2018

XXVI International Workshop on
Deep Inelastic Scattering and
Related Subjects

Collider Studies on Jet and Heavy Flavor Properties

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on behalf of the ATLAS,CMS and LHCb Experiments

University of Kobe, Japan 16/04/2018

Outline

- Jet Physics: Phenomenology at the LHC
- Jet Reconstruction in ATLAS, CMS, LHCb
- Selected Measurements at $\sqrt{s}$=7/8/13 TeV

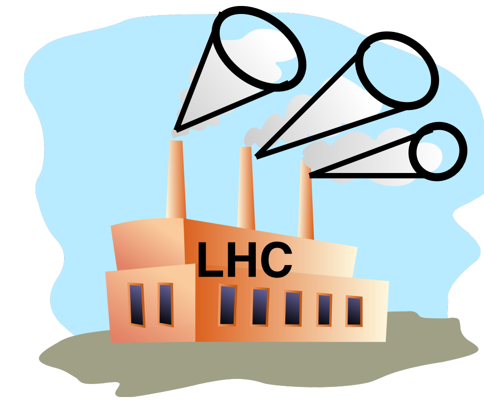
1. QCD: Inclusive jet production
2. Jets from b quarks: properties and measurements
3. Latest Top quark results at colliders

- Summary and Conclusions

Jet Phenomenology at Hadron Colliders

LHC is the most efficient Jet Factory of the world!

Jets are the experimental signatures of quarks and gluons



what can we do with jets?

pure-QCD

- Explore the pQCD in brand new energy regions
- Constrain the PDFs
- Probe and measure α_S
- Access the dynamics of heavy flavors
- Compare to NLO/NNLO predictions
- Tune Monte Carlo Generators

… much more!

not-purely-QCD

- Extensive test of the Standard Model: V+Jets, H+Jets, V+heavy flavors…
- Test the SM at NNLO precision
- Beyond the Standard Model:
  - dijet resonances
  - monojet & dark matter
  - new strongly produced states
  - hadronic resonances

… much more!

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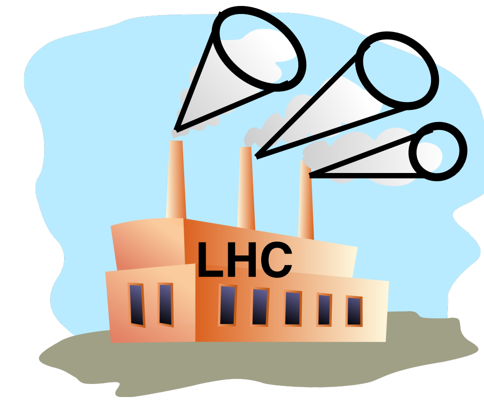
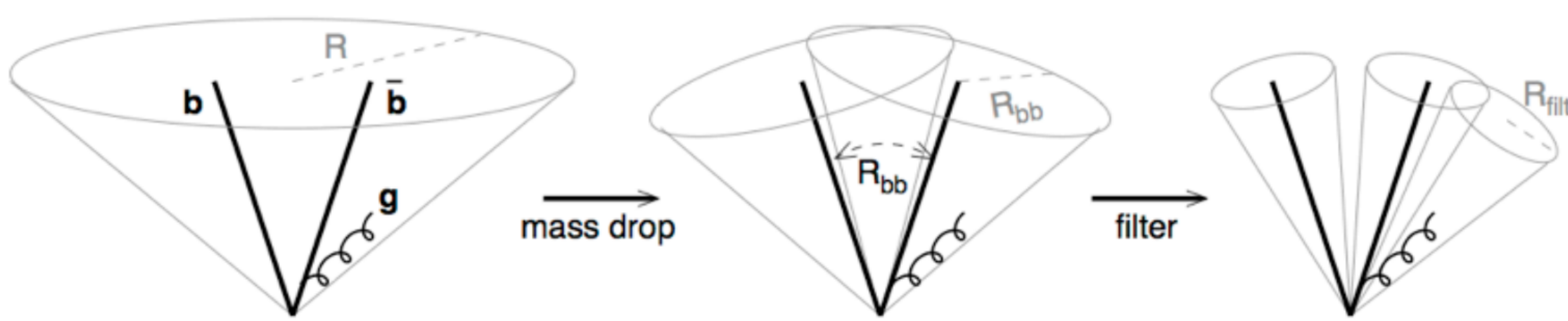


what can we do with jets?

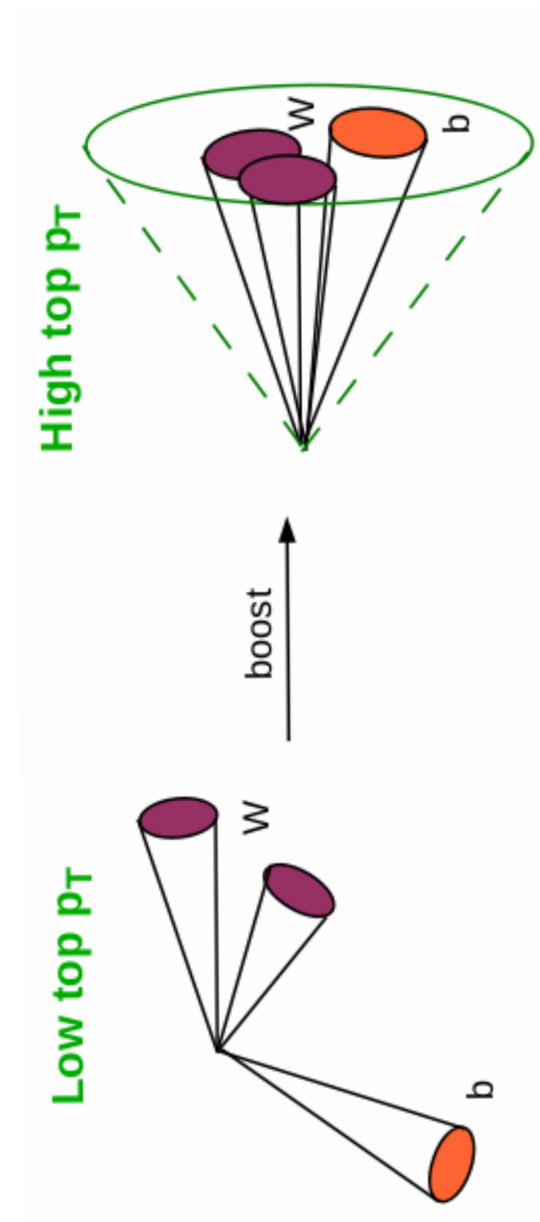
explore substructure

- exploring the inner structure of jets



- highly boosted bosons reconstructed as jets

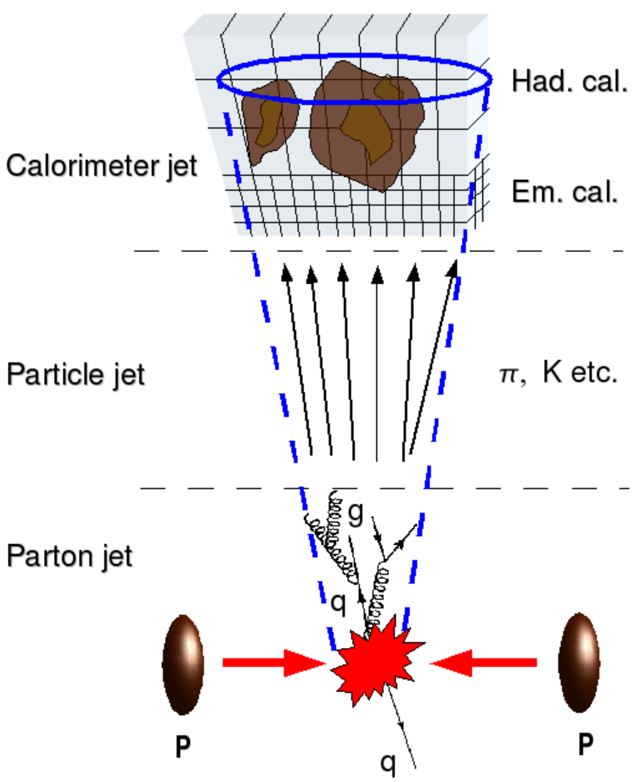
- using sub-jets as a powerful tool for measurements such as *H(bb) - jets*, *Z(bb) - jets*, *top-jets*…



Jet Reconstruction: Strategy

ATLAS

topological calorimeter-cell **clusters**



anti-k$_T$ clustering algorithm

(infrared and collinear safe)

ATLAS/CMS: R=0.4 (Run II)

LHCb: R=0.5

←

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

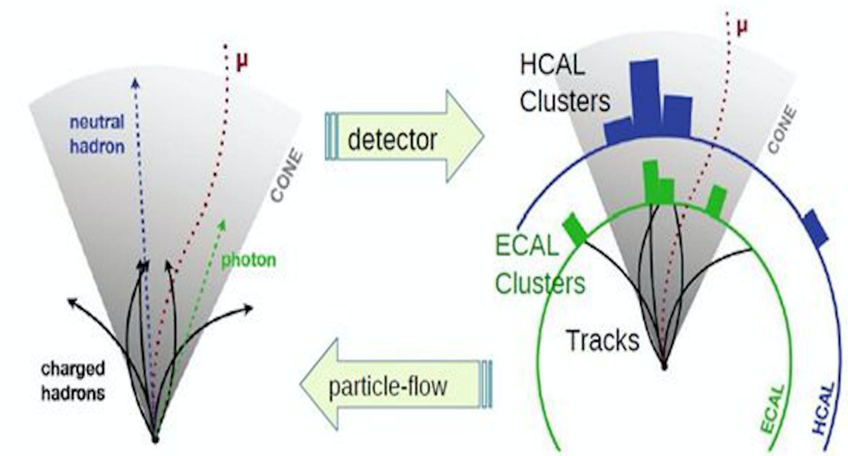
$$d_{iB} = k_{ti}^{2p} ,$$

→

↓

CMS

particle-flow



uses all the sub-detectors information to reconstruct objects

LHCb

LHCb acceptance forward direction

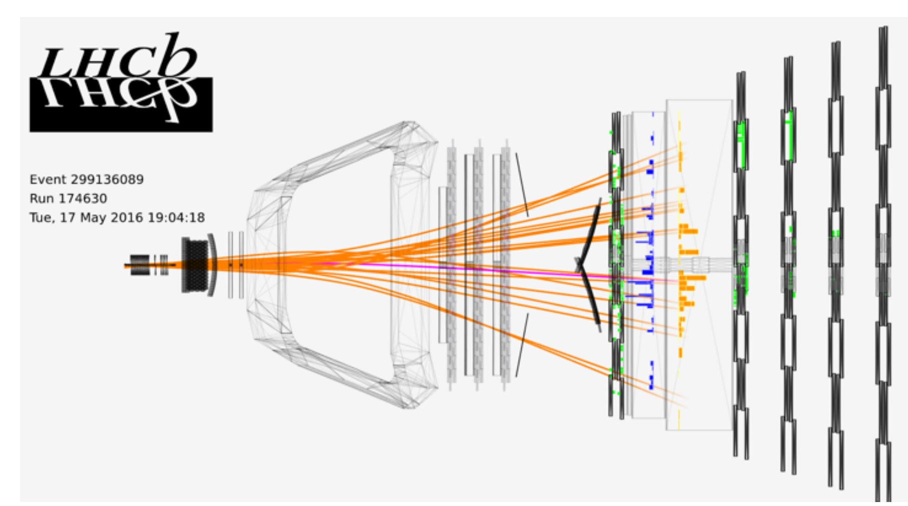
- **Particle Flow**

calo cell E$_T$~10 GeV saturation

↓

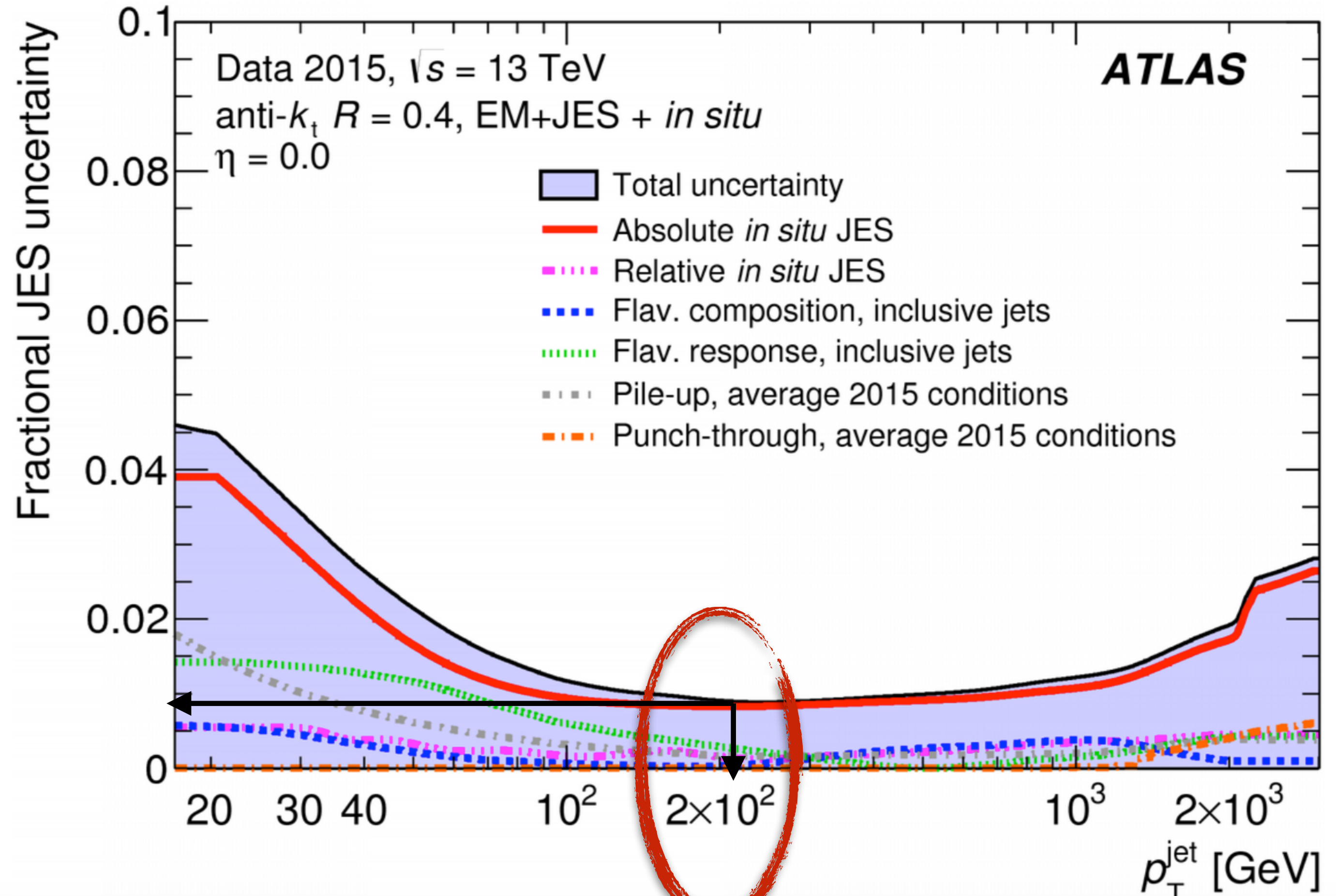
use the precise tracking information → use particles! (Λ,Ks,π,..)

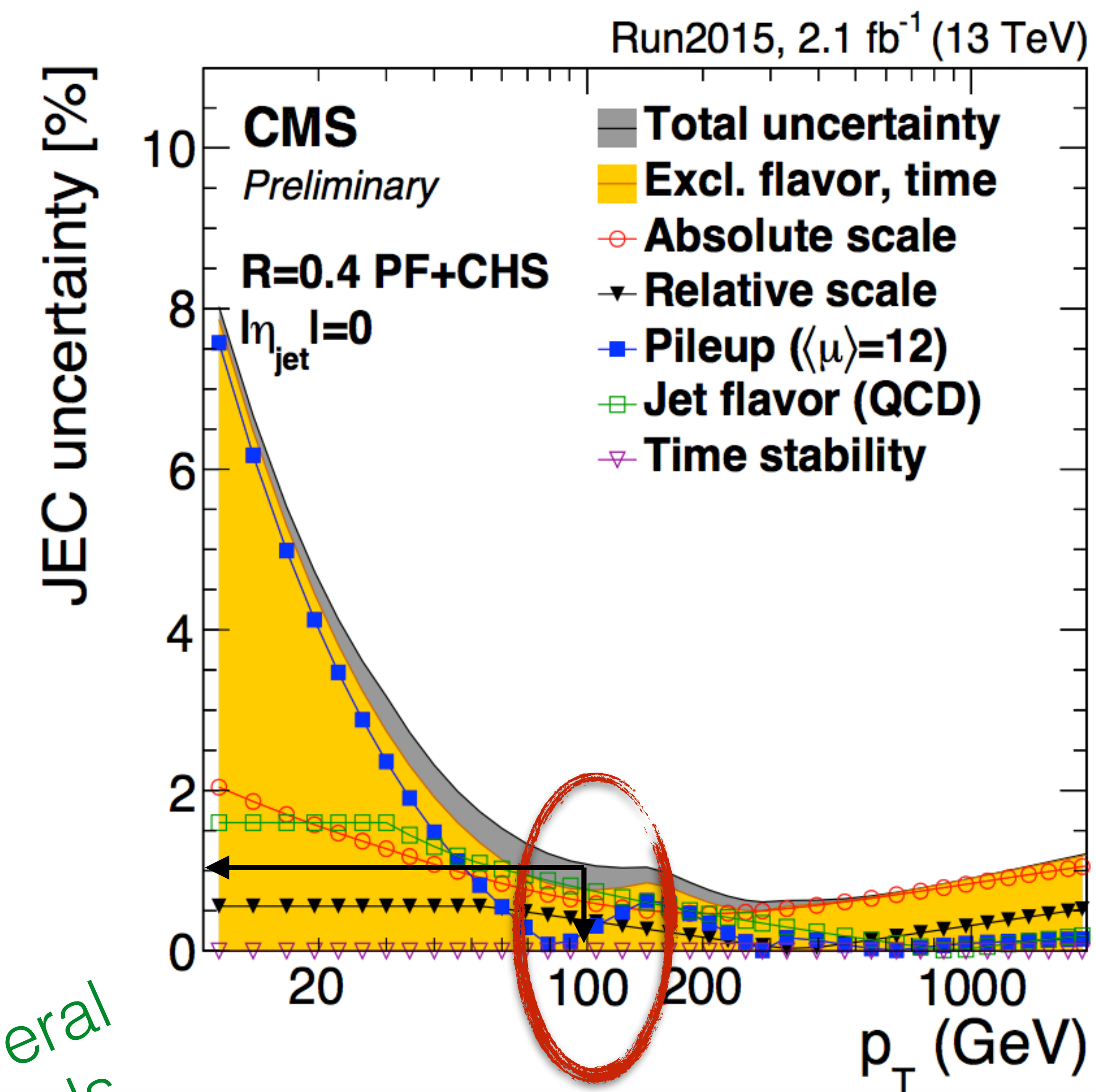
$(2 < \eta < 5)$



Jet Reconstruction: Energy Corrections

ATLAS ← both deliver jet energy corrections → **CMS**





Correct for

- Pile-Up
- Jet Flavor Composition
- Absolute/Relative Scale

thanks to several in-situ methods

Less than 2% in the region p_T > 100 GeV!

LHCb: ~10-15% for p_T of 10–100 GeV

Selected Results

Selected Results

disclaimer!

huge amount of results from the experiments on QCD, b jets, top physics…
this is just a (personal) selection!

see the end of the talk for links to the full list of results from the experiments

Selected Results

part I

QCD

Inclusive jet differential cross section at 13 TeV

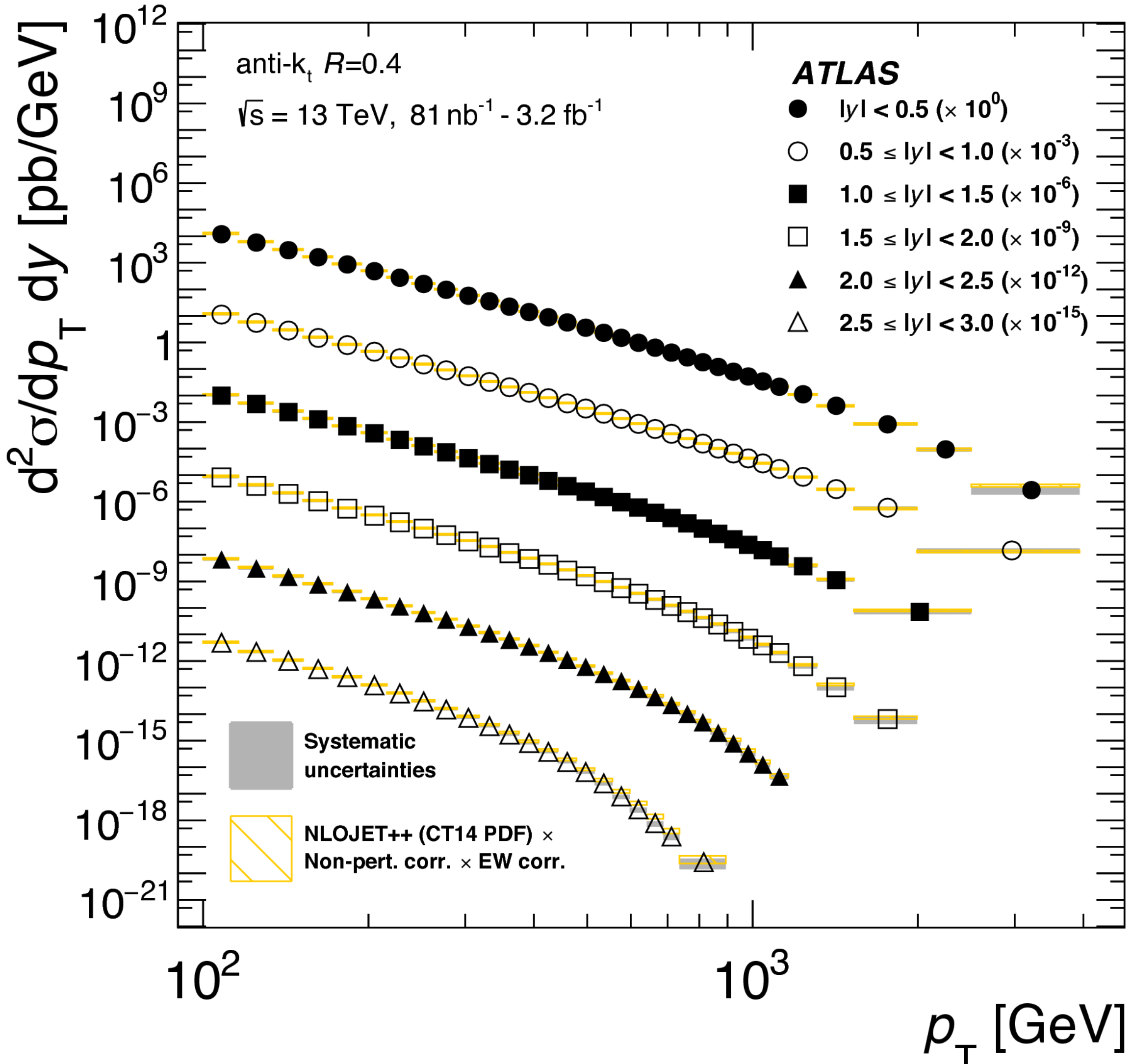
Anti-k_T R=0.4 Jets

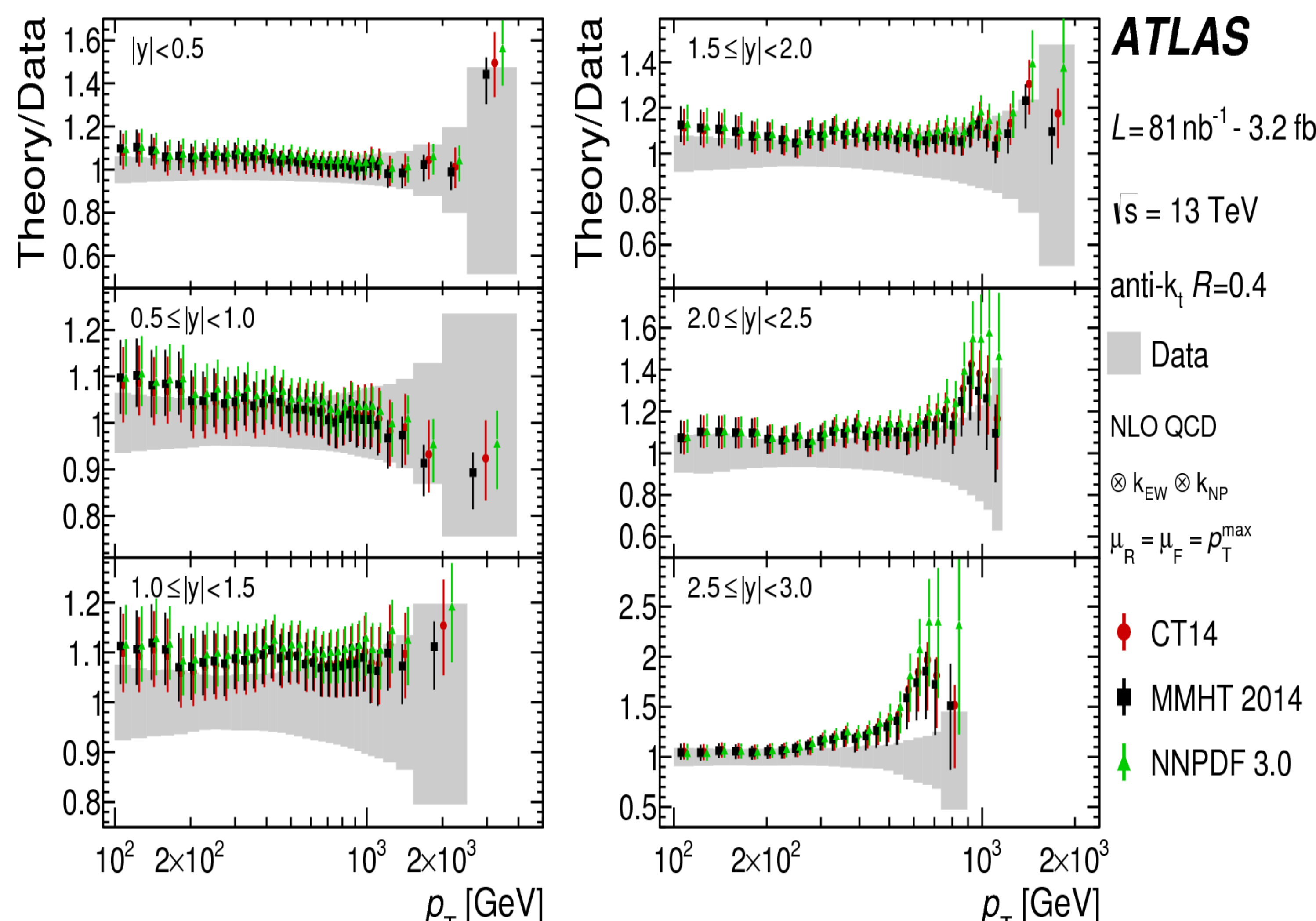
- inclusive jets cross section in six *y* bins
- theoretical comparison: NLOJet++ using CT14, MMHT, NNPDF3.0
- corrected for non-perturbative and EWK effects
- modified Bayesian unfolding

ATLAS EXPERIMENT

overall good agreement with NLO predictions!

arXiv:1711.02692





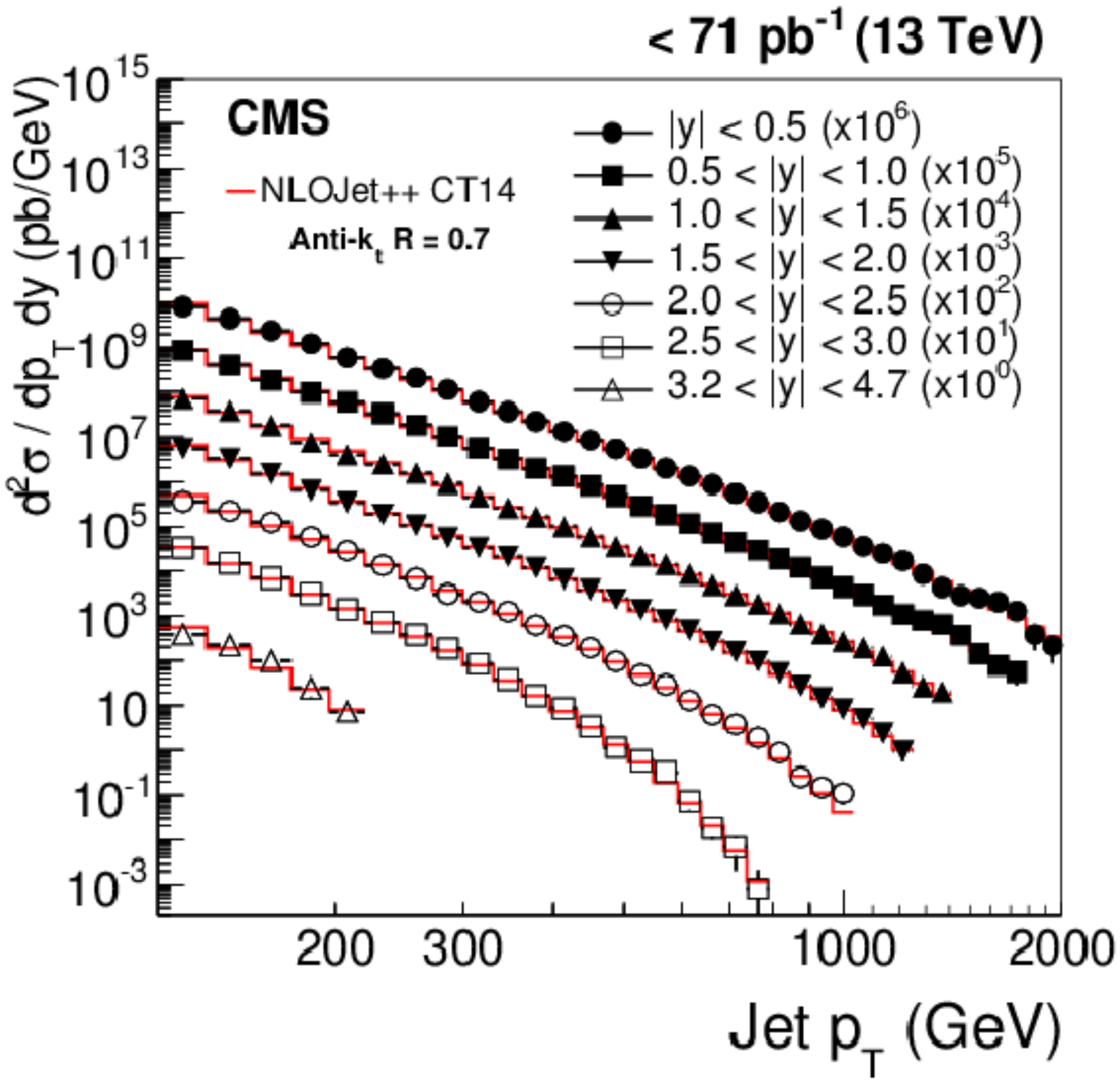
comparisons with NNLO also in the paper

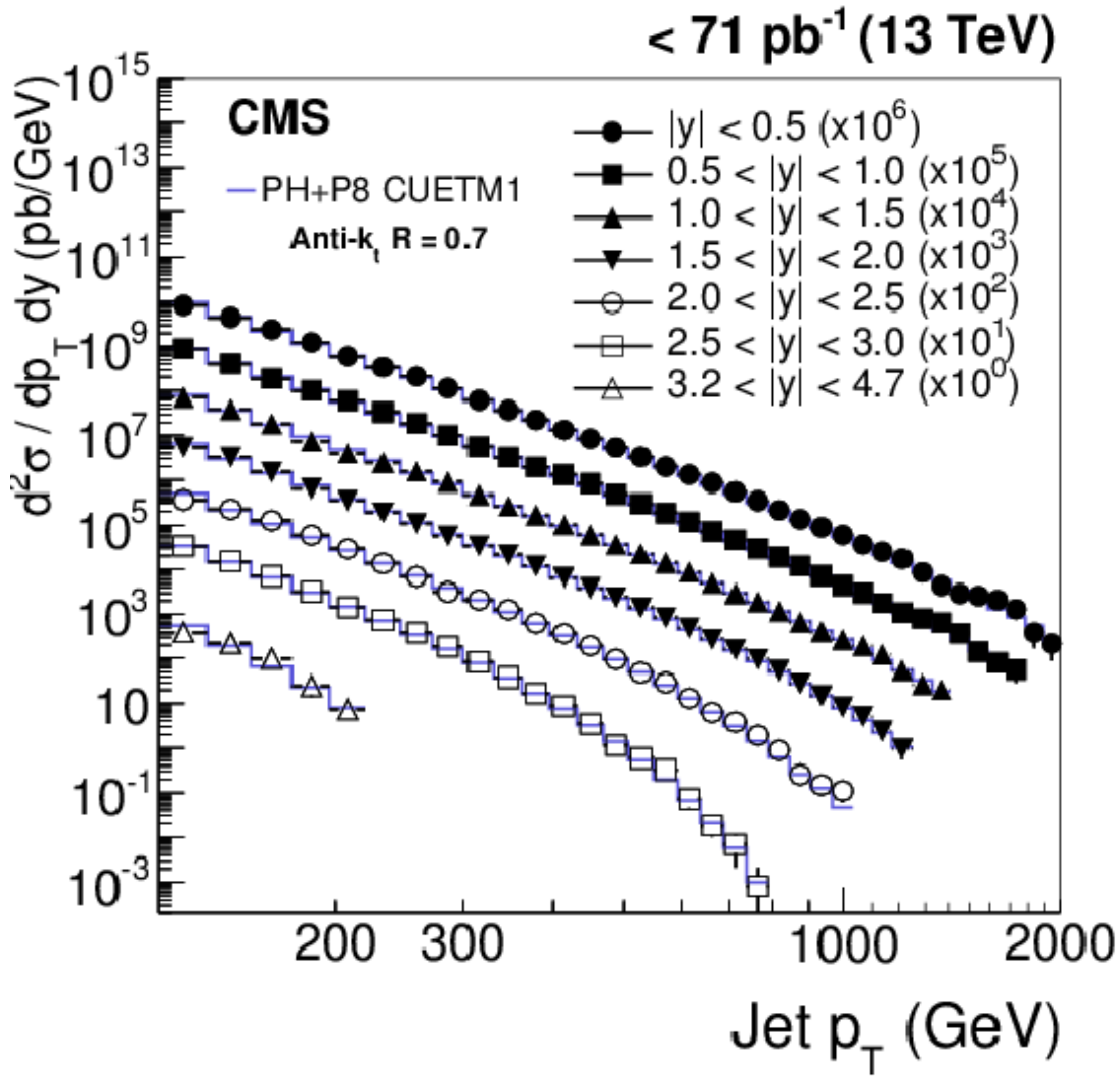
Inclusive jet differential cross section at 13 TeV

Anti-k_T R=0.4 ; Anti-k_T R=0.7

- inclusive jets cross section in seven *y* bins
- theoretical comparison: NLOJet++ and Powheg+Pythia8, CT14 PDF
- measured jets up to 2 TeV and |*y*|<4.7
- Bayesian unfolding

Eur. Phys. J. C 76 (2016) 451





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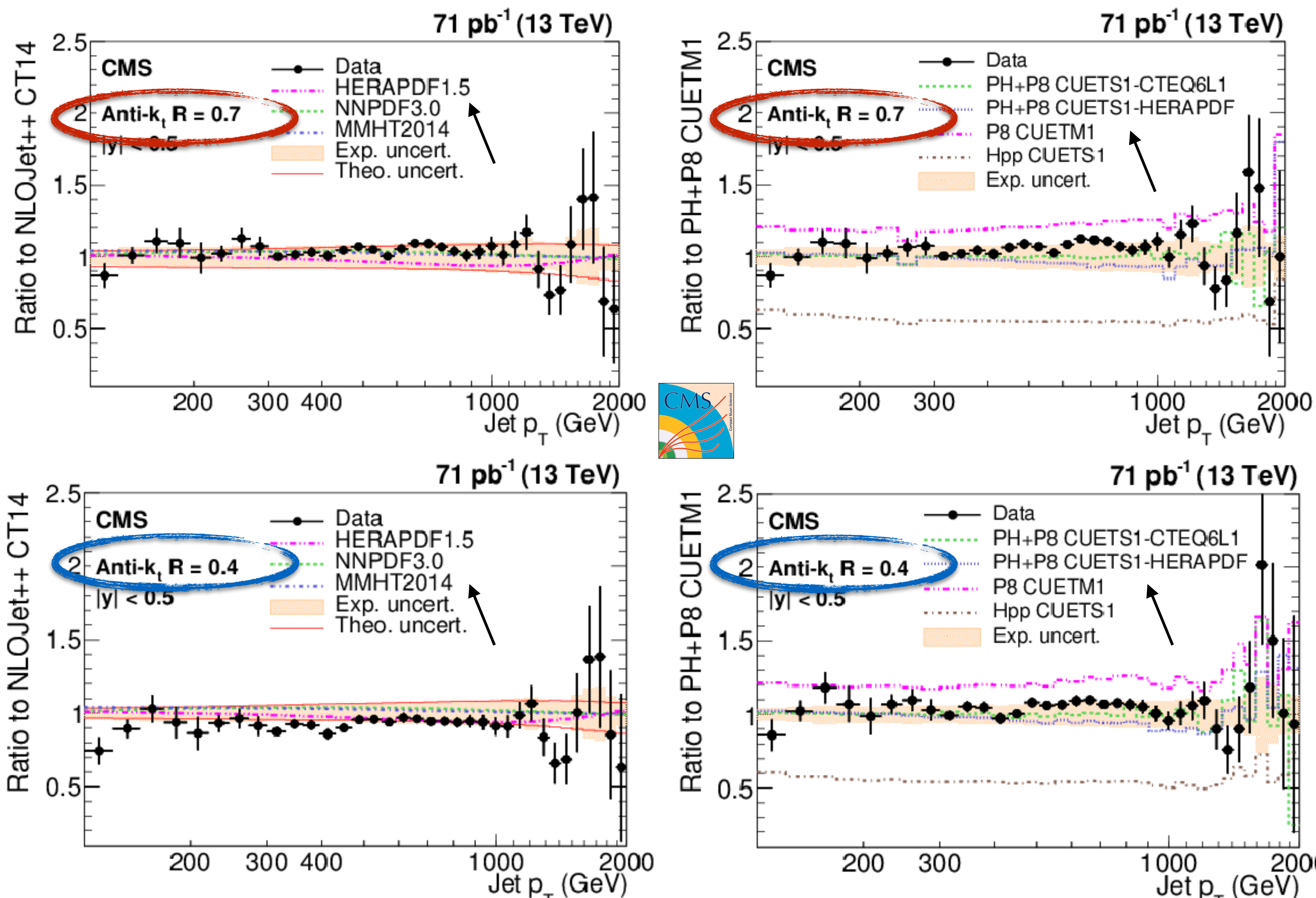
Inclusive jet differential cross section at 13 TeV



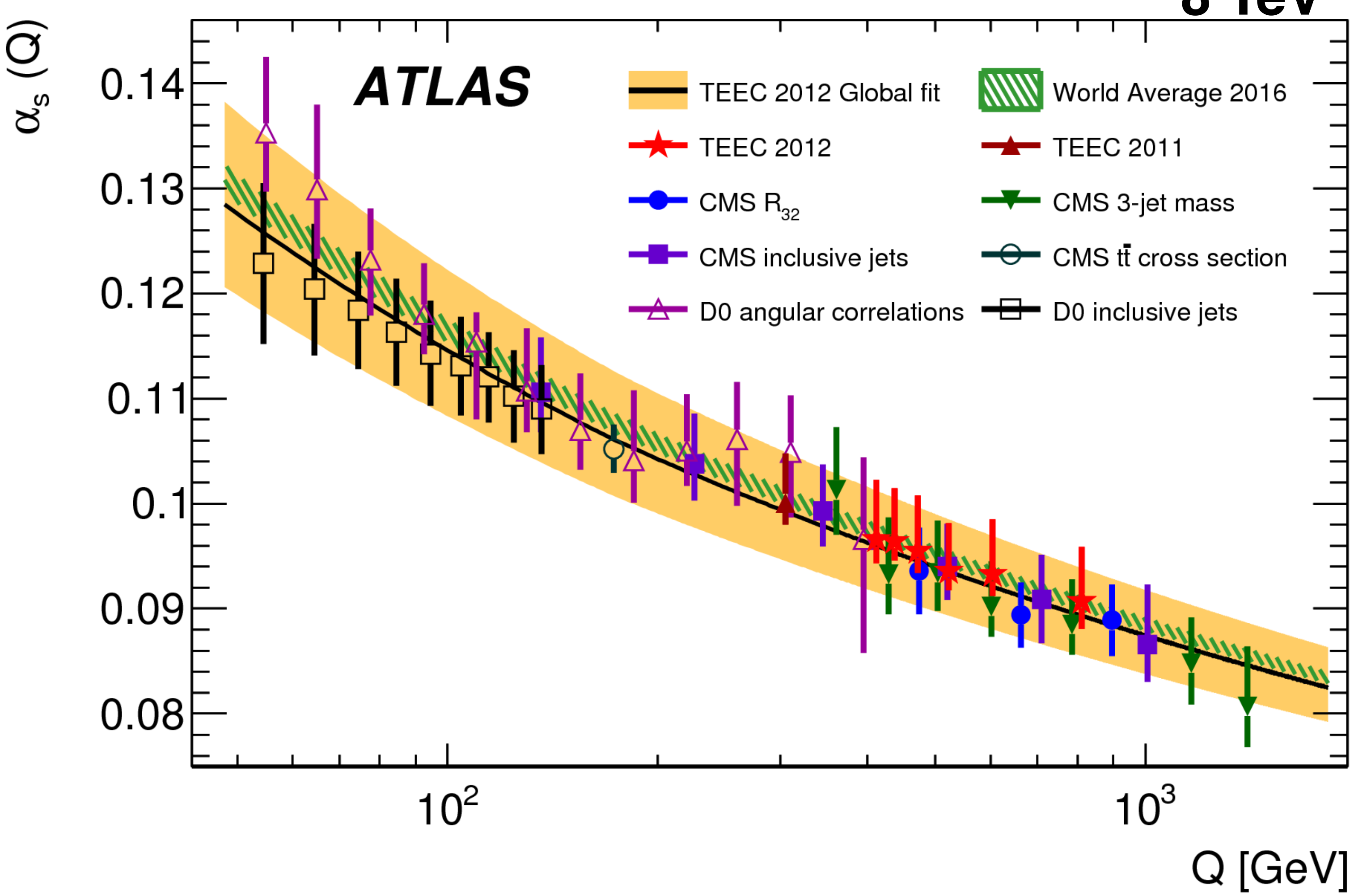
Determination of the strong coupling α_S

- p_T>100GeV, |η|<2.5, anti k_T - R=0.4

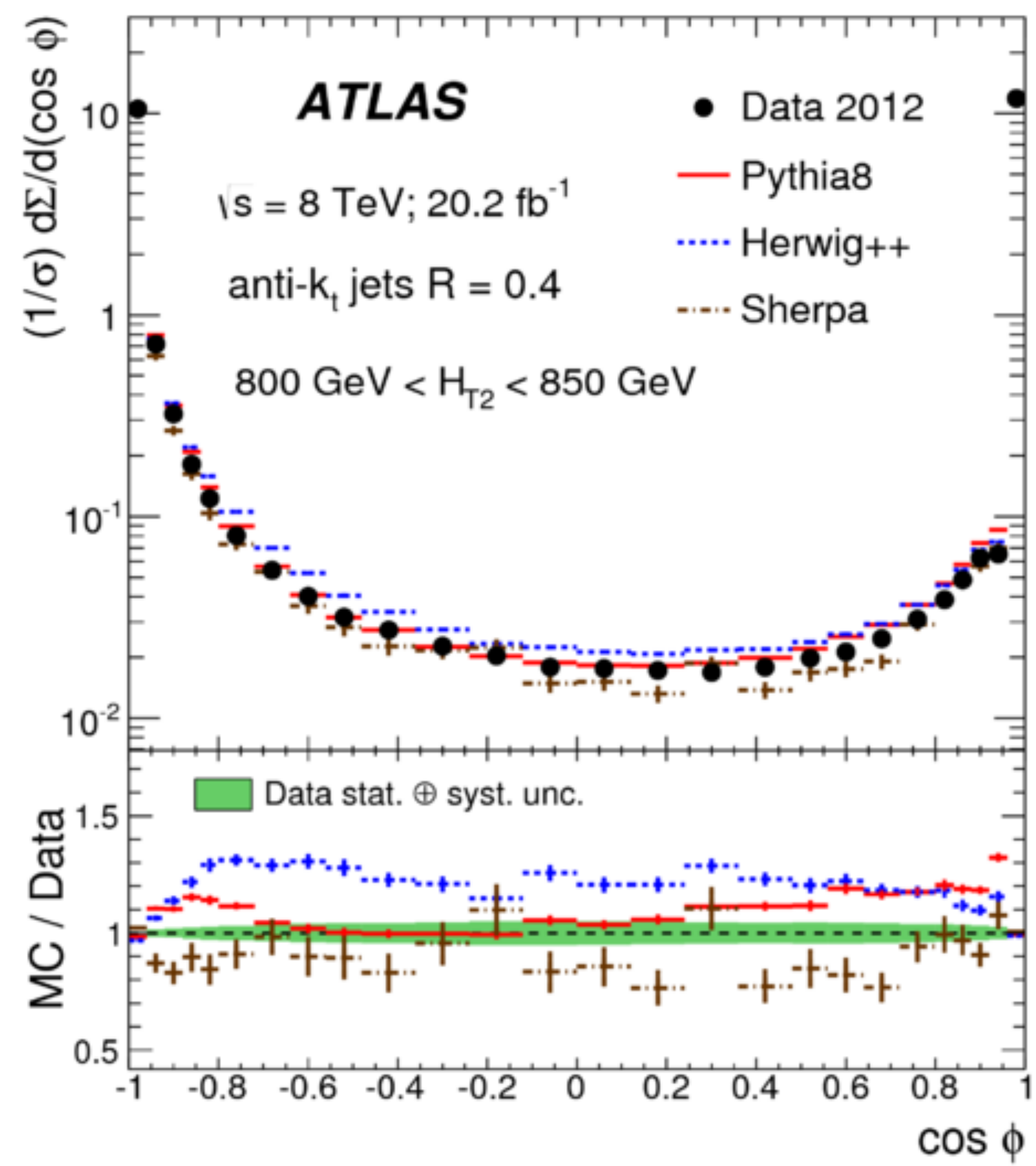
Eur. Phys. J. 77 (2017) 872

- energy-energy correlations and their associated asymmetries in multi-jet event
- bins of the scalar sum of the transverse momenta of the two leading jets
- unfolded distributions fitted to NLO calculations

8 TeV



8 TeV

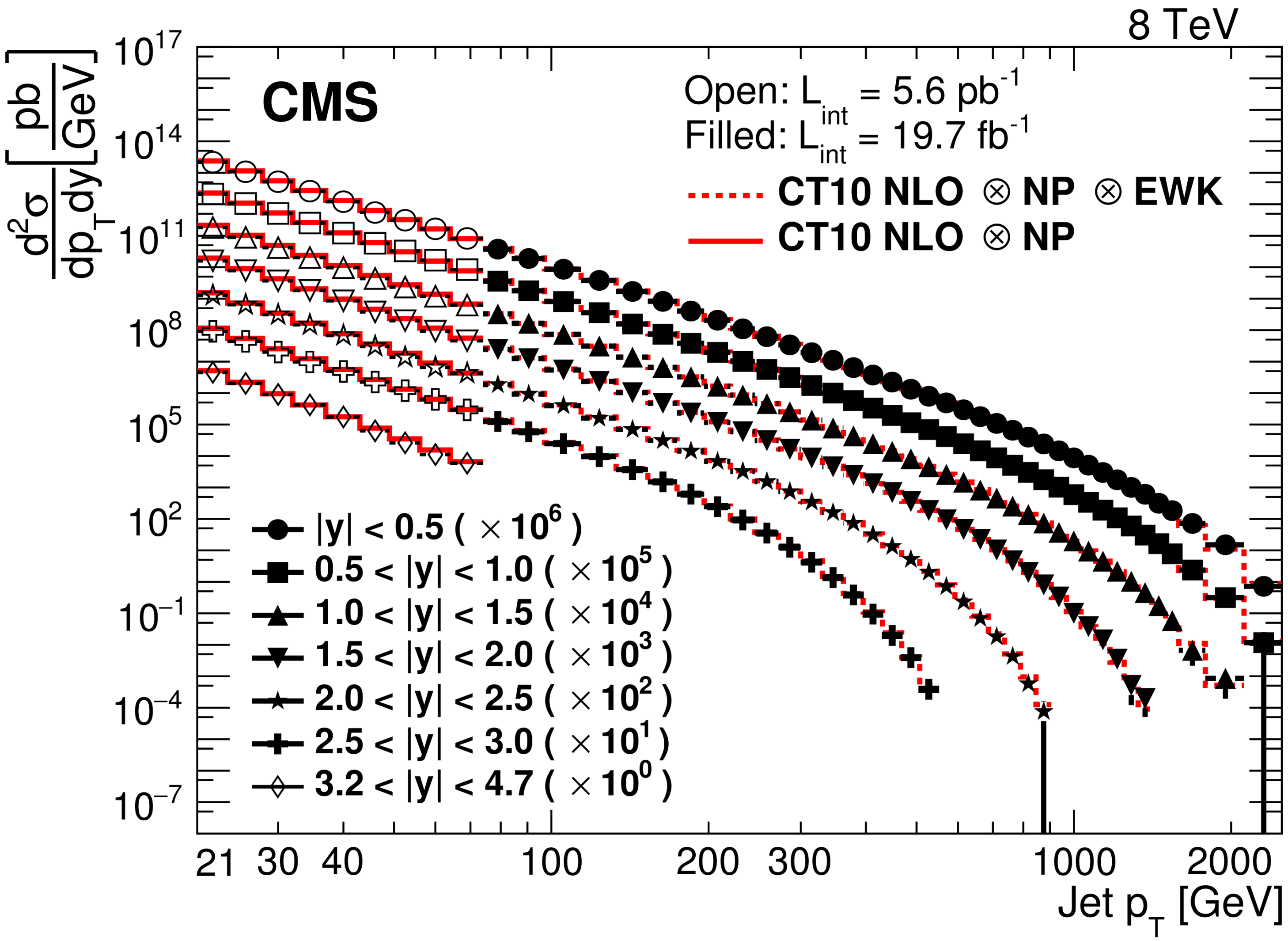


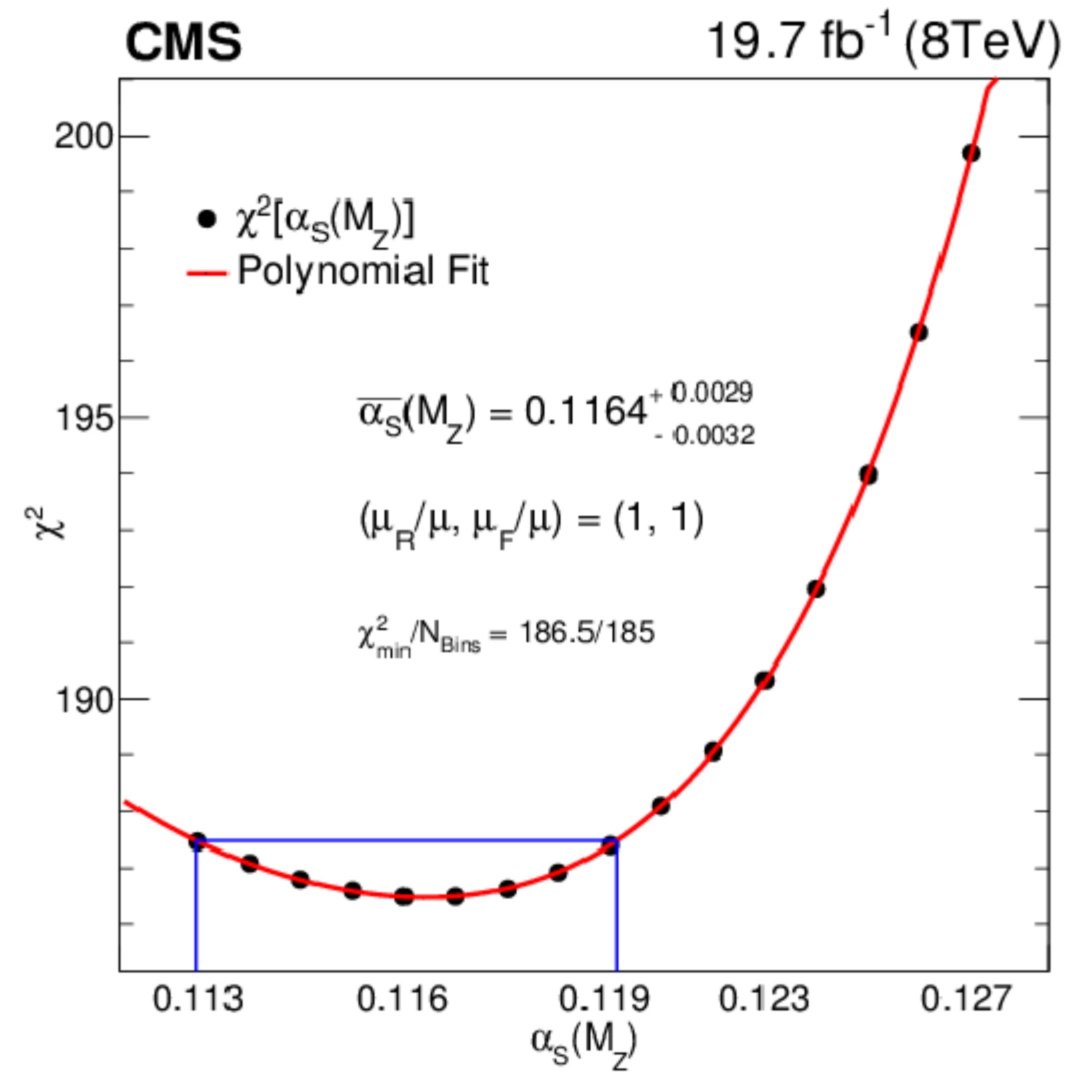
$$\alpha_S = 0.1162 \pm 0.0011(exp.) + 0.0084 - 0.0070(th.)$$

Determination of the strong coupling α_S

JHEP 03 (2017) 156

- coupling extracted from double-diff **σ** at 8 TeV
- theoretical comparison: CT10 NLO x NP x EW PDF
- measured jets up to 2.5 TeV and $|y|<4.7$
- ratio between 8 and 7, 2.76 TeV also performed





$$\alpha_S = 0.1164^{+0.0014}_{-0.0015}(exp.)^{+0.0025}_{-0.0029}(NP)^{+0.0053}_{-0.0028}(scale)$$

Measurement of the jet charge

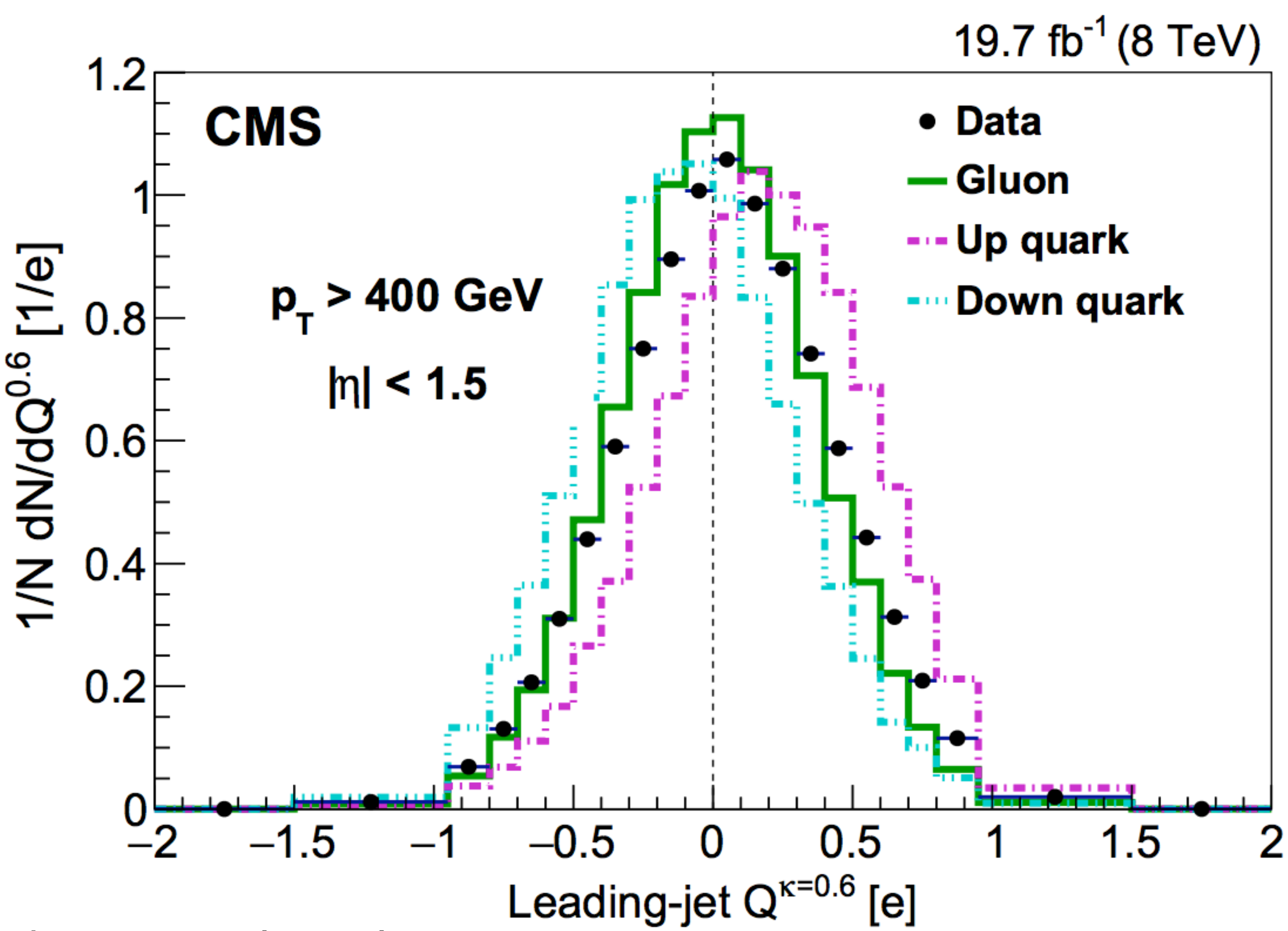
8 TeV

JHEP10(2017)131

access the initiated parton charge

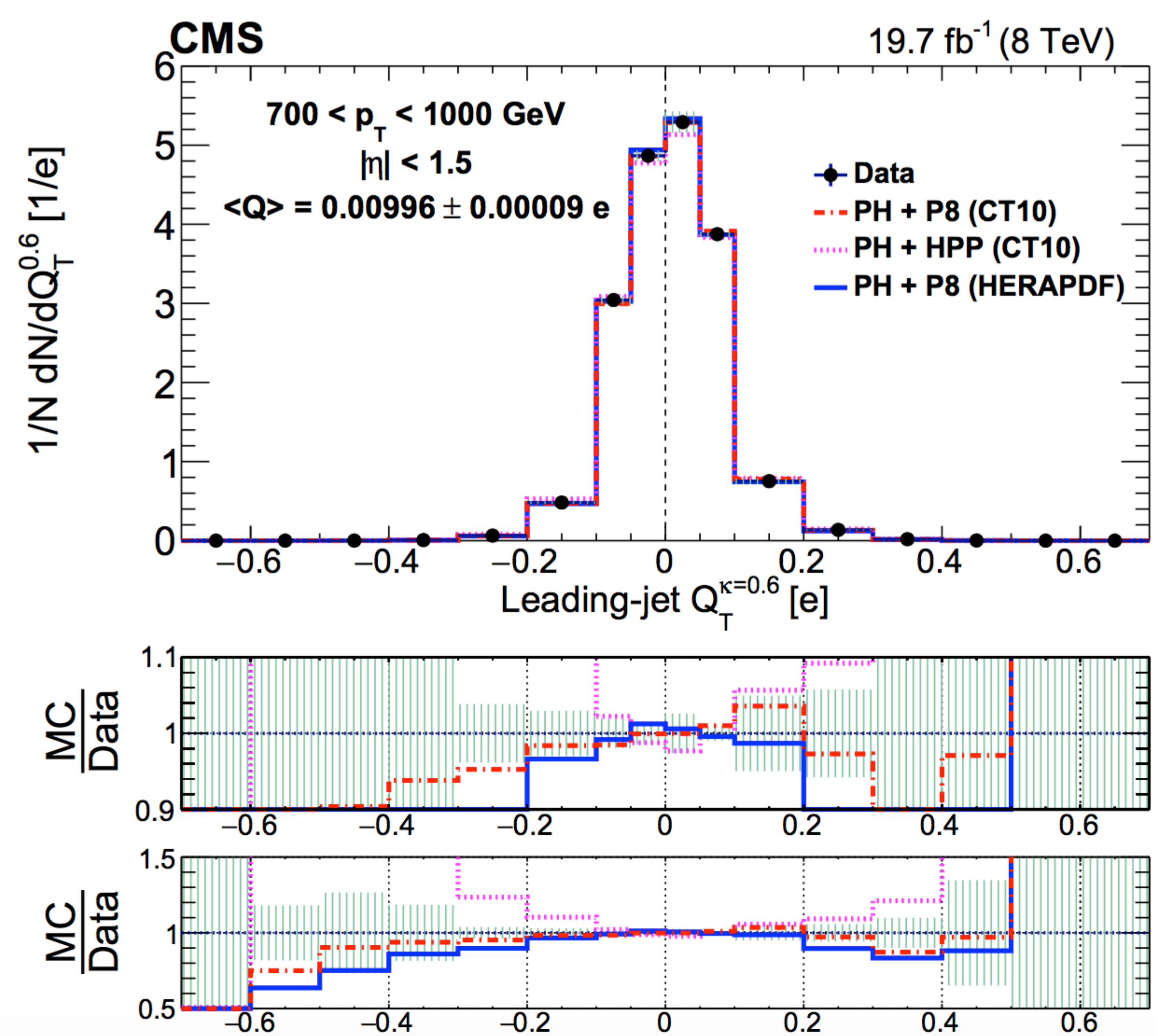
$$Q^j = \frac{1}{p_T^j} \sum_k Q_k (p_T^k)^j$$

- data compared to LO predictions Pythia/Herwig CTEQ6L1 and NNPDF30



detector level jet charge

0,1,-1 = *g,u,d* quarks



unfolded jet charge, p_T> 400 GeV

Measurement of the jet charge

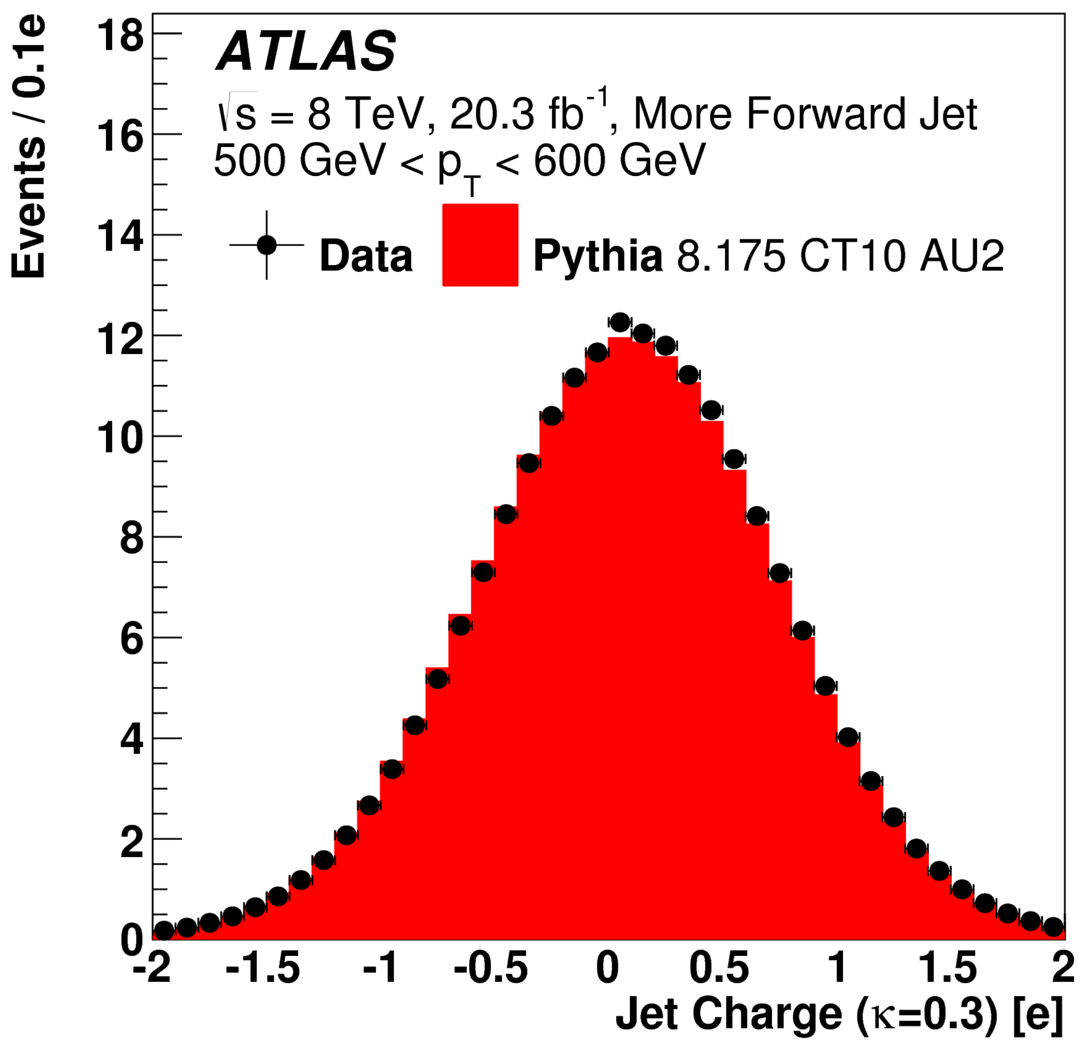
8 TeV

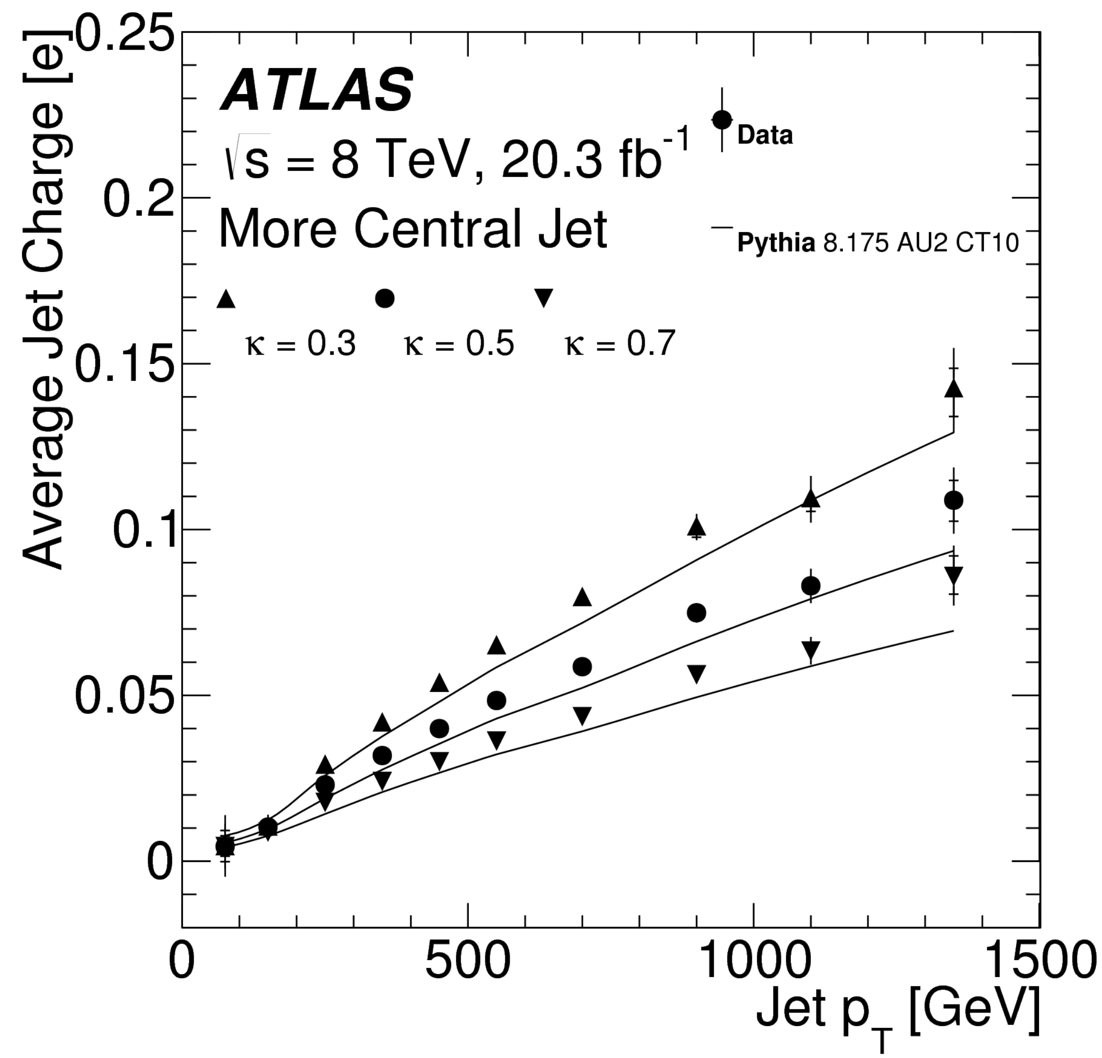
Phys. Rev. D93 (2016) 052003

access the initiated parton charge

$$Q^j = \frac{1}{p_T^j} \sum_k Q_k (p_T^k)^j$$

- unfolded data compared to LO predictions Pythia8 w/ CT10





- average jet charge of quark-initiated jets decreases as the jet energy increases

Selected Results

part II

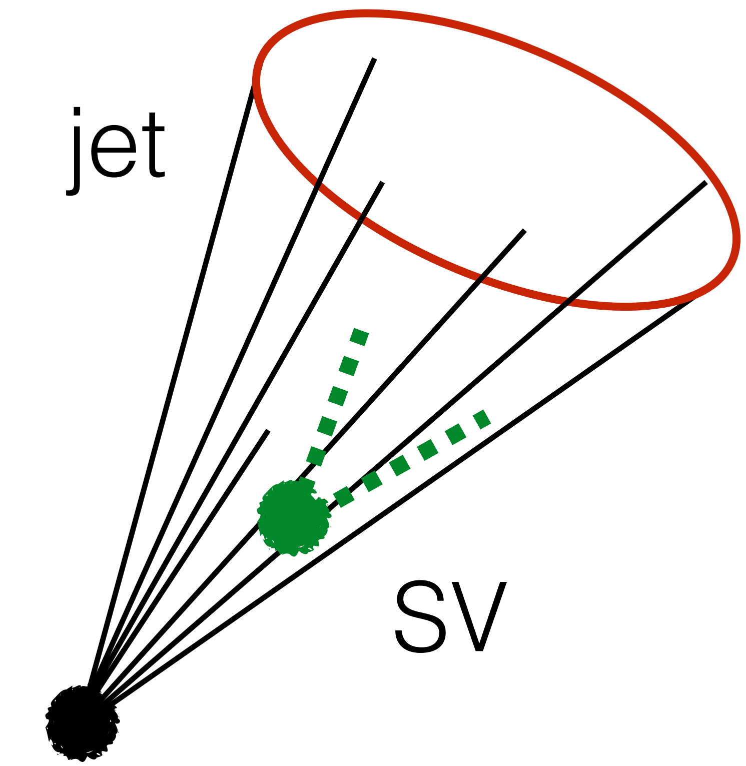
Jets from b quark

Heavy flavor tagging at collider

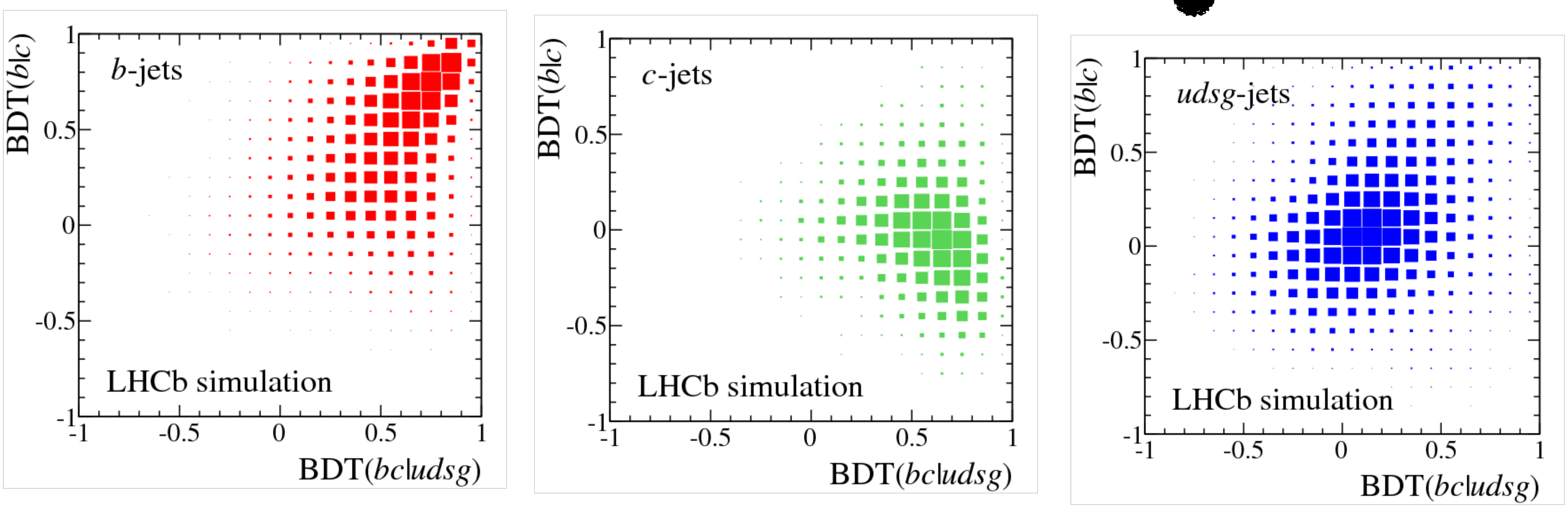
JINST 10 (2015) P06013

recipe

- reconstruct jets with the anti-kT05 algorithm
- tagging using b- and c- inclusive tagger
- reconstruct the two-body vertices in the event
- merge SV n-body by linking tracks and vertices associated
- associate vertices/jets requiring ΔR(SV, jet) < 0.5



BDT trained on SV/j properties to separate **heavy**/**light**



light-jet mistag rate < 1% for b-tag efficiency of 65% and c-tag efficiency of 25%

Heavy flavor tagging at collider

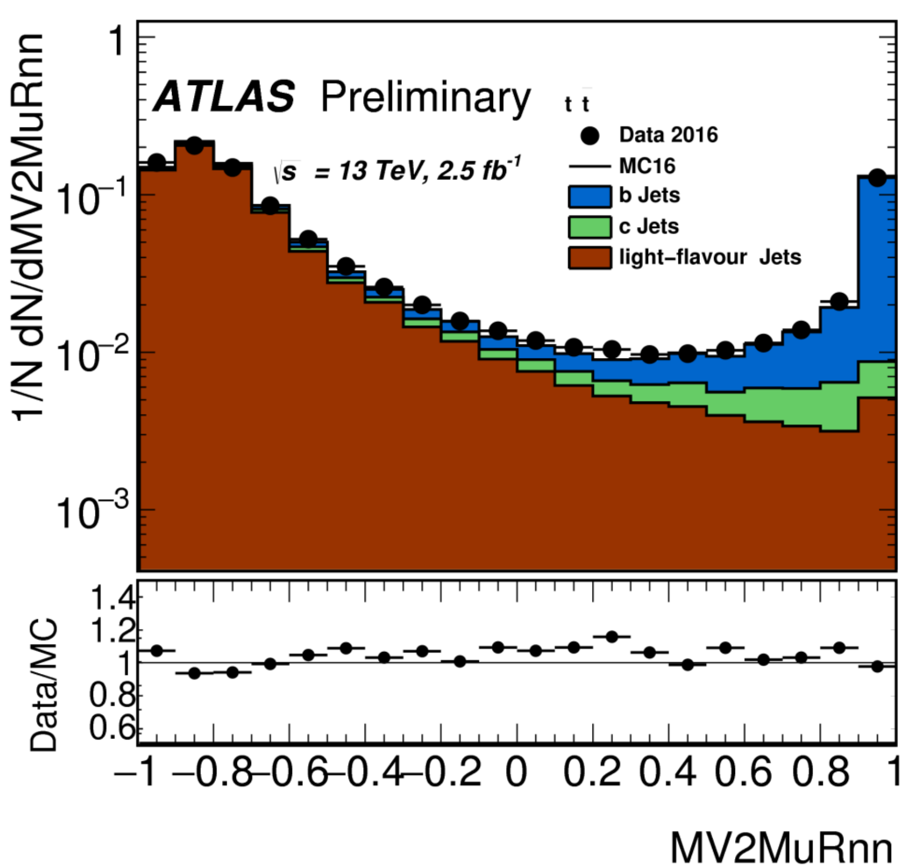
ATL-PHYS-PUB-2017-013
ATLAS-FTAG-2017-003

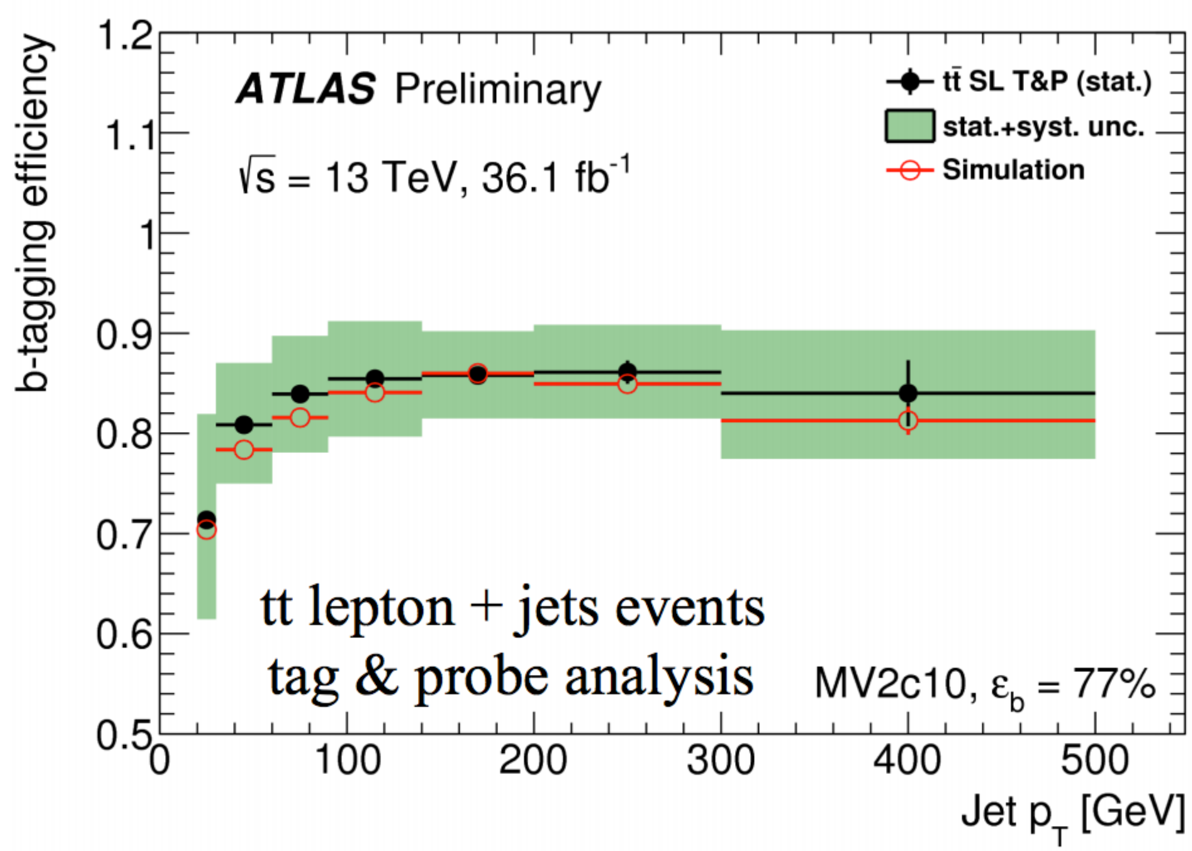
- several taggers:
  - track based (impact parameter tag)
  - soft muon (discriminate μ from b decays)
  - vertex based
- high-level taggers: MVA using all the information available to maximize the b-tag performance

→ BDT — trained on top + Z'bb events (*hybrid training*)

→ Deep Learning Neural Network

combine inputs from track, particle and vertex-based physics taggers using multivariate classifier





b-tag efficiency of 77% and c-tag efficiency of 25%

mistag rate of light flavored jets using dijet events with negative tag

< 2% under pT = 1 TeV

Heavy flavor tagging at collider

CERN-CMS-DP-2017-005
CMS-PAS-BTV-15-001

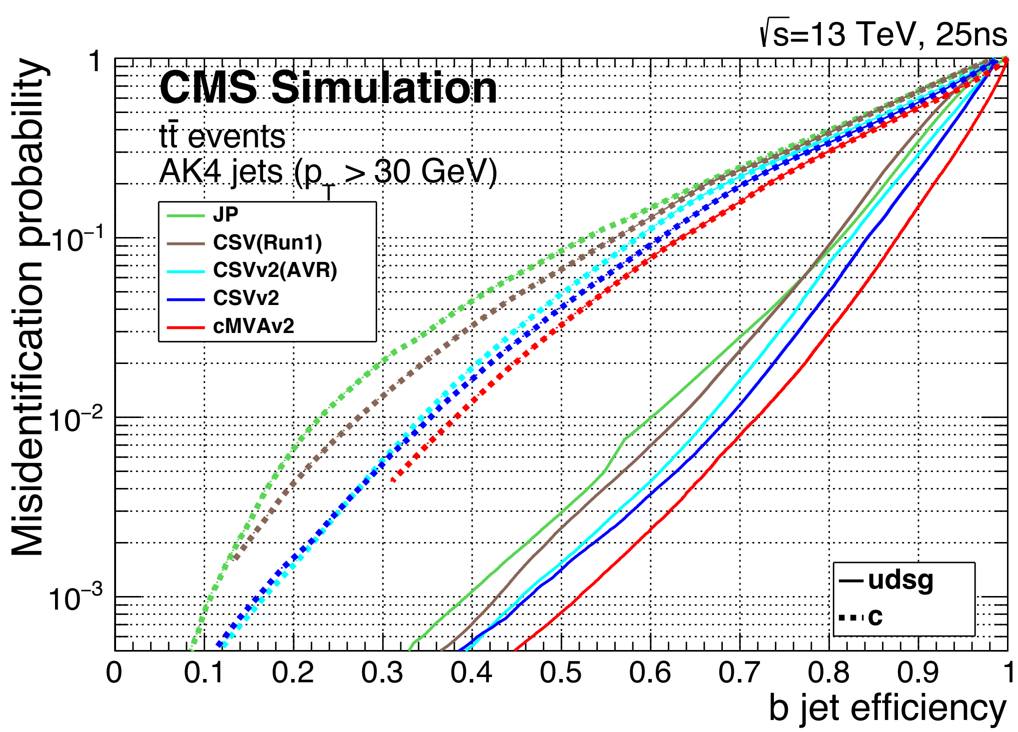
- several taggers:
  - Jet Probability: likelihood that jets is coming from primary vertex using tracks
  - Combined (CSV): combination of displaced tracks with SV info associated to the jet using an MVA
  - **CSVv2** evolution of CSV using neural networks

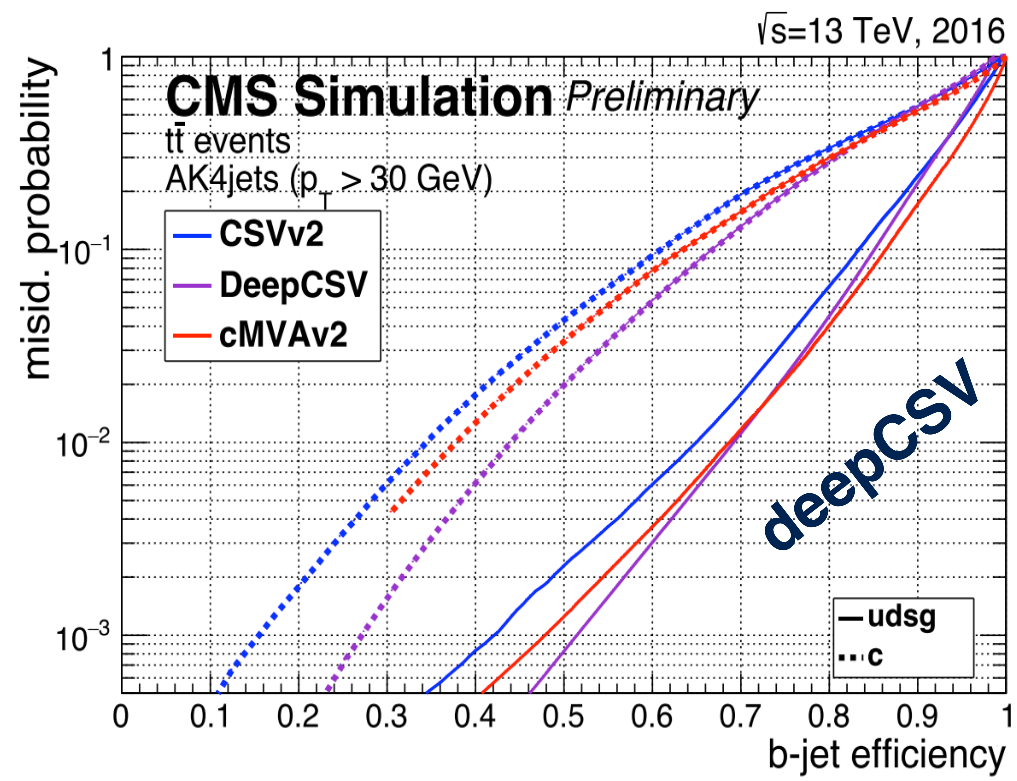
    cMVAv2 combines all the taggers

Tagger	operating point	discriminator value	ϵ_b (%)
JetProbability (JP)	JPL	0.245	≈ 82
	JPM	0.515	≈ 62
	JPT	0.760	≈ 42
Combined Secondary Vertex (CSVv2)	CSVv2L	0.460	≈ 83
	CSVv2M	0.800	≈ 69
	CSVv2T	0.935	≈ 49
Combined MVA (cMVAv2)	cMVAv2L	-0.715	≈ 88
	cMVAv2M	0.185	≈ 72
	cMVAv2T	0.875	≈ 53

- **deepCSV**: based on CSVv2

  + more charged particles, based on deep NN





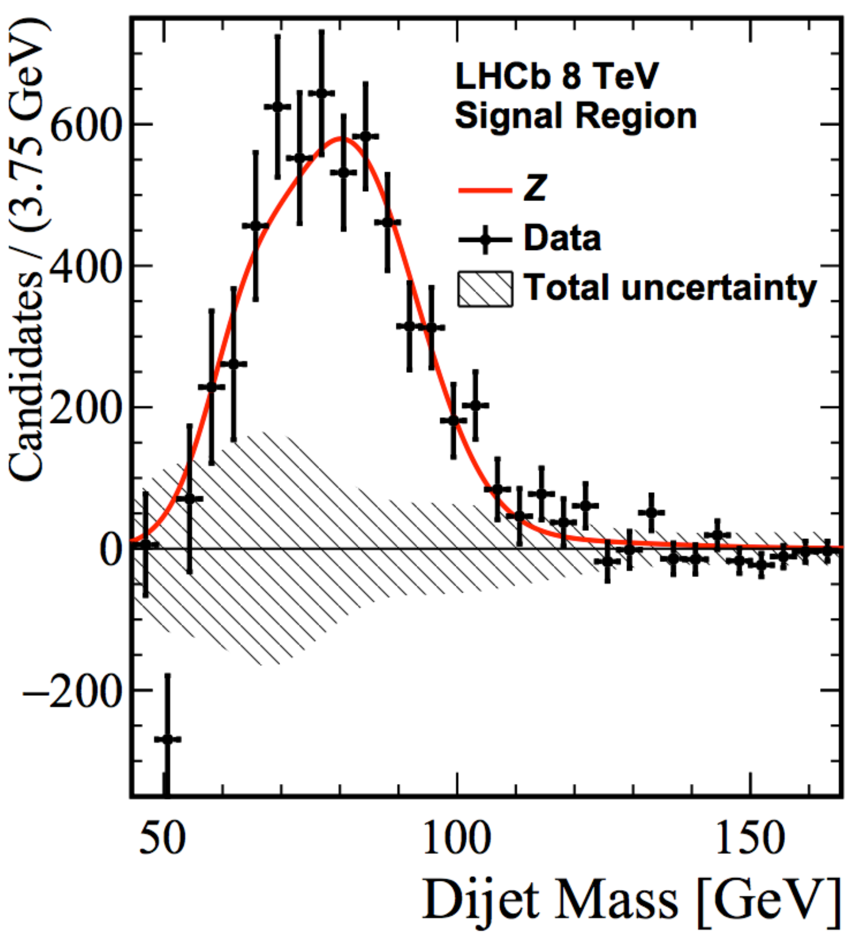
improves ~4% the b-tag efficiency with a mistag rate of 0.1%

First observation of forward $Z \to b\bar{b}$

8 TeV
2/fb

Phys. Lett. B776 (2017) 430-439

- standard candle of the SM: background for many new physics processes, Hbb
- first measurement in forward region ever made!
- challenging measurement (huge QCD background at colliders)
- >2 antikT05 jets, =2 b-tagged, p_T>20 GeV and 45 < m_{JJ}< 165 GeV ; $\Delta\phi$(bb)<2.5 .
- MVA to separate QCD from signal b-jets



simultaneous fit to the dijet mass in the signal+control regions

$$\sigma(pp \to Z)\mathcal{B}(Z \to b\bar{b}) = \frac{N_Z^s}{\mathcal{L} \cdot (1 - f_{\mathrm{uGB}}) \cdot \epsilon_Z^s \cdot (1 + f_{Z \to c\bar{c}})}$$

syst: flavor tagging eff. ~17%, JEC ~2%, trig. eff. ~2%

stat.

measured $\sigma(pp \to Z)\mathcal{B}(Z \to b\bar{b}) = 332 \pm 46 \pm 59 \text{ pb}$

theory $\sigma(pp \to Z)\mathcal{B}(Z \to b\bar{b}) = 272^{+9}_{-12}(\text{scale}) \pm 5(\text{PDFs}) \text{ pb}$

NLO using aMC@NLO+Pythia;NNPDF3.0

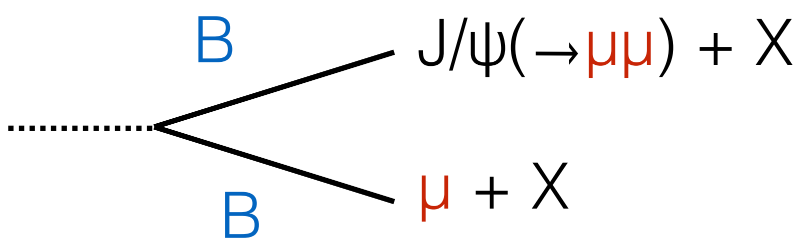
b-hadron pairs cross sections

8 TeV
11.4/fb

ATLAS EXPERIMENT

JHEP 11 (2017) 62

- production of two b hadrons in the 3 muons final state through:



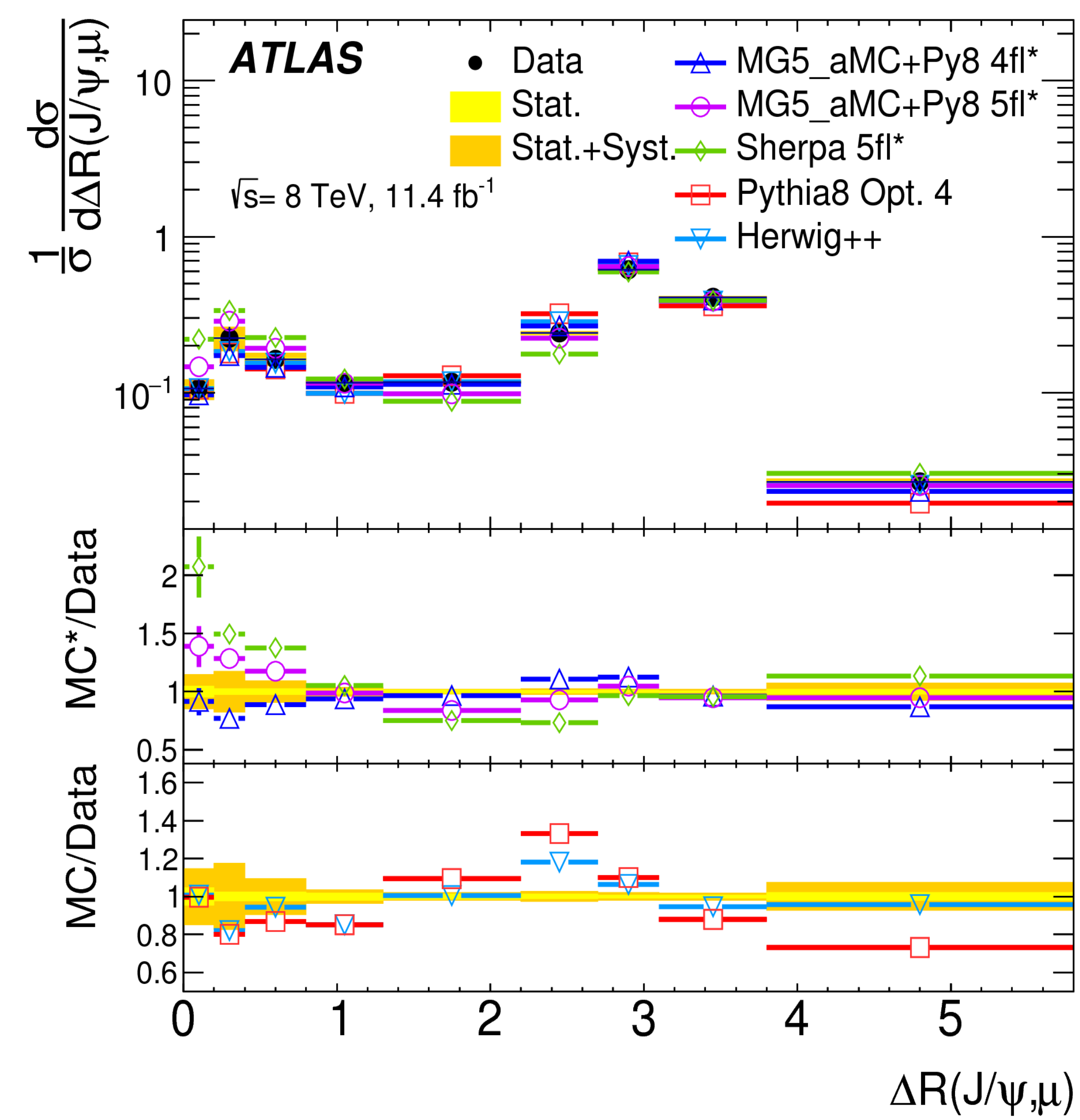
- **3 muons fiducial, particle level total and differential σ**
  several observables:
  Δϕ(J/ψ, μ), pT (J/ψ, μ), ΔR(J/ψ, μ),m(J/ψ, μ), pT/m(μμμ)…

- modelling of b dynamics in generators and background for Higgs measurements
- access small-angle $b\bar{b}$ pair sensitive to pQCD (loosely constrain by data)

Event Selection

- first B: pT(μ) > 4 GeV and |η(μ)| < 2.4,
- 2.5 < m(μμ) < 4.3 GeV
- second B: third μ in the event required
- signal extracted by fitting Mμμ and B decay time
  +3rd μ from B is determined

- BDT + IP for prompt/signal discrimination
- several g → bb splitting options investigated in P8



4-flavor and 5-flavor modes tested using MG5_aMC
MG5_aMC 4-flavor best agreement!

b-hadron pairs cross sections

8 TeV
11.4/fb

JHEP 11 (2017) 62

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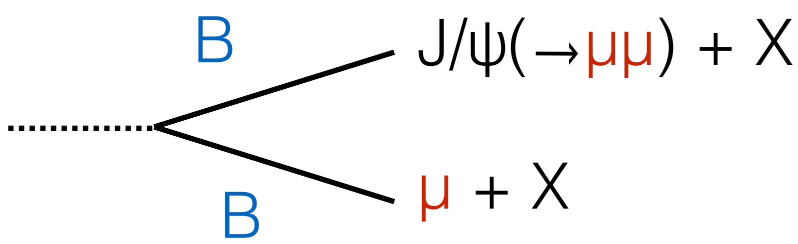

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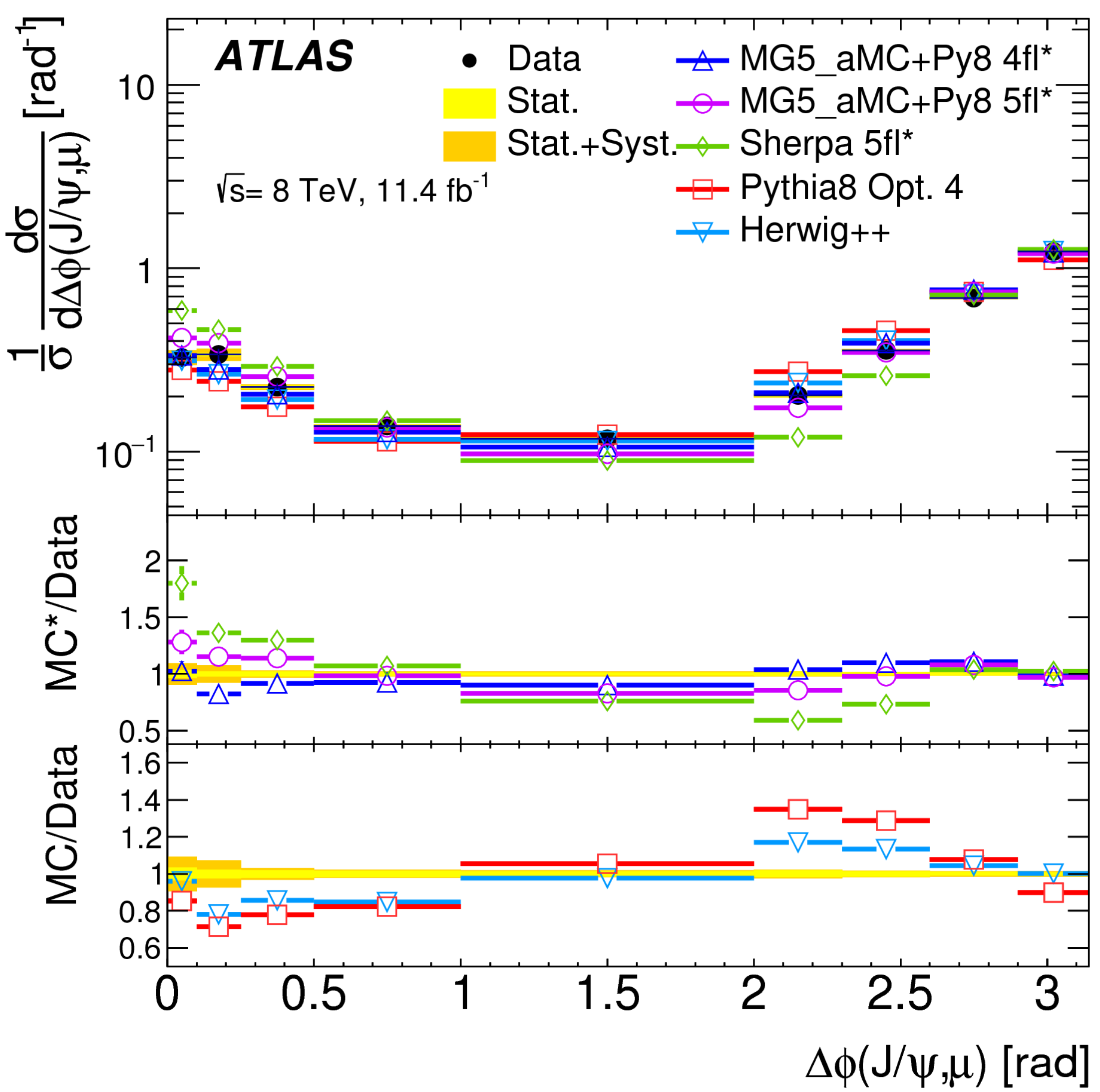


b quarks in association with a Z boson

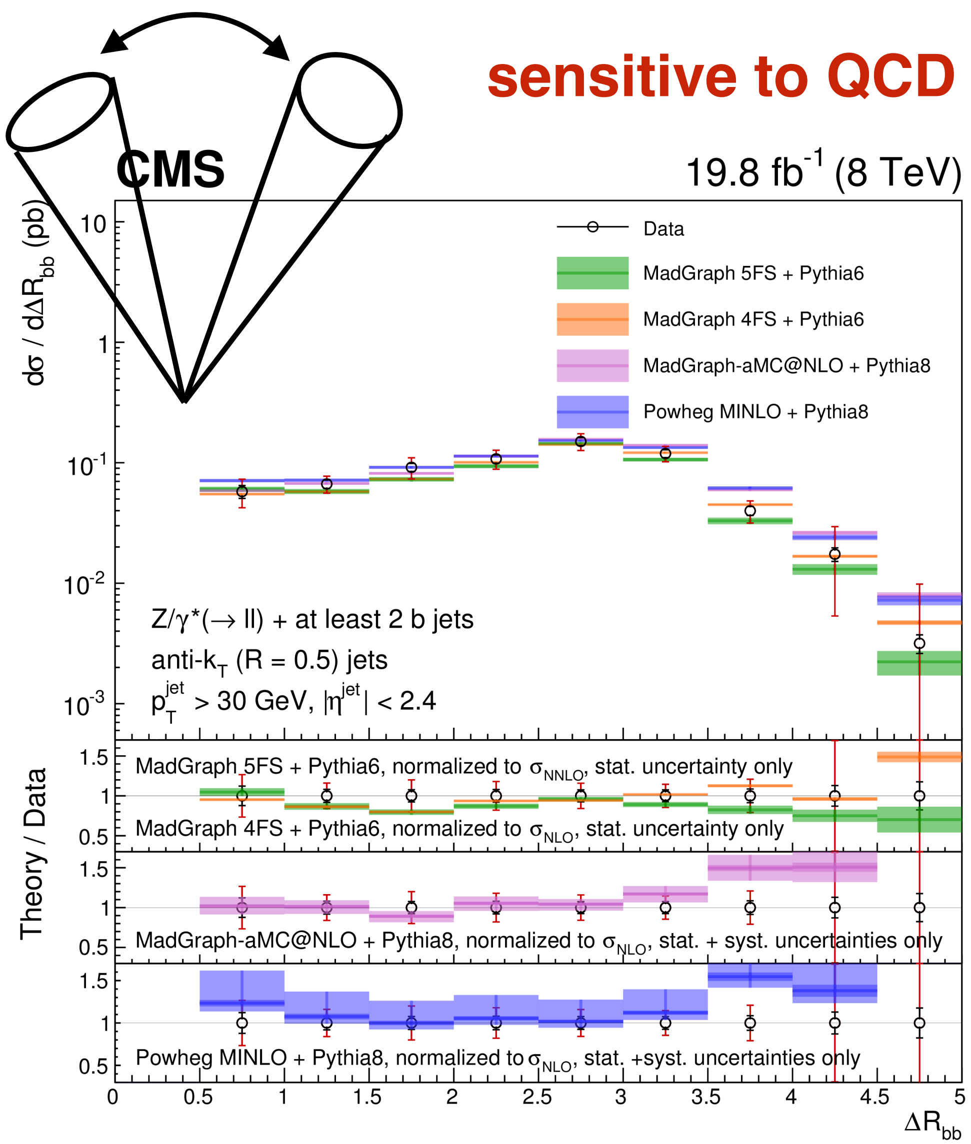
Eur. Phys. J. C 77 (2017) 751

- two categories: Z boson (μμ+ee) plus >0 and >1 b tagged jets (CSV tagging)
- b jets p_T > 30 GeV, |e| <2.5, Z+b unfolded to particle level
- several differential cross sections: angles, pT, HT, bbZ and bZ system explored
- compared to NLO predictions by MadGraph and Powheg, 4F and 5F schemes tested

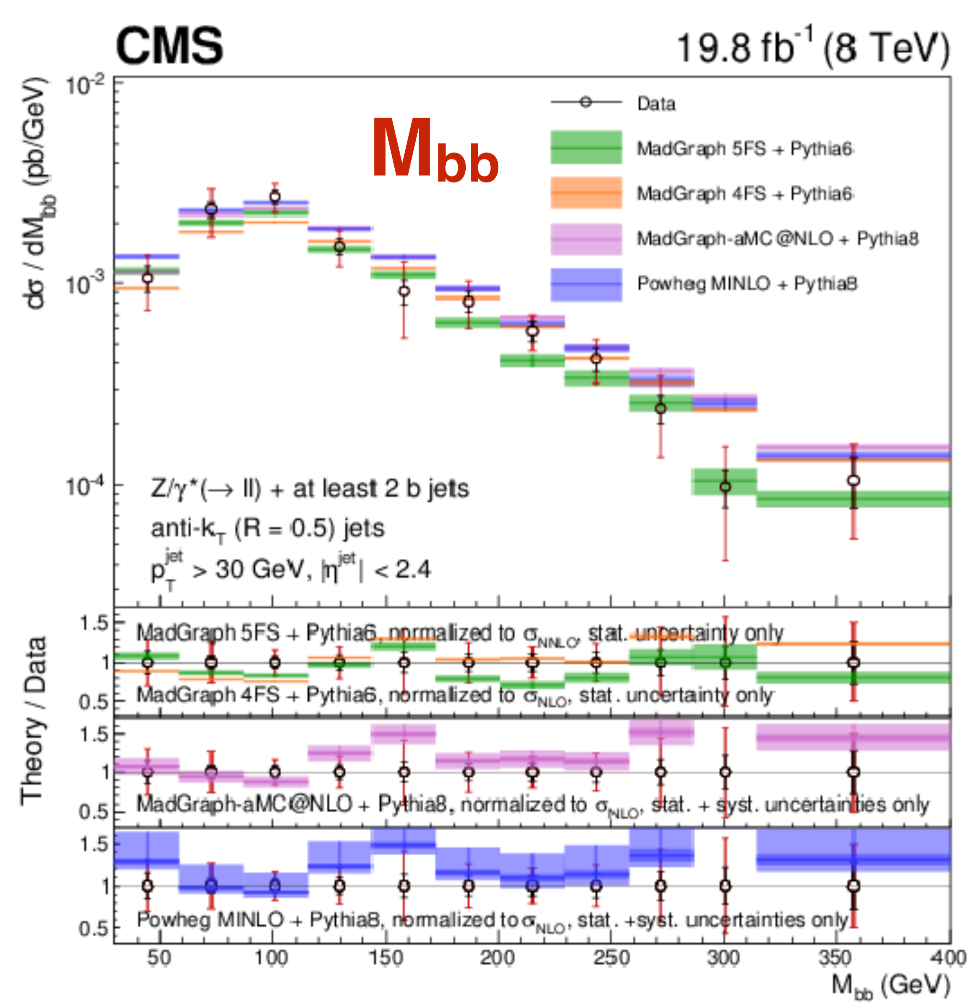
8 TeV

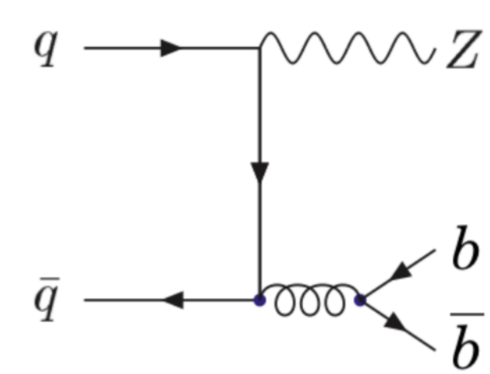
19.8/fb

sensitive to QCD

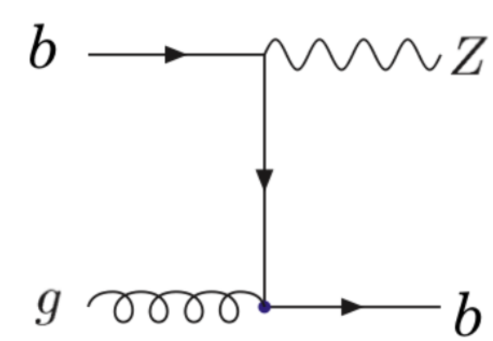


sensitive to new physics





4-flavor, mb=0



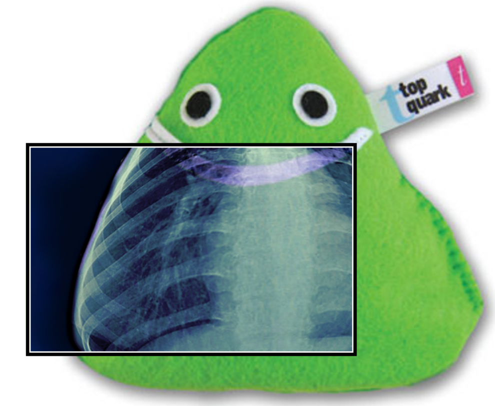
5-flavor, mb≠0

Selected Results

part III

Top Quark

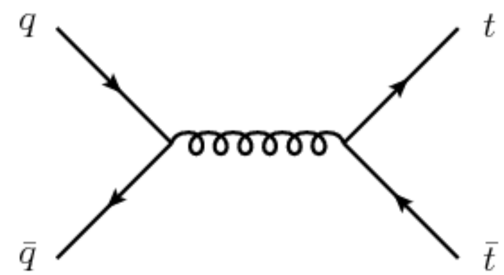
Top quark production at colliders



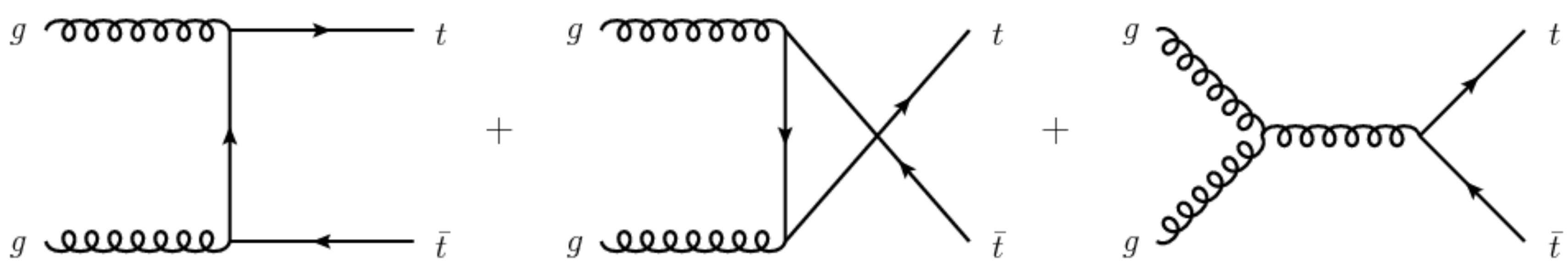
$t\bar{t}$ dominated by gluon fusion (qq/gg=10%/90%) at LHC

LO diagrams @ LHC

top Factory:
High rate of $t\bar{t}$ at LHC
(30m only in 2016)

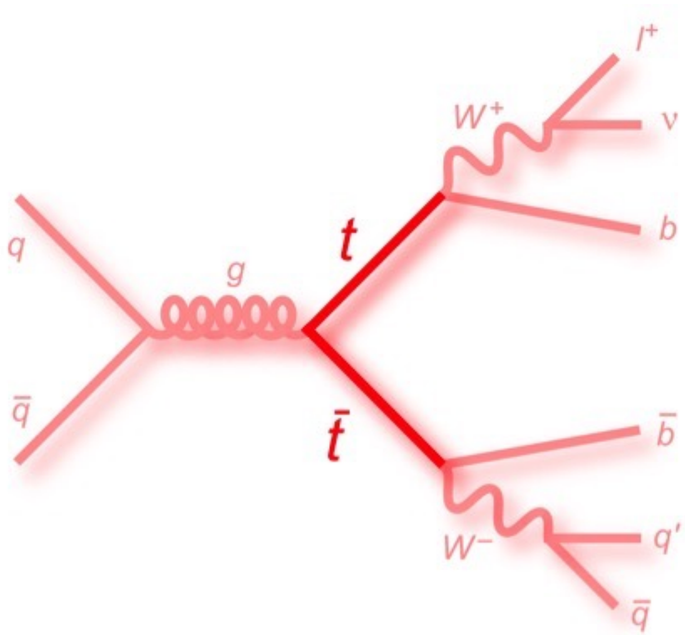


vast phenomenology: standard model, QCD calculation and new physics searches



calculations are challenging: NNLO/NNLL corrections important

final states:
- fully hadronic
- dilepton
- lepton+jets



Present times top quarks general news

- $t\bar{t}$ production cross section @ 13 TV measured at ~5.5%(beyond NNLO+NNLL precision!)
- Jet substructure and shape observables @ 13 TeV
- first measurement of the forward production (LHCb)

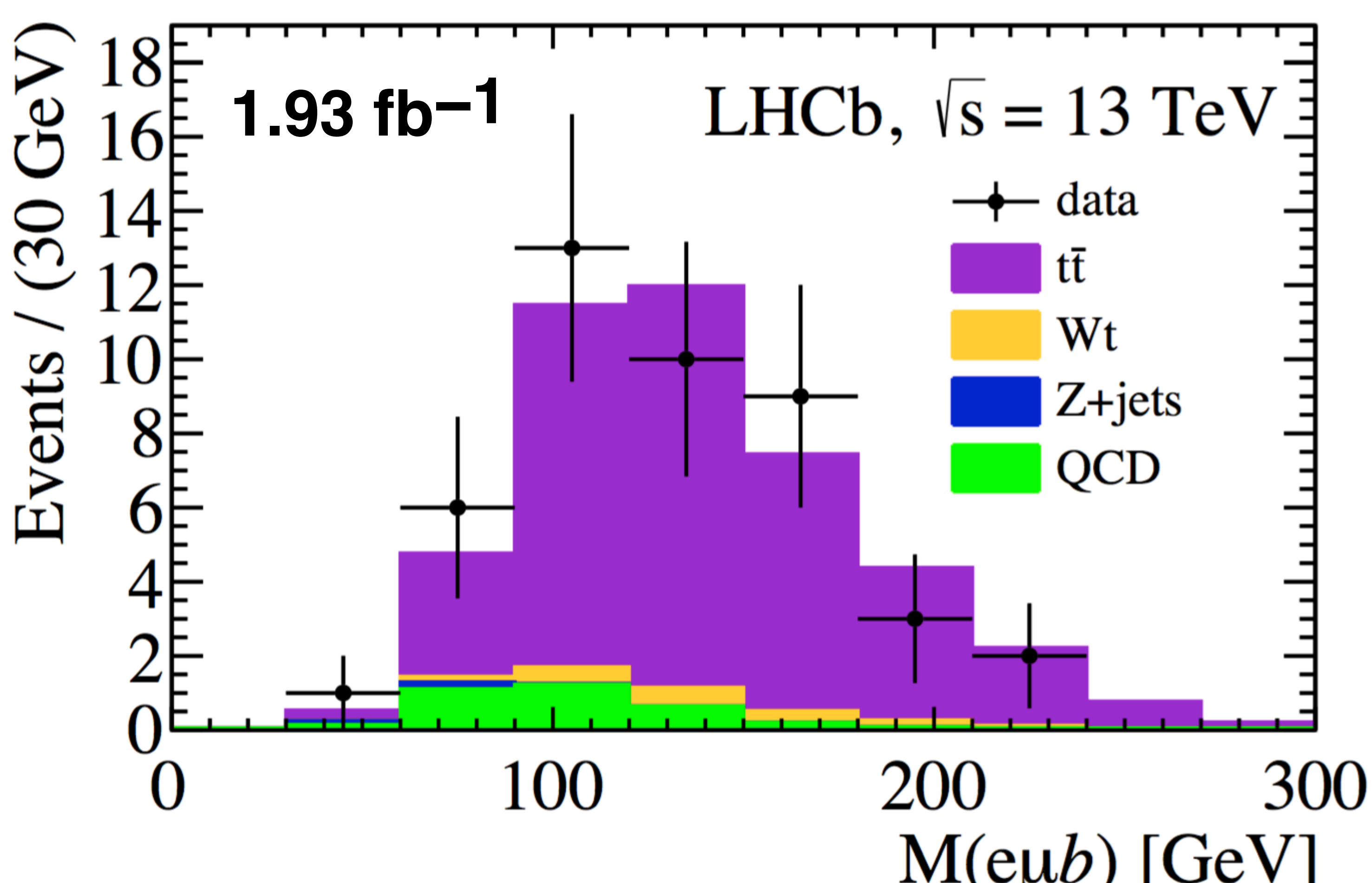
First observation of forward top at 13 TeV

13 TeV

arXiv:1803.05188
(submitted to JHEP)

Forward top quarks in LHCb

- unique probe of **higher Bjorken-*x*** and constrain PDF in this region
- expected **larger charge asymmetry** in the forward region than in the central region.
- previously measured at 7+8 TeV. With 13 TeV **x10** in **σ**($t\bar{t}$)



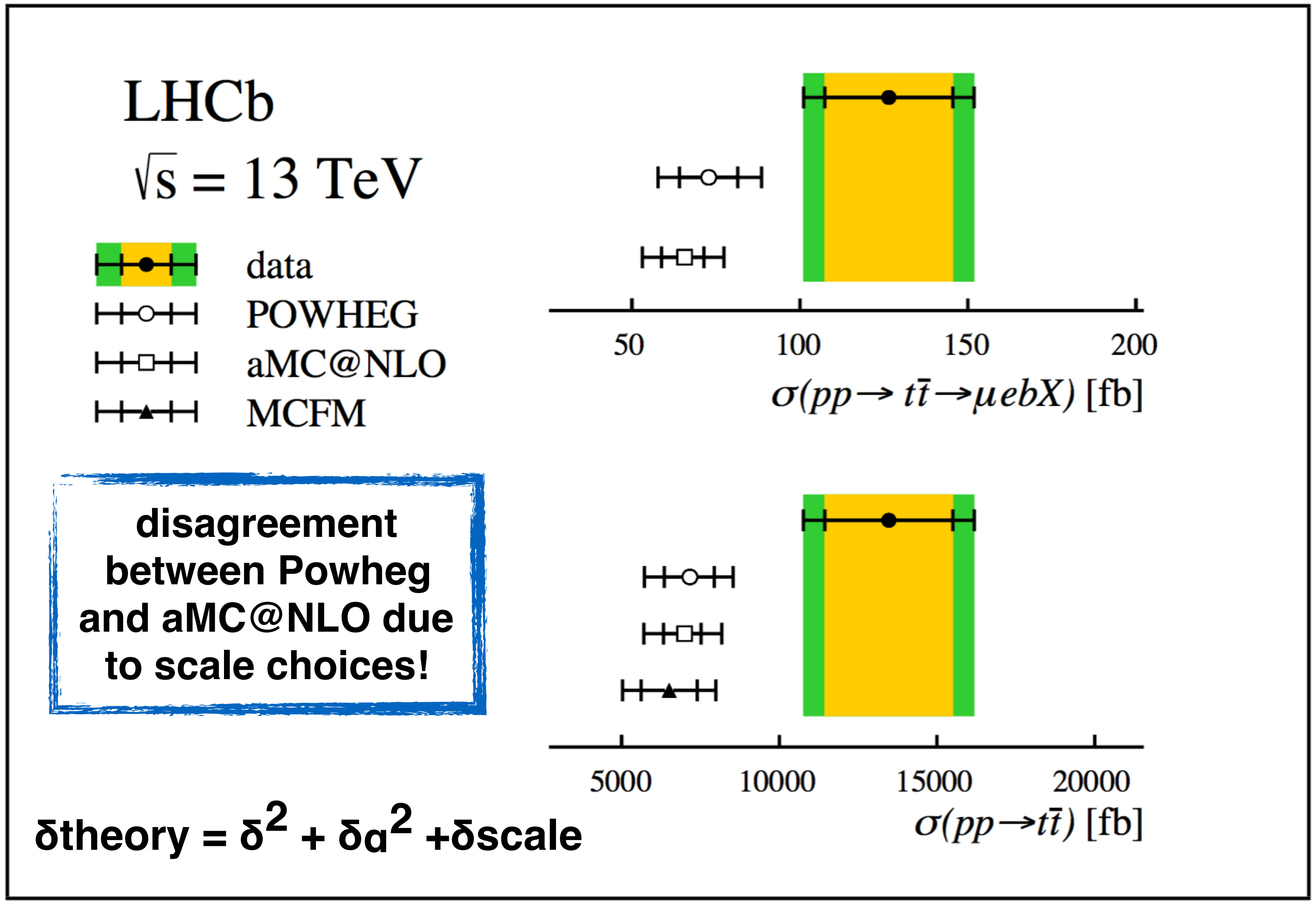
***μeb* channel**

- isolated prompt *μ,e*
  p_T > 20 GeV, 2.0<η< 4.5
- SV-tagged Jet
- ΔR(*l,J*) > 0.5, ΔR(*μ,e*) > 0.1
- $t\bar{t}$ shape normalised to data
  purity of ~ 87%

First observation of forward top at 13 TeV

arXiv:1803.05188
(submitted to JHEP)

13 TeV



Source	%
trigger	2.0
muon tracking	1.1
electron tracking	2.8
muon id	0.8
electron id	1.3
jet reconstruction	1.6
jet tagging	10.0
selection	4.0
background	5.1
acceptance	0.5
total	12.7

$$\sigma_{t\bar{t}} = \frac{N - N_{bkg}}{L \cdot \epsilon} \cdot F_{res}$$

1.93 fb^{-1}

calculated in MC validated in Data

migration in to and out of the fiducial region

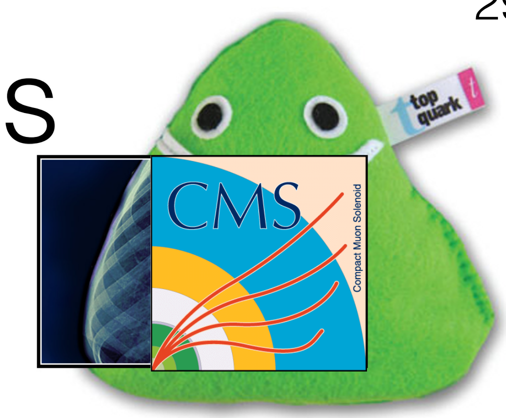
$\sigma_{t\bar{t}}$ = 126 ± 19 (stat) ± 16 (syst) ± 5 (lumi) fb

extrapolated to top quark level 2.0 < y^t < 5.0, p^t_T > 10 GeV

compatible with the SM (<2σ)

20% precision achieved!

Jet substructure observables in $t\bar{t}$ events



- using lepton+jets final states to measure several unfolded substructure observables: tuning generators and describe fragmentation of quarks
- relative uncertainties relevant for top measurements (i.e. top mass)

35.9/fb 13 TeV
CMS-PAS-TOP-17-013

- lots of different shape-observables have been measured!

phace space (gen~reco)	=1 e/μ pT > 26 GeV, |η| < 2.4
	≥ 4j anti-kT04, pT > 30 GeV, |η| < 2.5
	=2b-tag + ≥ 2 untag from W (within 15 GeV Mw)

Eccentricity

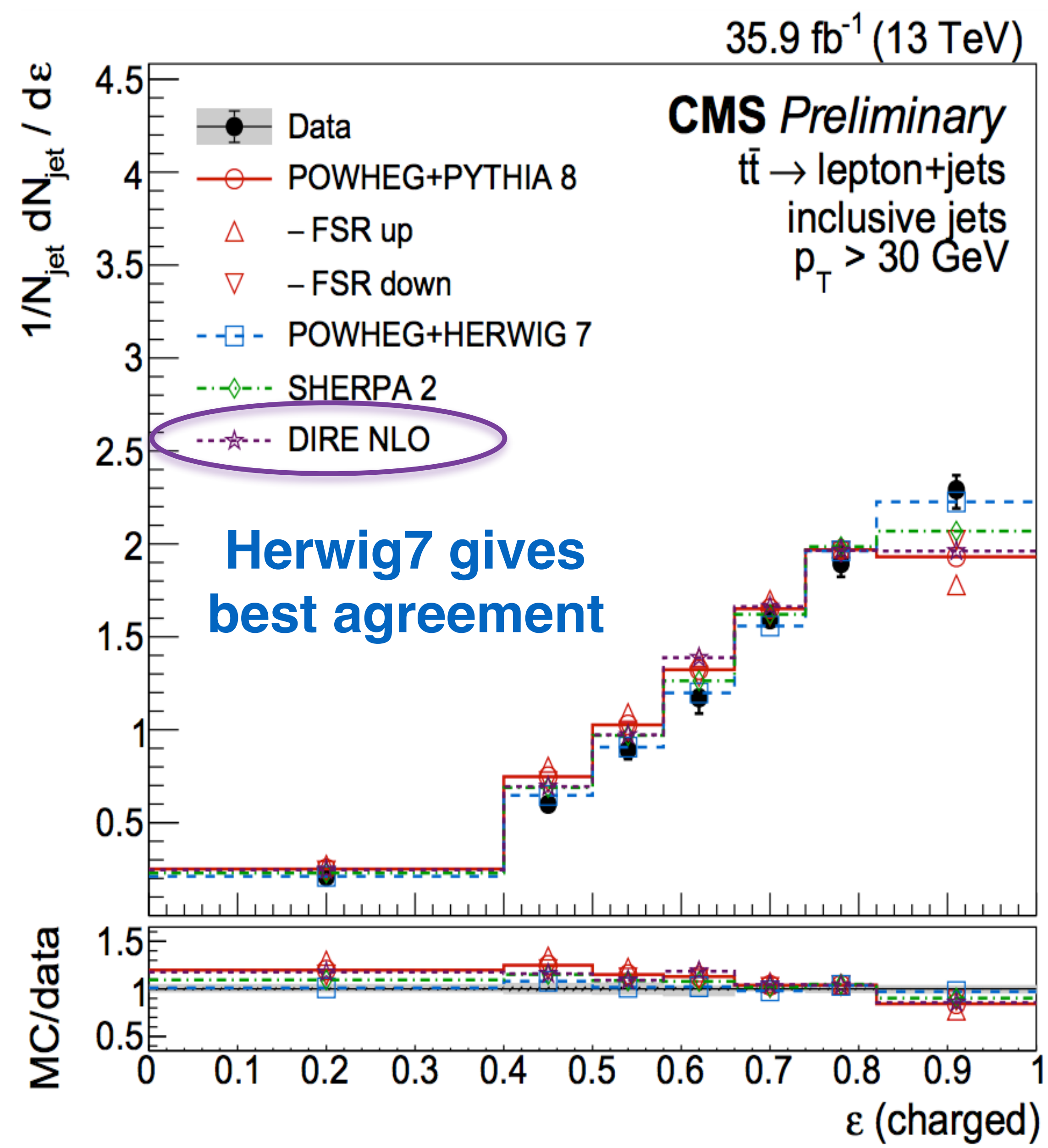
$$\epsilon = 1 - \frac{v_{min}}{v_{max}}$$

→0: perfectly circular jet

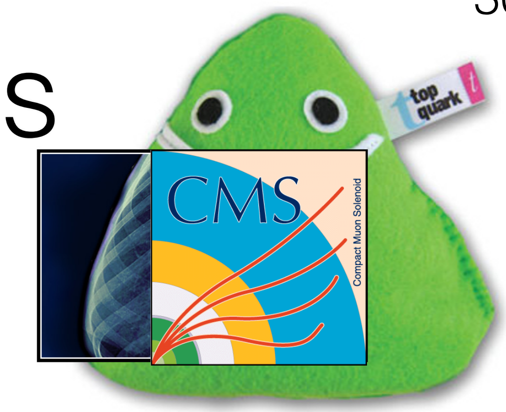
→1: elliptical jet

with $\mathbf{v_{min}}$, $\mathbf{v_{max}}$ eigenvalues of

$$M = \sum_i E_i \times \begin{pmatrix} (\Delta\eta_{i,\hat{n}_r})^2 & \Delta\eta_{i,\hat{n}_r}\Delta\phi_{i,\hat{n}_r} \\ \Delta\phi_{i,\hat{n}_r}\Delta\eta_{i,\hat{n}_r} & (\Delta\phi_{i,\hat{n}_r})^2 \end{pmatrix}$$



Jet substructure observables in $t\bar{t}$ events



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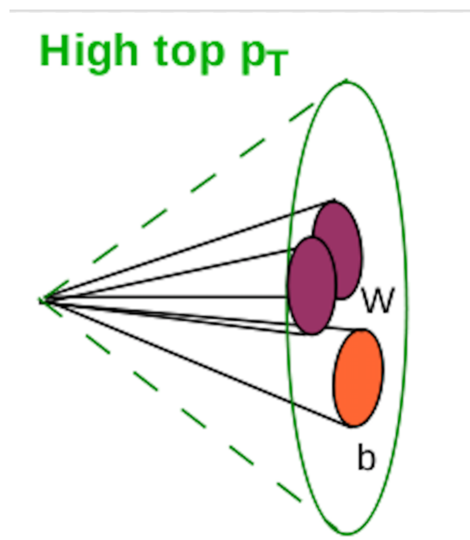
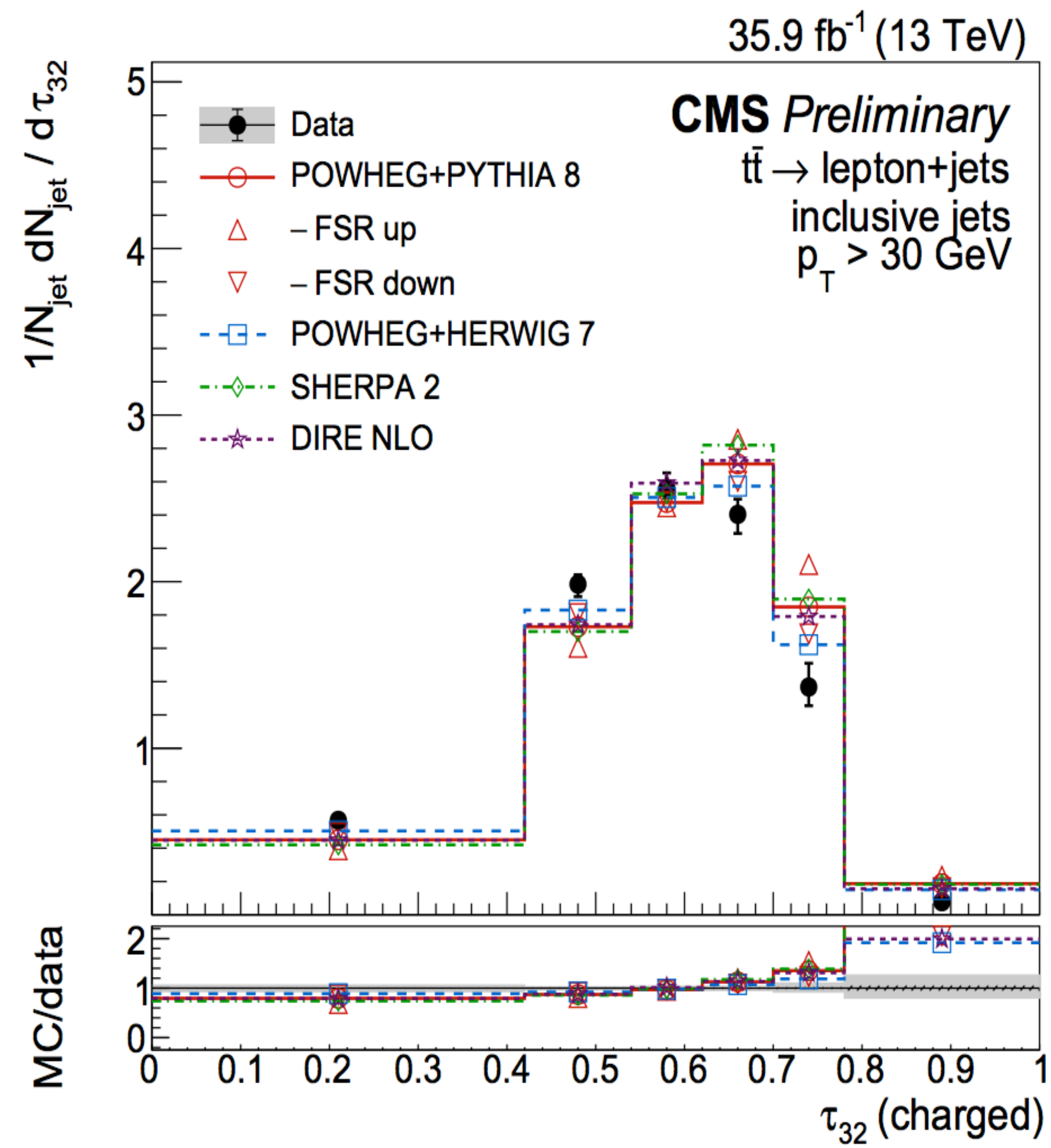
N-subjettiness

$$\tau_N^\beta = d_0^{-1} \sum_i p_{T,i} \cdot min[(\Delta R_{1,i})^\beta, (\Delta R_{2,i})^\beta ... (\Delta R_{N,i})^\beta]$$

$$\tau_{MN} = \tau_M / \tau_N$$

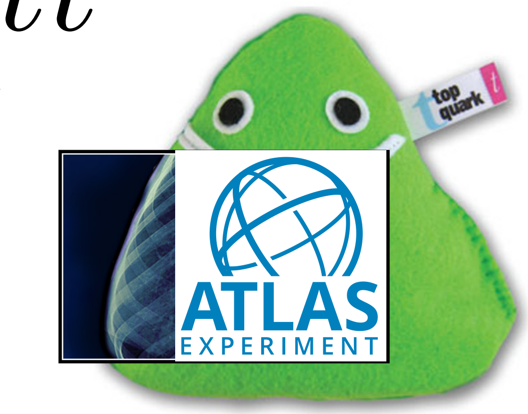
- evaluate compatibility with N sub-jet hypothesis
- allows to distinguish between **M** and **N** subjets within a jet





Color flow using jet-pull observables in $t\bar{t}$

13 TeV
36.1/fb



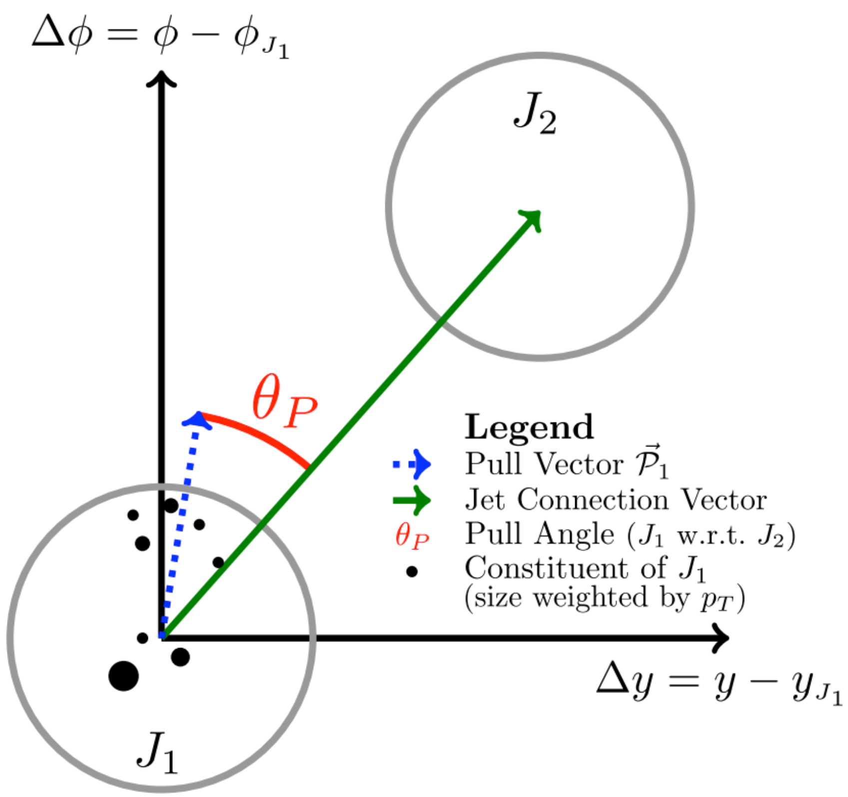
ATLAS-CONF-2017-069

- gluon radiation and the jet structure are affected by the color connection of the generating particles (*color flow*)
- color connection may be used to distinguish different event topologies

Strategy: the **jet-pull** vector/angle is predicted to encode color information:

$$\vec{\mathcal{P}}(J) = \sum_{i \in J} \frac{|\vec{\Delta r}_i| \cdot p_{\mathrm{T}}^i}{p_{\mathrm{T}}^J} \vec{\Delta r}_i$$

→ *i* constituents of the jet J with momentum pTi located at Δri = (Δyi,Δϕi)



- system with 2 colour-connected jet : **θ_P~0**
- system with 2 jet with no C.C. : **θ_P~uniform**

↓

Two systems used to measure θP and color flow

- W→JJ in ttbar events (color singlet)
- bbar in ttbar events (uncorrelated colors)

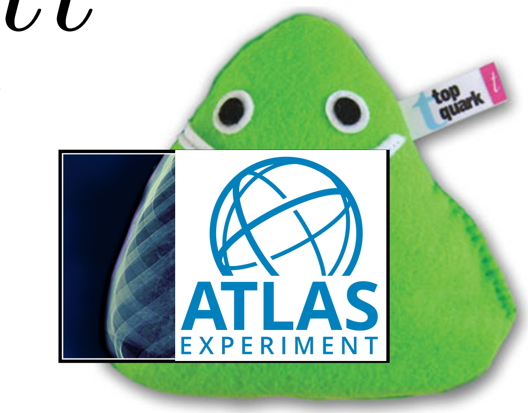
↓

unfolded differential cross section for in **θ_P** ttbar

θ_P (J1,J2) relates local color structure of J1 to the global structure of the dijet

Color flow using jet-pull observables in $t\bar{t}$

13 TeV
36.1/fb



- gluon radiation and the jet structure are affected by the color connection of the generating particles (*color flow*)
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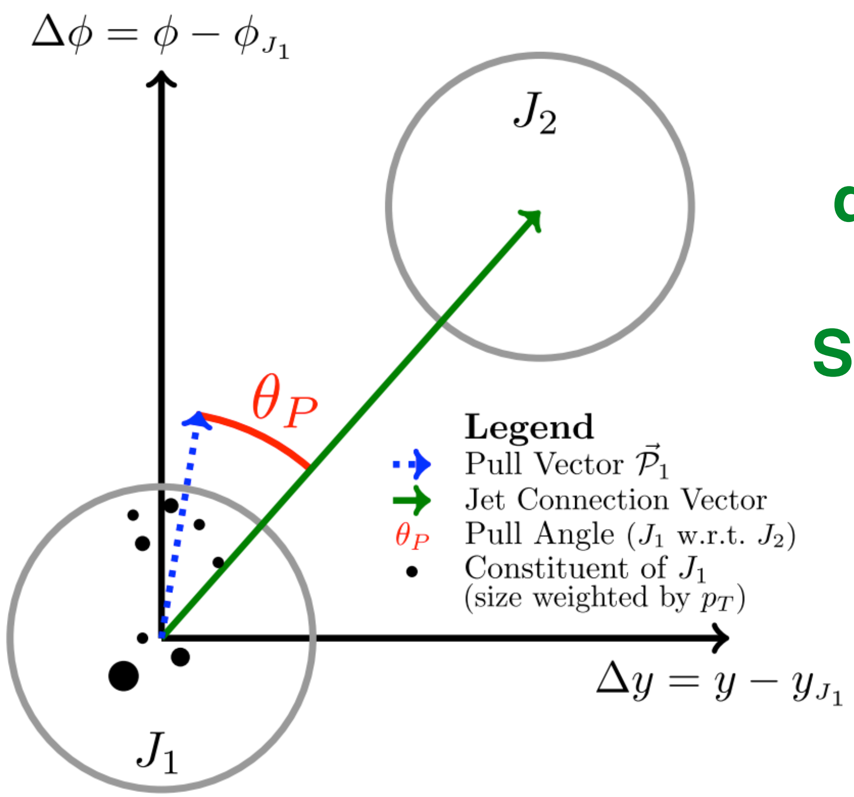
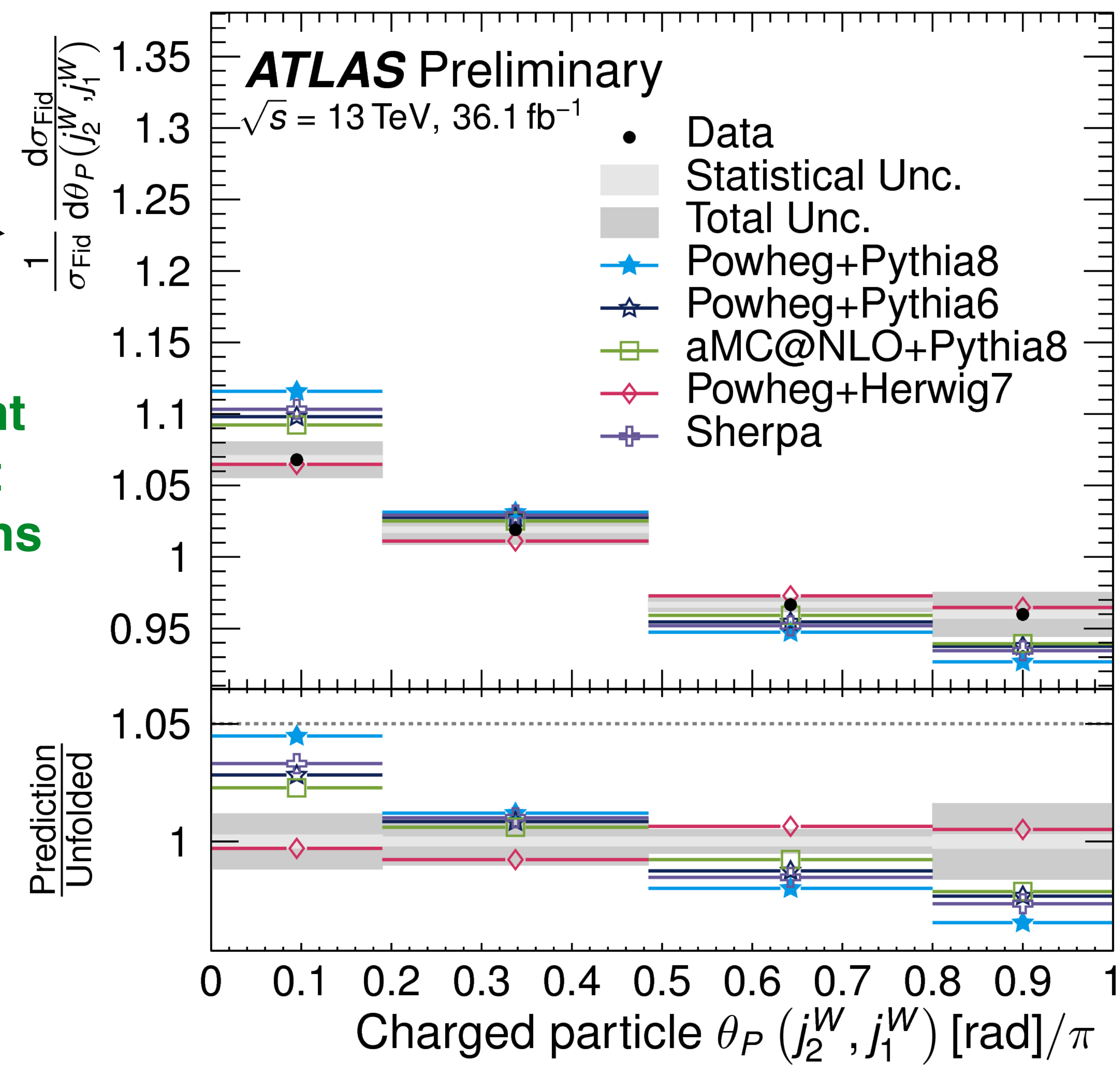
- **W→JJ in $t\bar{t}$ events (color singlet)**

$$\vec{\mathcal{P}}(J) = \sum_{i \in J} \frac{|\vec{\Delta r}_i| \cdot p_T^i}{p_T^J} \vec{\Delta r}_i$$



disagreement for different SM predictions



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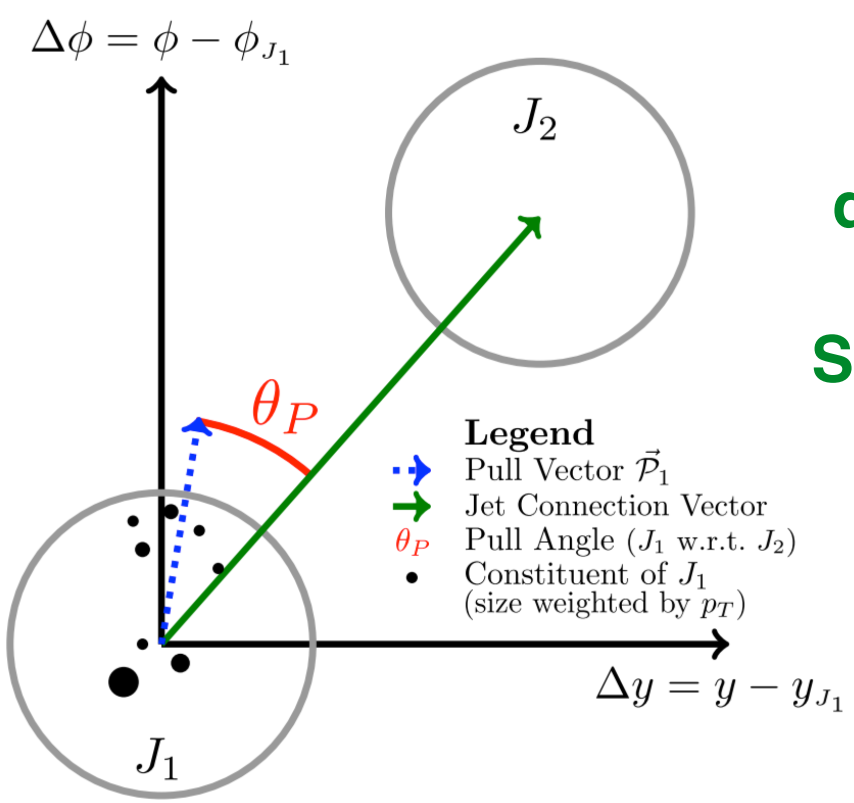
Color flow using jet-pull observables in $t\bar{t}$

13 TeV
36.1/fb

- gluon radiation and the jet structure are affected by the color connection of the generating particles (*color flow*)
- color connection may be used to distinguish different event topologies

- $b\bar{b}$ **in** $t\bar{t}$ **events (uncorrelated colors)**

$$\vec{\mathcal{P}}\,(J) = \sum_{i \in J} \frac{\left|\vec{\Delta r}_i\right| \cdot p_{\mathrm{T}}^i}{p_{\mathrm{T}}^J} \vec{\Delta r}_i$$



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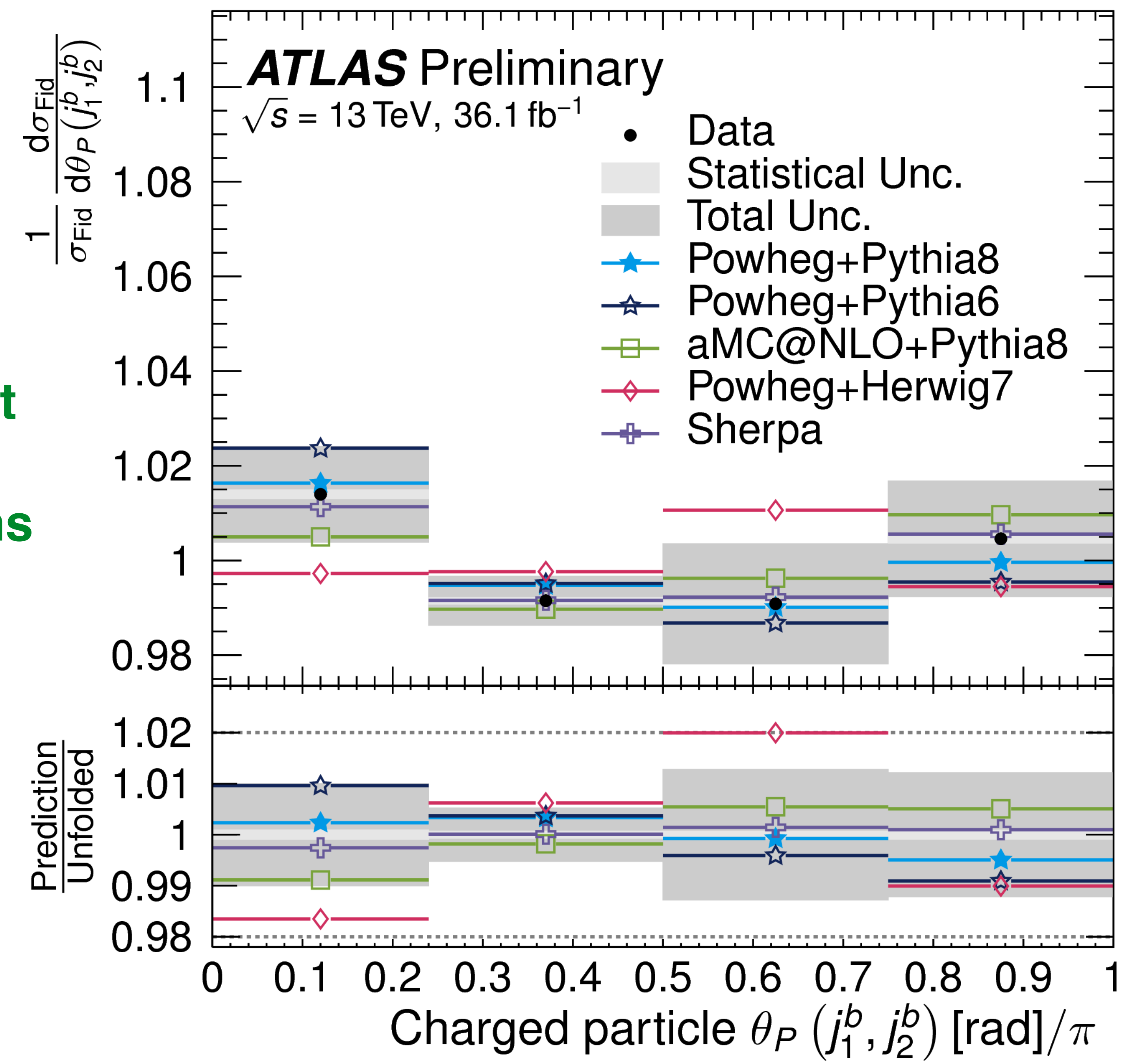


θ_P (J1,J2) relates local color structure of J1 to the global structure of the dijet

Summary and conclusions

- LHC is a jet factory: a rich QCD phenomenology can be explored with the experiments
- QCD can be tested at NLO with the latest generators on several aspects
- Several new measurements at 13 TeV with QCD jets, b-jets and top within the Standard Model, all resulting in outstanding precise measurements
- Many more are there and many more to come… stay tuned!!

Summary and conclusions

CMS Public Results

http://cms-results.web.cern.ch/cms-results/public-results/publications/

ATLAS Public Results

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

LHCb Public Results

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/

backup

Inclusive b quarks cross section

13 TeV
3/fb

JHEP 10(2015) 172

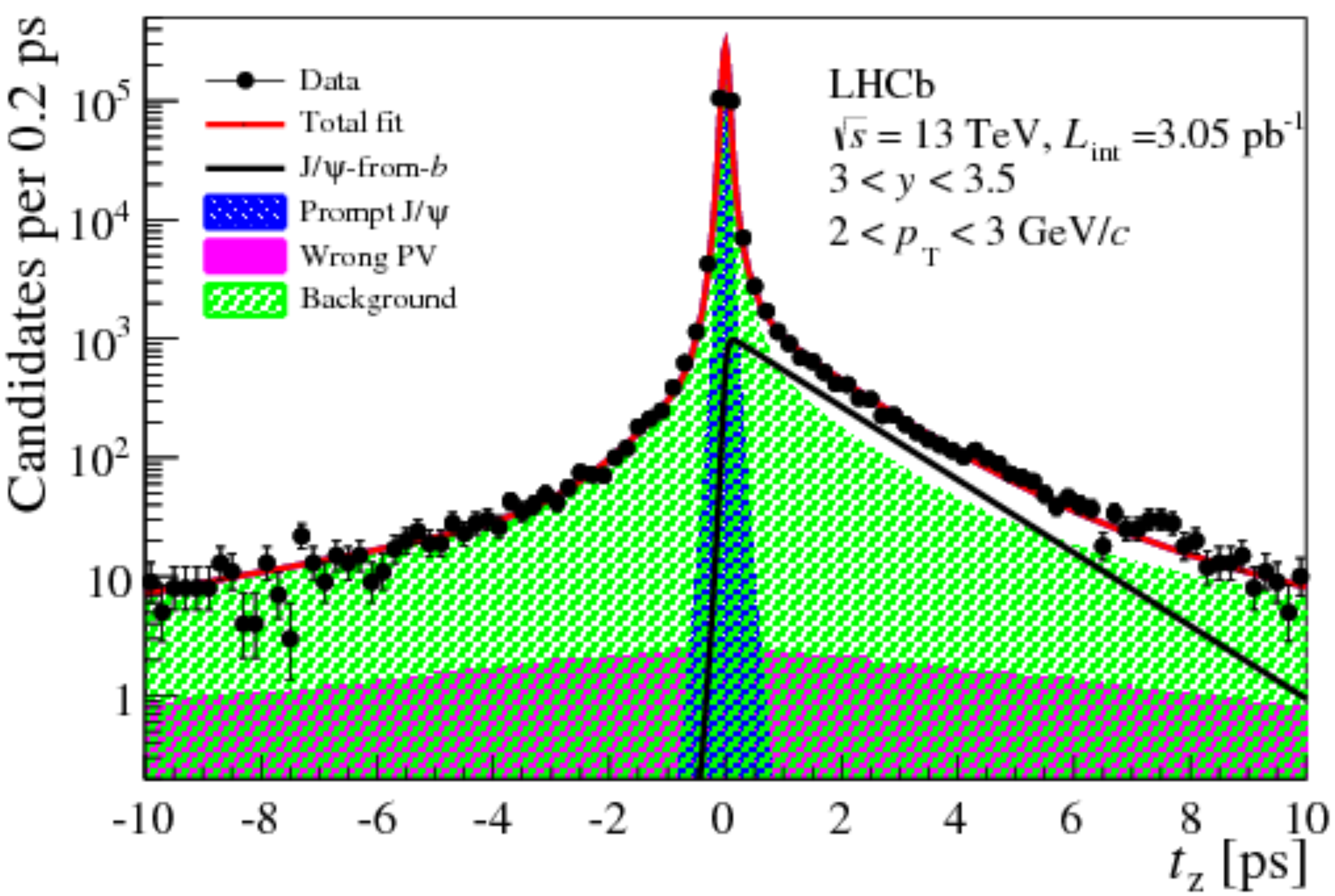
- production σ of forward J/ψ
- prompt and b-decays - J/ψ determined
- fitting the J/ψ 's pseudo-lifetime

$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$

- σ(J/ψ) from b-hadron decays used to extrapolate to a total σ(bb) @ 13 TeV

$$\sigma(pp \to b\bar{b}X) \quad = \alpha_{4\pi} \frac{\sigma\left(J/\psi\text{-from-}b,\ p_T < 14\ \text{GeV}/c,\ 2.0 < y < 4.5\right)}{2\mathcal{B}\left(b \to J/\psi X\right)}$$

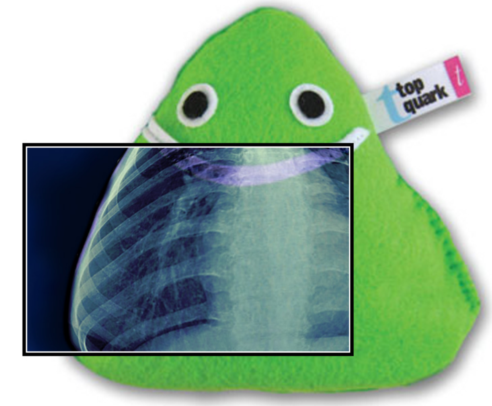
$\alpha_{4\pi}$= extrapolation factor

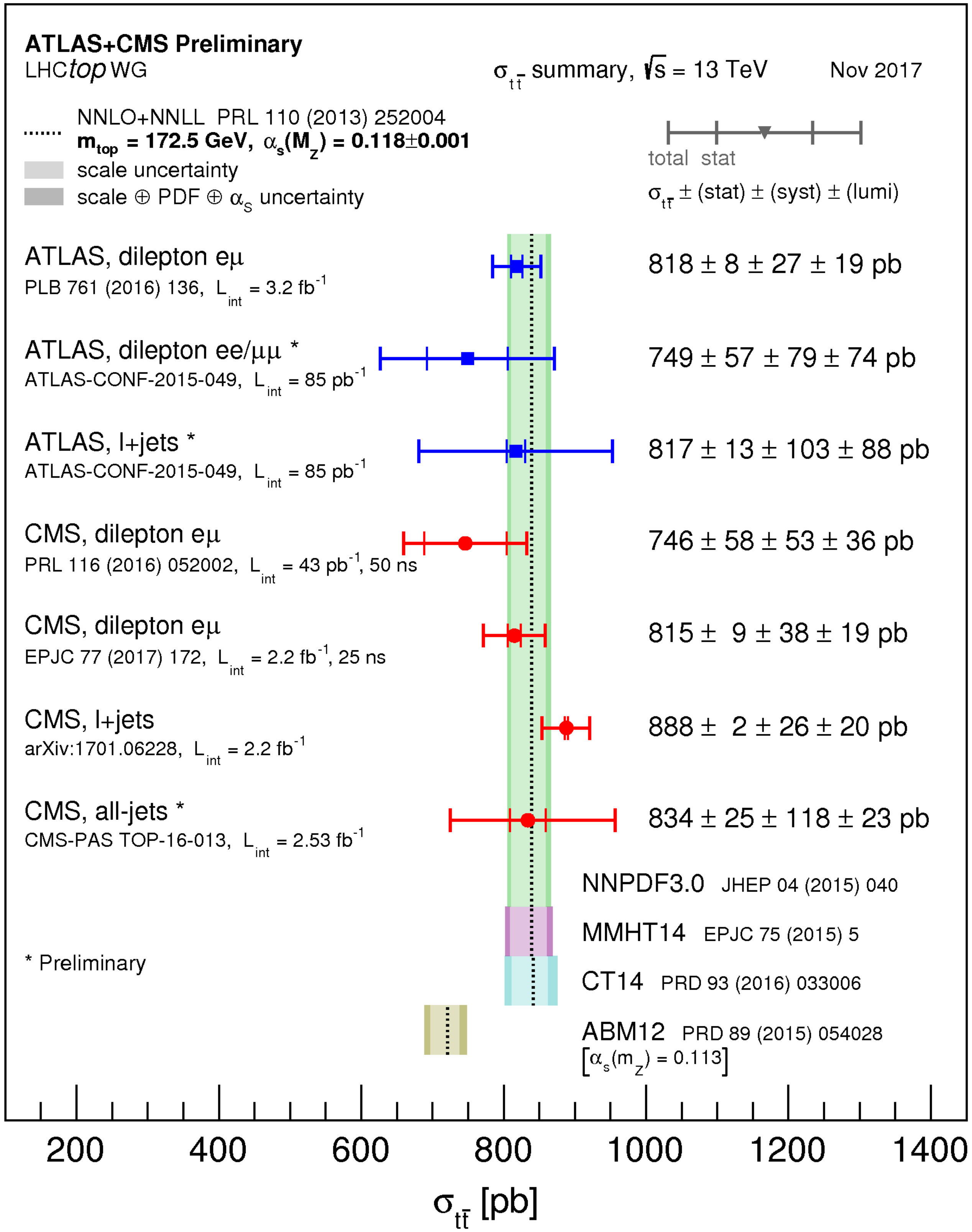


- σ(J/ψ) vs. pT and y of the J/ψ
- pT<14GeV/c and 2.0<y<4.5
- prompt J/ψ -> δ (tz = 0),
- J/ψ-from-b -> exp decay function (both convolved with a double-Gaussian resolution function)

σ(pp → bbX) = 495 ± 2 ± 52 μb

State-of-Art of $t\bar{t}$ cross sections





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/

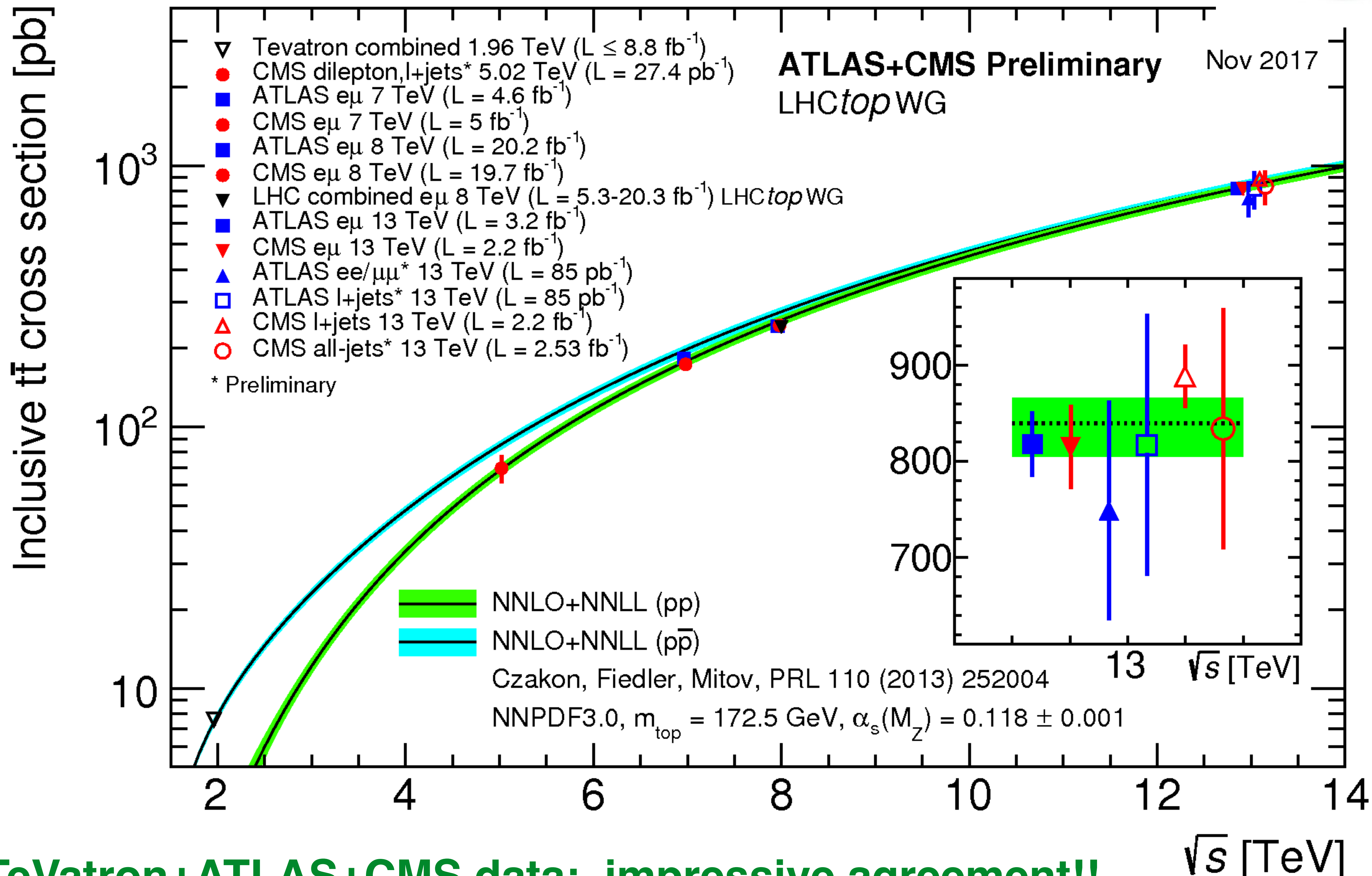
tt production cross section grand summary at 13 TeV for ATLAS+CMS

Most precise measurements from *eμ* at 7+8 TeV, and *l*+jets at 13 TeV

Individual analyses with precision of 3-4%

$t\bar{t}$ cross section and energy

Measured $t\bar{t}$ cross section versus $\sqrt{s}$



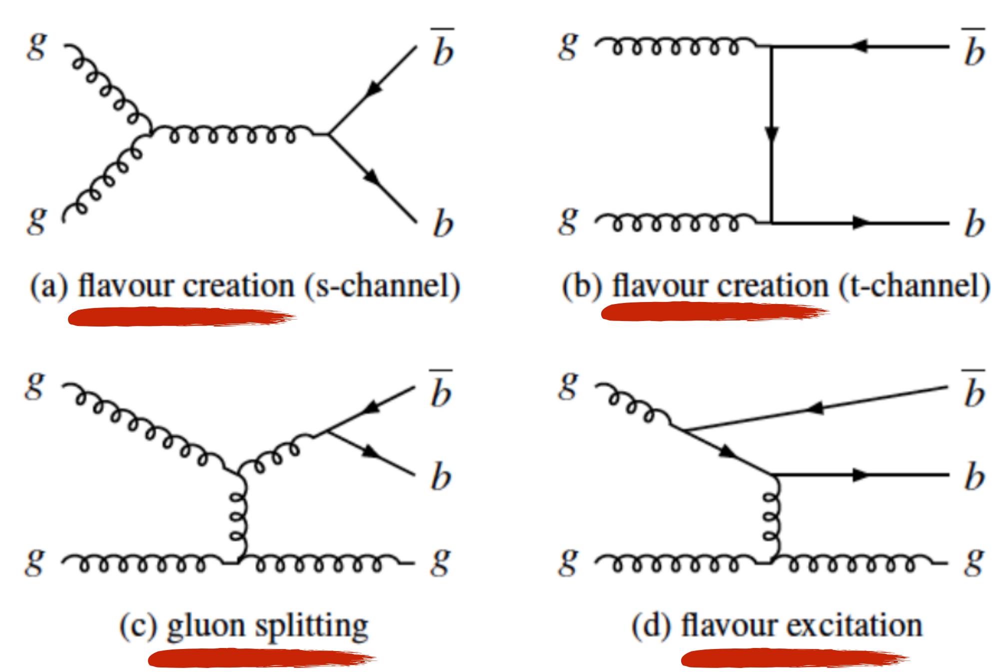
TeVatron+ATLAS+CMS data: impressive agreement!!

Inclusive $b\bar{b}$ production

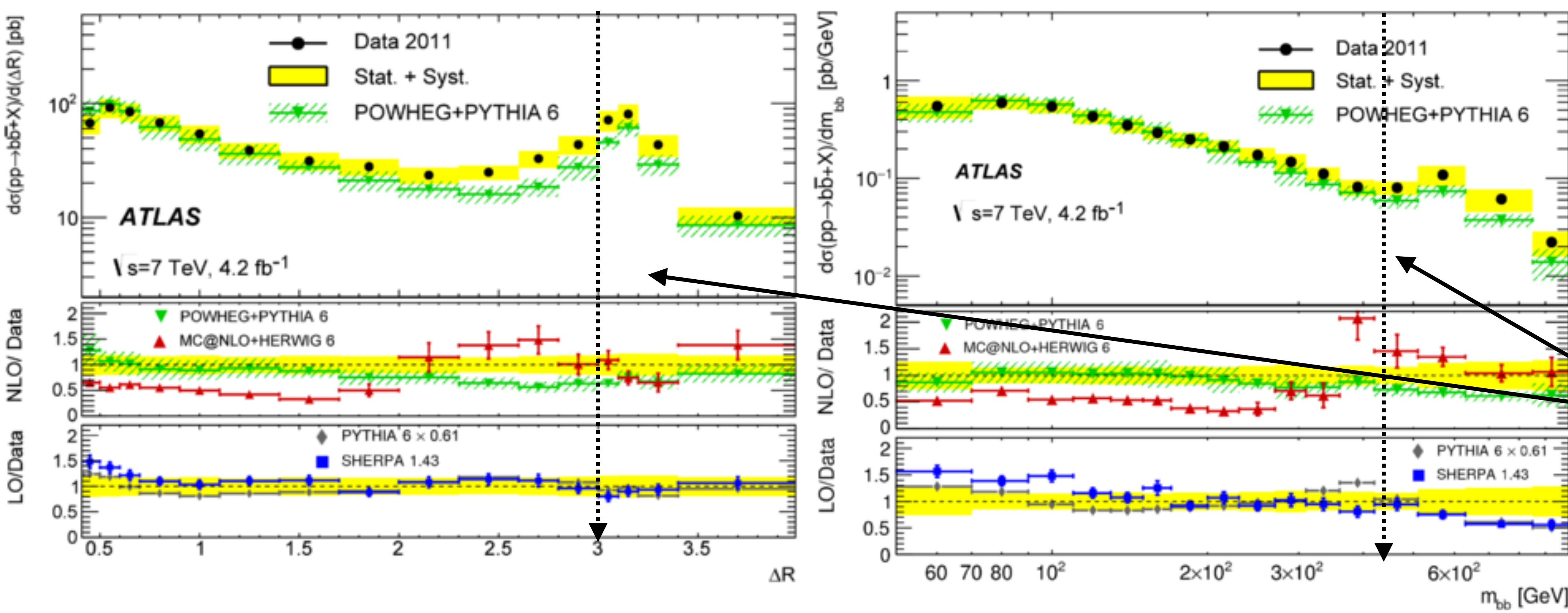
7 TeV

Eur. Phys. J. C 76 (2016) 670

- pp->bb: testing different Feynman diagrams
- two jets p_T > 20 GeV, $|\eta|$ < 2.5, b-tagged
- p_{T1} > 270 GeV [enhance (b), (c)], p_{T2}>20GeV
- data compared to NLO by Powheg+Pythia6, Sherpa1.4 and MC@NLO+Herwig6



different ranges of measured observables probe different production mechanisms

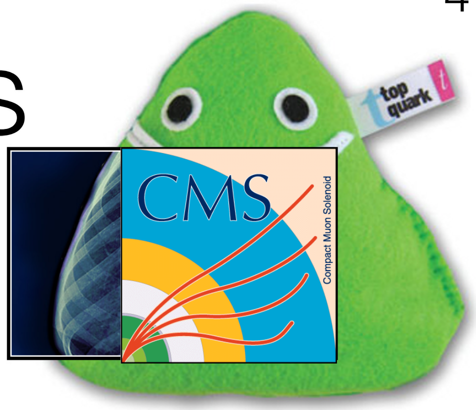


NLO predictions show large discrepancies

LO generally OK

significant contribution from flavour creation

Jet substructure observables in $t\bar{t}$ events



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Soft-drop

Iterative clustering regulated by a parameter $z_g = p_T(j_k/j_i)$

$$j_i \rightarrow j_j + j_k$$

ΔR_g = angle between j,k subjets

z_g = momentum fraction of the last iteration

best agreement with angular-ordered Herwig7