QCD results at LHC

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ATLAS CMS LHCb

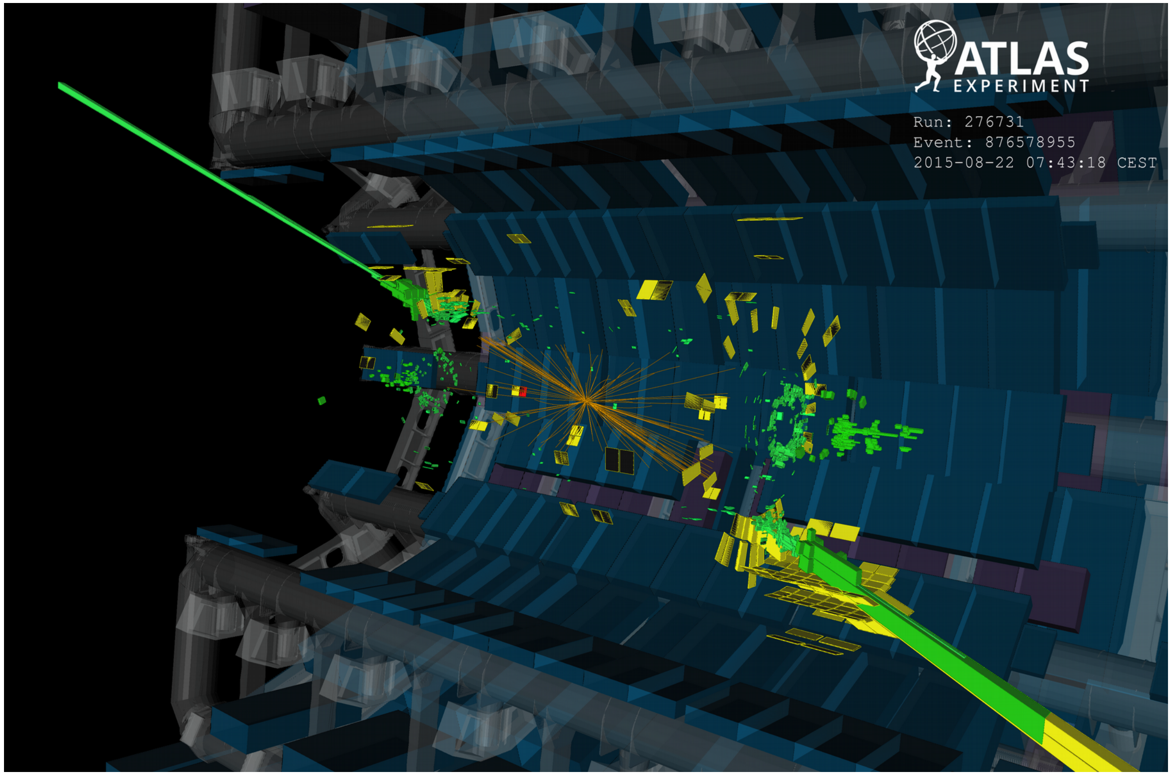
Outline

talk presents recent results on production of

- jets
- isolated photons
- top
- vector bosons

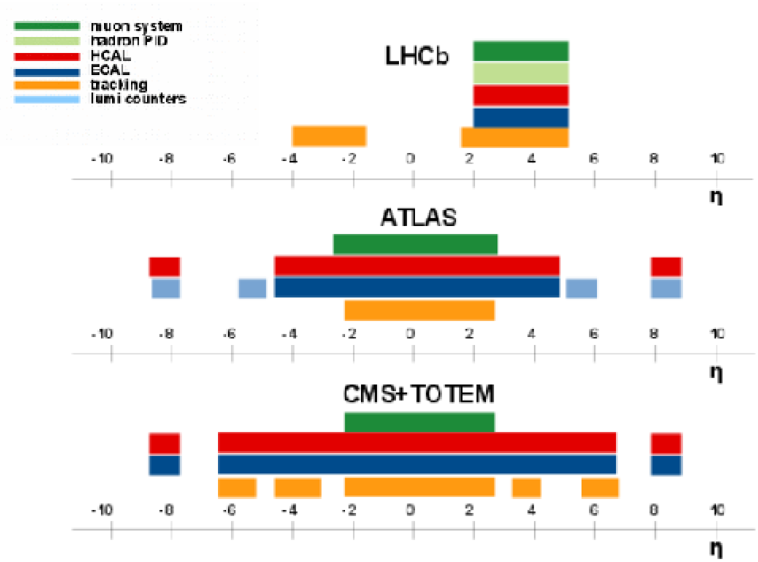
does not cover

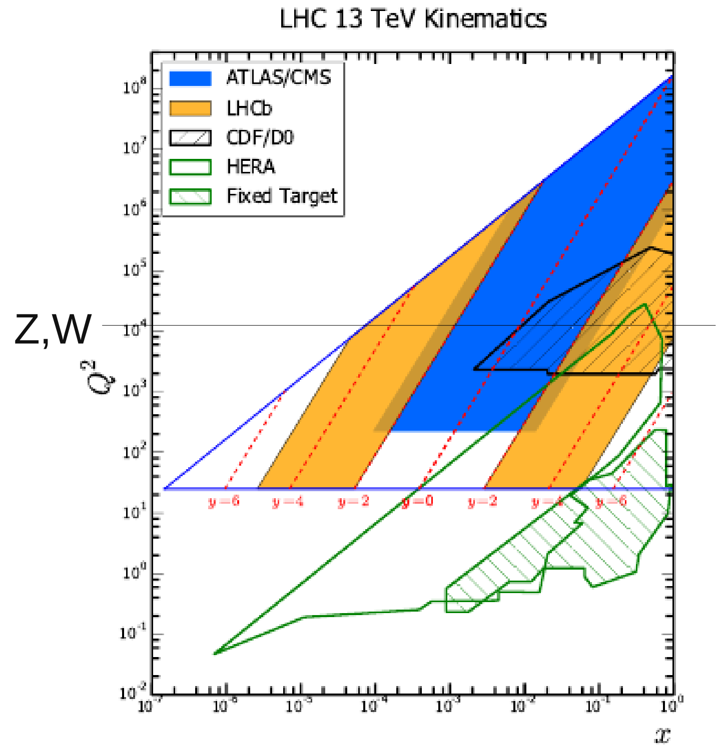
- multibosons
- heavy ion
- Higgs
- diffraction
- ...



ATLAS high mass central dijet event – M= 6.9 TeV
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions

Coverage of LHC detectors





- ATLAS and CMS:
  precision tracking and muon identification in central region
  forward calorimetry - measurements of electrons and jets for |η| < 5
- LHCb:
  coverage for η > 2 – excellent tracking and particle identification
  low p_T, low mass triggers
  → complementary measurements

precision QCD measurements

- standard candles
  background for New Physics and Higgs
  → important validation of ME+PS MC Generators
- sensitive to parton density functions (PDFs)
  → constrain PDFs
- precision tests of pQCD

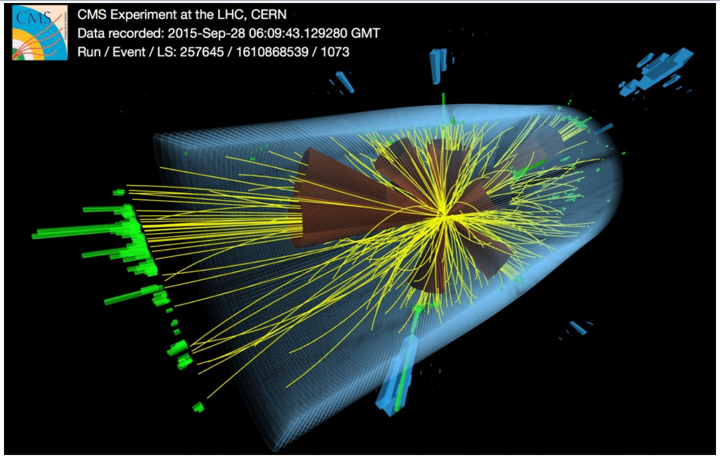
Jets
the experimental signatures of quarks and gluons

What can we do with jets?

jets result from fragmentation of quarks and gluons in a short-distance scattering process

are powerful probes of QCD:

- explore pQCD in brand new energy regions
- yield information on structure of the proton
- probe and measure α_s
- access to dynamics of heavy flavors
- compare to NLO/NNLO predictions
- tune Monte Carlo Generators



CMS multijet event: 12 jets with p_T> 50 GeV, and the mass of the system is 6.4 TeV
http://cms.web.cern.ch/news

there is more than QCD:

- extensive test of the Standard Model: V+Jets, H+Jets, V+heavy flavors…
- jets are background for most of the searches
- beyond the Standard Model:

  - dijet resonances
  - monojet & dark matter
  - new strongly produced states
  - hadronic resonances

Inclusive jets and dijets @ 13 TeV

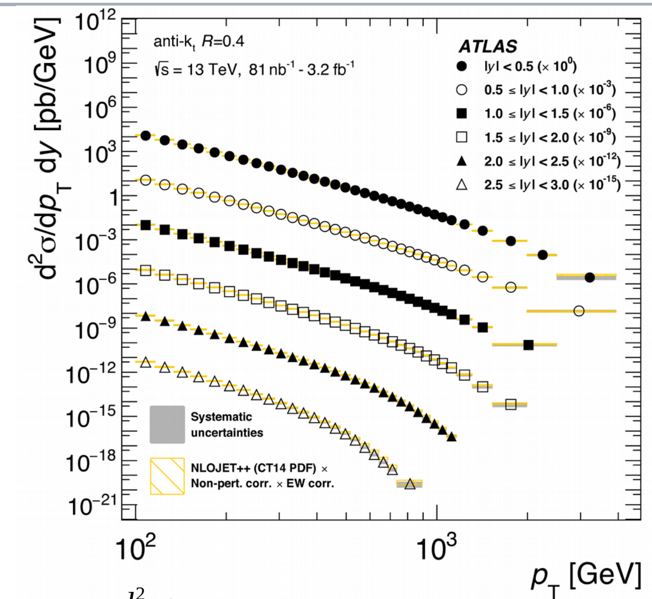
ATLAS JHEP 05 (2018) 195

p_T(jet)>75 GeV, anti-k_T R=0.4, modified Bayesian unfolding
double differential x-section: inclusive (p_T,y), di-jet (m_{jj},Δy)
dominant syst. uncertainty: jet energy scale

compared to: NLOJet++ using CT14, MMHT, NNPDF3.0

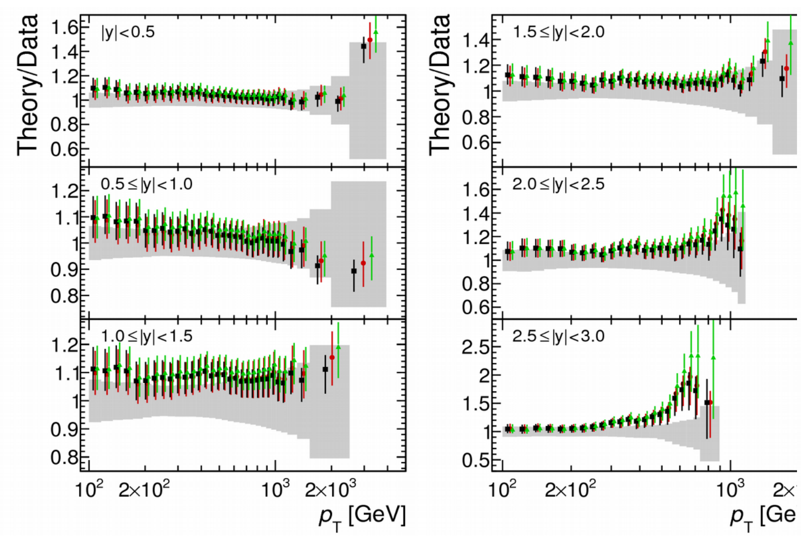
overall good agreement for di-jets
slight underestimation at high p_T and high y

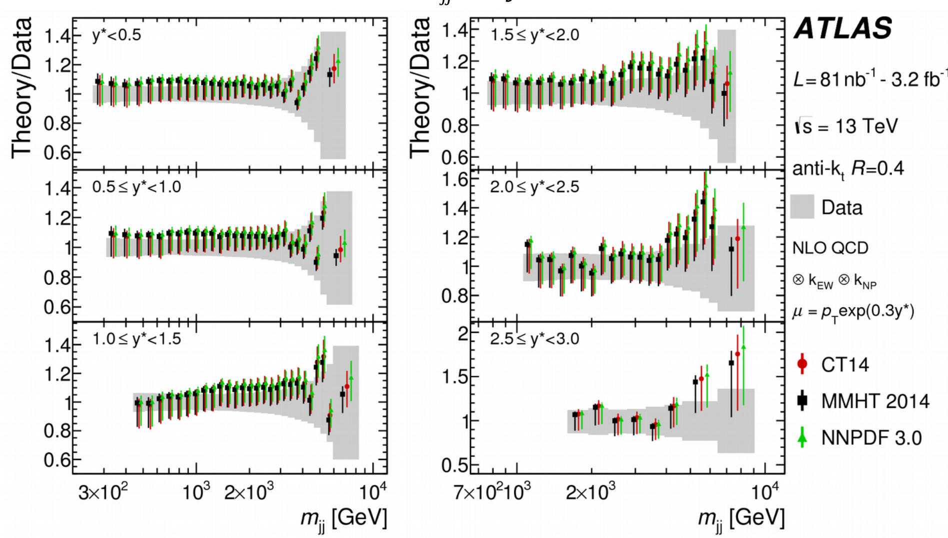
CMS: Eur. Phys. J. C 76 (2016) 451
measurement with R=0.4 and 0.7



inclusive jets (p_T,y) $\frac{d^2\sigma}{dp_T\,dy}$

di-jets (m_{jj},Δy) $\frac{d^2\sigma}{dm_{jj}\,d\Delta y}$





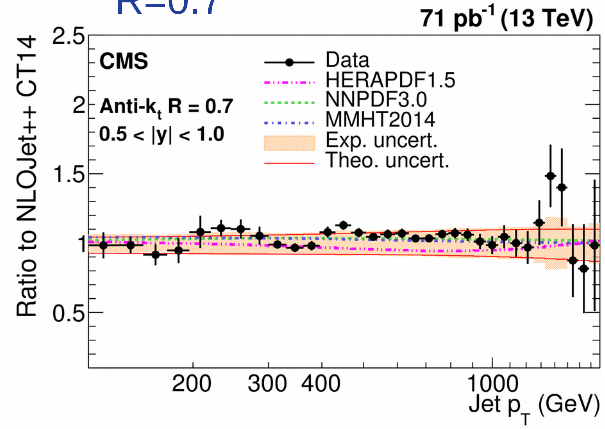
Inclusive jets @ 13 TeV

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

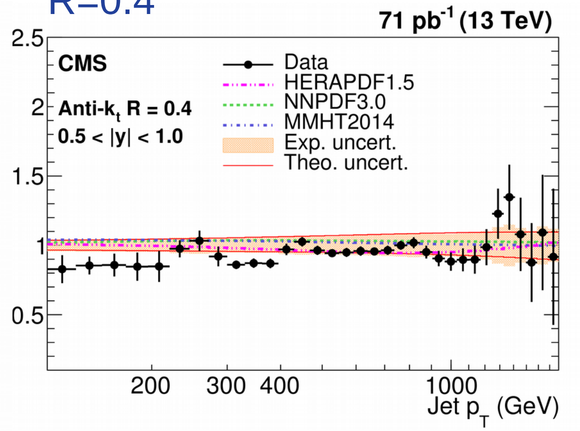
p_T(jet)>114 GeV, anti-k_T R=0.4 and R=0.7 $\frac{d^2\sigma}{dp_T\,dy}$

NLO predictions (NLOJet++)

R=0.7



R=0.4

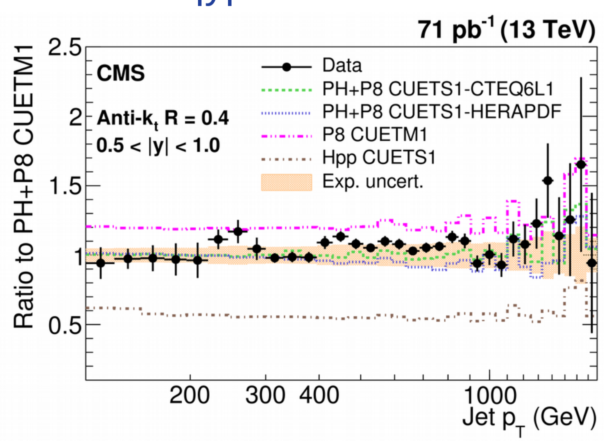


- R = 0.4 x-section overestimated by about 5–10%
- R=0.7: better description

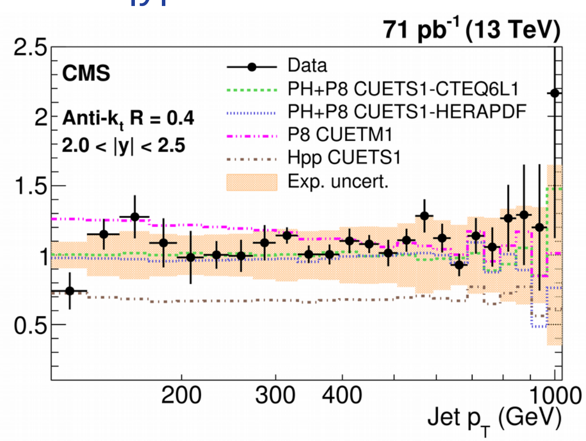
→ PS and soft-gluon resummation contributions, which are missing in fixed-order calculations are more relevant for smaller jet cone sizes

comparison to MC generators

0.5<|y|<1.0



2.0<|y|<2.5



POWHEG+Pythia

good agreement

HERWIG++:

good in shape, poor in scale

Pythia 8

does describe shape for y<2.0

CMS JHEP 10 (2017) 131
ATLAS Phys. (2016) Rev. 052003 D93

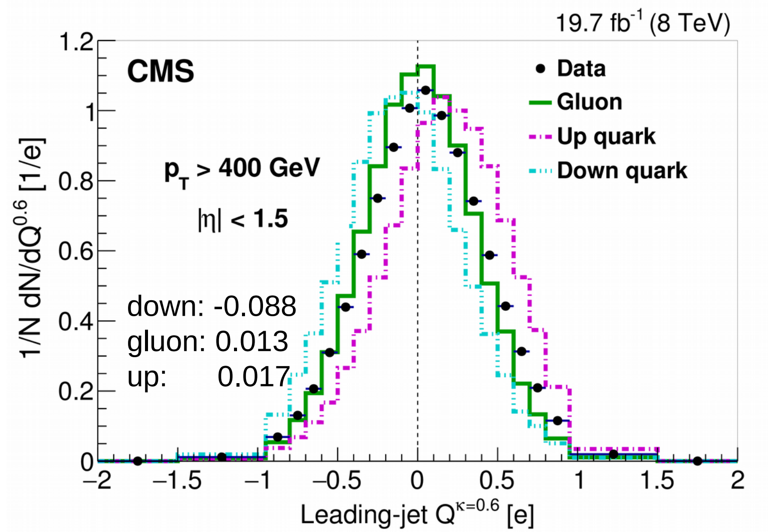
Q: estimator for charge of parton initiating the jet
→ momentum weighted sum of charges

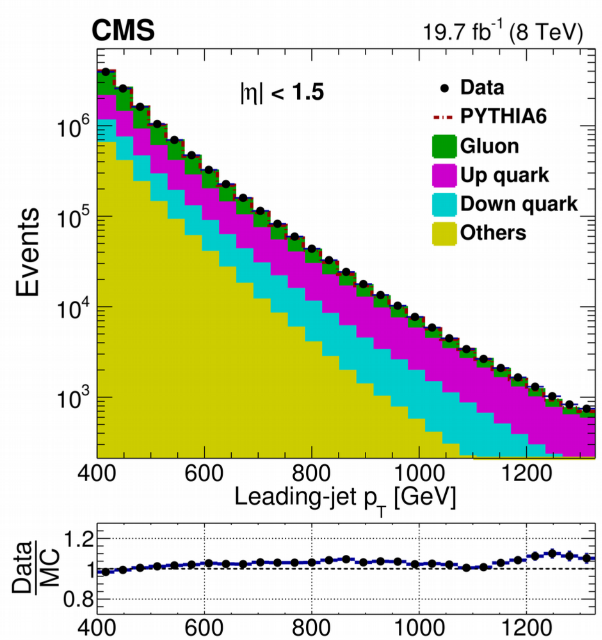
$$Q^{\kappa} = \frac{1}{p_T^{\kappa}(jet)} \sum_i Q^i (p_T^i)^{\kappa}$$

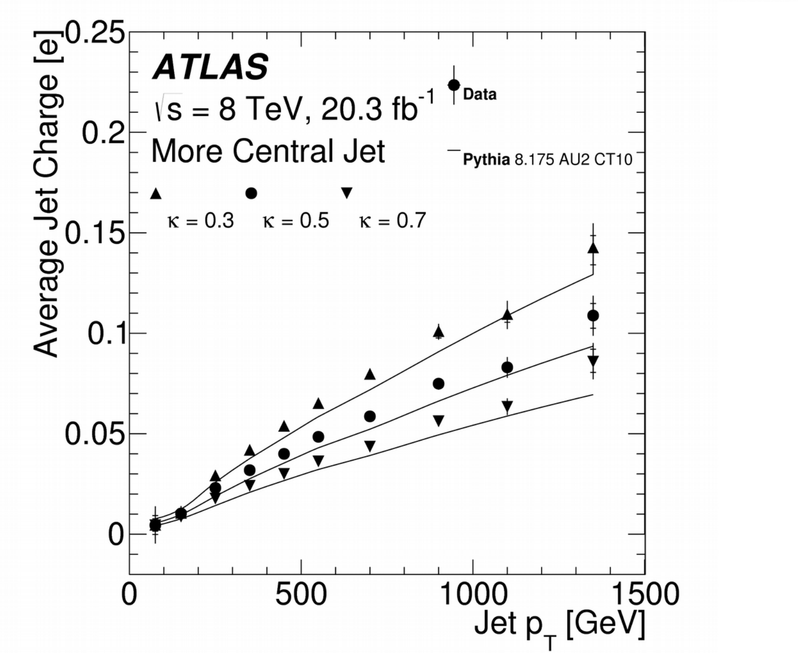
κ controls rel. weight of low and high p_T particles

gluon initiated jets dominant at low p_T,
quark initiated more at high p_T → Q increases with p_T

predictions tend to underestimate Q







Jet charge

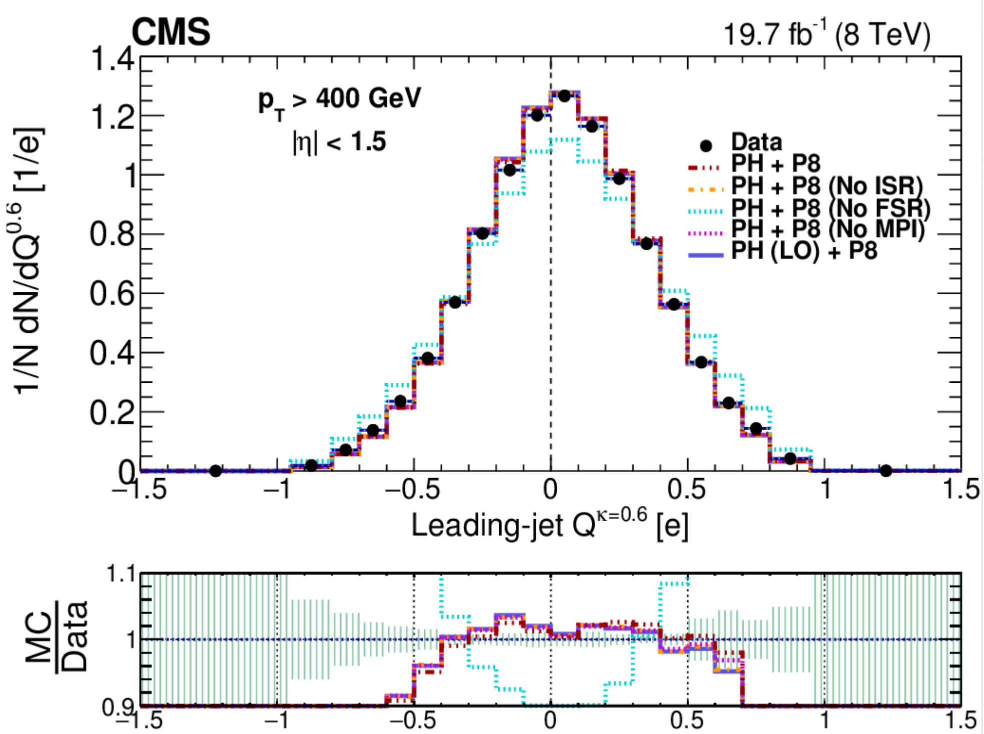
CMS JHEP 10 (2017) 131

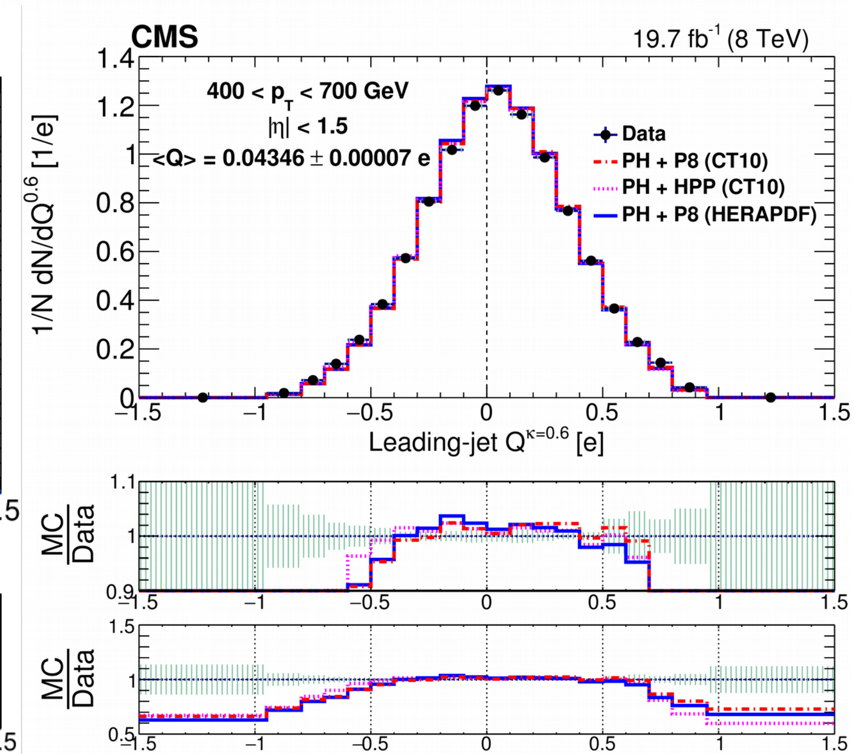
(similar: ATLAS Phys. (2016) Rev. 052003 D93)

unfolded jet charge, $p_T > 400$ GeV
compared to (N)LO predictions
Powheg+Pythia8, Powheg+Herwig++

$$Q^j = \frac{1}{p_T^\kappa(jet)} \sum_i Q^i (p_T^i)^\kappa$$

- Q unaffected by NLO effects, ISR or MPI
- FSR narrows the distribution
- data slightly broader than predictions





Strong coupling constant α_s

p_T(jet)>20GeV, |η|<4.7, anti-k_T – R=0.4

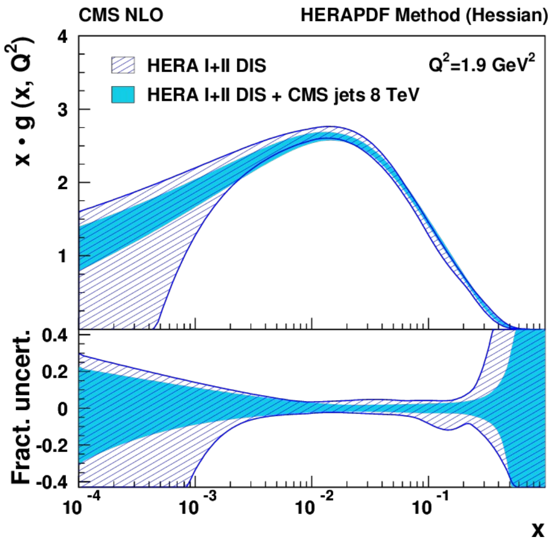
from double-diff x-section at 8 TeV

theoretical comparison: CT10 NLO x NP x EW PDF (NP: non perturbative)

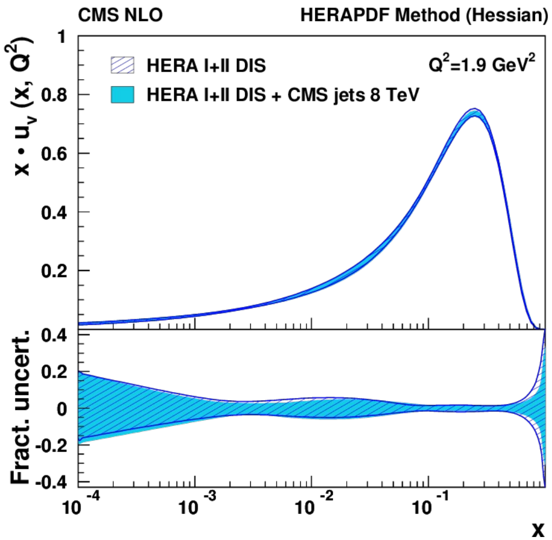
QCD fit → parton density functions and α_s

$$\alpha_s(M_Z)=0.1164^{+0.0014}_{-0.0015}(\mathrm{exp})^{+0.0025}_{-0.0029}(\mathrm{NP})^{+0.0053}_{-0.0028}(\mathrm{scale})=0.1164^{+0.0060}_{-0.0043}$$

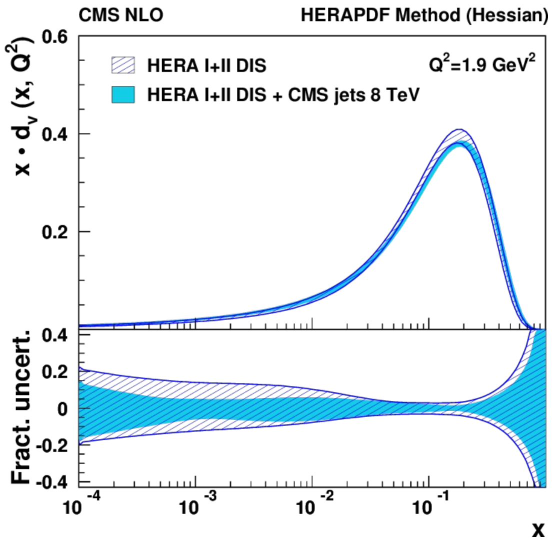
gluon



up



down



Di-jet azimuthal decorrelation and α_s @ 8 TeV

ATLAS arXiv:1805.04691

α_s from cross-sections: affected by knowledge of PDFs and their Q dependence
→ dependence on normalization group equations, used in PDF extraction

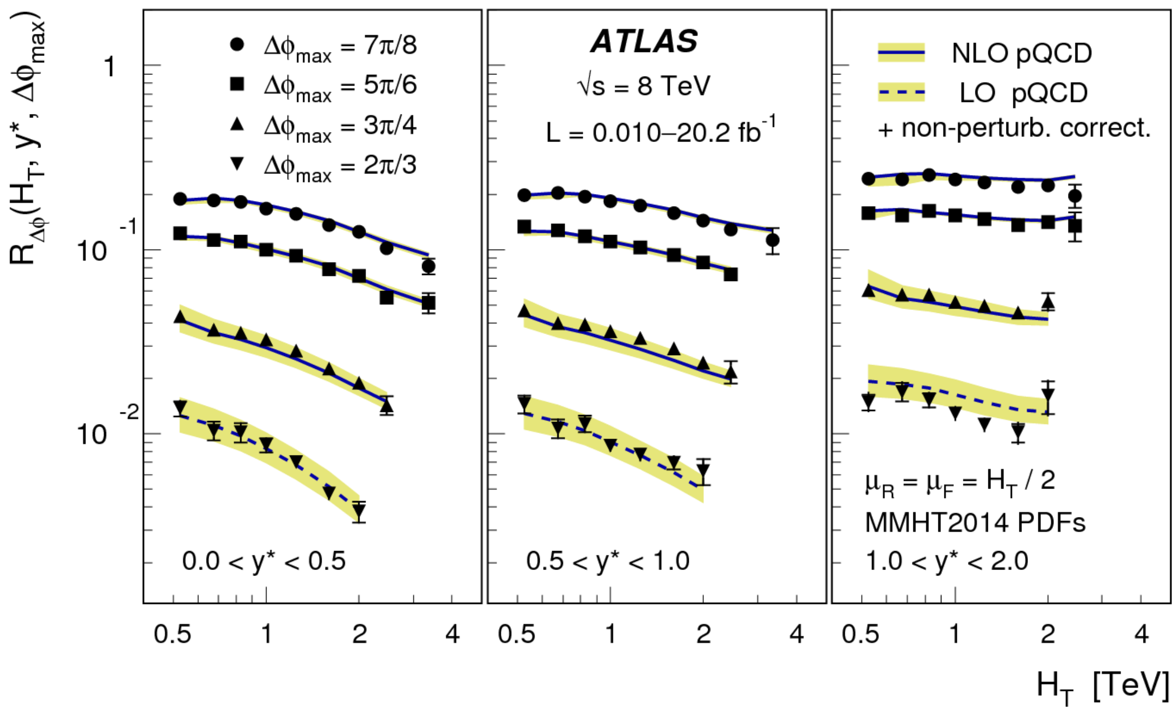
cross-section ratios: PDF uncertainty cancels to a large extend
→ theoretical cleaner extraction of α_s and its running

jet algorithm: anti-k_T R=0.6
large enough to include soft and hard radiation, but avoiding underlying event

measure R(ΔΦ): fraction of di-jet events in which $\Delta\Phi < \Delta\Phi_{max}$

$$R_{\Delta\phi}(H_T, y^*, \Delta\phi_{max}) = \frac{\dfrac{d^2\sigma_{dijet}(\Delta\phi_{dijet} < \Delta\phi_{max})}{dH_T\, dy^*}}{\dfrac{d^2\sigma_{dijet}(\text{inclusive})}{dH_T\, dy^*}}$$

H_T: transverse momentum sum, $y^*=|y_1-y_2|/2$



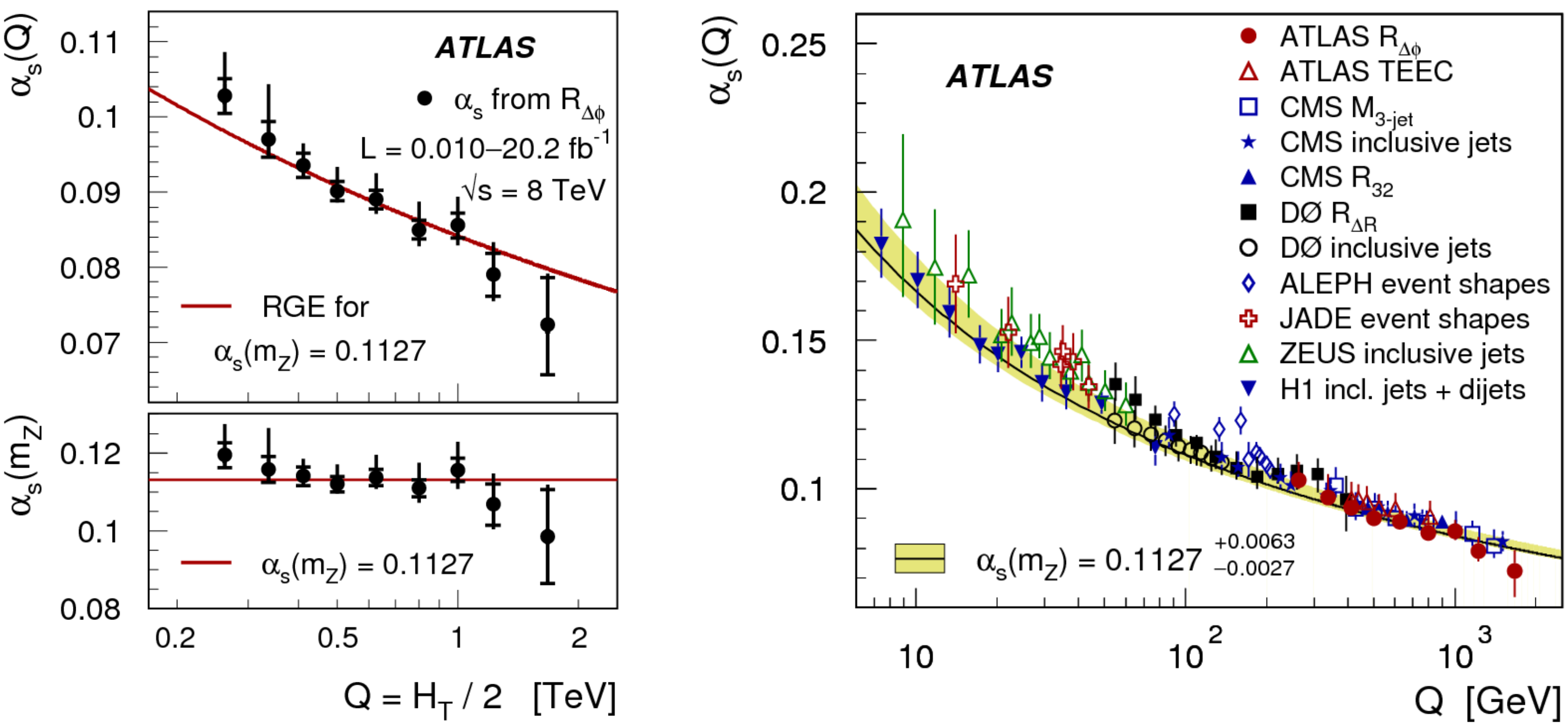
Di-jet azimuthal decorrelation @ 8 TeV

ATLAS arXiv:1805.04691

α_s extracted from measurement of R(Δφ) with $\Delta\varphi_{max}$ = 7π/8, 0 < y* < 0.5 and 0.5 < y* < 1.0.

$\alpha_S(m_Z)$	Total uncert.	Statistical	Experimental correlated	Non-perturb. corrections	MMHT2014 uncertainty	PDF set	$\mu_{R,F}$ variation
0.1127	$^{+6.3}_{-2.7}$	±0.5	$^{+1.8}_{-1.7}$	$^{+0.3}_{-0.1}$	$^{+0.6}_{-0.6}$	$^{+2.9}_{-0.0}$	$^{+5.2}_{-1.9}$

$$\alpha_s(M_Z) = 0.1127^{+0.0063}_{-0.0027}$$

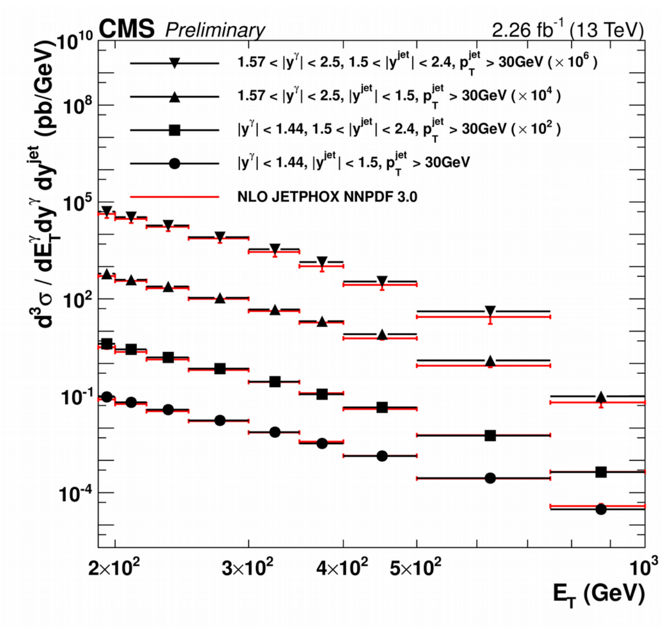


Isolated Photons

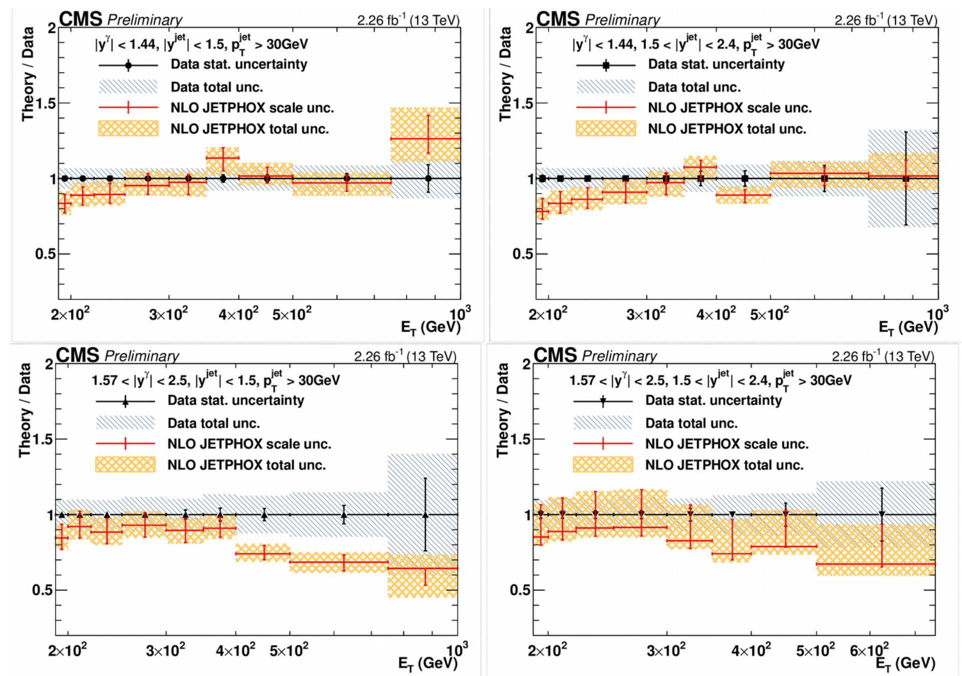
unique colorless probe to test pQCD predictions

- dominant production process: qg → qγ → constrain on gluon at medium x, x~0.1
- isolated photons: background for many searches → important to understand production and MC modeling
- CMS: $E_T(\gamma)$ > 190 GeV, |y(γ)|< 2.5, BDT for separation of signal and backgrounds
- agreement with NLO JETPHOX predictions within uncertainties
  but large uncertainties due to missing higher order terms in pQCD

inclusive measurement



photon plus jet (E_T>30 GeV)

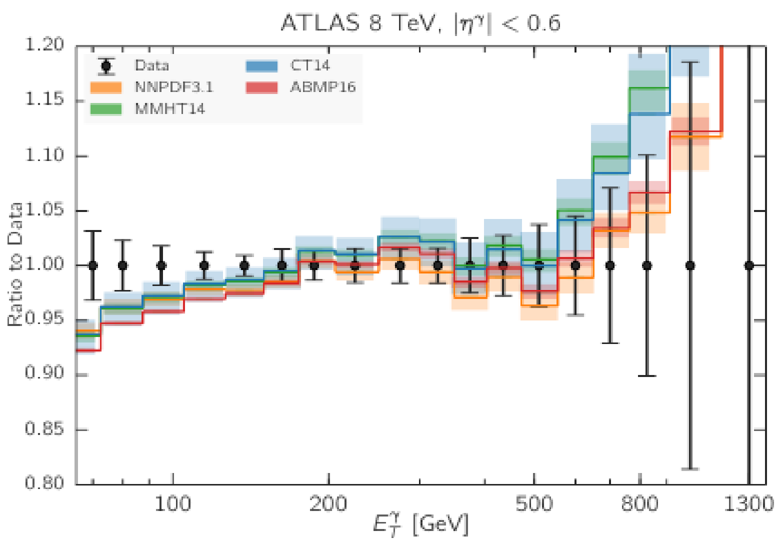


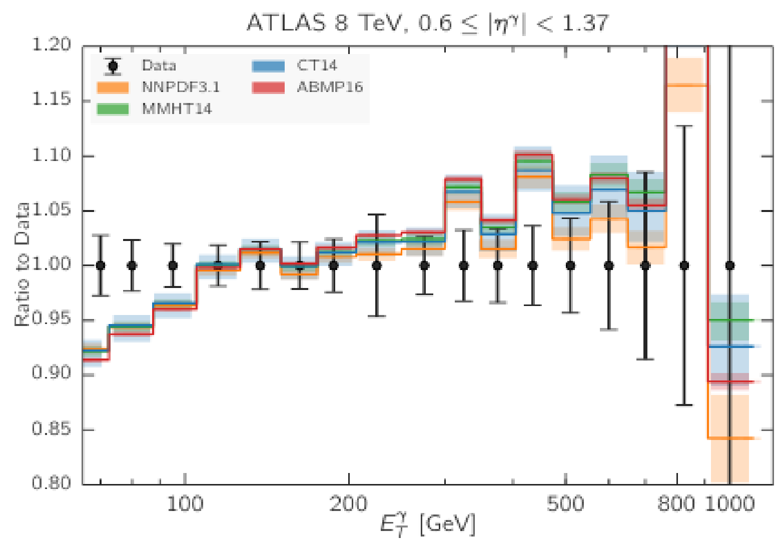
NNLO predictions

NNLO calculations now available

Campbell, Ellis and Williams, Phys. Rev. Lett. 118 (2017) 222001 [arXiv:1612.04333]

Campbell, Rojo, Slade and Williams,EPJC 786 (2018) 470 [arXiv: 1802.03021]





→ theory uncertainties reduced by a factor 2

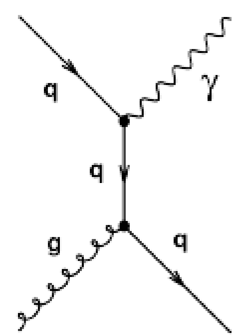
→ new opportunities for precision QCD and inclusion of photon data into PDF fits

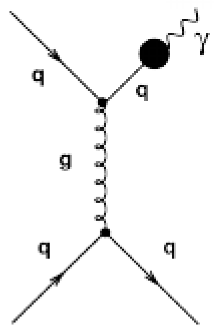
Isolated photons plus jets @ 13 TeV

ATLAS Phys. Lett. B 780 (2018) 578

two contributions to cross-section: direct and fragmentation

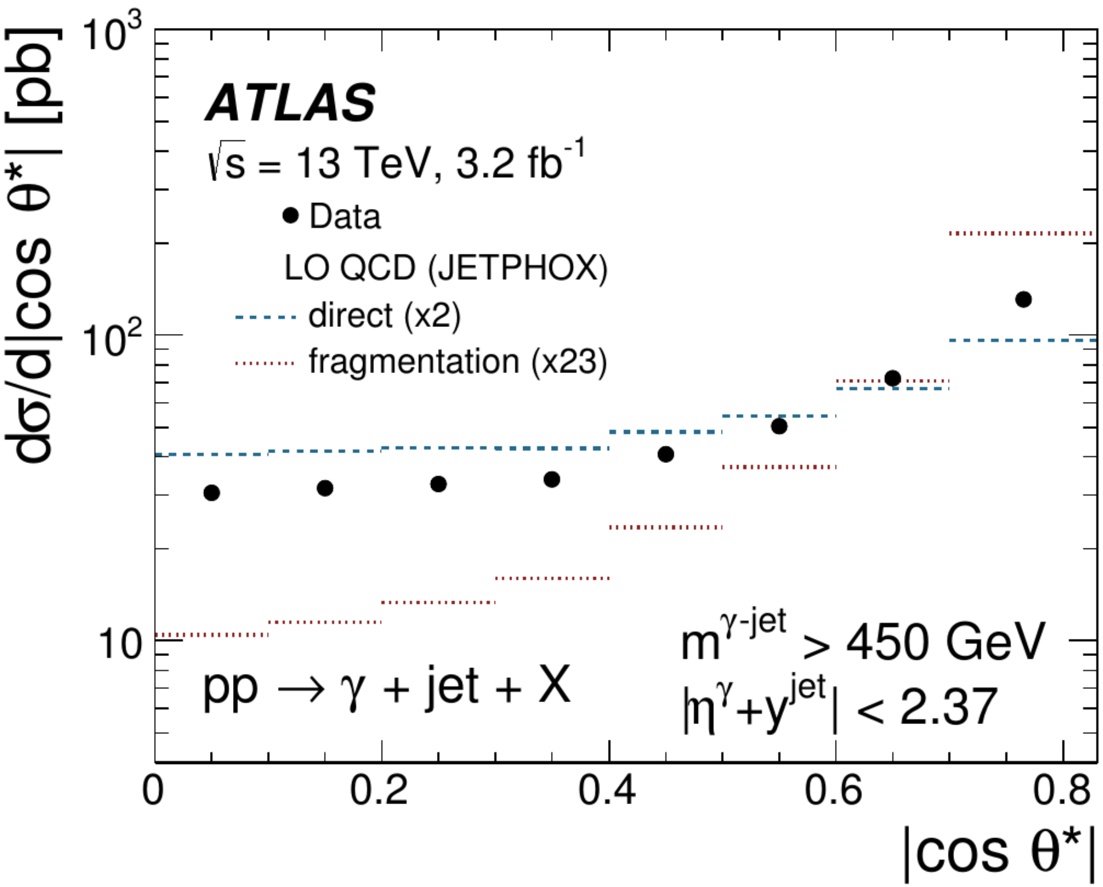
cross-section as function of θ* → insight into relative contributions of direct vs fragmentation components, and testing of dominance of t-channel quark exchange





direct: $(1-|\cos\theta^*|)^{-1}$

fragmentation: $(1-|\cos\theta^*|)^{-2}$



shape agrees better with direct contribution

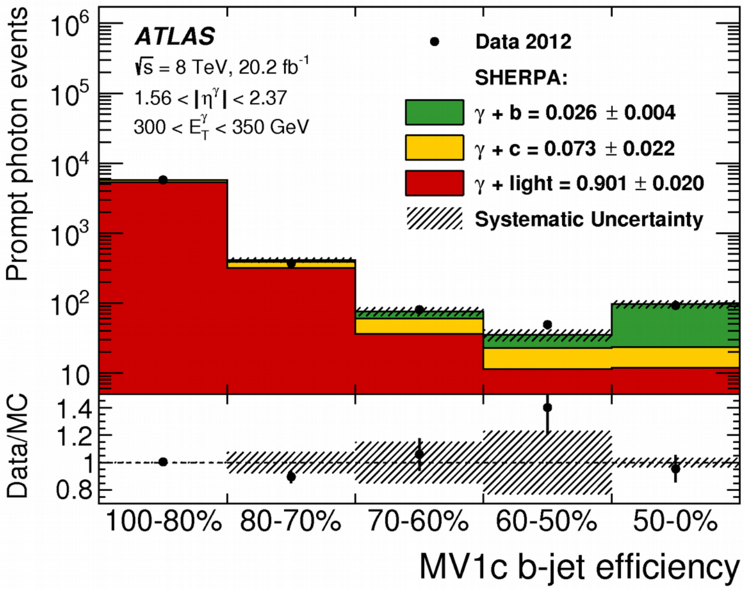
→ in agreement with expectation of process with quark exchange

Photon plus b/c @ 8 TeV

ATLAS Phys. Lett. B 776 (2018) 295

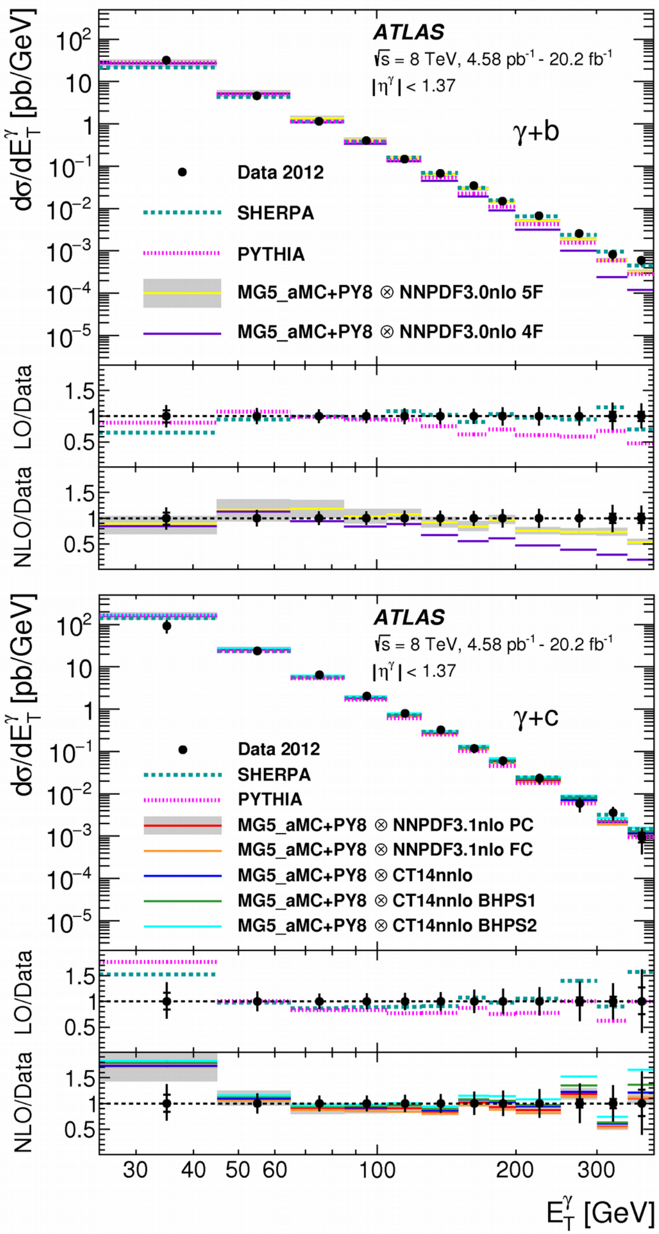
sensitive to heavy quark content of proton, test of HF modeling in MC generators

tagger discriminant distribution



HF yield extracted from a template fit to the distribution of the discriminant

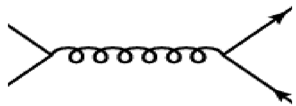
- LO and NLO give a good description
- 5F scheme better agreement than 4F at high E_T
- predictions with intrinsic charm (BHPS1/2) higher at high E_T

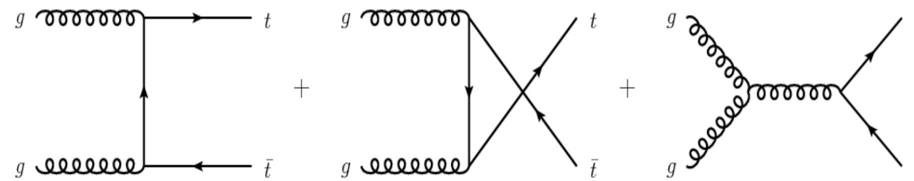


Top quarks
focussing on tt-bar production

Top production @ LHC

dominated by gluon fusion:
qq/gg = 10% / 90% at LHC

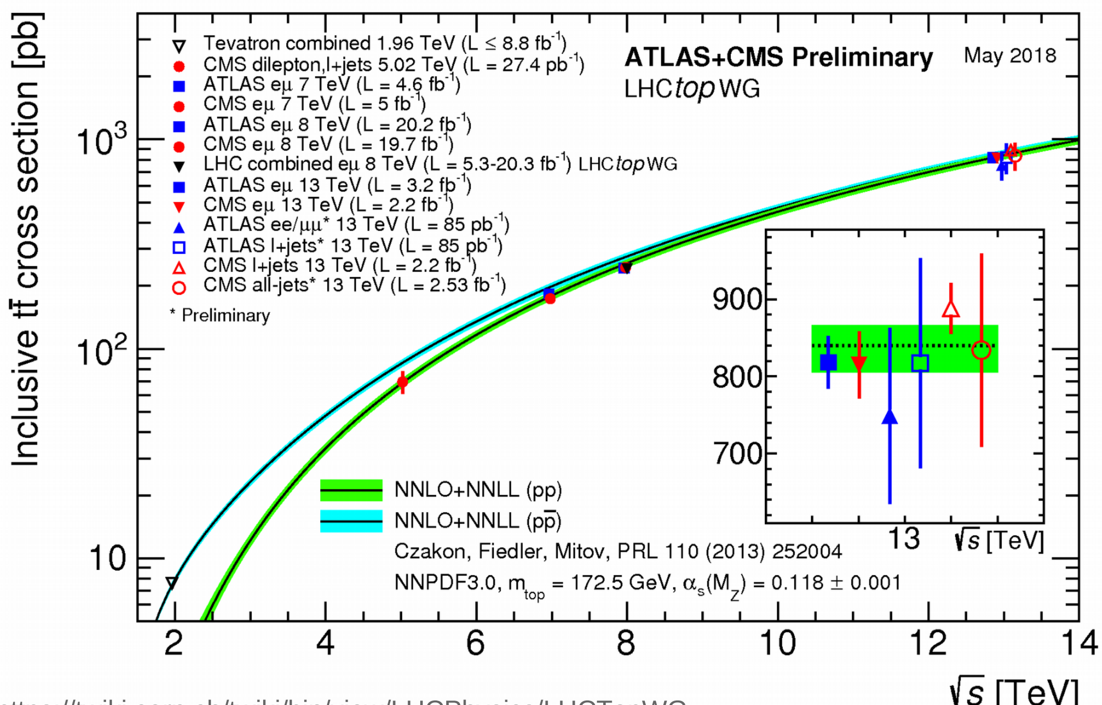




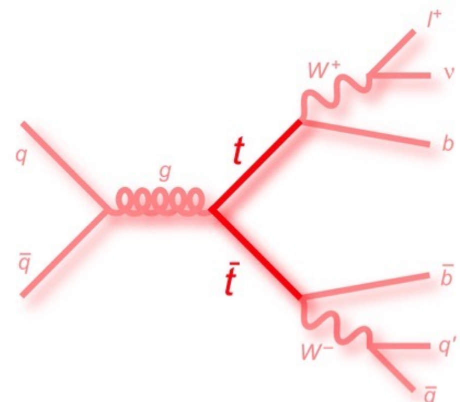
rich phenomenology → test of SM predictions, sensitivity to PDF, α_s, m_t

background for many searches (SUSY, ttH, ...)

but: calculations are challenging: NNLO/NNLL corrections important



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG



final states: di-lepton, fully hadronic (6 jets), lepton+jets

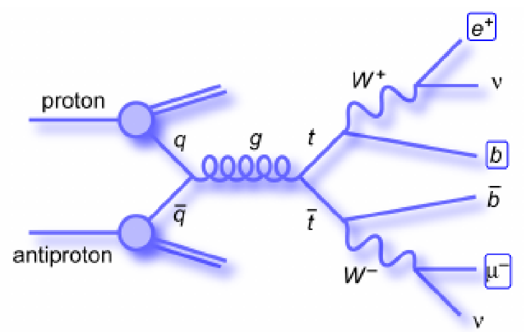
Forward top pair production @ 13 TeV

LHCb arXiv: 1803.05188

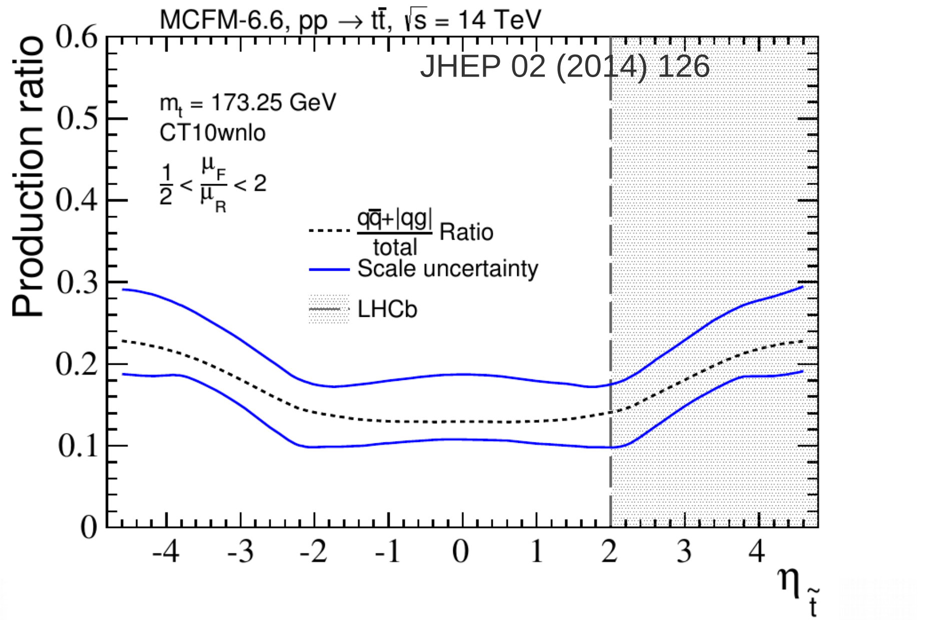
forward: enhanced qq-bar contribution
→ larger charge asymmetry
→ better sensitivity to New Physics

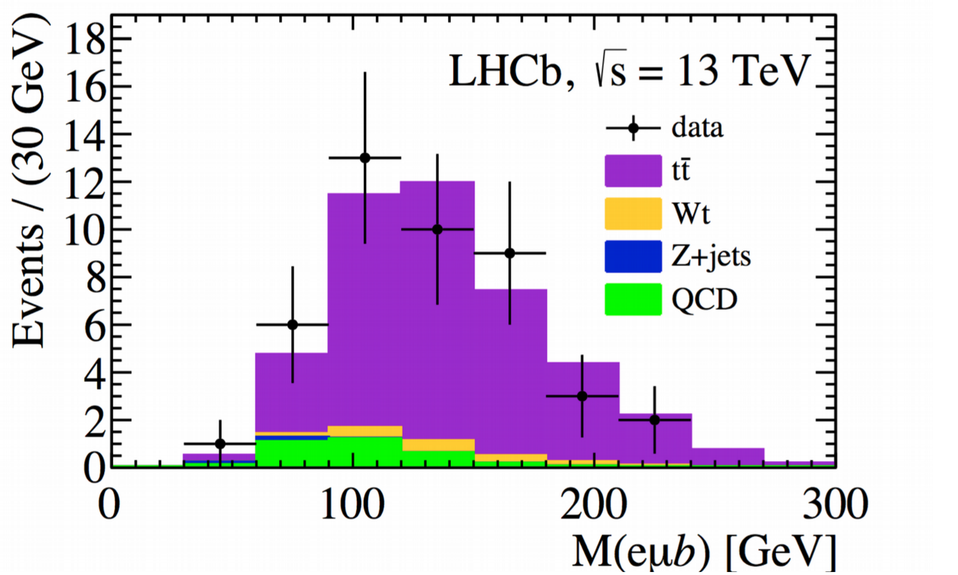
sensitive to PDF at large and low x
previously measured at 7+ 8 TeV
13 TeV 10 times higher x-section

μeb channel:
isolated prompt μ,e, one b-jet
b-tagging: secondary vertex in jet
p_T (l) > 20 GeV and p_T (jet) > 20 GeV
ΔR(l,J) > 0.5, ΔR(μ,e) > 0.1



→ 44 candidates, 86% purity
main background QCD multijets



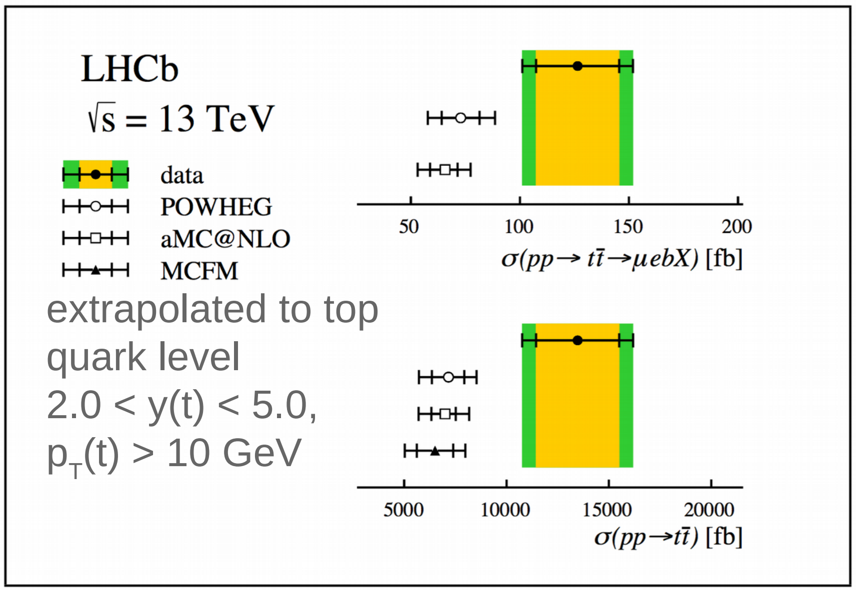


First observation of forward top @ 13 TeV

$$\sigma(t\,\bar{t}) = 126 \pm 19\,(\mathrm{stat}) \pm 15\,(\mathrm{syst}) \pm 5\,(\mathrm{lumi})\,\mathrm{fb}$$

20% precision, compatible with the SM within 2σ

dominating systematic uncertainty: jet tagging: 10%



extrapolated to top quark level
2.0 < y(t) < 5.0,
$p_T(t)$ > 10 GeV

syst. uncertainties

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

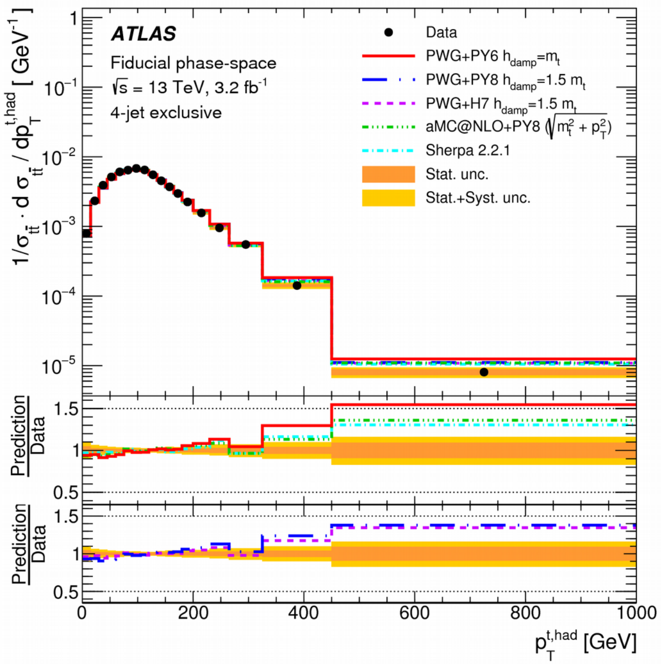
LHCb upgrade: measurement not statistically dominated
→ very promising channel for tt-bar studies

Differential tt-bar +jets @ 13 TeV

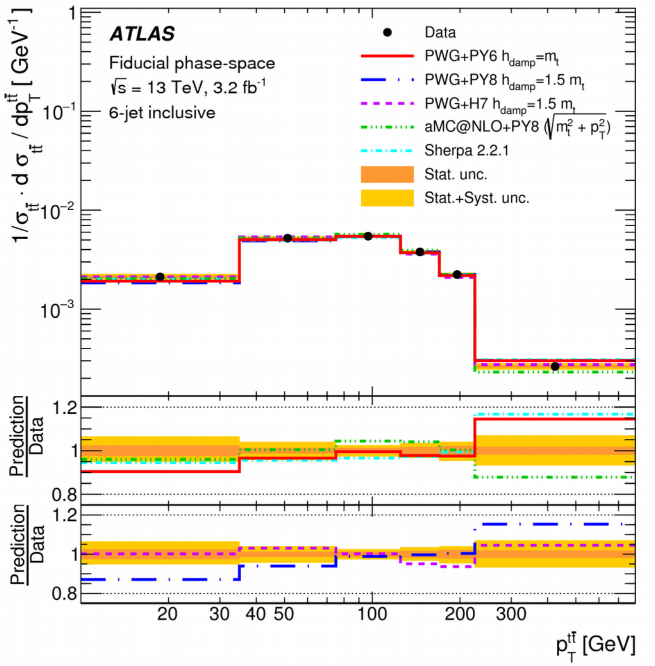
top reconstructed in lepton plus jets channel

sensitive to gluon radiation
study 4,5 and 6 jets samples separately

p_T(t,had) with 4 jets



p_T(tt-bar) with 6 jets



measurements have potential to further constrain the models:
p_T(t,had) with 4 jets underestimated at high p_T(t,had)
p_T(tt-bar) disfavours some models

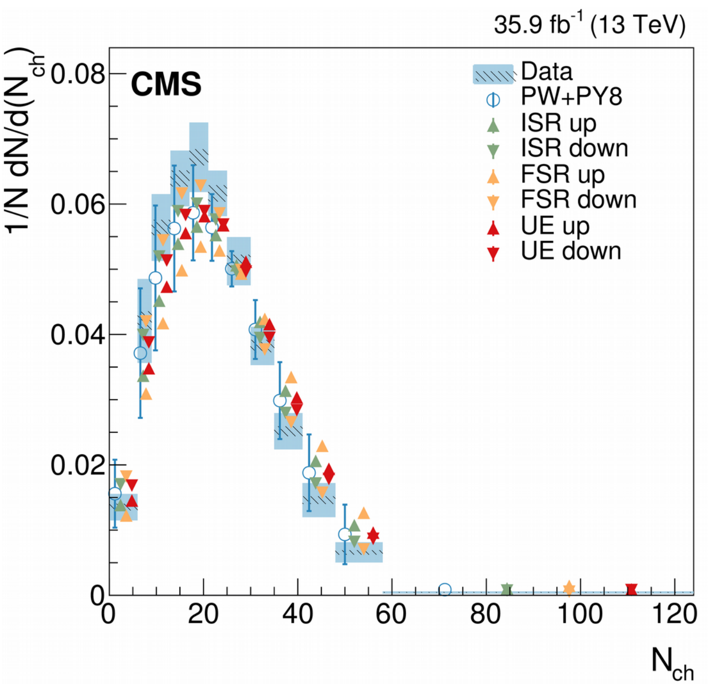
Underlying event in tt-bar @ 13 TeV

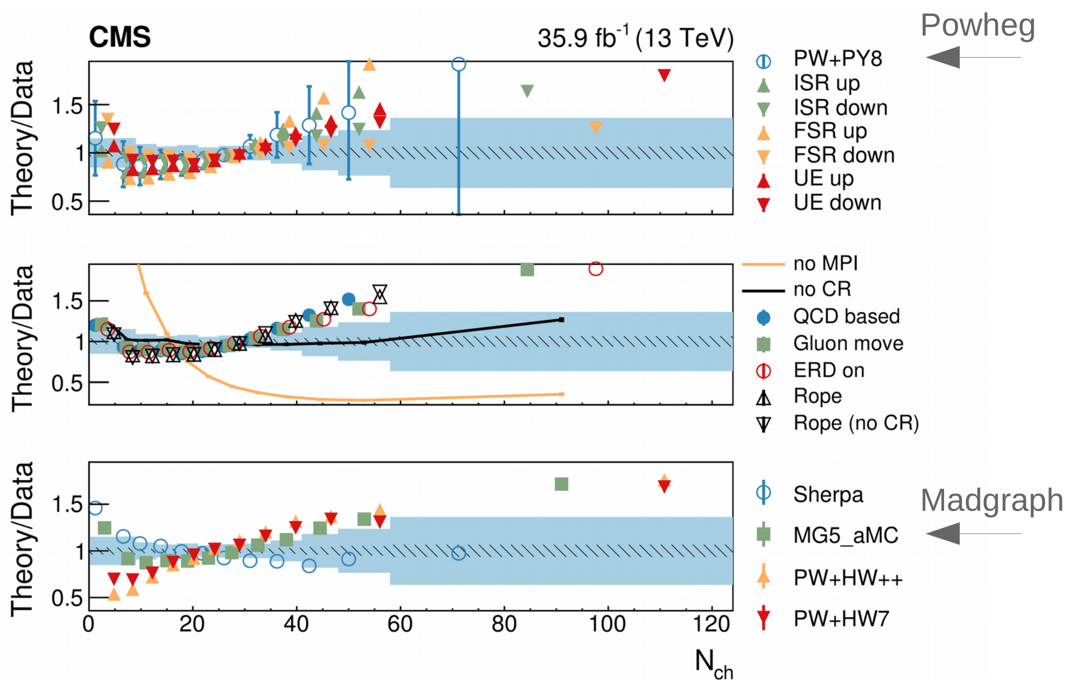
underlying event (UE): partons not participating in hard scattering process, multiple parton interactions, gluon radiation

electron, muon + 2b-jets → first measurement of UE properties at Q up to $2m_t$

various variables investigated (N_{ch}, p_T, sphericity, …), various event categories

- UE event: typically 20 charged particles, average p_T and p_z about 2 GeV
- Powheg+Pythia gives a good description
- models with MPI switched off and default Sherpa (o), Herwig (▲,▼) configuration disfavoured
- no dependence on ME (Powheg or Madgraph5aMC@NLO)





Vector bosons
standard candles of the Standard Model

Forward Z→bb-bar @ 8 TeV

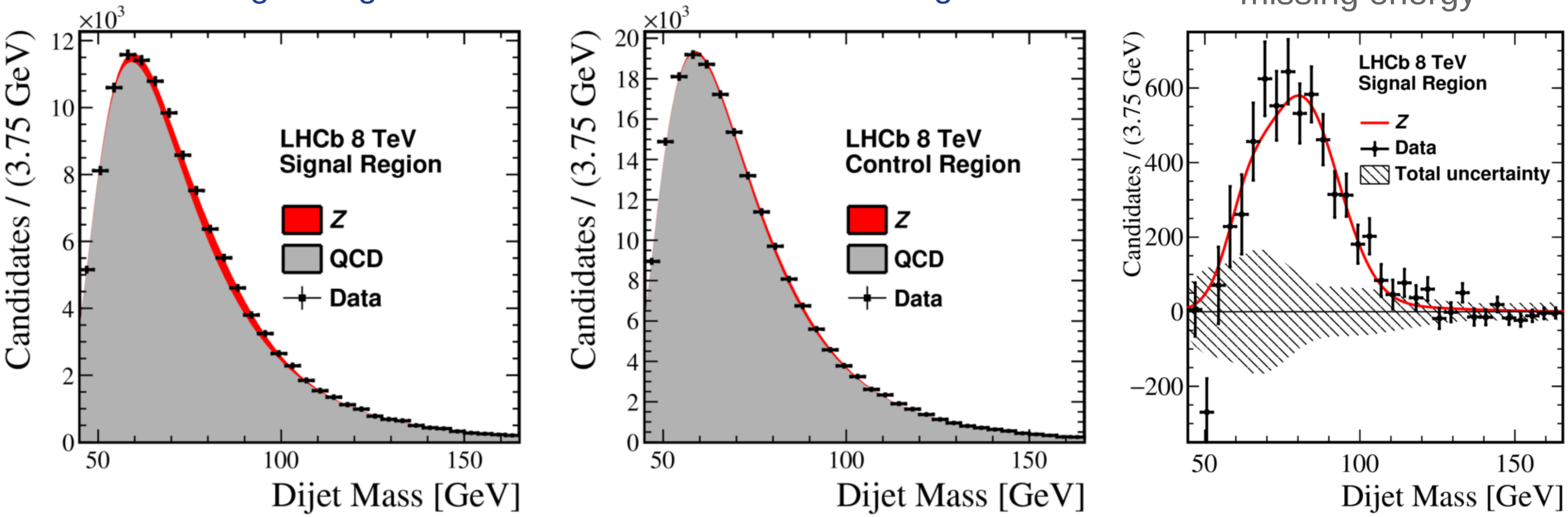
LHCb: Phys. Lett. B776 (2017) 430-439

- standard candle of the SM: background for many new physics processes, Hbb
- first measurement in forward region ever made!
- challenging measurement, huge QCD background → MVA for separation
- 2 b-tagged jets, p_T>20 GeV and 45 < m_{JJ}< 165 GeV ; Δφ(bb)<2.5
- simultaneous fit to dijet mass in signal and control regions

no correction for radiation outside the jet cone and missing energy

signal region

control region



$$\sigma(pp \to Z)\mathrm{B}(Z \to b\bar{b}) = 332 \pm 46(\mathrm{stat}) \pm 50(\mathrm{syst})\,\mathrm{pb}$$

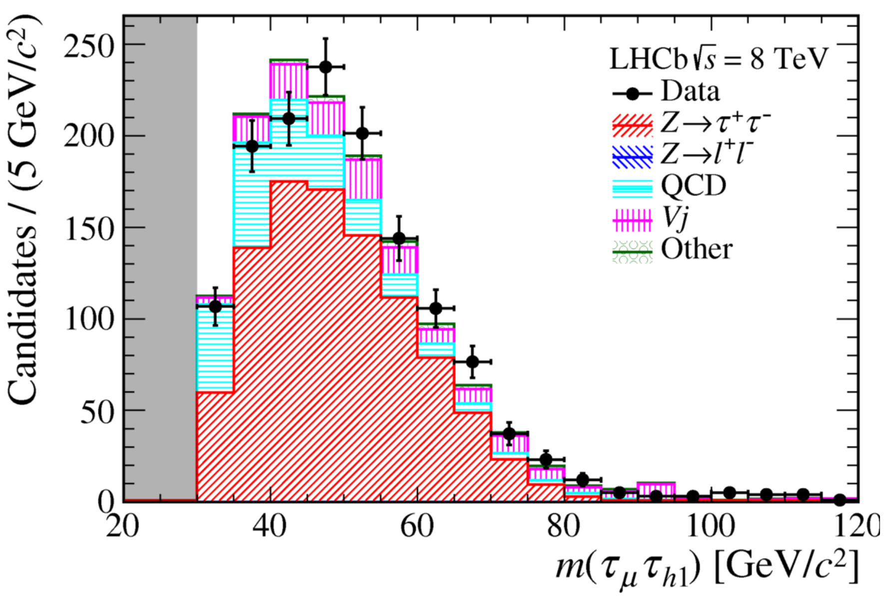
$$\sigma(pp \to Z)\mathrm{B}(Z \to b\bar{b}) = 272^{+9}_{-12}(\mathrm{scale}) \pm 5(\mathrm{PDF})\,\mathrm{pb}\,(\mathrm{aMC@NLO})$$

Forward $Z \to \tau^+\tau^-$ @ 8 TeV

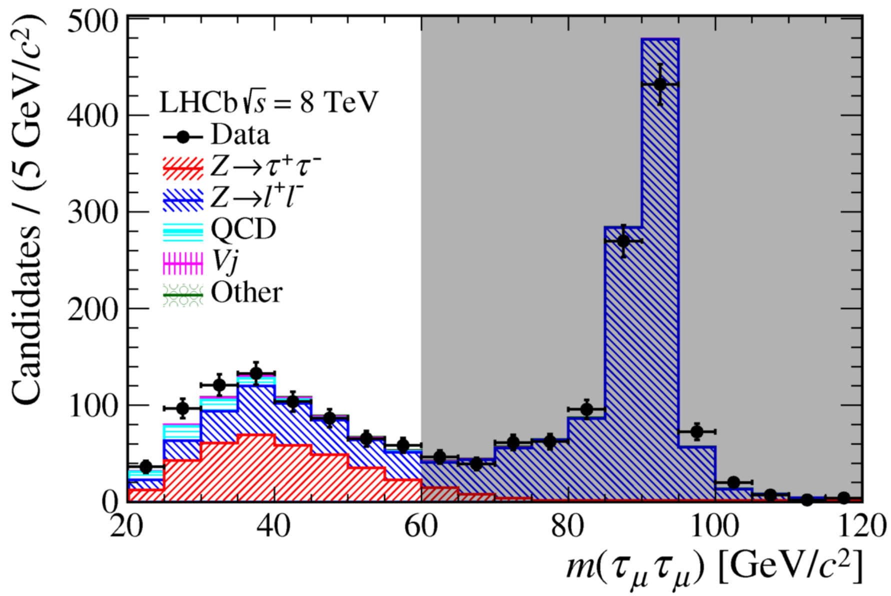
LHCb: arXiv:1806.05008

- probe of high energy tau reconstruction at LHCb
- reconstruction in leptonic (electron, muon) or hadronic (one or three) final state
  7 streams: ee, μμ, eμ, μh_1, μh_3, eh_1, eh_3
- main backgrounds: data driven techniques
- signal yield: data – expected background

μh_1 channel



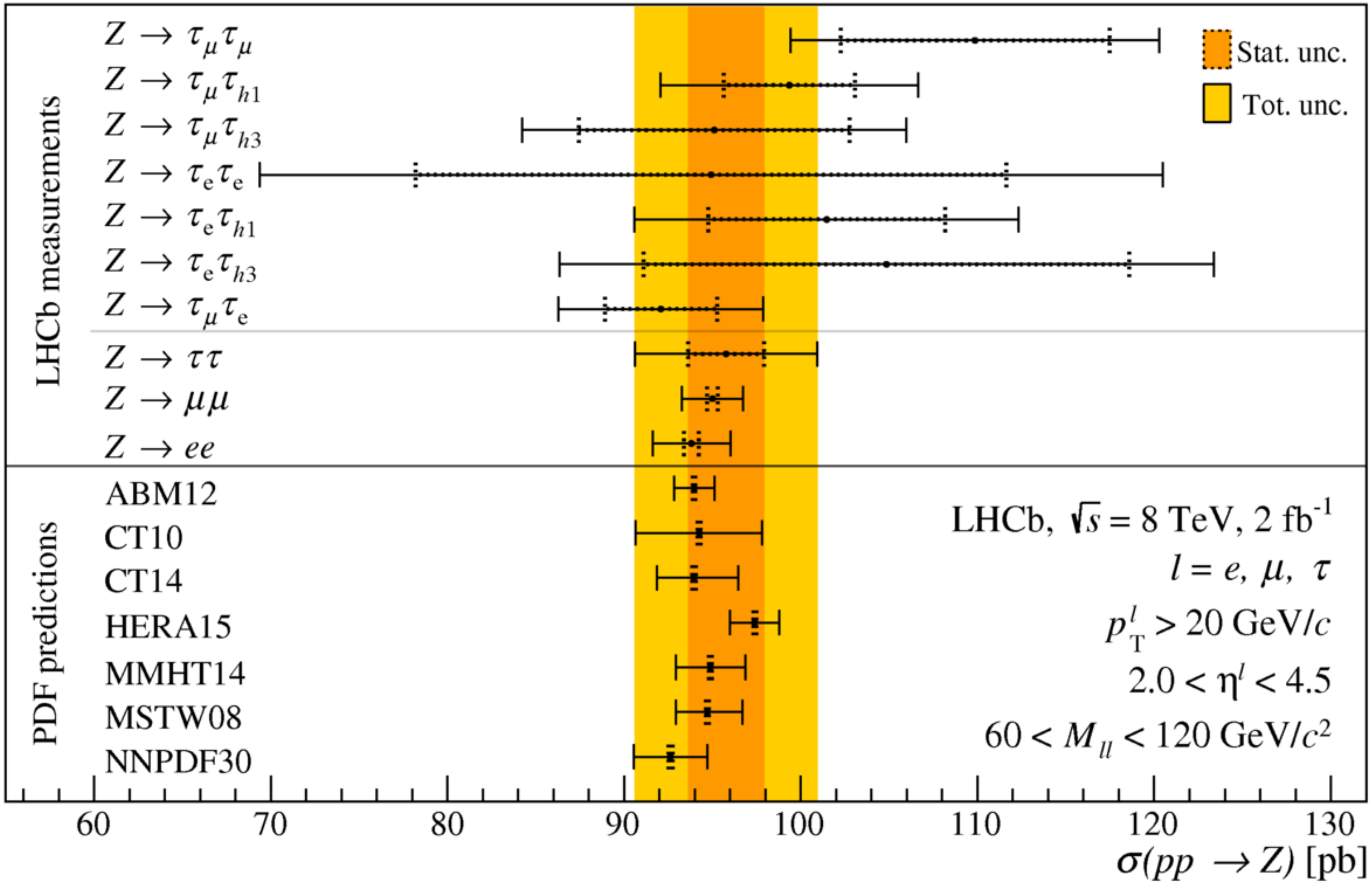
μμ channel



$Z \to \tau^+\tau^-$ @ 8 TeV

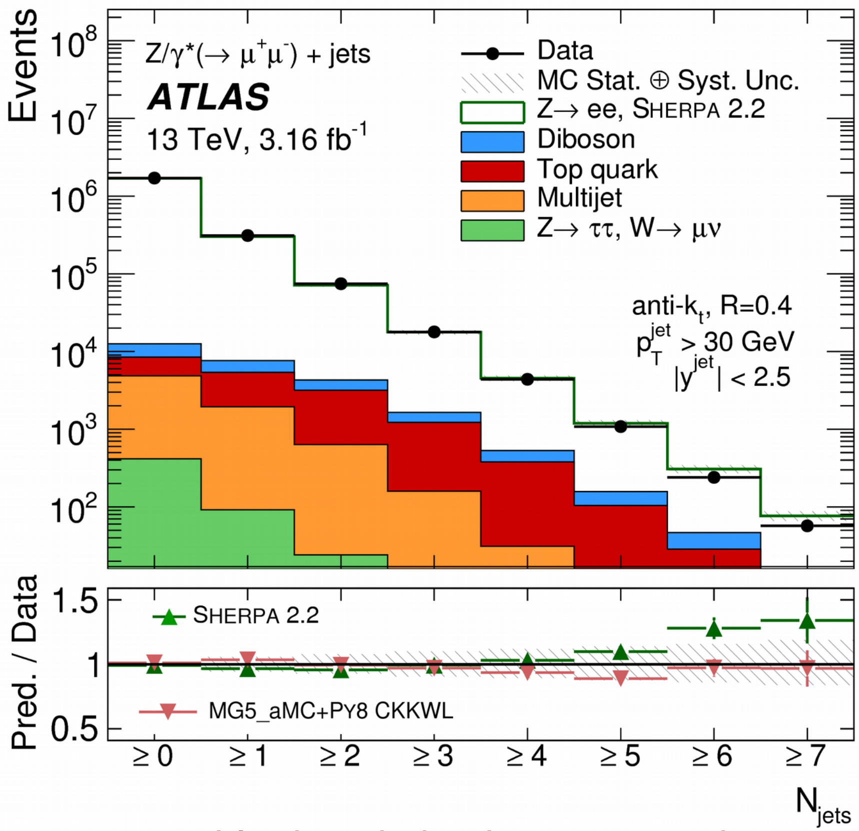
fiducial region: 2.0<η(τ)<4.5, pT(τ)>20 GeV, 60<M(ττ)<120 GeV

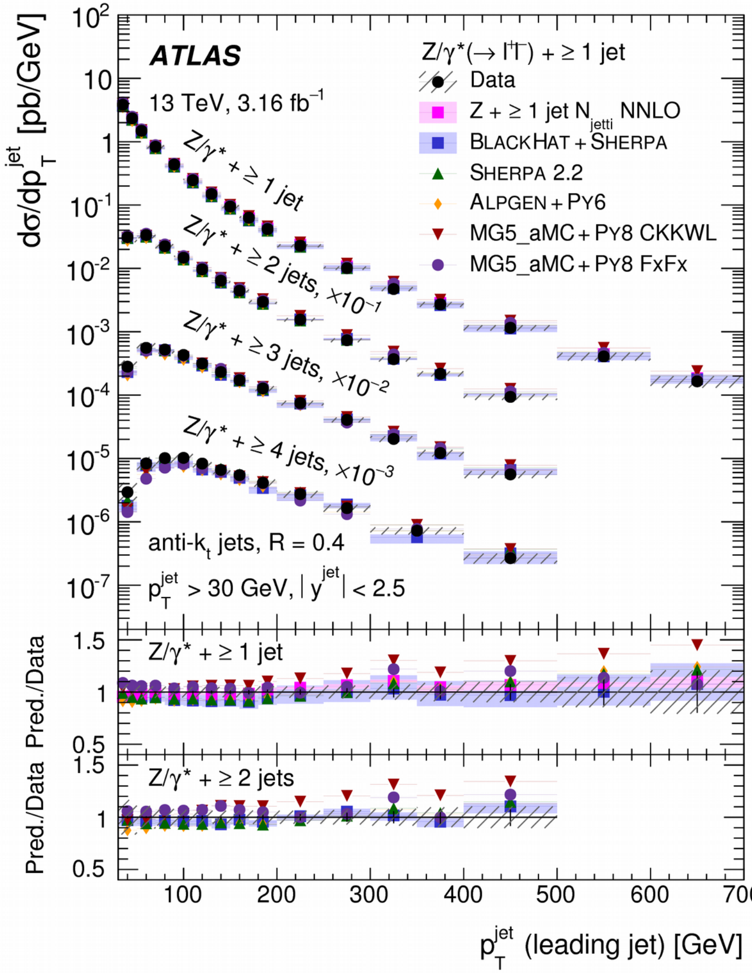
measurements agree with each other, compatible with NNLO predictions



Z+jets @ 13 TeV

high cm energy allows production of a large number of jets, background for tt-bar, Higgs, ...
main background at large jet multiplicities: tt-bar and diboson





reasonable description by NNLO and NLO predictions

MC generators: LO (MG5_aMC+PY8 CKKWL) predicts too hard p_T distribution

Z+jets @ 13 TeV

measurement of the transverse momentum balance between Z and the jets, sensitive to soft gluon radiation

multiparton predictions:

- NLO: good
- LO: softer distribution

→ NLO corrections important

- Geneva: NNLO Z prod. +NNLL resummation

fails to describe distribution

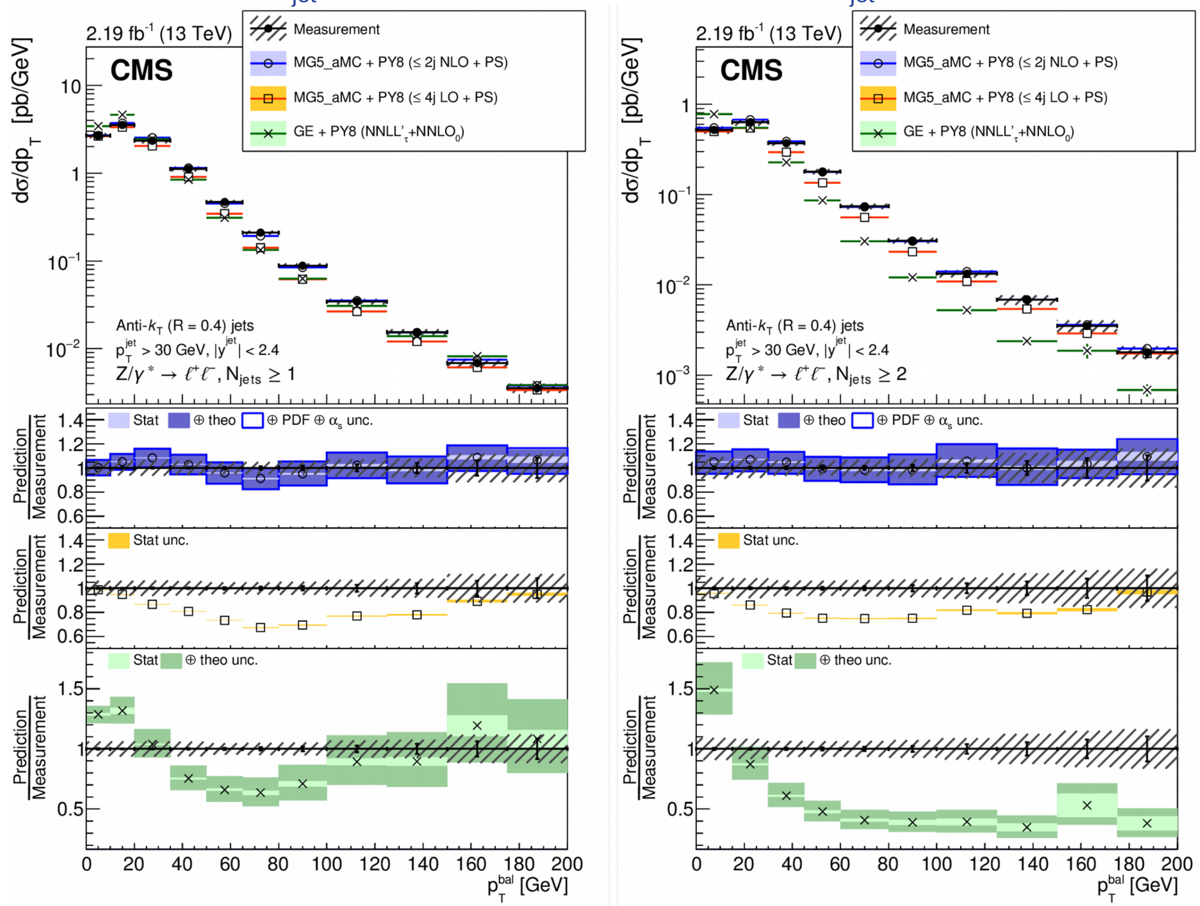
for N_{jet}>1

$N_{jet}>0$ $N_{jet}>1$

NLO

LO

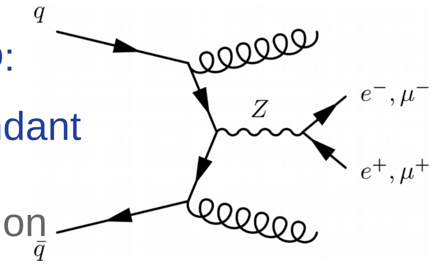
Geneva



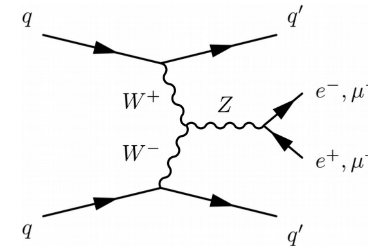
Z+di-jets @ 13 TeV

ATLAS: Phys. Lett. B 775 (2017) 206

production mechanism: QCD: abundant



electroweak: rare



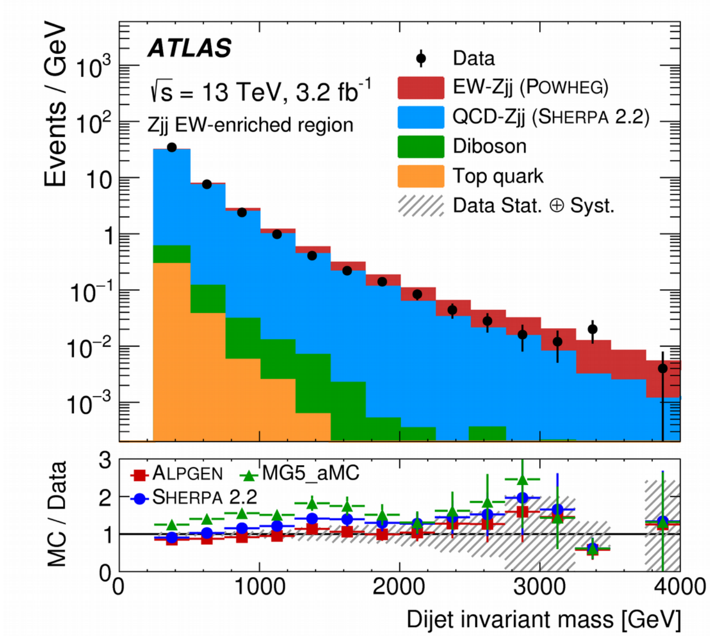
EW:

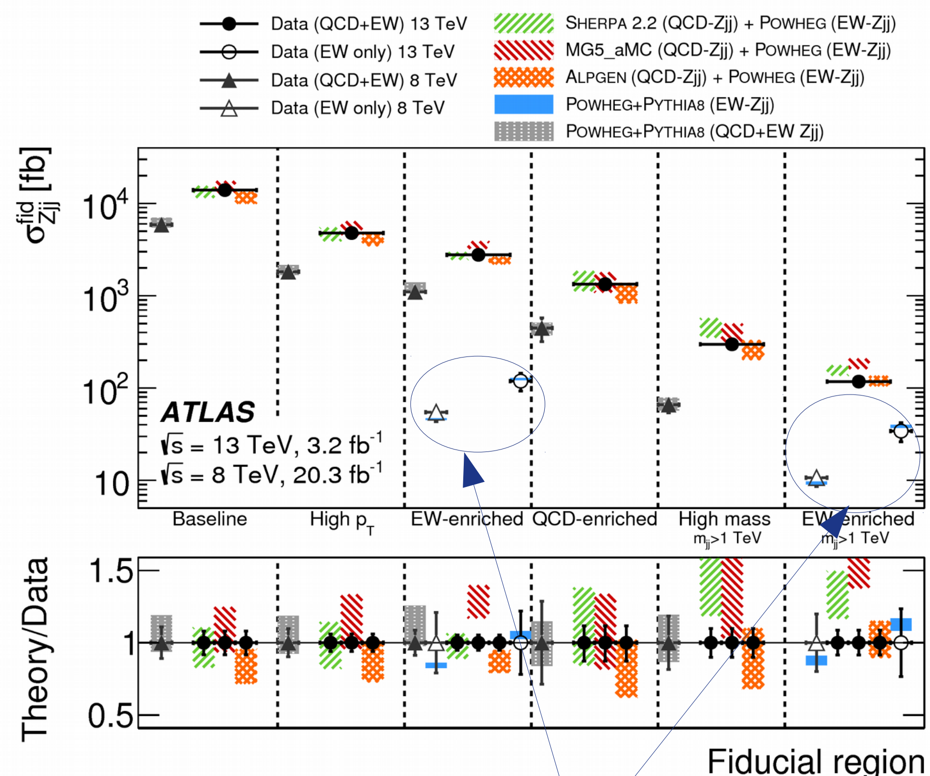
jets: large E, large η-separation

large di-jet mass

no colour connection between protons

→ less hadronic activity (veto on jets)





EW Zjj x-section

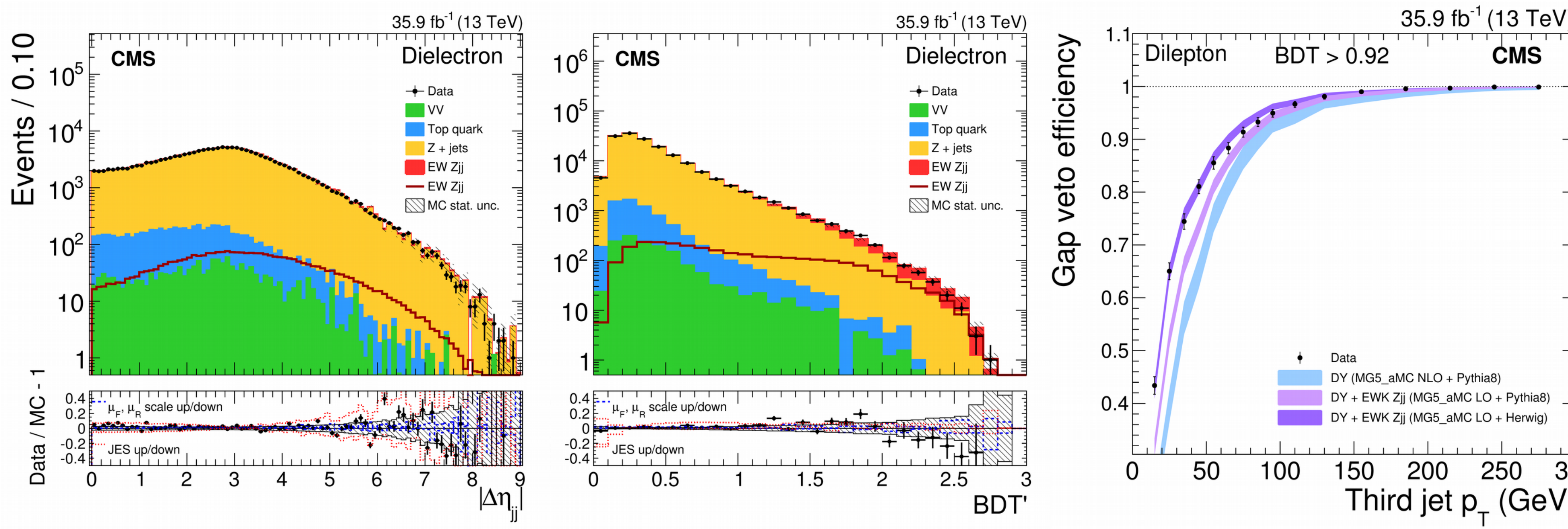
EW Zjj x-section extracted in EW enriched sample

high di-jet mass (M>1 TeV): Sherpa+PH, MG+PH overestimate x-section

Z+di-jets @ 13 TeV

CMS: arXiv:1712.09814 (accepted by EPJC)

EW contribution from fit to BDT with 6 discriminating variables (event and jet properties)



signal established → study event activity in EW enhanced region (BDT>0.92)

→ Data disfavours background only prediction

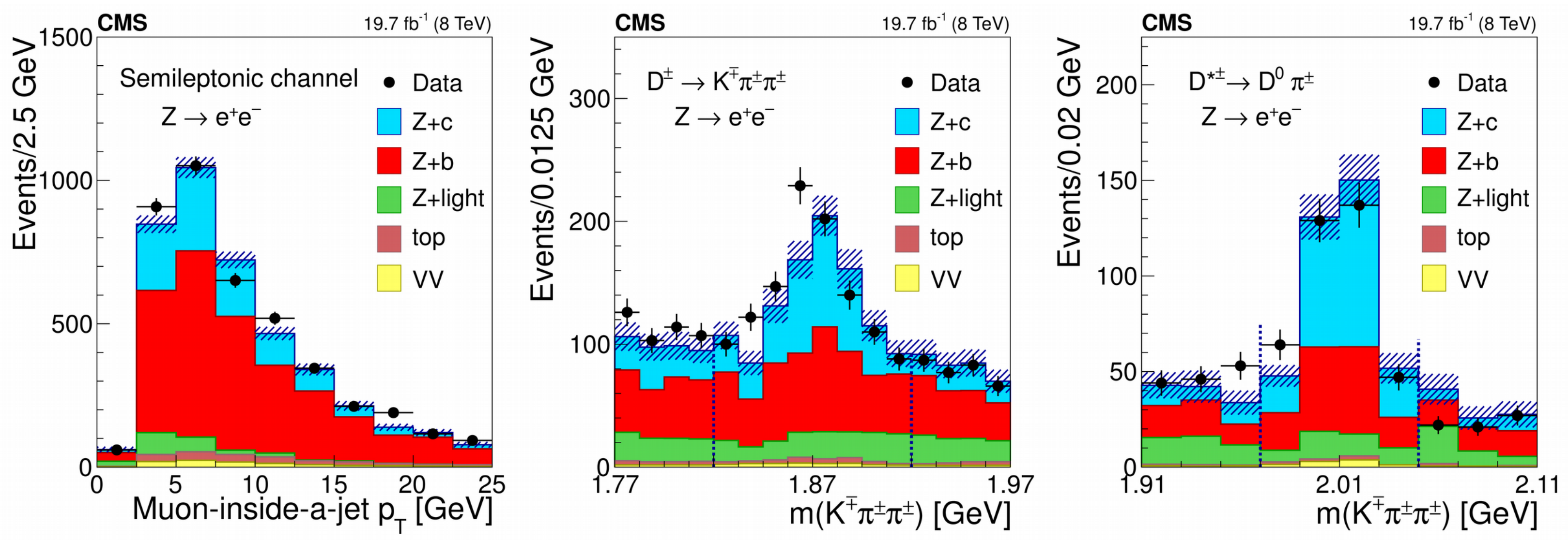
$$\sigma(\mathrm{EW}) = 552 \pm 19\,(\mathrm{stat}) \pm 55\,(\mathrm{syst})\,\mathrm{fb}$$

$$\text{SM prediction (LO) } \sigma(\mathrm{EW}) = 543 \pm 24\,\mathrm{fb}$$

ATLAS-CMS results cannot be directly compared because of different phase space first measurement of Z plus c-jets in central region (plus ratios to Z+b jets)

- sensitivity to intrinsic charm
- $p_T(l)>20$ GeV, $|\eta(l)|<2.71, 71<m_{ll}<111$ GeV, $p_T(\text{jet})>25$ GeV, $|\eta(\text{jet})| < 2.5$
- HF selection in three modes:

semileptonic D± D*



data driven techniques to control modelling and tagging efficiency

c-jets: W+c events, b-jets: tt-bar events

Z+c-jets @ 8 TeV

CMS: Eur. Phys. J.C. (2018) 78:287

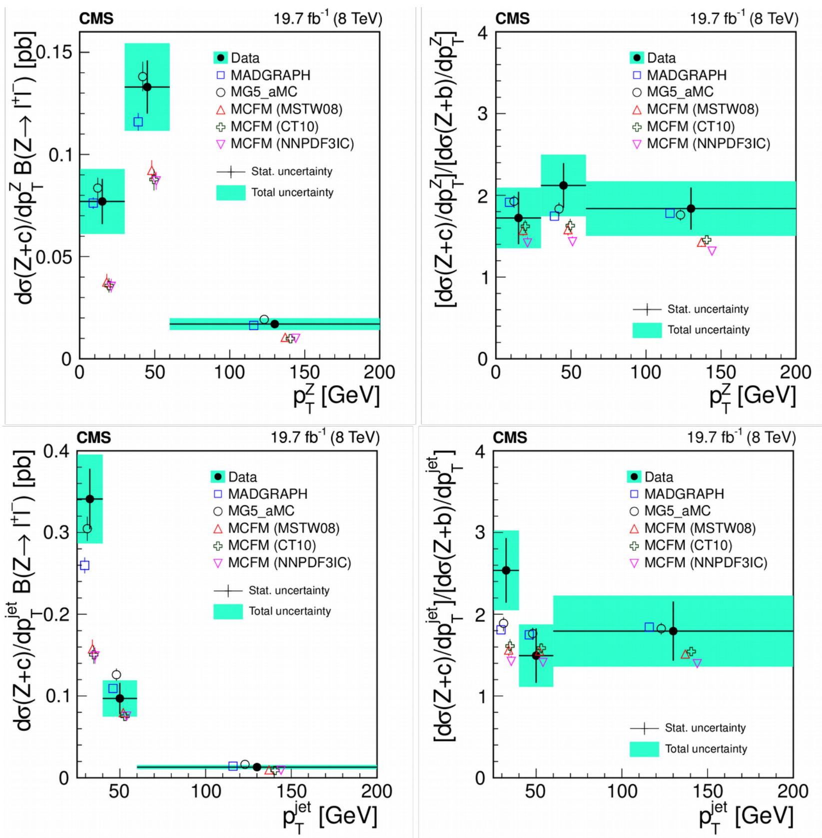
extraction of Z+c and Z+b yields from template fits to

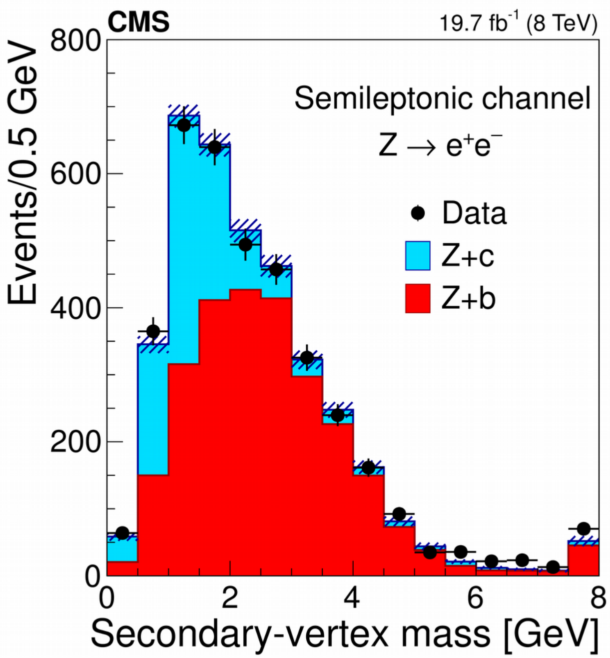
- corrected secondary vertex mass (semileptonic)

$$M^{\mathrm{corr}}_{\mathrm{vertex}} = \sqrt{M^2_{\mathrm{vertex}} + p^2_{\mathrm{vertex}} \sin^2\theta} + p_{\mathrm{vertex}} \sin\theta,$$

- probability that tracks come from primary vertex ($D^{\pm}$, D^* modes)

$d\sigma(Z+c)/dp_T$ $d\sigma(Z+c)/dp_T/d\sigma(Z+b)/dp_T$





Comparison with predictions:

LO (□) and NLO (**o**) Madgraph: good

MCFM (incl. corrections for hadronisation) is too low: missing PS and non pert. effects

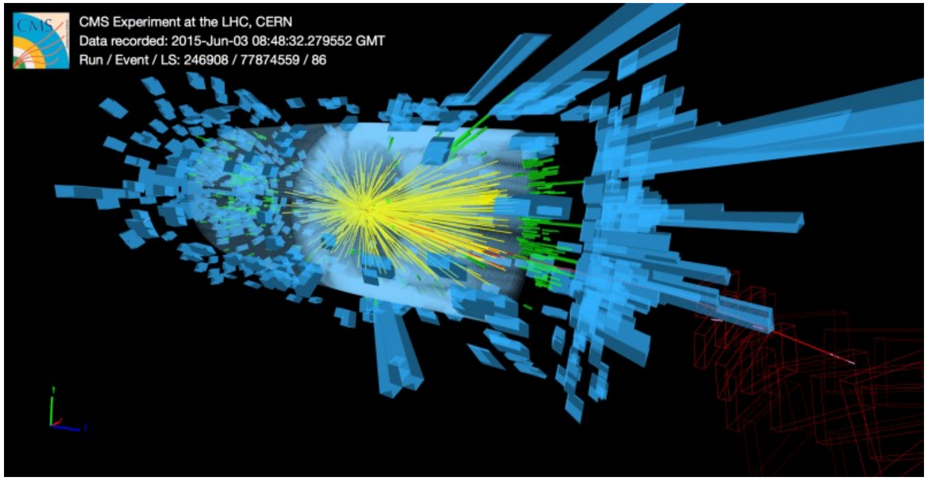
sensitivity to intrinsic charm ▽ at high p_T(Z, jet) mostly through ratio to Z+b

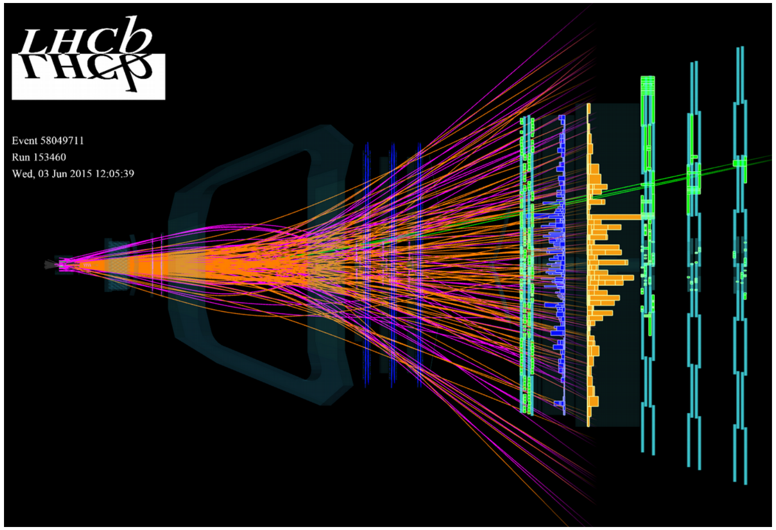
→ experimental uncertainties too large

Conclusions

the LHC experiments allow for extensive tests of QCD

- many standard candle measurements - important for Higgs physics and searches beyond the SM
- Measurements sensitive to structure of the protons and α_s
- measurements of multiple final states
  → explore regions of phase space where current theory still struggles to match data
- systematic exploration of final states with several beam energies
  → may improve our understanding of QCD



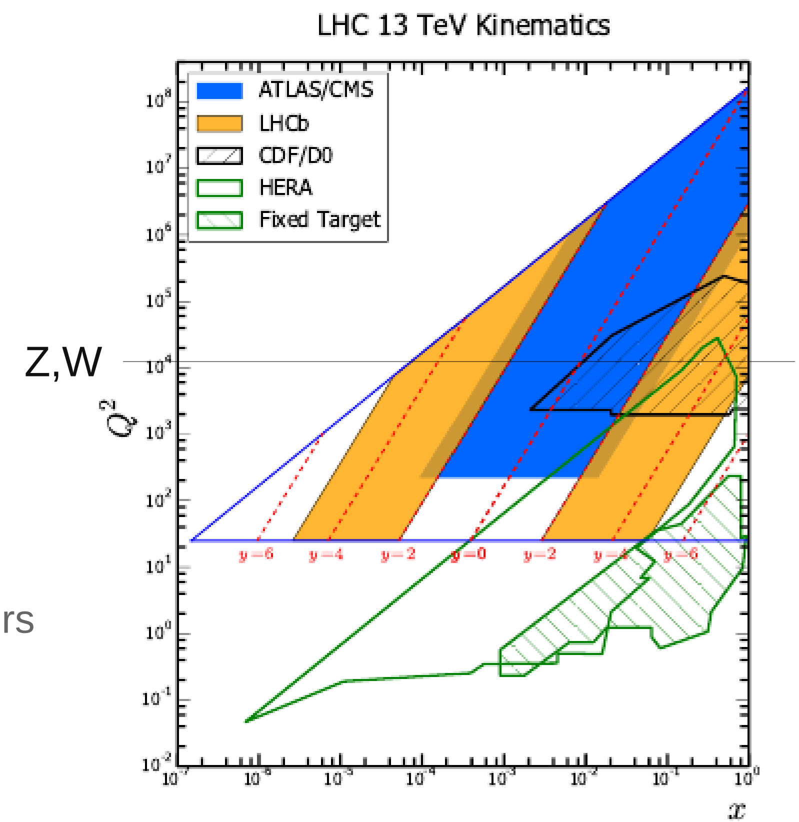


Backup

Kinematic range

$$\underbrace{\sigma(x,Q^2)}_{hadronic\ x-sec.} = \sum_{a,b} \int_0^1 dx_1\, dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{PDFs\ 2-8\ \%} \times \underbrace{\hat{\sigma}(x_{1,} x_{2,} Q^2)}_{partonic\ x-sec:\ NNLO\ 1\%}$$

- x-section measurements and ratios
  sensitive to parton density functions (PDFs)
- measurements used to constrain PDFs
  → important for e.g. searches
- LHC, HERA, Tevatron and
  fixed target data: wide range in x-Q^2 plane
- precision tests of pQCD
- background for new physics and Higgs
  → important validation of ME+PS MC Generators



two categories: Z plus >0 and >1 b tagged jets

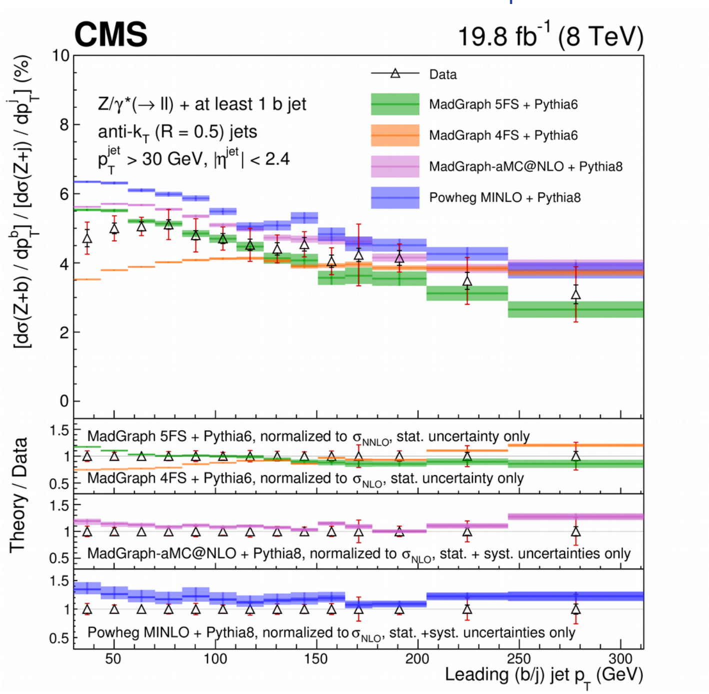
b jets $p_T > 30$ GeV, $|\eta| < 2.5$, Z+b unfolded to particle level

several differential cross sections:

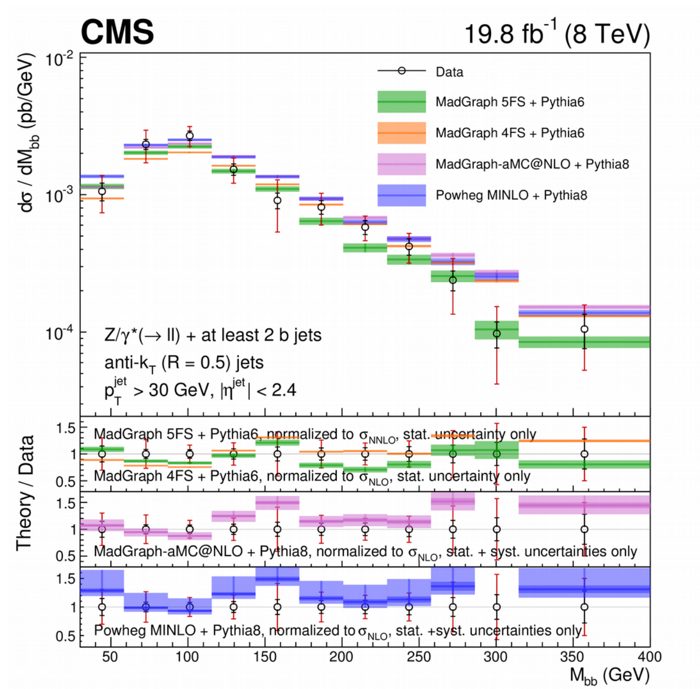
angles, p_T, H_T, bbZ and bZ system explored

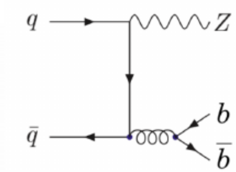
compared to NLO predictions by MadGraph and Powheg, 4F and 5F schemes tested

fraction of Z+b-jet vs p_T

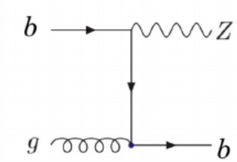


Z+2b-jets: cross-section vs M_{bb}





4-flavor, mb=0



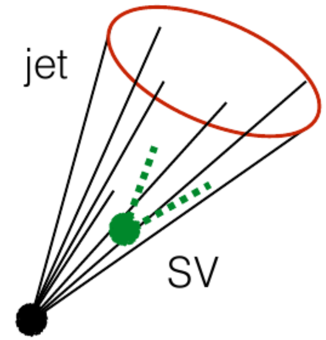
5-flavor, mb≠0

- 4F scheme fails to describe fraction of b-jet events vs pT, 20% low in normalisation
- Z plus 2 b-jets in general well described

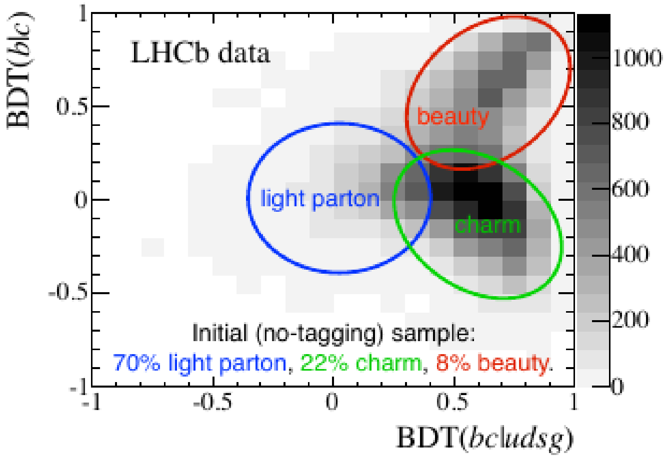
Z → bb-bar: Jet tagging

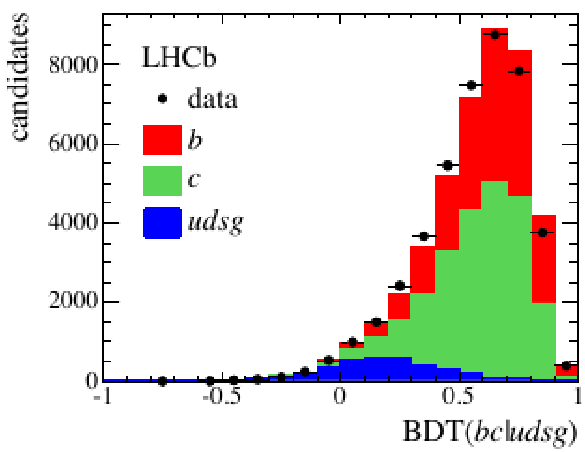
LHCb JINST 10 (2015) P06013

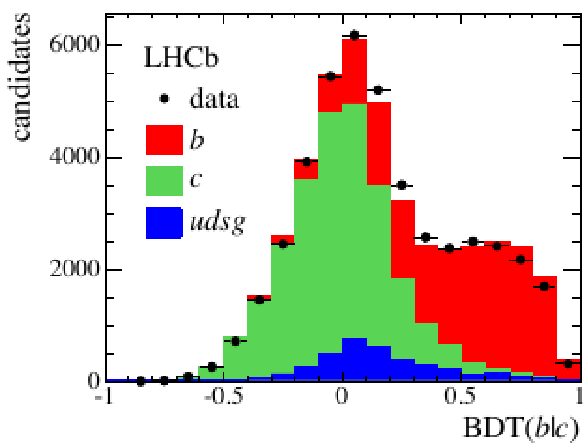
b, c tagging with secondary vertex in jet cone
two BDTs to separate
1) heavy from light jets (bc|udgs)
2) bottom from charm jets (b|c)



D+jet sample: enriched in b- and c-jets







powerful heavy jet tagging
jets with 20 GeV < p_T < 100 GeV :
- efficiency of b-jet tagging ~ 65%
- efficiency of c-jet tagging ~ 20%
- misidentification of a light-jet ~ 0.3%

performance validated in data

ATLAS & CMS:
several taggers based on tracks, muon, SV
using MVA and NN

CERN-CMS-DP-2017-005, CMS-PAS-BTV-15-001
ATL-PHYS-PUB-2017-013, ATLAS-FTAG-2017-003

Differential tt-bar @ 13 TeV

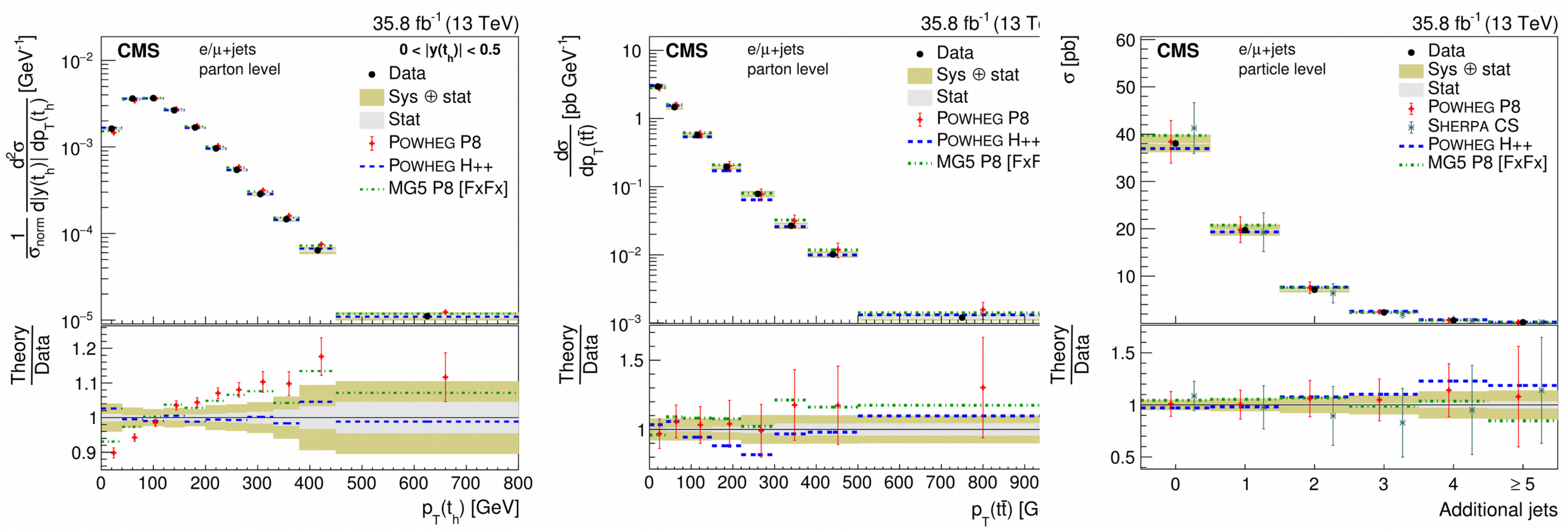
CMS PRD 97, 112003 (2018)

lepton + jets channel: absolute and normalised cross sections

particle level (fiducial phase space), parton level (full phase space)

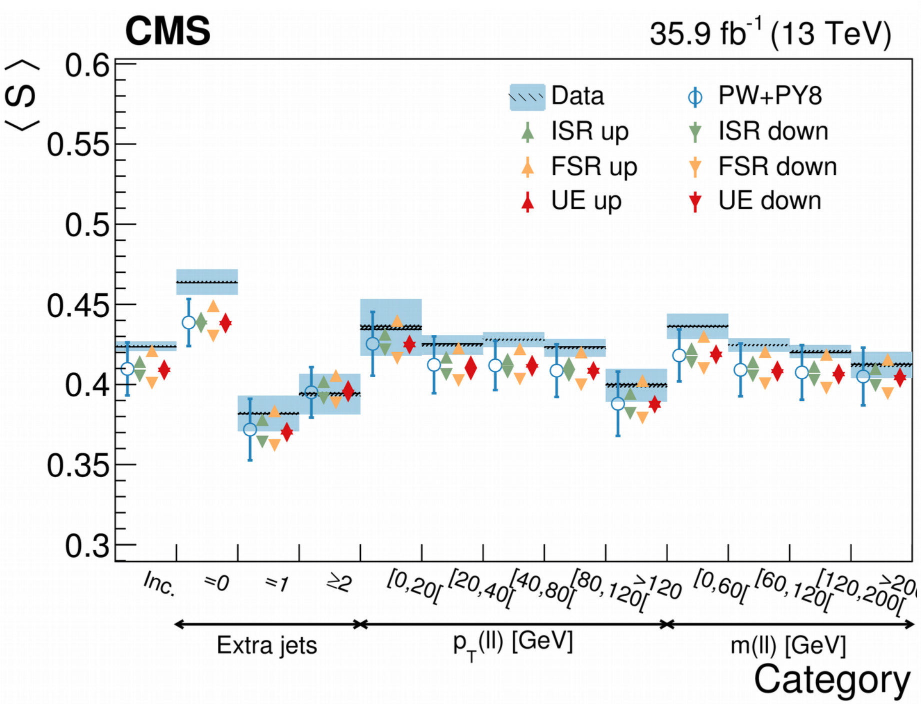
compared to several SM predictions

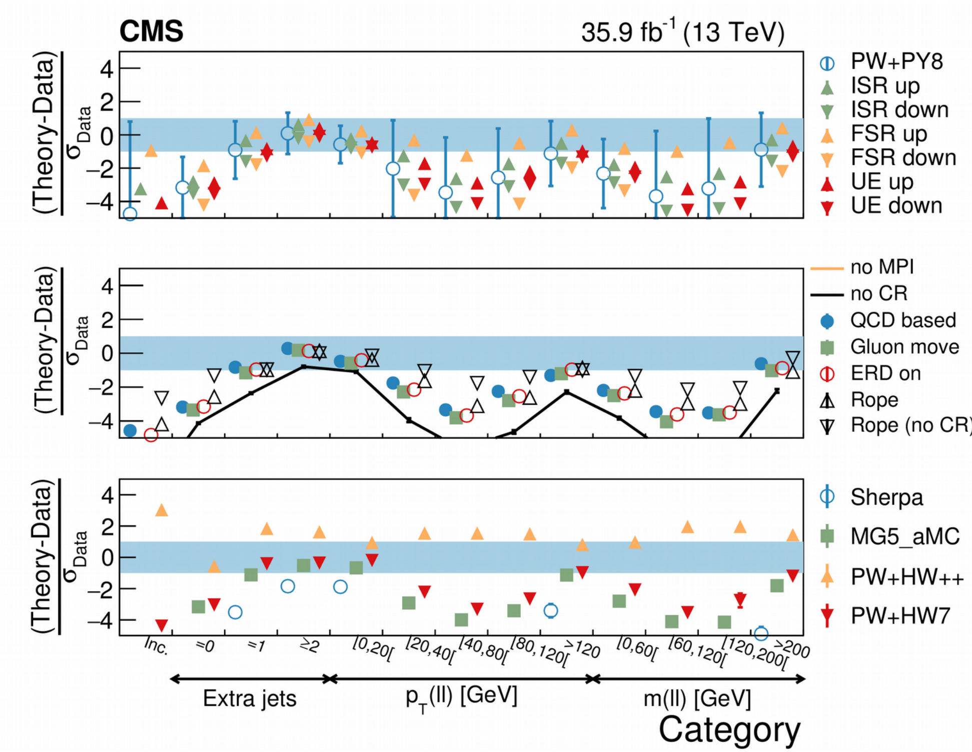
- reasonable description of kinematic variables of the top quarks and the tt-bar system
- no prediction describes all the measured distributions
- largest deviation $p_T(t)$: softer than predicted



sphericity for different event categories

- UE is anisotropic (S<1)
- no extra jet: UE more isotropic
- MPI contribution is crucial
- sensitivity to colour reconnection





Strong coupling constant α_s

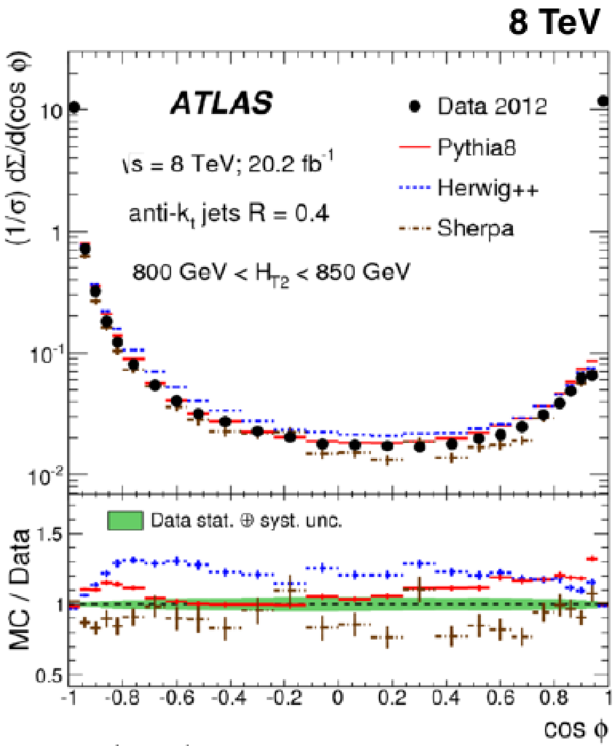
p_T(jet)>100GeV, $|\eta|<2.5$, anti k_T – R=0.4

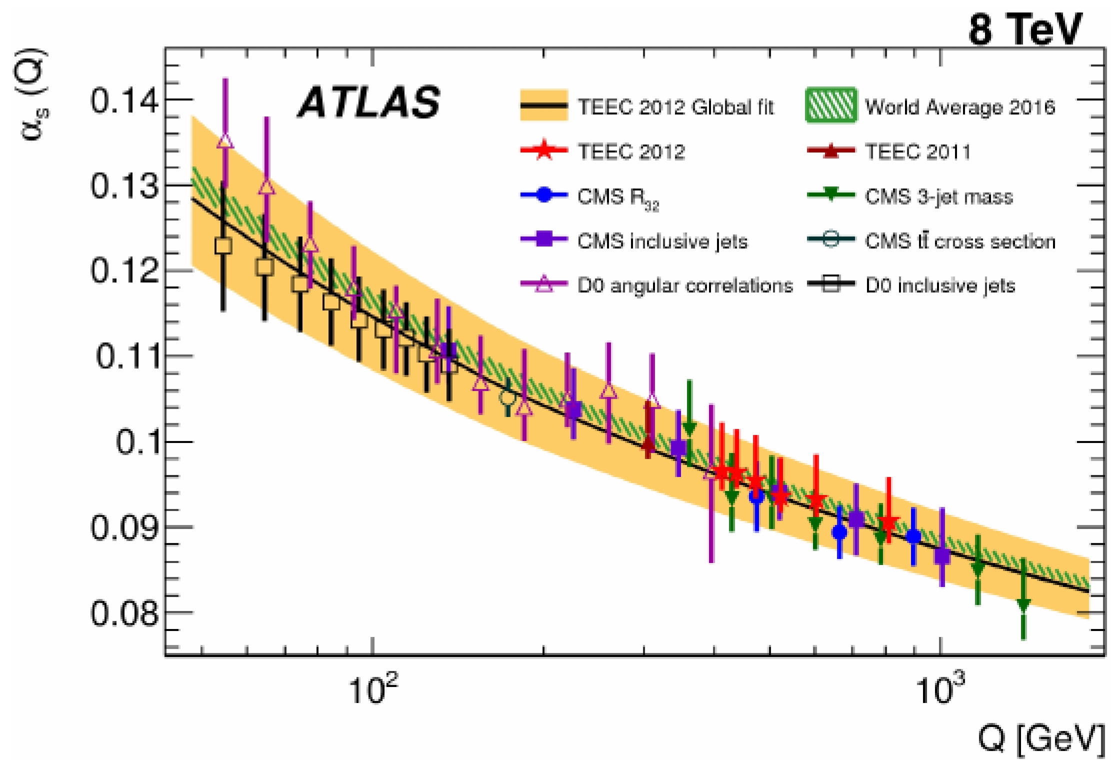
energy-energy correlations and their associated asymmetries in multi-jet even

bins of the scalar sum of the transverse momenta of the two leading jets

unfolded distributions fitted to NLO calculations

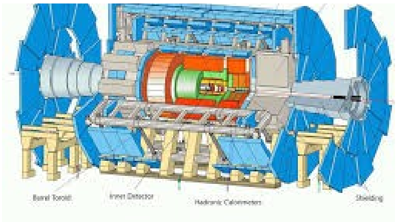
α_s = 0.1162 ± 0.0011(exp.) + 0.0084 -0.0070(th.)



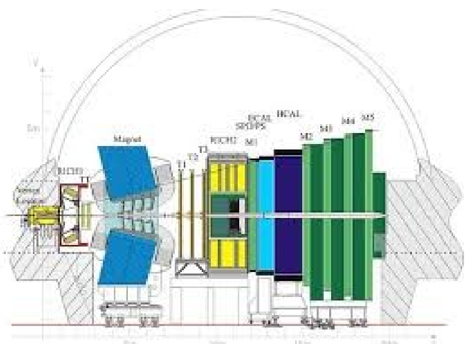


Detectors

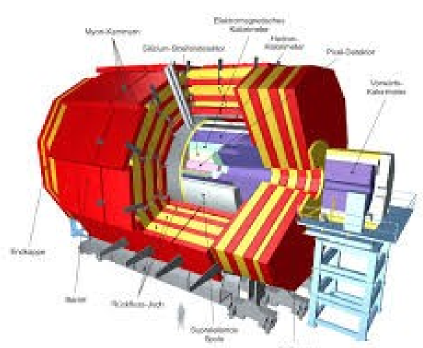
ATLAS JINST 3 (2008) S08003



LHCb JINST 3 (2008) S08005



CMS JINST 3 (2008) S08004



Experiment	cm energy [TeV]	integrated luminosity [fb^{-1}]
ATLAS, CMS	7 8 13	6 22 4
ALICE	7 8 13	0.005 0.01 0.007
LHCb	7 8 13	1.0 2.0 0.3

ALICE: JINST 3 (2008) S08002