Karlsruhe Institute of Technology

QCD measurements at LHC: Jets, multi-jets, α_s

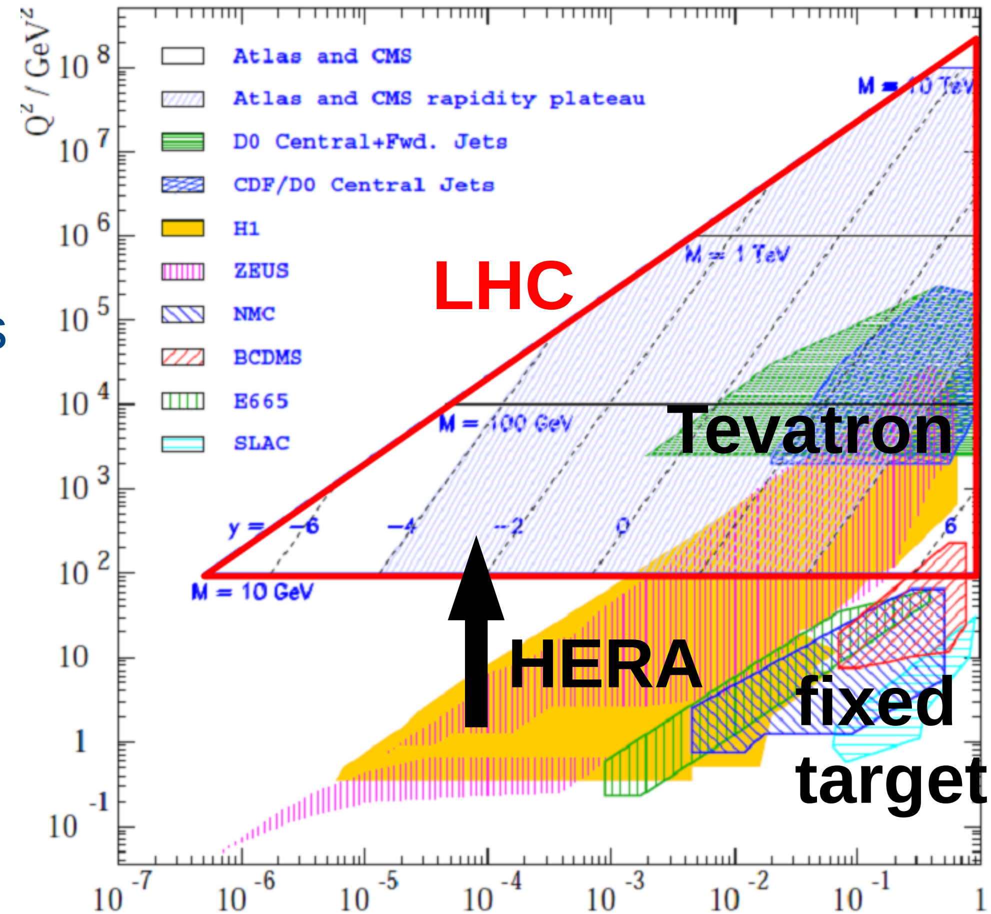
SM@LHC Conference

Fred Stober
on behalf of the ATLAS and CMS Collaboration

INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK (EKP) · DEPARTMENT OF PHYSICS

Introduction

- QCD processes dominant @ LHC
  → hadron colliders are jet factories
- Motivations
  - **UNDERSTAND** backgrounds for virtually all new physics channels
  - **TUNE** Monte Carlo generators
  - **TEST** QCD in unexplored regions of the phase space
  - **STUDY** the proton structure, non-perturbative effects, ...
  - DETERMINE strong coupling
- Measurements
  - Jet cross-sections (Differential & Ratios)
  - Events shapes
  - Angular Distributions, ….



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

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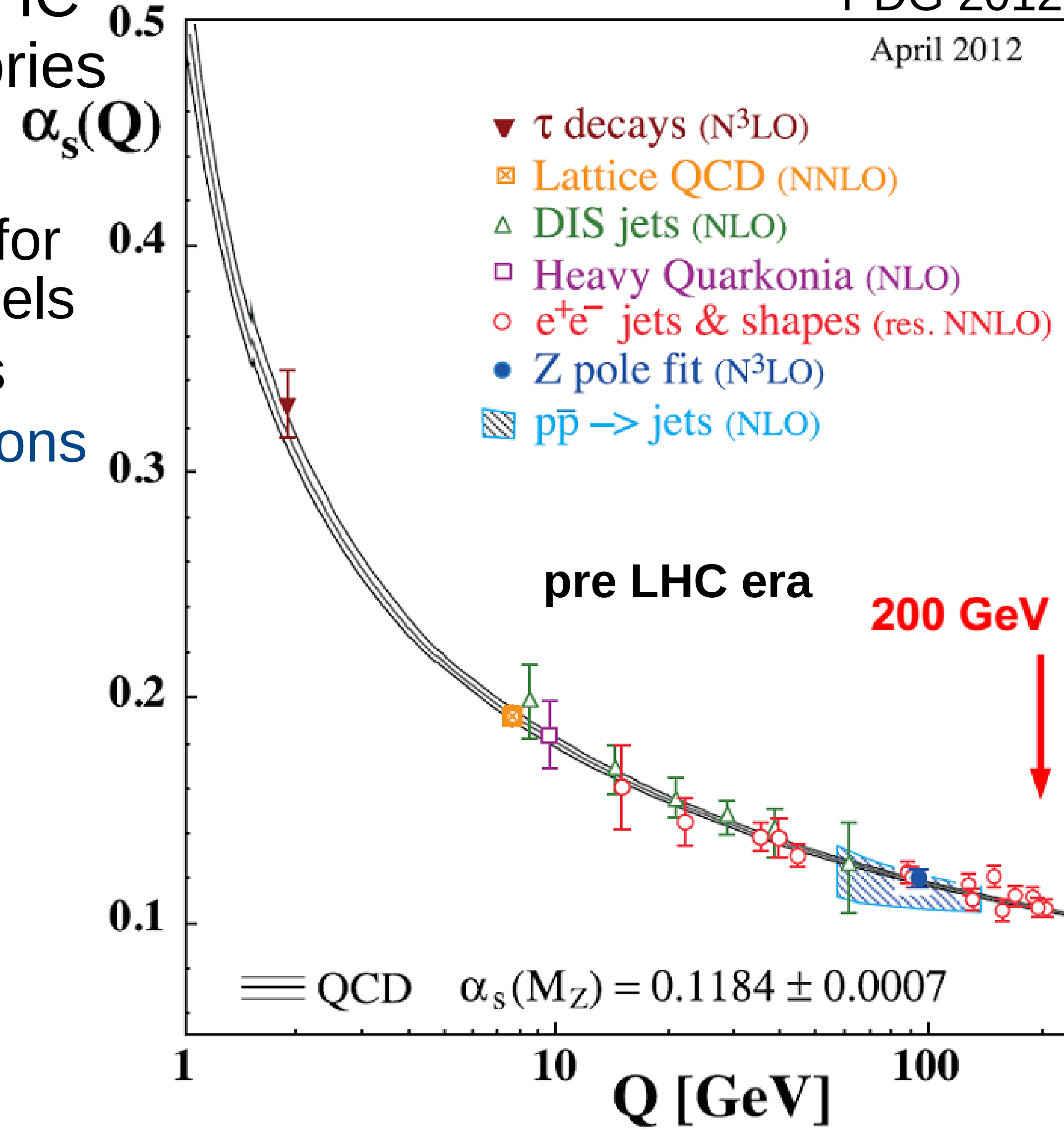
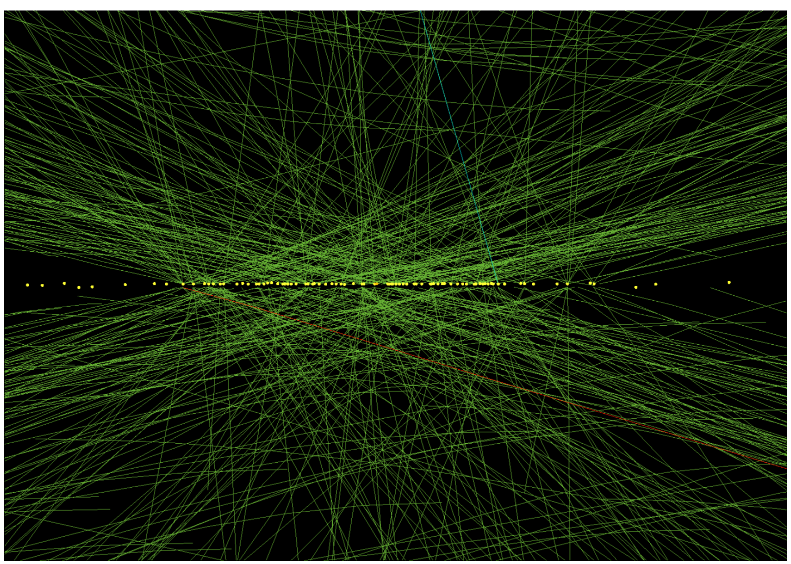
PDG 2012

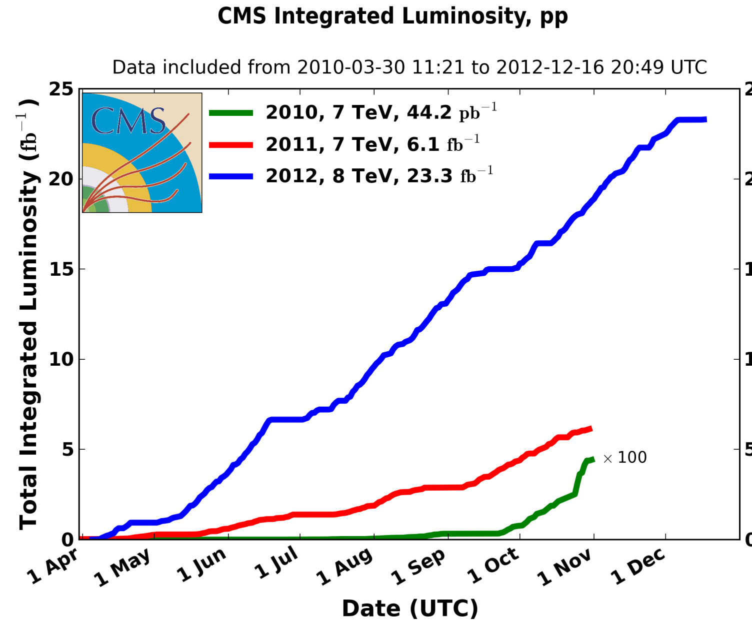


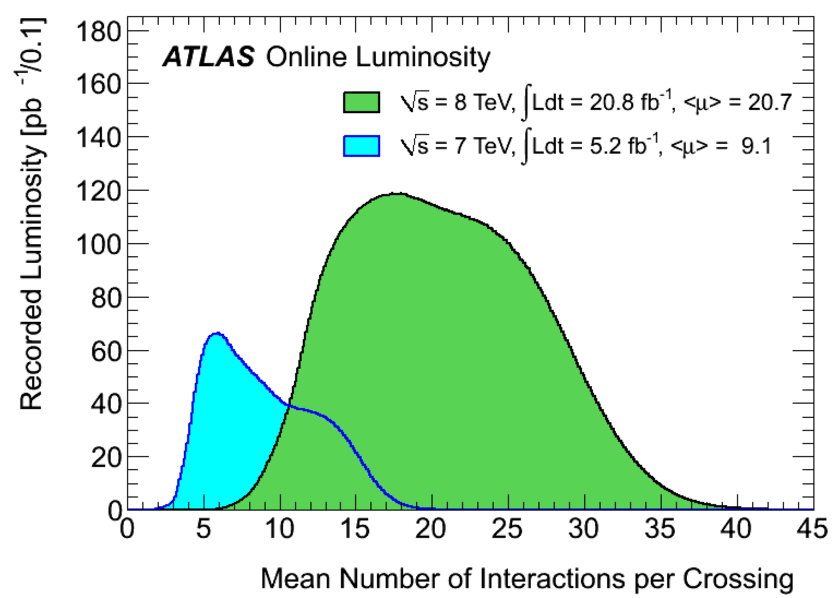
The Large Hadron Collider

- Very successful LHC operations in 2010-2012
- 8 TeV: Challenging environment
  - Very high pile-up, new techniques
- 13 TeV in 2015
  - LHC may exceed design lumi and run at higher than design pile-up



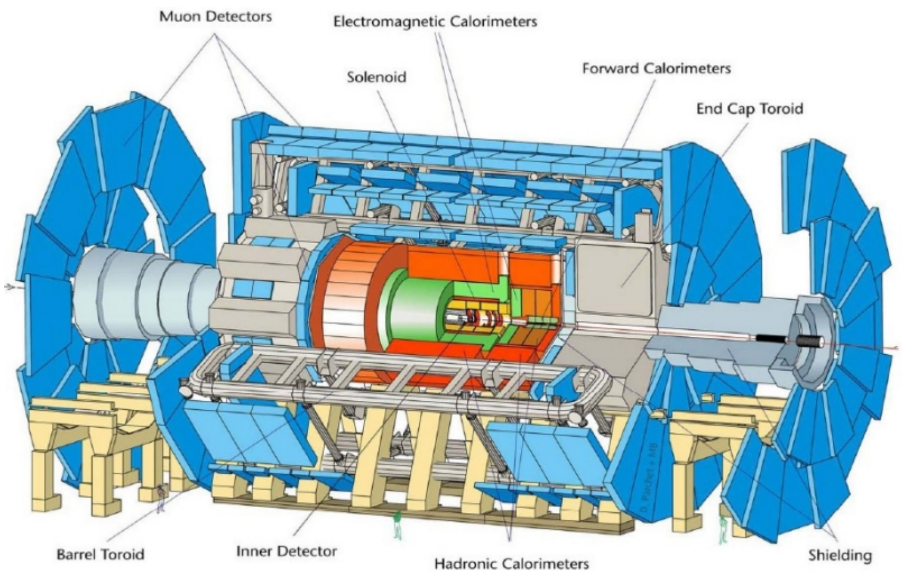
78 reconstructed vertices (CMS)

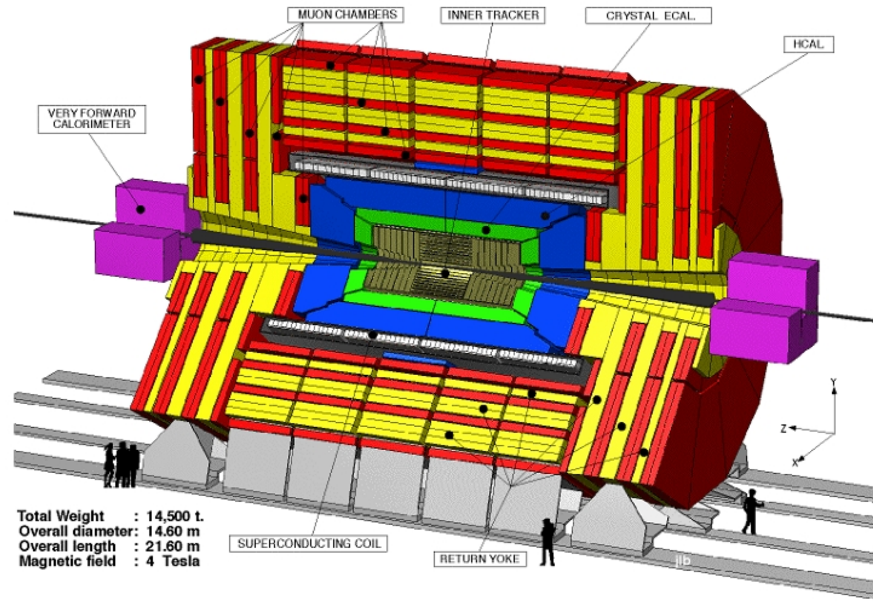




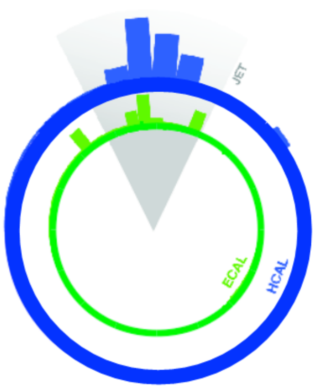
ATLAS-CONF-2013-085

The LHC Experiments



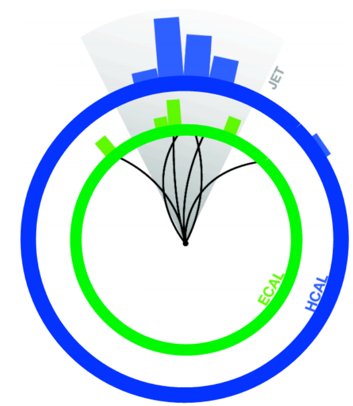


ATLAS
Calorimeter Jets



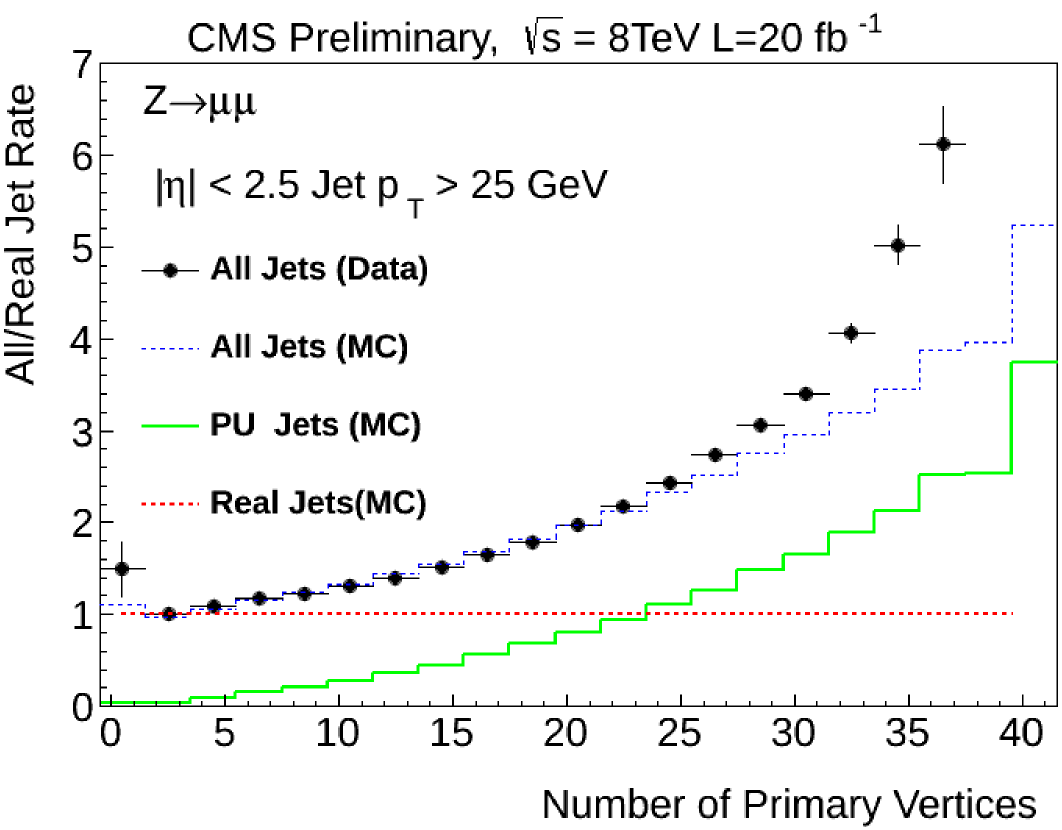
- Tracking |η| = 2.5, Calorimetry |η| ~ 5.0, Muon detector |η| = 2.4-2.7
- Jets are clustered from the reconstructed objects in the event
  - ATLAS: Topological clusters (ECAL / HCAL, corrected for event pile-up)
  - CMS: Particle-flow candidates (ECAL / HCAL towers + tracking information)

CMS
Particle Flow Jets

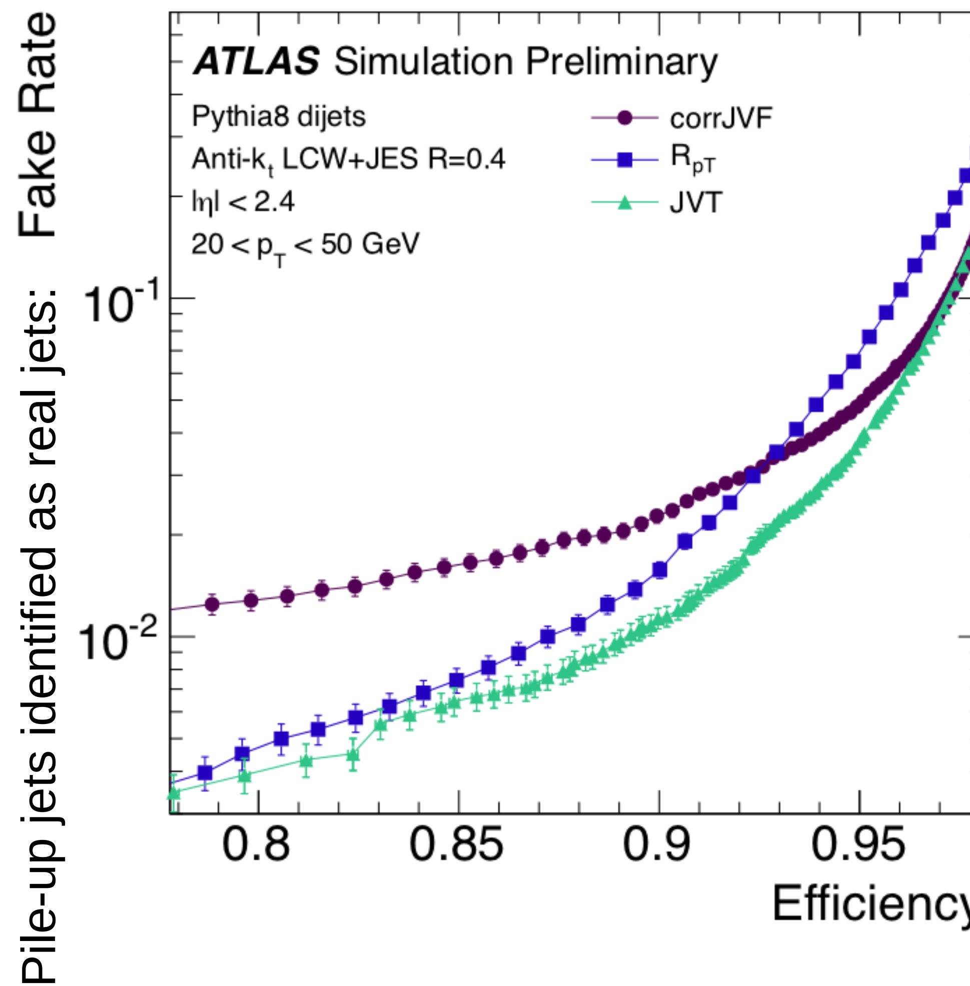


Tagging and suppression of pileup jets

- With increasing pile-up, the identification of pile-up jets becomes more important → pile-up jet tagger



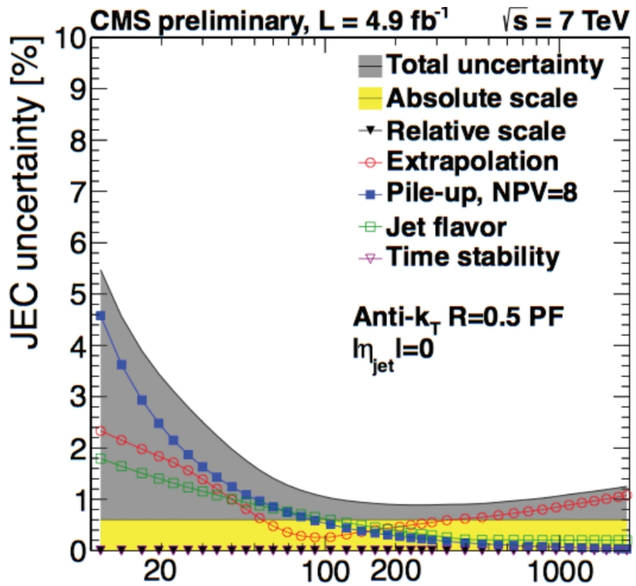
CMS-PAS-JME-13-005



Jet Energy Scale

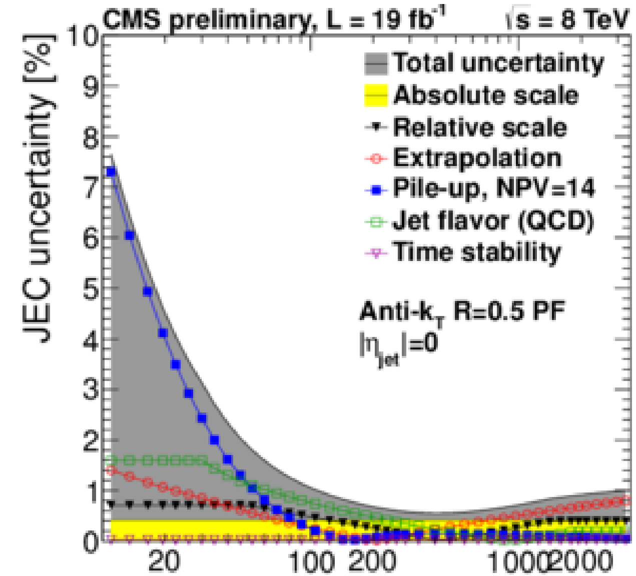
- ATLAS & CMS achieved excellent jet energy scale uncertainties within a short time
- 1% uncertainty in important parts of the phase space
- **How**: Study balance between jets and well measured objects like photons or Z

7 TeV

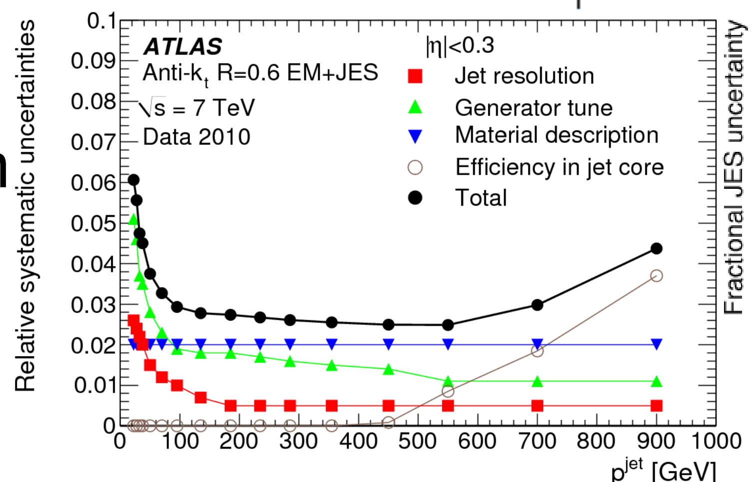


CMS-DP-2012-006

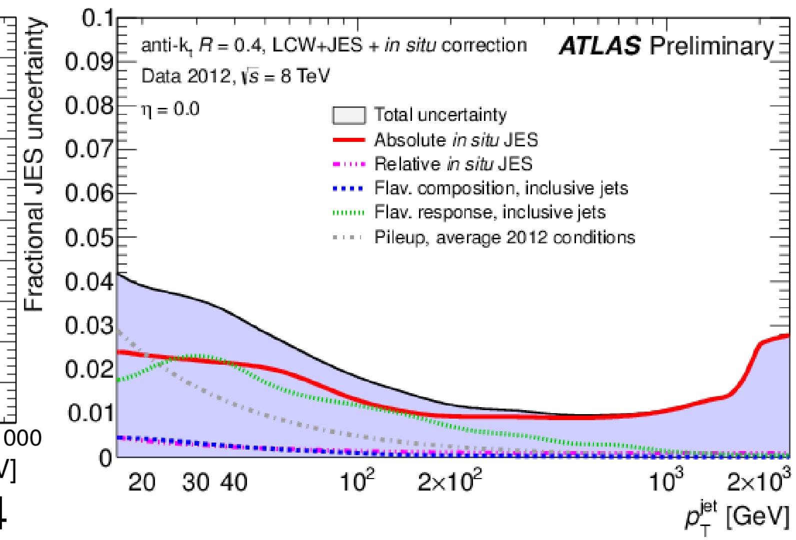
8 TeV



CMS-DP-2013-033



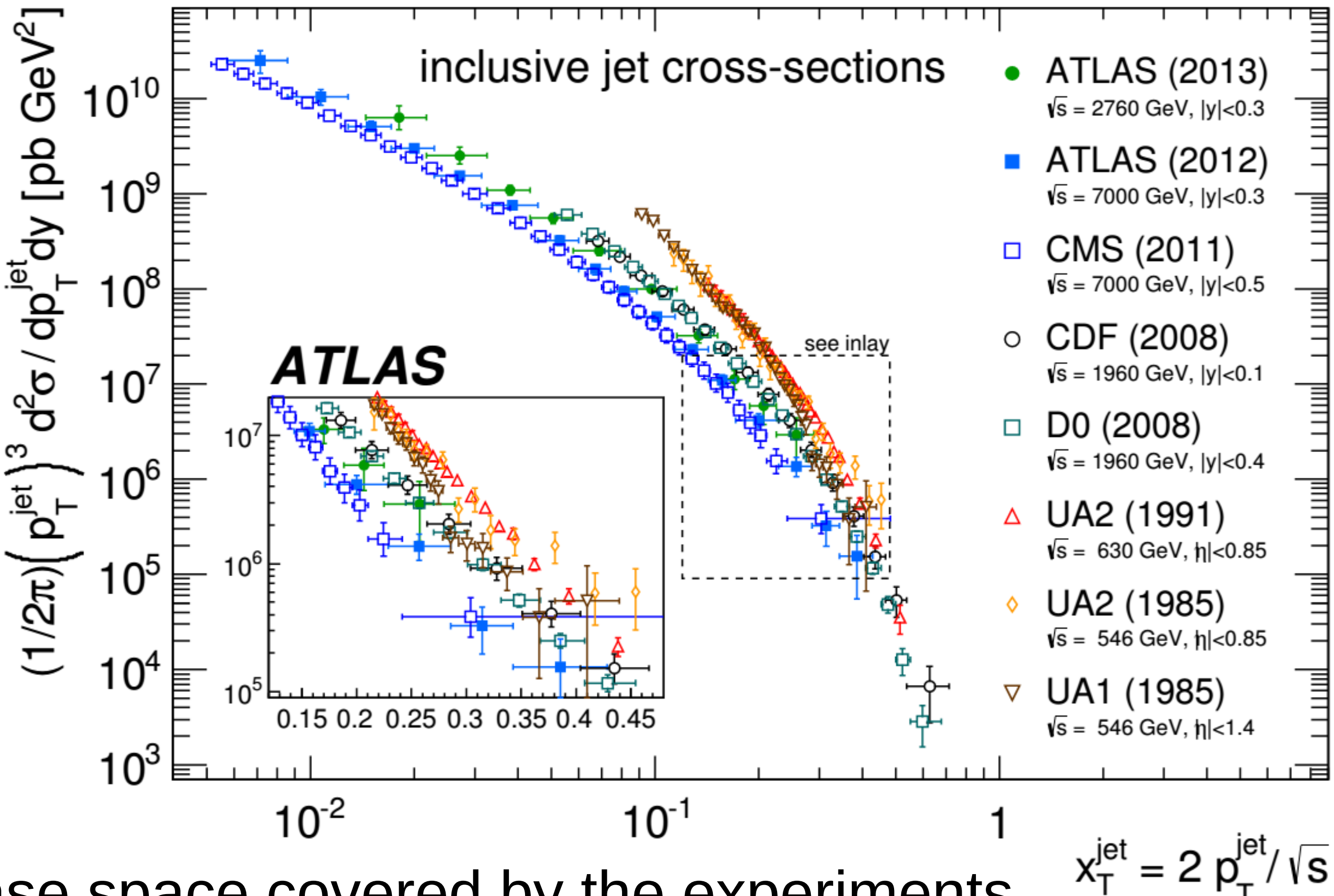
Eur. Phys. J. C, 73 3 (2013) 2304



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
JetEtmissApproved2013JESUncertainty

Inclusive Jets

- One of the most fundamental tests of QCD is the measurement of the inclusive jet cross section

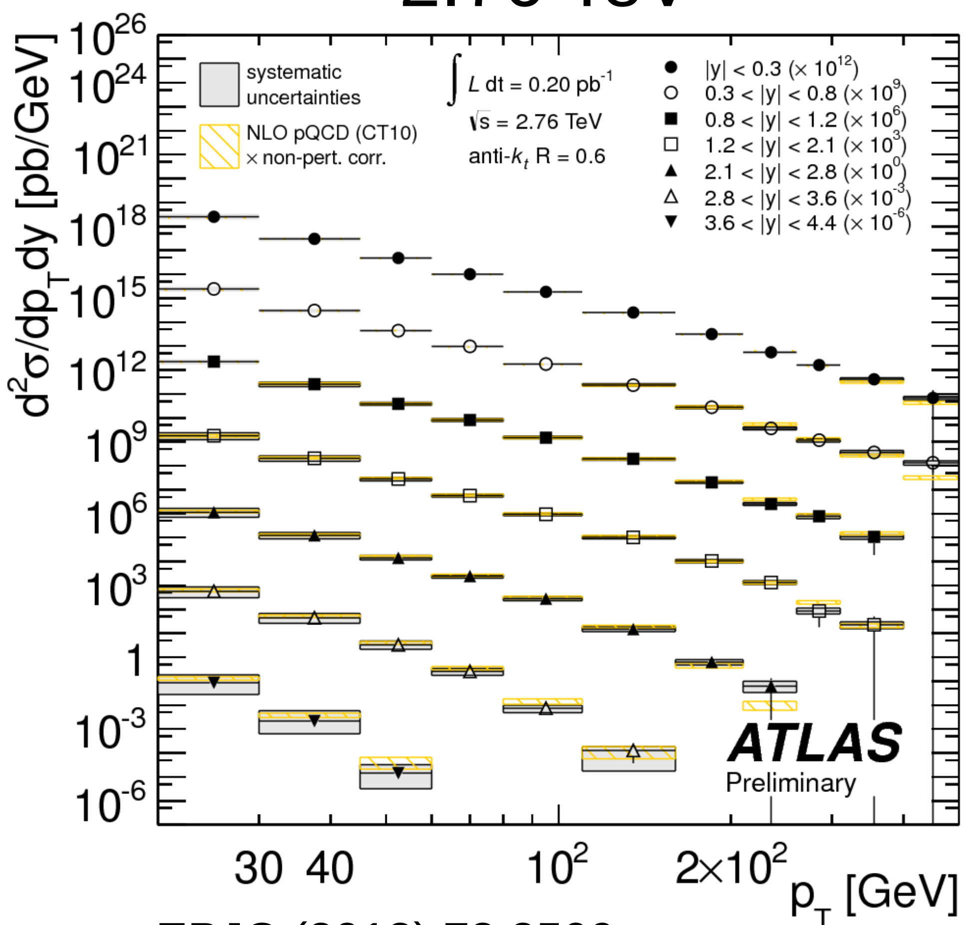


- Huge phase space covered by the experiments

Inclusive Jets

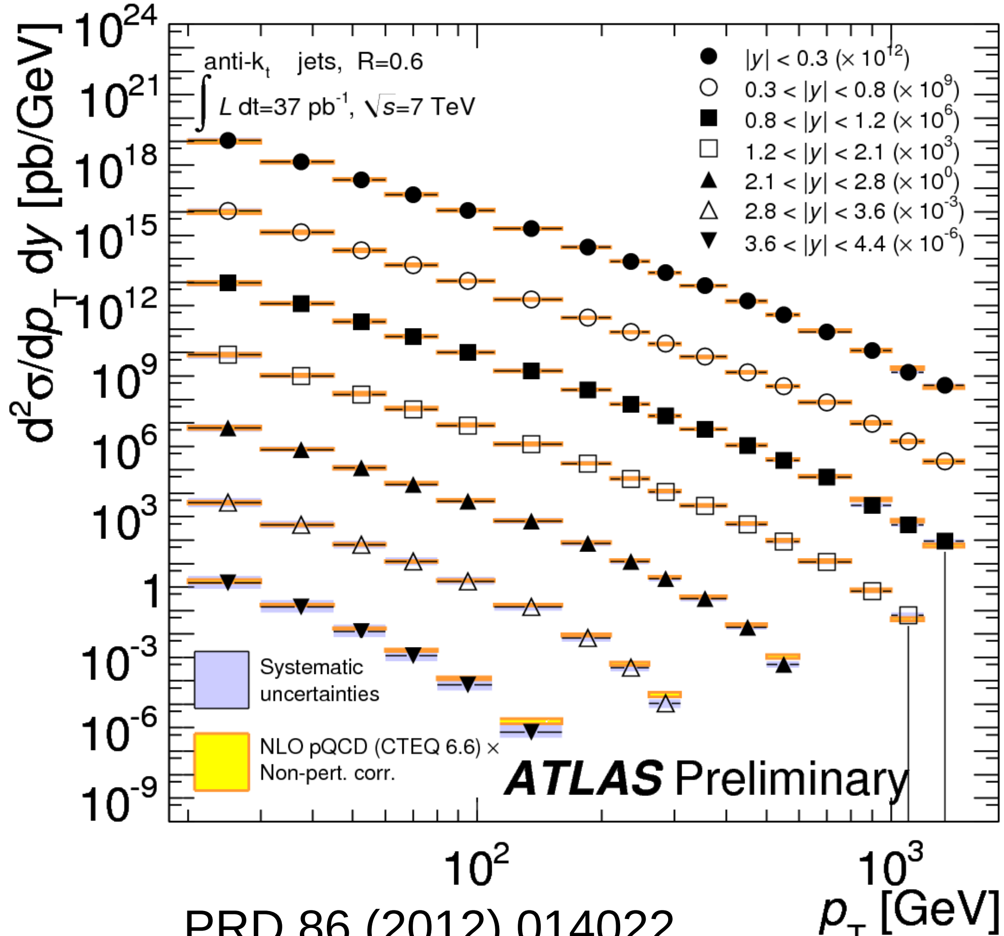
- The inclusive jet cross section was measured by ATLAS / CMS at all available center of mass energies (2.76, 7 and 8 TeV)

2.76 TeV



EPJC (2013) 73 2509

7 TeV



PRD 86 (2012) 014022

CMS: PRD 87 (2013) 112002
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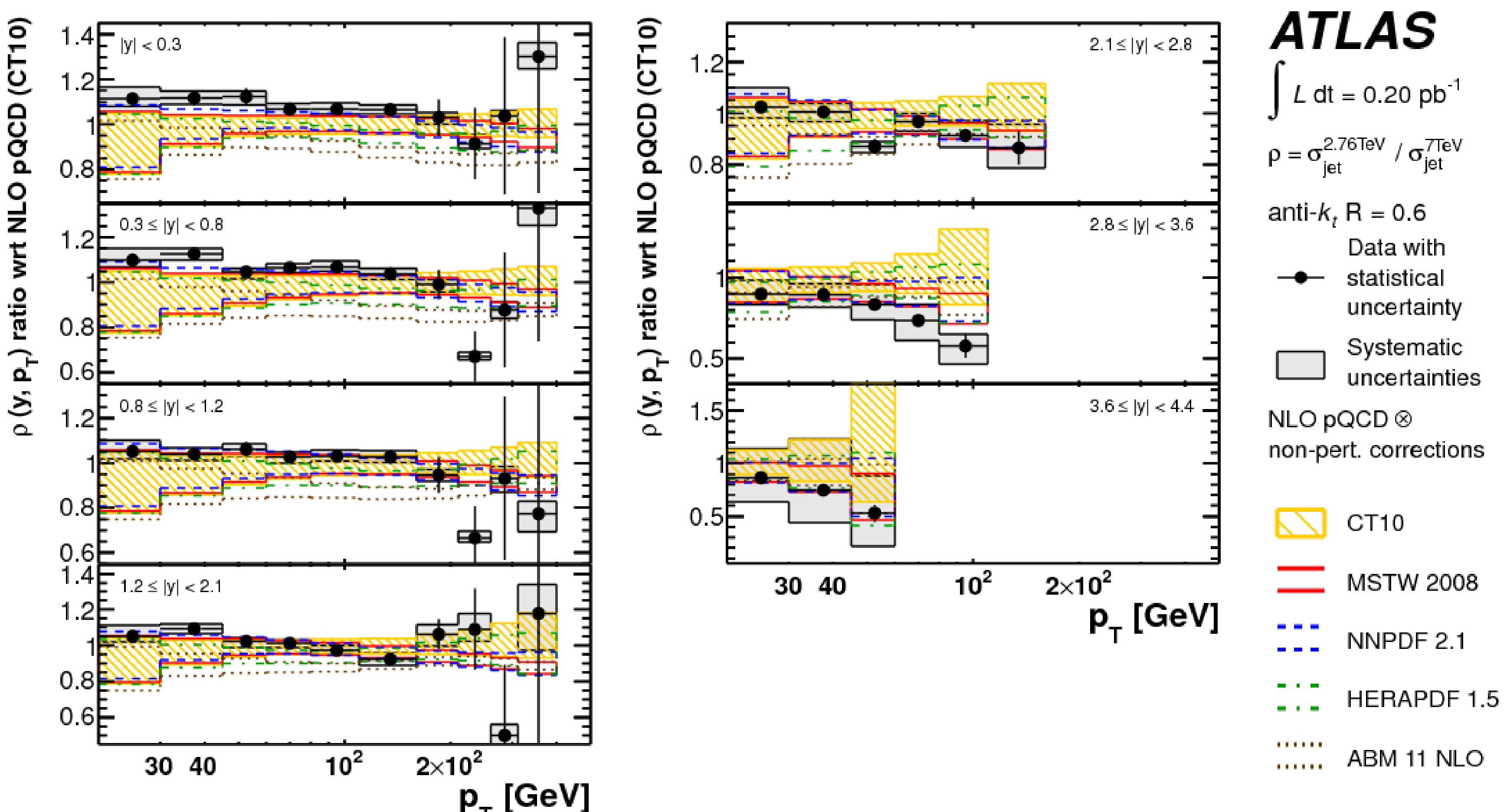
Inclusive Jets – Ratio of 2.76 and 7 TeV results

- Systematic uncertainties can be reduced by studying the ratio of the inclusive cross sections (correlated uncertainties cancel)

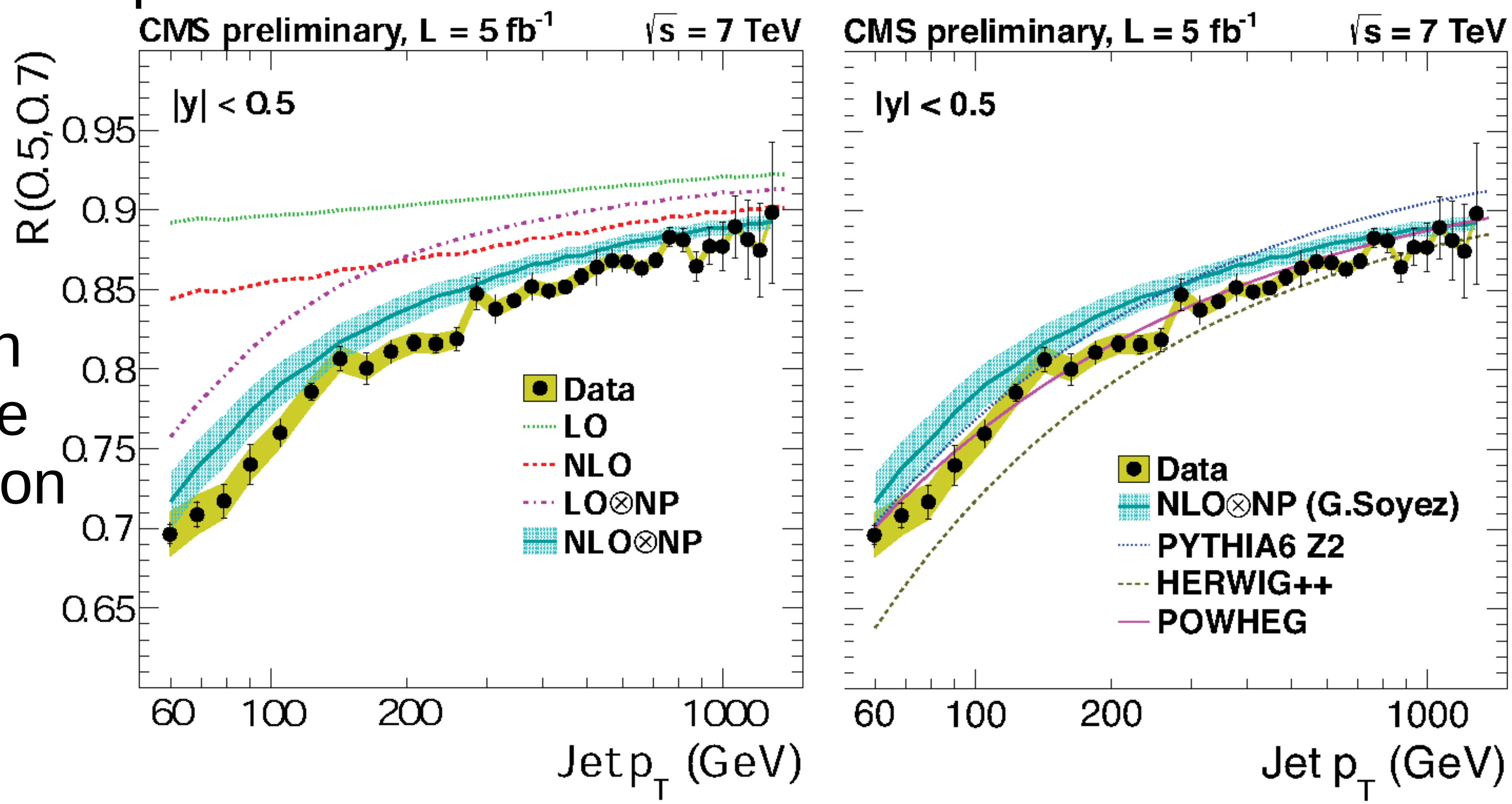


EPJ C 73 (2013) 2509

Sensitive to PDFs

Inclusive Jets – Ratio of R=0.5 and 0.7 results

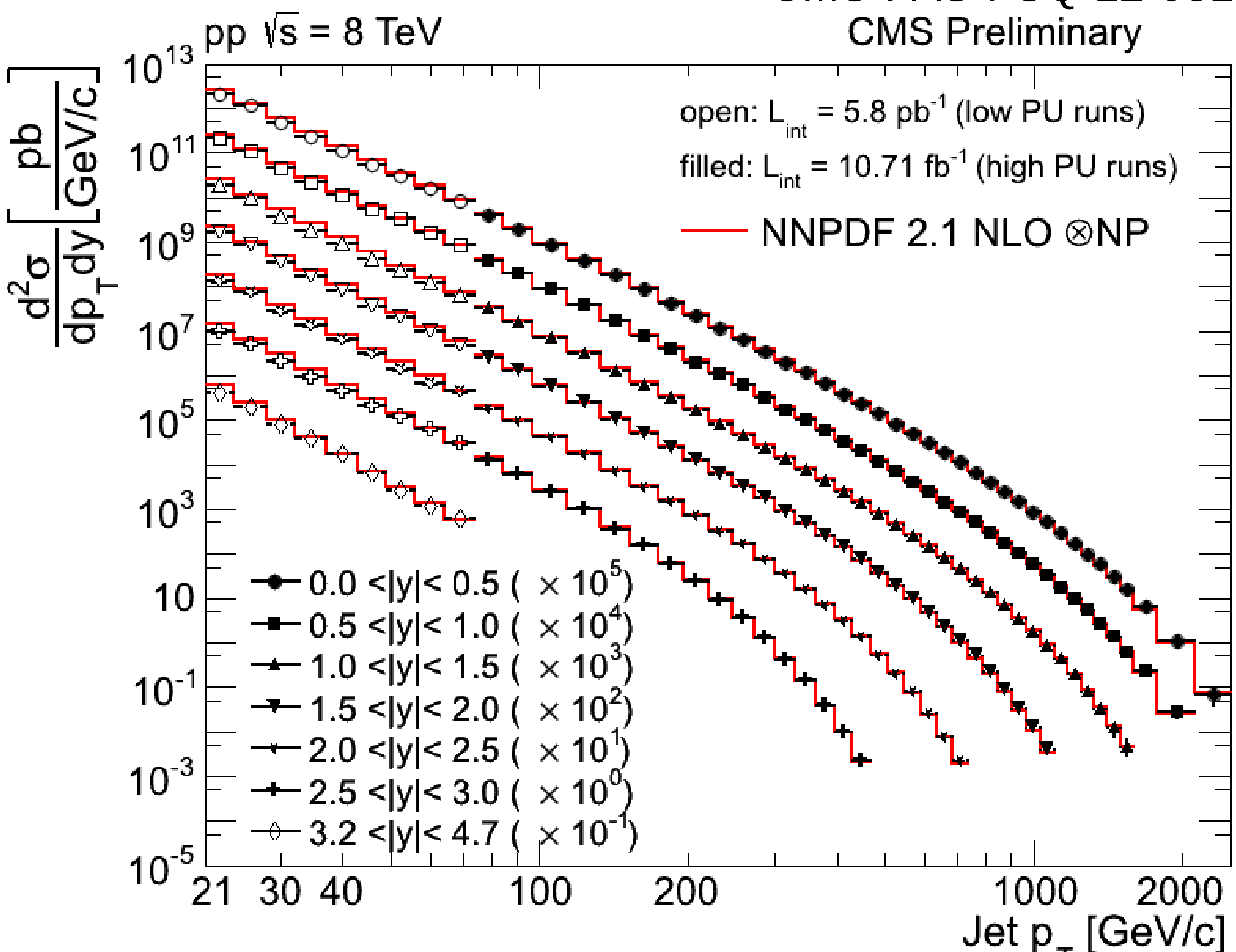
- Discrepancies when comparing data to LO simulations and to fixed order calculations at NLO, corrected for non-perturbative effects
- Simulations with NLO matrix elements + matched parton showers describe the data quite well
- Indicates the importance of final state radiation in the description of the inclusive jet cross-section

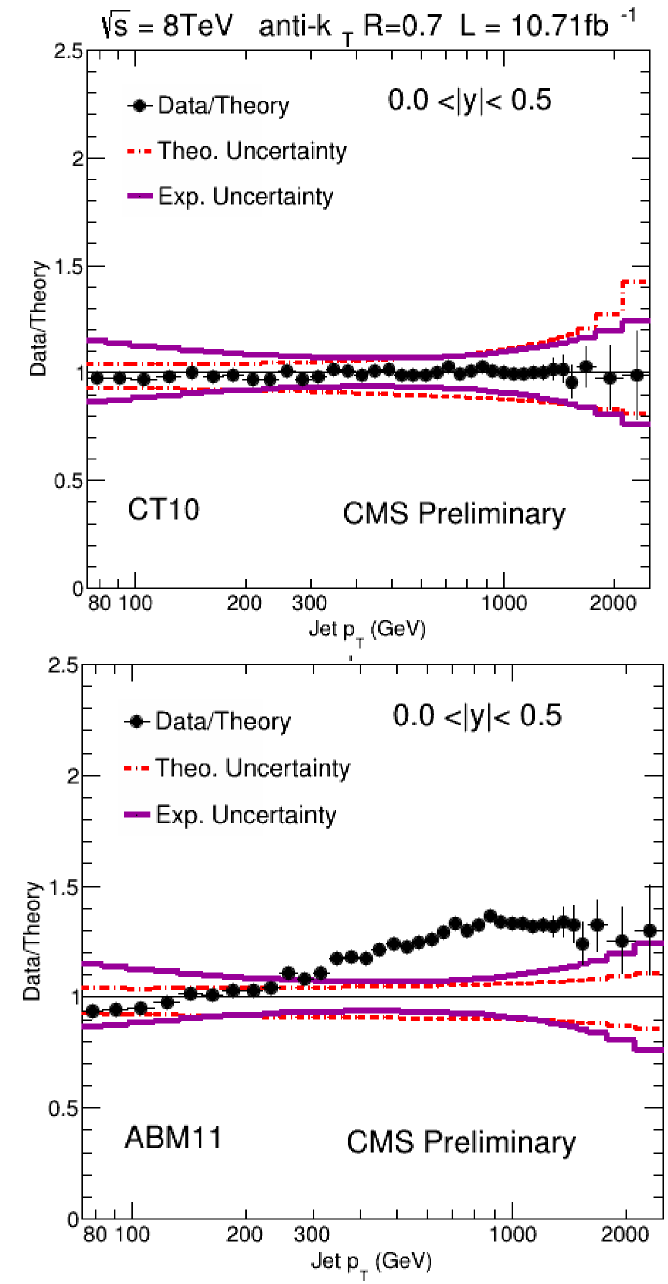


CMS-PAS-SMP-13-002

Inclusive Jets

CMS-PAS-FSQ-12-031





CMS-PAS-SMP-12-012

- In general agreement with NLO+NP over **several orders of magnitude**
- ABM11 PDF shows larger discrepancies

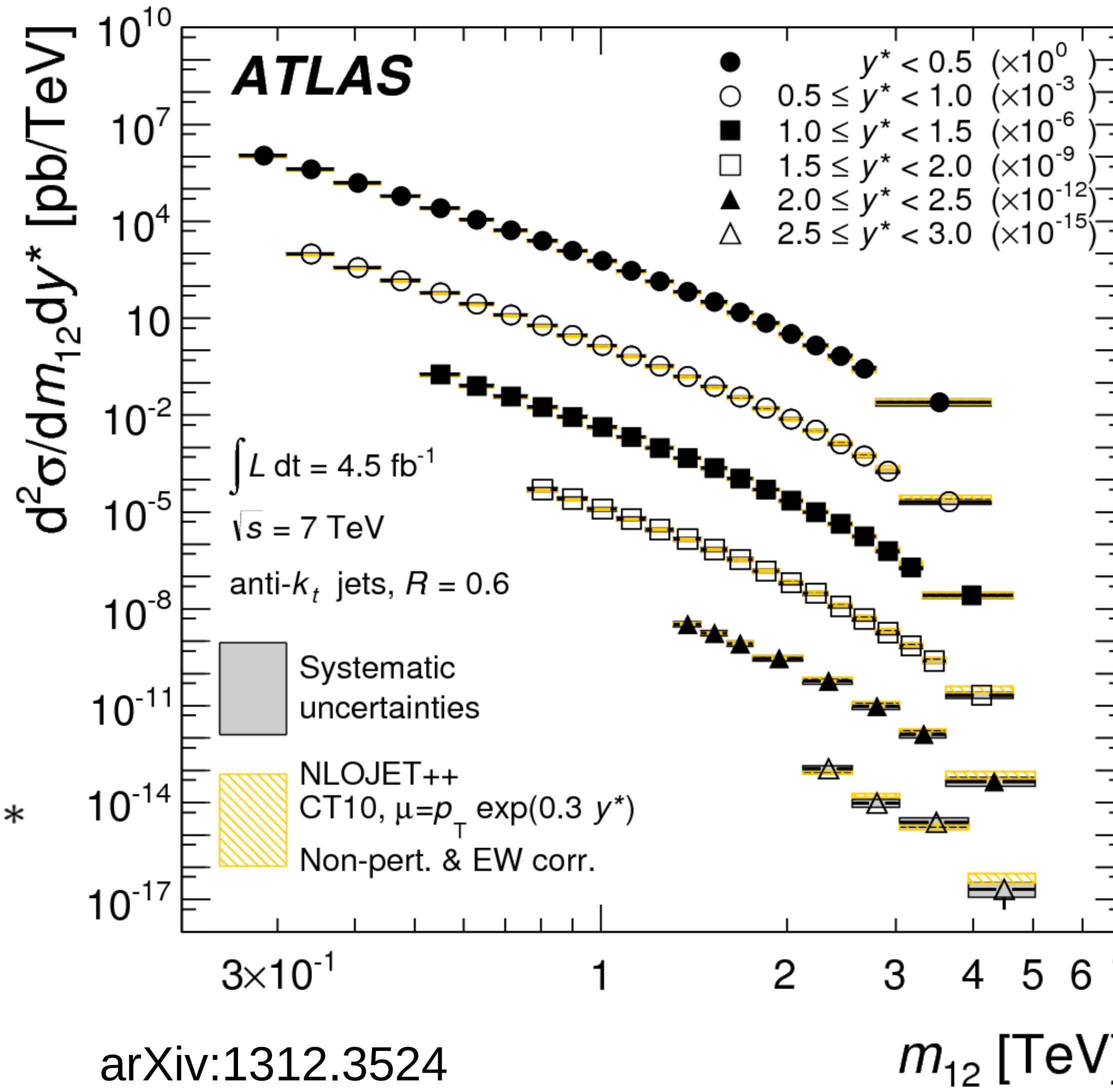
Dijet Mass Cross Section

- Study of the invariant mass in dijet events
  - $p_{T1} > 100$ GeV
  - $p_{T2} > 50$ GeV
- Double differential in
  - dijet mass m12
  - rapidity separation (6 ranges)

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

- Comparison with NLOJet++ prediction + NP & EW corr.

$$\mu = \mu_\mathrm{R} = \mu_\mathrm{F} = p_\mathrm{T}^\mathrm{max} \mathrm{e}^{0.3y^*}$$

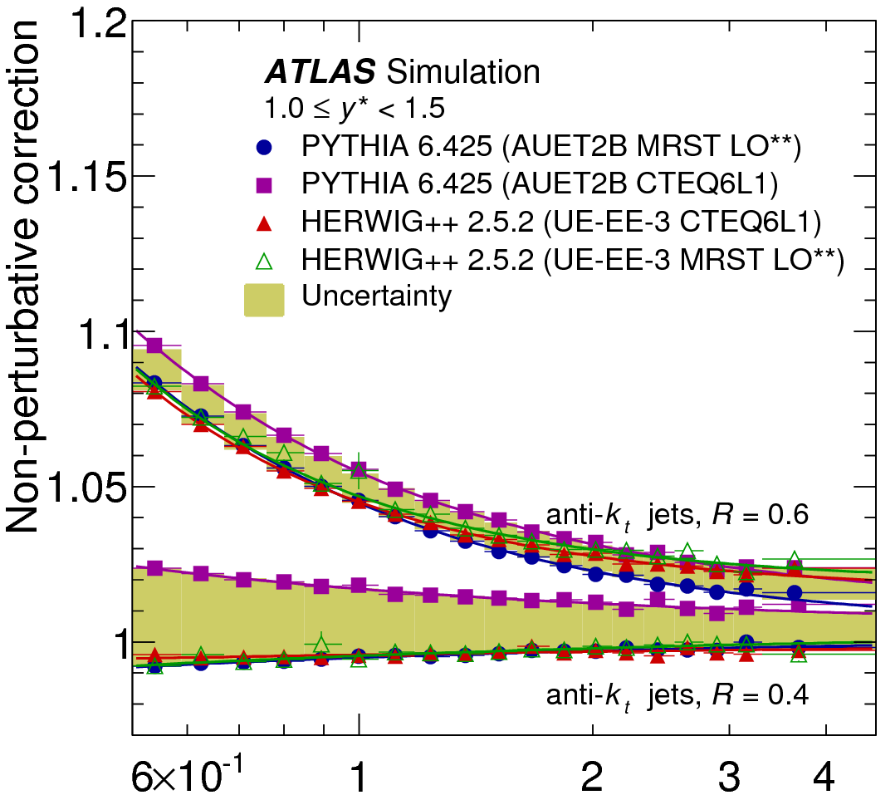


arXiv:1312.3524

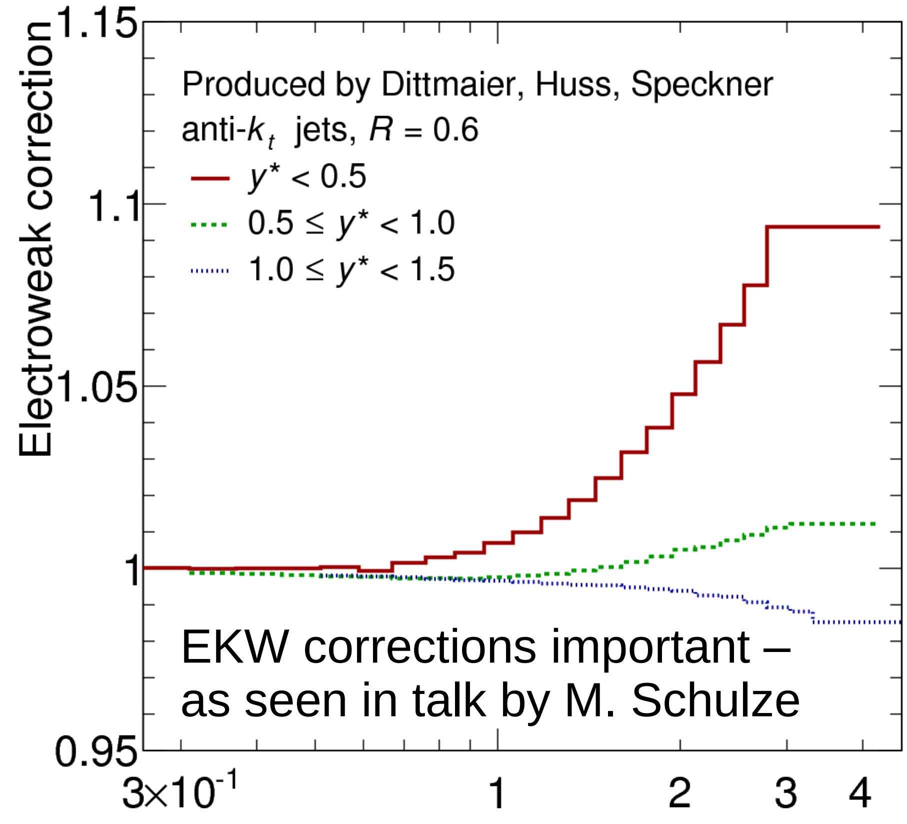
CMS: PRD 87 (2013) 112002 (backup slide 43)

Dijet Mass Cross Section

- Data comparison with NLO pQCD predictions need non-perturbative corrections (derived from general purpose generators)
- EKW corrections derived for NLO EWK processes on LO QCD prediction (tree-level $O(\alpha\alpha_s,\alpha^2)$) and loop effects $O(\alpha\alpha_s^2)$)



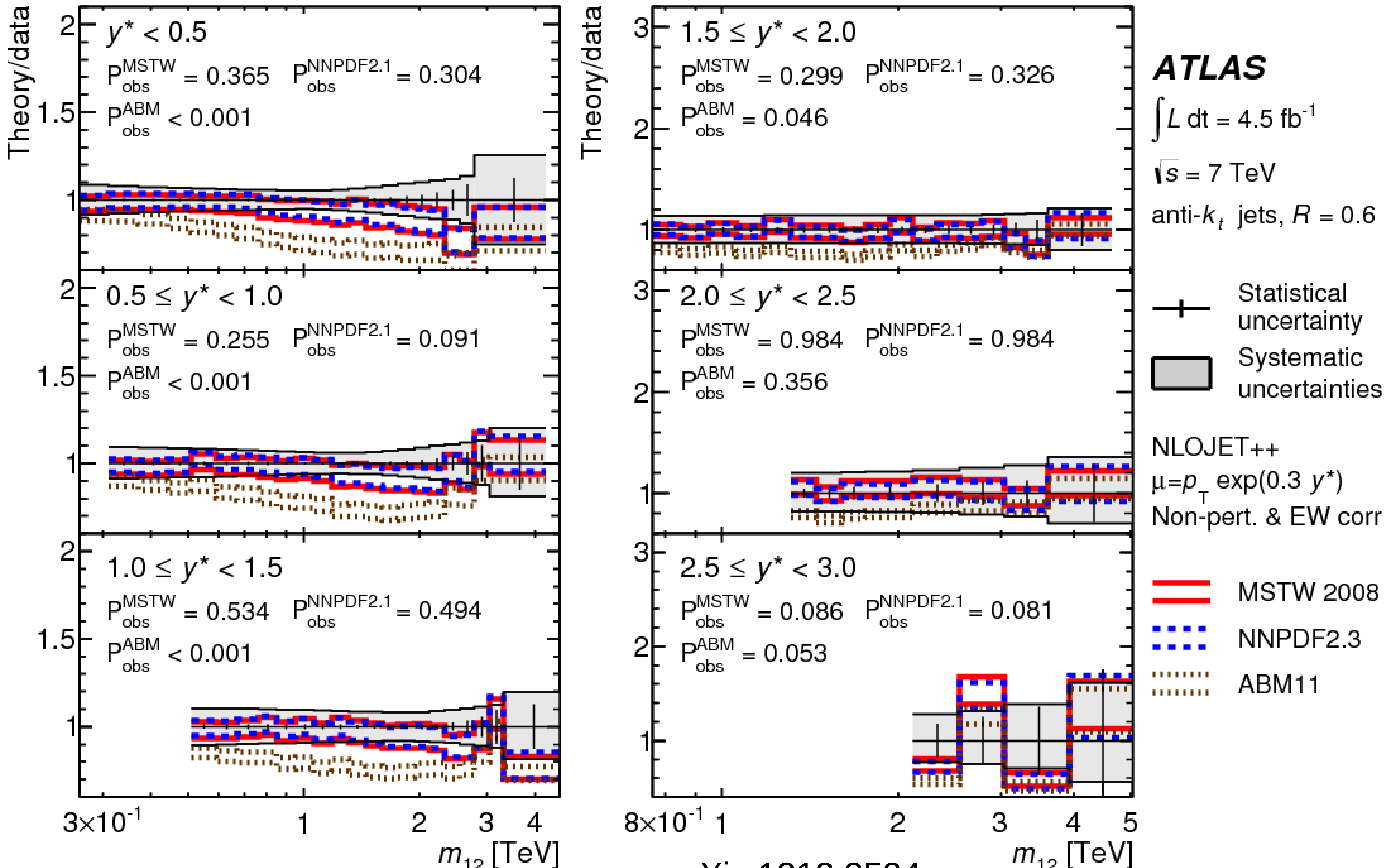
arXiv:1312.3524



arXiv:1312.3524

CMS: PRD 87 (2013) 112002 (backup slide 43)

Dijet Mass Cross Section



arXiv:1312.3524

CMS: PRD 87 (2013) 112002 (backup slide 43)

Three-Jet Mass Cross Section

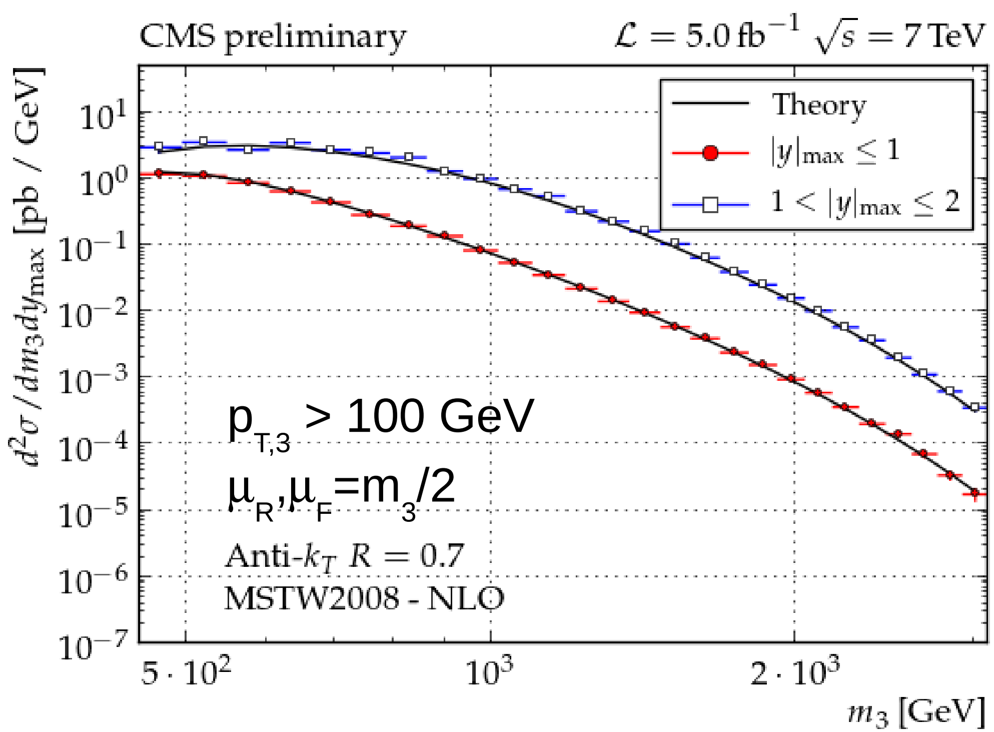
- Using maximal rapidity $y_{\max}$ of the three-jet system to define disjoint phase-spaces:

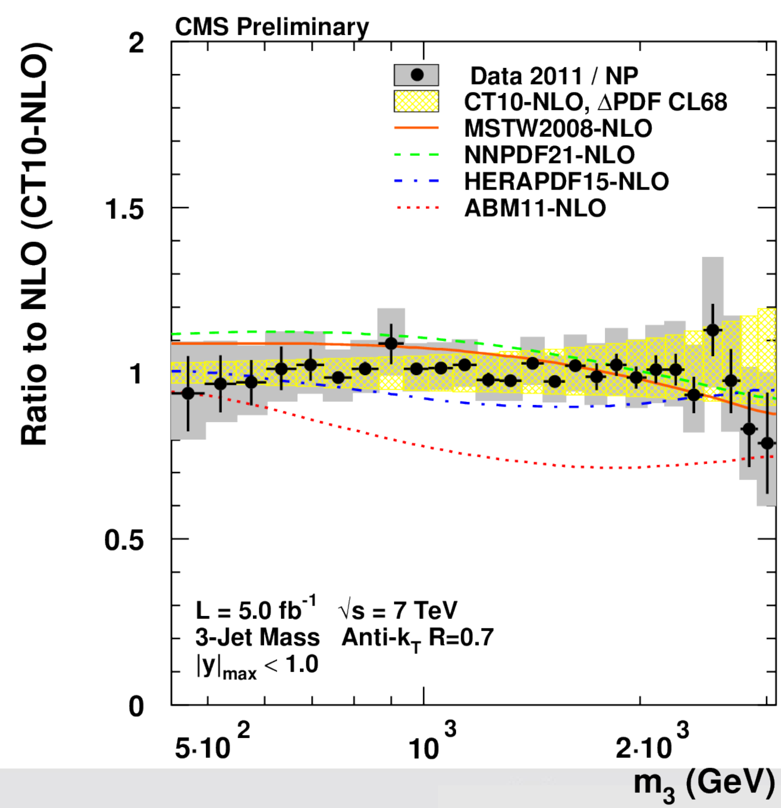
$$\mathrm{sign}(|\max(y_1,y_2,y_3)| - |\min(y_1,y_2,y_3)|) \cdot \max(|y_1|,|y_2|,|y_3|)$$

- Measure double differential three-jet cross section:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_3\mathrm{d}y_{\max}}$$

CMS-PAS-SMP-12-027

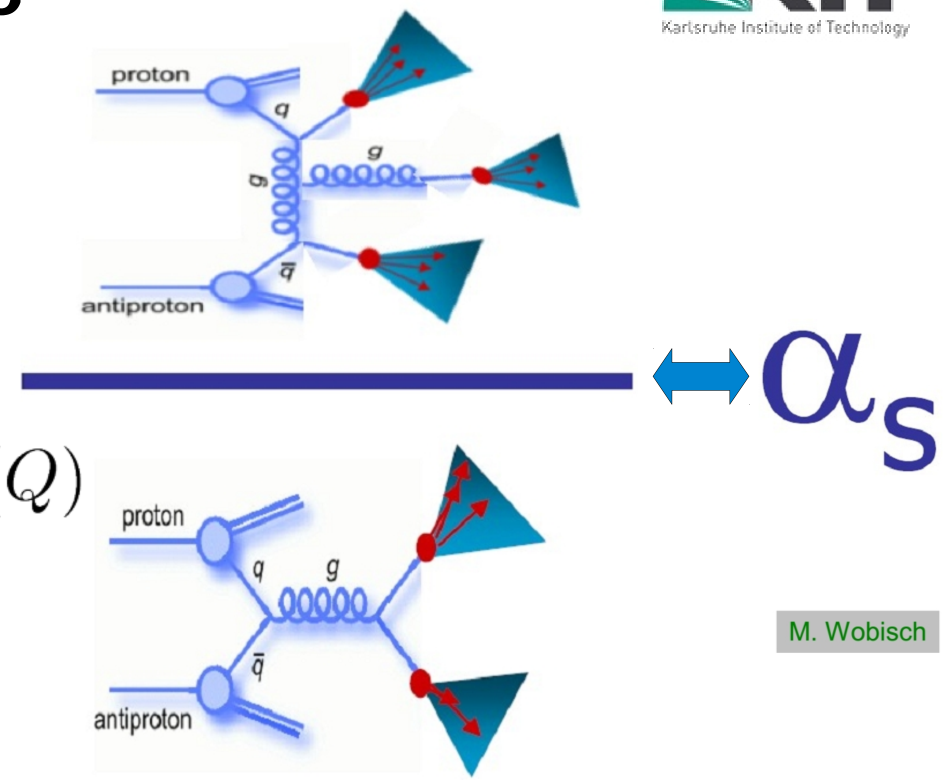




3-jet to 2-jet cross section ratio

- CMS: Ratio between 3-jet and 2-jet production as a function of the average p_T

$$R_{32}\left(\langle p_{T1,2}\rangle\right) \equiv \frac{\mathrm{d}\sigma^{n_j\geq 3}/\mathrm{d}\langle p_{T1,2}\rangle}{\mathrm{d}\sigma^{n_j\geq 2}/\mathrm{d}\langle p_{T1,2}\rangle} \propto \alpha_s(Q)$$



- Advantages of studying the ratio:
  - Luminosity uncertainty removed
  - Avoids the direct dependence on PDFs & the RGE of QCD
- ATLAS: Looking at two related observables:

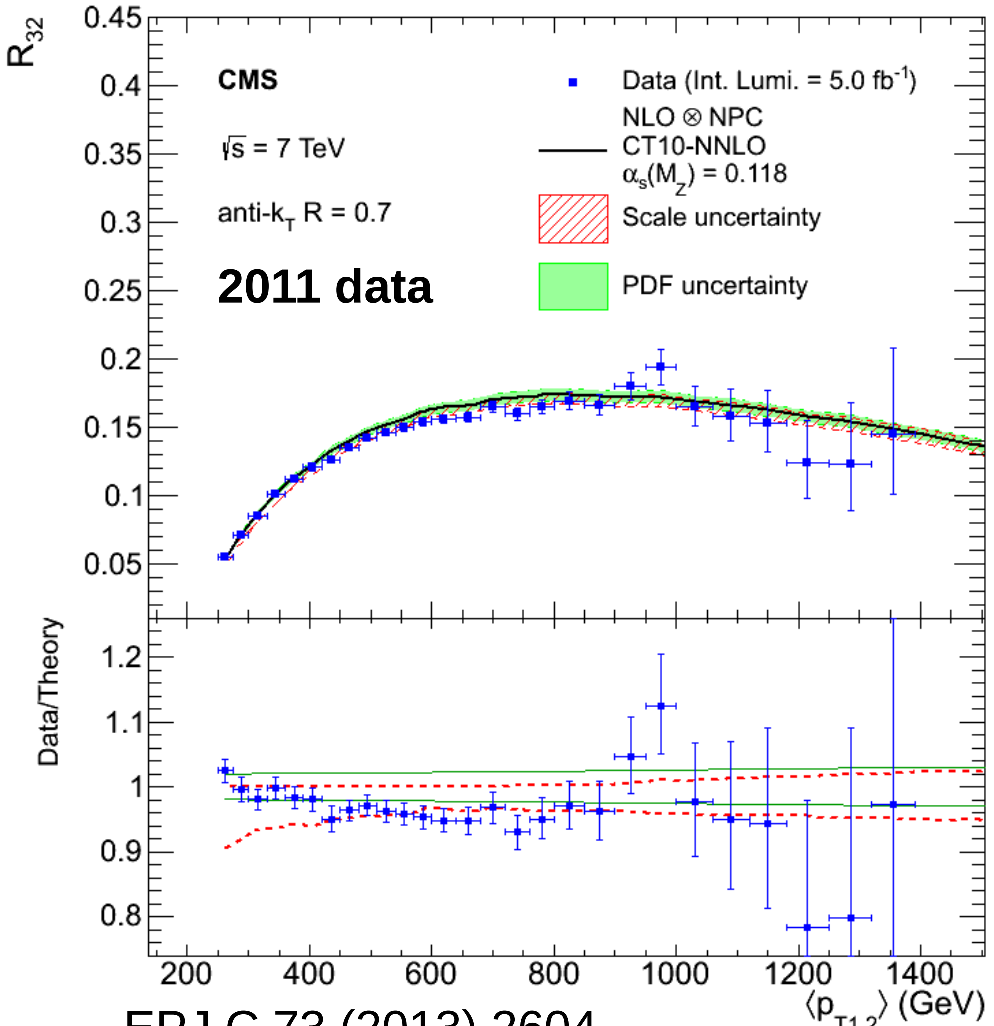
$$R_{3/2}(p_{\mathrm{T}}^{\mathrm{lead}}) = \frac{d\sigma_{N_{\mathrm{jet}}\geq 3}/dp_{\mathrm{T}}^{\mathrm{lead}}}{d\sigma_{N_{\mathrm{jet}}\geq 2}/dp_{\mathrm{T}}^{\mathrm{lead}}} \qquad N_{3/2}(p_{\mathrm{T}}^{(\mathrm{all\ jets})}) = \frac{\sum_i^{N_{\mathrm{jet}}}\left(d\sigma_{N_{\mathrm{jet}}\geq 3}/dp_{\mathrm{T},i}\right)}{\sum_i^{N_{\mathrm{jet}}}\left(d\sigma_{N_{\mathrm{jet}}\geq 2}/dp_{\mathrm{T},i}\right)}$$

3-jet to 2-jet cross section ratio

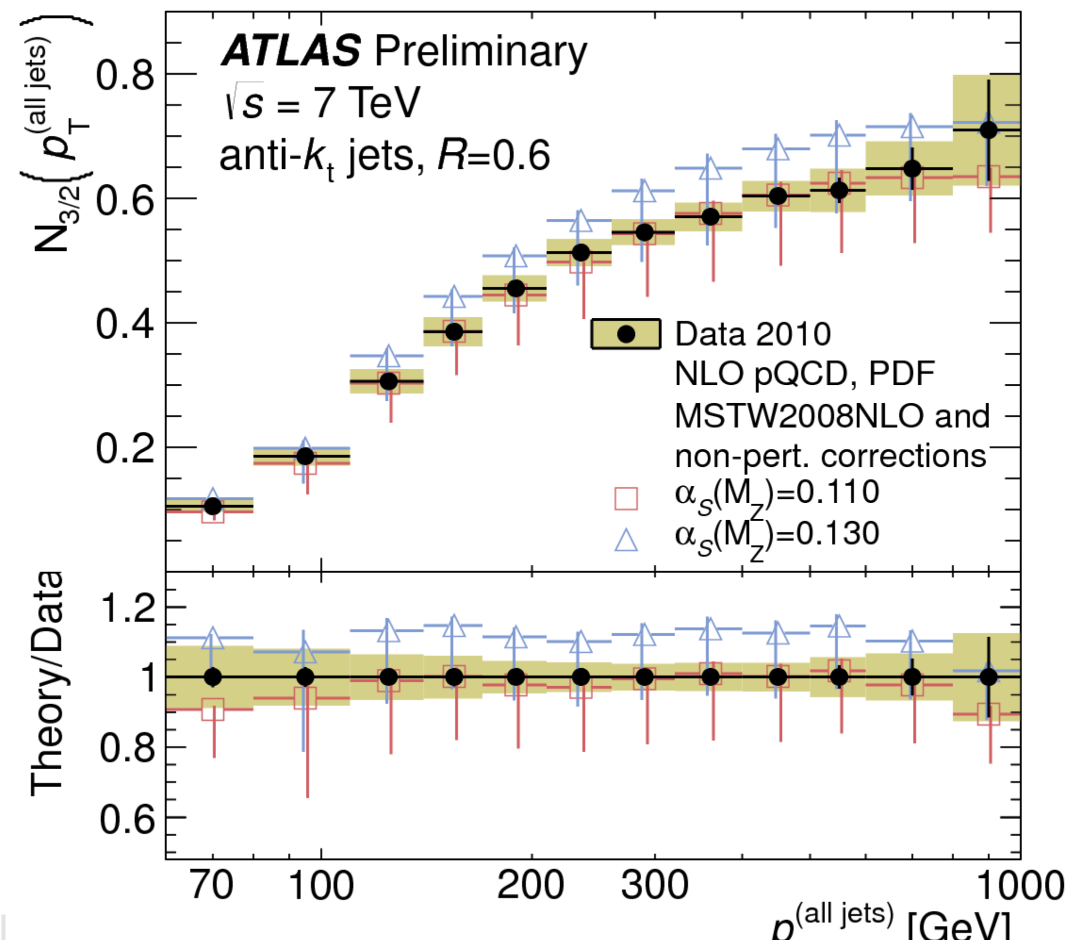
- Theory prediction (NLO+NP) – Scale:

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

$Q = p_T$ (evaluated for all jets)



EPJ C 73 (2013) 2604



ATLAS-CONF-2013-041

Event Shapes

CMS-PAS-SMP-12-022

ATLAS: EPJC (2012) 72: 2211
(backup slide 45)

Events shapes variables provide good sensitivity to the structure of QCD radiation

- Transverse Thrust

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

defines upper / lower part

- Jet Broadenings

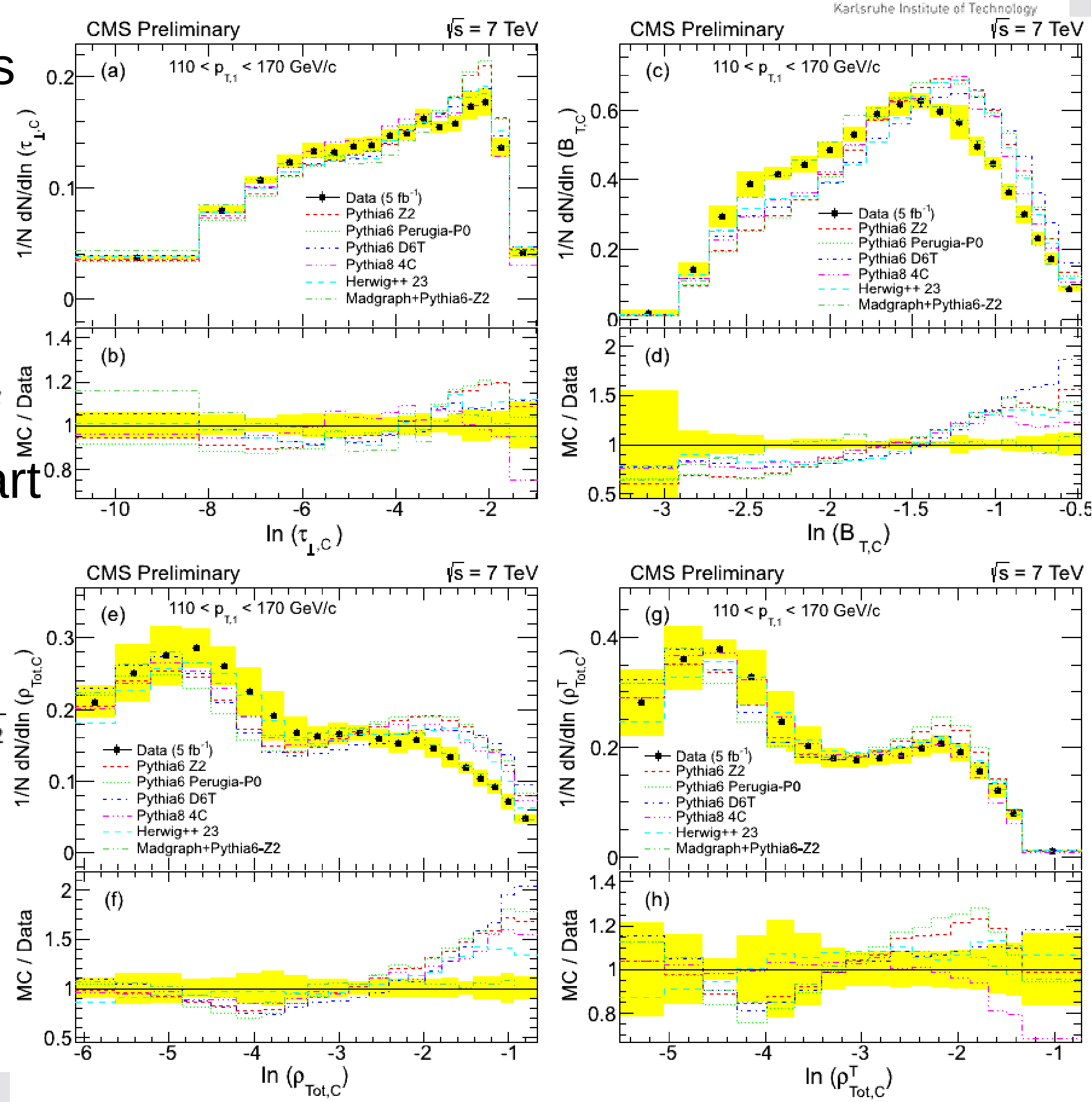
$$\eta_X \equiv \frac{\sum_{i\in\mathcal{C}_X} p_{\perp i}\eta_i}{\sum_{i\in\mathcal{C}_X} p_{\perp i}}, \quad \phi_X \equiv \frac{\sum_{i\in\mathcal{C}_X} p_{\perp i}\phi_i}{\sum_{i\in\mathcal{C}_X} p_{\perp i}}$$

$$B_{X,\mathcal{C}} \equiv \frac{1}{2P_\perp} \sum_{i\in\mathcal{C}_X} p_{\perp i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

$$B_{T,\mathcal{C}} \equiv B_{U,\mathcal{C}} + B_{L,\mathcal{C}}$$

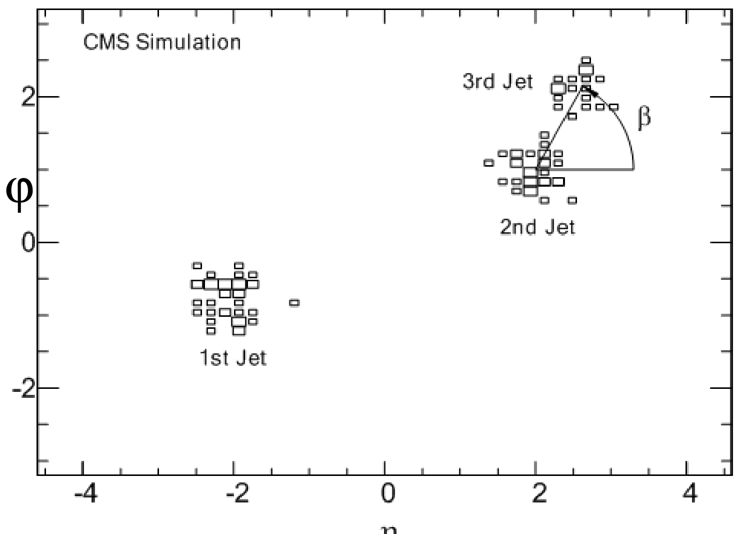
- Jet Masses

$$\rho_X \equiv \frac{1}{Q^2}\left(\sum_{i\in\mathcal{C}_X} q_i\right)^2 \quad \rho_{Tot,\mathcal{C}} \equiv \rho_U + \rho_L$$

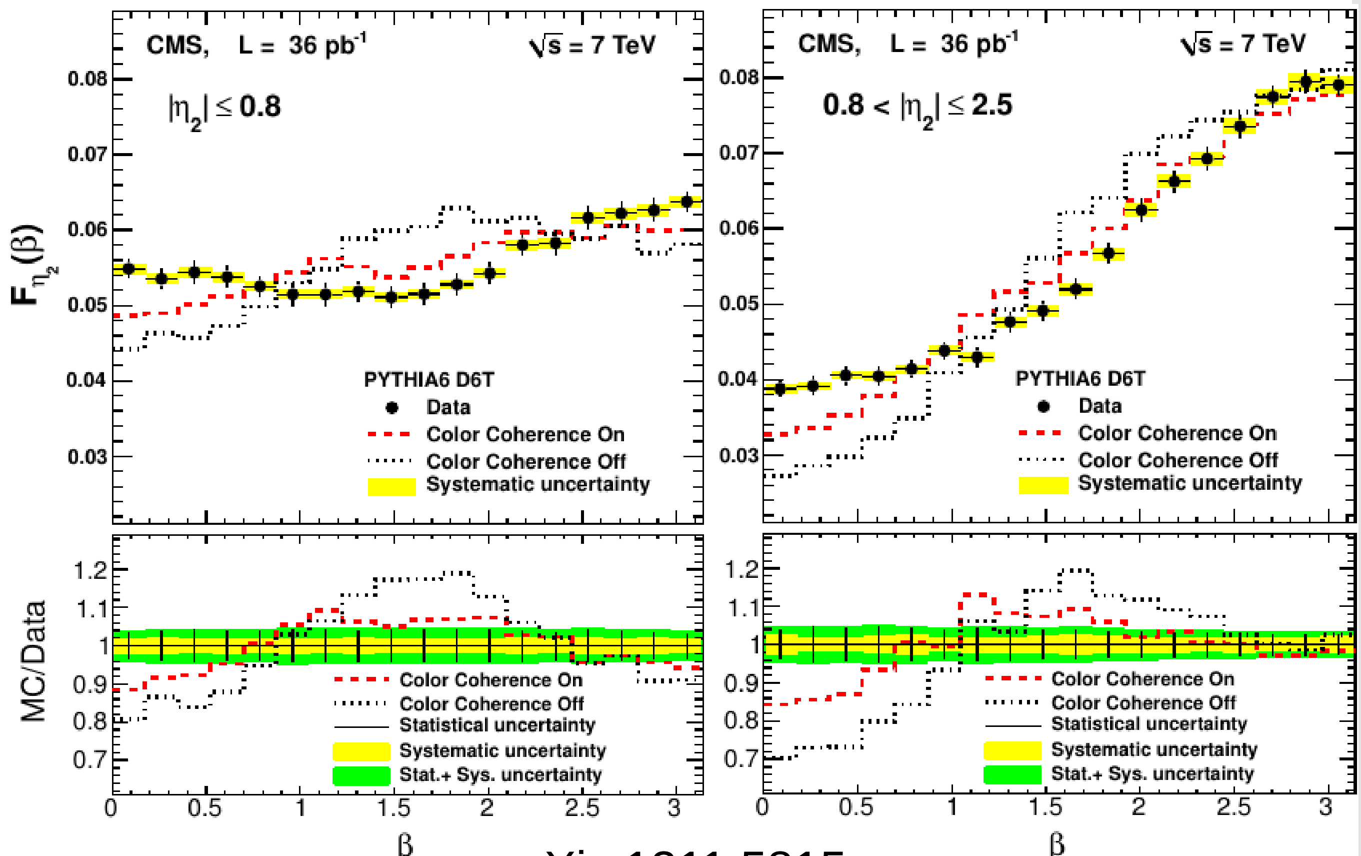


Color coherence effects

- Study of three-jet events where the two jets with the largest transverse momentum exhibit a back-to-back topology
- The measured angular correlation between the second- and third-leading jet is shown to be sensitive to color coherence effects



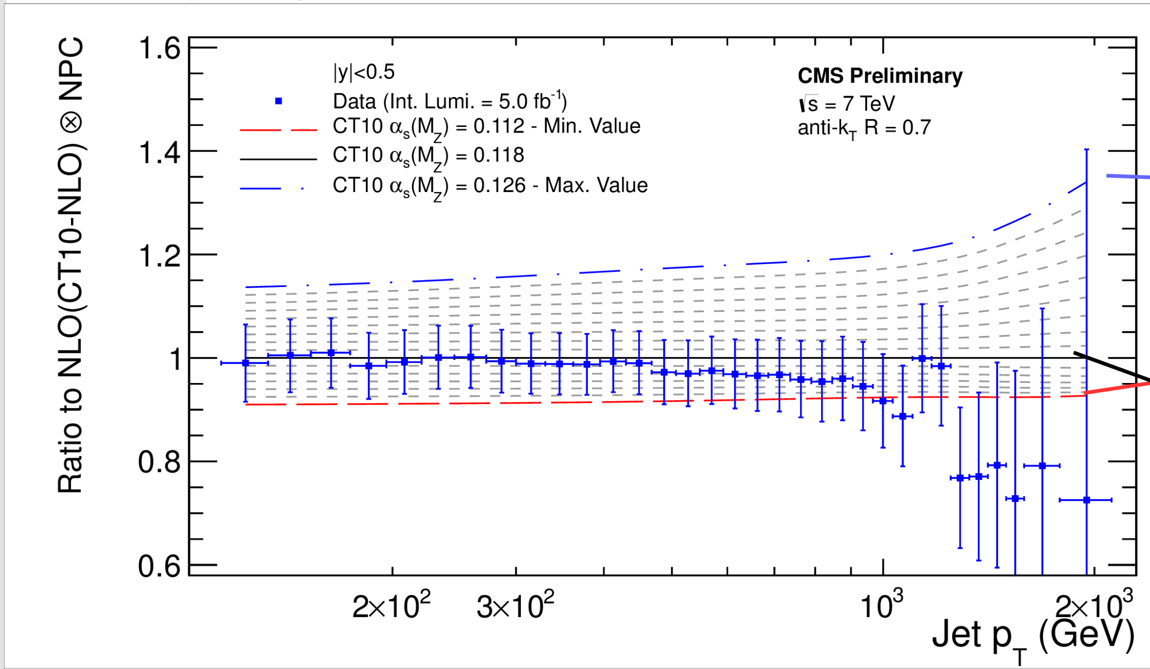
- None of the models describe the data satisfactorily



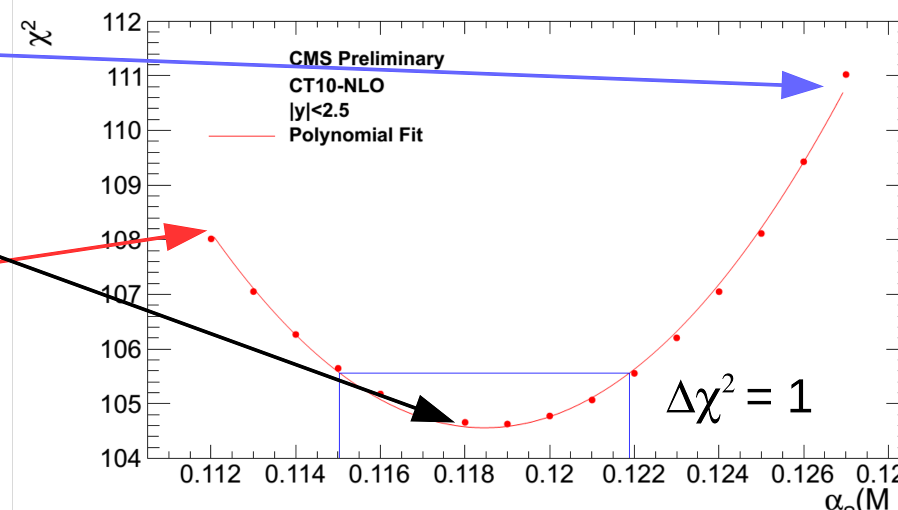
arXiv:1311.5815

α_s Extraction

- Study sensitivity to the strong coupling by comparing
  - Data with well understood uncertainties and correlations
  - Theory (usually NLO+NP) prediction using the α_s series of the PDF groups



CMS-PAS-12-028
7 TeV Inclusive Jet data



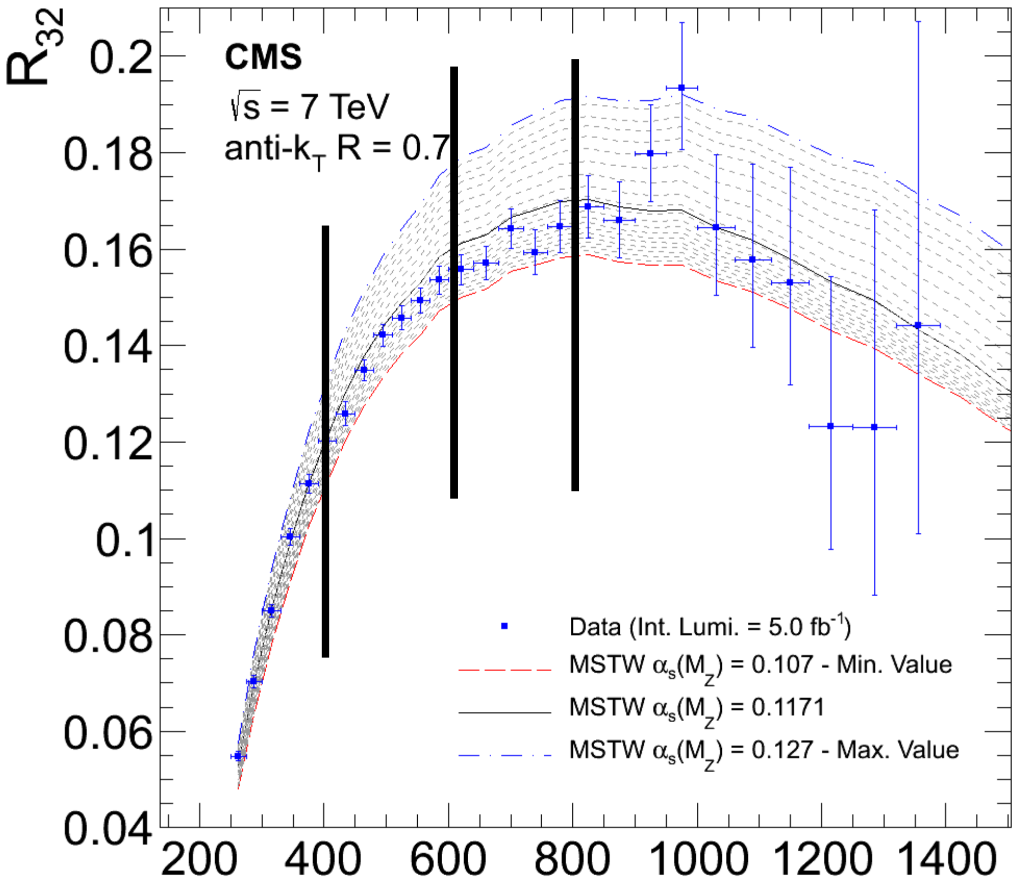
$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp.}) \pm 0.0028\,(\text{PDF})\; 0.0004\,(\text{NP})^{+0.0055}_{-0.0022}\,(\text{scale})$$

- Scale uncertainties are treated separately
  - Envelop based on 6 point scale variation

- Alternative: Simultaneous fit of PDF & α_s (eg. with HERAFitter)

α_s Extraction – 3-jet to 2-jet cross section ratio

- In order to avoid threshold effects, fits only > 400 GeV
  $\alpha_S(M_Z) = 0.1148 \pm 0.0014$ (exp.) ± 0.0018 (PDF) ± 0.0050 (theory)
- Running can be checked by splitting measurements into regions



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Results at different scales:

$\langle p_{T1,2}\rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/N_{dof}
420–600	474	0.1147 ± 0.0061	0.0936 ± 0.0041	6	4.4/5
600–800	664	0.1132 ± 0.0050	0.0894 ± 0.0031	5	5.9/4
800–1390	896	0.1170 ± 0.0058	0.0889 ± 0.0034	10	5.7/9

Detailed uncertainties:

$\langle p_{T1,2}\rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	exp.	PDF	theory
420–600	474	0.1147	±0.0015	±0.0015	±0.0057
600–800	664	0.1132	±0.0018	±0.0025	±0.0039
800–1390	896	0.1170	±0.0024	±0.0021	±0.0048

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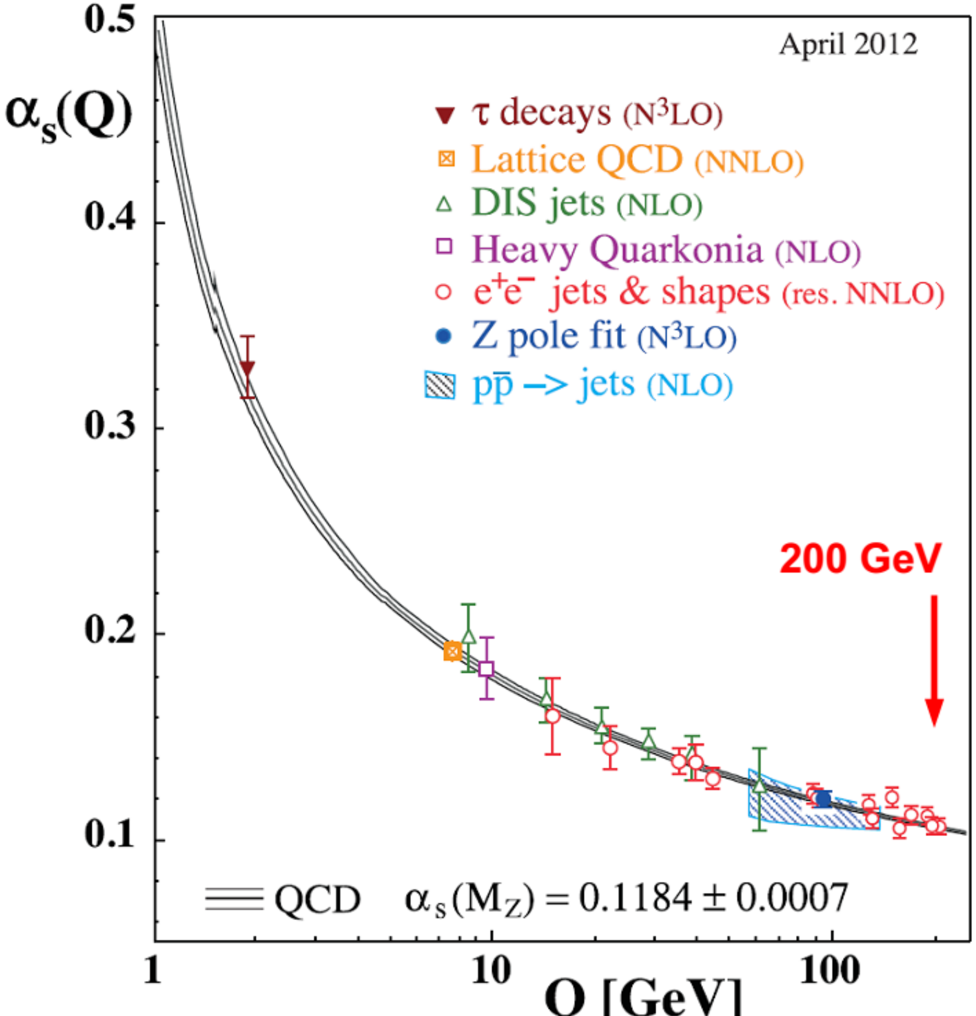
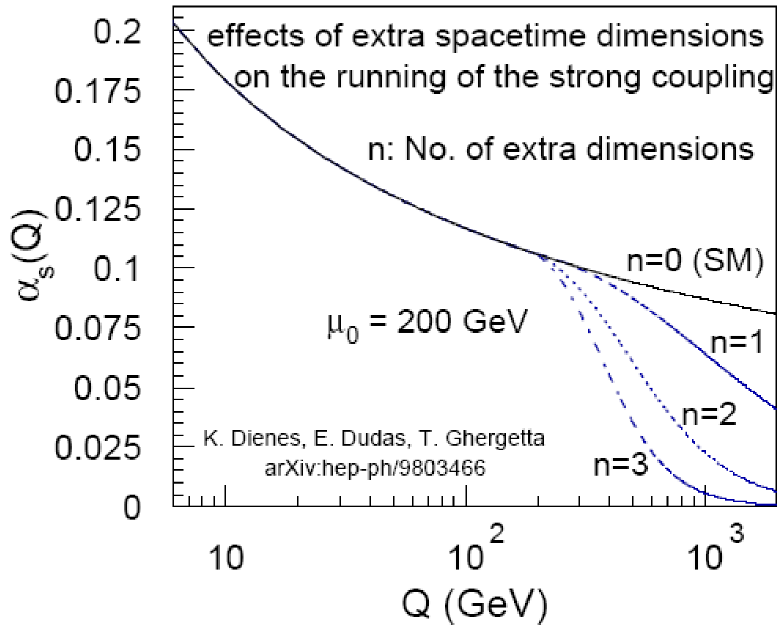
Running of the Strong Coupling

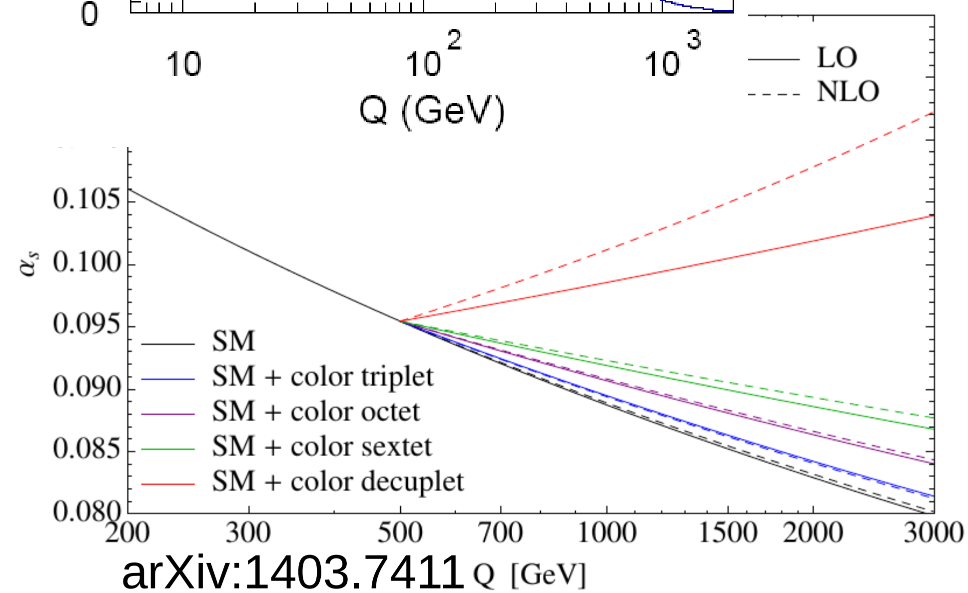
- Running of the strong coupling is sensitive to new physics



PDG 2012

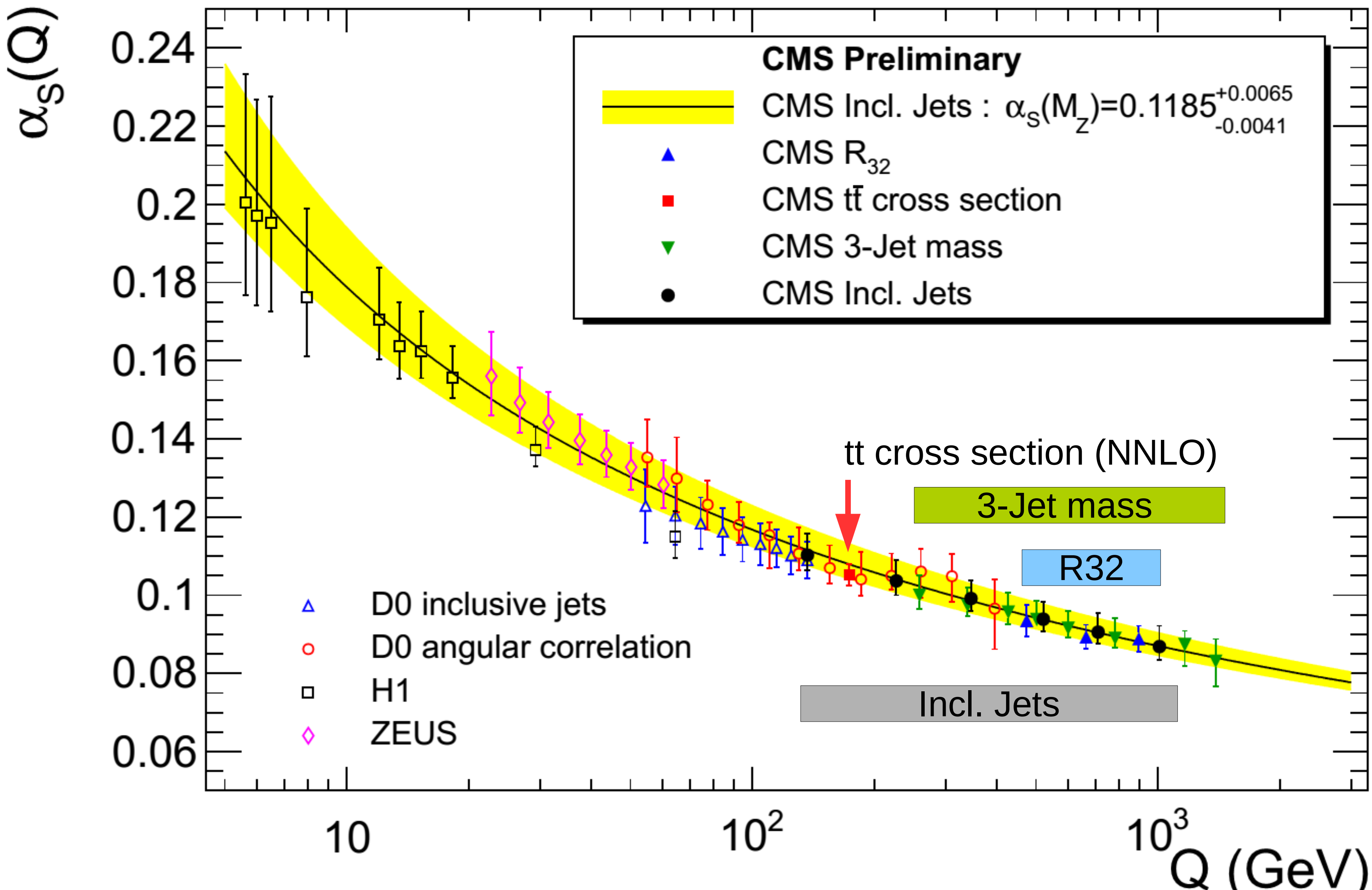


M.Wobisch



arXiv:1403.7411

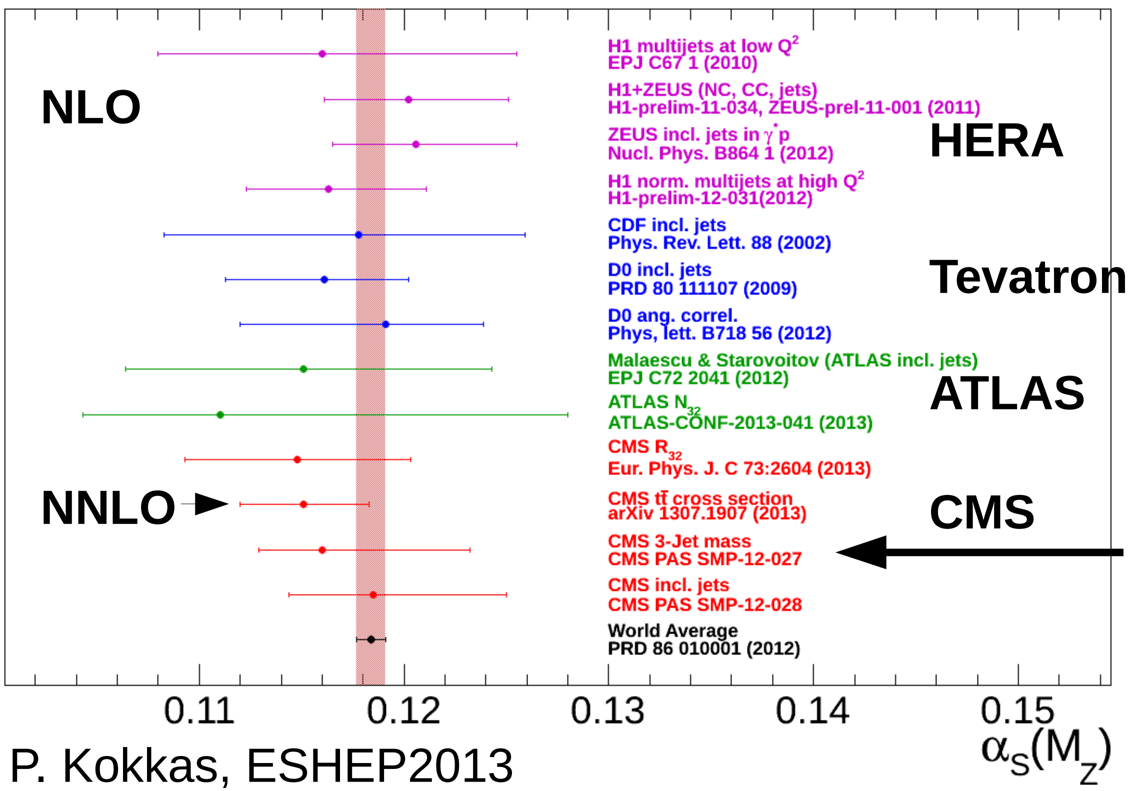
Running of the Strong Coupling



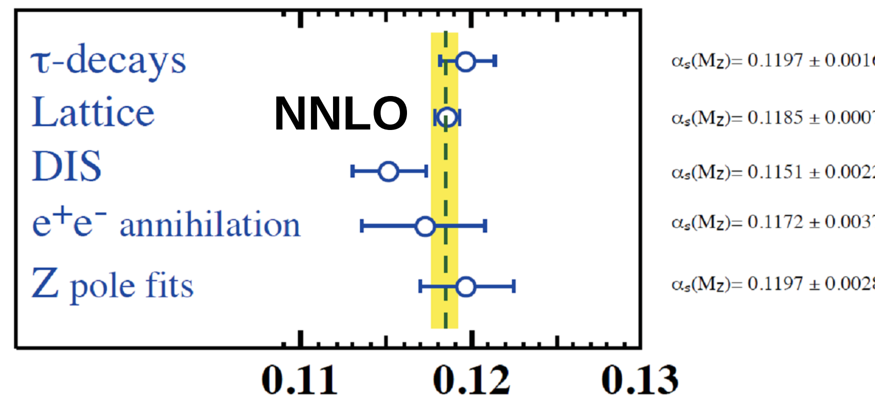
CMS-PAS-12-028

Strong Coupling – Summary

- LHC jet data probes the strong coupling above 1 TeV
  - Uncertainties dominated by theory
    - NNLO jet predictions needed
    - Electroweak corrections become increasingly important



P. Kokkas, ESHEP2013



S.Bethke, PDG2012 $\alpha_s(M_Z)$

$$\alpha_S(M_Z) = 0.1160 \pm^{0.0025}_{0.0023} \text{ (exp, PDF, NP)}$$

$$\pm^{0.0068}_{0.0021} \text{ (scale)}$$

Three-jet mass (NLO):
Scale uncertainty major
contributor to uncertainties!

Summary

- LHC Jet measurements with 2.76 TeV, 7TeV and 8TeV data
  - Many observables studied & good agreement with the SM
- Precision physics
  - Excellent understanding of the detector, very small jet energy scale uncertainties
- Theory:
  - LO not sufficient – NLO & NP corrections widely used
  - Some measurements: large scale uncertainties → NNLO (preceeding Talk by N.Glover)
- Extraction of the strong coupling:
  - Confirmed running of up to very high scales (0.2TeV → 2TeV)
  - Results in agreement with world average

Fitting PDFs → see Talk tomorrow by C. La Licata

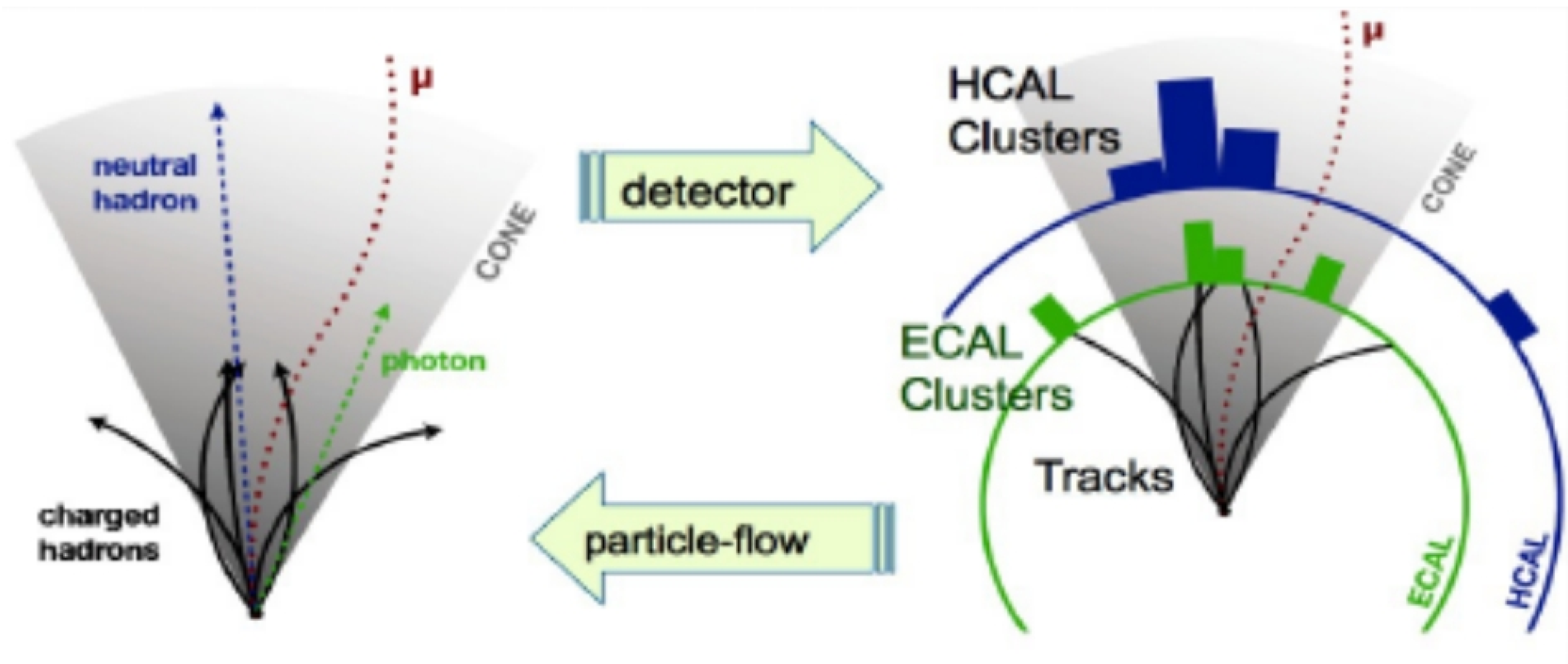
More Results

- Many more public results are available from the LHC experiments
  - ATLAS
    - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - CMS
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

BACKUP

Particle Flow

- Particle-Flow assigns tracks, HCAL and ECAL clusters to Particle-Flow candidates (e, μ, photons, charged & neutral hardrons)
- PF Candidates used to cluster jets, reconstruct MET, isolation, ….

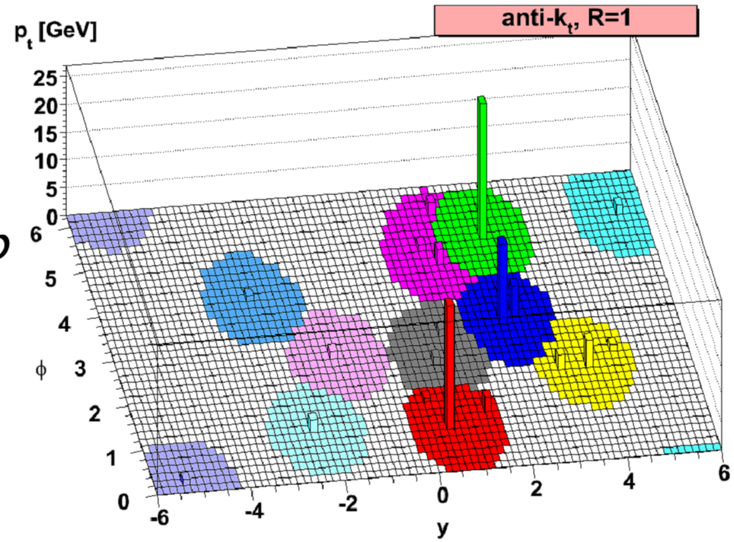


Jet Reconstruction

- Distance dij between objects and distance diB to the beam

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}$$

$$p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

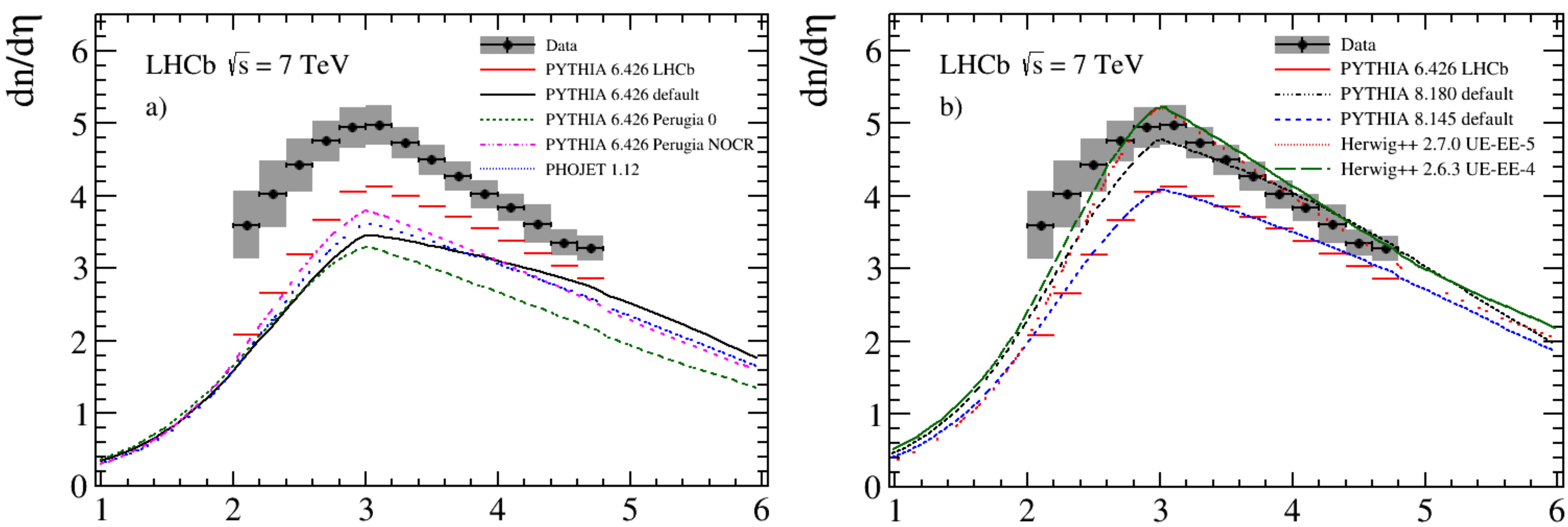


M. Cacciari, G. P. Salam and G. Soyez, JHEP 04 (2008) 063

- Compute all dij diB and calculate d = min(dij, diB)
  - If d = dij, combine objects i and j
  - If d = diB, define object i as jet and remove from further calculations
- Continue until all objects are jets (cone-like)
  → collinear and infrared safe procedure
- ATLAS and CMS use Anti-kT jets by default (but different sizes)

Charged particle multiplicities

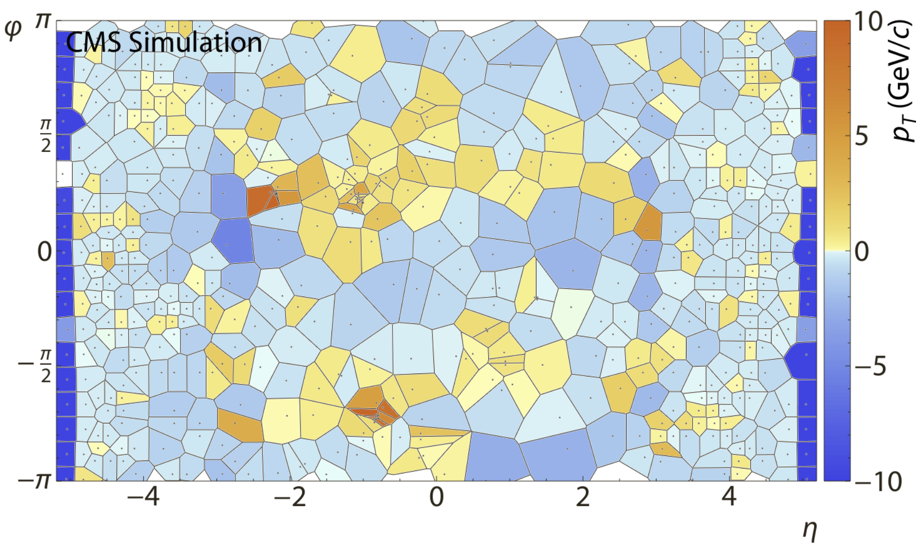
- LHCb uniquely suited to study the forward region
- Recent QCD result:
  Charged particle multiplicities are studied at 7 TeV
- New tunes are able to describe the observed spectrum very well



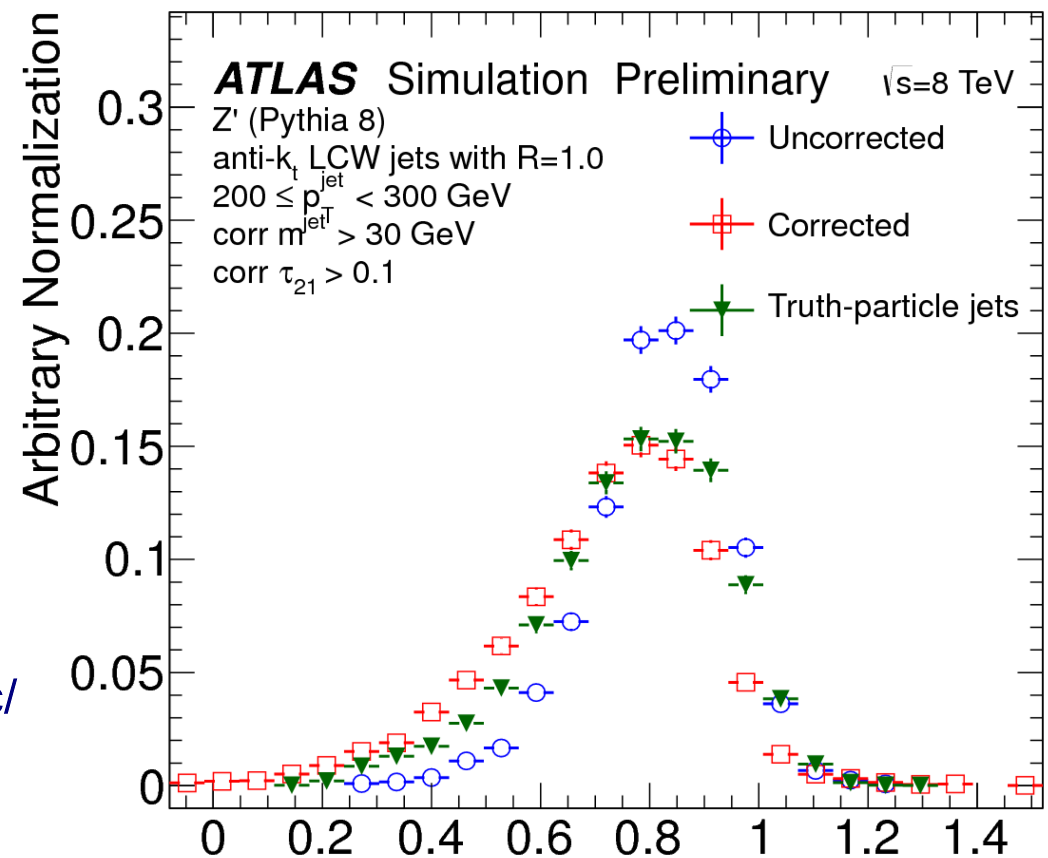
LHCB-PAPER-2013-070

Pile-up

- Experiments have developed techniques to cope with the pile-up by substracting the additional energy from the event

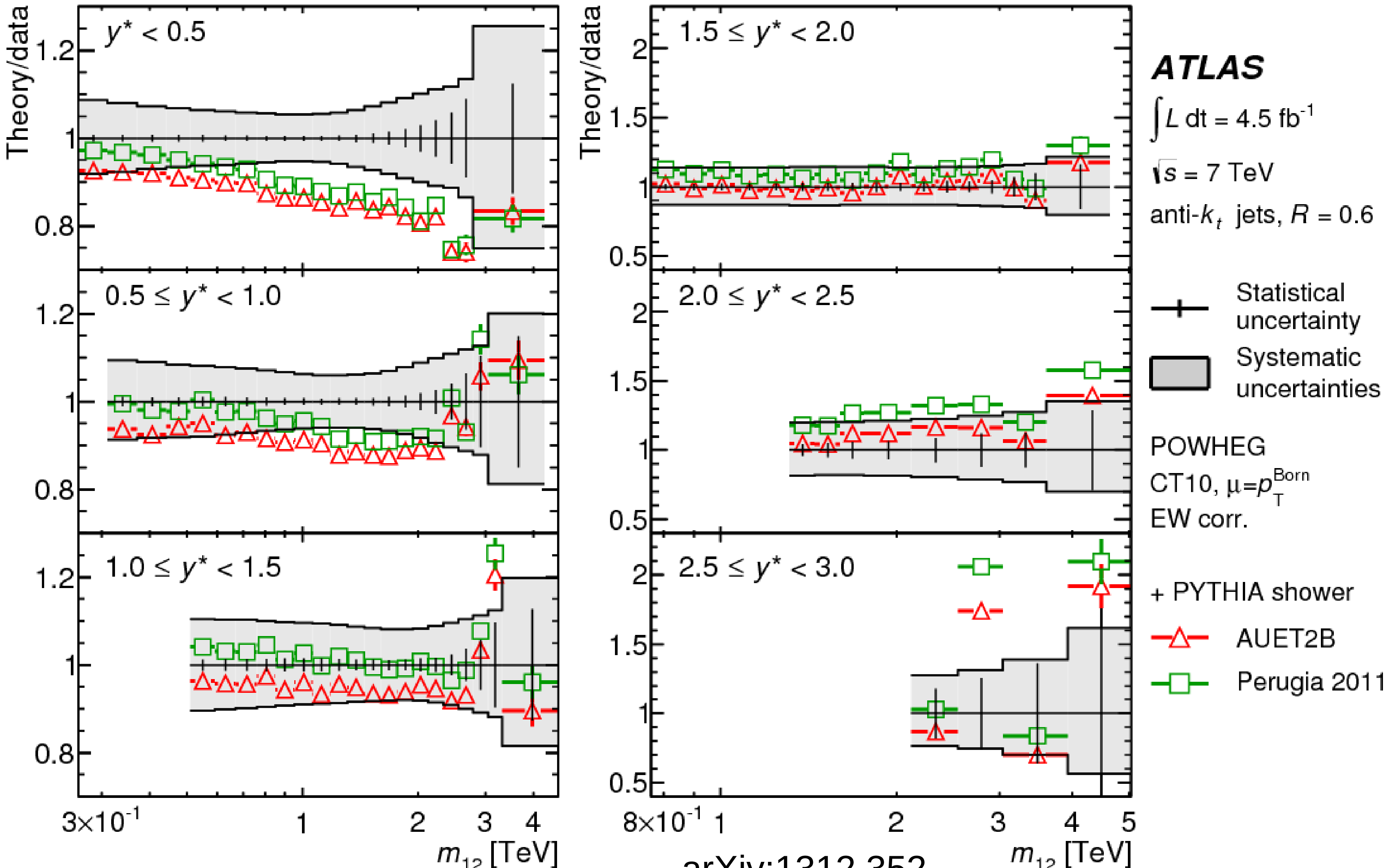


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsDPSUESubtractionPF



ATLAS-CONF-2013-085

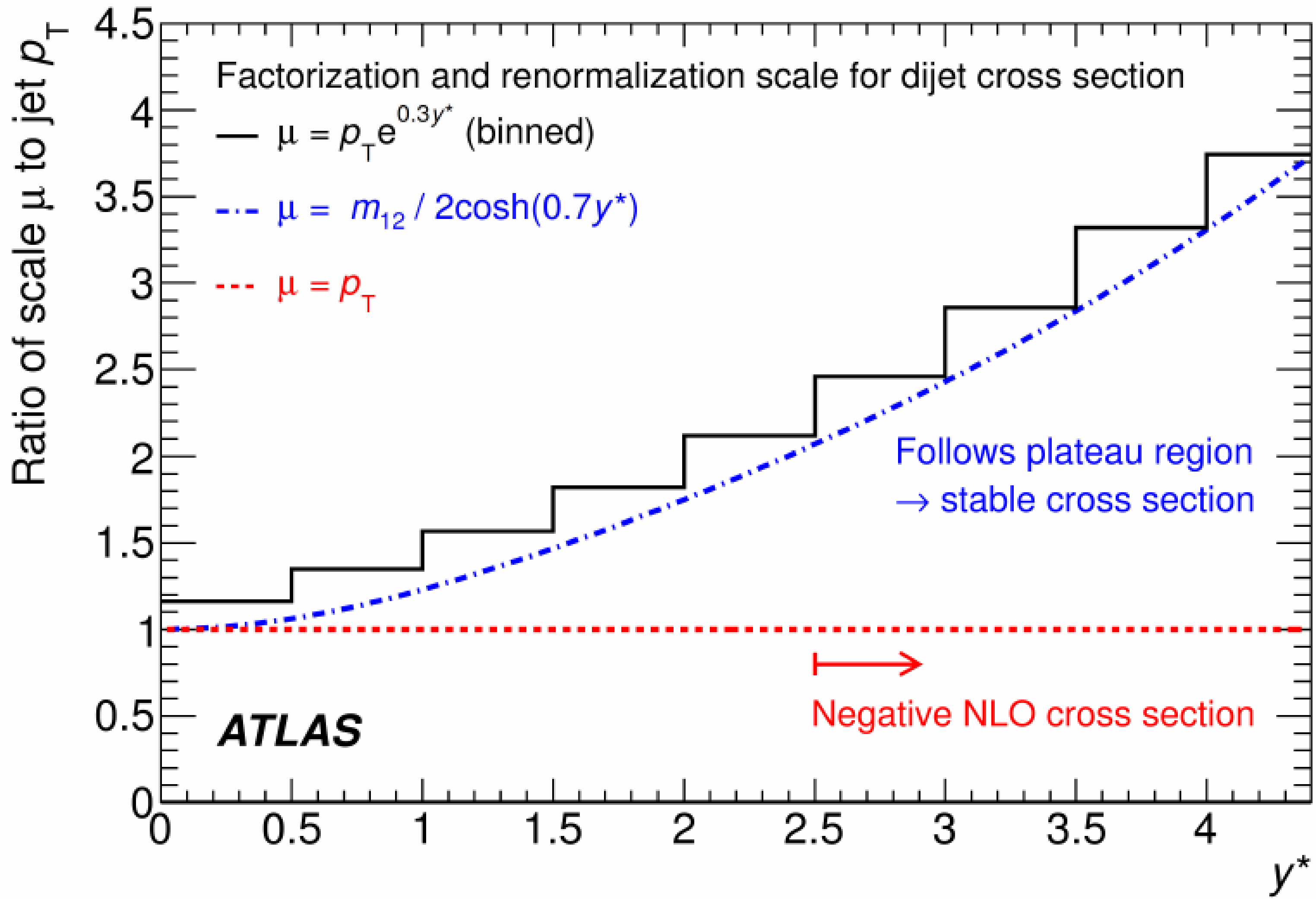
Dijet Mass Cross Section



arXiv:1312.3524

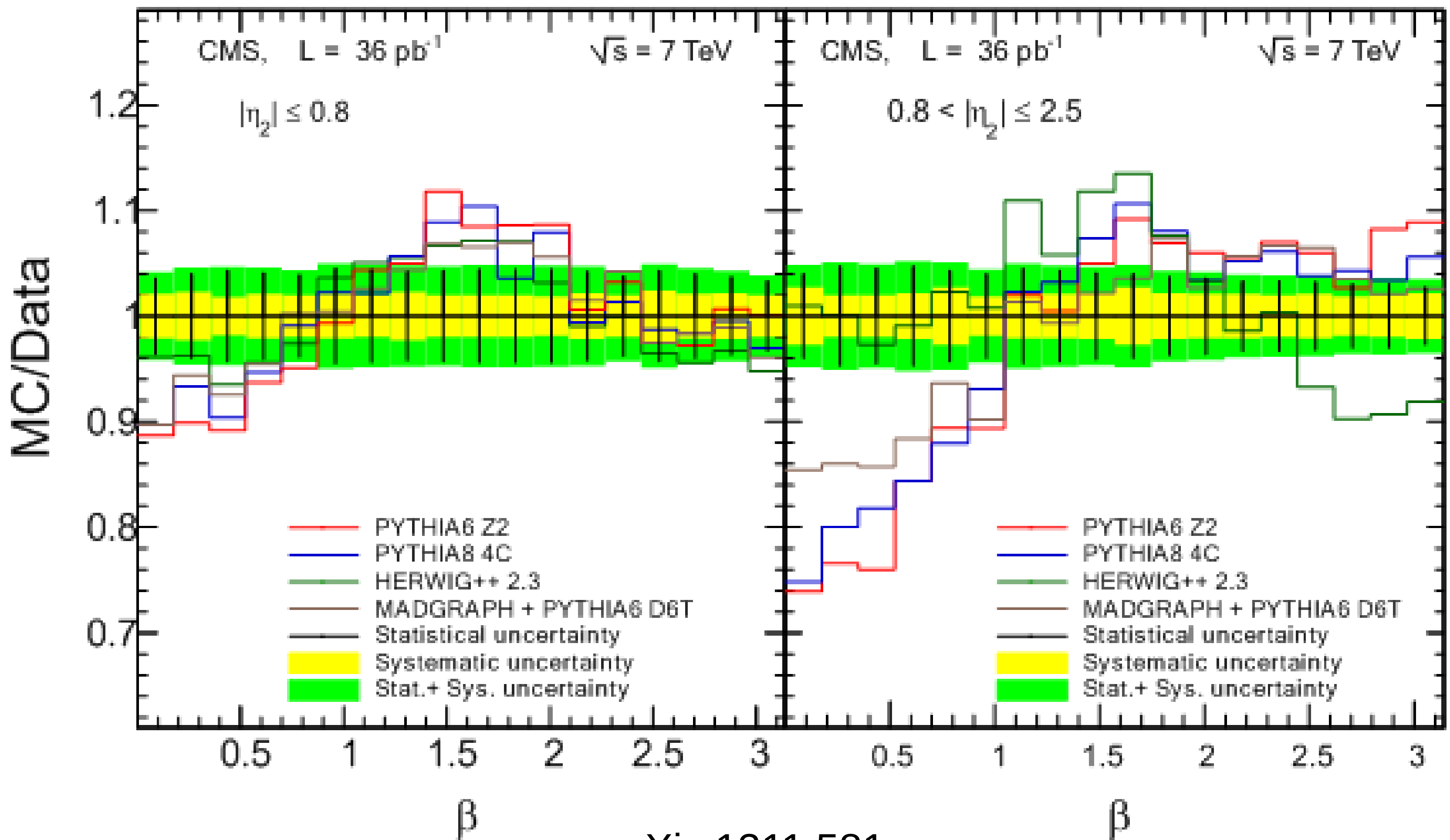
Dijet Mass Cross Section

- Choice of scale: $\mu = \mu_R = \mu_F = p_T^{max} e^{0.3y^*}$



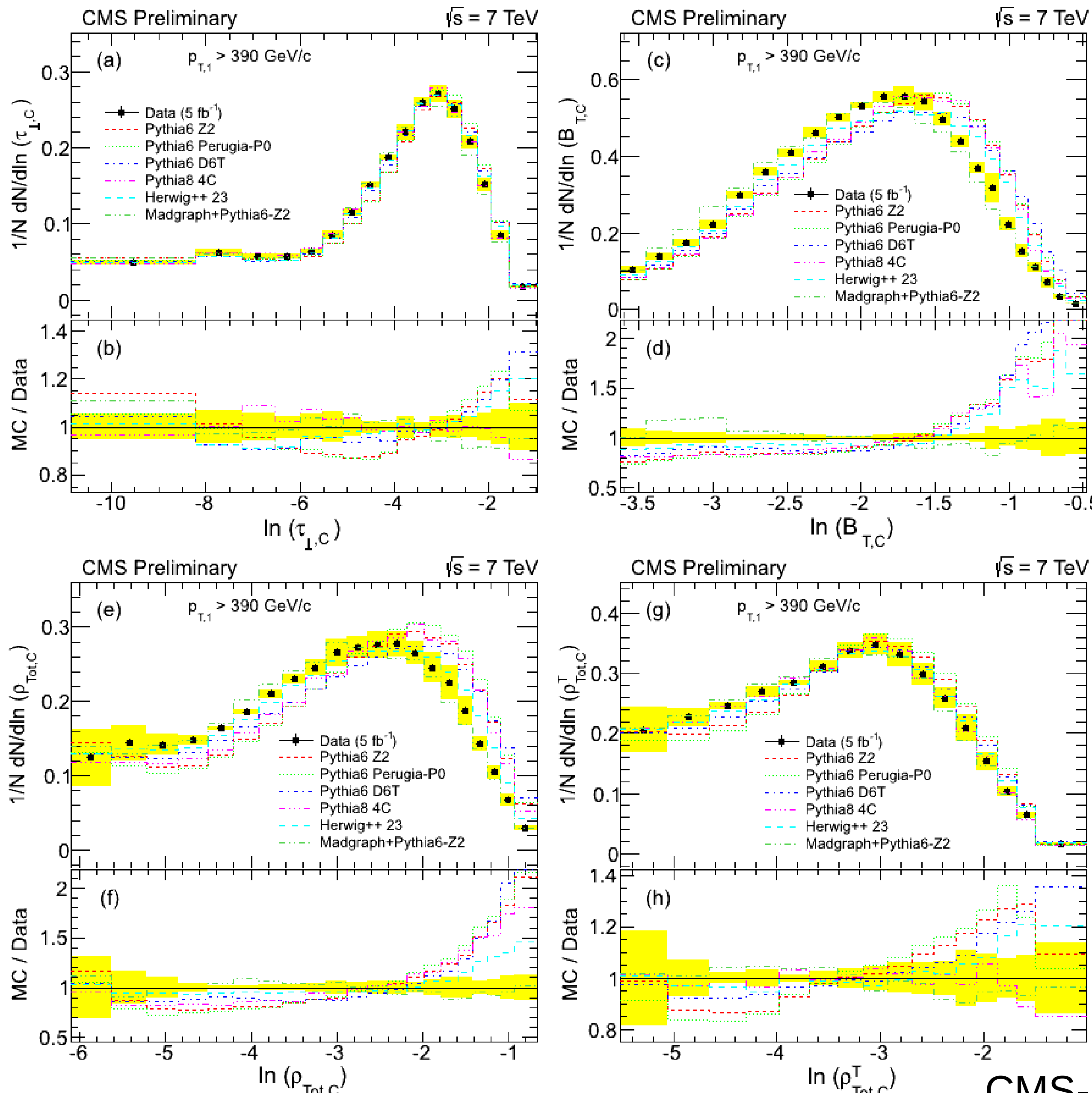
Color Coherence Effects

- Comparison with additional tunes / generators



arXiv:1311.581
5

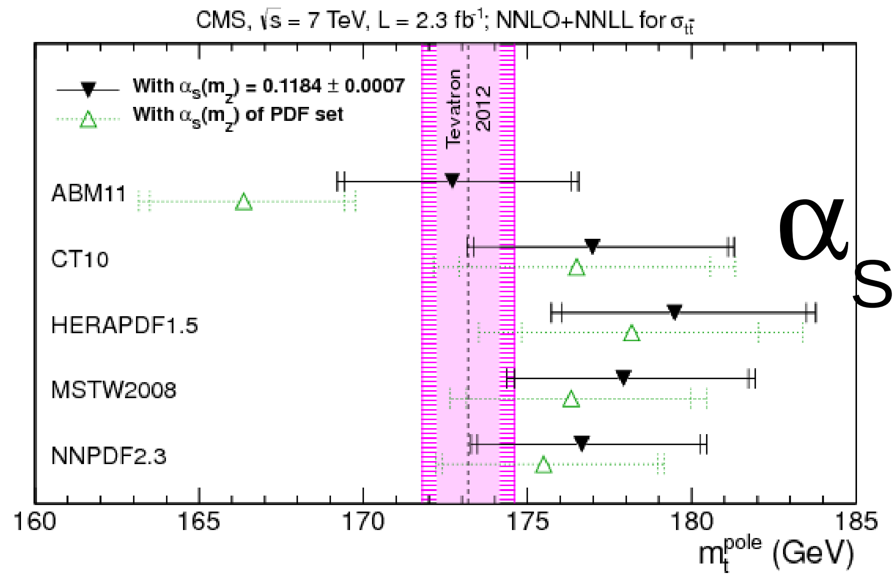
Event Shapes – high leading pT

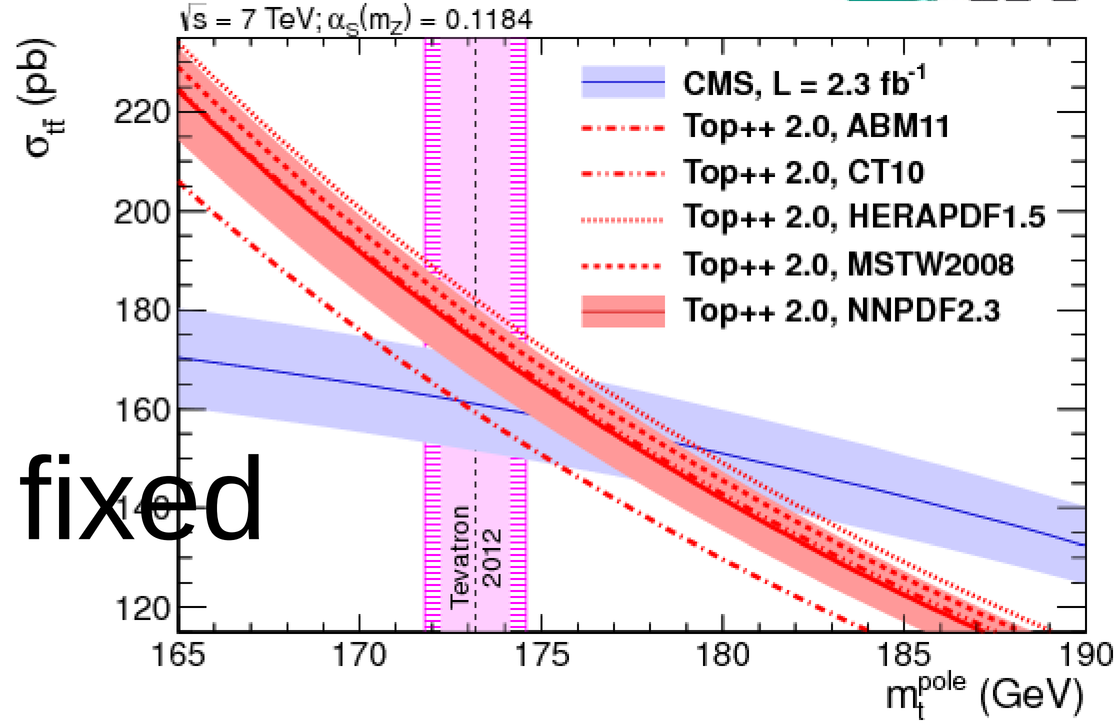


CMS-PAS-SMP-12-022

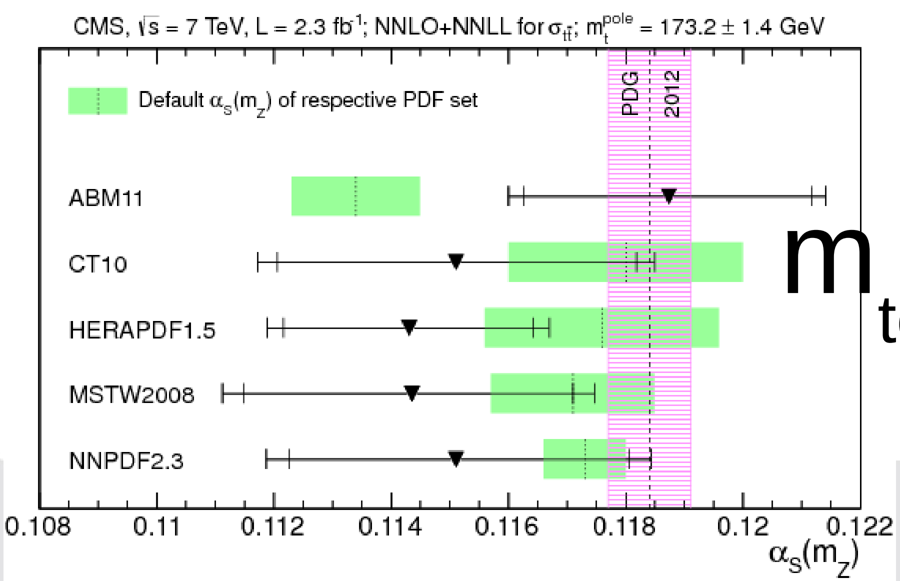
Determination of the Strong Coupling from tt Production

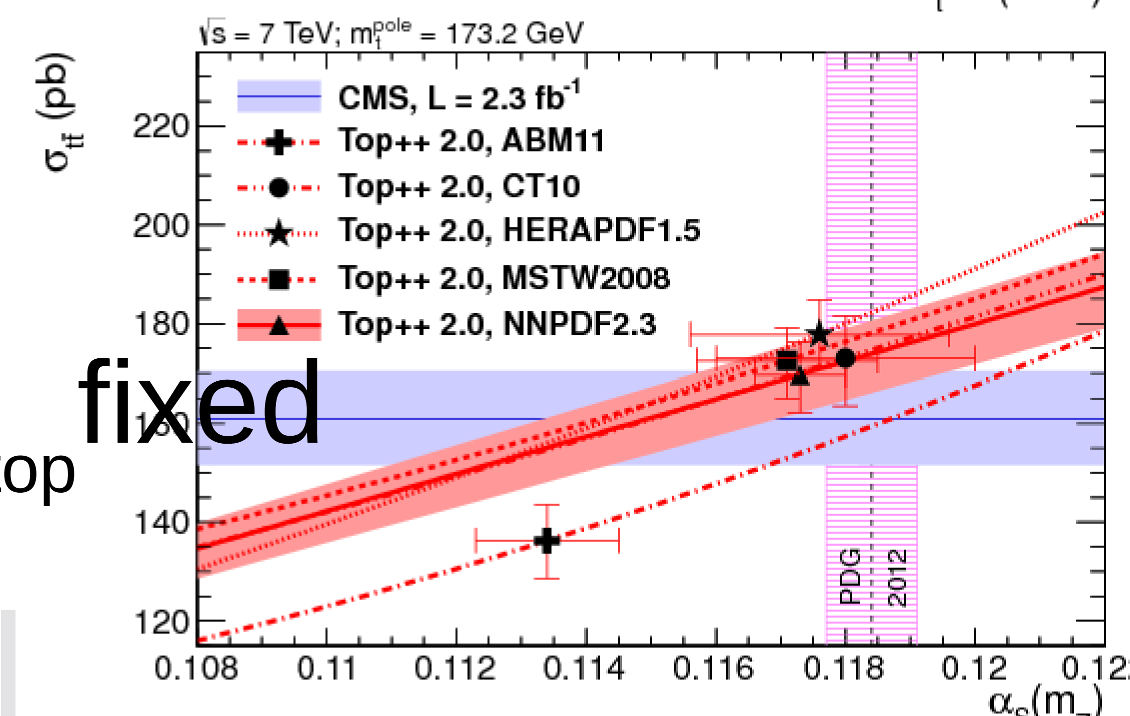
- Predicted tt cross section at **NNLO+NNLL**





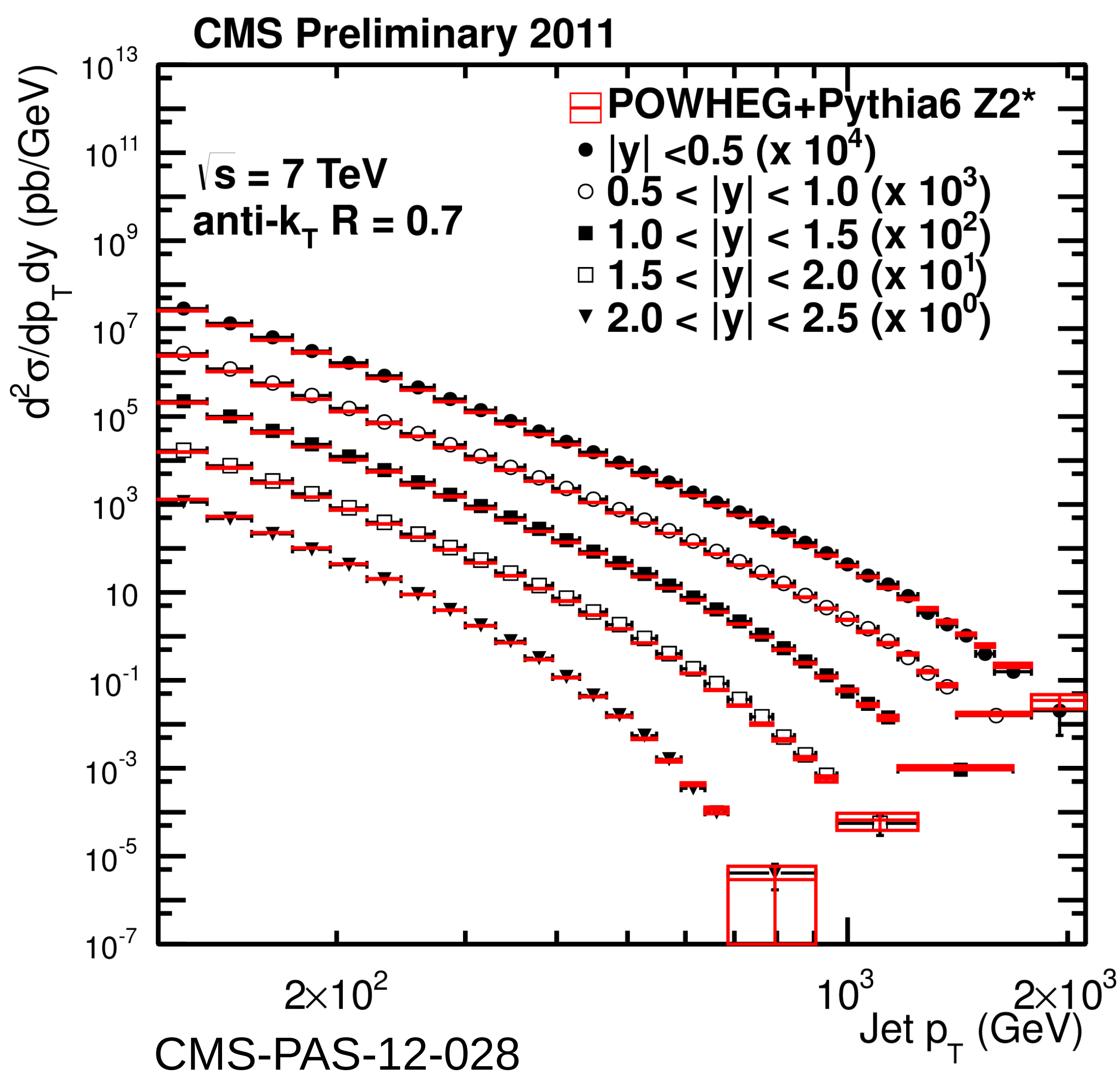
α_s fixed



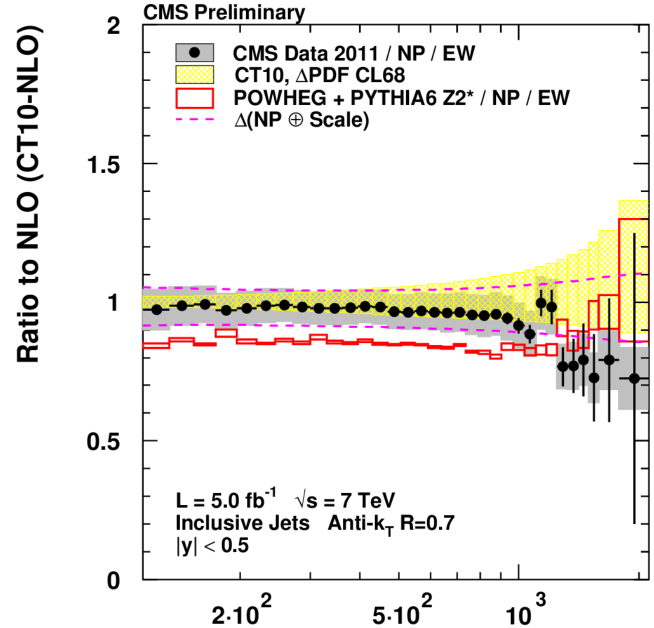


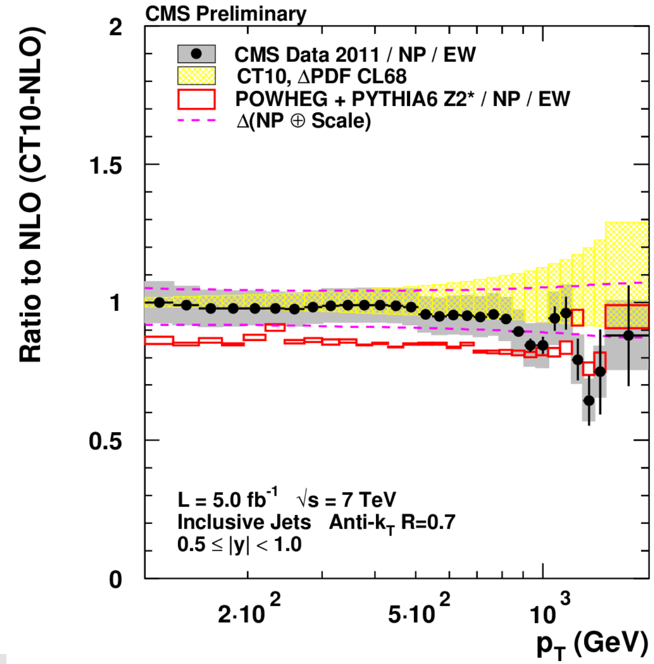
m_{top} fixed

Inclusive Jets



CMS-PAS-12-028





Strong Coupling – Inclusive Jet

Base set	Refs.	Evol.	N_f	M_t (GeV)	M_Z (GeV)	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ range
ABM11	[13]	NLO	5	180.	91.174	0.1180	0.110–0.130
ABM11	[13]	NNLO	5	180.	91.174	0.1134	0.104–0.120
CT10	[14]	NLO	≤ 5	172.	91.188	0.1180	0.112–0.127
CT10	[14]	NNLO	≤ 5	172.	91.188	0.1180	0.110–0.130
HERAPDF15	[15]	NLO	≤ 5	180.	91.187	0.1176	0.114–0.122
HERAPDF15	[15]	NNLO	≤ 5	180.	91.187	0.1176	0.114–0.122
MSTW2008	[16, 17]	NLO	≤ 5	10^{10}	91.1876	0.1202	0.110–0.130
MSTW2008	[16, 17]	NNLO	≤ 5	10^{10}	91.1876	0.1171	0.107–0.127
NNPDF21	[18]	NLO	≤ 6	175.	91.2	0.1190	0.114–0.124
NNPDF21	[18]	NNLO	≤ 6	175.	91.2	0.1190	0.114–0.124

Table 4: Determination of $\alpha_S(M_Z)$ in bins of rapidity using the **CT10-NLO** PDF set. The last row presents the result of a simultaneous fit in all rapidity bins.

$\|y\|$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\|y\| < 0.5$	33	$0.1187 \pm 0.0024(\text{exp}) \pm 0.0029(\text{PDF}) \pm 0.0008(\text{NP})^{+0.0047}_{-0.0024}(\text{scale})$	16.5/32
$0.5 < \|y\| < 1.0$	30	$0.1181 \pm 0.0024(\text{exp}) \pm 0.0029(\text{PDF}) \pm 0.0008(\text{NP})^{+0.0052}_{-0.0023}(\text{scale})$	25.3/29
$1.0 < \|y\| < 1.5$	27	$0.1165 \pm 0.0027(\text{exp}) \pm 0.0024(\text{PDF}) \pm 0.0008(\text{NP})^{+0.0043}_{-0.0019}(\text{scale})$	9.6/26
$1.5 < \|y\| < 2.0$	24	$0.1146 \pm 0.0035(\text{exp}) \pm 0.0030(\text{PDF}) \pm 0.0013(\text{NP})^{+0.0038}_{-0.0020}(\text{scale})$	20.3/23
$2.0 < \|y\| < 2.5$	19	$0.1161 \pm 0.0046(\text{exp}) \pm 0.0053(\text{PDF}) \pm 0.0015(\text{NP})^{+0.0035}_{-0.0031}(\text{scale})$	12.8/18
$\|y\| < 2.5$	133	$0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(\text{PDF}) \pm 0.0004(\text{NP})^{+0.0055}_{-0.0022}(\text{scale})$	104.6/132

CMS-PAS-12-028

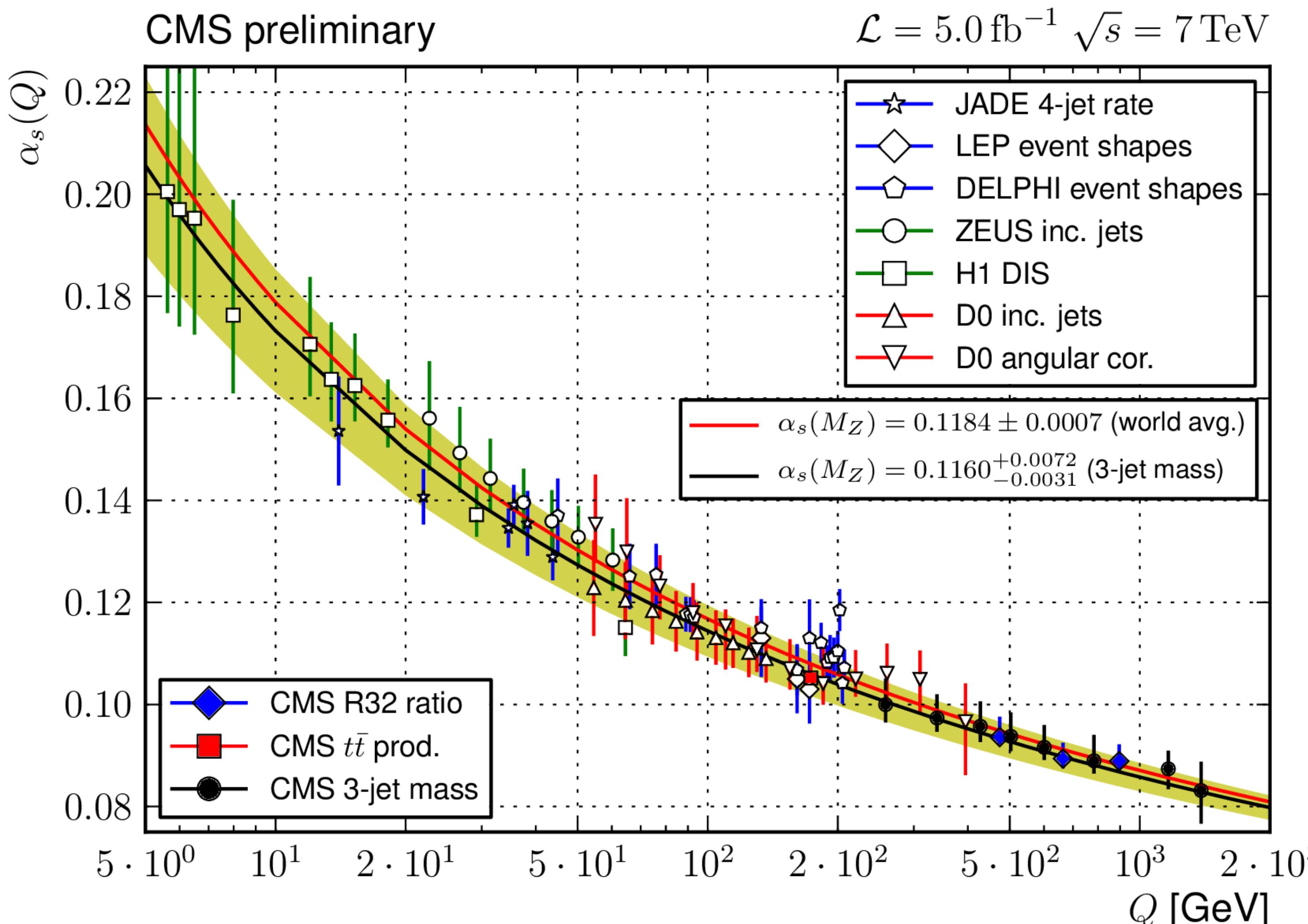
Strong Coupling – Three-Jet Mass

PDF	χ^2/N_{dof}	$\alpha_S(m_Z)$	$\pm(\mathrm{exp},\mathrm{PDF},\mathrm{NP})$	$\pm(\mathrm{scale})$
CT10-NLO	8.92/26	0.1169	$\pm^{0.0031}_{0.0032}$	$\pm^{0.0059}_{0.0025}$
CT10-NNLO	8.51/26	0.1164	± 0.0028	$\pm^{0.0055}_{0.0022}$
HERAPDF15-NLO	14.76/26	0.1200	± 0.0014	$\pm^{0.0063}_{0.0010}$
HERAPDF15-NNLO	9.00/26	0.1159	$\pm^{0.0012}_{0.0011}$	$\pm^{0.0028}_{0.0007}$
MSTW2008-NLO	9.11/26	0.1160	$\pm^{0.0025}_{0.0023}$	$\pm^{0.0068}_{0.0021}$
MSTW2008-NNLO	9.54/26	0.1167	$\pm^{0.0026}_{0.0024}$	$\pm^{0.0059}_{0.0026}$
NNPDF21-NLO	9.01/26	0.1140	$\pm^{0.0027}_{0.0026}$	$\pm^{0.0049}_{0.0014}$
NNPDF21-NNLO	9.47/26	0.1168	$\pm^{0.0021}_{0.0024}$	$\pm^{0.0042}_{0.0018}$

m_3 [GeV]	$\langle Q \rangle$ [GeV]	χ^2/N_{dof}	$\alpha_S(m_Z)$	$\pm(\mathrm{exp},\mathrm{PDF},\mathrm{NP})$	$\pm(\mathrm{scale})$
445–604	258 ± 12	0.05/3	0.1152	$\pm^{0.0044}_{0.0042}$	$\pm^{0.0053}_{0.0019}$
604–794	339 ± 14	0.28/3	0.1163	$\pm^{0.0034}_{0.0032}$	$\pm^{0.0058}_{0.0022}$
794–938	427 ± 12	0.46/2	0.1179	$\pm^{0.0042}_{0.0041}$	$\pm^{0.0063}_{0.0023}$
938–1098	502 ± 13	0.01/2	0.1177	± 0.0039	$\pm^{0.0065}_{0.0024}$
1098–1369	600 ± 20	0.70/3	0.1174	$\pm^{0.0032}_{0.0031}$	$\pm^{0.0066}_{0.0025}$
1369–2172	783 ± 32	2.22/7	0.1175	± 0.0034	$\pm^{0.0085}_{0.0027}$
2172–2602	1163 ± 31	1.40/3	0.1218	$\pm^{0.0037}_{0.0060}$	$\pm^{0.0061}_{0.0048}$
2602–3092	1386 ± 34	0.33/3	0.1166	$\pm^{0.0075}_{0.0100}$	$\pm^{0.0088}_{0.0075}$
445–3092	304 ± 15	9.11/26	0.1160	$\pm^{0.0025}_{0.0023}$	$\pm^{0.0068}_{0.0021}$

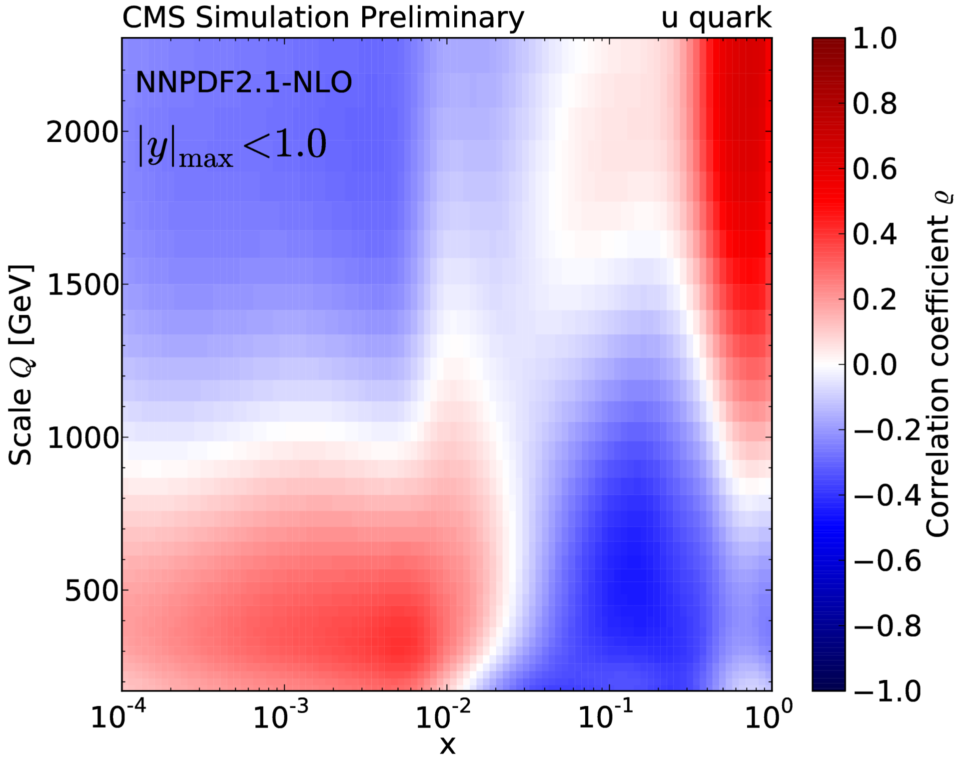
CMS-PAS-SMP-12-027

Running of the Strong Coupling

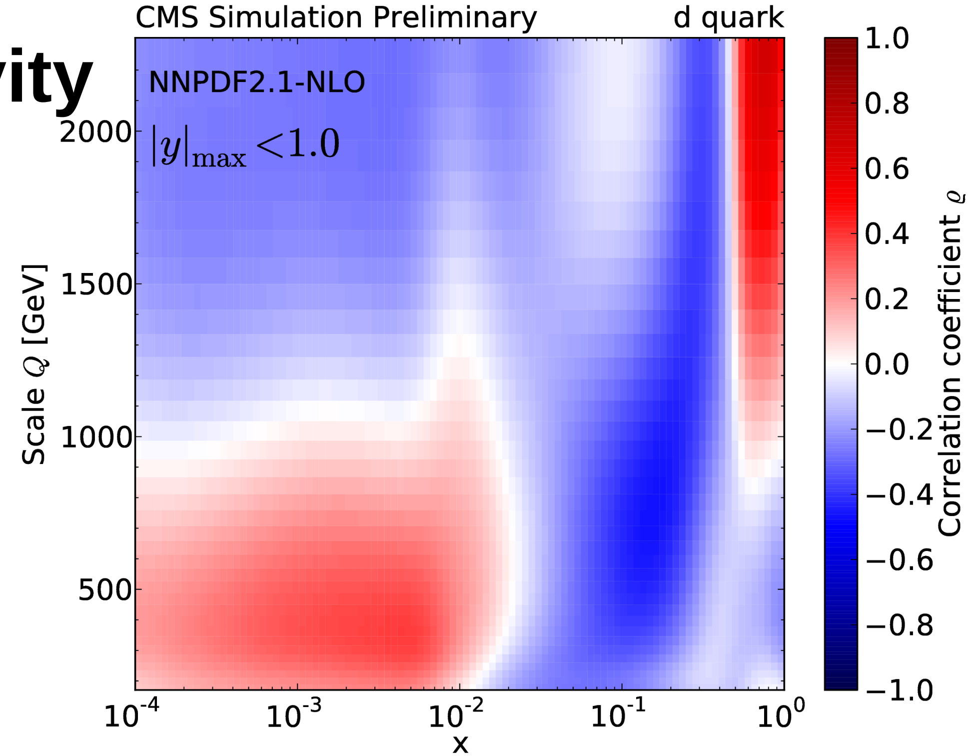


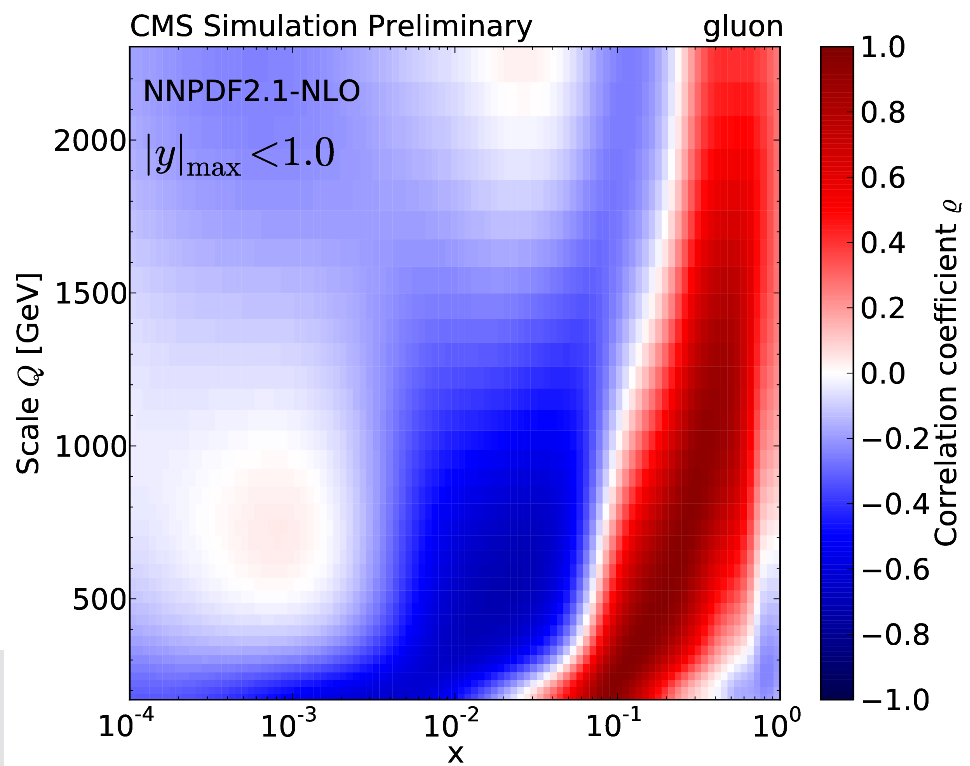
CMS-PAS-SMP-12-027

Three-jet Mass – PDF sensitivity

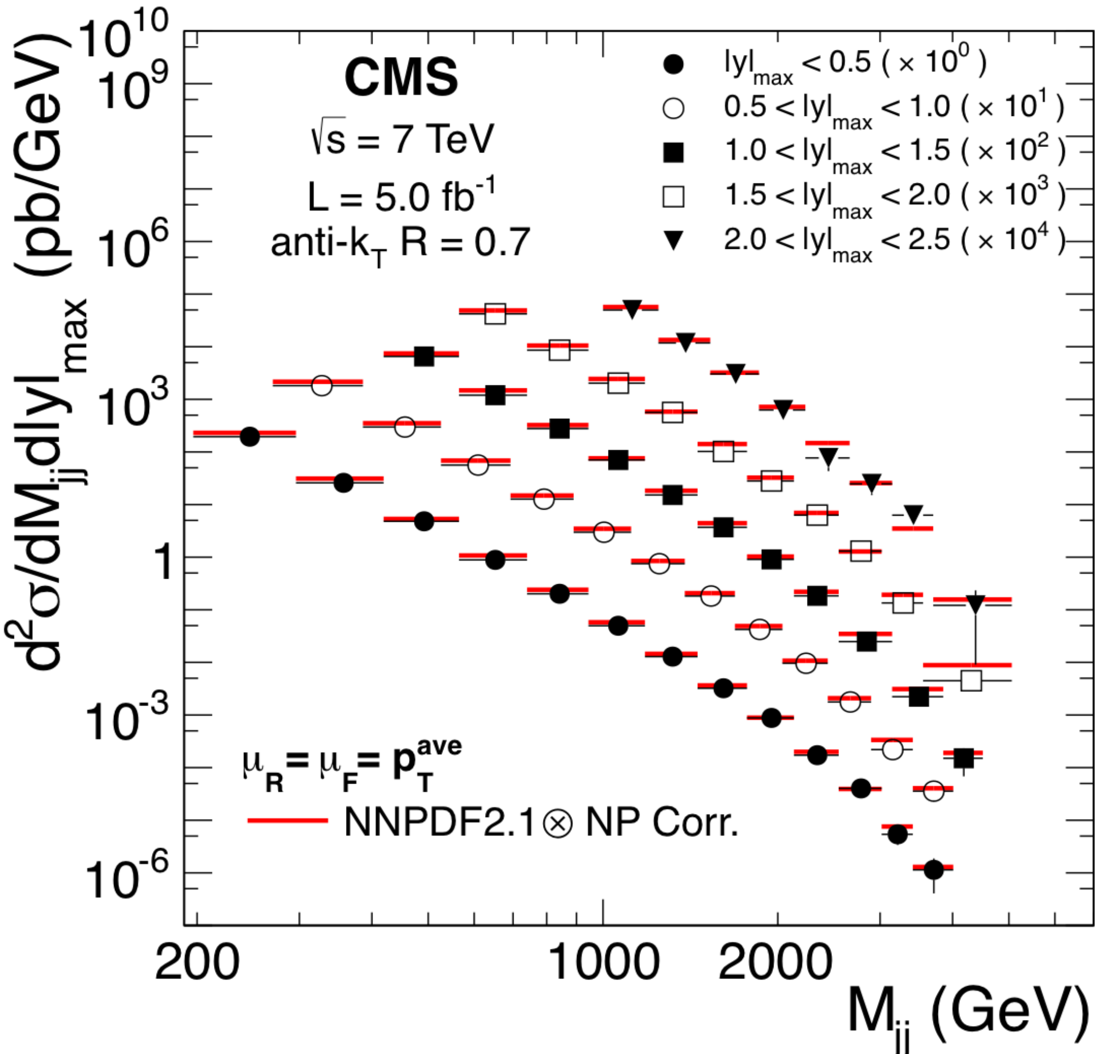


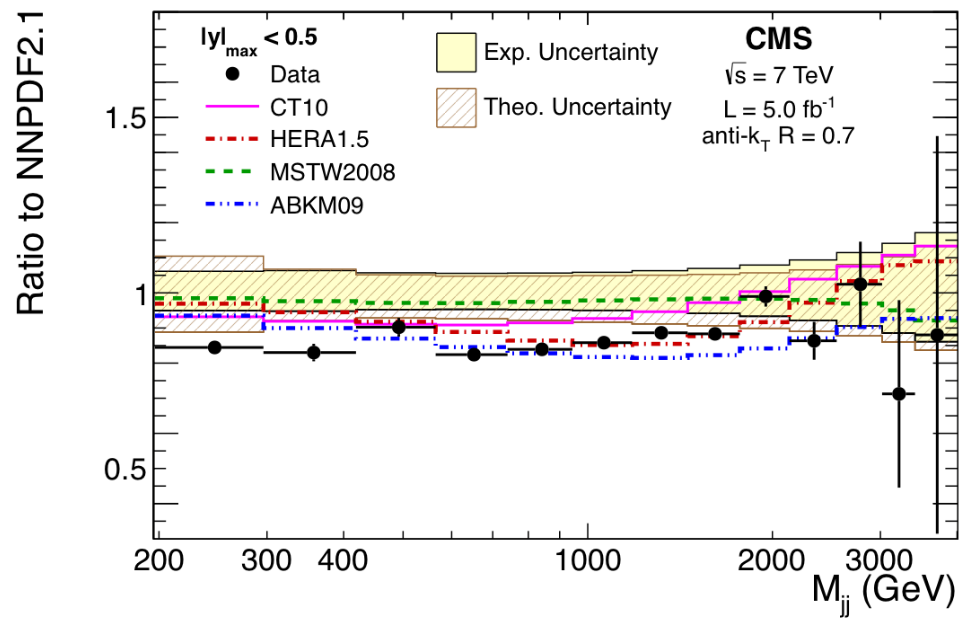
CMS-PAS-SMP-12-027

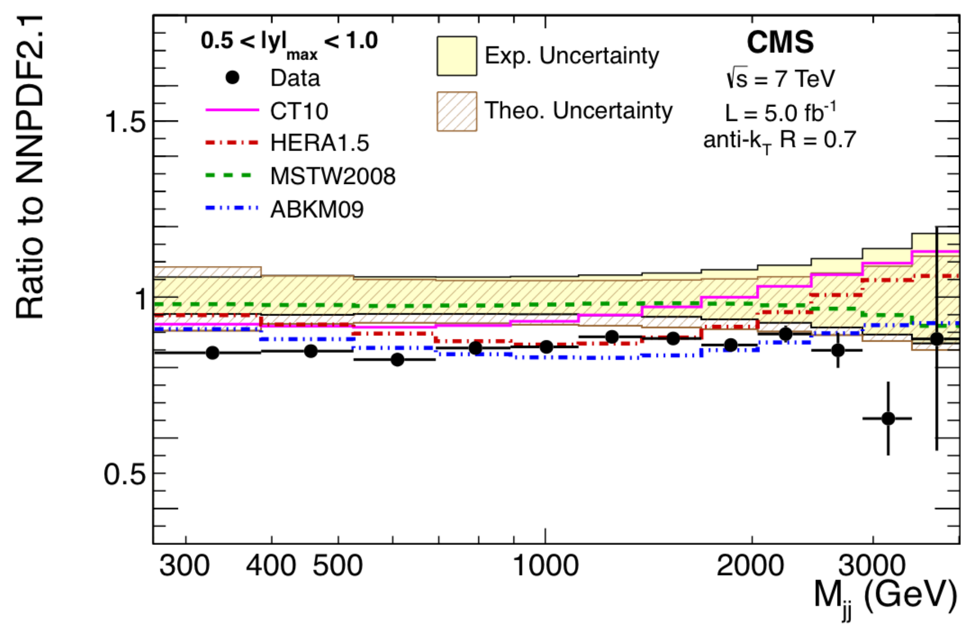




Dijet mass



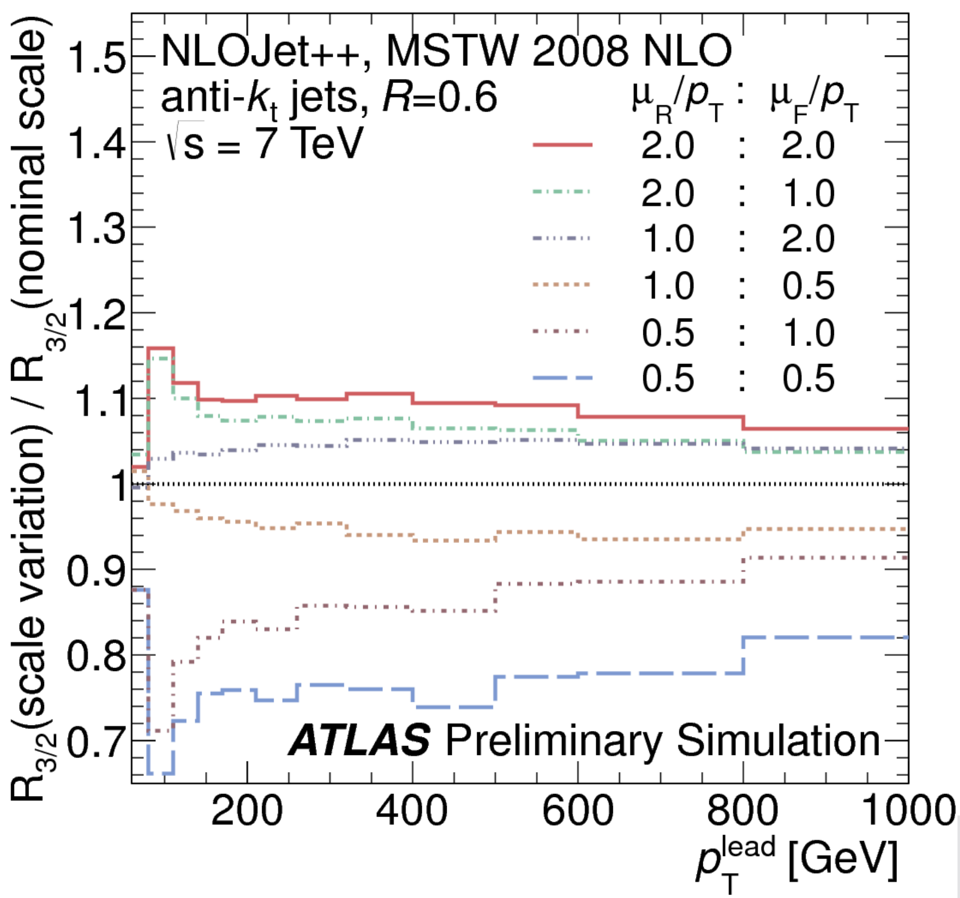


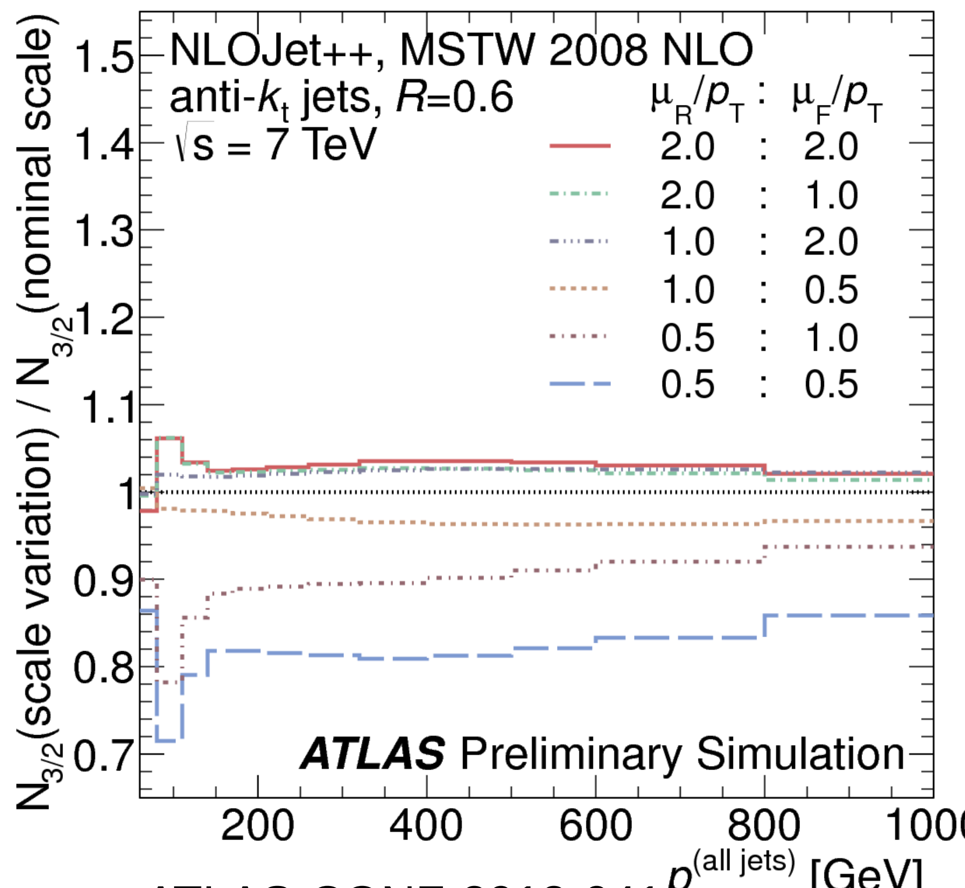


arXiv:1212.6660

3-jet to 2-jet cross section ratio

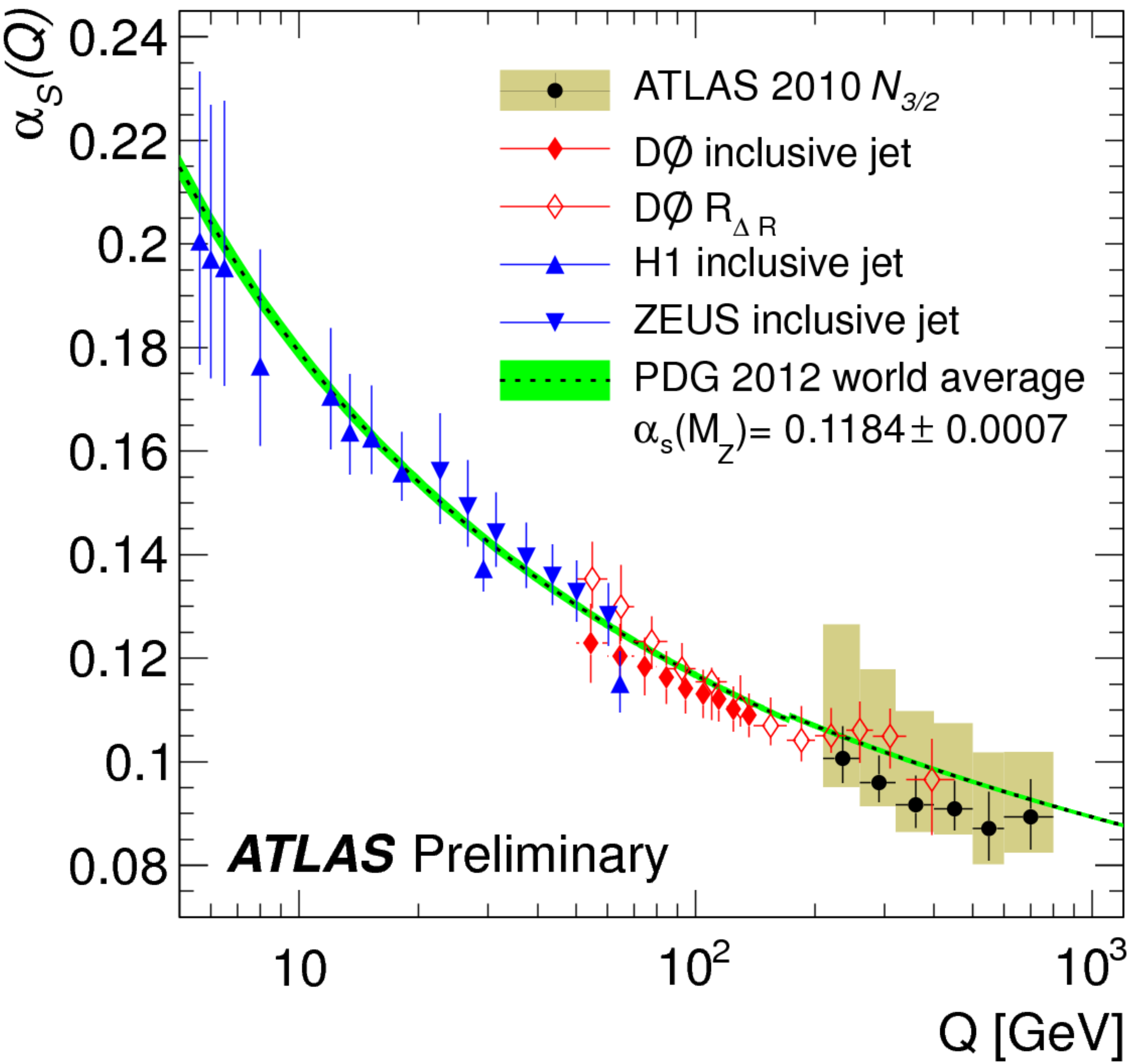
NLO pQCD predictions for the values of $R_{3/2}$ and $N_{3/2}$ are obtained by dividing the respective inclusive two-jet differential cross-section distributions by the inclusive three-jet differential cross-section distributions. The NLO pQCD predictions for $R_{3/2}$ are obtained by setting the renormalization and factorization scales to the simulated leading jet $p_{\rm T}$ ($\mu_{\rm R} = \mu_{\rm F} = p_{\rm T}^{\rm lead}$), while theoretical predictions for $N_{3/2}$ are obtained by setting the renormalization and factorization scales to the $p_{\rm T}$ of each jet (i.e the value of the matrix element is evaluated at the scale of each jet $p_{\rm T}$ in an event). These scale values are chosen because they provide a good approximation of the energies at which the strong force produces outgoing partons in multijet events. The same definition of scales is used to obtain NLO pQCD predictions for events with at least two jets and events with at least three jets, thereby ensuring that the ratio predictions are obtained with a consistent scale definition. Futhermore, for $N_{3/2}$, this choice ensures that all jets in a given $p_{\rm T}^{\rm (all\ jets)}$ bin of the distribution are evaluated at scales within that $p_{\rm T}^{\rm (all\ jets)}$ bin's width.





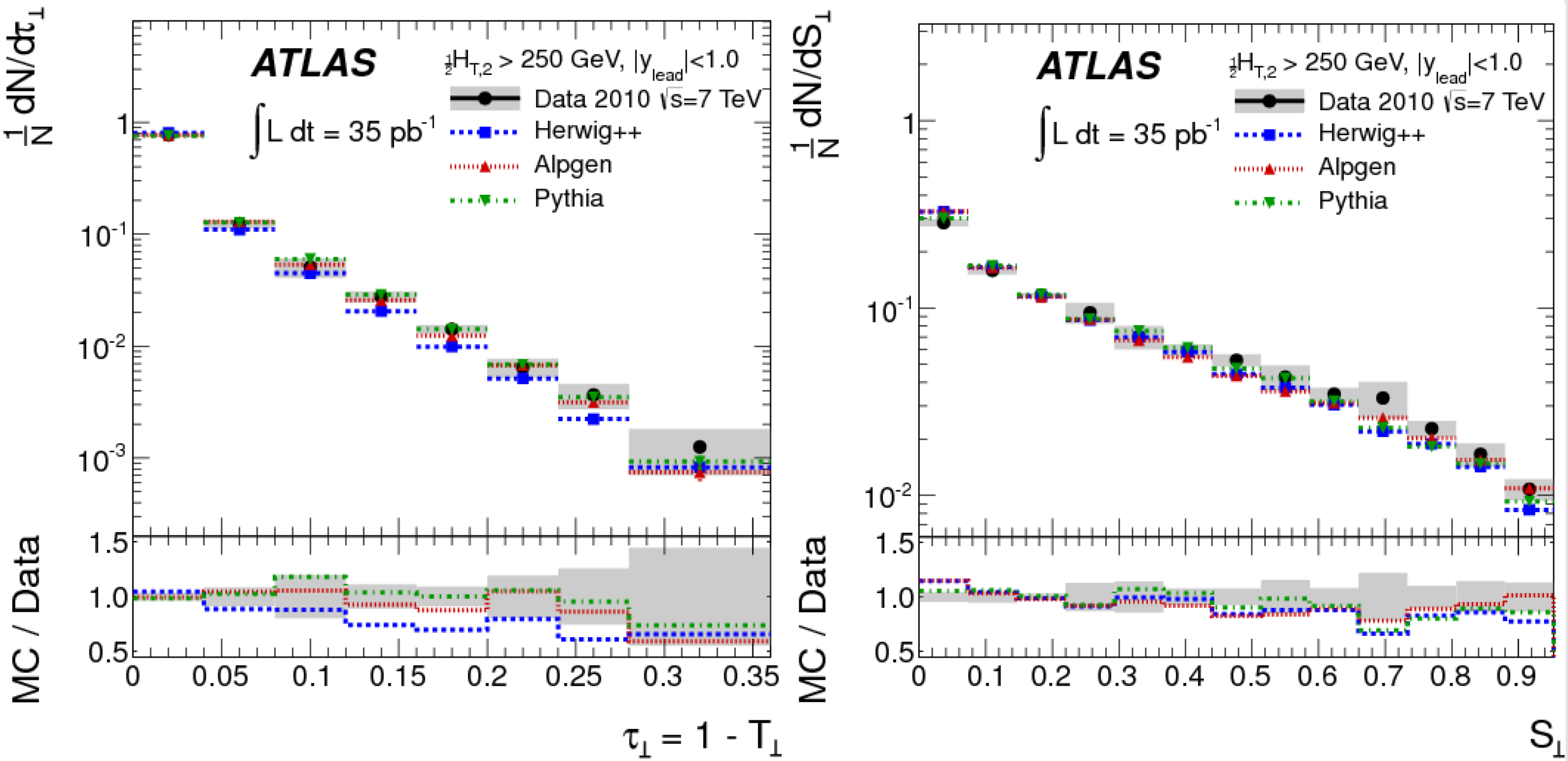
ATLAS-CONF-2013-041

3-jet to 2-jet cross section ratio



Event Shapes

Eur. Phys. J. C (2012) 72: 2211



Pileup Jet ID

- Pileup jets can be effectively removed by a minimal jet-vertex-fraction (JVF) requirement. The JVF variable is defined as the scalar transverse momentum (pT) sum of the tracks that are associated to the jet and originate from the hard-scatter vertex divided by the scalar pT sum of all associated tracks:

$$\mathrm{JVF} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_0) + \sum_{n\geq 1}\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_n)}$$

- corrJVF is a variable similar to JVF, but corrected for the NVtx dependent average scalar sum pT from pileup tracks associated to a jet

$$\mathrm{corrJVF} = \frac{p_{\mathrm{T}}^{\mathrm{HS}}}{p_{\mathrm{T}}^{\mathrm{HS}} + p_{\mathrm{T}}^{\mathrm{PU,corr}}}$$

  where pT HS is the scalar pT sum of the tracks that are associated to the jet and originate from the hard-PU,corr scatter vertex and pT is a measure of the pileup pT of a jet relative to the average pileup activity in the event

- The variable RpT is defined as the scalar pT sum of the tracks that are associated to the jet and originate from the hard-scatter vertex divided by the fully calibrated jet pT, which includes pileup subtraction:

$$R_{\mathrm{pT}} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{p_{\mathrm{T}}^{jet}}$$

- The jet-vertex-tagger (JVT) is constructed using RpT and corrJVF as a 2-dimensional likelihood, based on a k-nearest neighbor (kNN) algorithm.

Inclusive Jet R=0.5 / 0.7