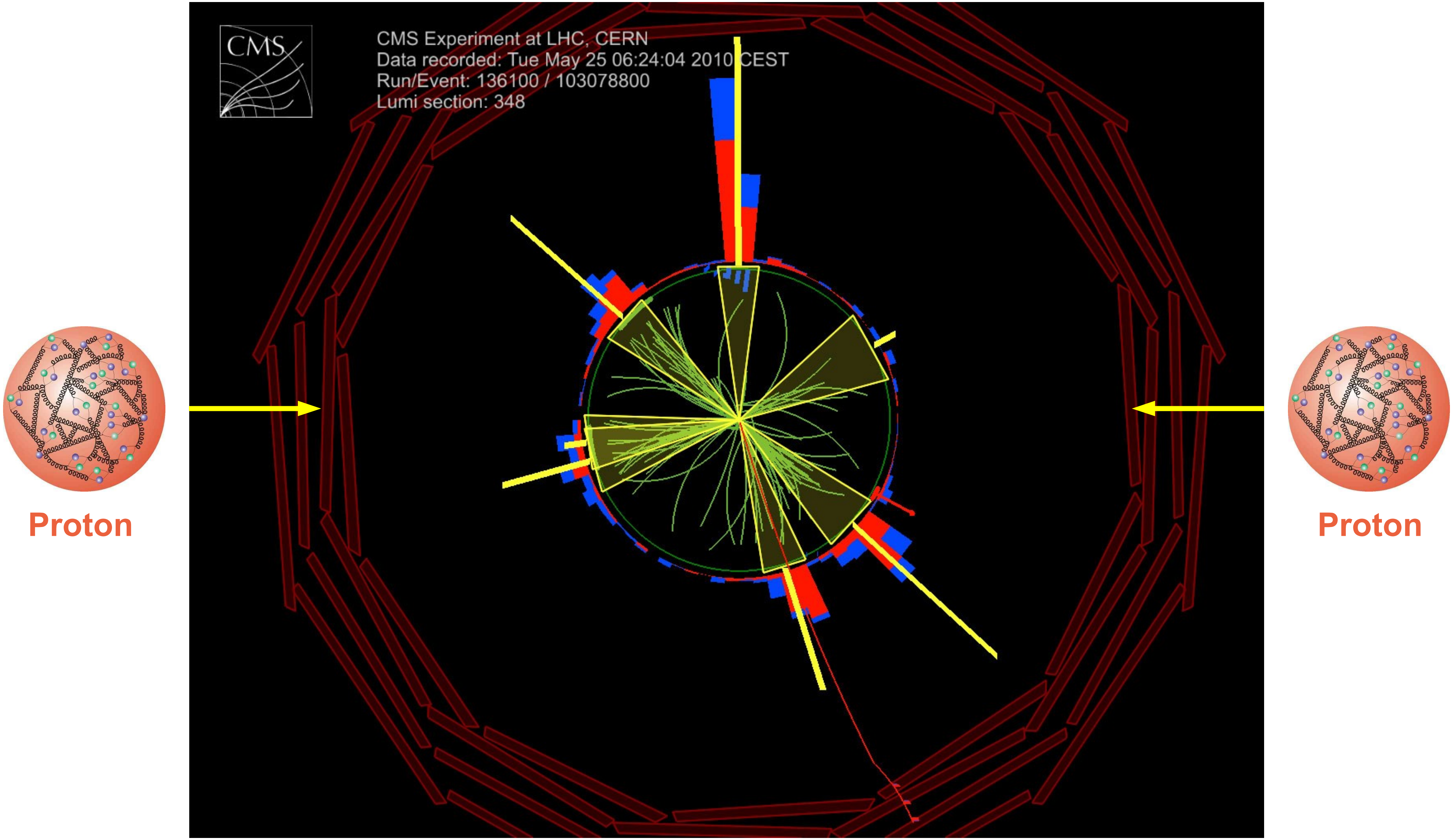
ATLAS, EPJC72, 2012

In hh collisons:
- only NLO so far
- in praxis, need to restrict rapidity range: $|\eta| < \eta_{max}$

→ central transverse thrust
→ spoils resummation

Banfi et al., JHEP06 (2010).

Bundles of Particles

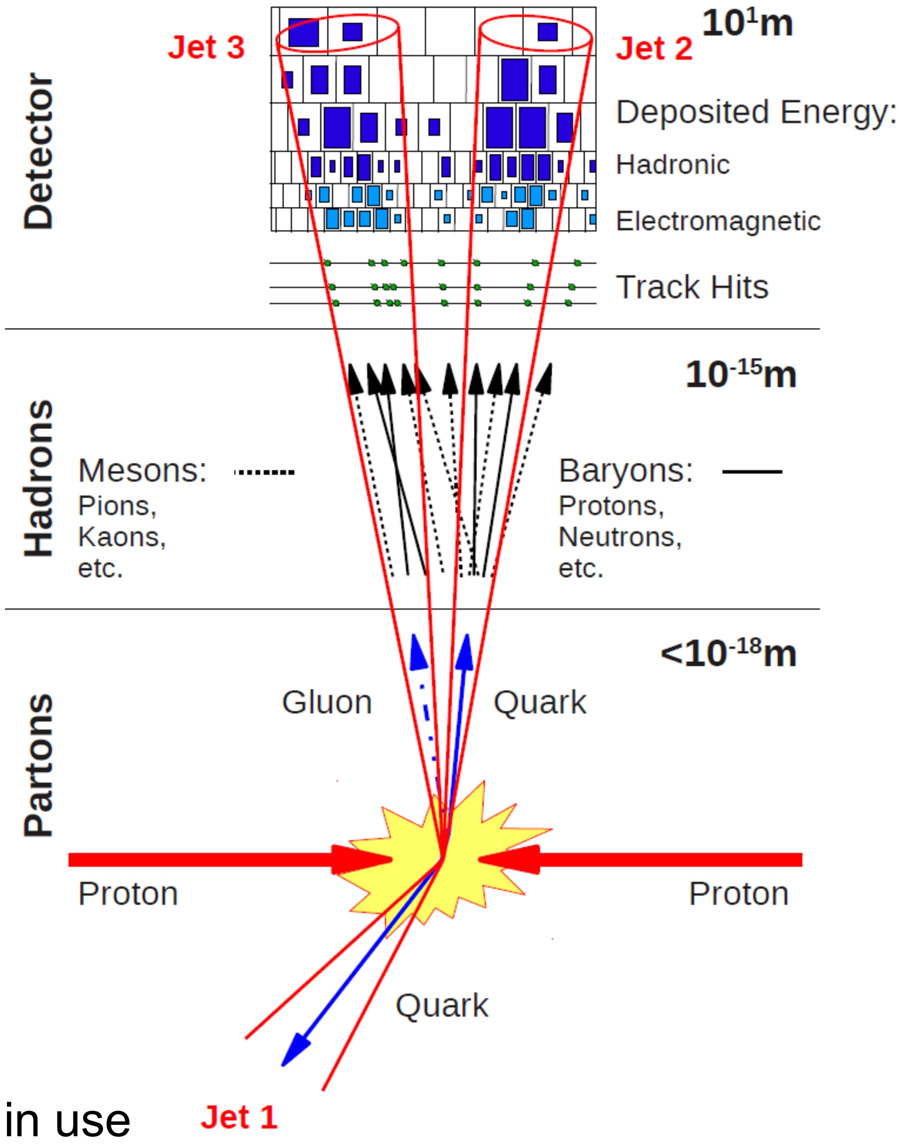


Jet Algorithms

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

Jet Algo Desiderata --- Today

- **Theory:**
  - Infrared safety
  - Collinear safety
  - Longitudinal boost invariance
    (recombination scheme!)
  - Boundary stability
    (→ 4-vector addition, rapidity y)
  - Order independence
    (parton, particle, detector)
  - Ease of implementation
    (standardized public code: fastjet)

Many of these points were red, i.e. not fulfilled, in times just before the LHC!

- **Experiment:**
  - Ease of calibration
  - Insensitivity to pile-up
  - Minimal resolution smearing and angular biasing
  - Maximal reconstruction efficiency
  - Computational efficiency and predictability
    (use in reconstruction, trigger)
  - Detector independence
  - Fully specified
    (fastjet) Cacciari et al., EPJC72 (2012).
  - Ease of implementation
    (standardized public code: fastjet)

Jet Algorithms at LHC

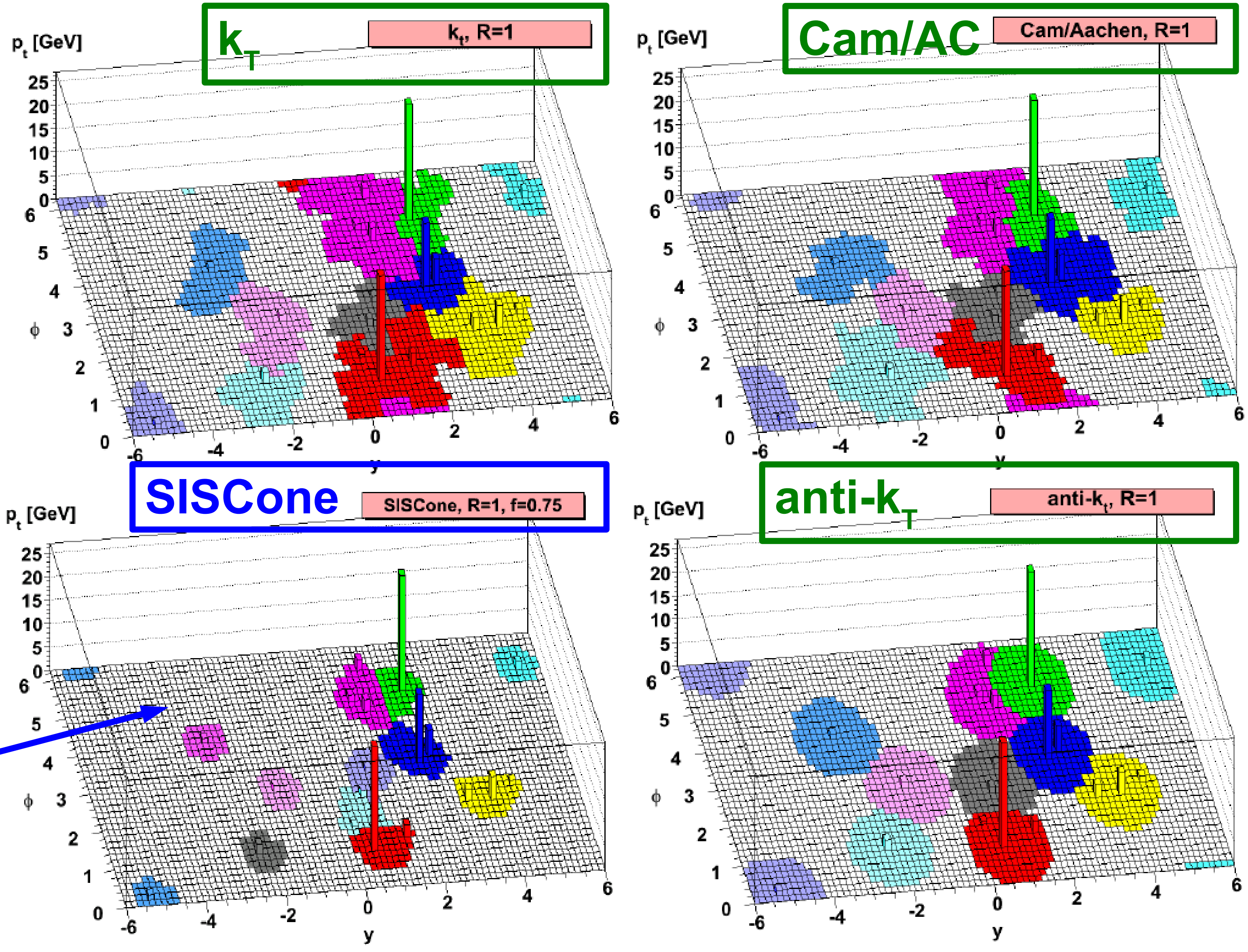
Primary algorithm at LHC:

- **Anti-k_T:**
  ATLAS R = 0.4, 0.6
  CMS R = 0.5, 0.7

- k_T
- SISCone ("real" cone algo)
- Cambridge/Aachen
  used in jet substructure, for example in boosted top

General interest to work with all four!

Only "real" cone algorithm!



kT, Ellis, Soper, PRD48 (1993),
Cam/AC, Dokshitzer et al., JHEP08 (1997),
Wobisch, Wengler, arXiv:hep-ph/9907280,
SISCone, Salam, Soyez, JHEP05 (2007)

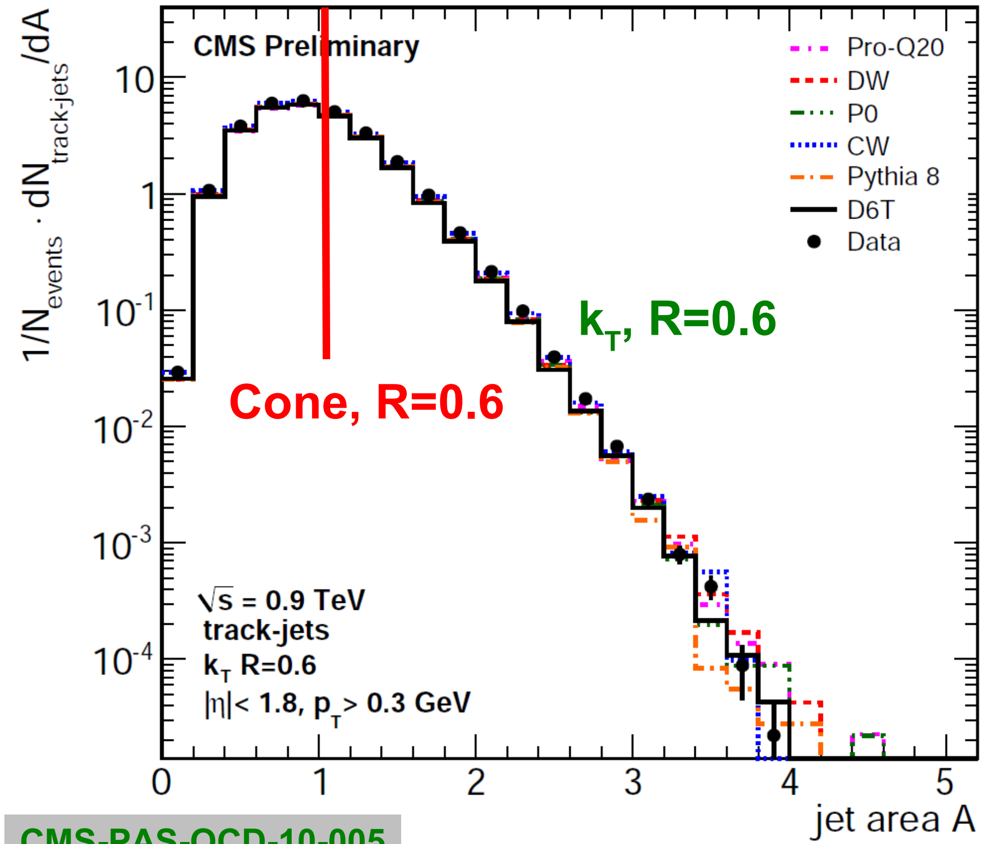
Jet Areas

Measured jet area distribution

k_T algorithm with R = 0.6

Naively expect for cone algorithm

R = 0.6 → A = π R^2 = 1.1



Cone, R=0.6

k_T, R=0.6

CMS-PAS-QCD-10-005

- **Jet Areas can be measured!**
- **More useful when not forced into fixed shape (cone) but adaptable to event activity**
  - **Measure the underlying event (UE)**
  - **Subtract additional energy in jets due to pile-up collisions**

ignore outliers (leading jets)

jet pT per area

$$\rho' = \underset{j\in physical\ jets}{\text{median}}\left[\left\{\frac{p_{T,j}}{A_j}\right\}\right]*C$$

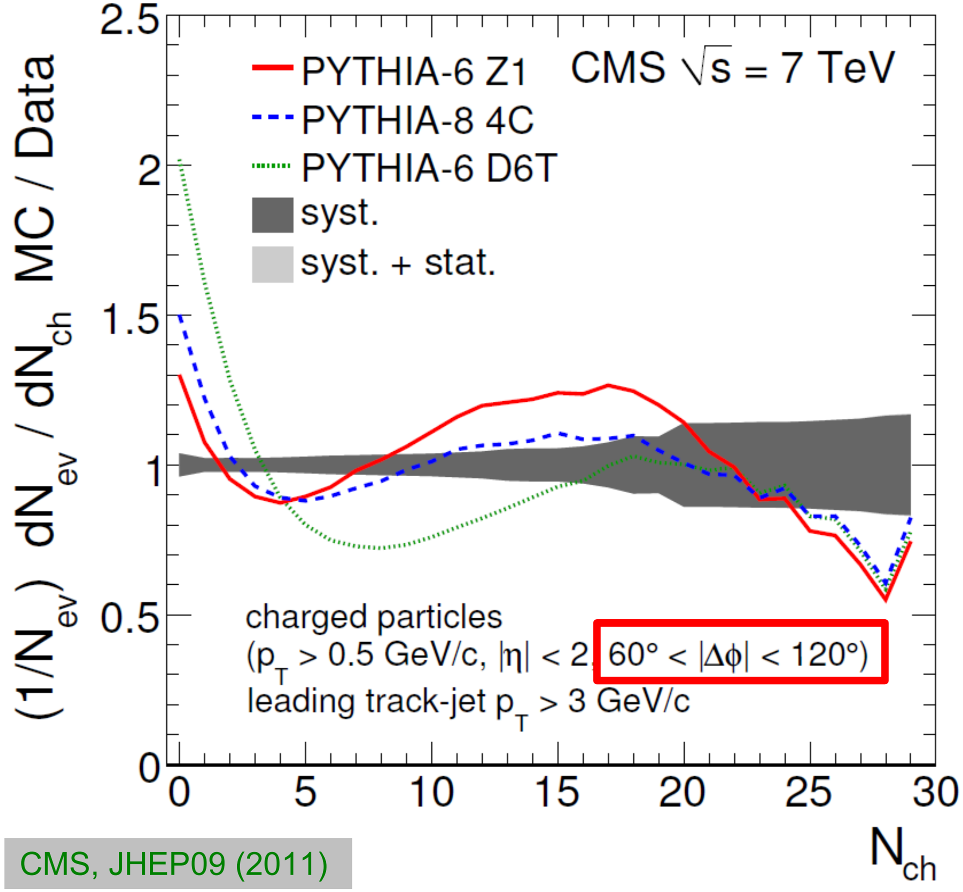
event-wise measure of UE activity

correction for empty events

Underlying Event - Jet Areas

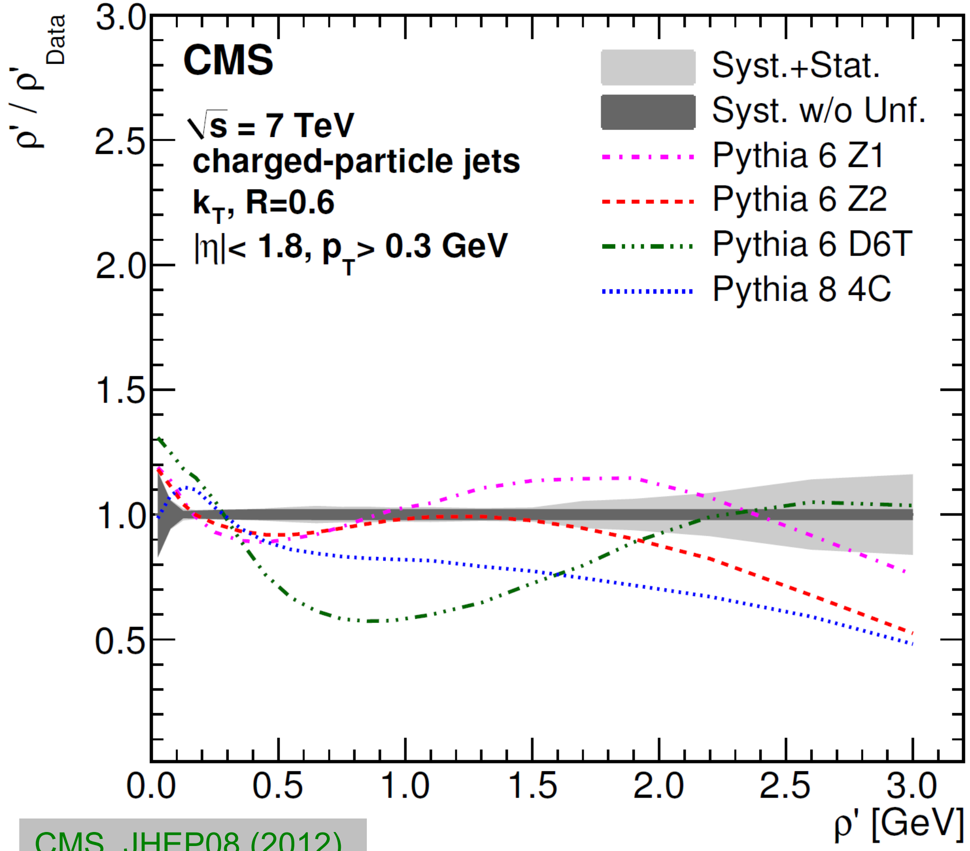
Ratio of MC to data, no MC worked really well!

Conventional UE analysis,
in the transverse plane.
Charged particle density



CMS, JHEP09 (2011)

Jet Area UE analysis,
whole event analyzed.
Charged particle jets



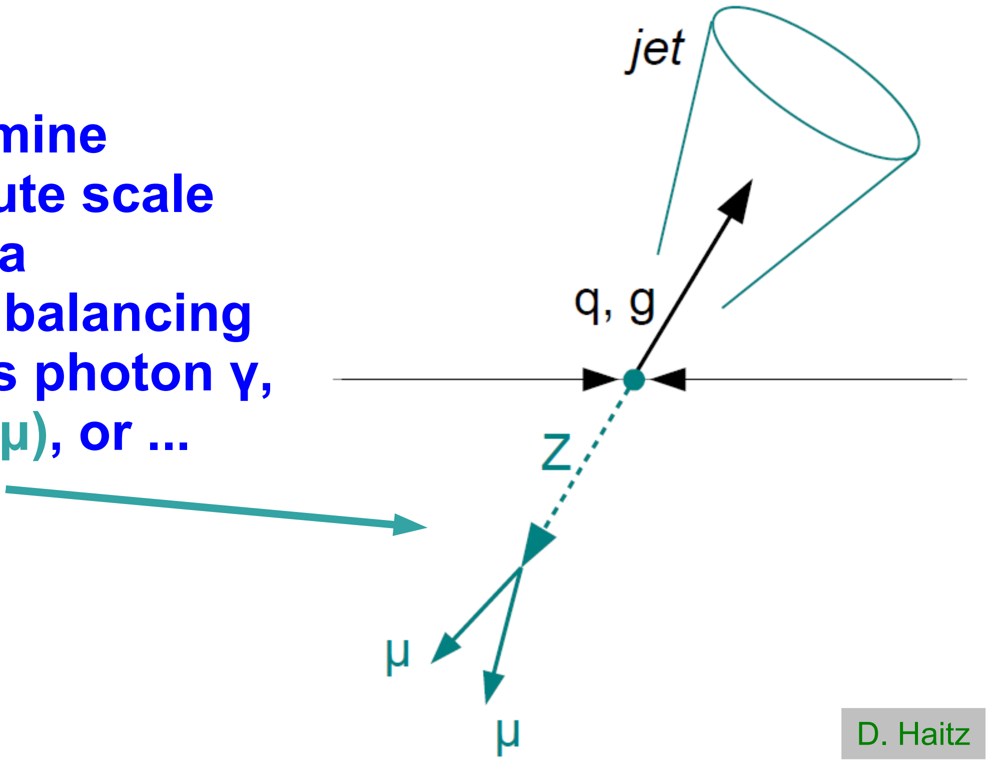
CMS, JHEP08 (2012).

Jet Energy Scale

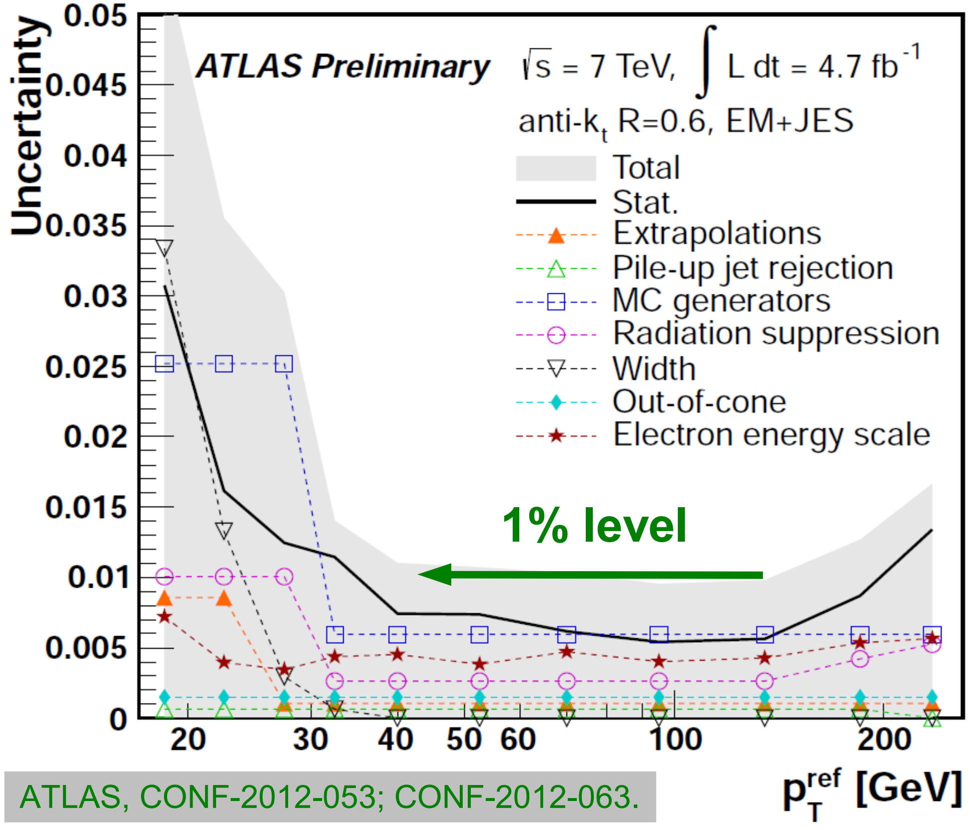
Dominant uncertainty for measurements of jet cross sections ...
Enormous progress … in two years LHC arrived where it took O(10) years at Tevatron!
QCD at hadron colliders is becoming precision physics.

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

Determine absolute scale e.g. via jet pT balancing versus photon γ, Z(→ μμ), or ...



D. Haitz

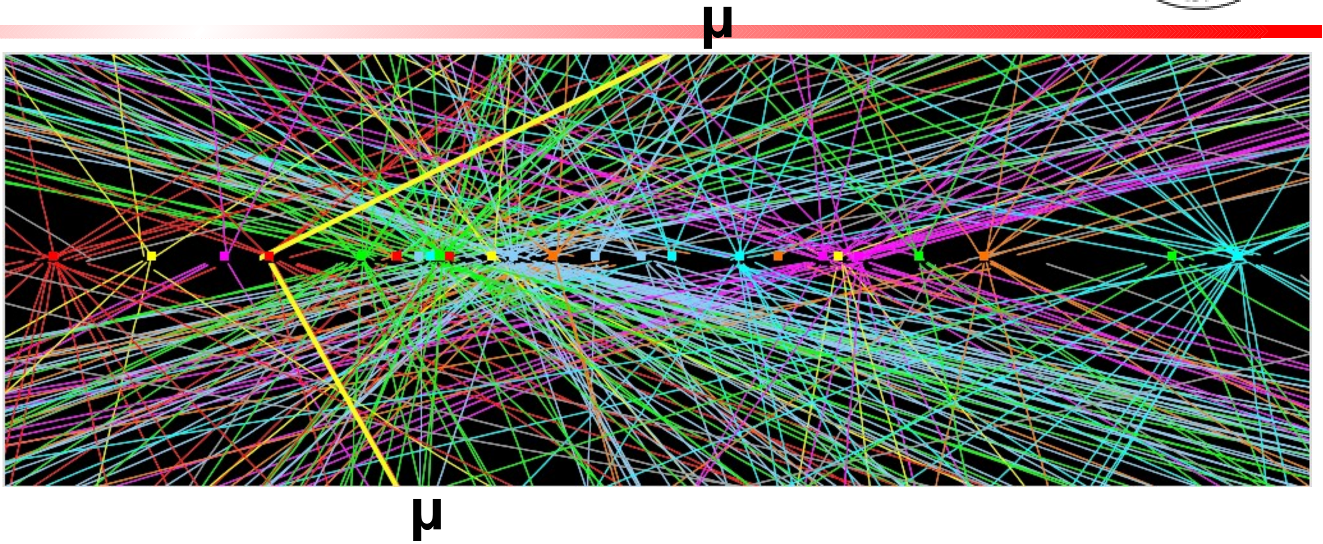


ATLAS, CONF-2012-053; CONF-2012-063.

Jet Energy Scale and Pile Up

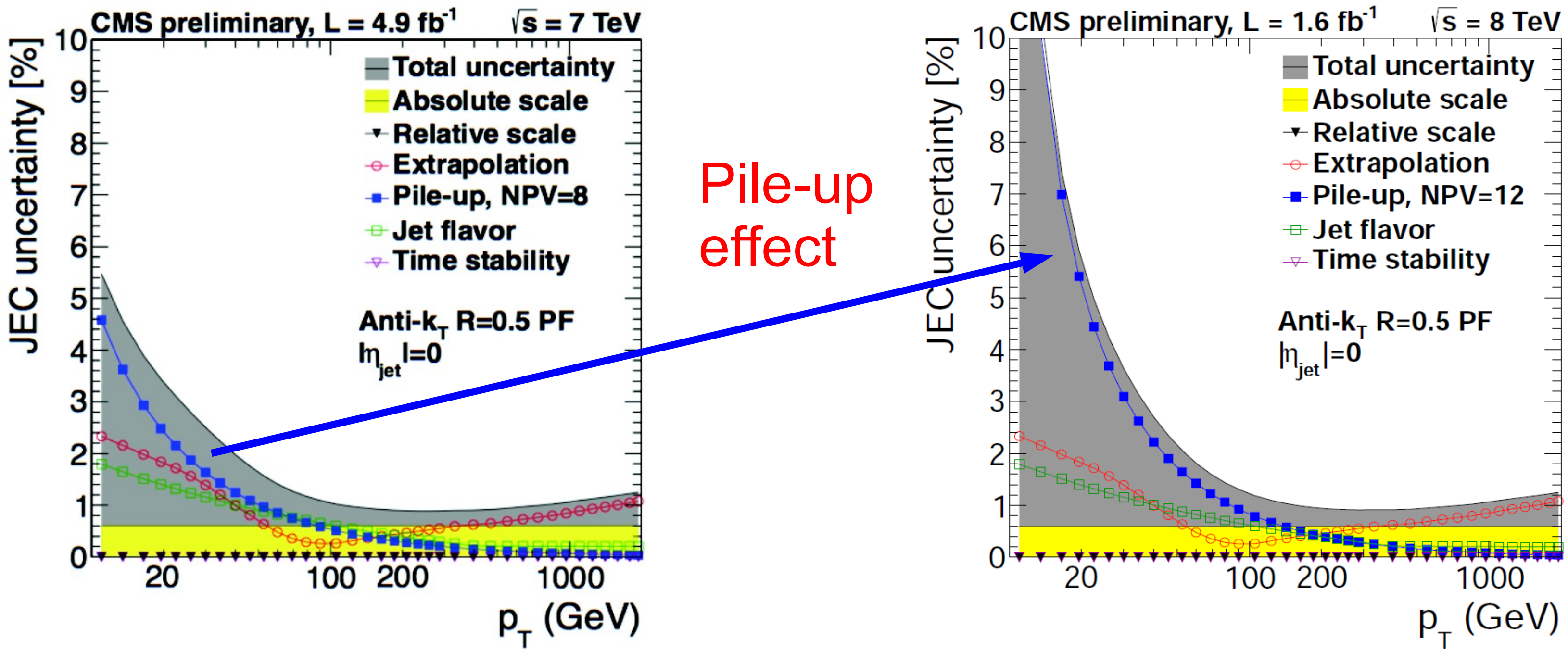
But:
New situation in 2012 at 8 TeV with many pile-up collisions!

ATLAS Z → μμ candidate with 25 reconstructed primary vertices:



CMS from 5/fb (7 TeV, 2011)

CMS from 1.6/fb (8 TeV, 2011)



Pile-up effect

CMS, DP2012-006
CMS, DP2012-012

Jet Analysis Uncertainties

- Experimental Uncertainties (~ in order of importance):
  - Jet Energy Scale (JES)
    - Noise Treatment
    - Pile-Up Treatment
  - Luminosity
  - Jet Energy Resolution (JER)
  - Trigger Efficiencies
  - Resolution in Rapidity
  - Resolution in Azimuth
  - Non-Collision Background
  - • • •

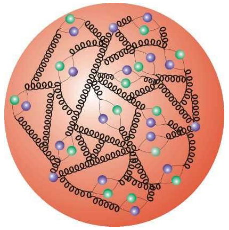
- Theoretical Uncertainties:
  - PDF Uncertainty
  - pQCD (Scale) Dependence
  - Non-perturbative Corrections
  - PDF Parameterization
  - NLO-NLL matching schemes
  - Electroweak Corrections
  - Knowledge of $\alpha_s(M_Z)$
  - • • •

↑

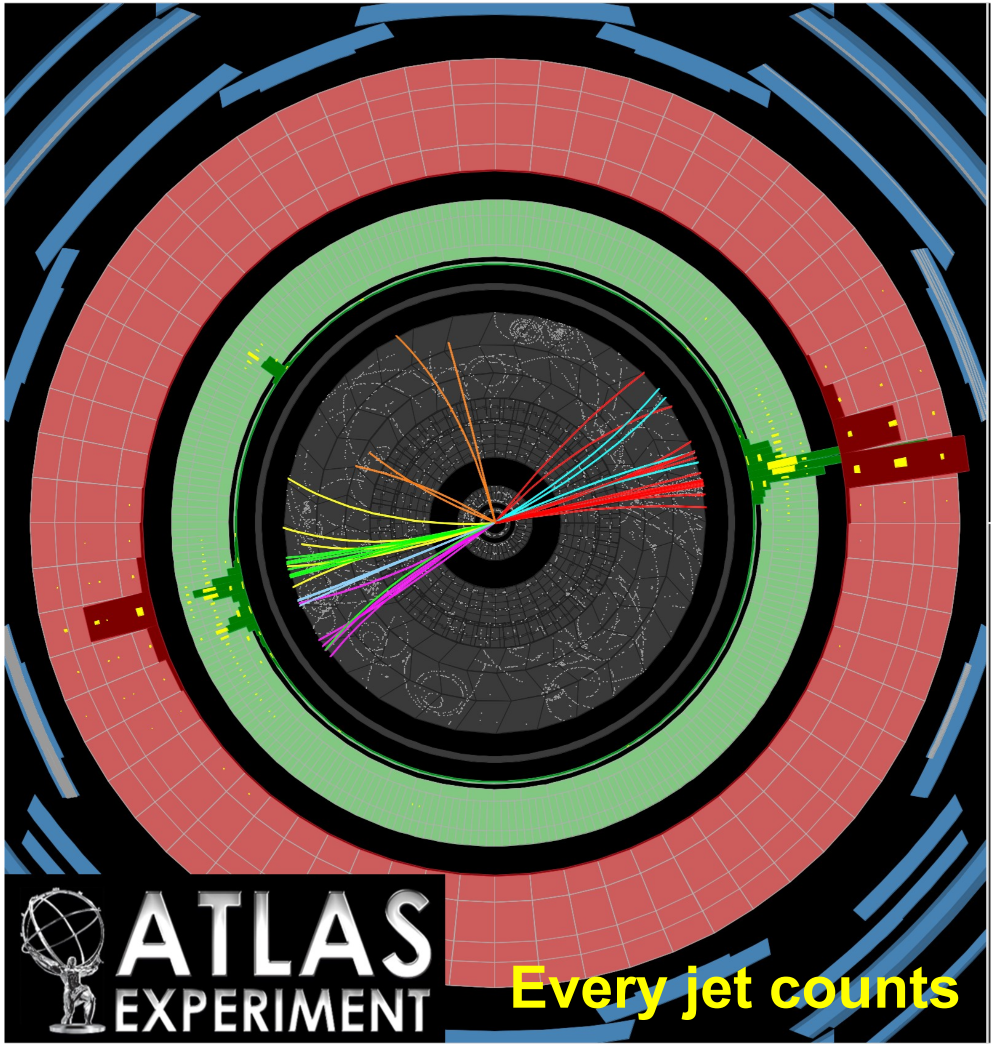
There is a lot to learn here from Comparison to actual measurements!

All Inclusive

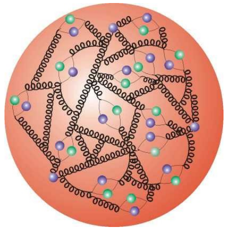
High transverse Momenta



Proton



Every jet counts



Proton

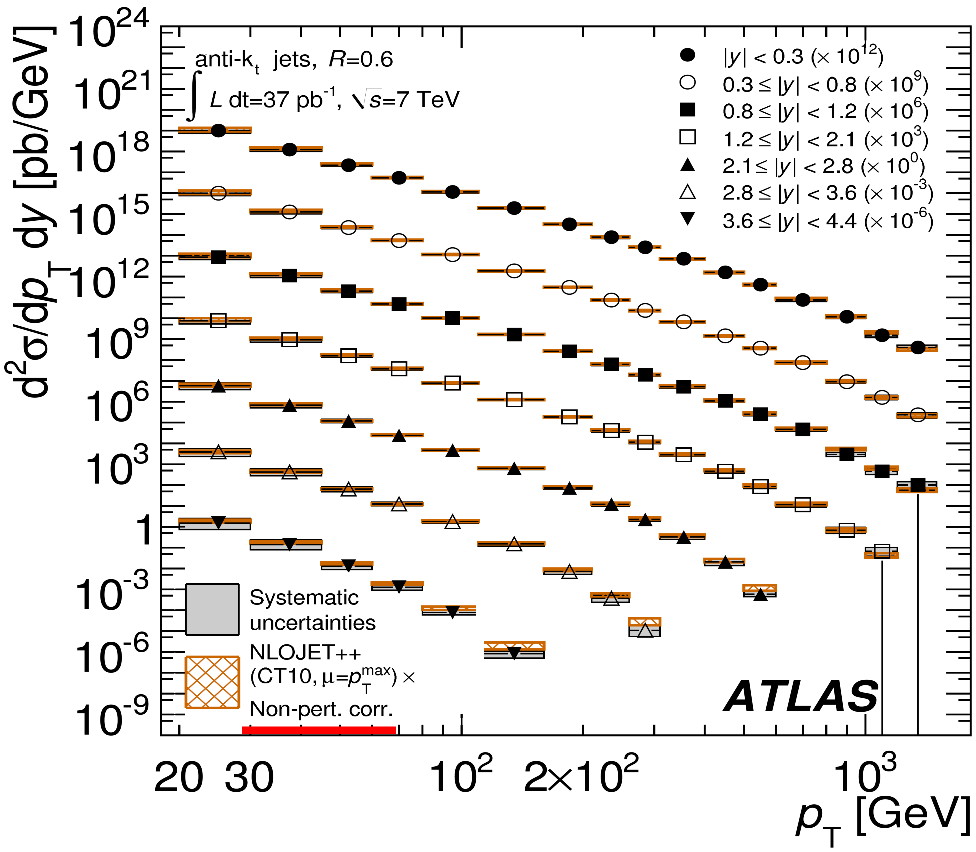
Inclusive Jets

Agreement with predictions of QCD over many orders of magnitude up to 2 TeV in jet p_T

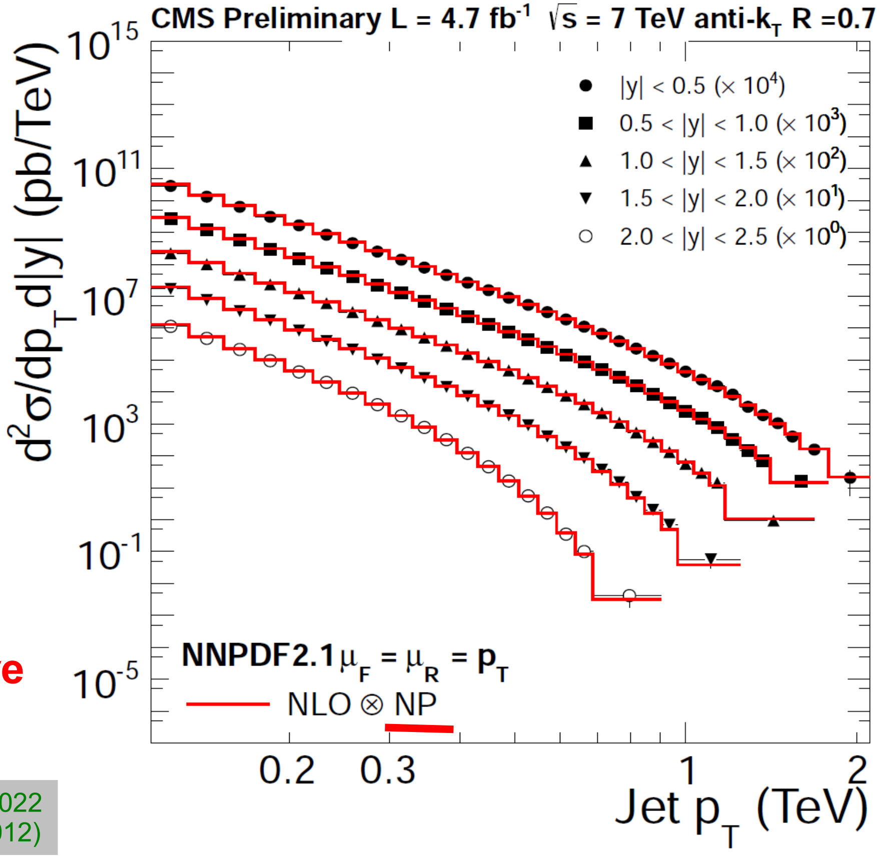
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

For the use with PDFs see talk by M. Cooper-Sarkar.

anti-kT, R=0.6, 7 TeV, 2010



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



pQCD ⊗ non-perturbative corrections

ATLAS, PRD 86 (2012) 014022
CMS, PAS-QCD-11-004 (2012)

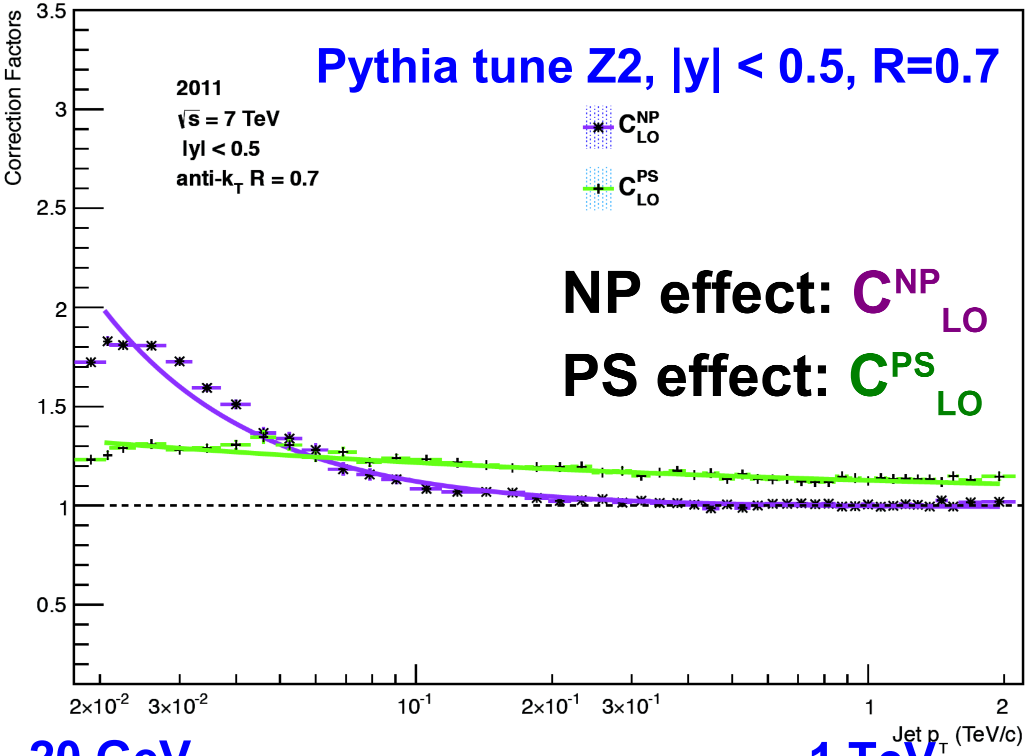
Non-perturbative Corrections

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



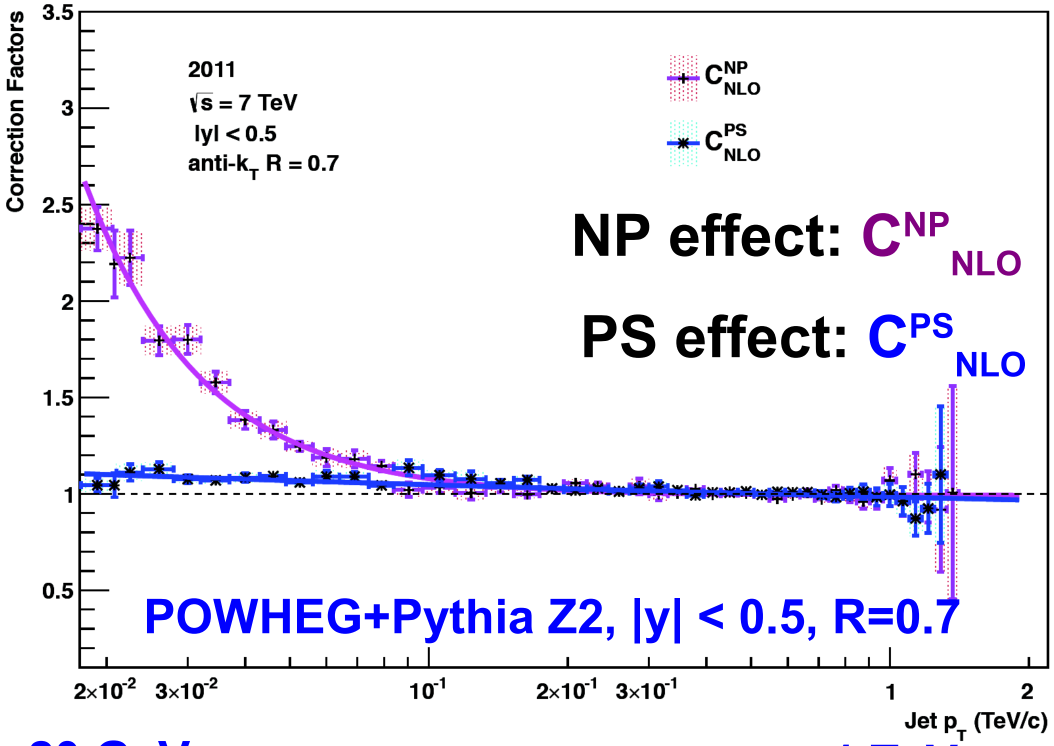
Pythia tune Z2, |y| < 0.5, R=0.7

NP effect: C^{NP}_{LO}

PS effect: C^{PS}_{LO}

20 GeV

1 TeV



NP effect: C^{NP}_{NLO}

PS effect: C^{PS}_{NLO}

POWHEG+Pythia Z2, |y| < 0.5, R=0.7

20 GeV

1 TeV

Observations:

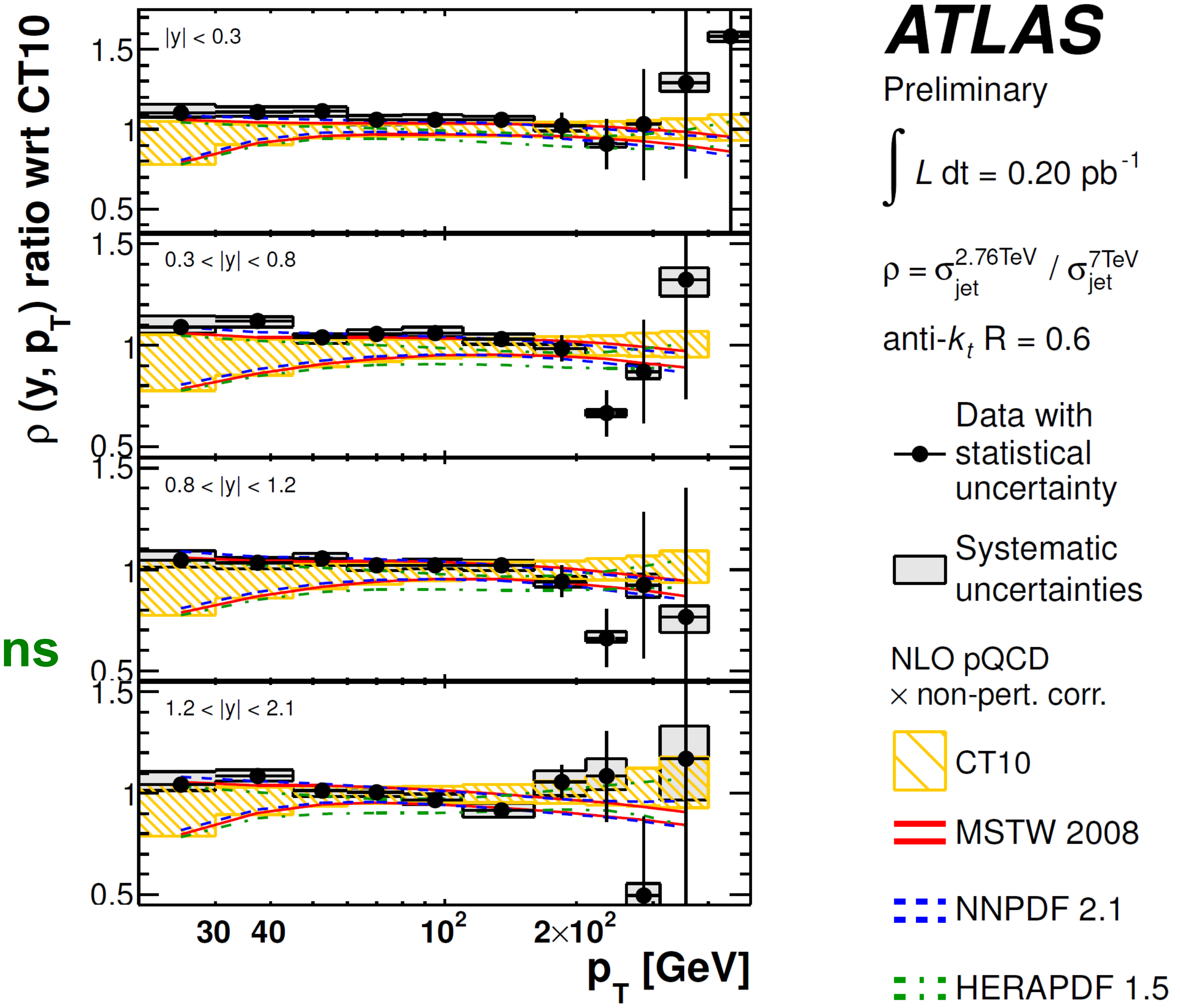
- assumptions fine at central rapidity (not shown here)
- comparison to data ok
- NP corrections larger for R=0.7 than 0.5
- for |y| > 2 PS effects visible

Figures courtesy of S.Dooling, H.Jung, P.Gunnellini, P.Katsas, A.Knutsson

Inclusive Jet Ratios of 2.76 / 7

New 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**



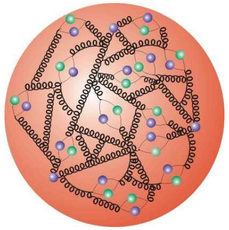
At least partial cancellation of uncertainties
→ more precise comparisons

Remark:
Other interesting ratios ...
different jet sizes

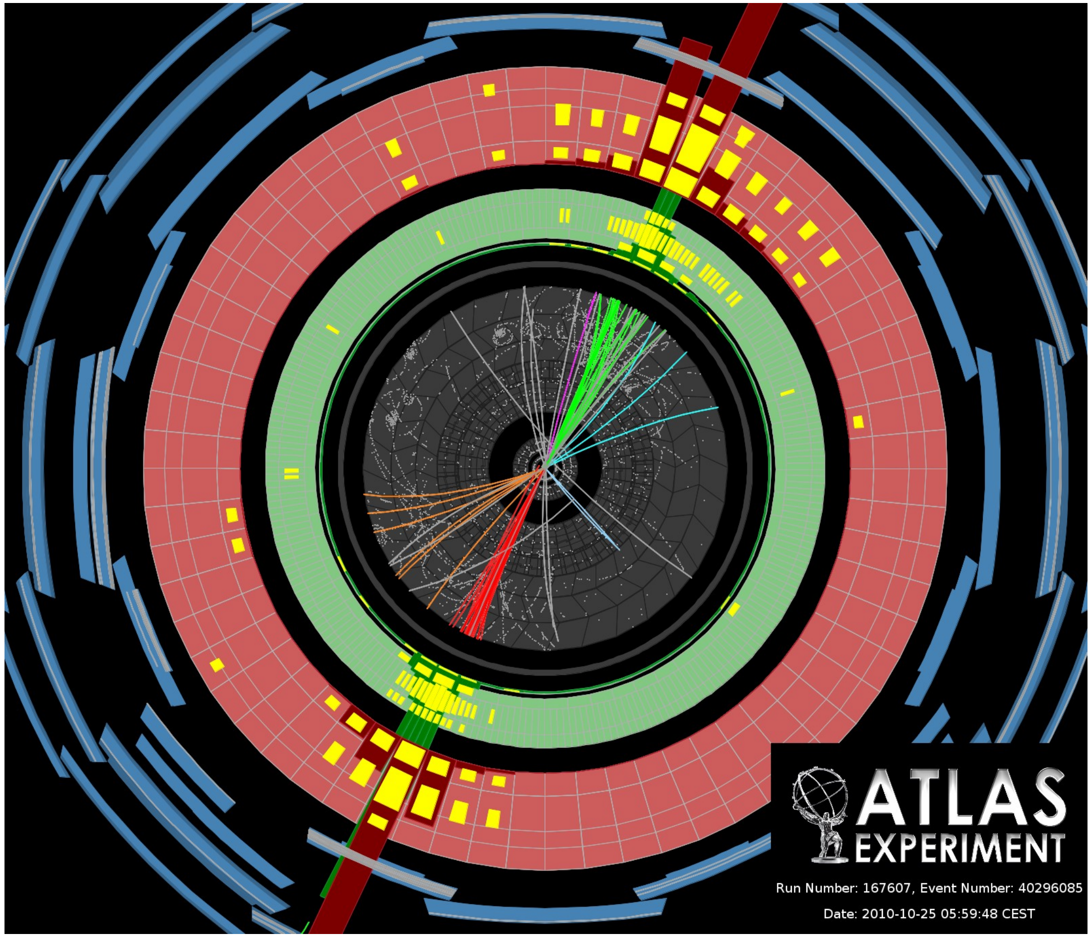
ATLAS, CONF-2012-128

Dijets

High Masses

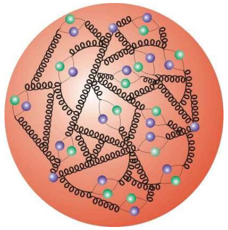


Proton



Run Number: 167607, Event Number: 40296085

Date: 2010-10-25 05:59:48 CEST



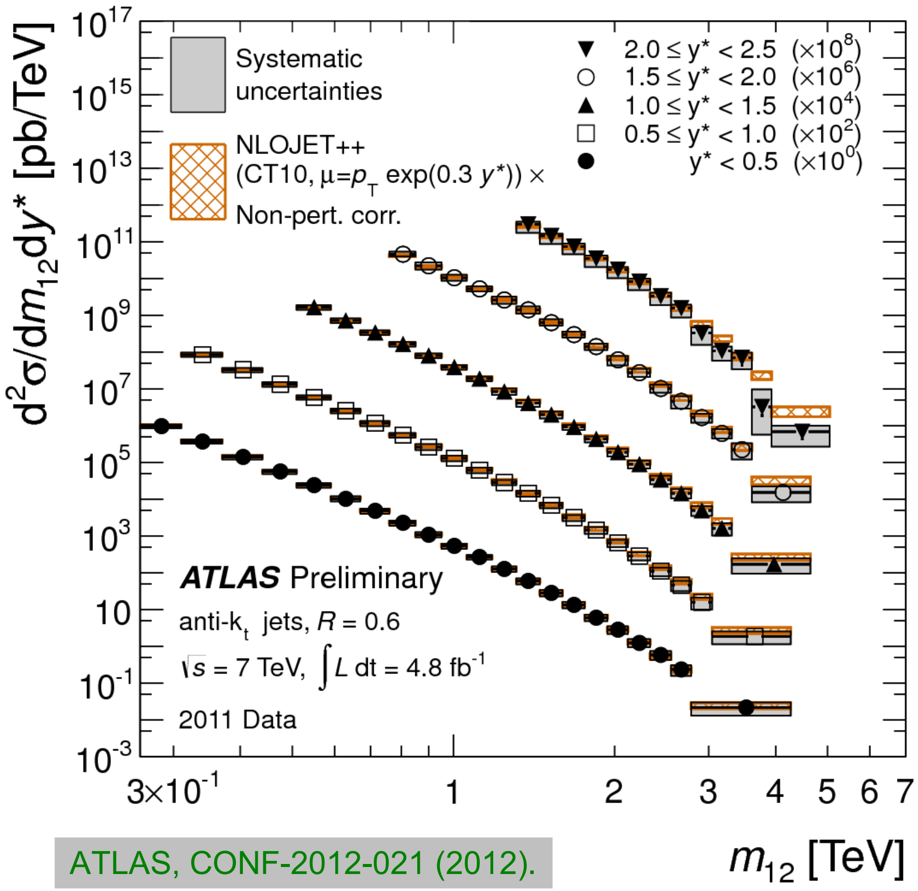
Proton

Dijet Mass

Again agreement with predictions of QCD over many orders of magnitude!

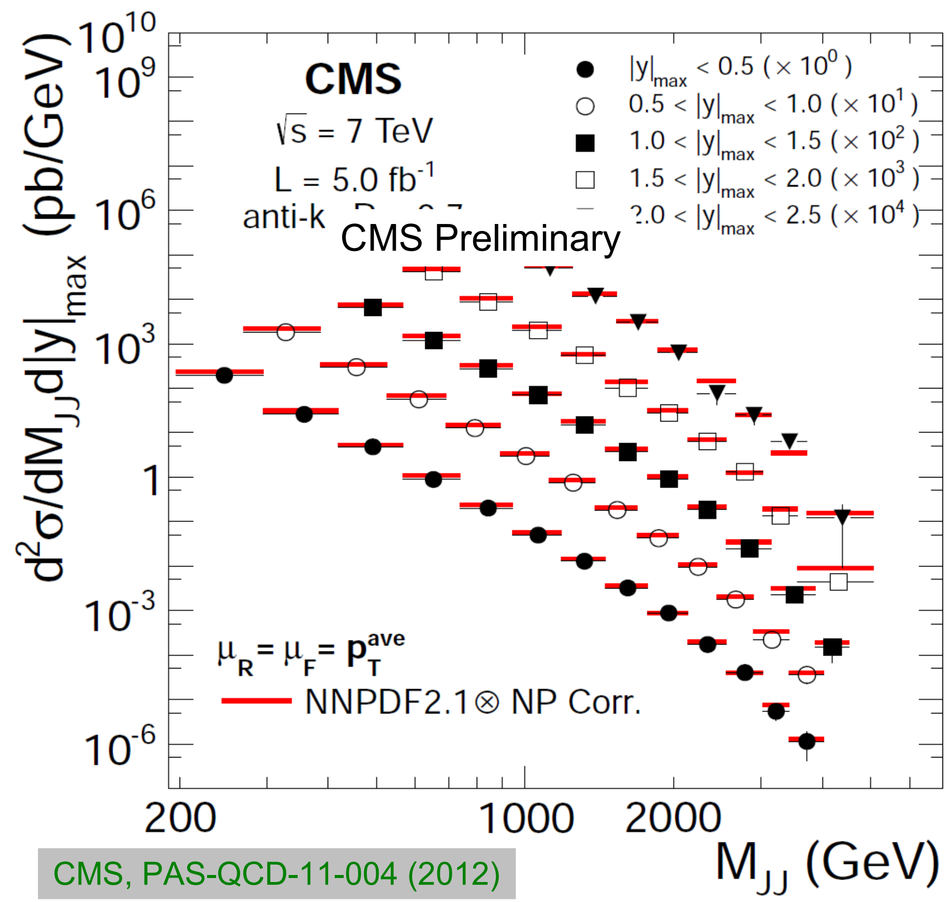
$$\frac{d^2\sigma}{dM_{JJ}d[|y|_{max}, y^*]} \propto \alpha_s^2$$

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



ATLAS, CONF-2012-021 (2012).

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

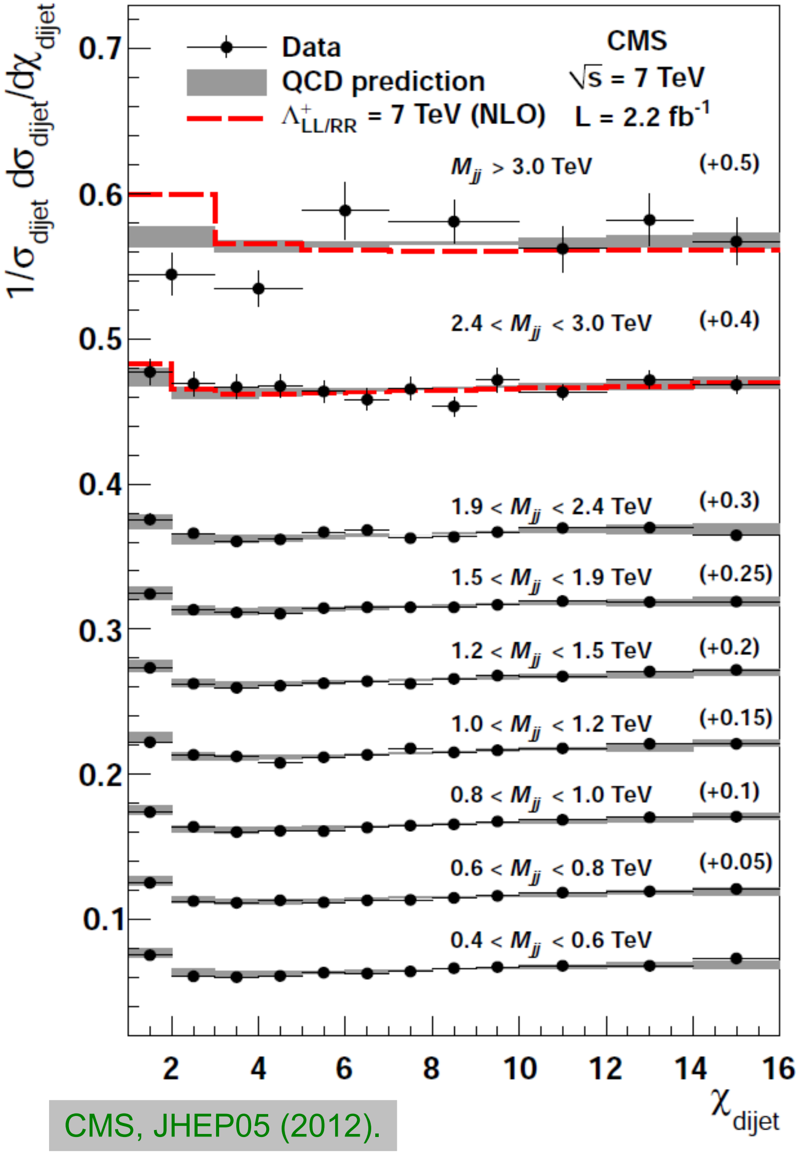


CMS, PAS-QCD-11-004 (2012)

Dijet Angular

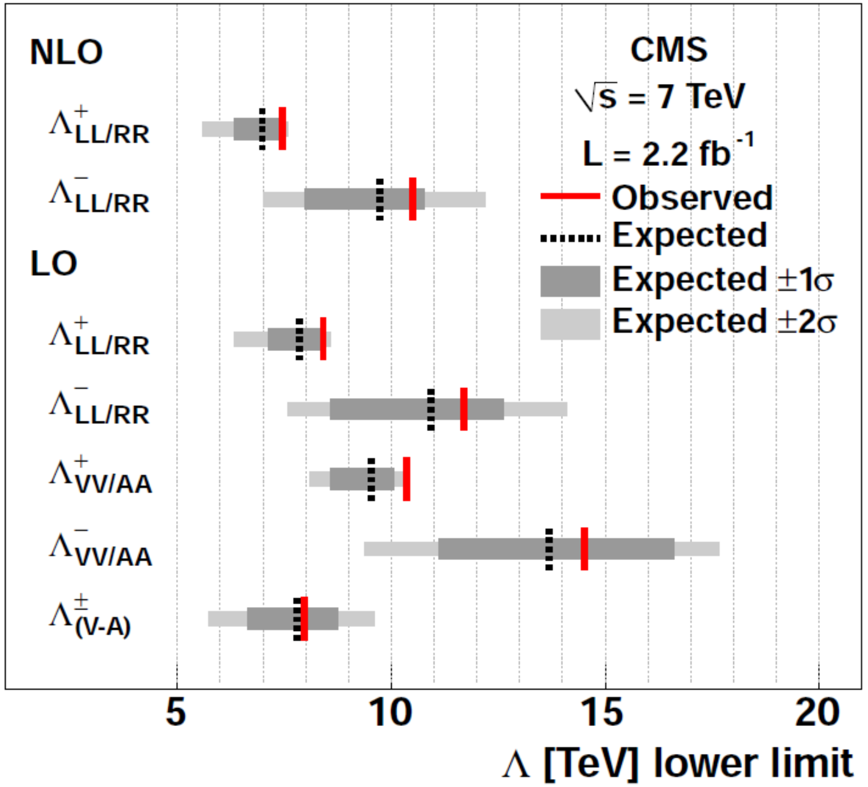
$$\chi = \exp(2y^*) = \exp(|y_1 - y_2|) = \frac{1 + |\cos\Theta^*|}{1 - |\cos\Theta^*|}$$

~ flat
for QCD



CMS, JHEP05 (2012).

Agreement with predictions of QCD →
Set lower limits on contact interaction scale Λ



NEW:
NLO means CI corrections to QCD at NLO

Decreases limits!

Gao et al., PRL106, 2011

Also other searches, see further talks

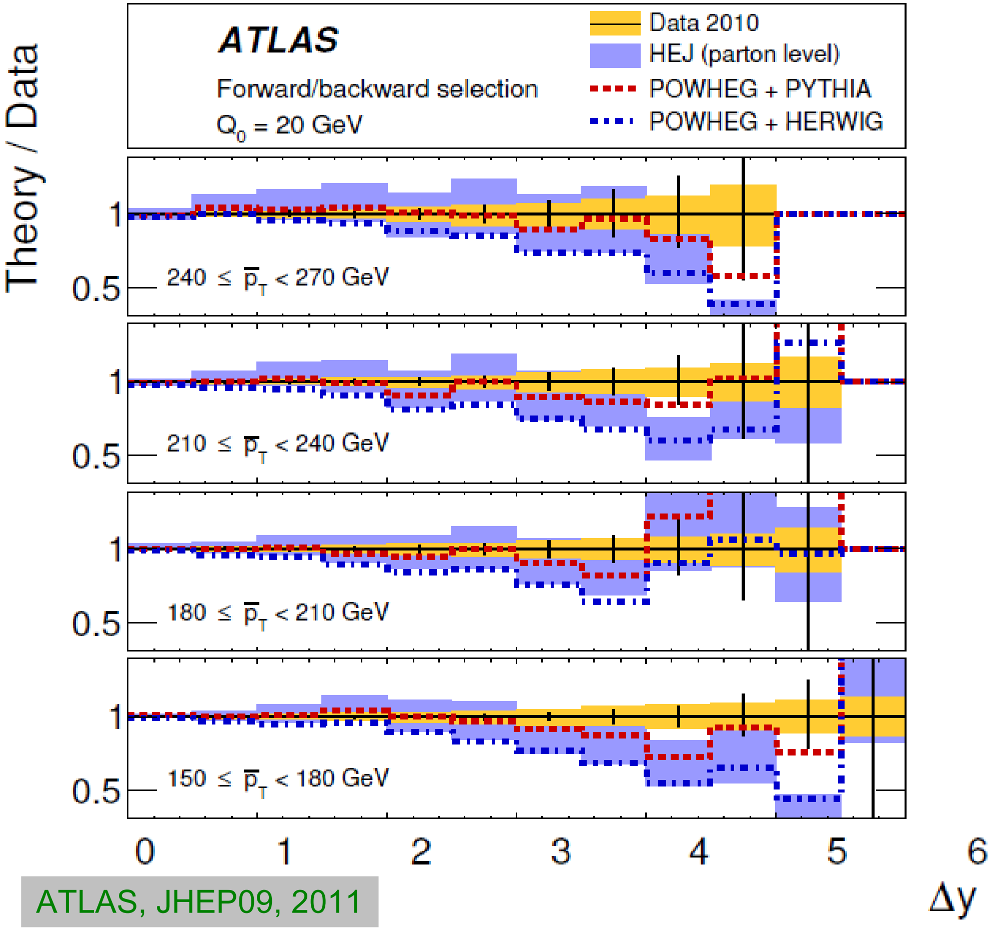
Dijets separated in Rapidity

Quantities sensitive to potential deviations from DGLAP evolution at small x

Some MC event generators run into problems … but also BFKL inspired ones!

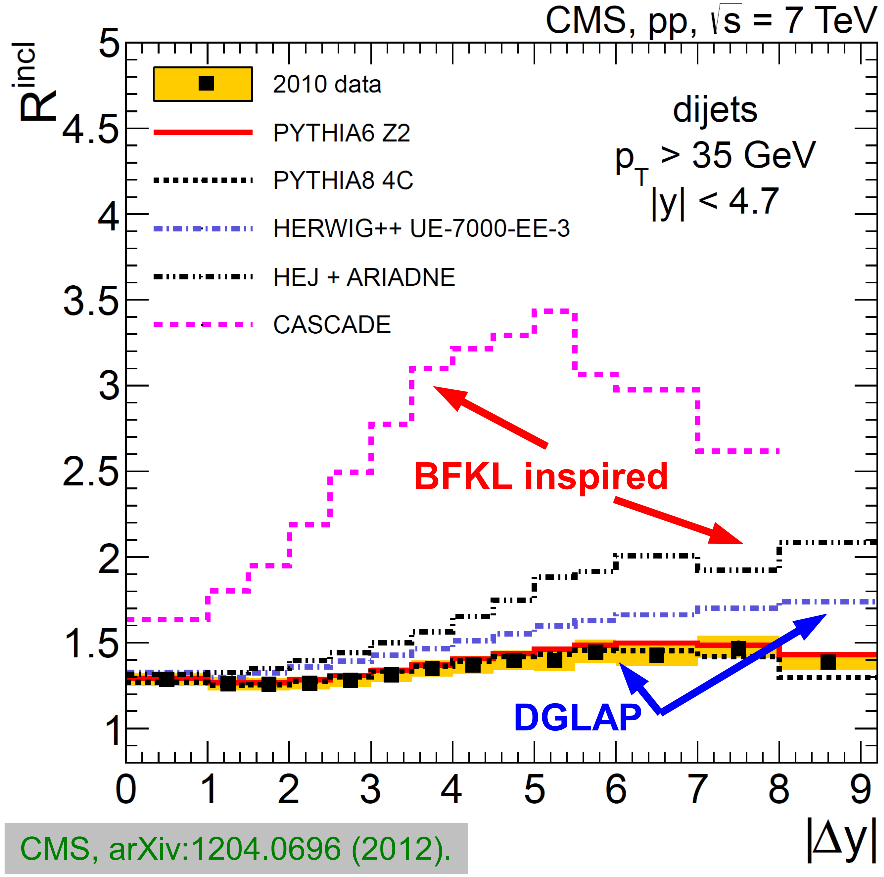
Large y coverage needed, also useful for WBF tagging jets.

Most forward-backward dijet selection



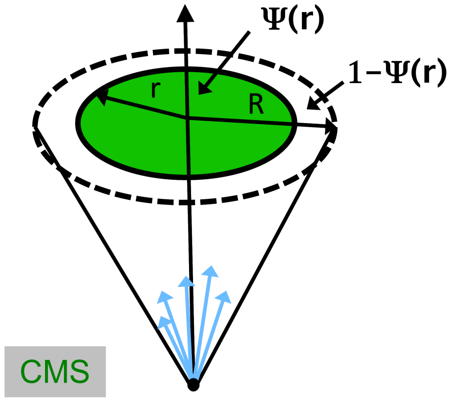
ATLAS, JHEP09, 2011

All possible dijet pair distances over leading dijet pair distance



CMS, arXiv:1204.0696 (2012).

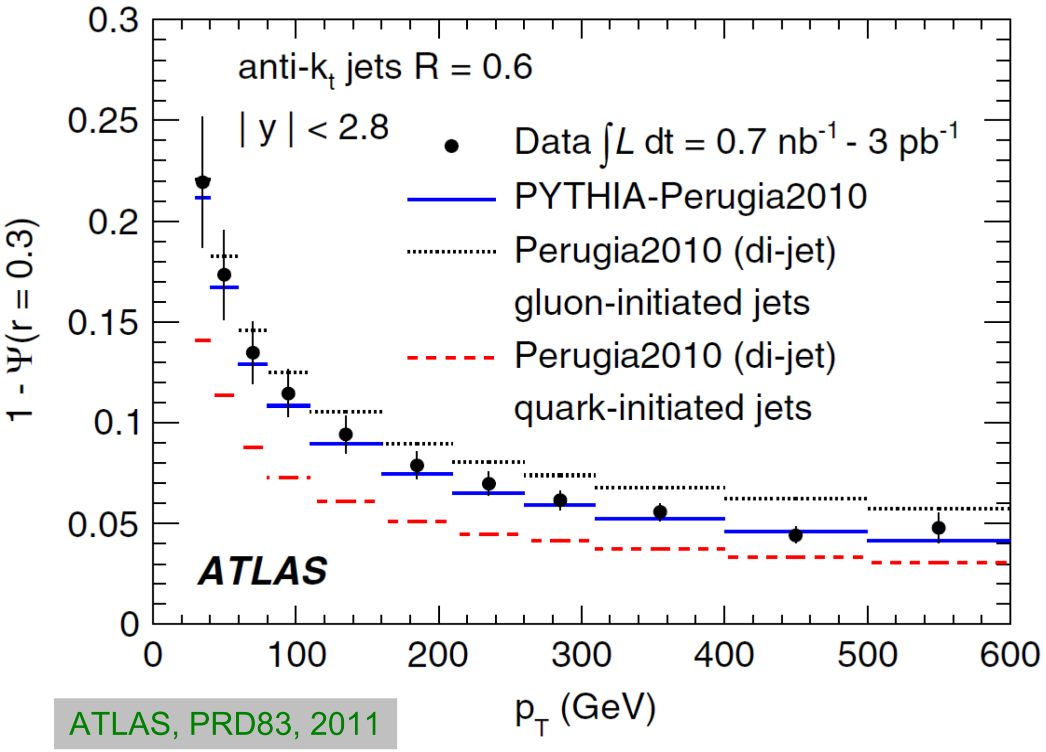
Jet Substructure



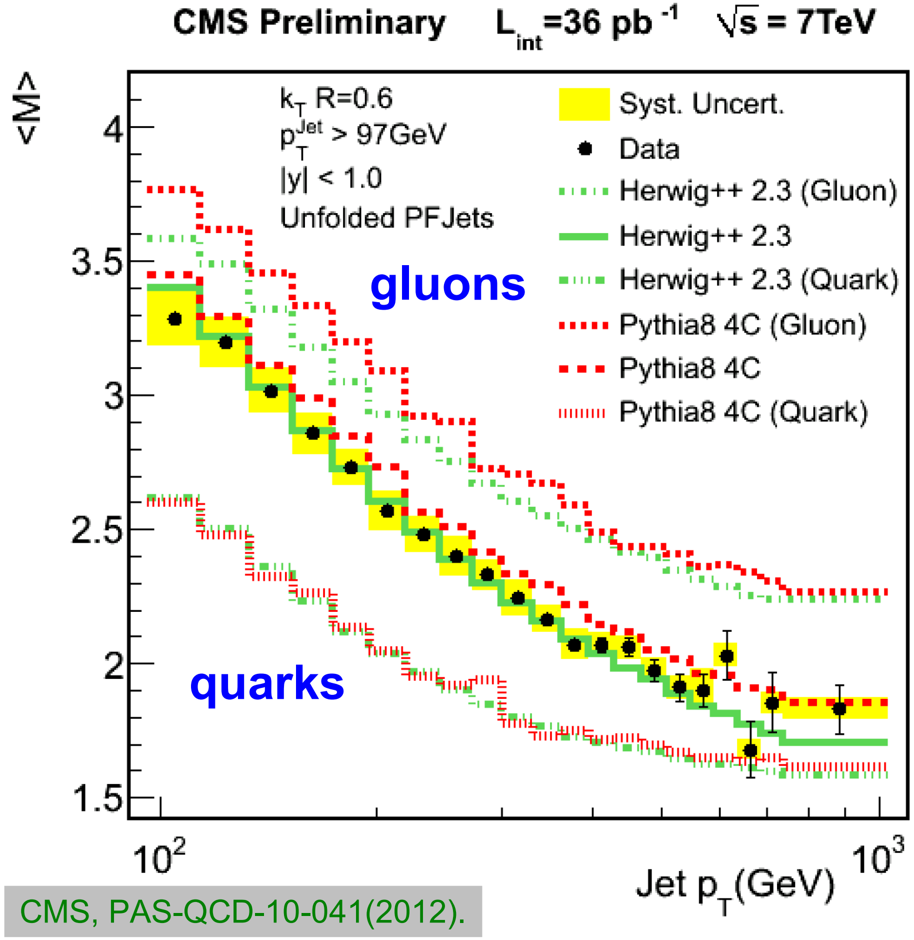
CMS

Jet shape (left) and subjet multiplicity (right) sensitive to differences in quark and gluon initiated jets

Can help also in differentiating boosted jets of heavy objects like Z' or t' … see searches talks for more on such tools.



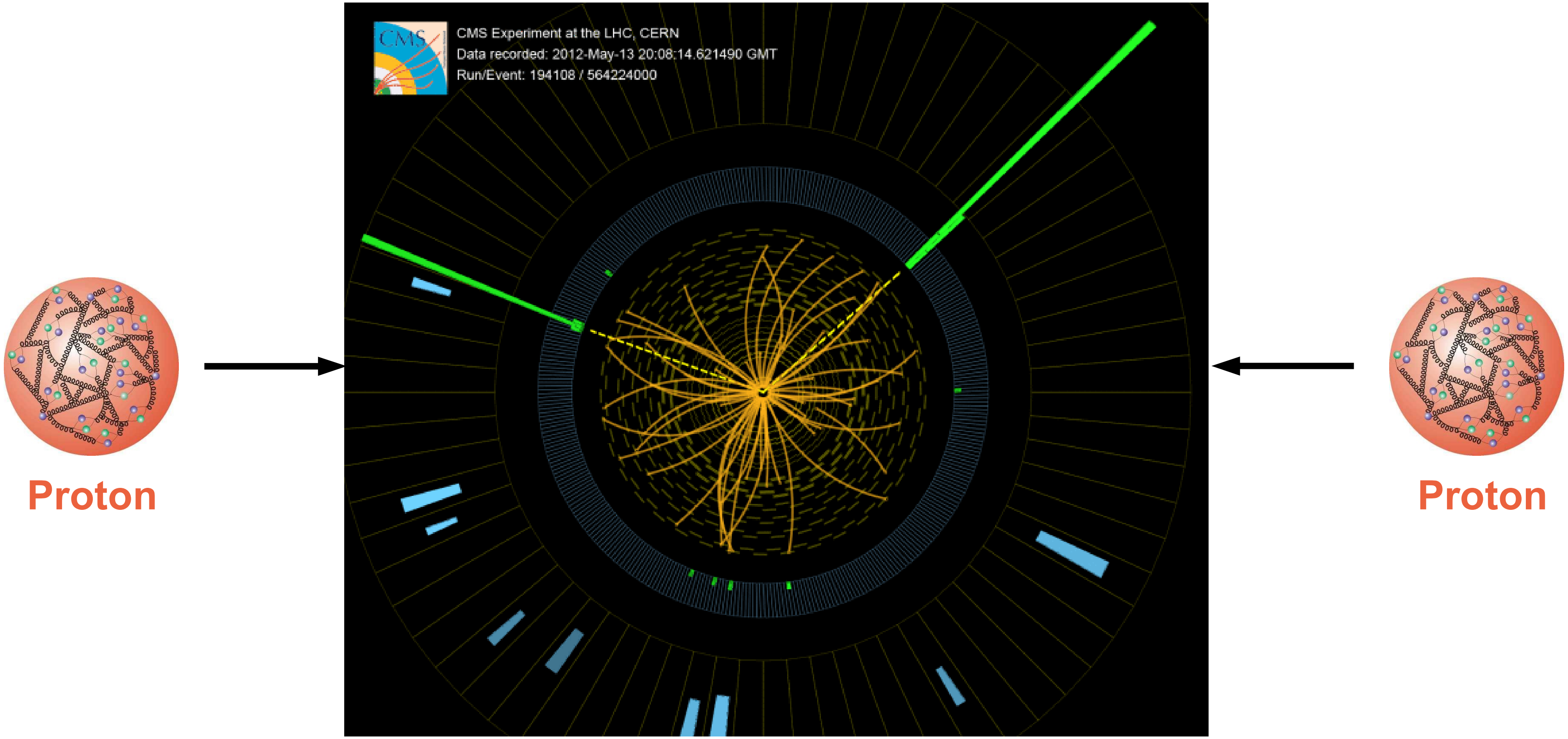
ATLAS, PRD83, 2011



CMS, PAS-QCD-10-041(2012).

(Di-)Photons

To Higgs or not?

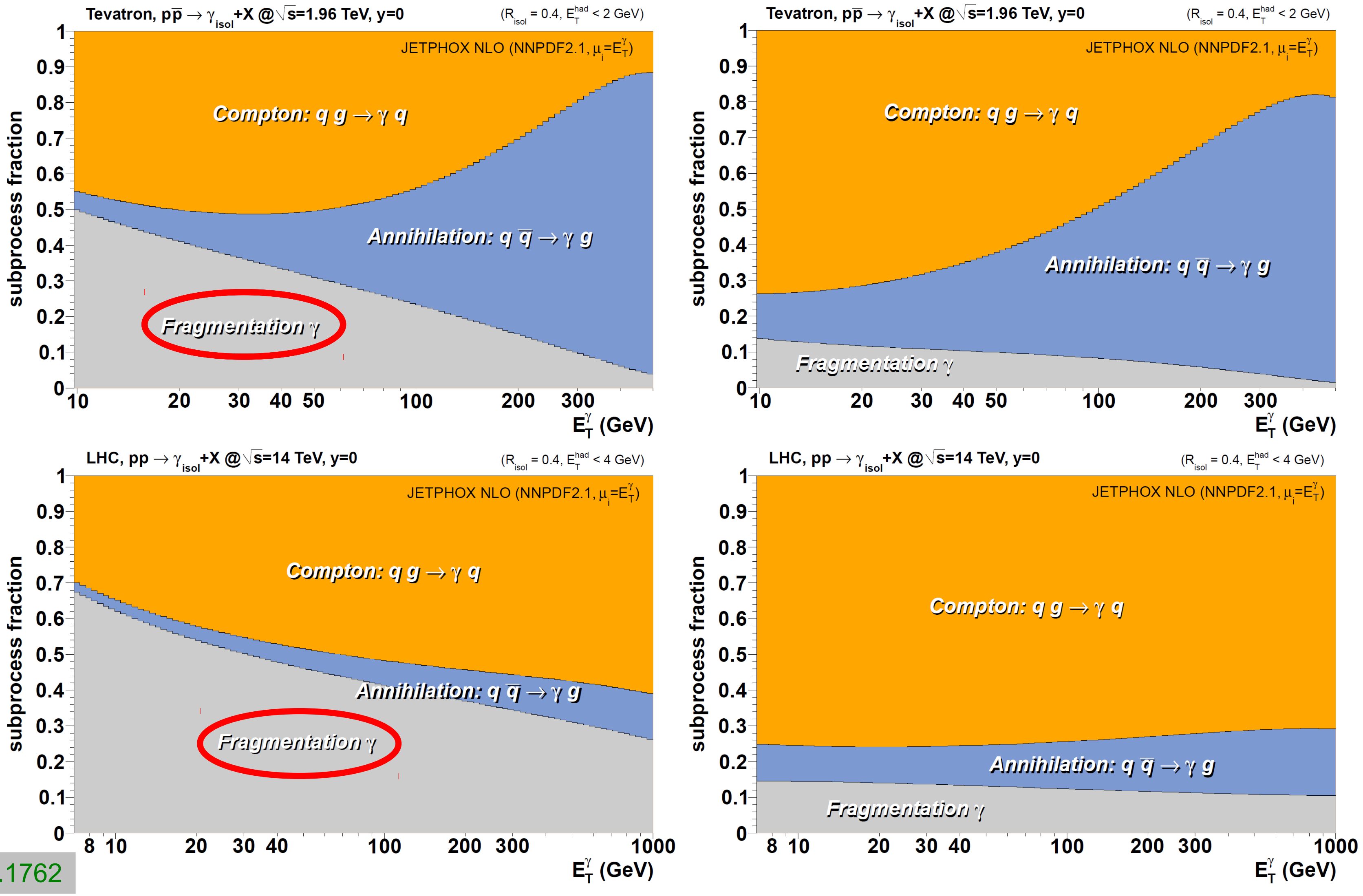


Signal Process Fractions

Inclusive **Isolated**

Tevatron

LHC 14 TeV



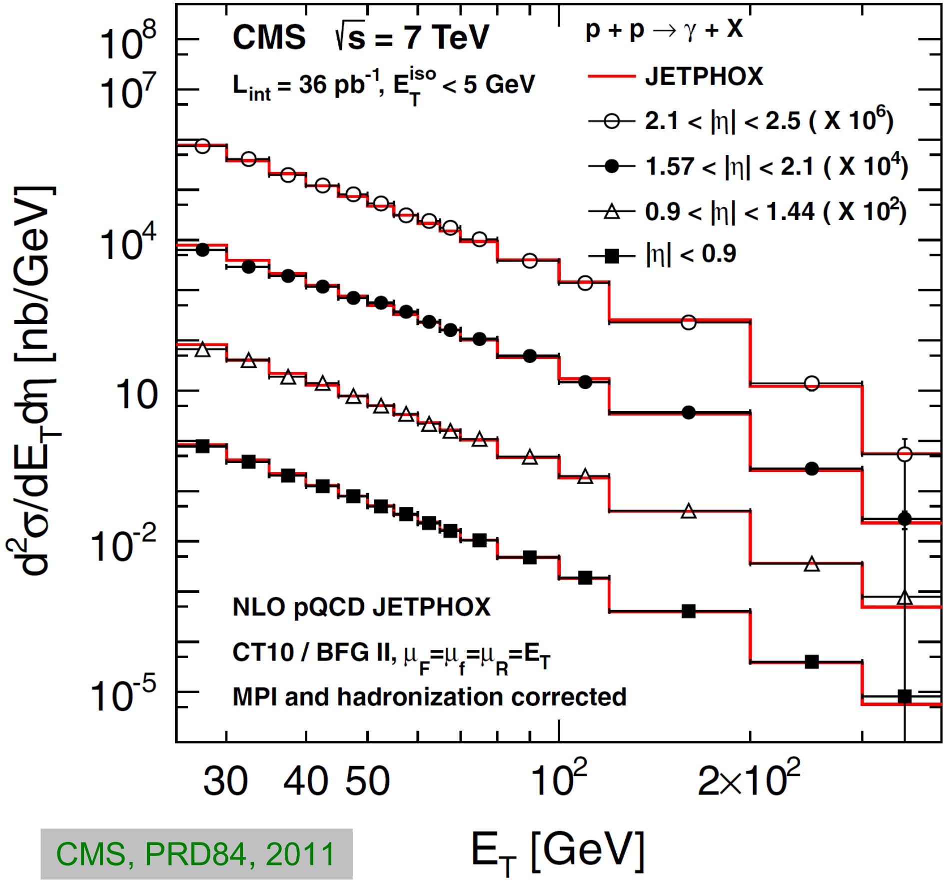
Background: Non-prompt Photons from Decays, e.g. π^0, η

d'Enterria, Rojo, arXiv:1202.1762

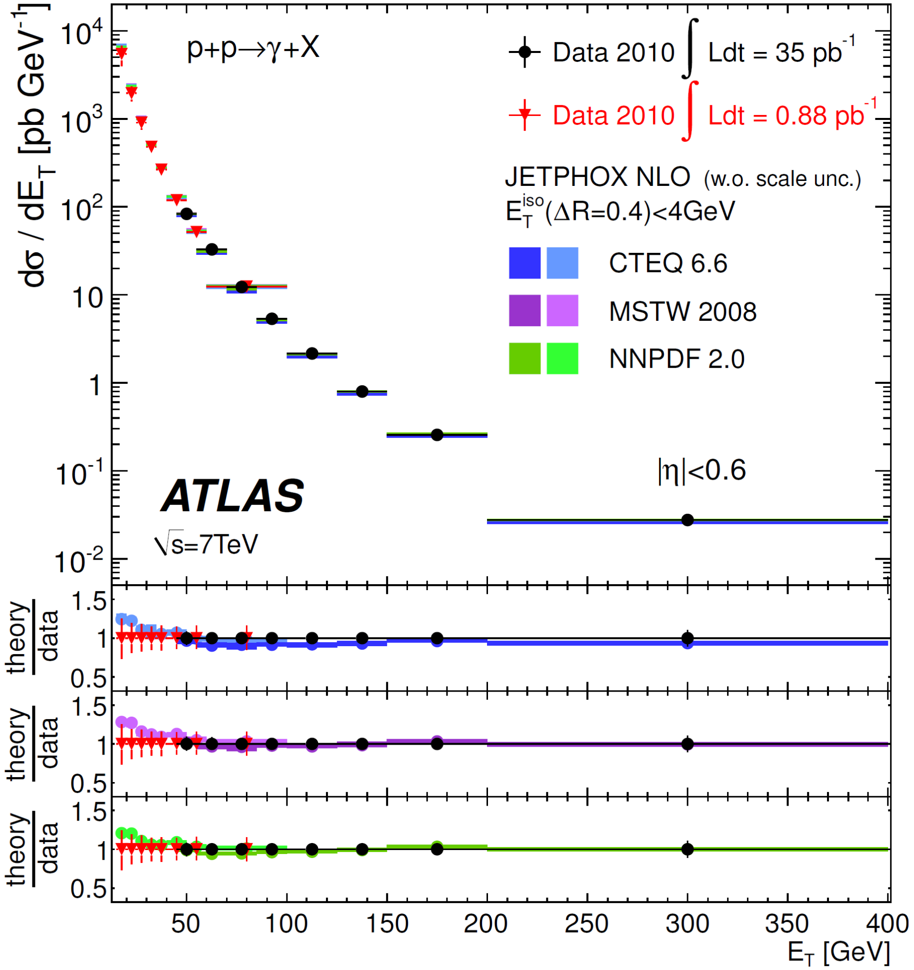
Isolated Prompt Photons

JetPhox, Catani et al., JHEP05, 2002

- Sensitive to the gluon density in the proton.
- In agreement with NLO (JetPhox) from ~25 up to 400 GeV, $|\eta| < 2.5$
- Limiting factor: Scale uncertainties in theory



CMS, PRD84, 2011

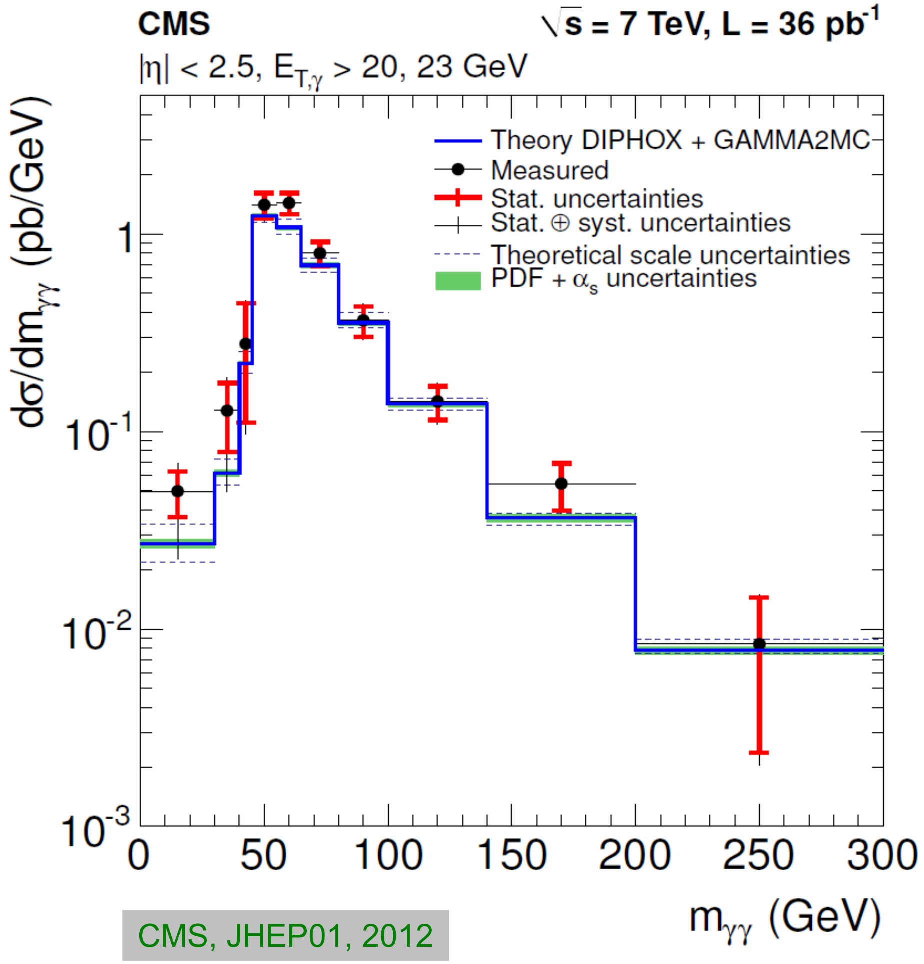


ATLAS, PLB706, 2011:ATL-PHYS-PUB-2011-013

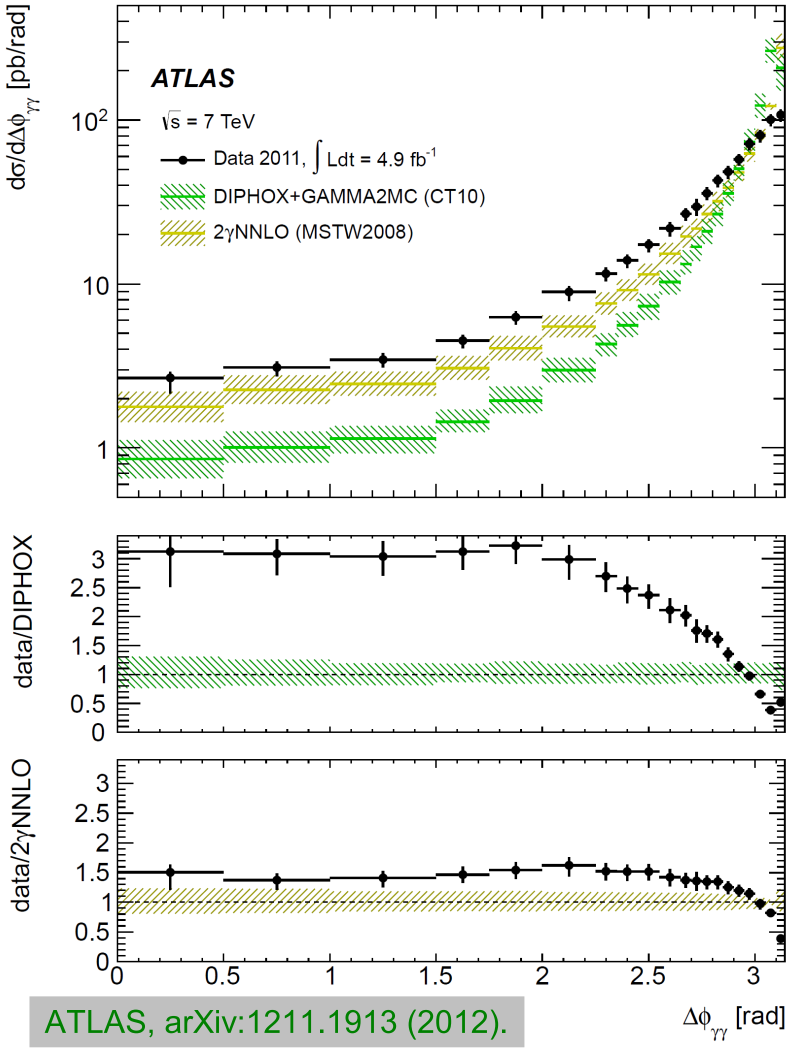
Di-Photons

- Irreducible background to Higgs → γγ
- In agreement with NLO in p_T, and mass spectra above ~50 GeV up to 400 GeV

New from ATLAS:
Now much better described by 2γNNLO

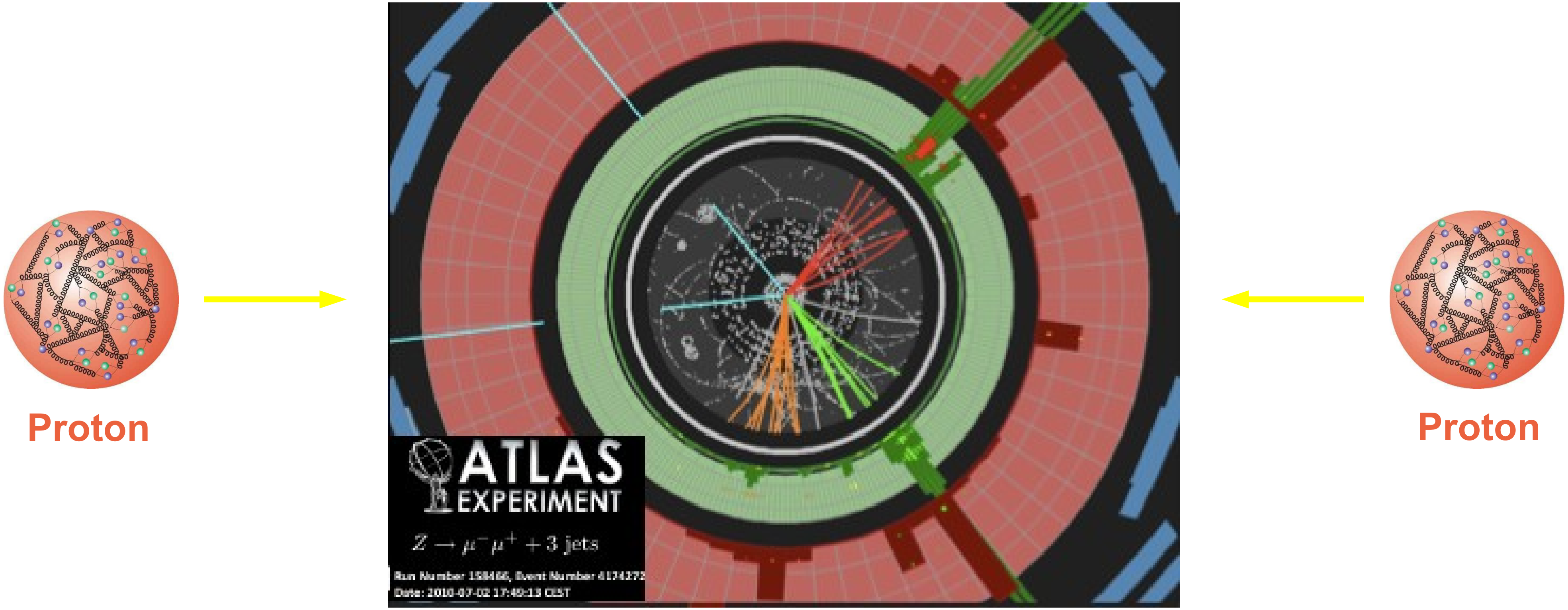


CMS, JHEP01, 2012



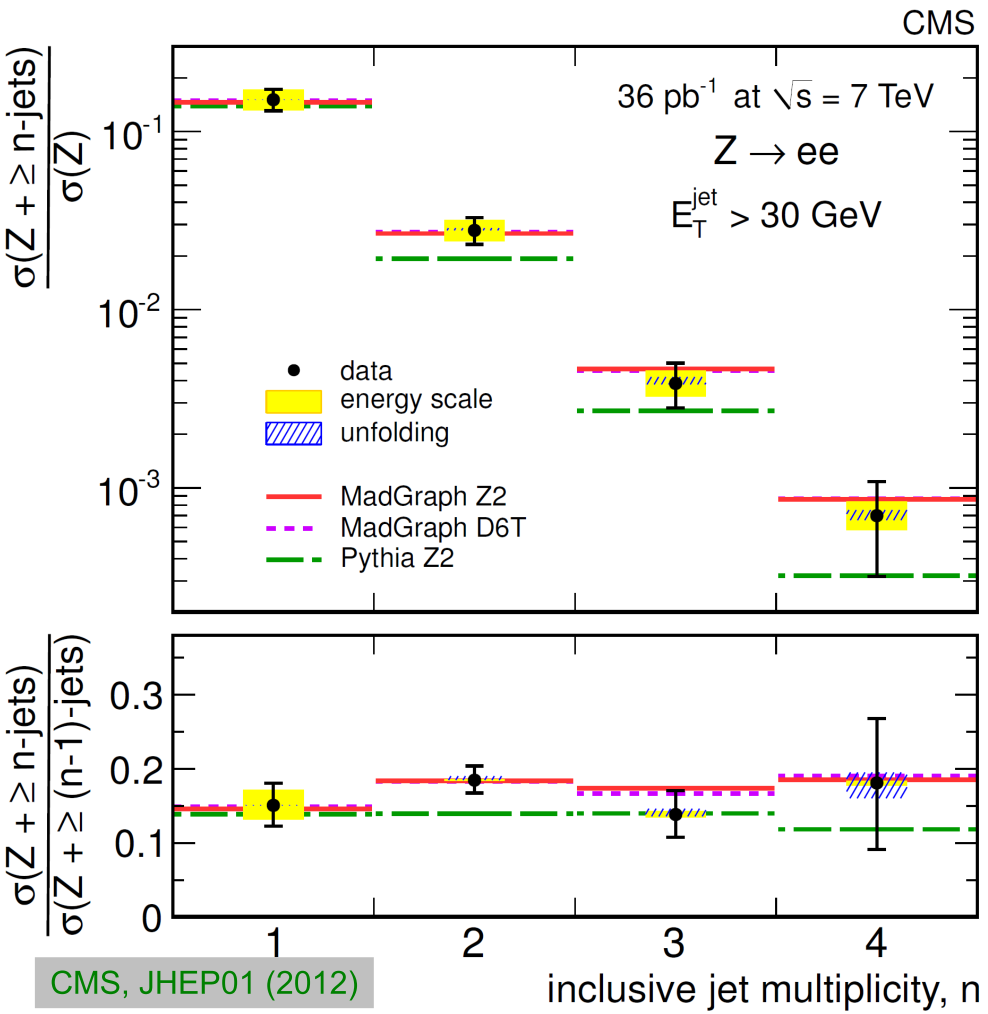
ATLAS, arXiv:1211.1913 (2012).

Boson + Jets

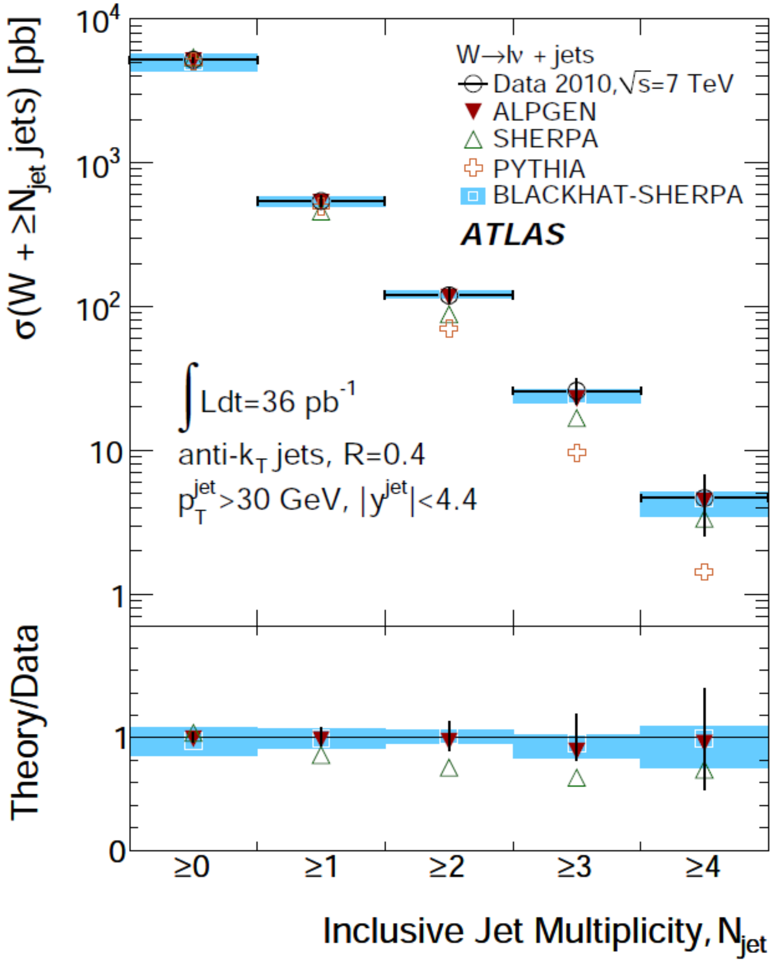

Proton
ATLAS
EXPERIMENT
$Z \rightarrow \mu^-\mu^+ + 3$ jets
Run Number 158466, Event Number 4174272
Date: 2010-07-02 17:40:13 CEST
Proton

W/Z + Inclusive Jet Multiplity

In general agreement between data and theory @ NLO up to 4 jets



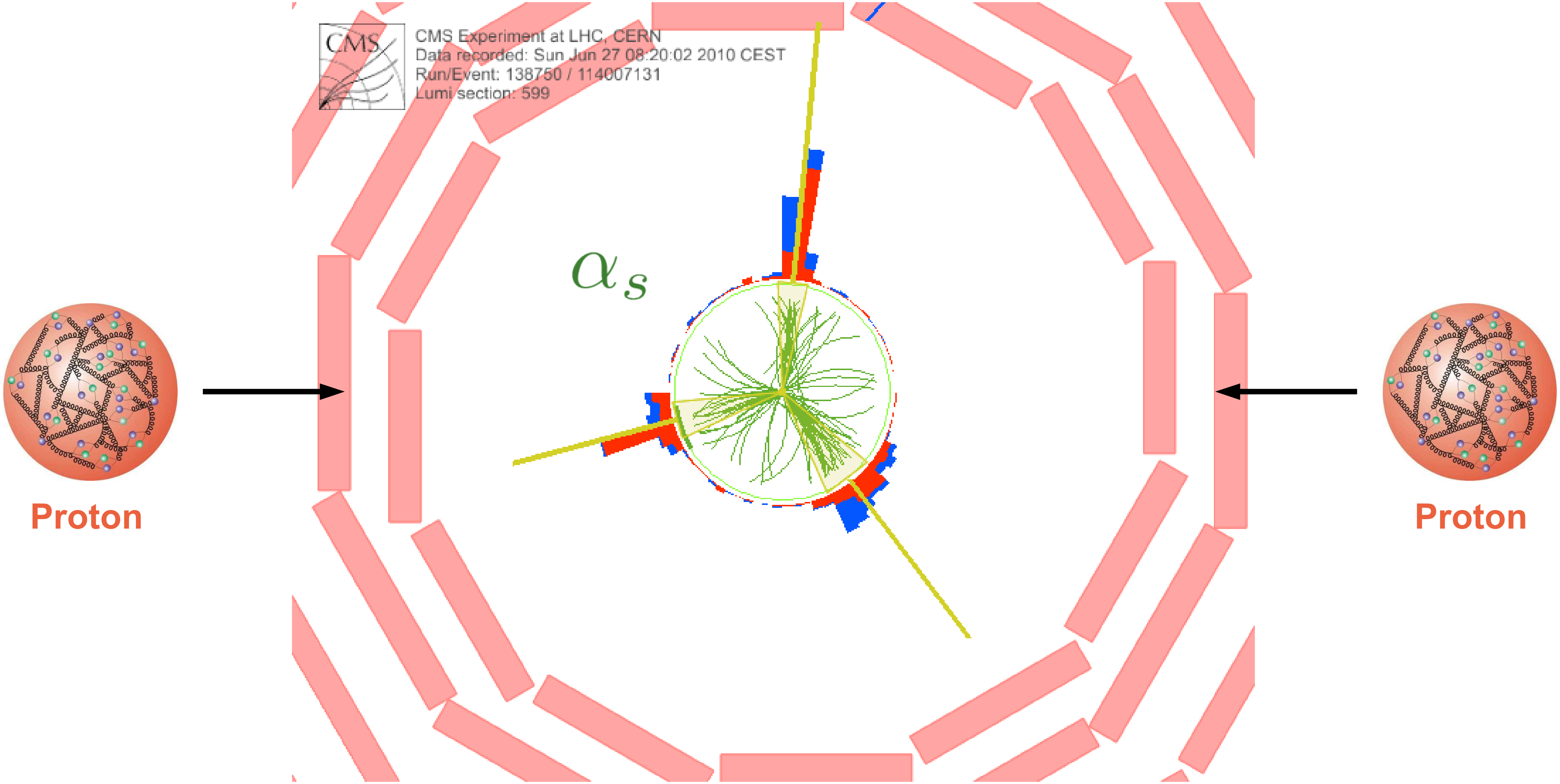
CMS, JHEP01 (2012)



ATLAS, PRD85 (2012)

Multijets and α_s

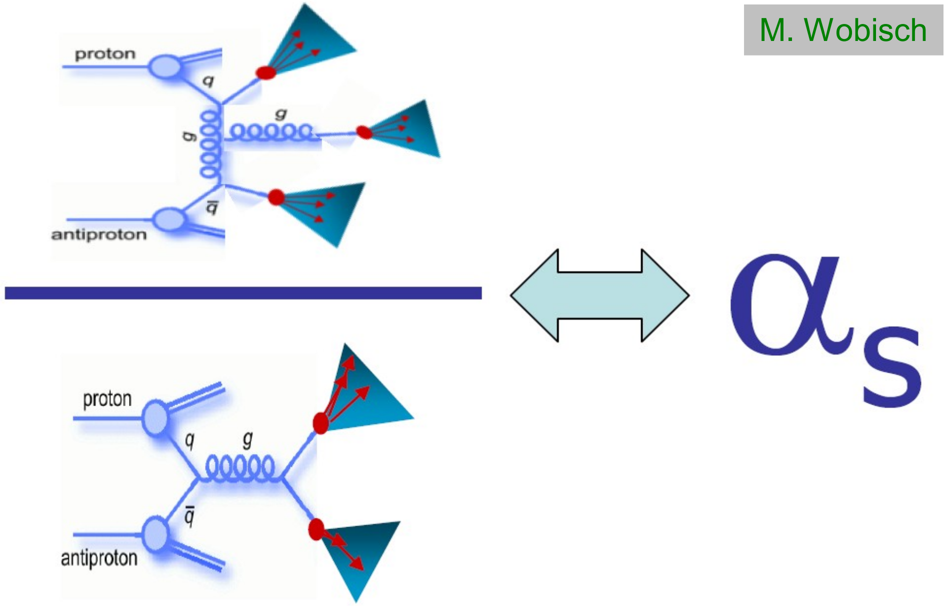
α_s at High Scales



3-Jets and α_s

- **Avoids direct dependence on PDFs and the RGE of QCD**
- **Use cross-section ratios!**
- **→ reduces other theor. and exp. uncertainties along the way**
- **→ eliminates luminosity dependence (normalization)**
- **Choices of CMS:**
  - **Ratio of inclusive 3-jet to 2-jet production**
  - **Average dijet p_T as scale**
- **Other 3-jet observables possible, see e.g. propositions by D0**

M. Wobisch



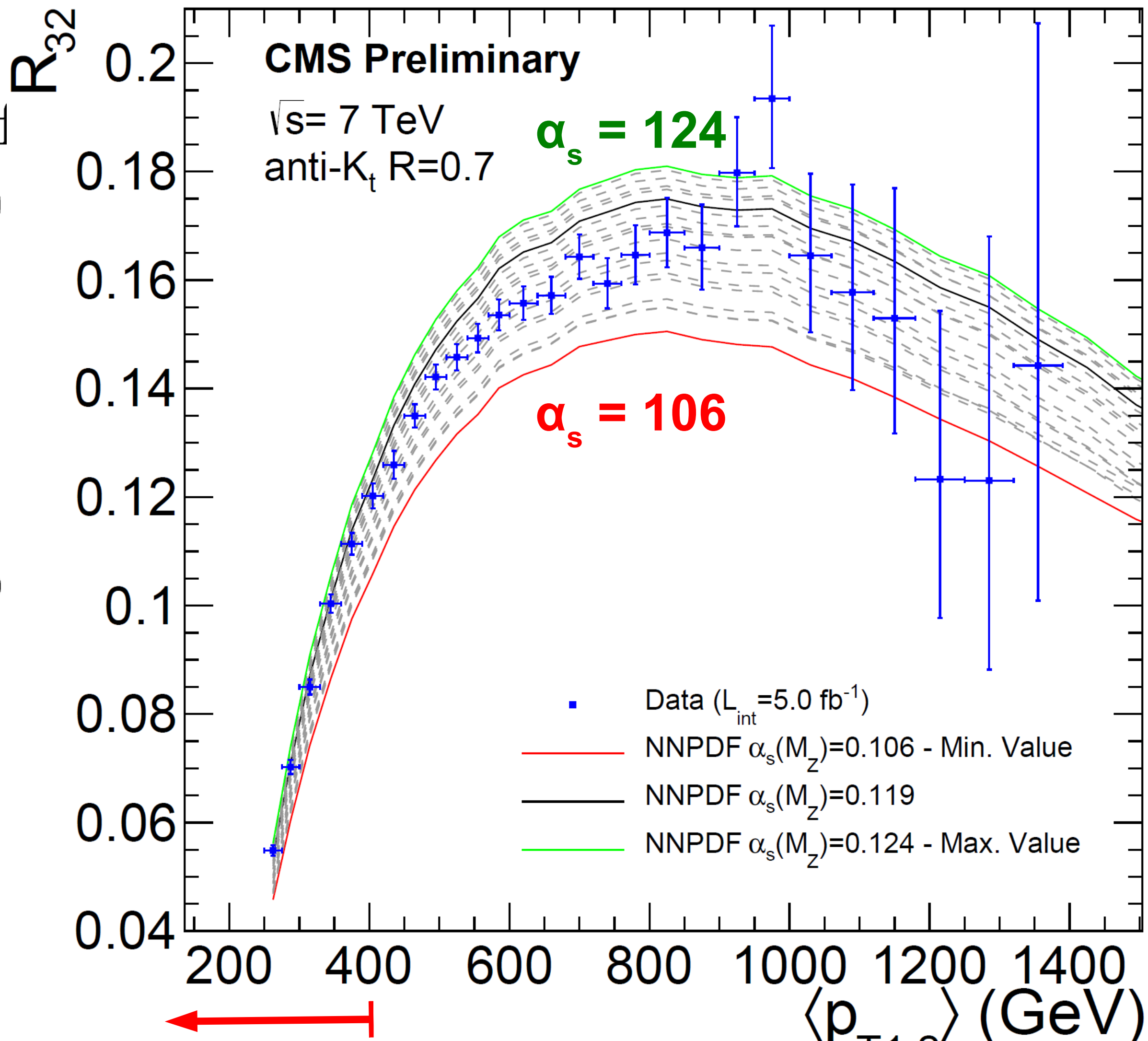
$$R_{32} = \frac{d\sigma_{3+}/dp_{\mathrm{T}}}{d\sigma_{2+}/dp_{\mathrm{T}}} \propto \alpha_s(Q)$$

$$Q = \langle p_{\mathrm{T}1,2} \rangle = \frac{p_{\mathrm{T}1} + p_{\mathrm{T}2}}{2}$$

D0, PLB718 (2012) 56-63

Measurement of Ratio R_{32}

- **Integrated luminosity:** $\mathcal{L}_{\mathrm{int}} = 5.0\,$f
- **Minimal jet pT:** $p_{\mathrm{T}} > 150$
- **Maximal jet rapidity:** $|y| < 2.5$
- **Agreement within uncertainties**
  - **Scale uncertainty:** ${}^{+2}_{-5}\%$
  - **PDF uncertainty:** $1.5 - 2.3\%$
- **Fits only above 400 GeV to avoid threshold effects**



Not used

NNPDF21: $\alpha_s(M_Z) = 0.1143 \pm 0.0064$

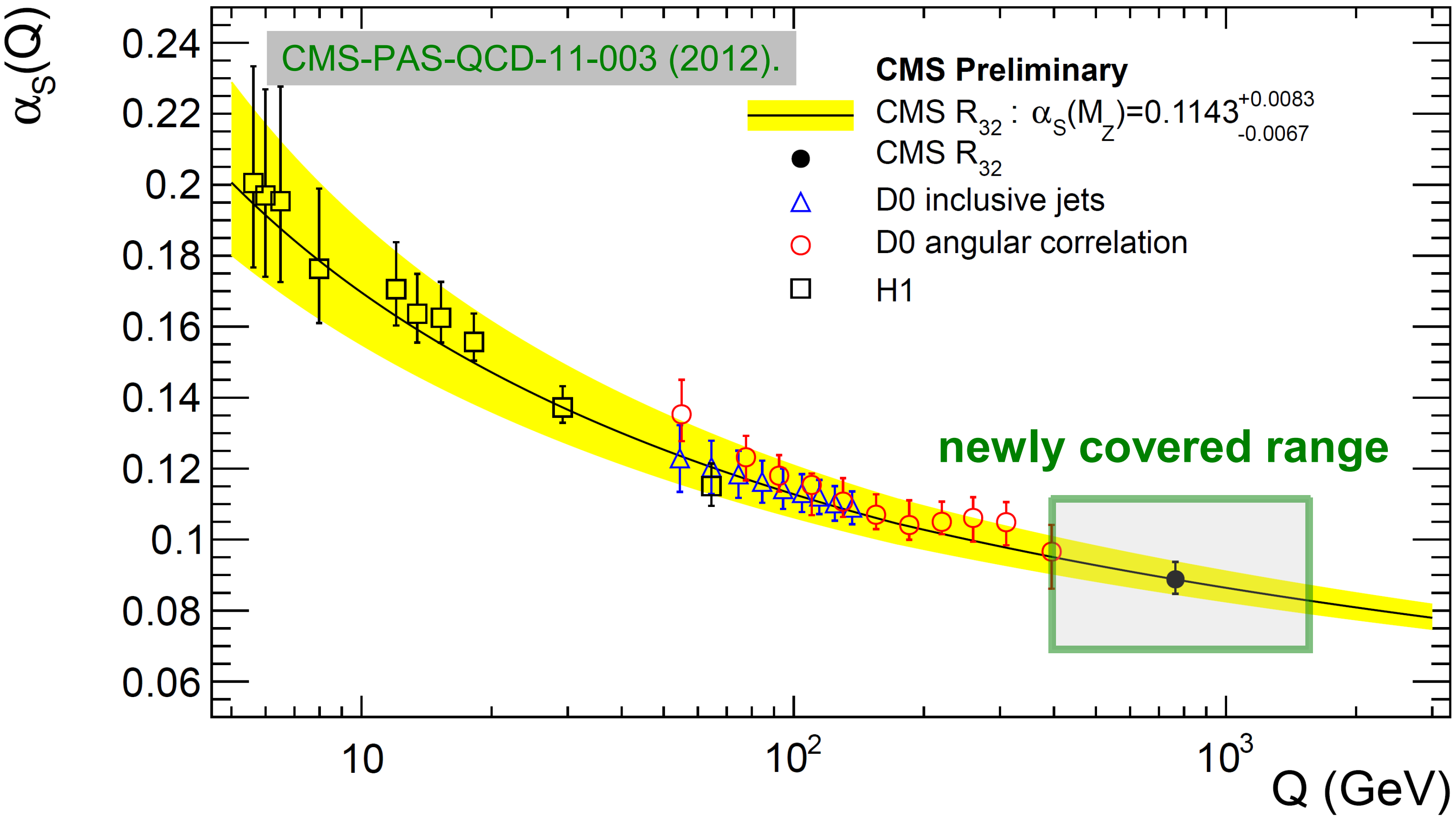
CT10: $\alpha_s(M_Z) = 0.1130 \pm 0.0080$

MSTW2008: $\alpha_s(M_Z) = 0.1135 \pm 0.0096$

CMS-PAS-QCD-11-003 (2012).

Determination of α_s (NLO)

- **Comparison to extractions from other hadron collider experiments**
- **Although only one point shown here extraction works equally well in e.g. four subranges**



PDF uncertainty: **Repeat fit for each replica → get estimators for μ and σ**
Scale uncertainty: **Repeat fit for all six variations → get maximal deviation**

NLO!

$$\alpha_s(M_Z) = 0.1143 \pm 0.0064\,(\mathrm{exp}) \pm 0.0019\,(\mathrm{PDF}) \pm^{0.0050}_{0.0000}\,(\mathrm{scale})$$

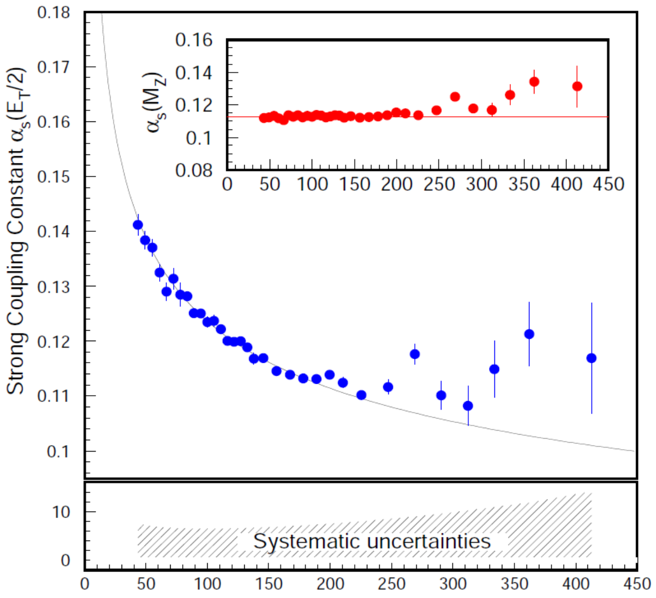
α_s from inclusive Jets (NLO)

CDF: $\alpha_s(M_Z) = 0.1178 \pm 0.0001(\mathrm{stat})^{+0.0081}_{-0.0095}(\mathrm{expt.syst})$

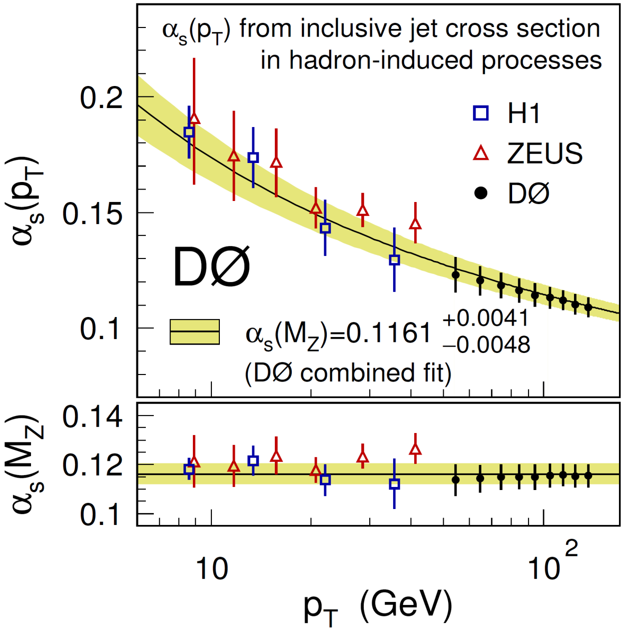
D0: $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}(\mathrm{total})$

M/S: $\alpha_s(M_Z) = 0.1151 \pm 0.0001(\mathrm{stat}) \pm 0.0047(\mathrm{expt.syst})^{+0.0080}_{-0.0073}(\mathrm{p_T}, \mathrm{R}, \mu, \mathrm{PDF}, \mathrm{NP})$

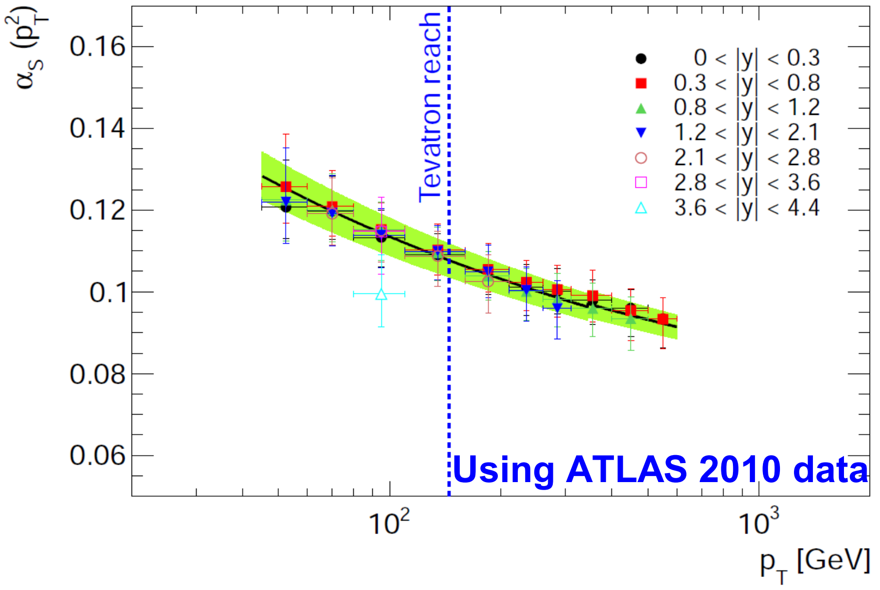
Attention:
Evolution of PDFs from low to high Q assumes the validity of the renormalization group equation (RGE).



CDF, PRL88, 2002



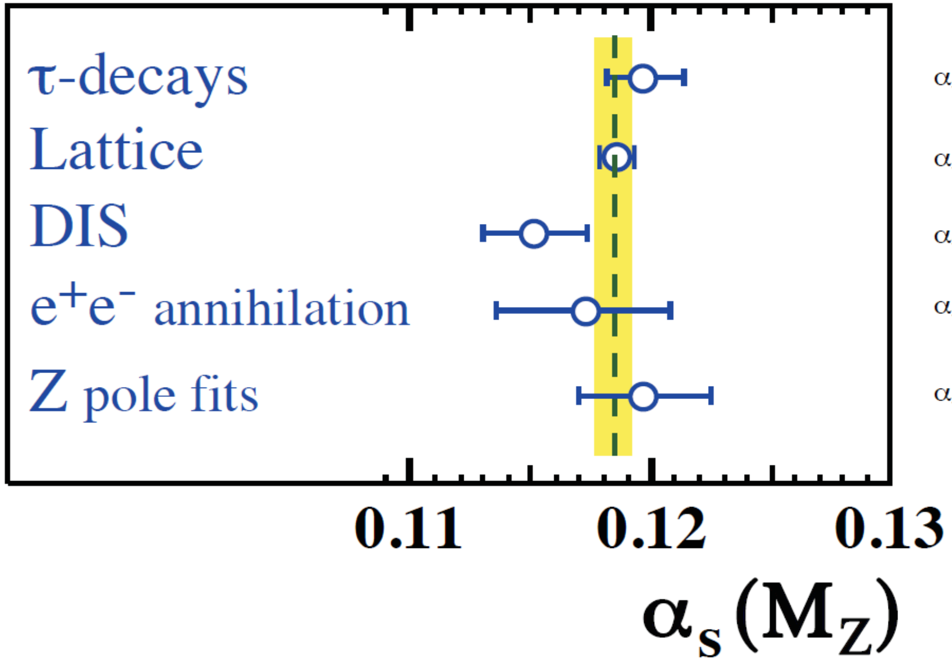
D0, PRD80, 2009



Malaescu/Starovoitov, EPJC72, 2012

α_s World Summary

S. Bethke, 2012:



$\alpha_s(M_Z)$= 0.1197 ± 0.0016

$\alpha_s(M_Z)$= 0.1185 ± 0.0007

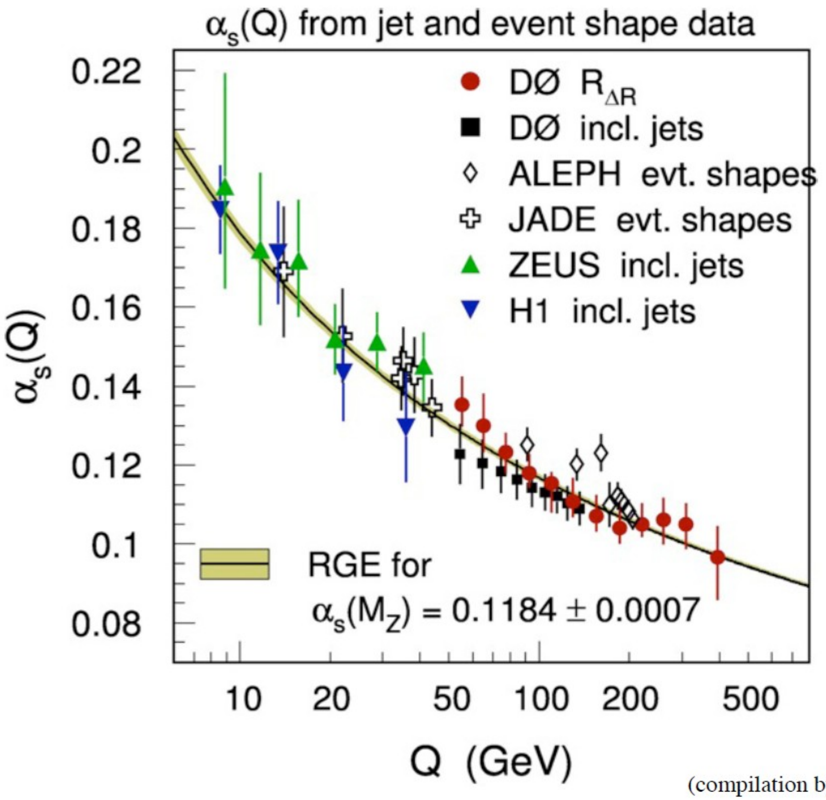
$\alpha_s(M_Z)$= 0.1151 ± 0.0022

$\alpha_s(M_Z)$= 0.1172 ± 0.0037

$\alpha_s(M_Z)$= 0.1197 ± 0.0028

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

PDG2012



D0, PLB718 (2012) 56-63

(compilation by D0)

But: Jet data from hadron colliders not included!
Jets at NNLO urgently needed!
In progress by at least groups of
Th. Gehrmann et al. and N. Glover et al.

Tevatron limit, published this year

LHC from jets starts here ...

Summary

- **We have a powerful accelerator and beautifully working detectors**
- **Data quantity and quality at the LHC open up new regimes in phase space and precision to be exploited**
  - **New measurements at highest scales and up to high y**
  - **PRECISION measurements**
- **We have a plethora of new $N^{?}LO$ calculations (plus showers) and only start to exploit all the new possibilities**
- **Interplay between strong and electroweak interactions becomes interesting at the TeV scale**
- **Carefully check everything for new features!**

Concluding Remark

- **Some people describe the LHC as a**
  - **SUSY search machine**

Concluding Remark

- Some people describe the LHC as a
  - SUSY search machine
  - Higgs-like boson discovery machine

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- I hope I could convince you that it is also a

Concluding Remark

- Some people describe the LHC as a
  - SUSY search machine
  - Higgs-like boson discovery machine
  - top factory
- I hope I could convince you that it is also a
  - **high-scale jet laboratory**

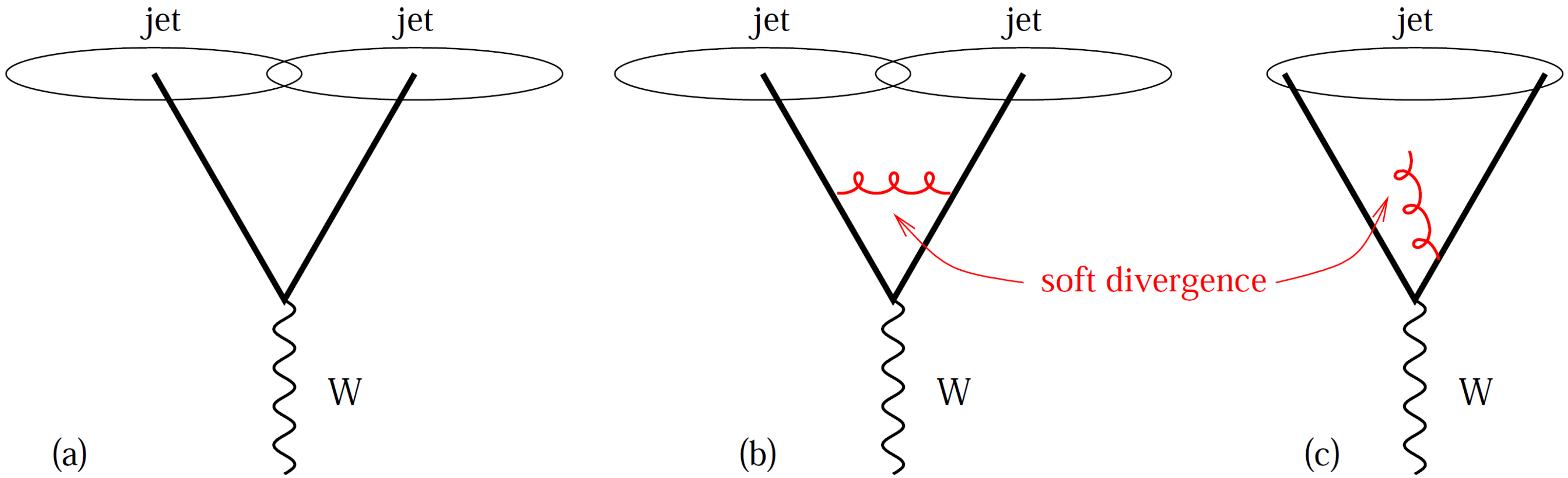
Make your choice and have fun.
Thank you for your attention!

Backup Slides

IC-SM Problem

Iterative Cone with Split/Merge (IC-SM)

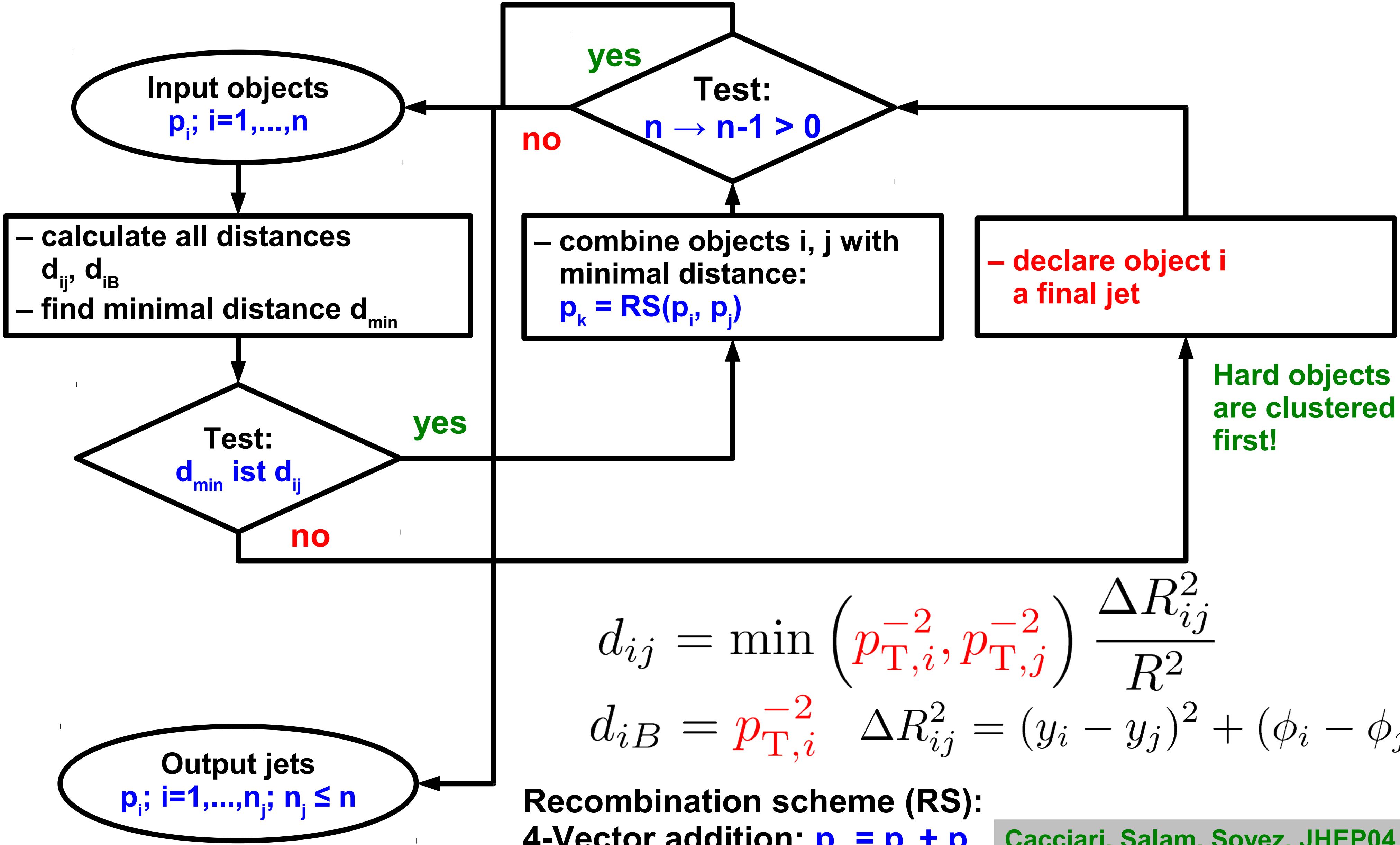
→ not all objekts end up in jets, e.g. when no starting cone close enough (dark jets)
→ collinear-unsafe because of minimal seed pT
→ infrared-unsafe ...



Fix Trial: MidPoint Cone → Additionally investigate all mid-points between seed cones
→ again unsafe, shows up in more complex topologie
Found late: Safe cone algorithm: Seedless Infrared-Safe Cone (SISCone)
→ needs ~ 2 orders of magnitude more computing time → rarely used

Jetography, G. Salam, hep-ph/0906.1833

anti-k_T – hh



Input objects
p_i; i=1,...,n

– calculate all distances d_{ij}, d_{iB}
– find minimal distance d_{min}

Test:
d_{min} ist d_{ij}

yes

– combine objects i, j with minimal distance:
$p_k = RS(p_i, p_j)$

Test:
n → n-1 > 0

yes

no

no

– declare object i a final jet

Hard objects are clustered first!

Output jets
p_j; i=1,...,n_j; $n_j \leq n$

$$d_{ij} = \min\left(p_{\mathrm{T},i}^{-2}, p_{\mathrm{T},j}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

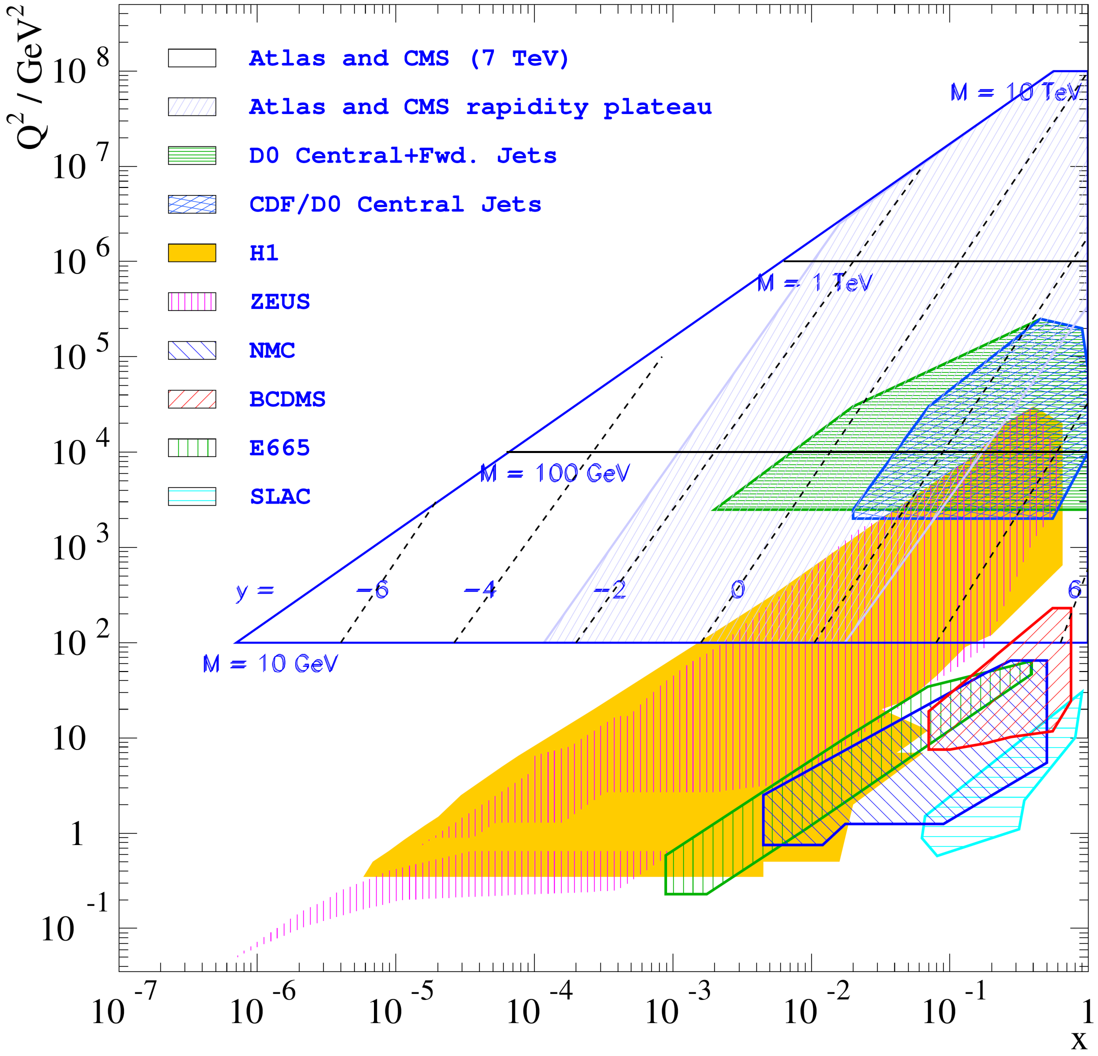
$$d_{iB} = p_{\mathrm{T},i}^{-2} \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Recombination scheme (RS):
4-Vector addition: $p_k = p_i + p_j$

Cacciari, Salam, Soyez, JHEP04 (2008).

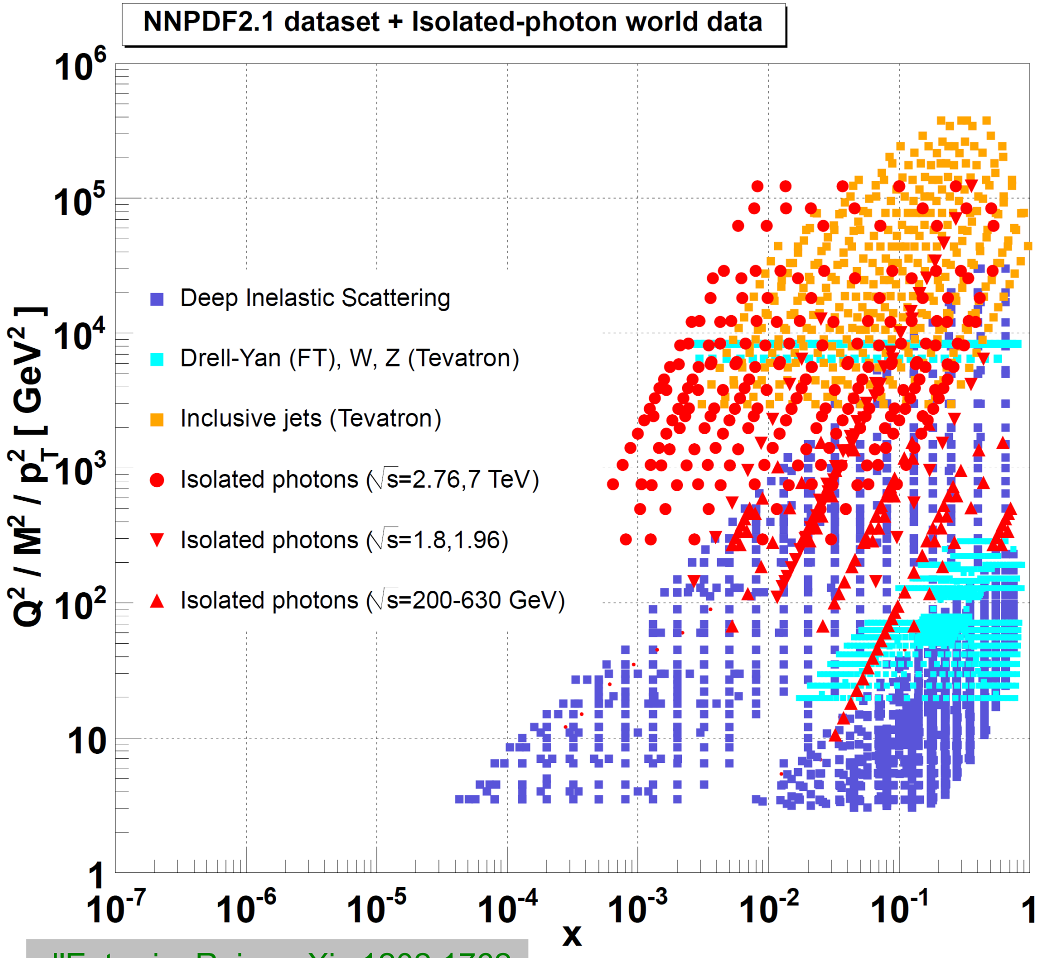
Kinematic Plane

Kinematic plane of process scale² vs. x



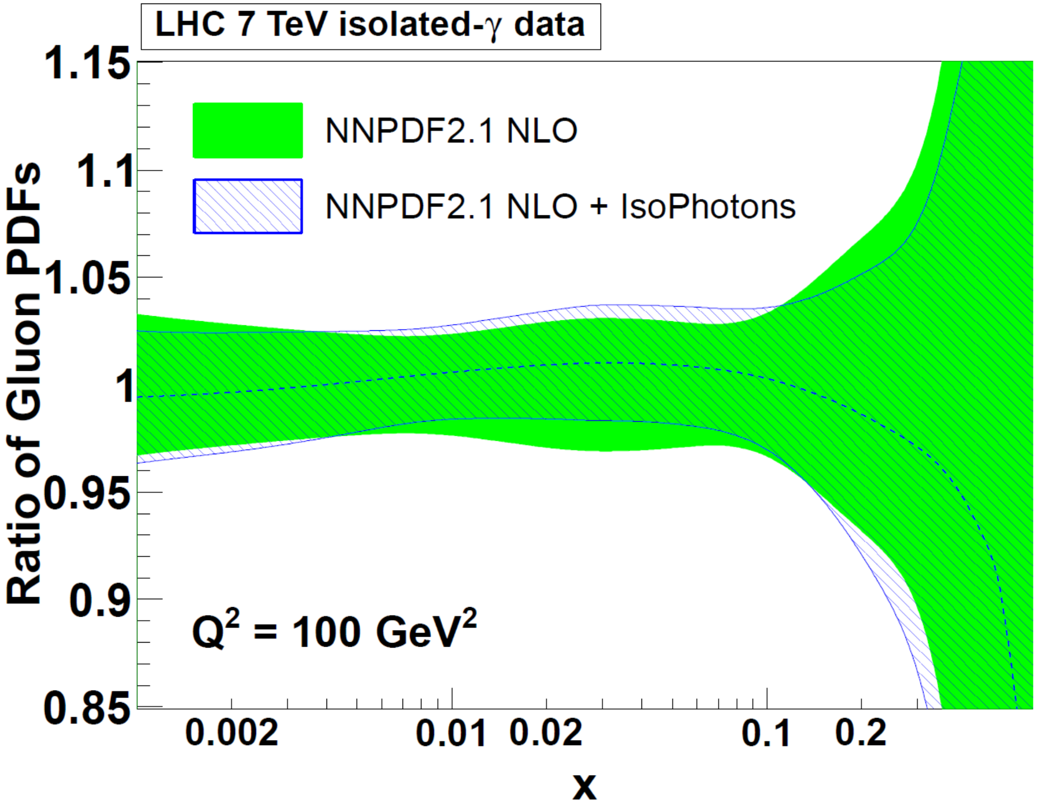
Photons and PDFs

Kinematic plane including photon data



d'Enterria, Rojo, arXiv:1202.1762

- Were abandoned for PDF fits due to discrepancies with fixed target experiments at E_{cms} of 20 – 40 GeV
- new investgation without inclusive data and At E_{CMS} > 200 GeV
- Moderate reduction in uncertainty of the gluon density at x around 0.02 by ~ 20%

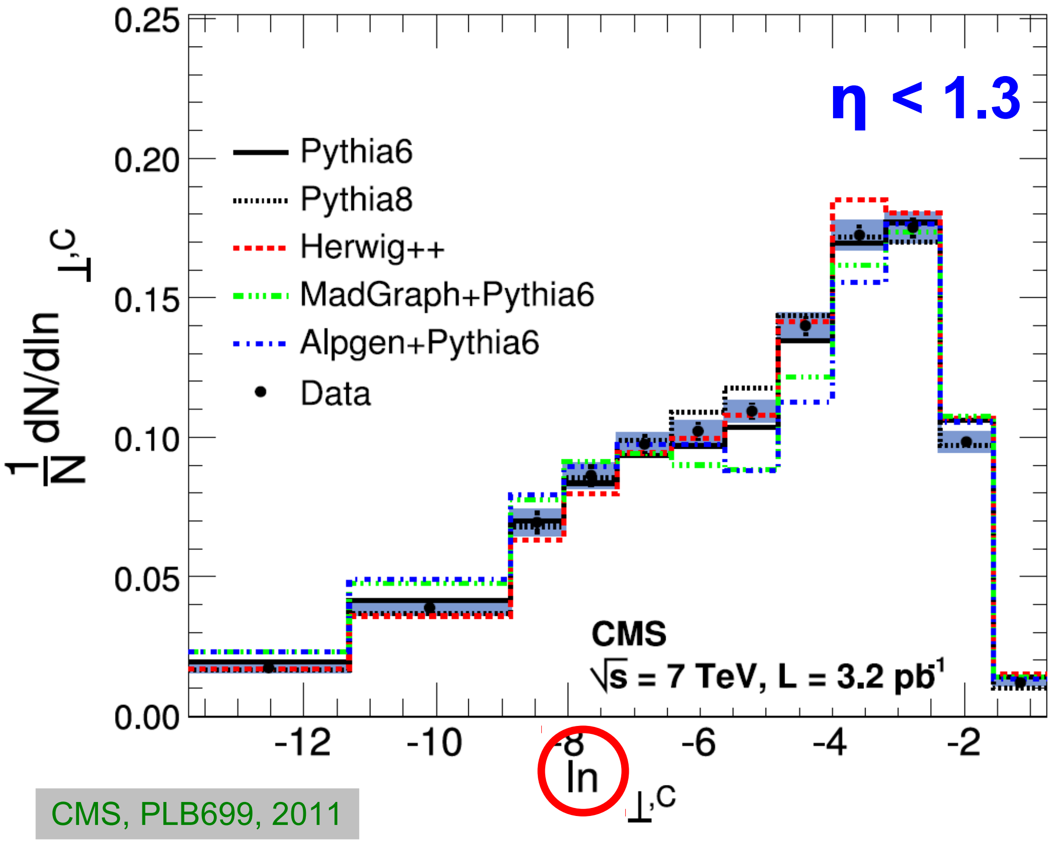


Transverse Thrust

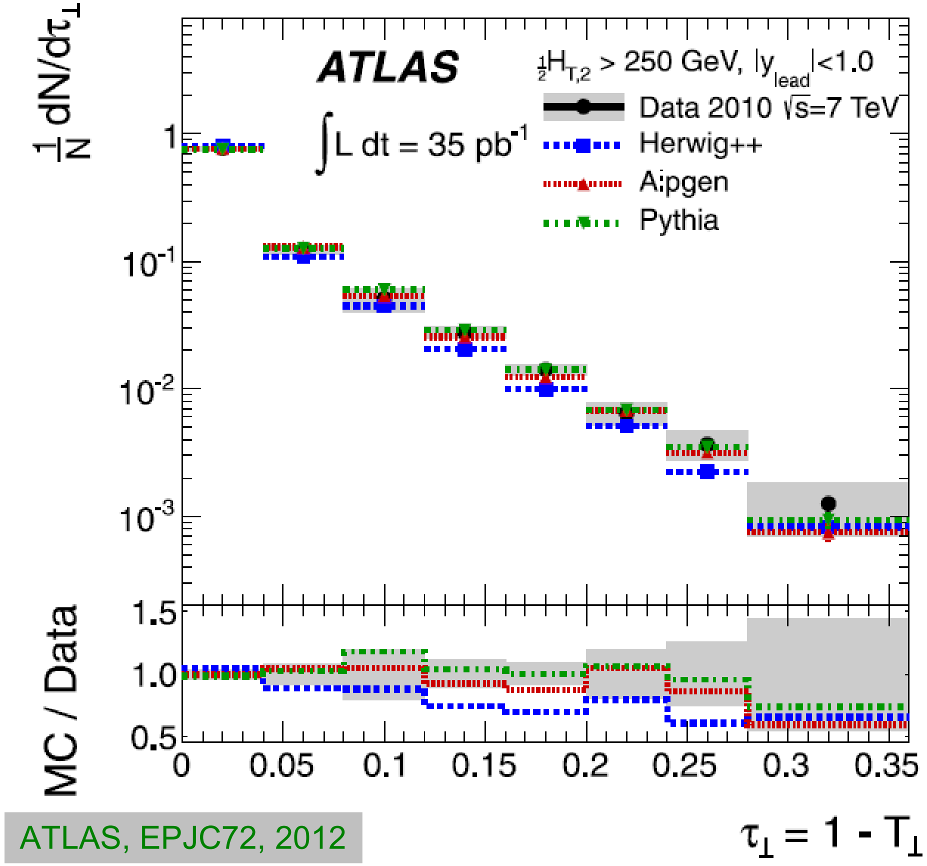
Comparison of unfolded data, CMS 3.2/pb and ATLAS 35/pb, to various MC event generators

Basic description ok, but improvements necessary

$$\tau_{\perp,C} \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

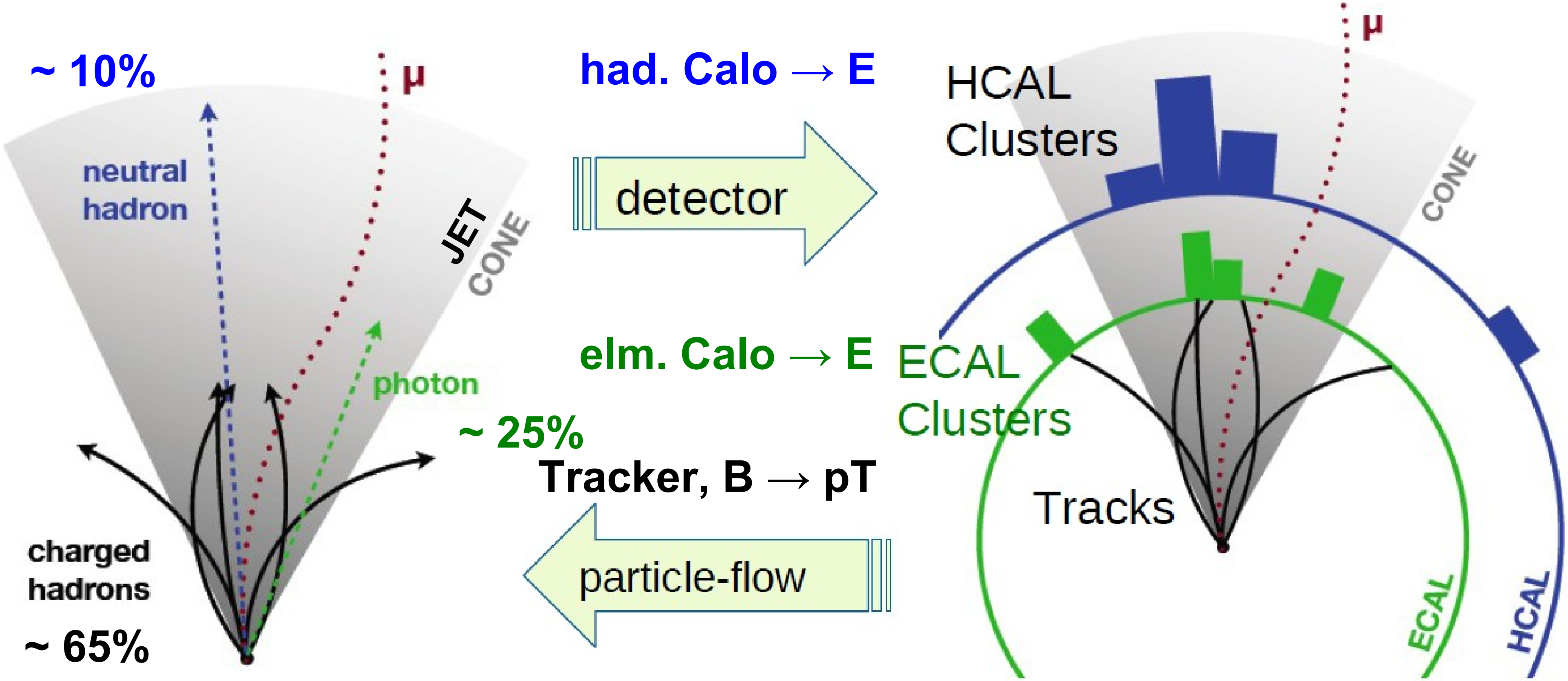


CMS, PLB699, 2011



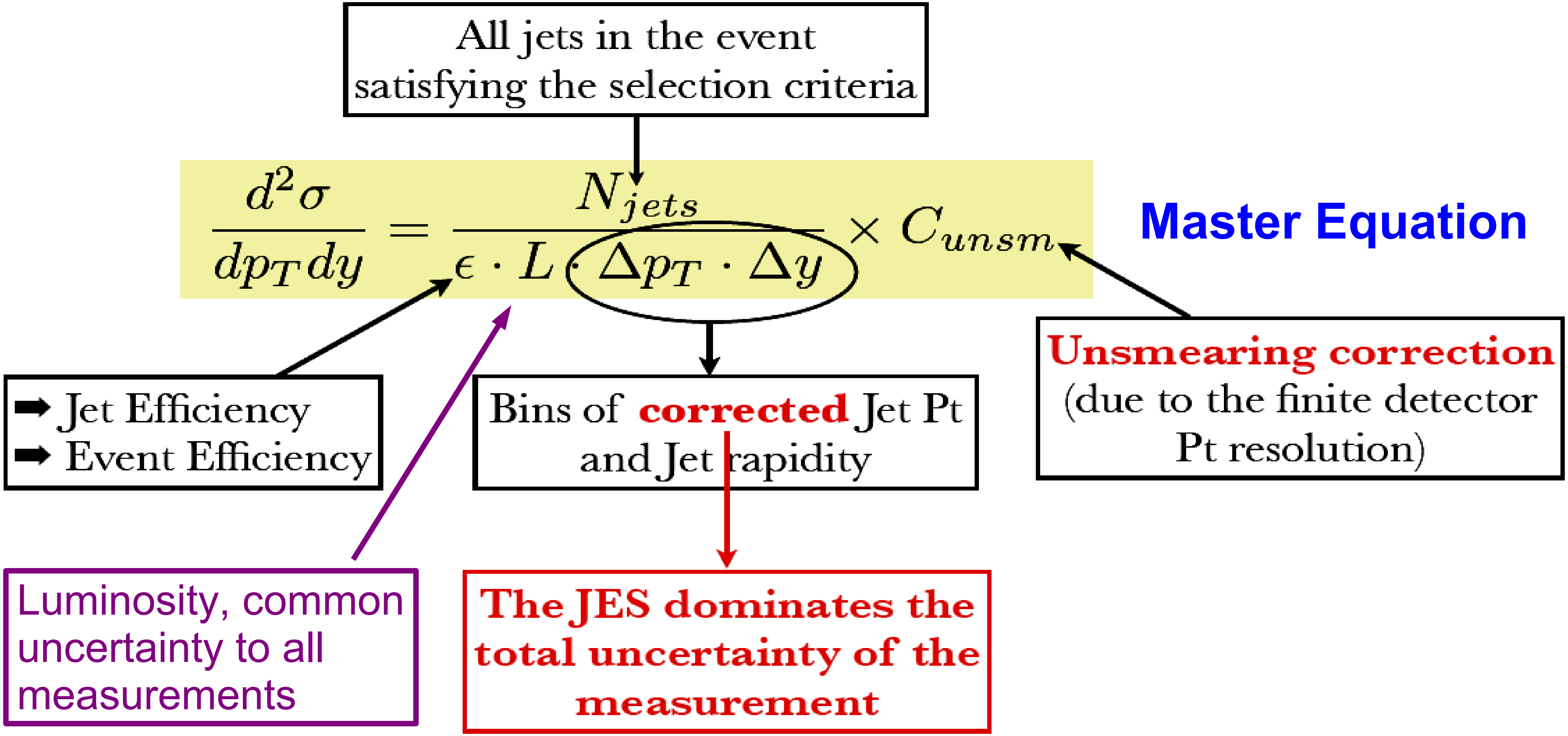
ATLAS, EPJC72, 2012

The “Particle Flow” Concept



- Combine measurements of different detector components
- Account for detector particularities with respect to particle type

Inclusive Jet Measurements



All jets in the event satisfying the selection criteria

$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\epsilon \cdot L \cdot \Delta p_T \cdot \Delta y} \times C_{unsm}$$

Master Equation

- ➡ Jet Efficiency
- ➡ Event Efficiency

Bins of **corrected** Jet Pt and Jet rapidity

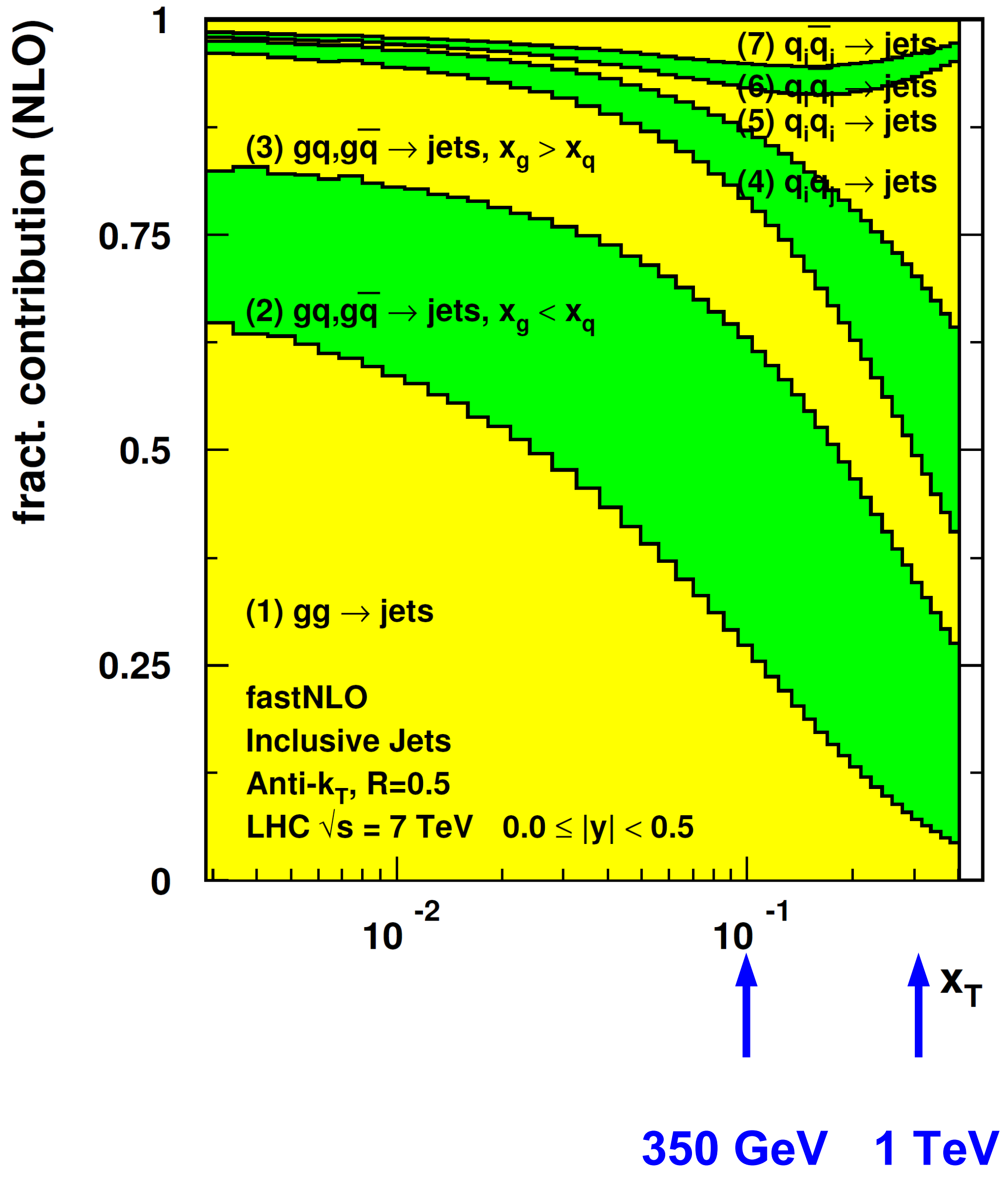
Unsmearing correction (due to the finite detector Pt resolution)

Luminosity, common uncertainty to all measurements

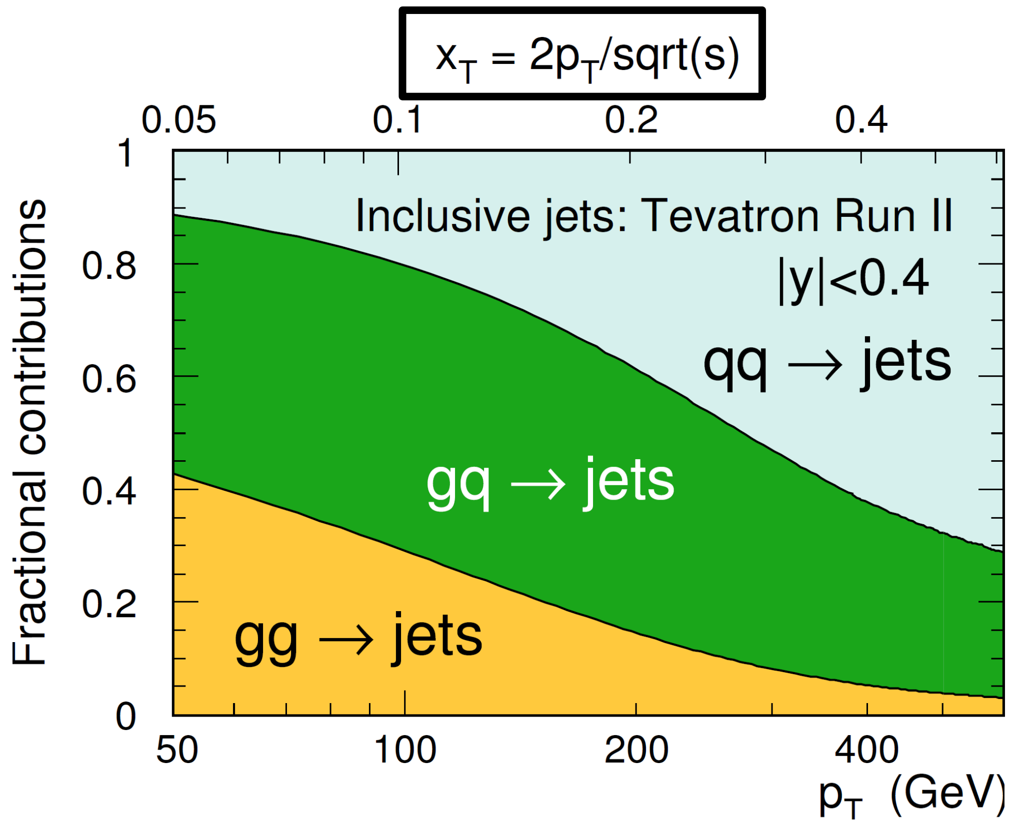
The JES dominates the total uncertainty of the measurement

K. Kousouris

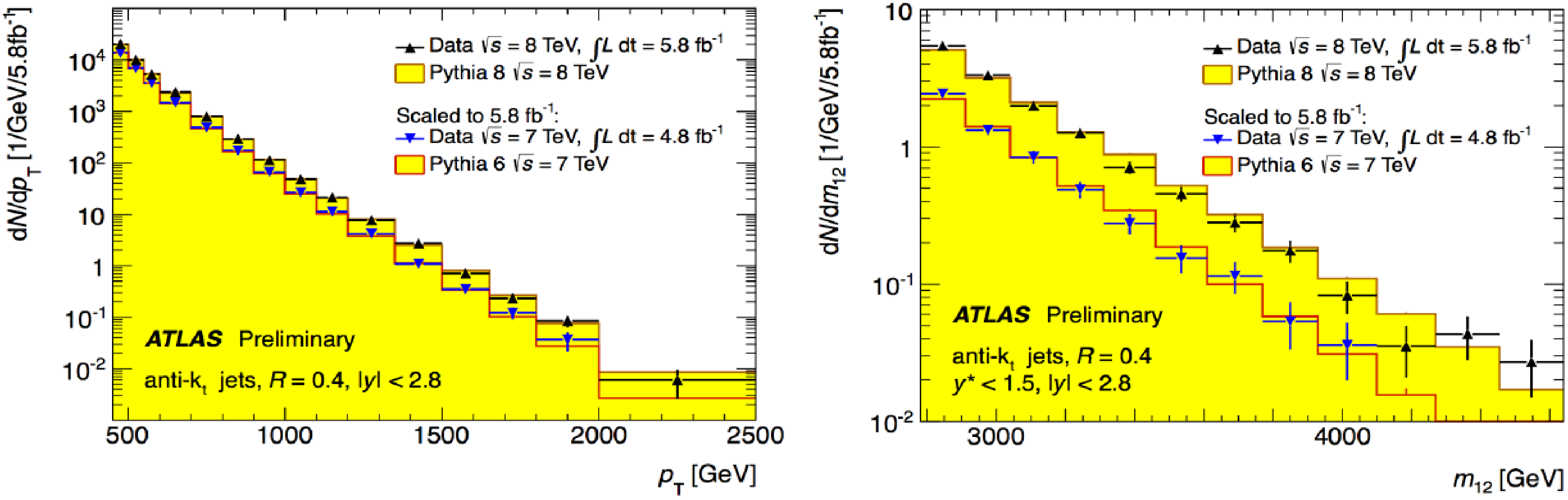
Inclusive Jets



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



Jets @ $\sqrt{s}$ = 8 TeV



- Inclusive jet pT (left) and dijet mass (right) spectrum for *pp* collisions at $\sqrt{s}$ = 8 TeV for anti-k_t R=0.4 jets.

- Comparison with $\sqrt{s}$ = 7 TeV 2011 data and to Pythia 6 (Pythia 8) MC predictions at $\sqrt{s}$ = 7 TeV ($\sqrt{s}$ = 8 TeV).

→ lower center of mass energy in 2011; therefore, lower cross section.

NLO and matched Showers

Ratios to NLO NLOJet++ times NP

Magenta squares: NLO POWHEG
→ agreement as expected

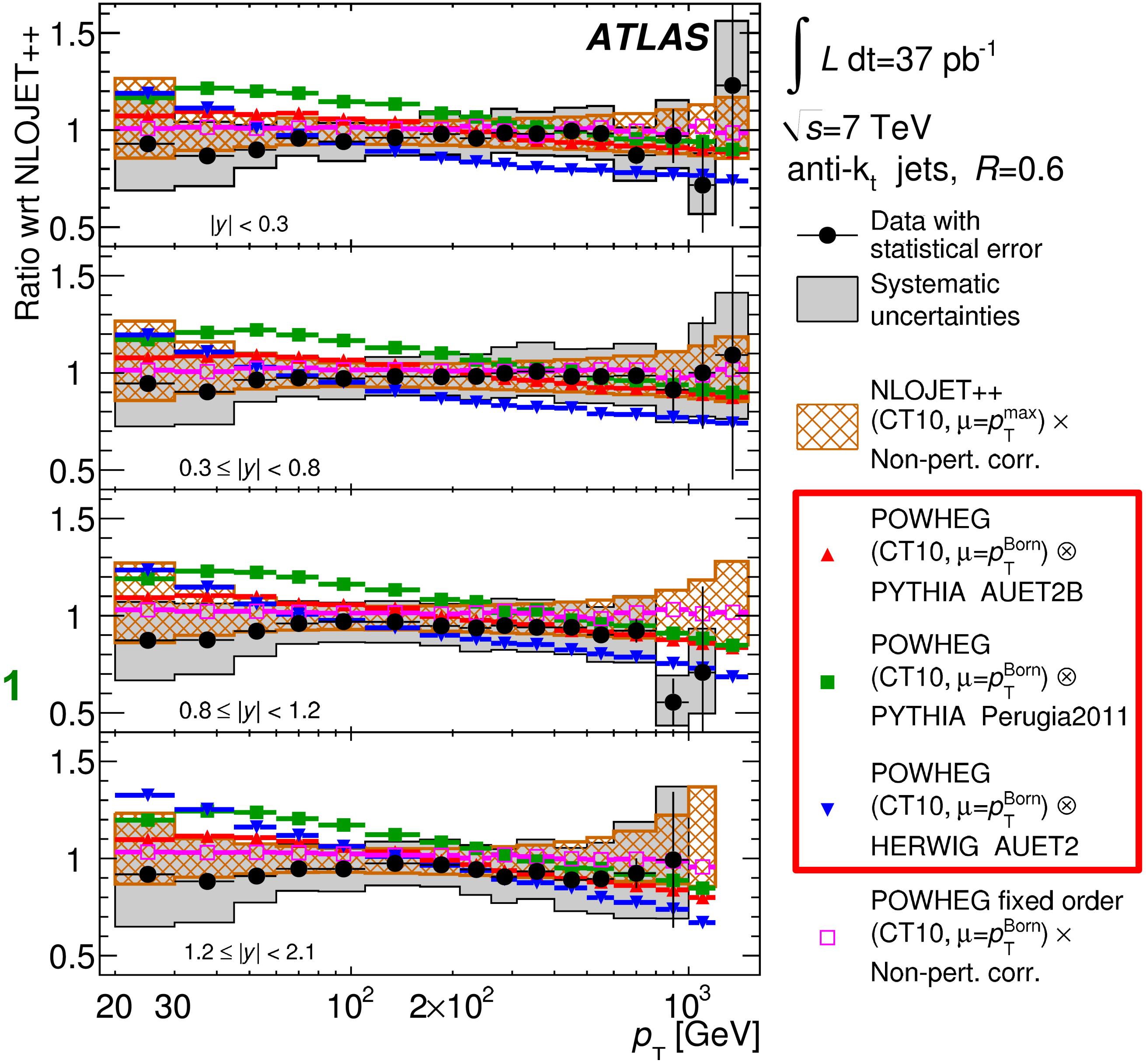
Black circles: Data
→ fine within uncertainties

New tool:
POWHEG NLO + matched parton showers using

Red triangles: Pythia tune AUET2B
Green squares: Pythia tune Perugia2011
Blue triangles: Herwig tune AUET2

→ discrepancies to be understood

NLOJet++, Z.Nagy, PRD68 (2003), PRL88 (2002),
POWHEG, S. Alioli et al., JHEP 1104 (2011),
Pythia, T. Sjöstrand et al., JHEP05 (2006),
Herwig, G. Marchesini et al., CPC67 (1992).



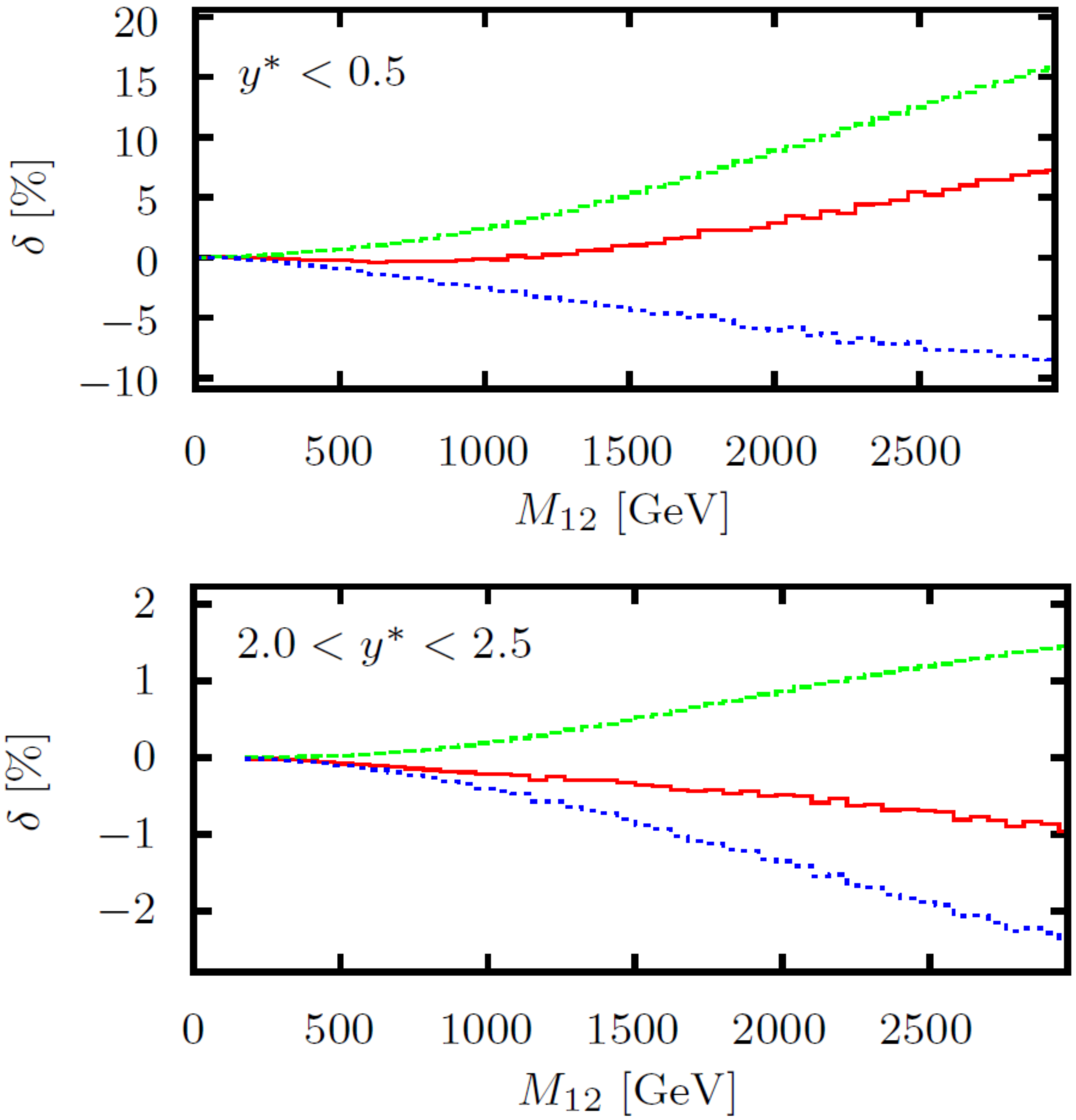
Electroweak Corrections

- **Net effect on dijet mass cross sections at the LHC in red**
  - **here O(8%) at high mass low y***
  - **negligible at higher y***

$$y^* = \frac{|y_1 - y_2|}{2}$$

See theory talk by L. Dixon.

$$\mathrm{pp} \longrightarrow jj + X \text{ at } \sqrt{s} = 8 \text{ TeV}$$



- - - - - $\delta^{\text{1-loop}}_{\text{weak}}$

– – – – – $\delta^{\text{tree}}_{\text{EW}}$

——— $\delta^{\text{tree}}_{\text{EW}} + \delta^{\text{1-loop}}_{\text{weak}}$

S. Dittmaier et al., JHEP11 (2012).

Dijet Mass ATLAS

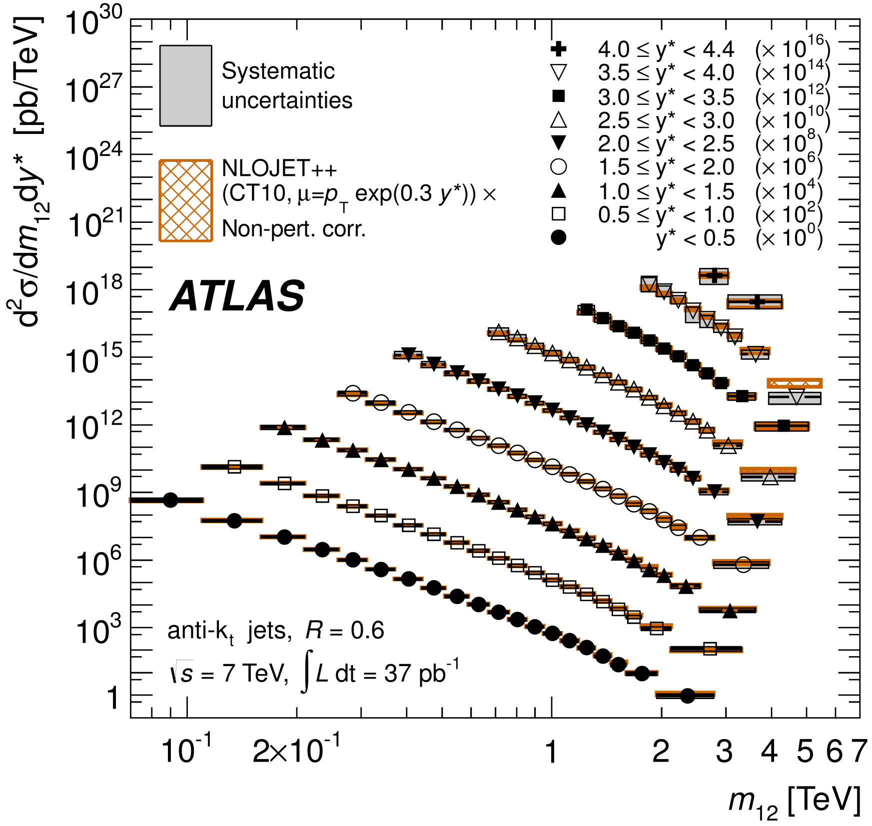
$$\frac{d^2\sigma}{dM_{JJ}dy^*} \propto \alpha_s^2$$

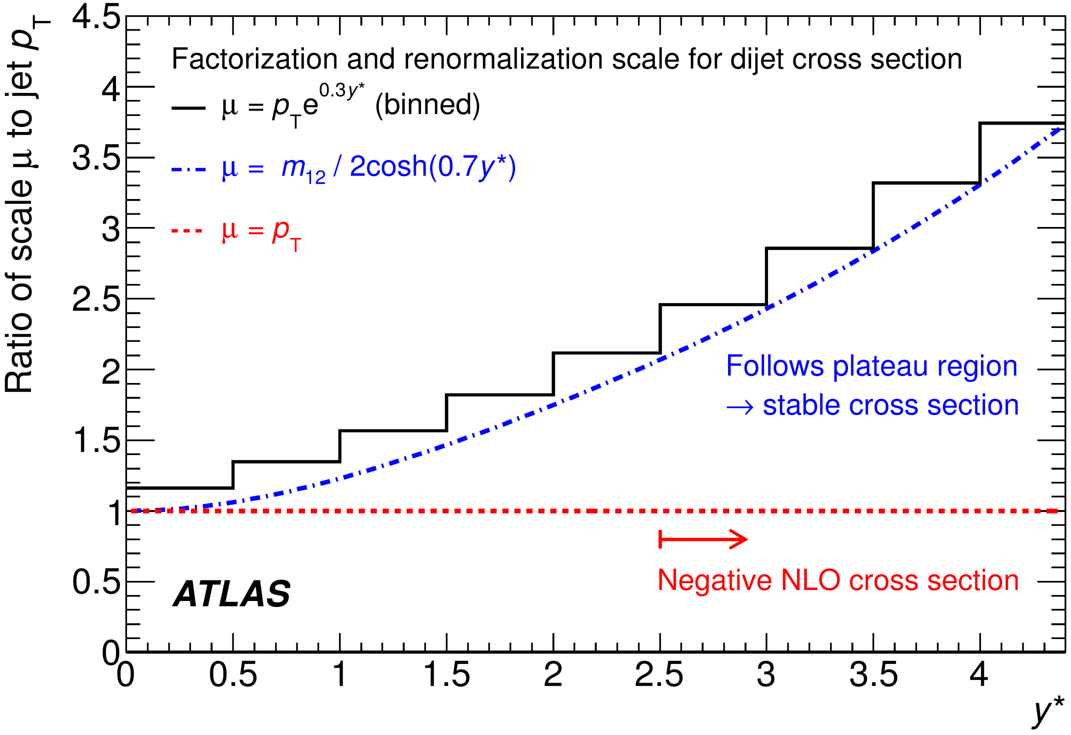
New choice for binning in rapidity by ATLAS
Also new choice for scale setting

$$\mu = p_T e^{0.3y^*}$$

$$y^* = \frac{1}{2}|y_1 - y_2| = \frac{1}{2}\ln\left(\frac{1+|\cos\Theta^*|}{1-|\cos\Theta^*|}\right)$$

Attention: Figure somewhat misleading ...
Negative NLO cross sections appear
when checking scale uncertainties μ → μ/2

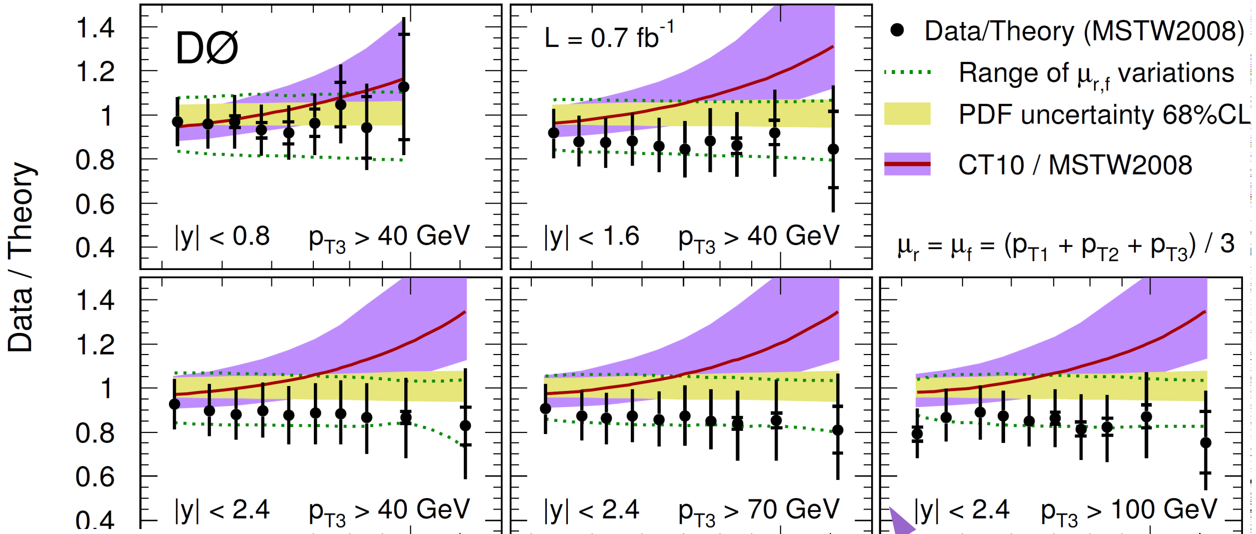




3-Jet Mass D0

No result from LHC yet: Here D0

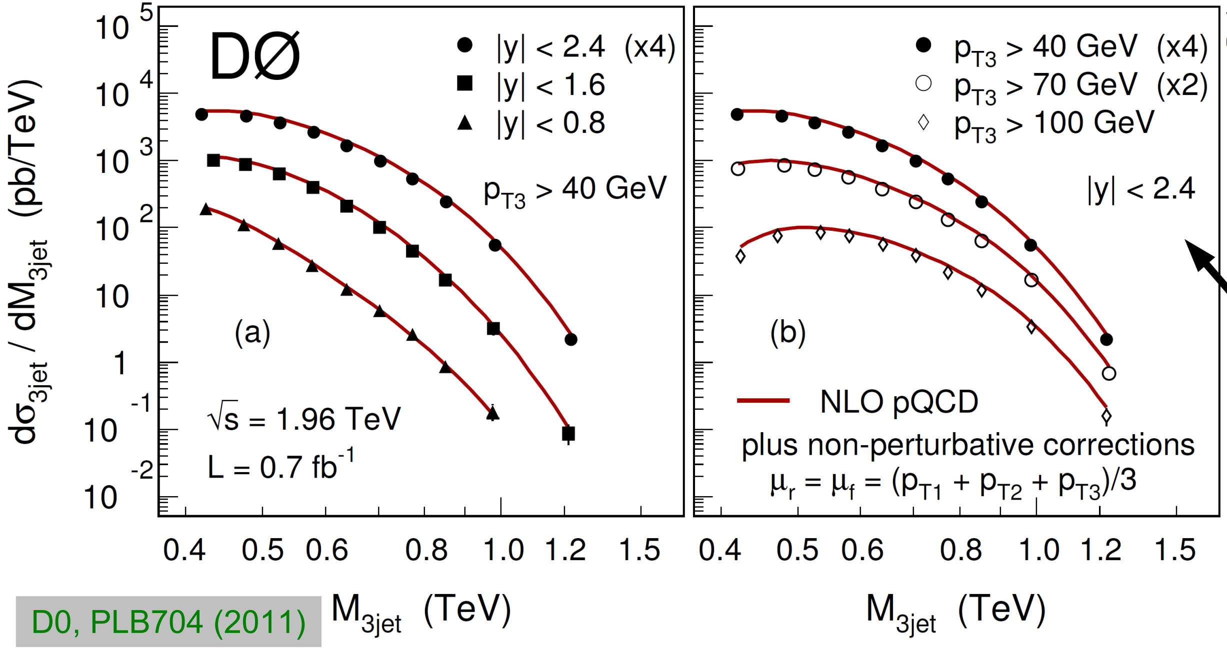
- Sensitive to α_s beyond 2→2 process
- Known at NLO (NLOJet++)
- Sensitive to PDFs
- Involves additional "scale" $p_{T,3}$



Most PDFs work ok, CT10 is off

D0 investigated 3 different lower pT thresholds $p_{T,3}$ and 3 max. rap. y

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

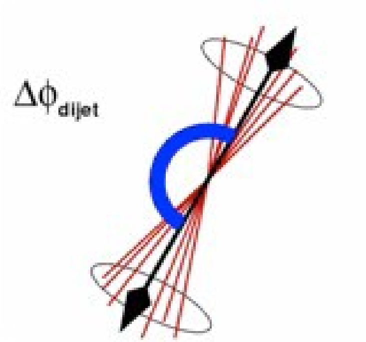


D0, PLB704 (2011)

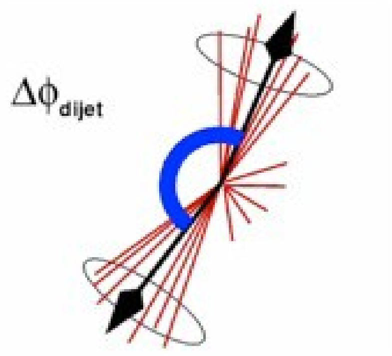
Dijet Azimuthal Decorrelation

Dijets in pp collisions:

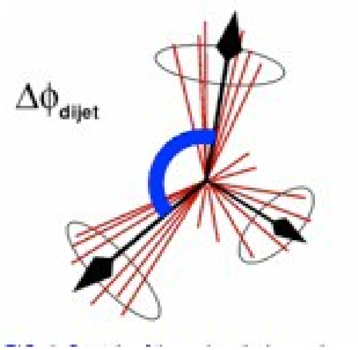
Δφ dijet = π →
Exactly two jets, no further radiation



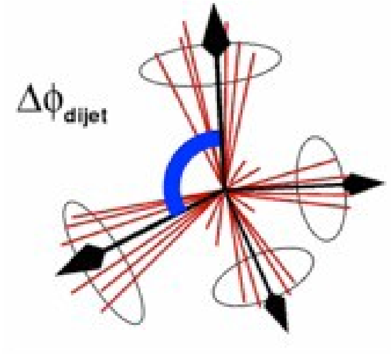
Δφ dijet small deviations from π →
Additional soft radiation outside the jets



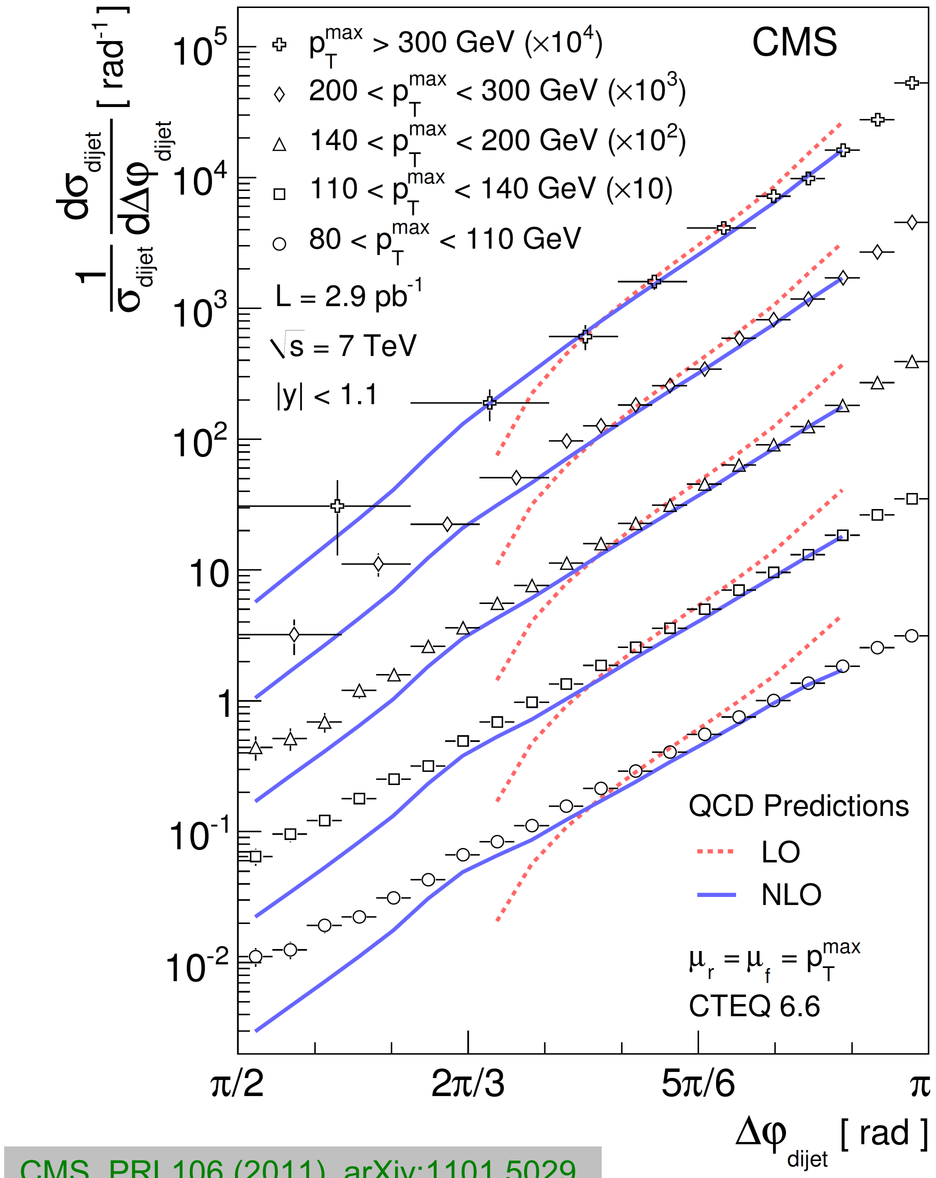
Δφ dijet as small as 2π/3 →
One additional high-pT jet



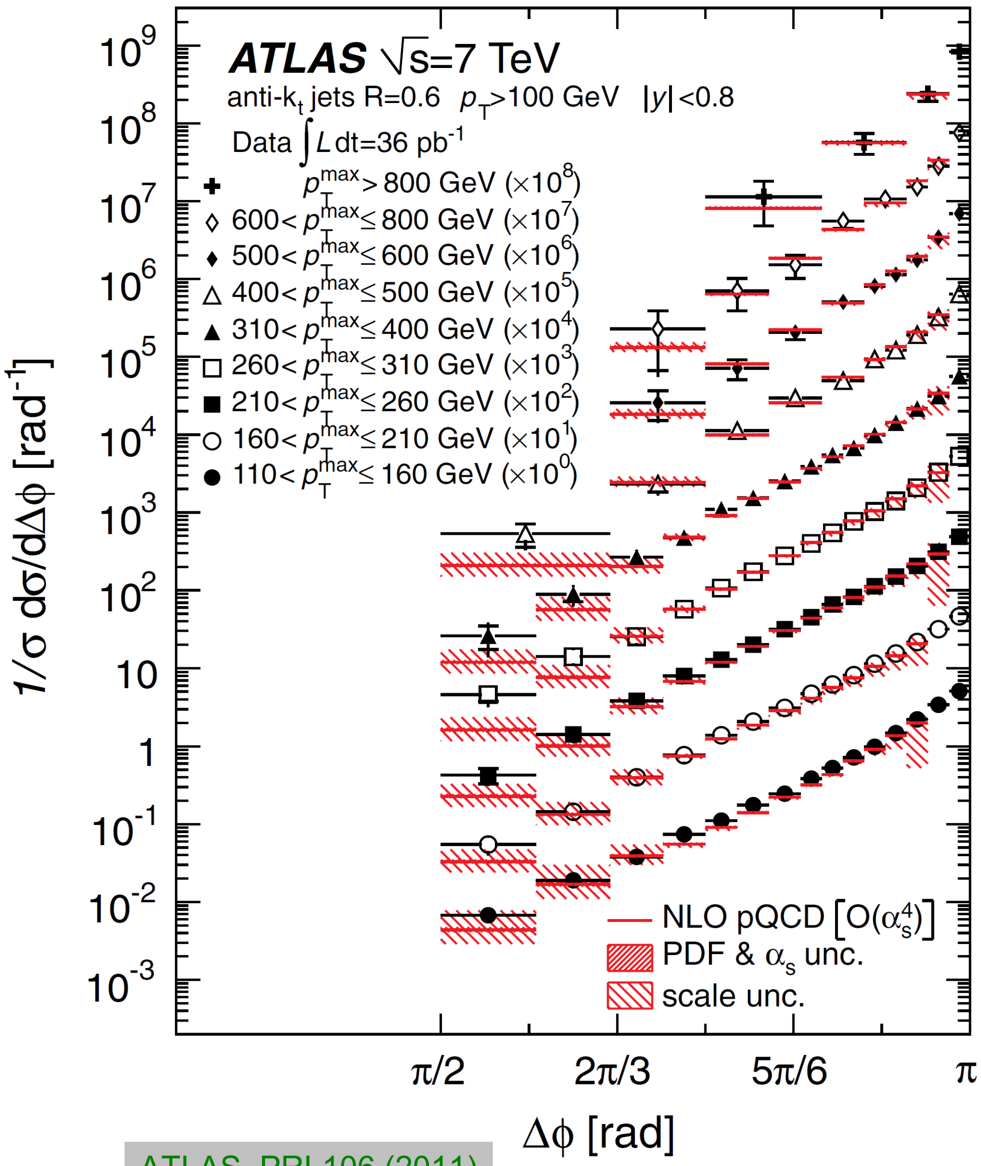
Δφ dijet small – no limit →
Multiple additional hard jets in the event



Dijet Azimuthal Decorrelation



CMS, PRL106 (2011), arXiv:1101.5029.



ATLAS, PRL106 (2011)