TESTS OF QCD USING JETS, BOSONS PLUS JETS, AND TOP QUARK PRODUCTION AT COLLIDERS

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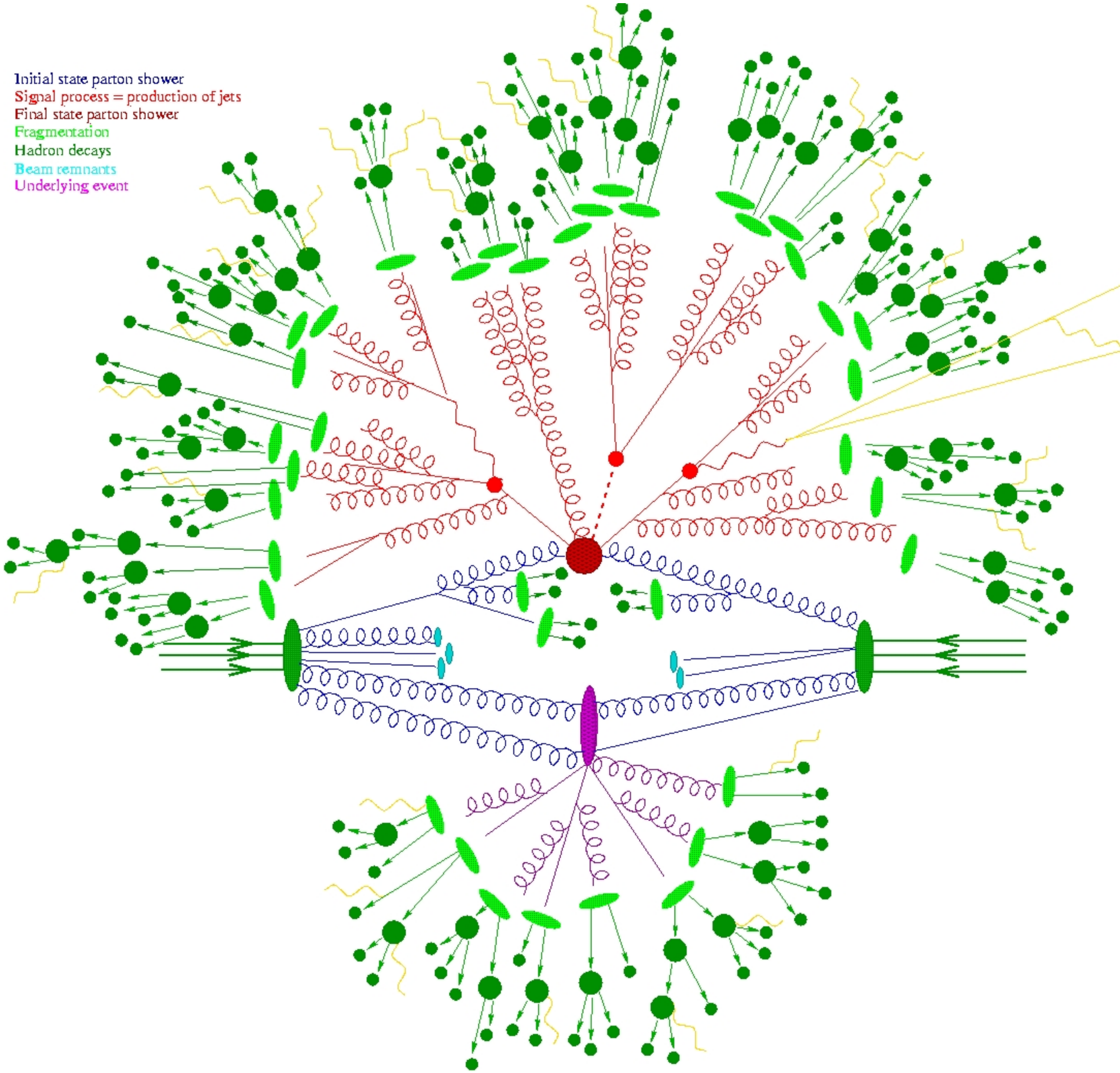
29th Rencontres de Blois – Particle Physics and Cosmology

Blois (France) - 30 May 2017

QCD at colliders



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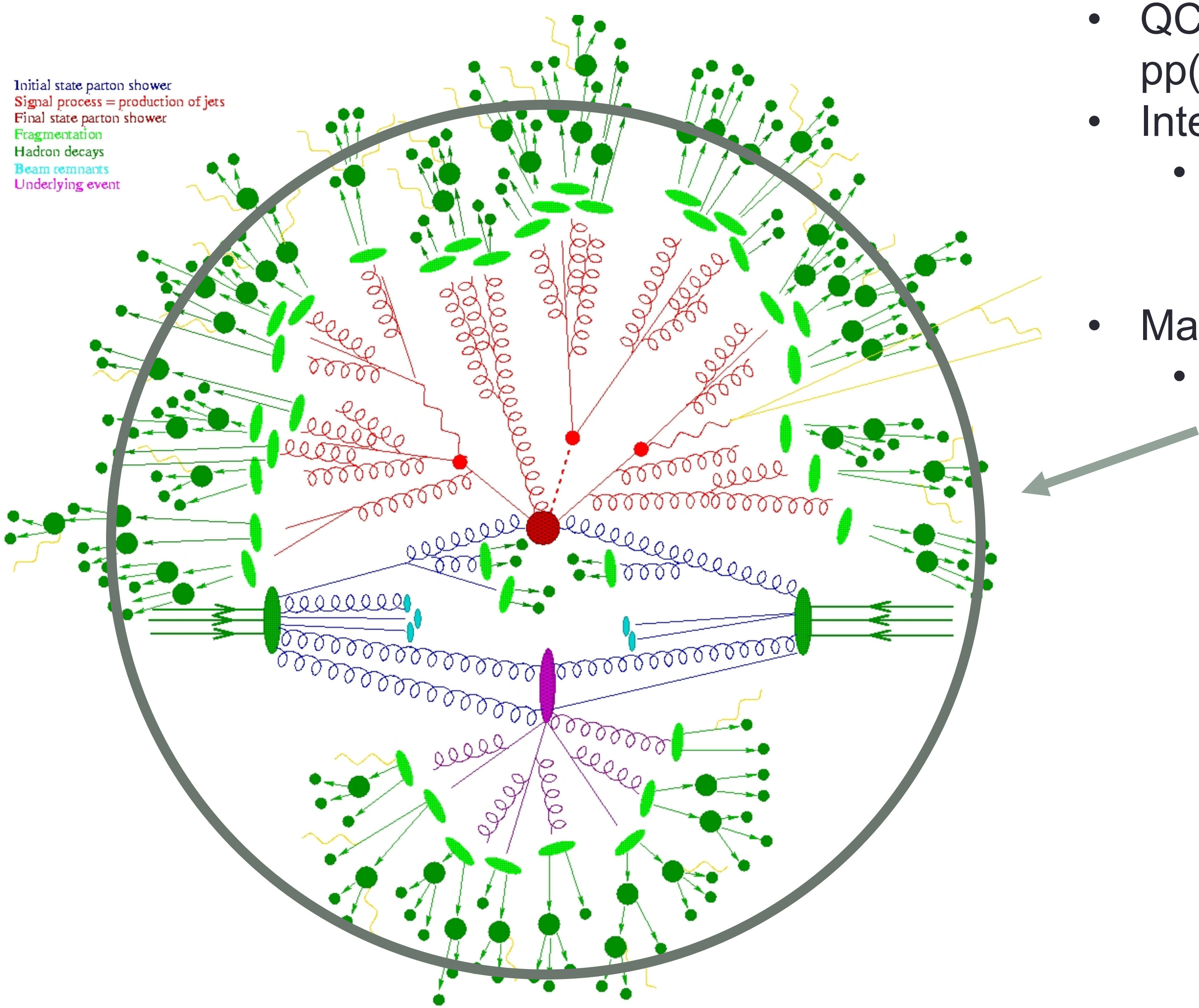
- Interesting in itself
    - but essential tool for any electroweak SM/BSM study

QCD at colliders



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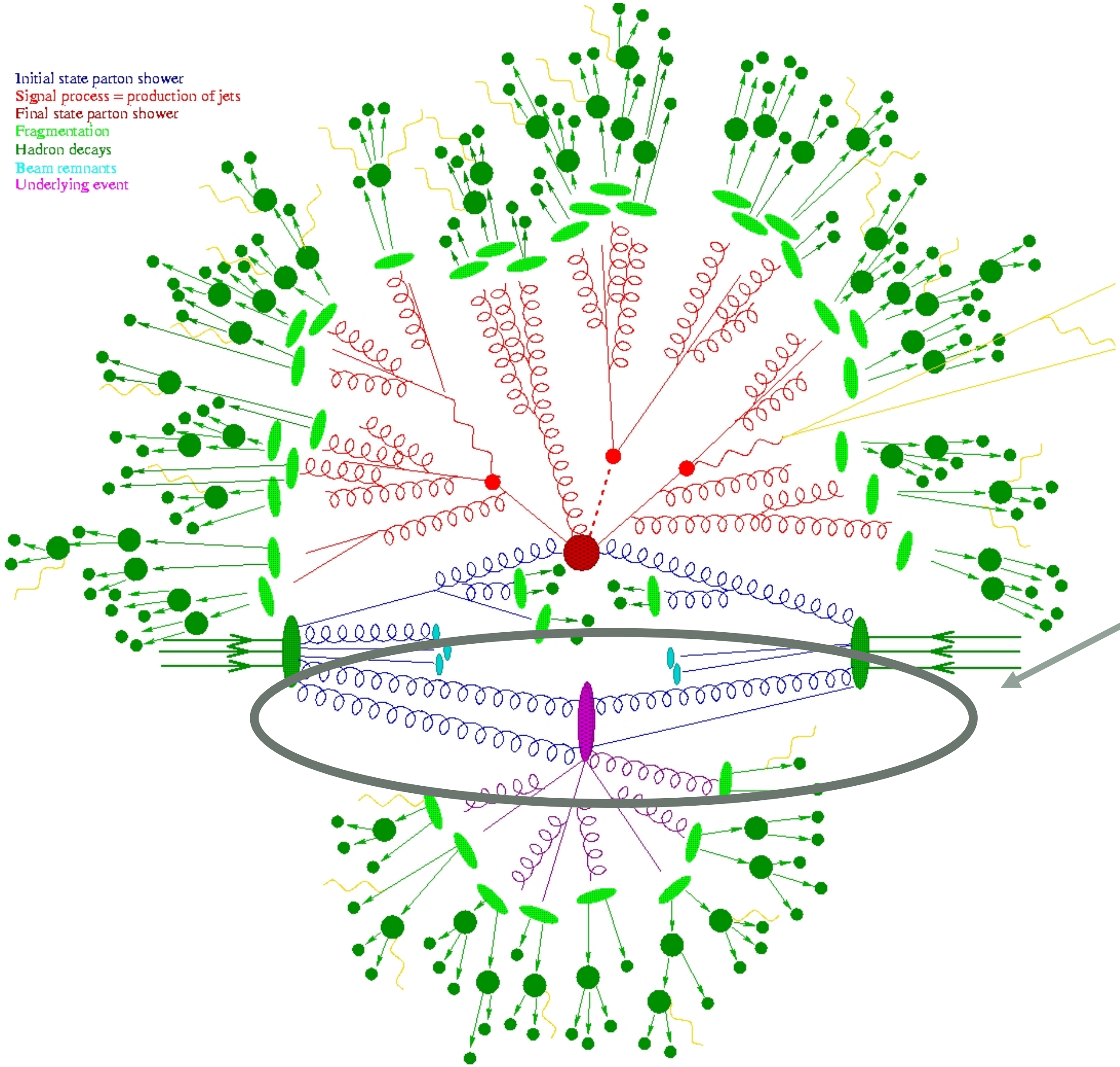

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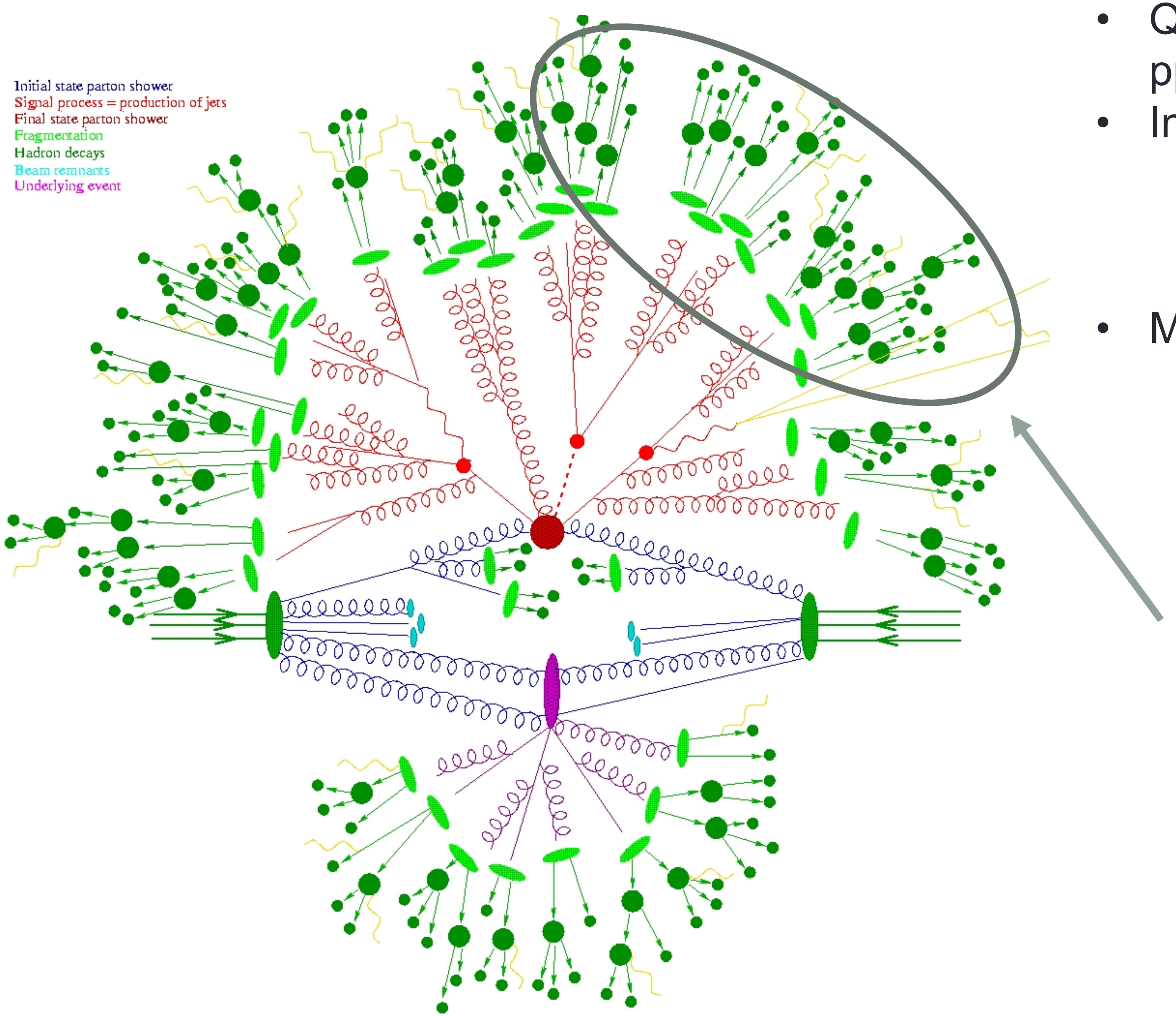

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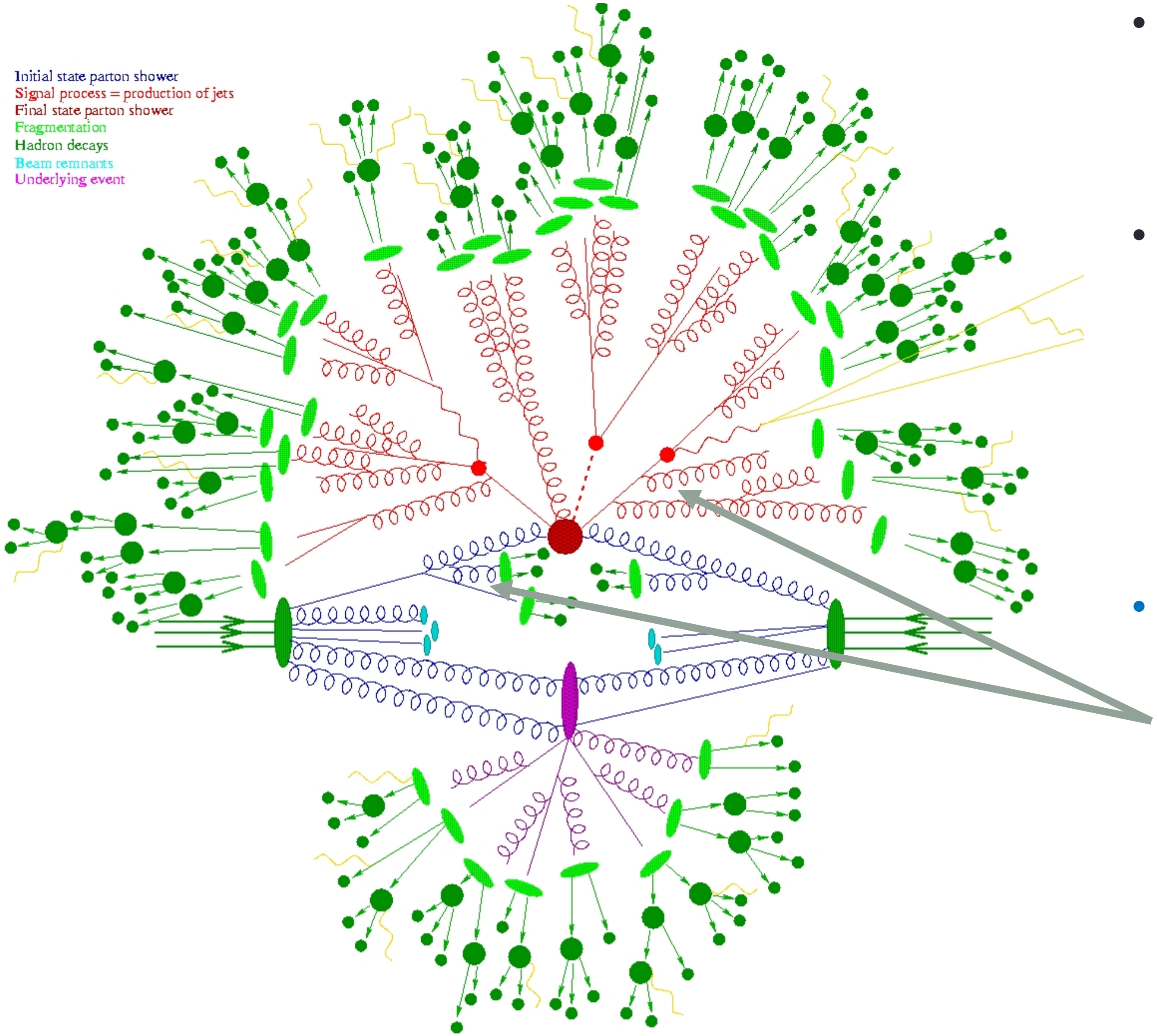

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- Many possible topics:
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  - "soft QCD", from partons to hadrons
- **Here concentrate on a specific aspect: hard scattering producing jets at LHC, Tevatron, HERA**
  - **quarks and gluons with high p_T**

From light to heavy partons

V = γ,W,Z

top quarks

charm and bottom quarks (+ V)

inclusive (+ V)

A personal selection of recent topics, not a complete list
Please see the QCD+EW+TOP parallel sessions for more details

From light to heavy partons

$V = \gamma, W, Z$

The most abundant processes in a hadronic collider

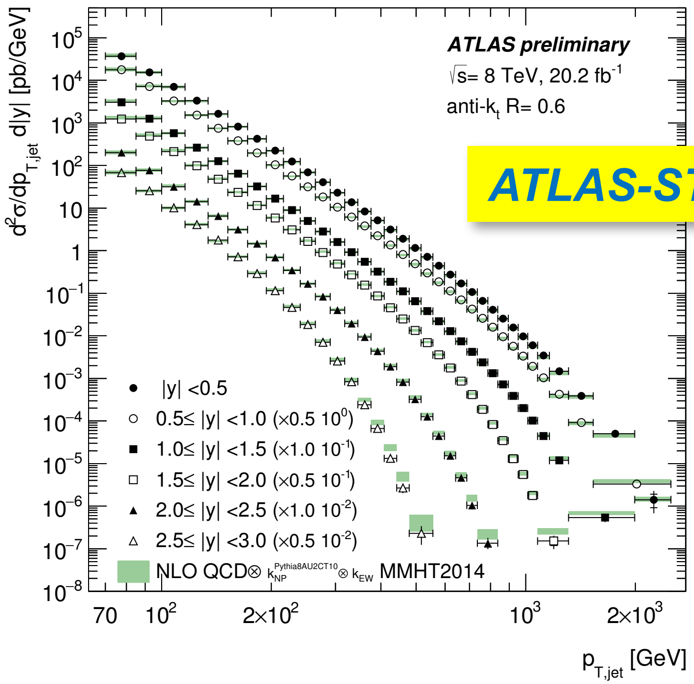
Essential testbed for any QCD calculation
Their understanding is needed:

- ***for EWK precision measurements***
- ***as background to most Higgs studies and BSM searches***

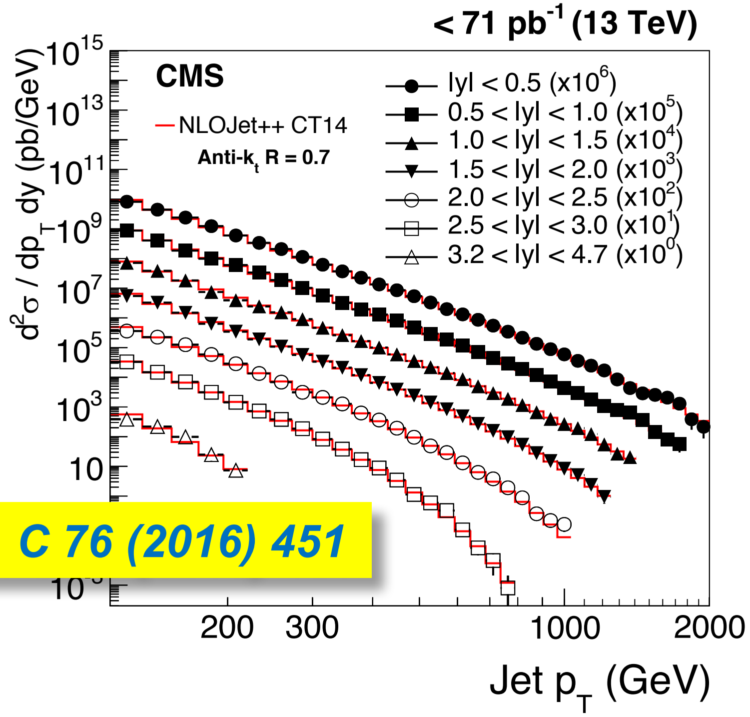
inclusive (+ V)

Inclusive jet cross section

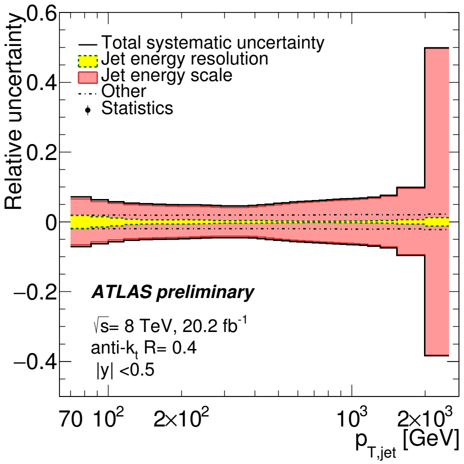
$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{\mathrm{int,eff}}} \frac{N_{\mathrm{jets}}}{\Delta p_T \, (2\Delta|y|)}$$



ATLAS-STDM-2015-01

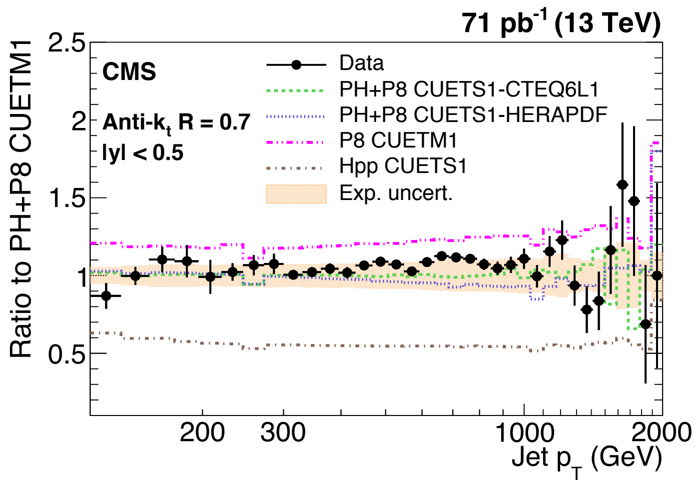


Eur. Phys. J. C 76 (2016) 451



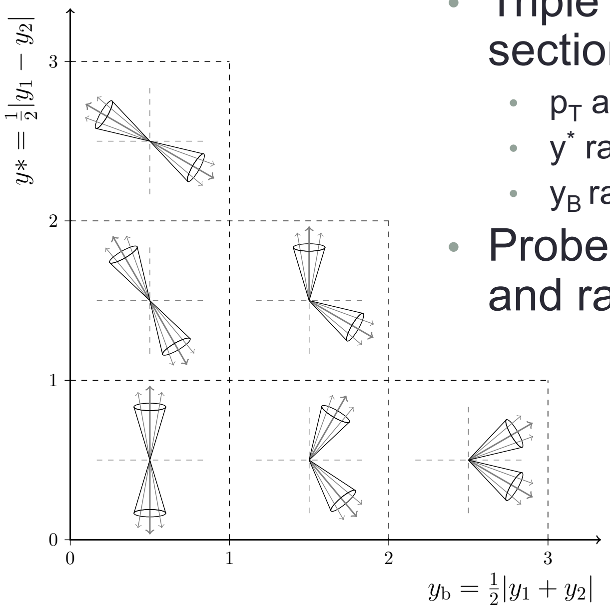
(a) $R = 0.4$, $|y| < 0.5$

- jet energy scale dominant systematic uncertainty
- test of both fixed order and ME+PS calculations
- both R= 0.6/0.7 and 0.4 studied
  - sensitive to hard structure and softer part of radiation
- overall good agreement



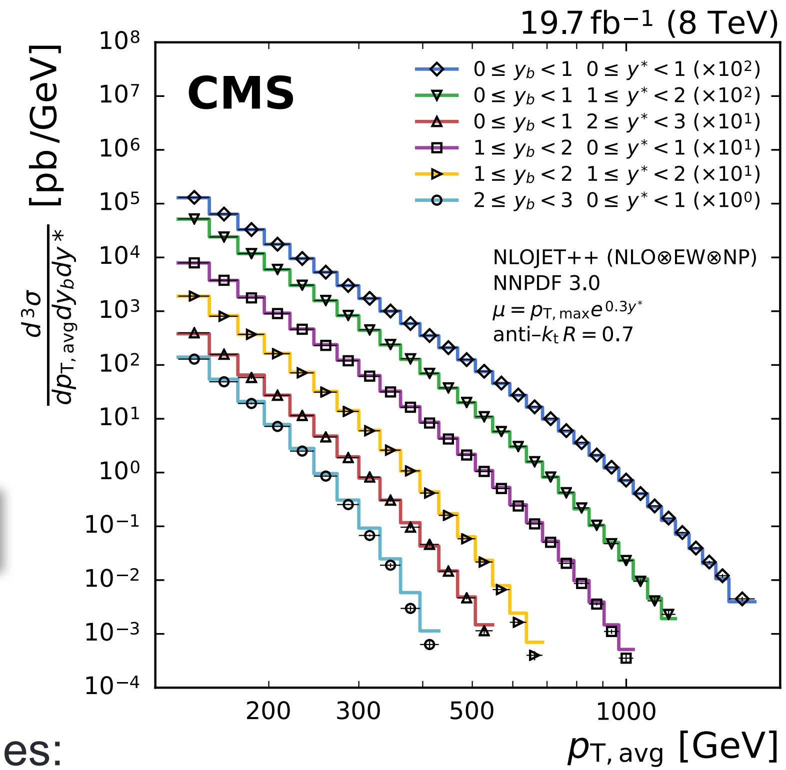
Dijet cross section

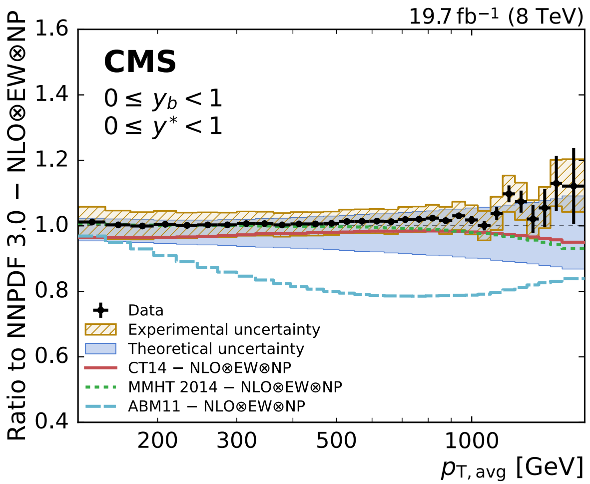
$$\frac{d^3\sigma}{dp_{T,avg}dy^*dy_b} = \frac{1}{\epsilon \mathcal{L}_{int}^{eff}} \frac{N}{\Delta p_{T,avg} \Delta y^* \Delta y_b}$$



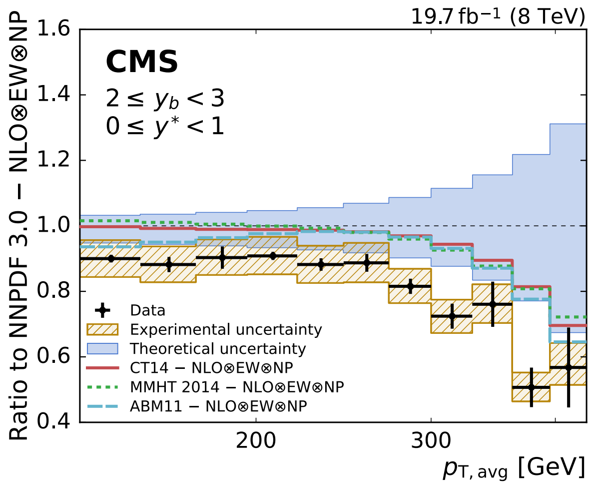
- Triple differential cross section as a function of:
  - p_T average of 2 leading jets
  - y^* rapidity half difference
  - y_B rapidity boost of dijet system
- Probe different topologies and radiation patterns

arXiv.1705.02628



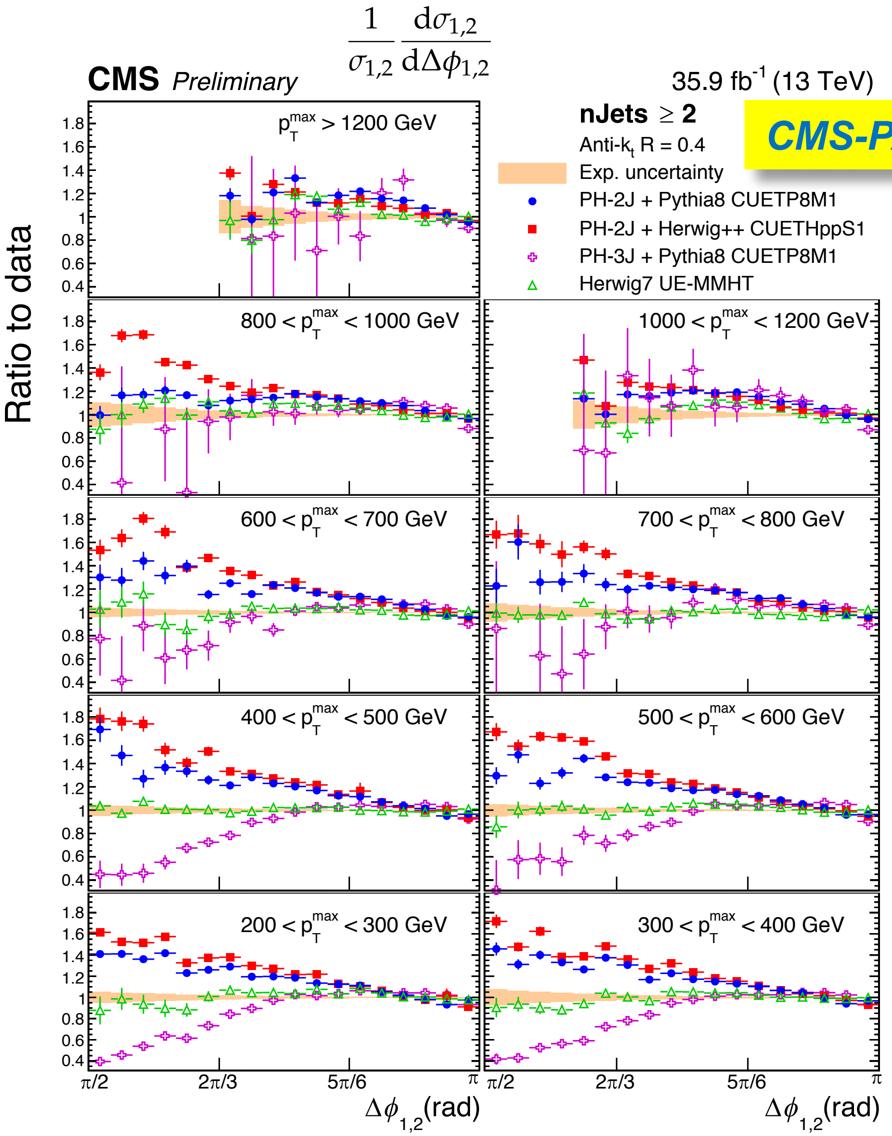


- Theoretical uncertainties:
  - scale dominates low p_T
  - PDF dominates high p_T, high boost
- data/theory discrepancies at high boost
  - where poorly known high-x PDF matters more
  - potential of constraining PDFs

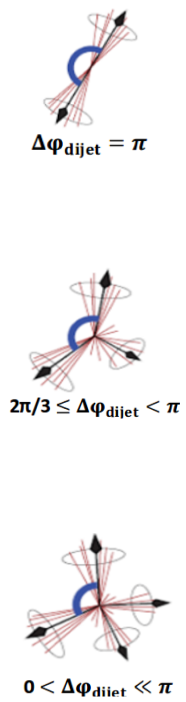


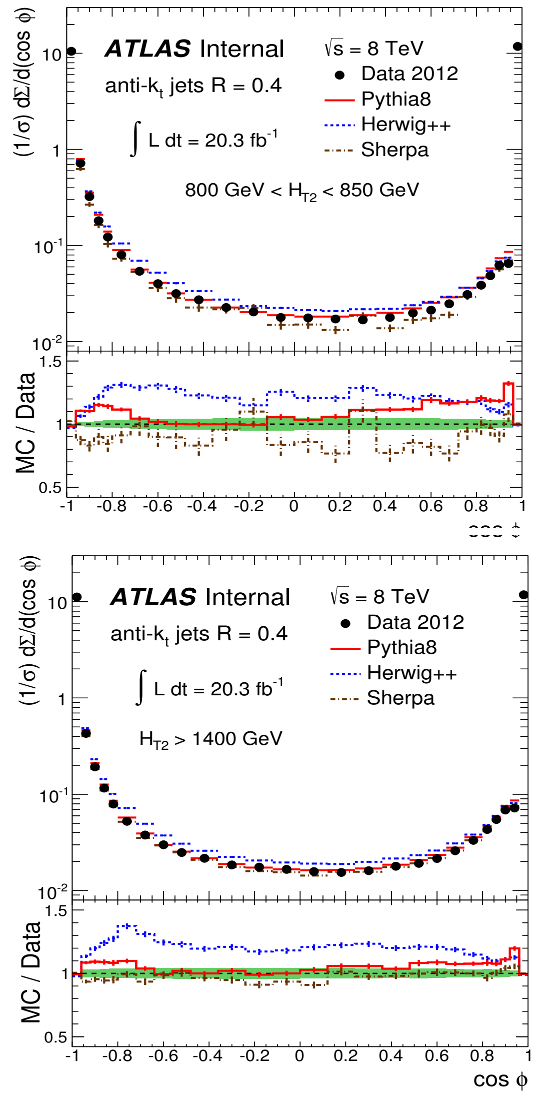
Correlations among jets

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi-\cos\phi_{ij}),$$



CMS-PAS-SMP-16-014



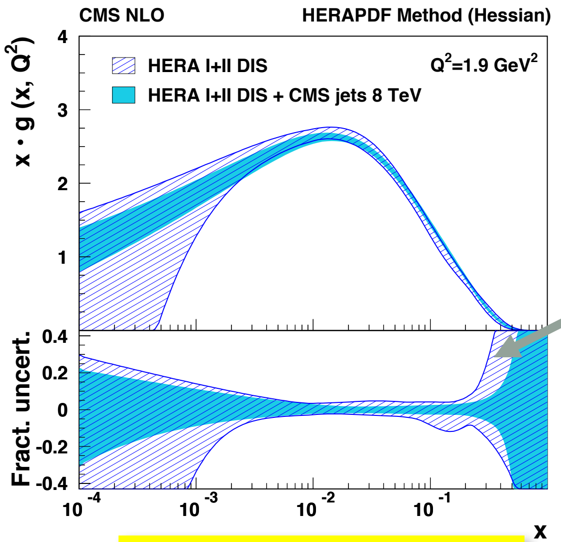


ATLAS-STDM-2016-10

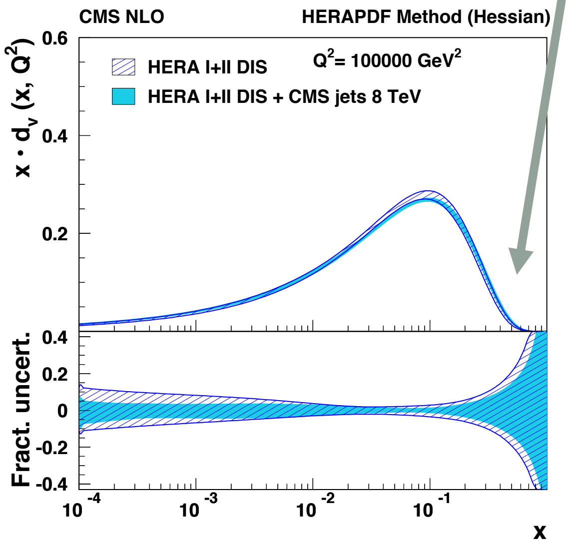
Test of higher order corrections in regions away from back-to-back topologies

Probe indirectly the modelling of 3, 4 jets (CMS looks also at higher multiplicities…)

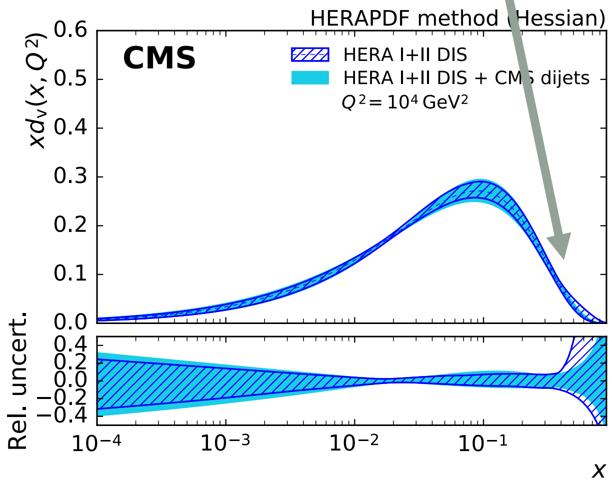
Constraints on PDFs

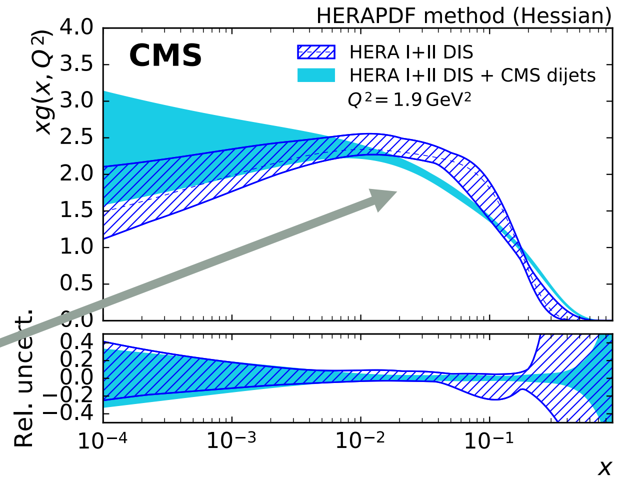


inclusive jets
JHEP 03 (2017) 156

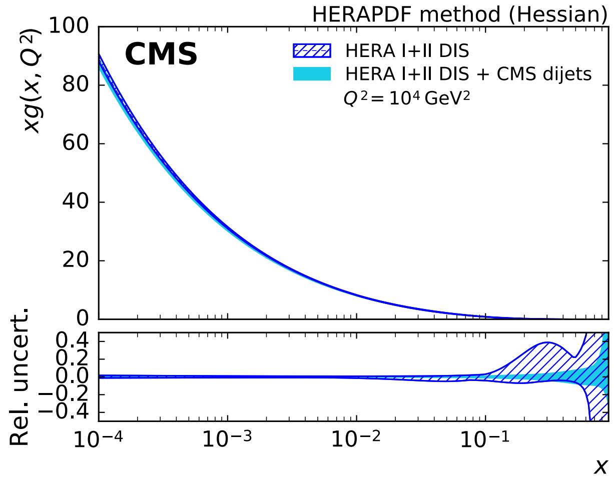


- HERAFITTER/xFITTER procedure
  - test improvements over HERA data alone
- Inclusive jets: improvements on gluon PDFs at high x
  - parameterization uncertainty reduced
  - compatible with 7 TeV constraints
- Dijets: significant impact on gluon PDF
  - changing also the shape at low Q^2
- Some impact also on valence quarks
  - compatible with inclusive jets

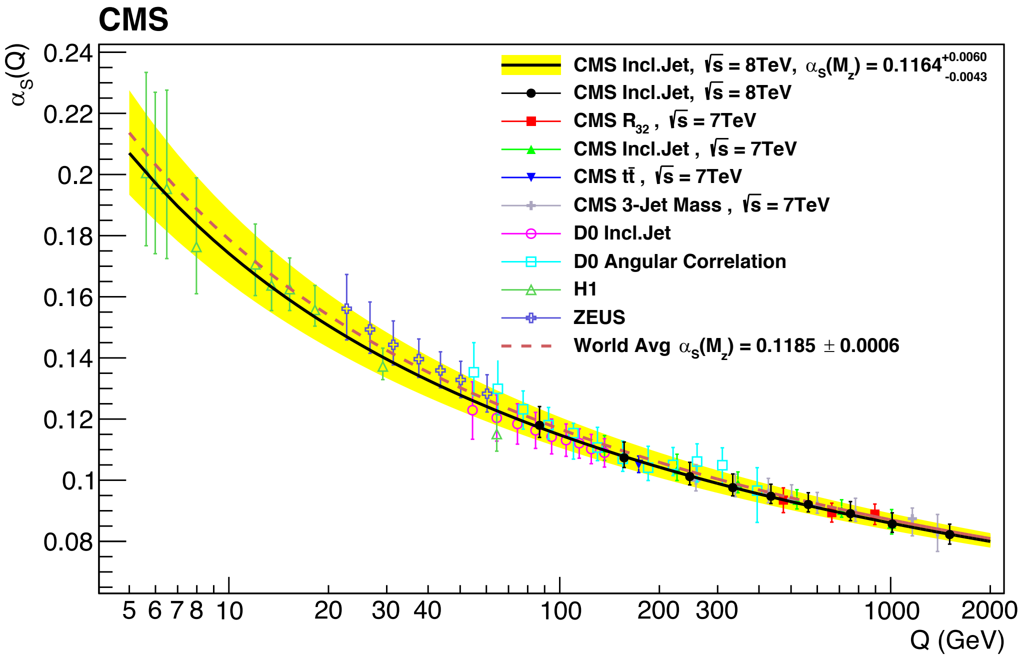


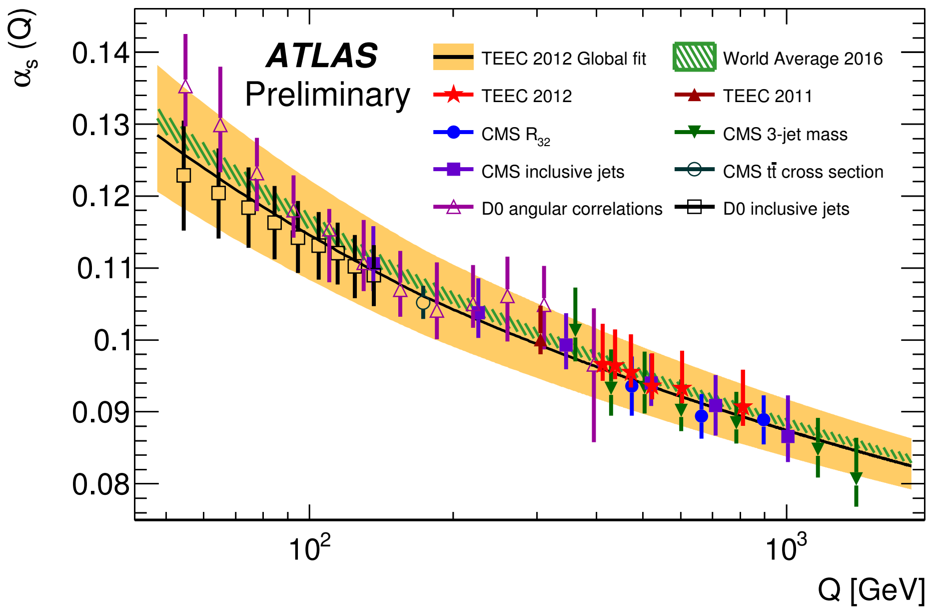


dijets



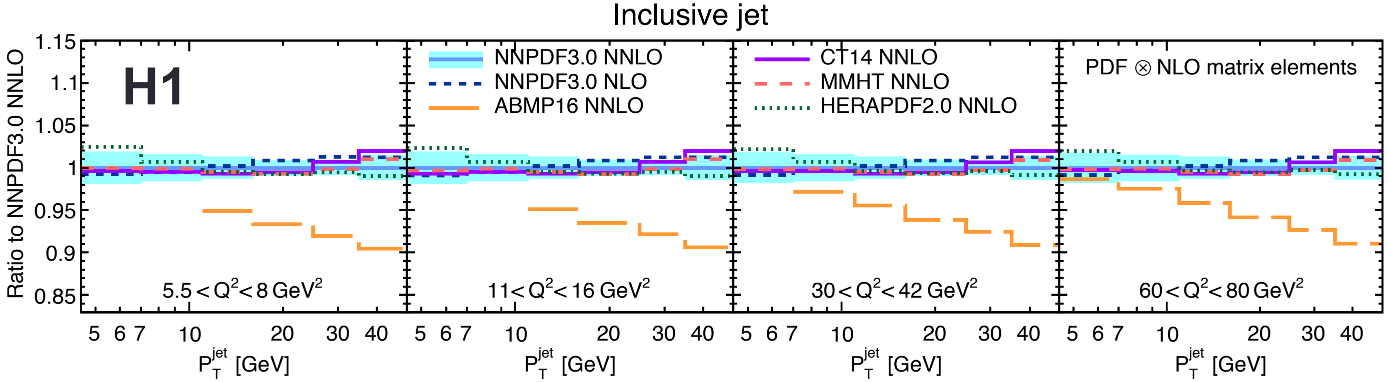
Strong coupling constant measurement

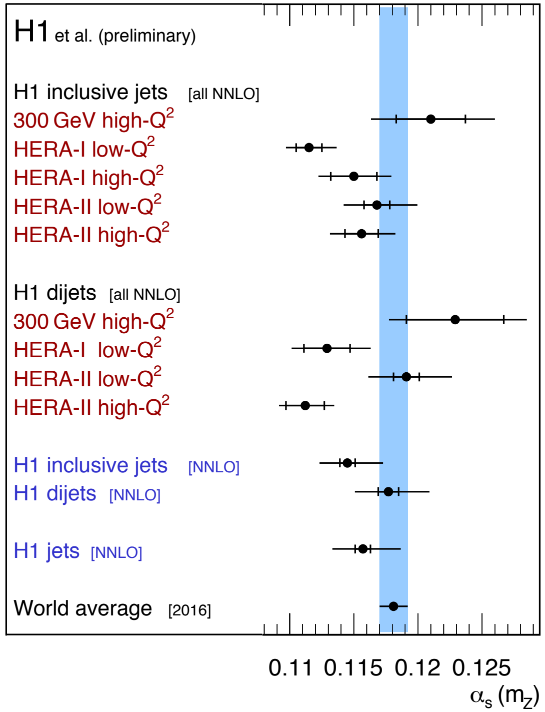




Observable	$\alpha_S(M_Z)$	exp.	scale	PDF	NP	others
Inclusive jets	0.1164	+0.0014 -0.0015	+0.0053 -0.0028	+0.0025 -0.0029	+0.0001 -0.0001	***JHEP 03 (2017) 156 (CMS)***
Dijets	0.1199	+0.0015 -0.0015	+0.0031 -0.0020		included in exp.	***arXiv.1705.02628 (CMS)***
R(3 j/2 j)	0.1150	+0.0010 -0.0010	+0.0050 -0.0000	+0.0013 -0.0013	+0.0015 -0.0015	***CMS-PAS-16-008***
TEEC	0.1162	+0.0008 -0.0008	+0.0076 -0.0061	+0.0018 -0.0018	+0.0003 -0.0003	+0.0007 -0.0007 ***ATLAS-STDM-2016-10***

DIS inclusive jets and α_s at NNLO





arXiv.1611.03421, EPJC

at NLO (NLOJet++, NNPF3.0):

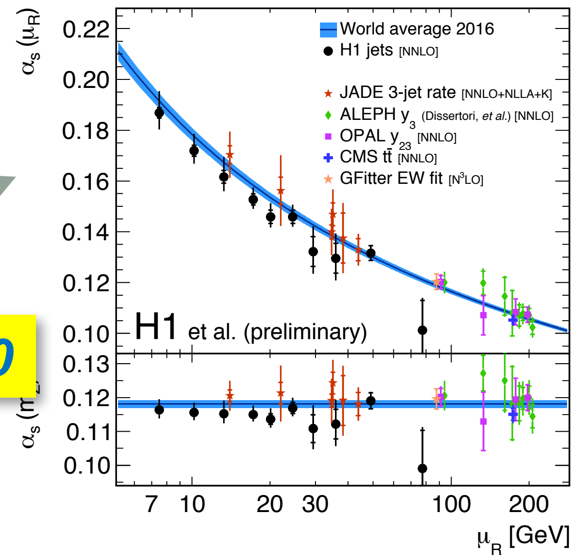
$$\alpha_s(M_Z) = 0.1172\,(4)_{\mathrm{exp}}\,(3)_{\mathrm{PDF}}\,(7)_{\mathrm{PDF}(\alpha_s)}\,(11)_{\mathrm{PDFset}}\,(6)_{\mathrm{had}}\,(^{+51}_{-43})_{\mathrm{scale}}$$

at NNLO (NNLOJet, NNPF3.0, $\mu_R{}^2=\mu_F{}^2=Q^2+p_T{}^2$):

$$\alpha_s(m_Z) = 0.1157\,(6)_{\mathrm{exp}}\,(3)_{\mathrm{had}}\,(6)_{\mathrm{PDF}}\,(12)_{\mathrm{PDF}\alpha_s}\,(2)_{\mathrm{PDFset}}\,(^{+27}_{-21})_{\mathrm{scale}}$$

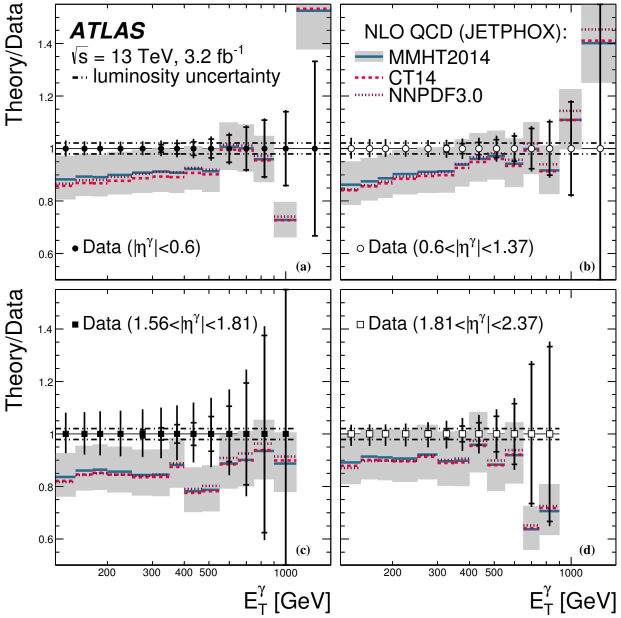
- k_T (D=1) jet production in DIS NC reanalyzed
  - $150 < Q^2 < 15000$ GeV^2 extended down to $p_T = 5$ GeV
  - $5.5 < Q^2 < 80$ GeV^2 added
- Compare with new NNLO calculation
  - very good agreement with data

arXiv.1705.03450

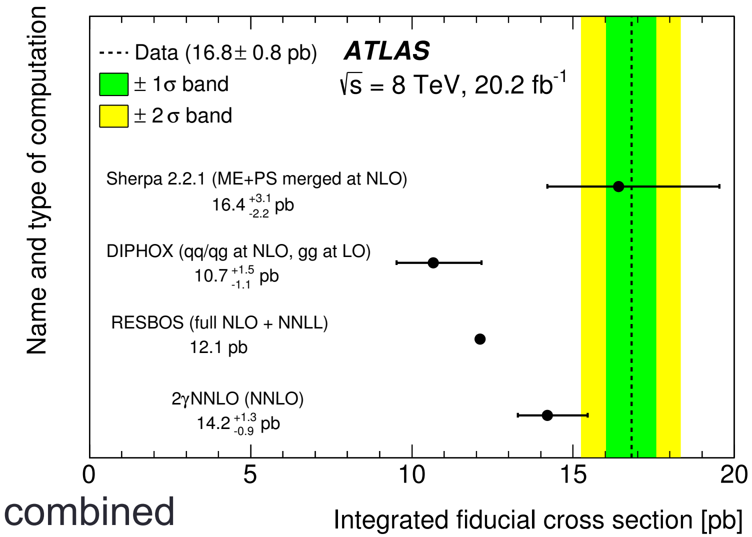


Photon and diphoton production

PLB 770 (2017) 473



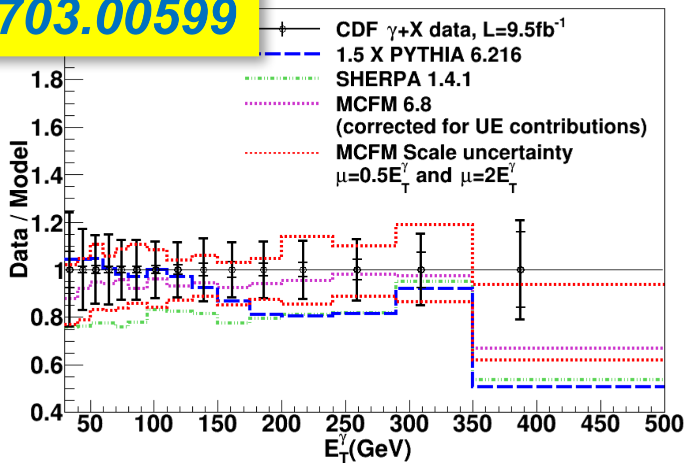
- Inclusive photon cross section well reproduced also by Pythia8 and Sherpa2 LO
  - but for E_T>500 GeV
- NNLO prediction available now…

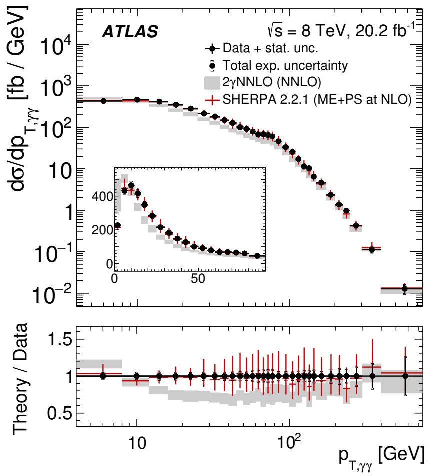


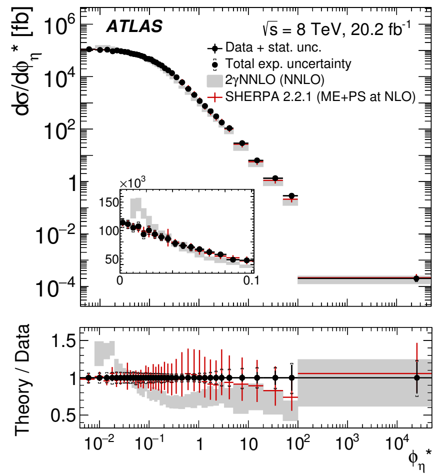
Sherpa2 combined NLO gives the best description of diphoton kinematics

arXiv.1704.03839

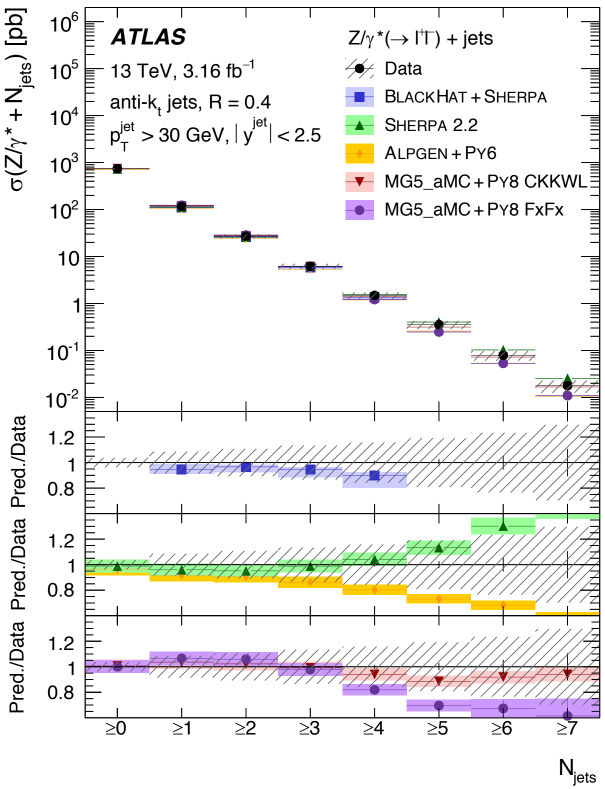
arXiv.1703.00599

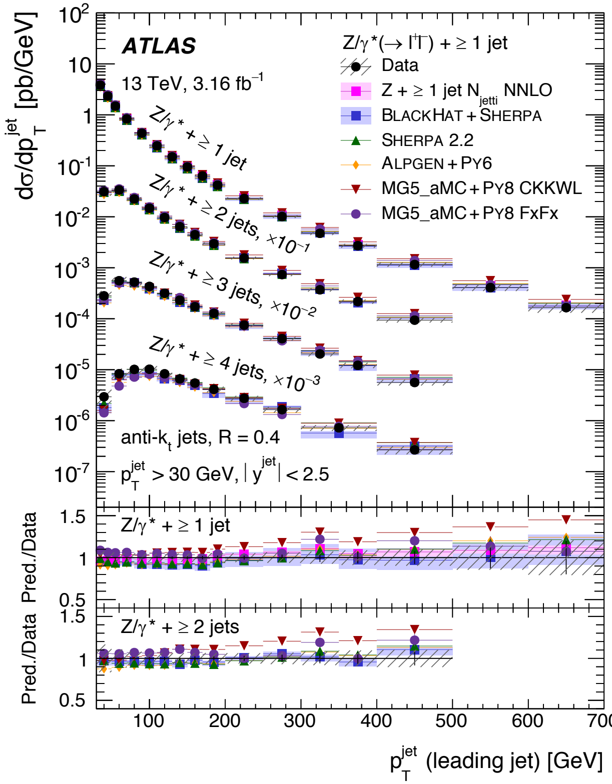


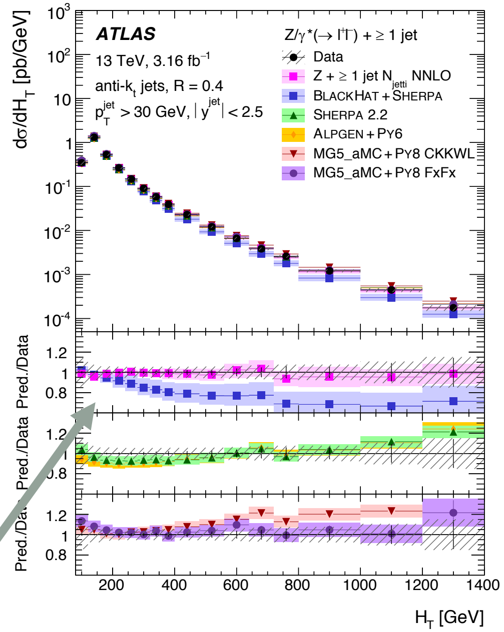


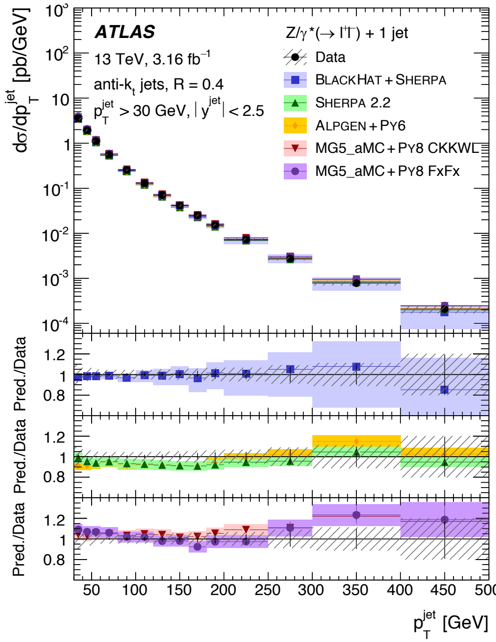


Vector bosons + jets: Z @ 13 TeV









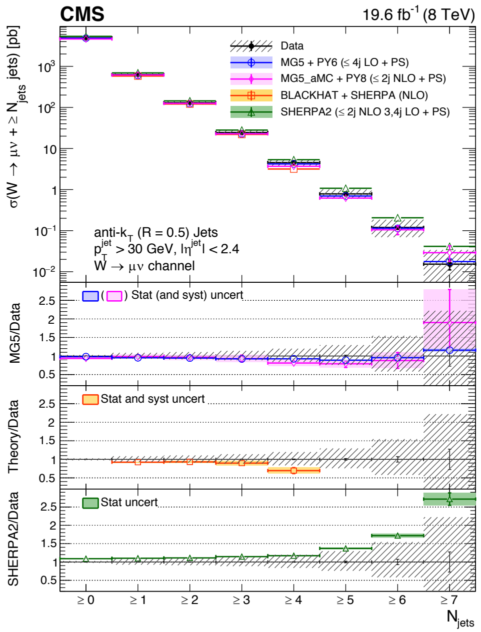
- New NNLO calculations performs well, even on H_T
  - where NLO is expected to fail when higher multiplicities matter
  - while single multiplicity is well described by NLO
- NLO merging (FxFx,MEPS@MLO) improves over LO merging (CKKL) in p_T spectra
- ME+PS calculations reproduce well jet multiplicity where ME partons dominate

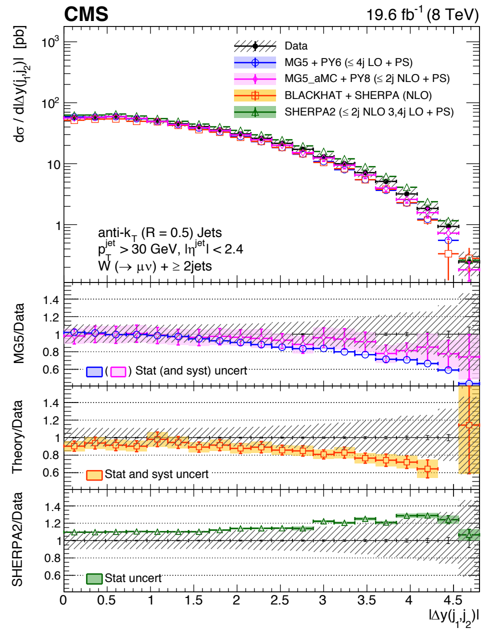
arXiv.1702.05725

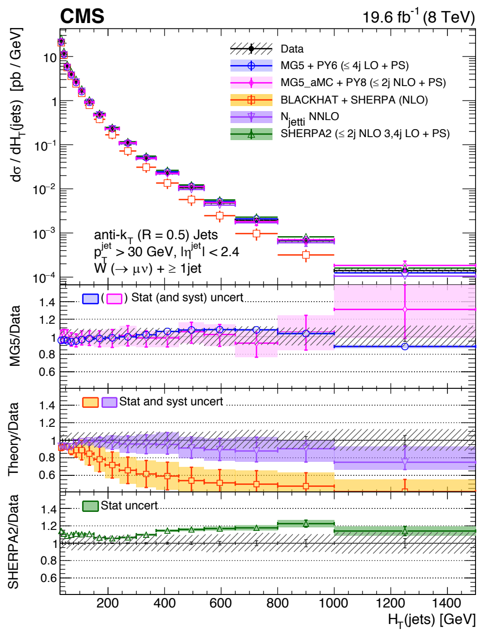
Vector bosons + jets: W @ 8 TeV

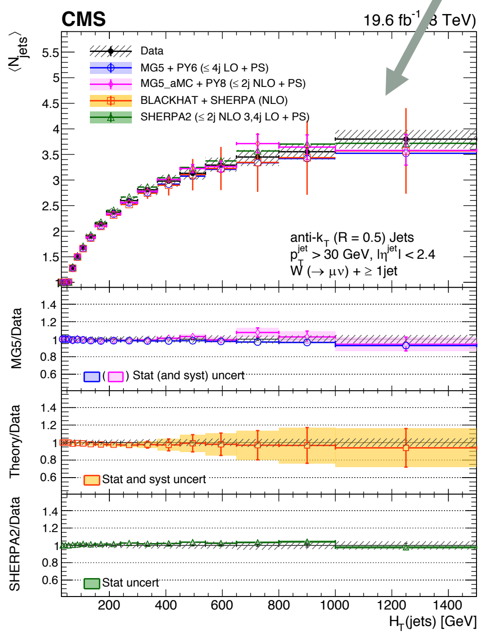
PRD 95 (2017) 052002

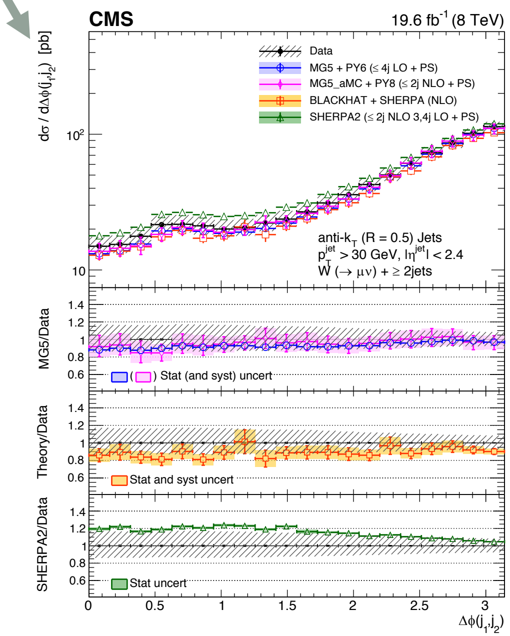
- Library of about 40 differential distributions, same for Z+jets
- Beyond classical jet spectra, look at jet-jet correlations, sensitivity to different parts of radiation:
  - rapidity differences: wide angle soft radiation (PS)
  - azimuthal differences: higher order radiation
  - average multiplicity vs H_T: wide angle gluon emission











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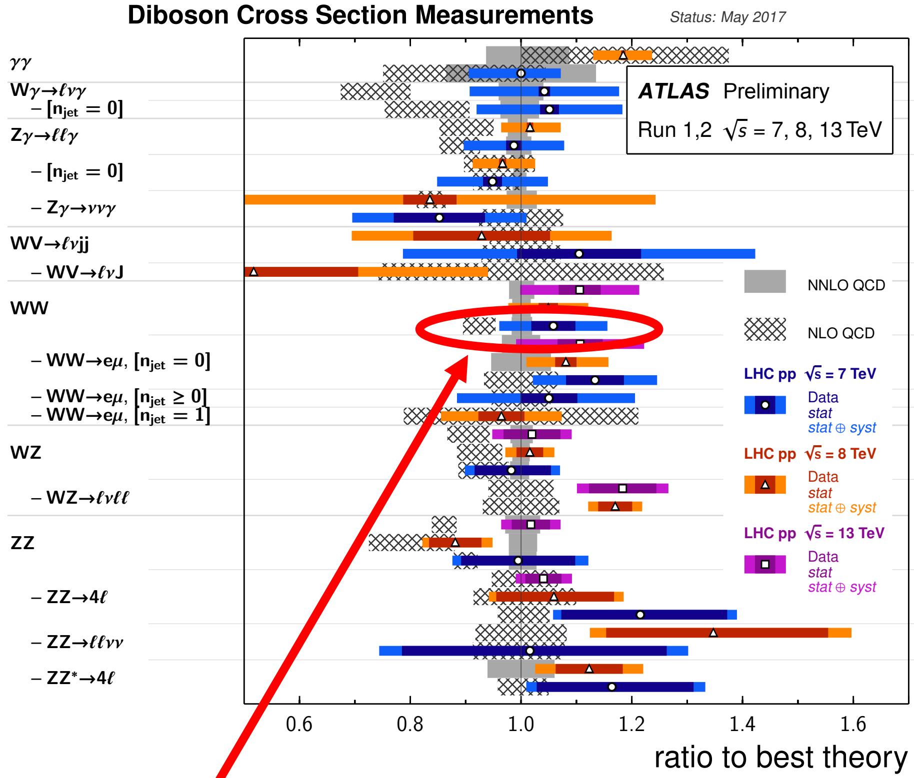
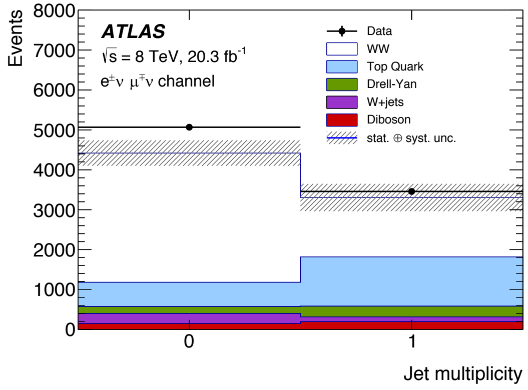
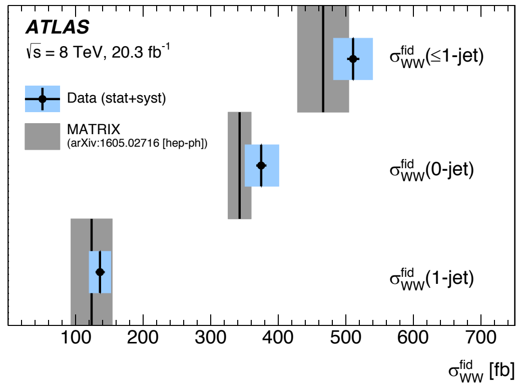
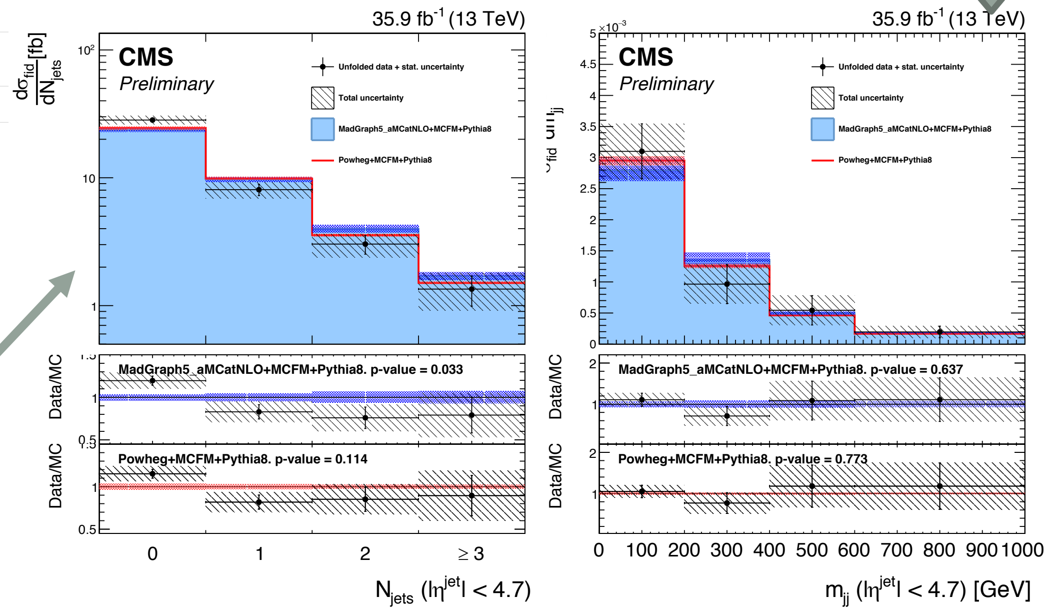
Dibosons + jets







- Study WW(eμ) +1 jet, p_T(j) > 25 GeV, |η(j)| < 4.5
  - tt background vetoed with anti b-tag
  - NNLO describes reasonably data
- ZZ(4ℓ)+jets, p_T(j)> 30 GeV, |η(j)| < 4.7
  - low statistics but clean sample



- Initial tensions of WW cross section with NLO calculations have shown the need for NNLO to describe dibosons processes
- With Run2 VBF/VBS start to become statistically interesting
  - understanding QCD jet production is fundamental for a proper measurement

CMS-PAS-SMP-16-019

From light to heavy partons

Heavy flavours can be tagged with high purity/efficiency

They play an important role in Higgs studies

- ***the most abundant Higgs decay, VH***

They are present in many BSM problems

Their heavy masses imply additional problems in calculations

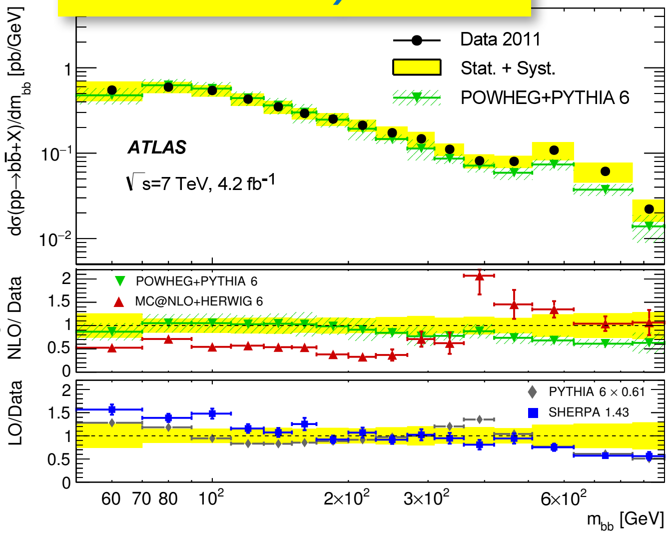
- ***e.g. 4FS vs 5FS flavour scheme to describe initial b states***

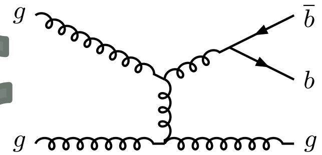
charm and bottom quarks (+ V)

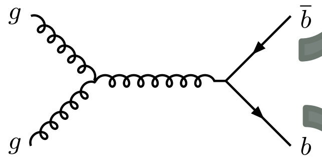
inclusive (+ V)

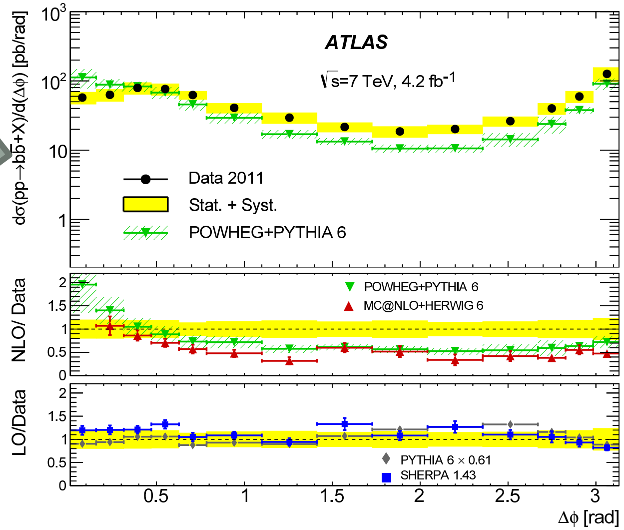
Probing b quark production: dijets and dihadrons

EPJC 92016) 76:670







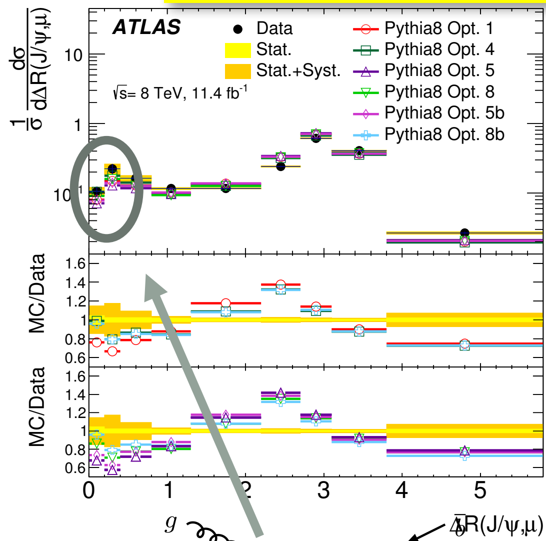


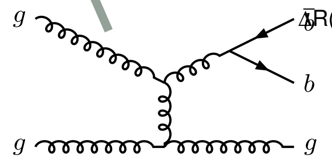
- b quark production: different topologies dominated by different mechanisms
- model of gluon splitting important for any study with associated b quarks
- testing QCD predictions for massive quark

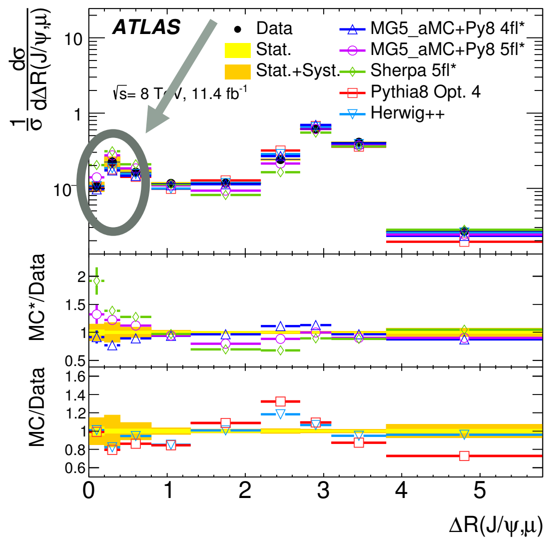
- reconstructed b dijets
  - well understood objects
  - but almost collinear gluon splitting may be missed

- b dihadrons
  - no finite jet size allows measurements of close objects
  - test of different gluon splitting kernels in PYTHIA8
  - comparing 4FS and 5FS descriptions

arXiv.1705.03374

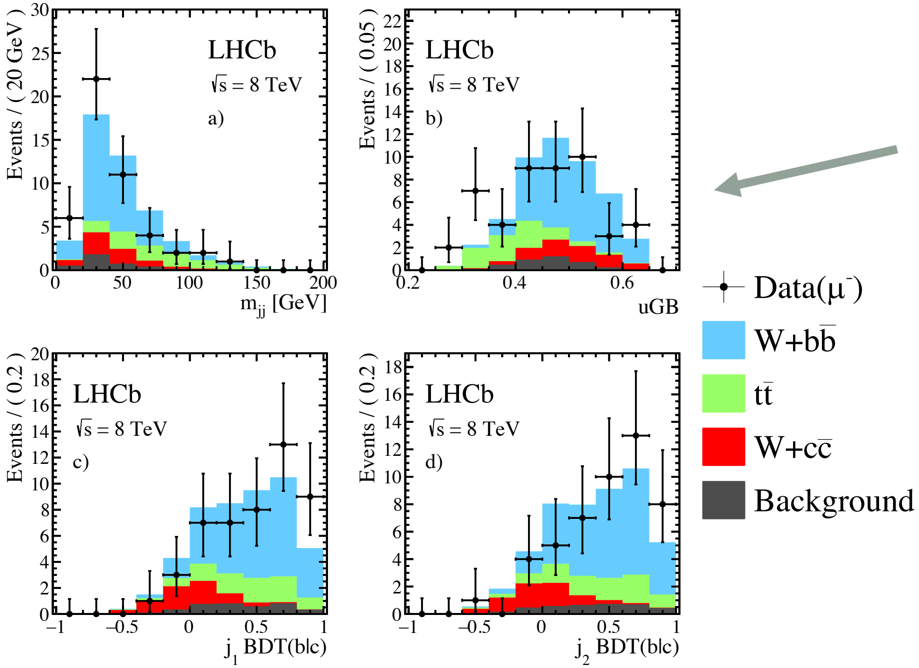






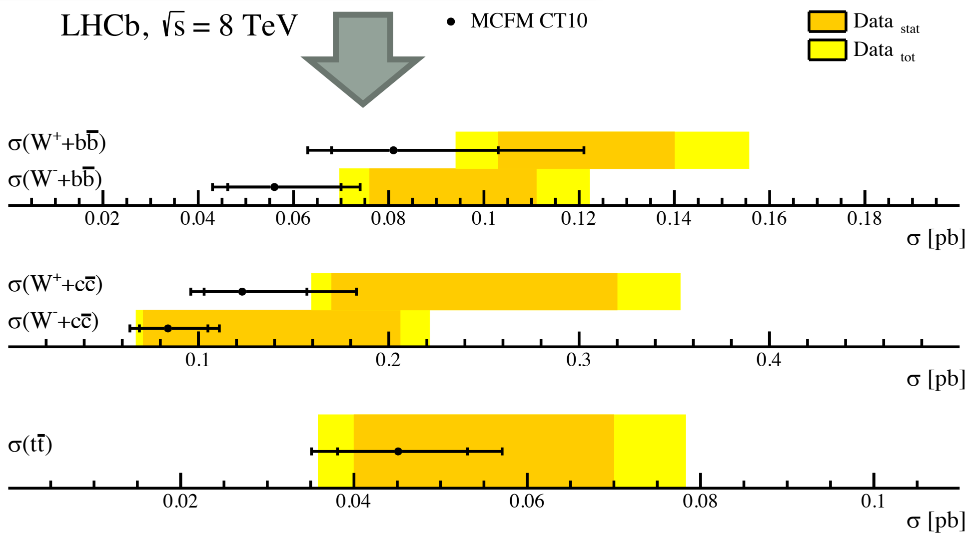
$B(\to J/\psi[\to \mu^+\mu^-]+X)B(\to \mu+X)$

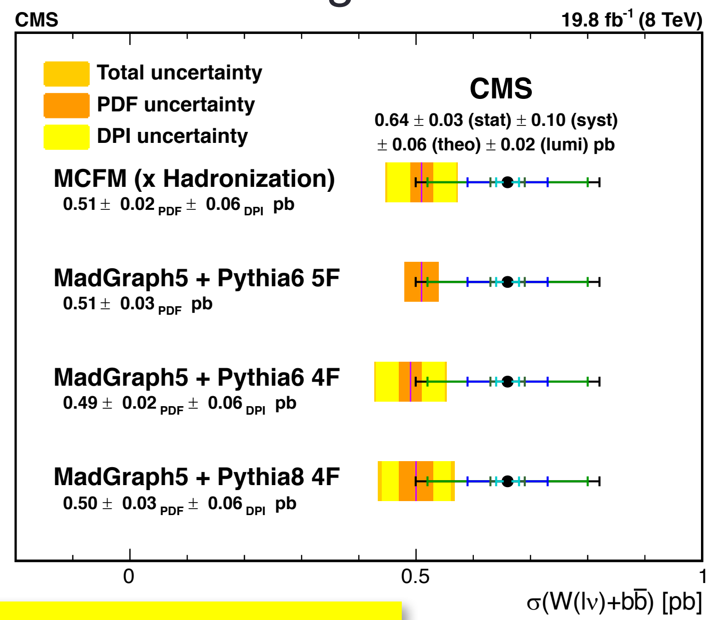
Vector bosons and HF jets: Wbb,Wcc



- LHCb: complementary acceptance to ATLAS/CMS
  - $p_T(e/\mu) > 20$ GeV, $2 < \eta(e/\mu) < (4.25/4.5)$
  - $p_T(j) > 12.5$ GeV, $2.2 < \eta(j) < 4.2$, $p_T(\text{miss}) > 15$ GeV
- Simultaneous fit of Wbb,Wcc and tt
  - BDT(j) for Wcc/Wbb separation
  - m_{jj} and uGB MVA discriminant for tt separation
- CMS: control samples of tt opposite leptons and + jets to extract Wbb signal

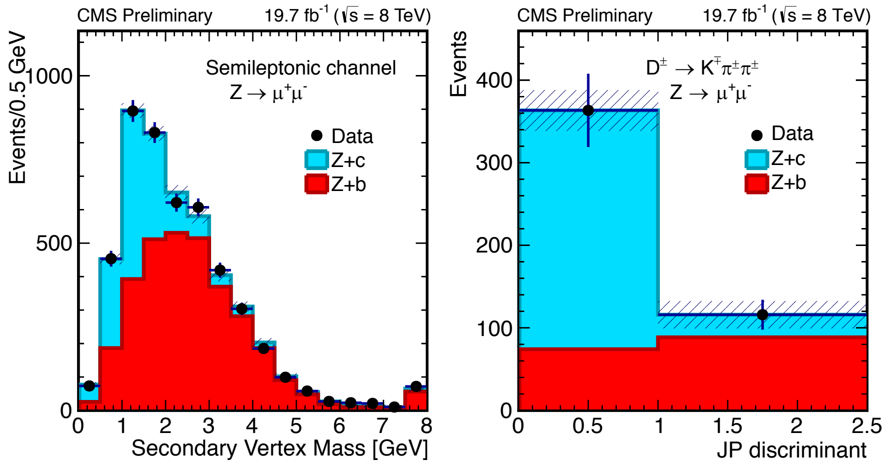
Phys Lett B 767 (2017) 110





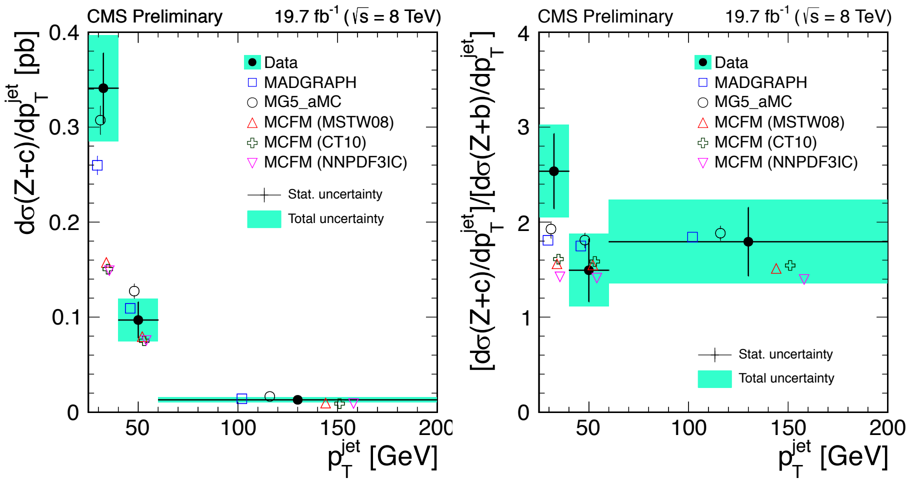
EPJC (2017) 77:92

Vector bosons and HF jets: Zc, Zb



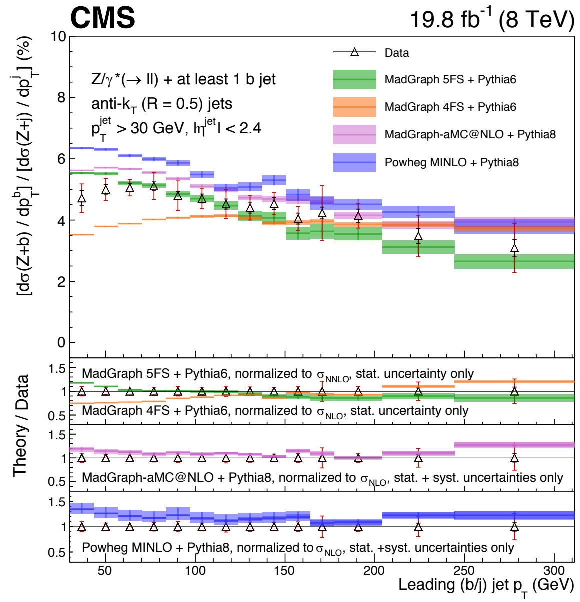
CMS-PAS-15-009

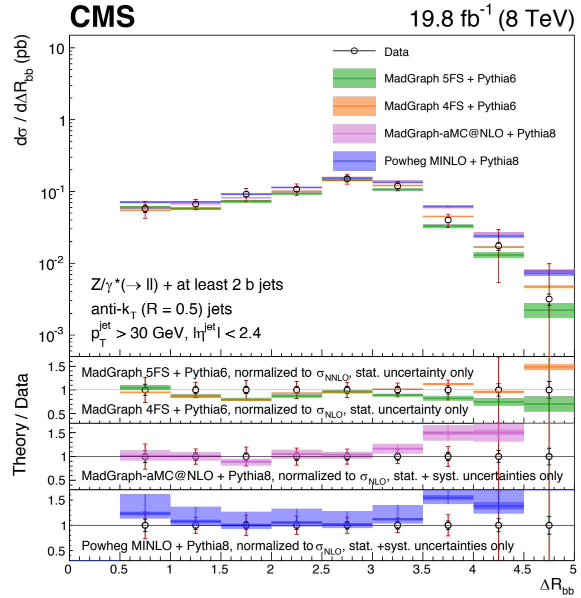
- Extraction of Zc and Zc/Zb ratio from jets with leptons decays or reconstructed exclusive D decays
- W+c pure jet sample allows a data driven efficiency estimate
- Fixed order calculations fail to predict soft jet spectra



arXiv.1611.06507

- High b jet selection purity/efficiency allows a detailed measurement of the event kinematics
- ~ 20 observables to characterize ≥ 1 and ≥ 2 b jets
- 4FS vs 5FS: normalization and slope differences
  - 4FS fails to describe several spectra in their whole range





From light to heavy partons

$V = \gamma$,W,Z

top quarks

inclu

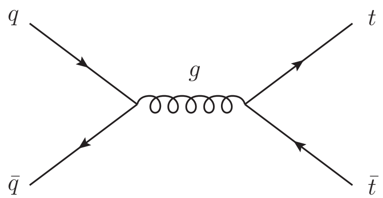
The heaviest fundamental particle of SM

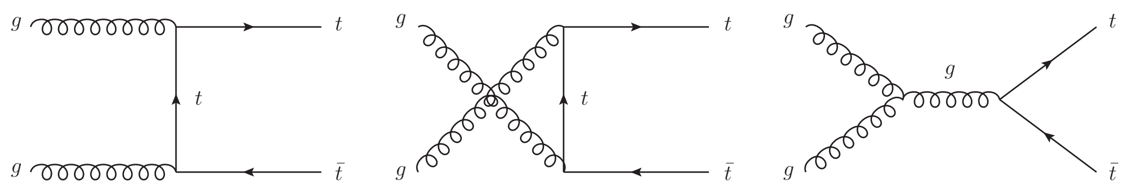
- ***heavier than Higgs boson***
- ***its mass plays a special role in global EWK fits through radiative corrections***

It doesn't form bound states, it cannot hadronize directly

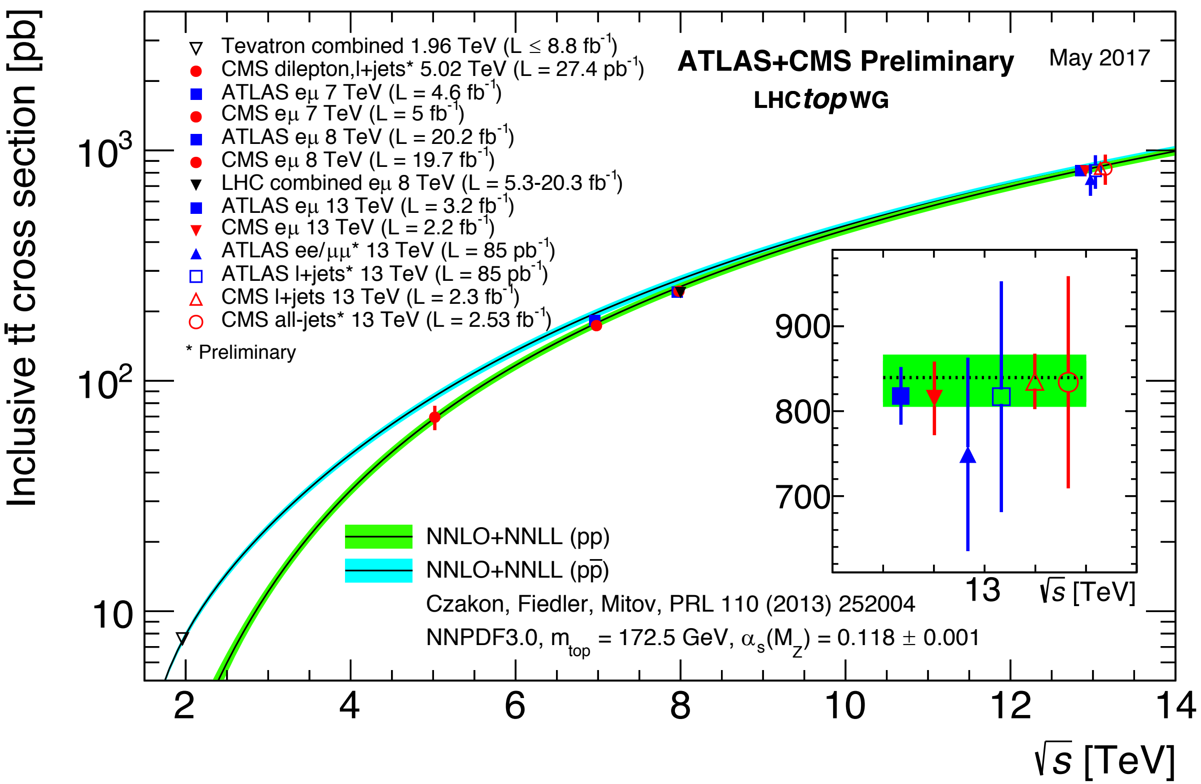
- ***decays and their properties are mostly related to EWK couplings***
- ***production is a particularly important process of QCD***

Top pair production: a QCD laboratory

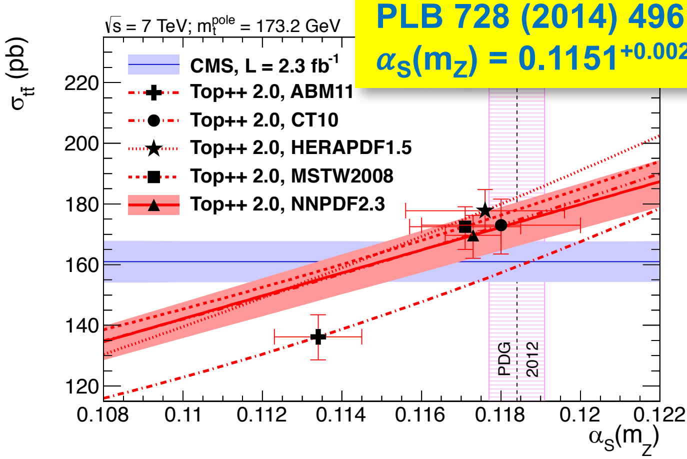




Tevatron	**85%**	**15%**
LHC	**10%**	**90%**



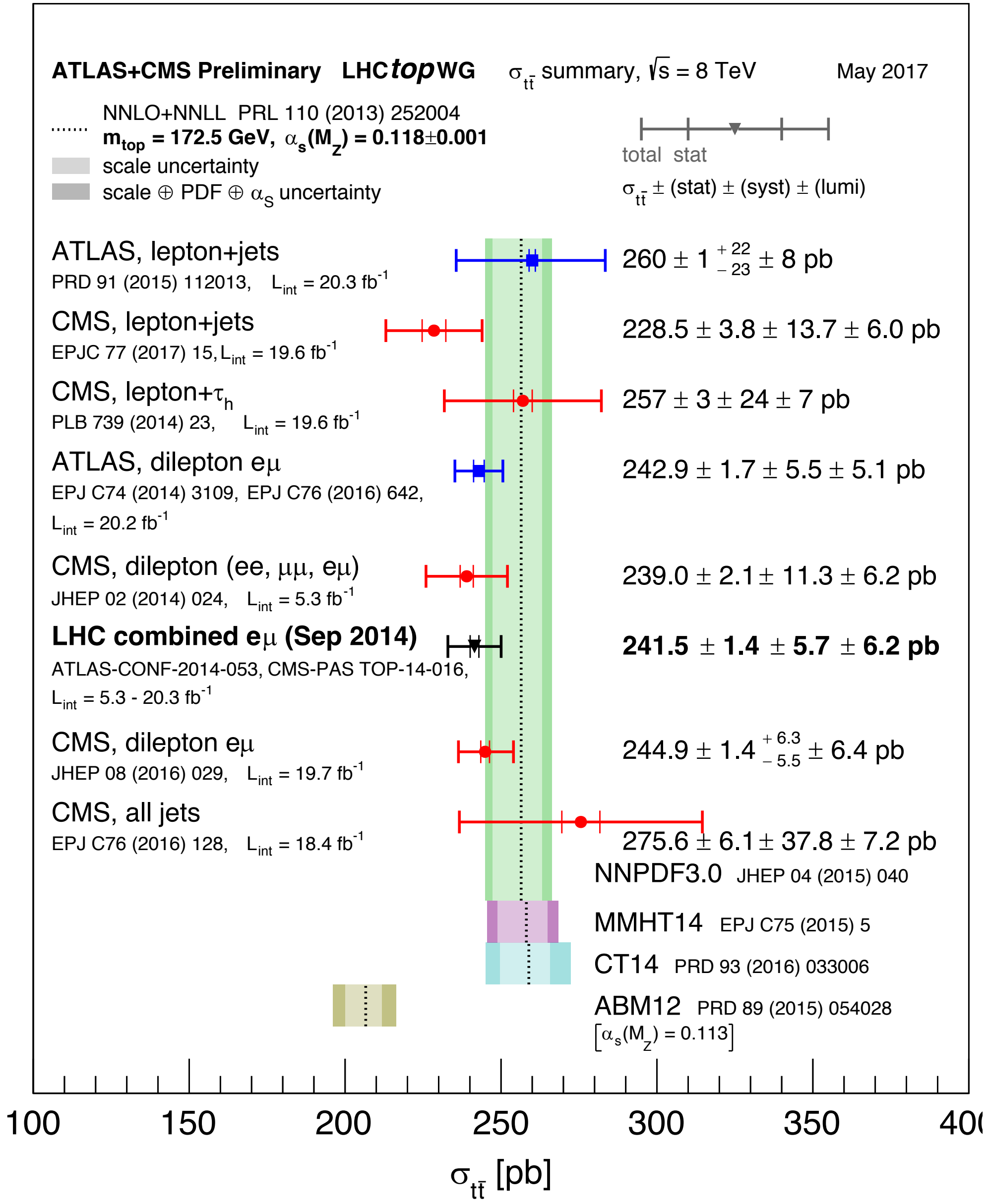
- Predictions available at NNLO+NNLL
  - evolution well described from Tevatron up to 13 TeV
- Gluon production dominating at LHC
  - helping in gluon PDF constraints
- If m_{top} fixed, determine α_S

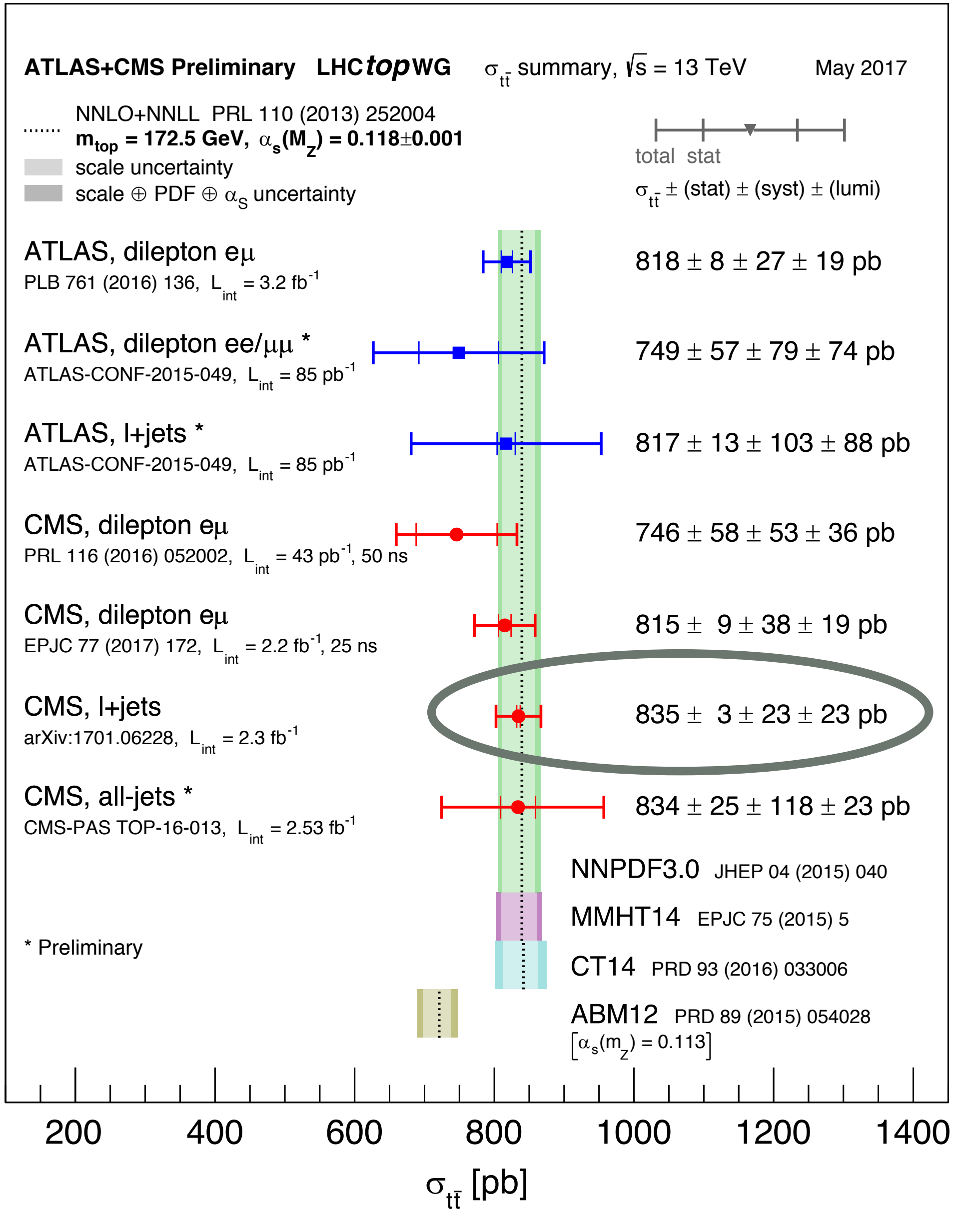


PLB 728 (2014) 496

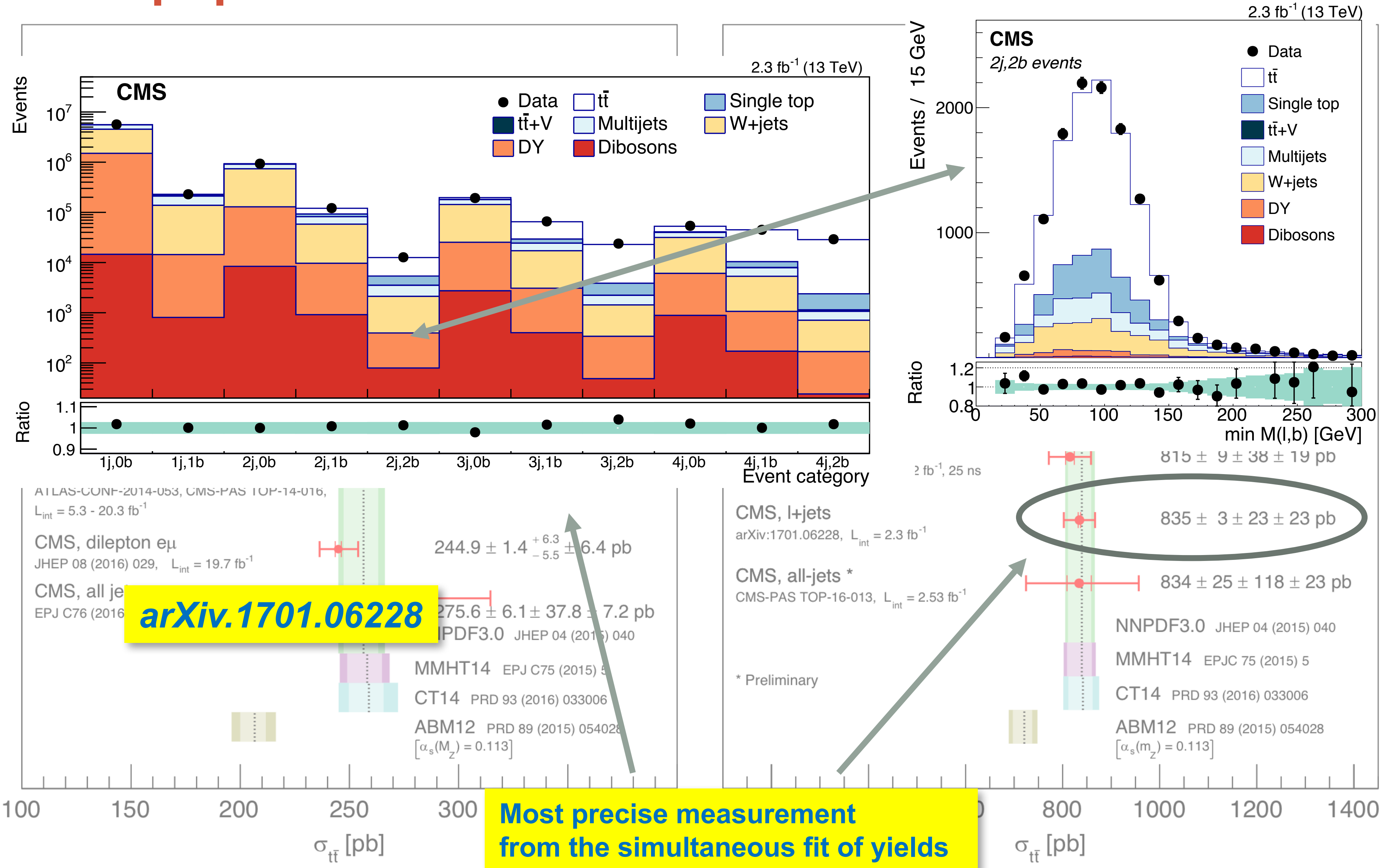
$\alpha_S(m_Z) = 0.1151^{+0.0028}_{-0.0027}$

Top pair inclusive cross section





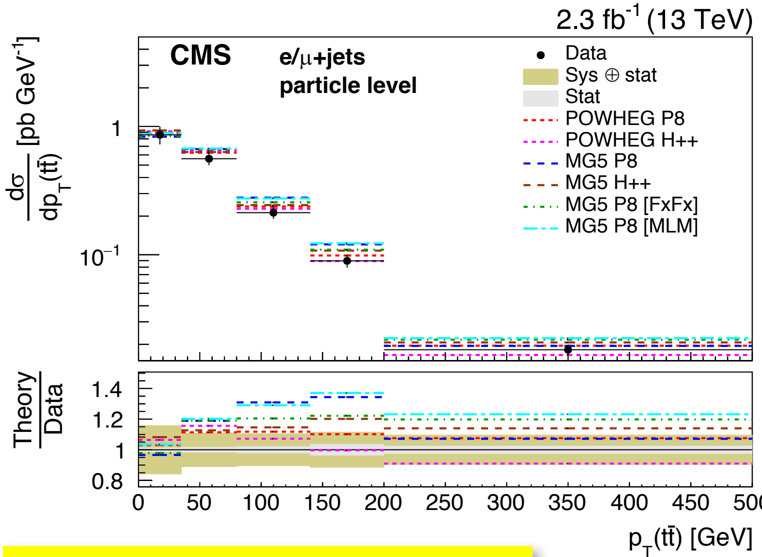
Top pair inclusive cross section



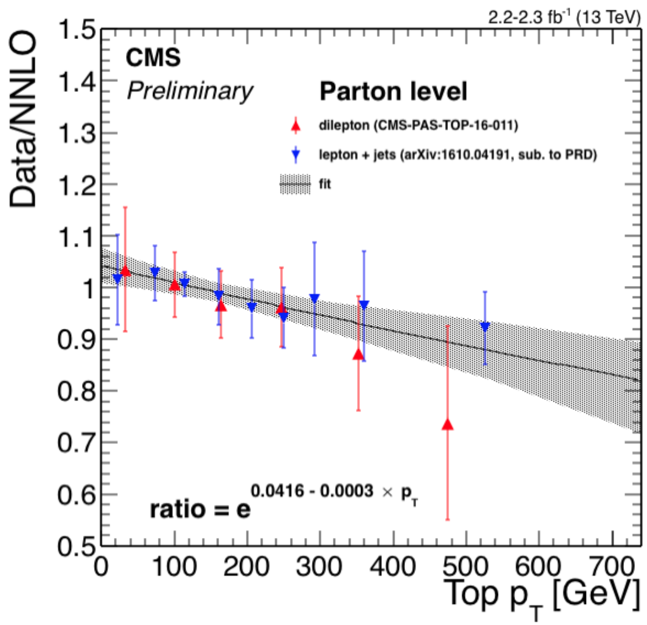
arXiv.1701.06228

Most precise measurement from the simultaneous fit of yields in 44 independent event categories

Top pair differential cross sections

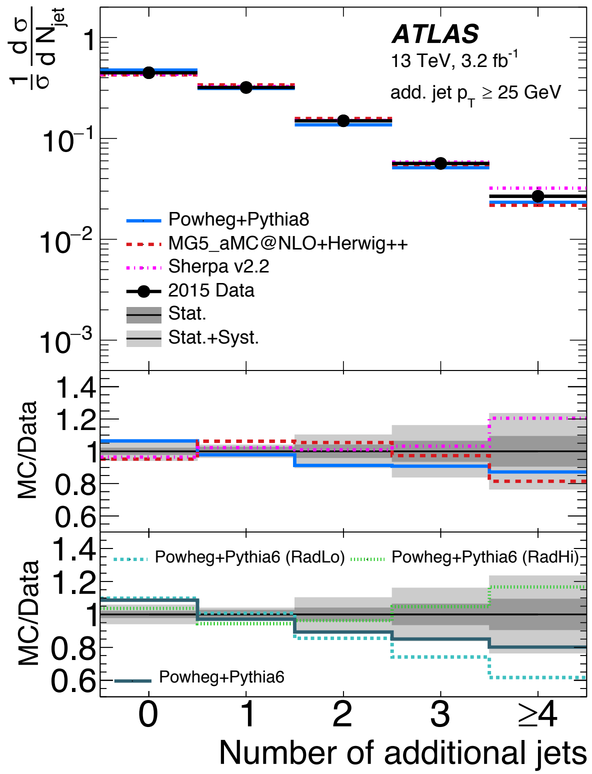


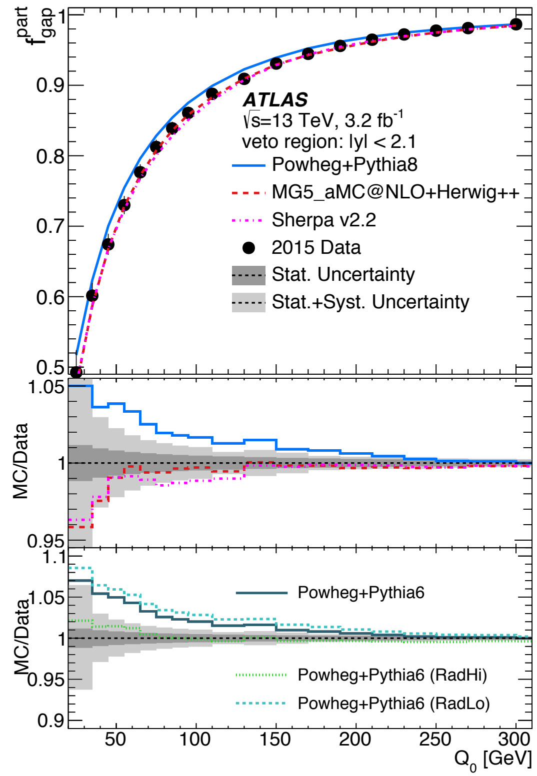
arXiv.1610.04191, PDR



- Large library of observables investigated
  - both inclusive and looking for additional jets, test of higher order corrections model
  - long standing issue in modelling the top and top pair p_T spectrum
    - studies to retune the PS to compensate for this

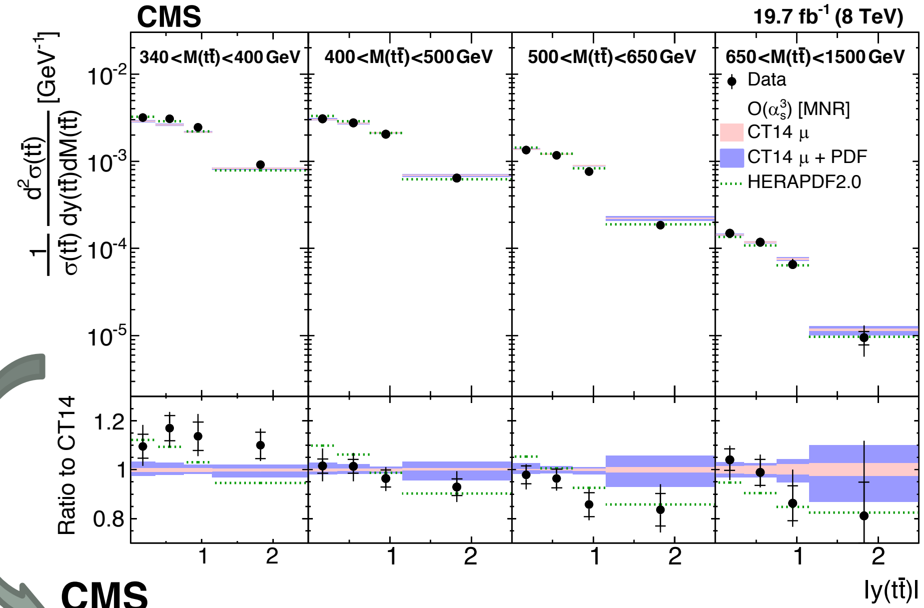
EPJC (2017) 77:200



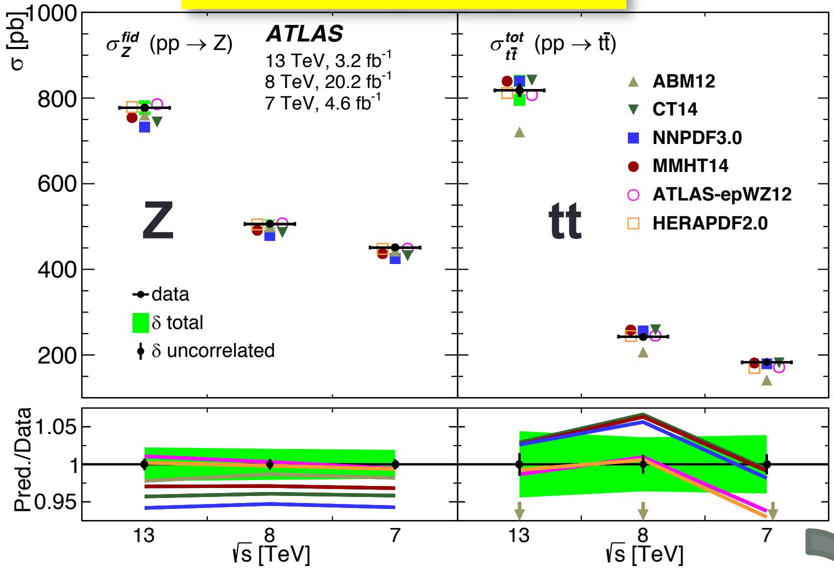


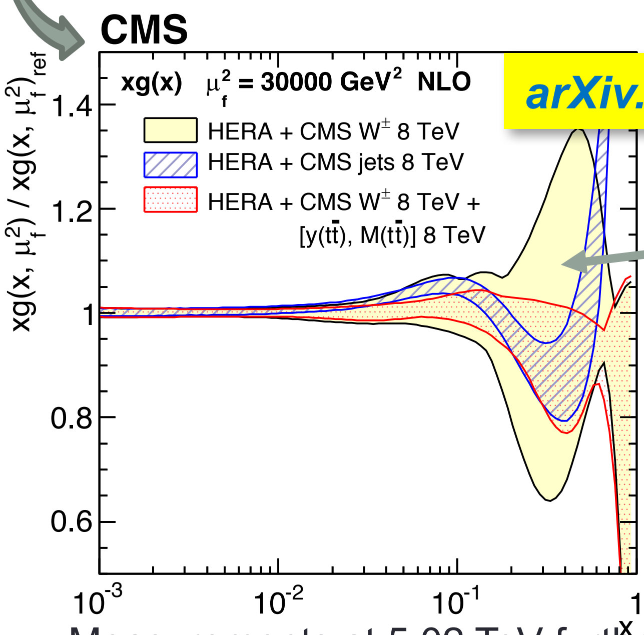
Study of extra jet production in $e\mu$ decays
small background and no contamination from top decay

Constraints on PDFs from tt cross sections



JHEP02 (2017) 117



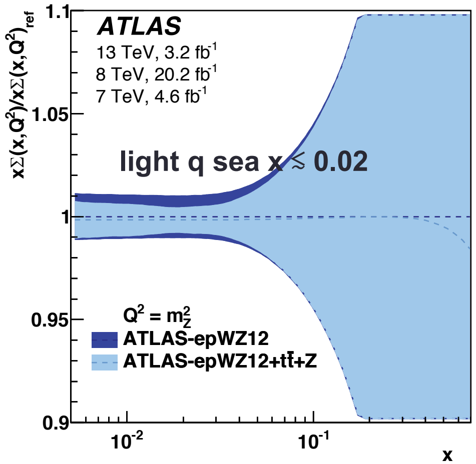


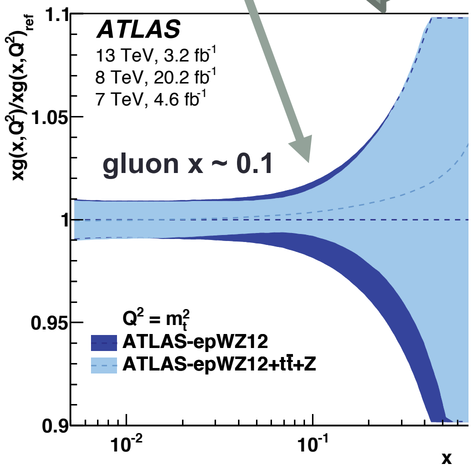
arXiv.1703.01630

- $e\mu$ double differential distributions can constrain gluon PDF
- use xFitter to evaluate impact

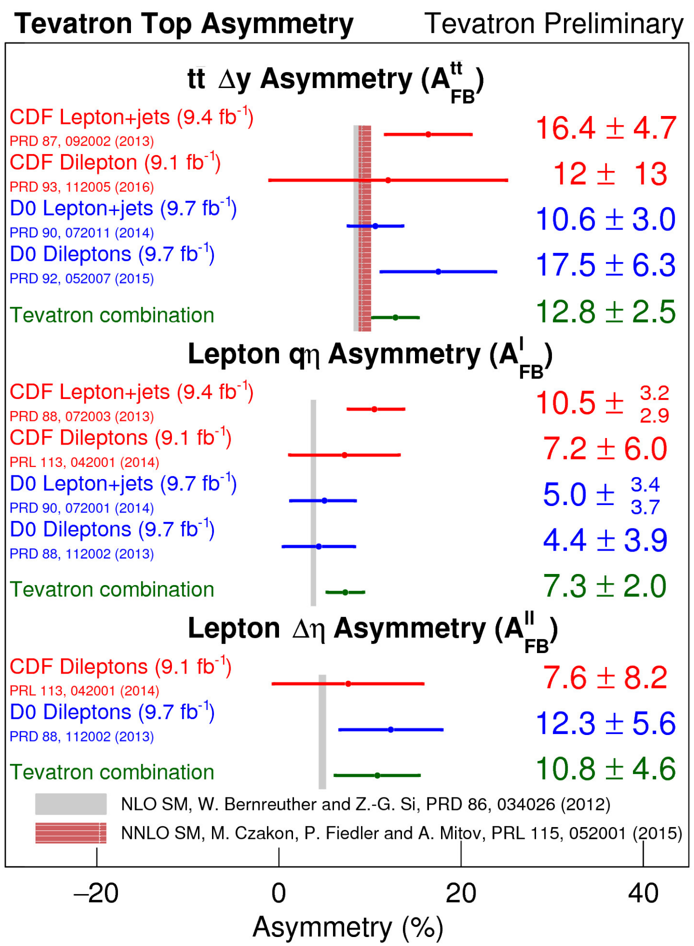
Measurements at 5.02 TeV further extends sensitivity to high-x gluons (CMS-PAS-TOP-16-023)

- Comparison of NNLO(+NNLL) predictions **simultaneously with Z and tt cross sections**
  - most systematics almost cancel in the ratio
- Alternative way to constrain mostly the gluon PDF

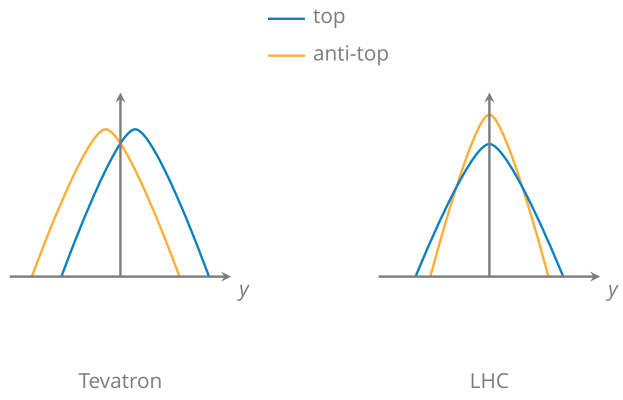




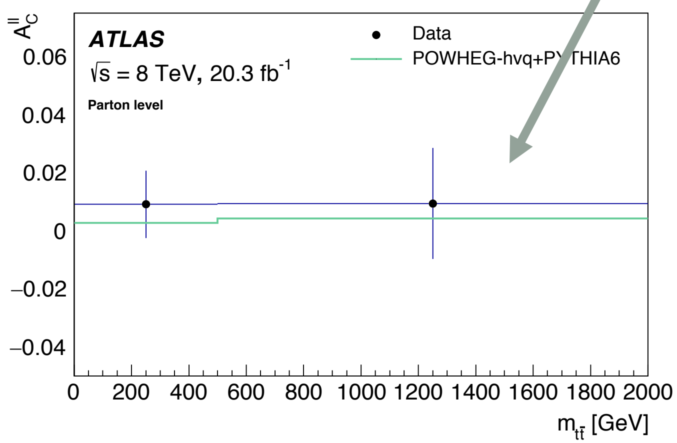
Top charge asymmetry

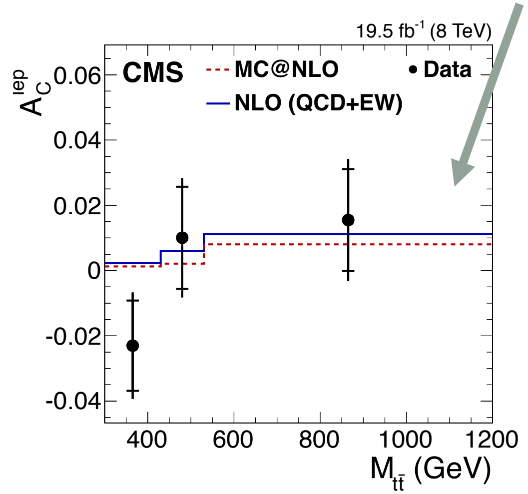


- Interference between LO and NLO qqbar top pair production causes asymmetry
- Tevatron: asymmetric state
  - top more abundant in proton direction
- LHC: symmetric state
  - but valence quarks more boosted than sea antiquarks



$$A_C^{\text{lep}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)},$$





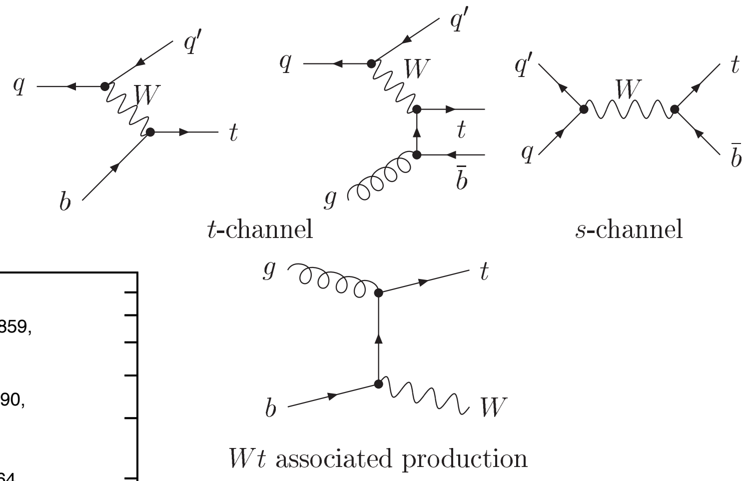
CDF Note 11206
D0 Note 6492

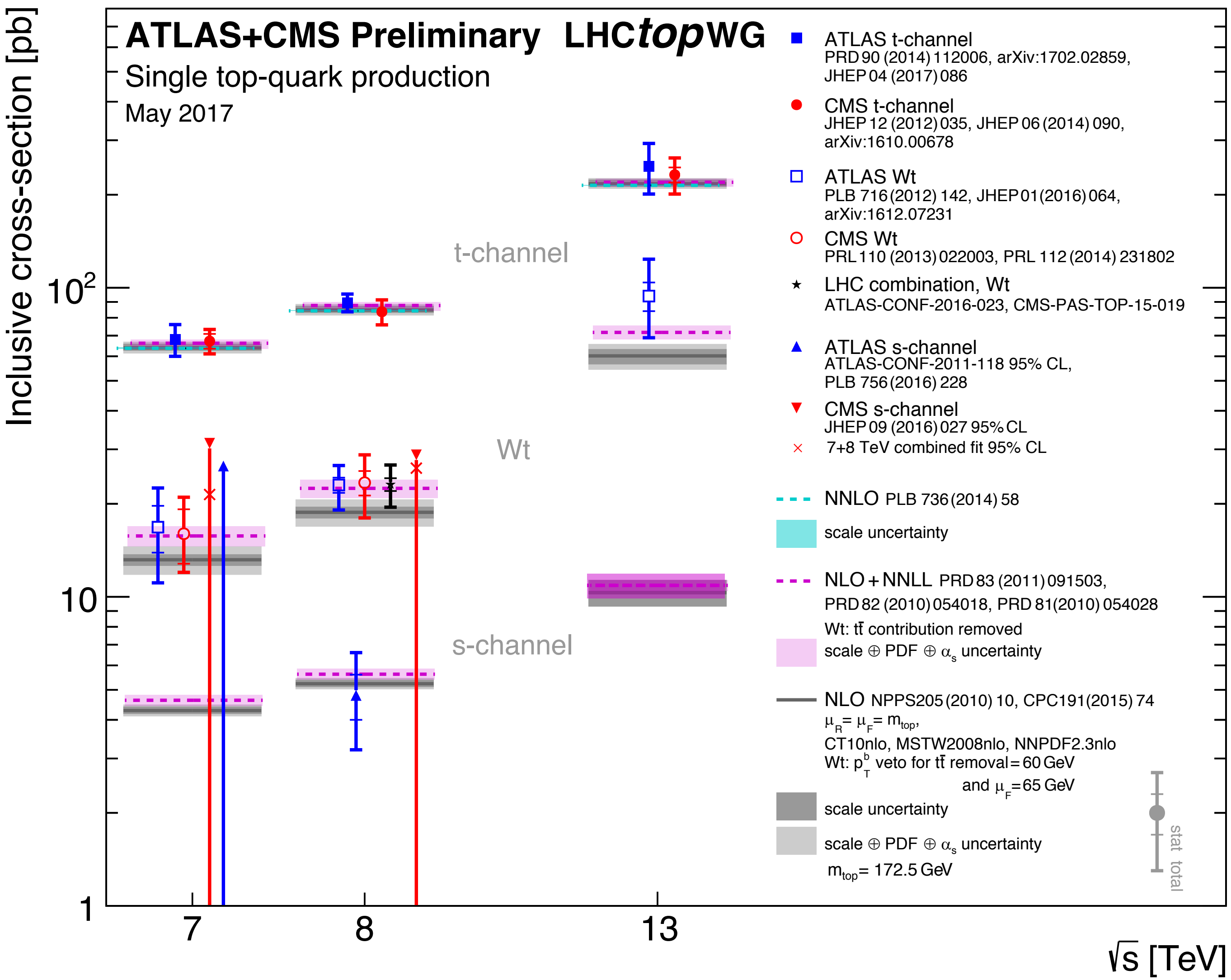
PRD 94 (2016) 032006

PLB 760 (2016) 365

- Leptonic asymmetry: the most direct experimental measurement
- No evidence of systematic departure from predictions

Single top production



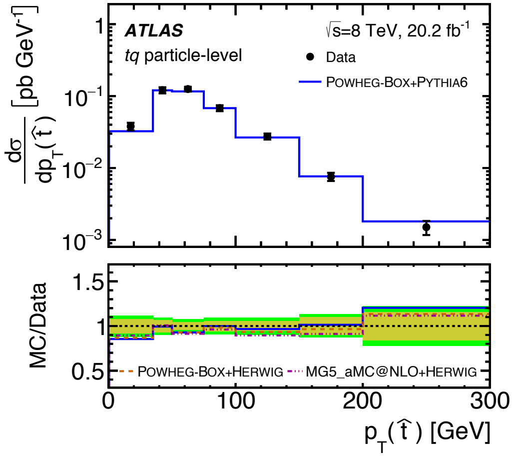


- Single top: mostly about EWK physics
  - Wtb, etc…
- Still important to have good QCD modelling
- t-channel particularly interesting
  - ratio of top and antitop cross sections: sensitivity to u/d PDF ratios

t-channel single top

- 1 lepton, 1 bj, 1j, signal extraction with NN/BDT
  - QCD background from control region
- Reasonably good description of kinematic
- Sensitivity to PDFs: compare with NLO calculations
  - NNLO calculation at present does not allow full uncertainty treatment, expected to be close to NLO

CMS-PAS-16-004



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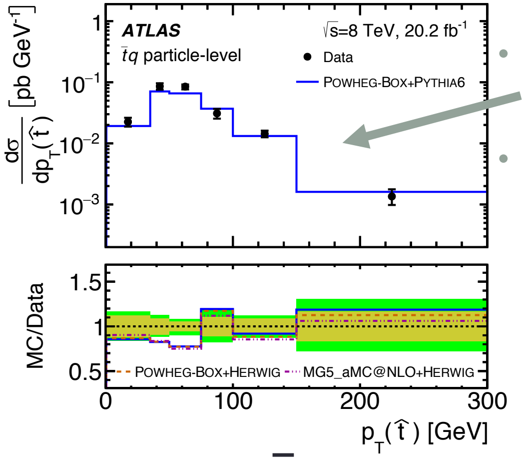
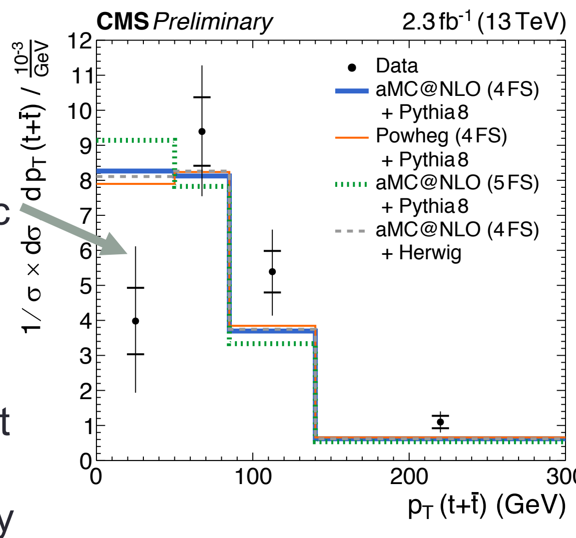
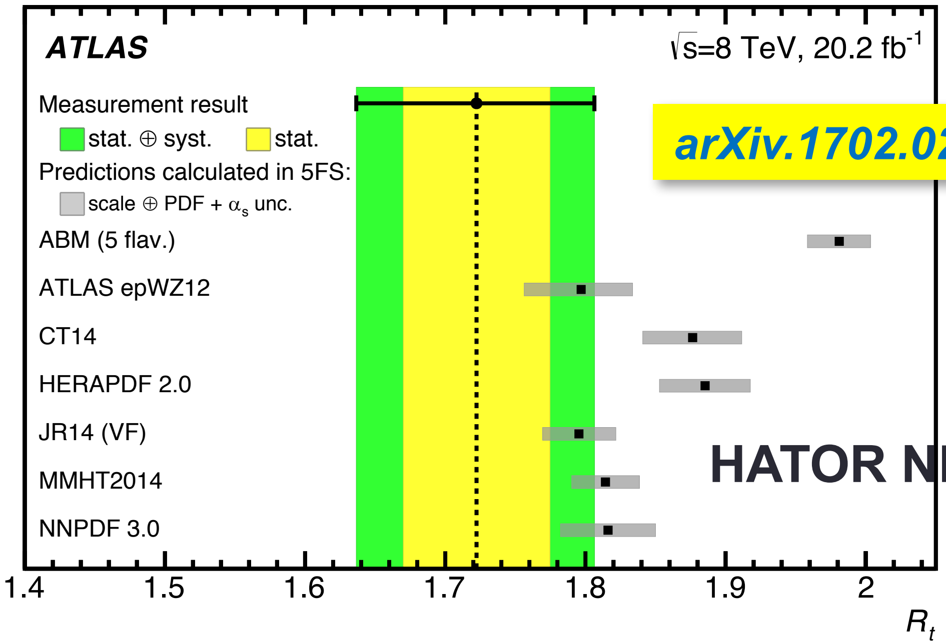


$\bar{t}$

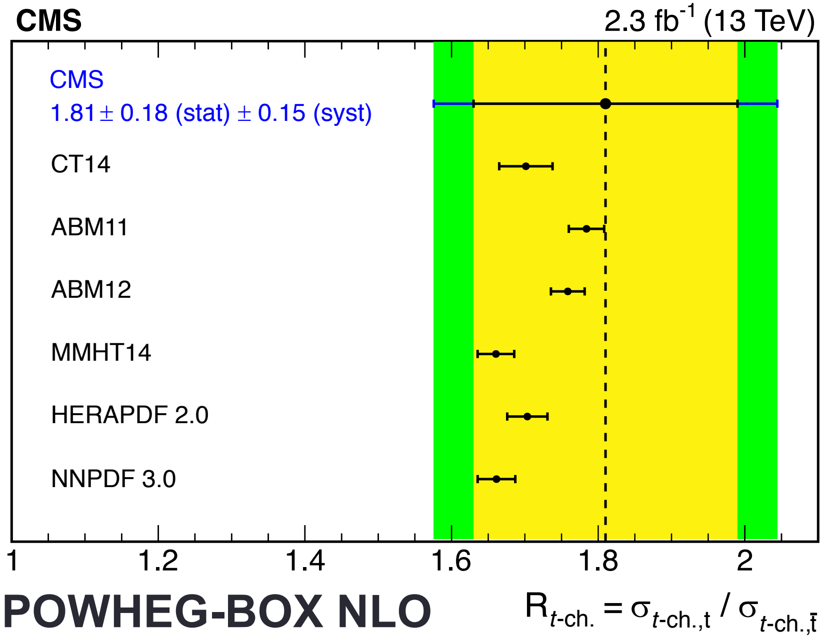


arXiv.1610.00678, PLB



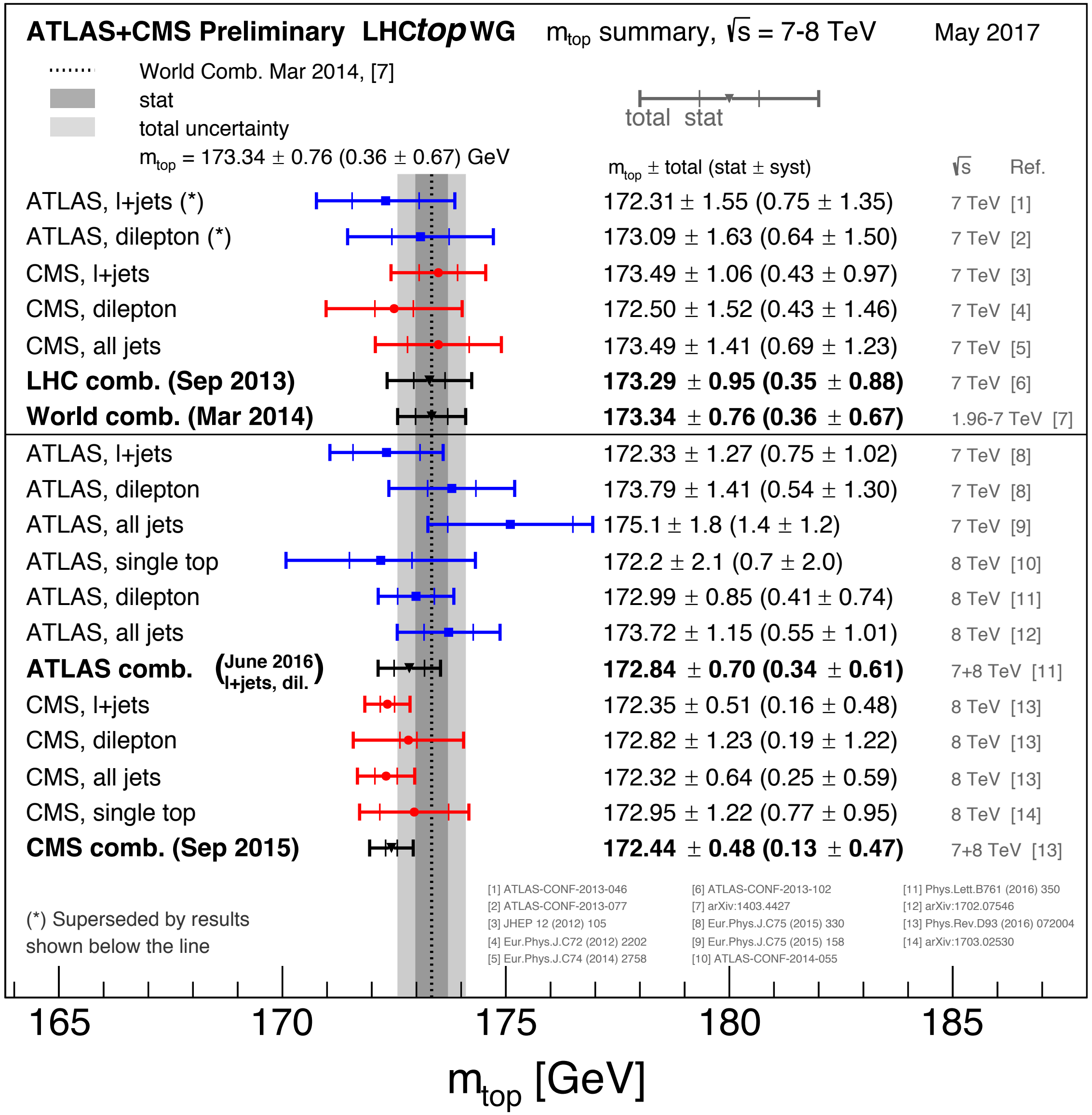
arXiv.1702.02859

HATOR NLO



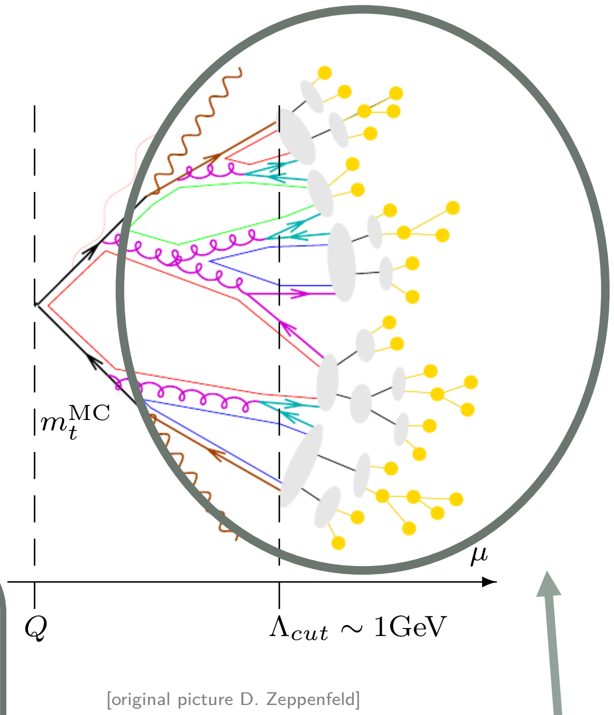
POWHEG-BOX NLO

Top mass: QCD interpretation issues



Preliminary Tevatron 2016 combination: 174.30 ± 0.65 arXiv.1608.01881

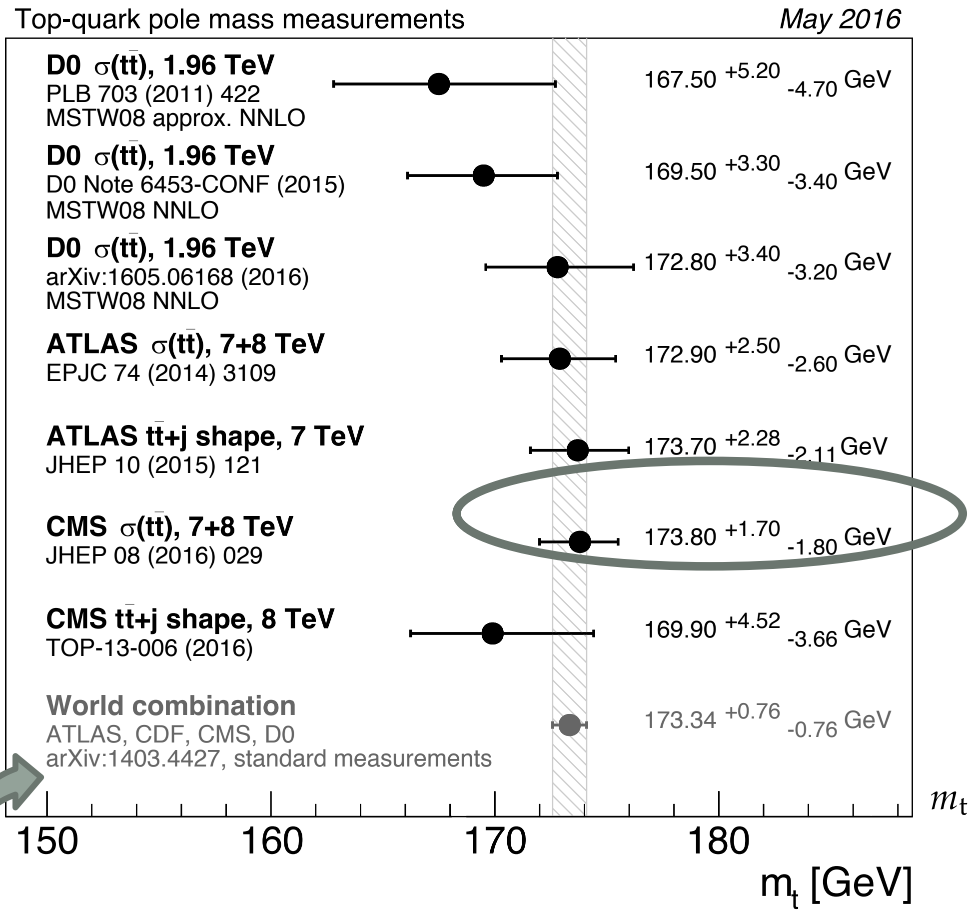
- Fundamental parameter of SM
  - key role in global EWK fits
- See parallel session for a detailed discussion



- Standard mass measurement: from kinematics of decay products
- rely on **PS+hadronization models**
- key interpretation problem: how is m_t^{MC} related to the top pole mass?
- O(Λ_{QCD} to 1 GeV) uncertainty?

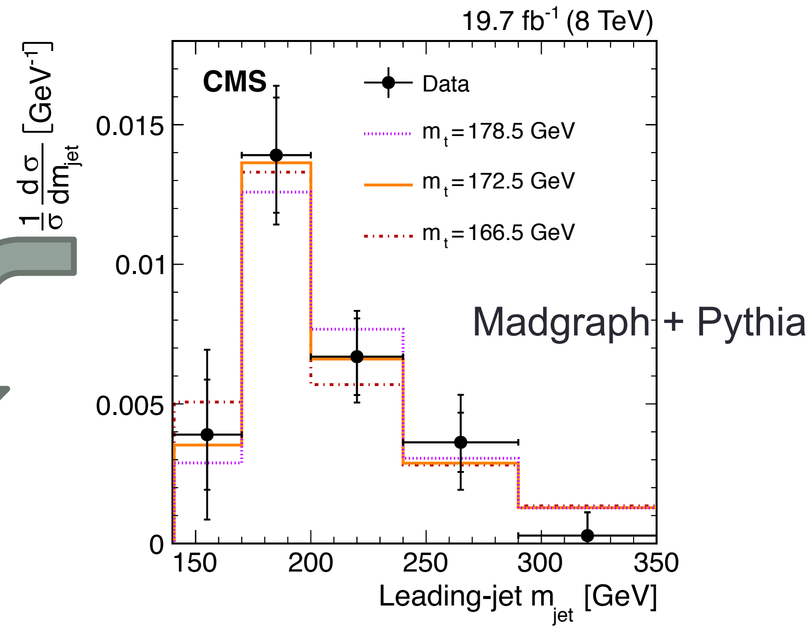
Top mass: could QCD provide alternative measurements?

arXiv.1703.06330



- Several alternative methods studied
- m_t^{pole} dependence on σ(tt) is theoretically clean
  - but systematically limited, main single source luminosity

- Boosted semileptonic tt pair:
  - leading jet: Cambridge-Aachen jet R = 1.2, p_T > 400 GeV
  - signature of fully hadronic top decay
  - +1 l, p_T > 45 GeV, only 1 j p_{T} > 150 GeV



$$m_t = 170.8 \pm 6.0\,(\text{stat}) \pm 2.8\,(\text{syst}) \pm 4.6\,(\text{model}) \pm 4.0\,(\text{theo})\,\text{GeV}$$

- Room to improve experimental precision in Run2 and beyond
  - more statistics, better understanding of jet mass systematics
- We need a high precision calibration relating particle MC and m_t^{pole} to reduce theoretical uncertainties

Conclusions

- QCD at colliders is an alive and dynamic field
  - just a (personal) selection of topics presented
- QCD is not only interesting in itself, but essential for the whole collider physics program in next years
  - any process at LHC is affected by proton structure and QCD corrections
  - no “easy” BSM signal $\Rightarrow$ we need to understand well SM processes to detect subtle deviations from SM
  - electroweak precision physics is not possible without mastering QCD corrections
- It’s very unlikely someone will get a Nobel prize by performing QCD studies at colliders
  - but we might miss one if we don’t do them…

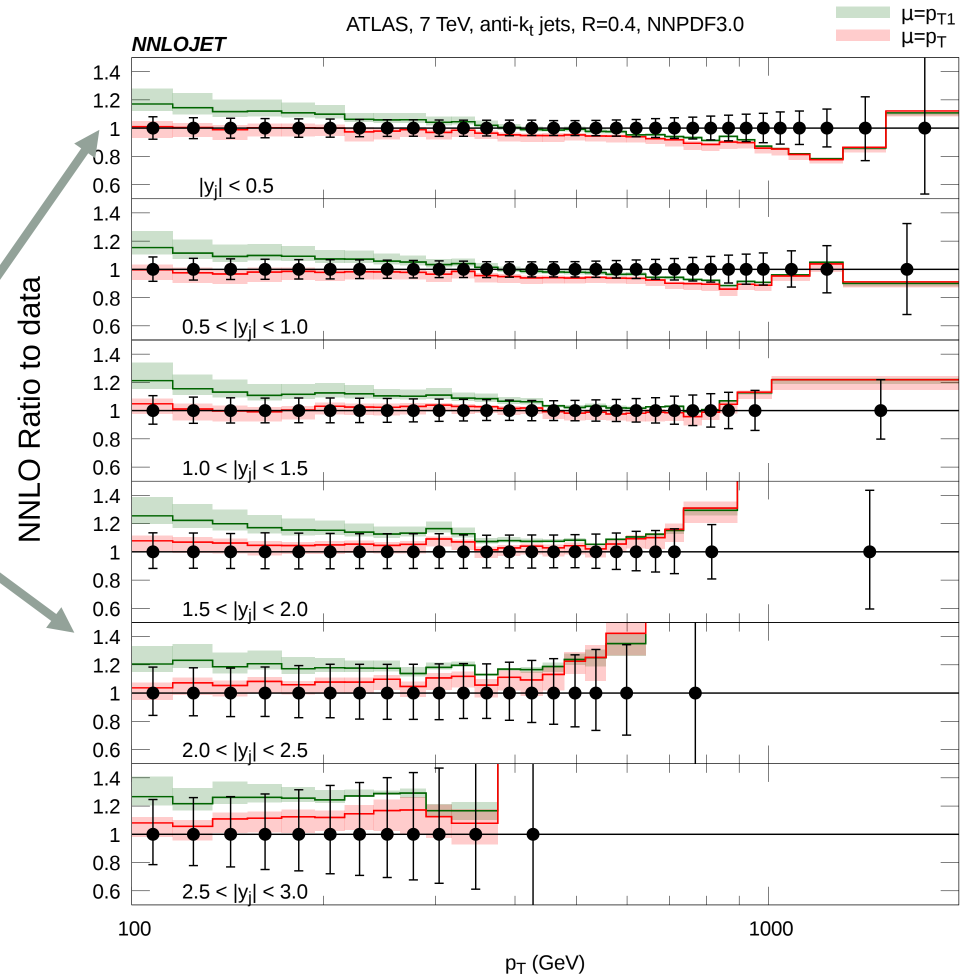
BACKUP

Theory intermezzo: the scale choice matters

- When comparing data and theory, the scale choice for calculations is essential
- arXiv.1704.00923: inclusive jet prediction at NNLO
- Different possible scale choices studied:
  - jet p_T (CMS)
  - leading jet p_T (ATLAS)
- Observed differences between predictions using these scales exceeds the estimated scale uncertainties (usual ×2,×0.5 recipe)
- NNLO: :-)
- NNLO uncertainty: :-{ ?

- dijets, multijets: usual choice is average p_T of 2 leading jets
  - but if the topology is 3-jet (or more) like?

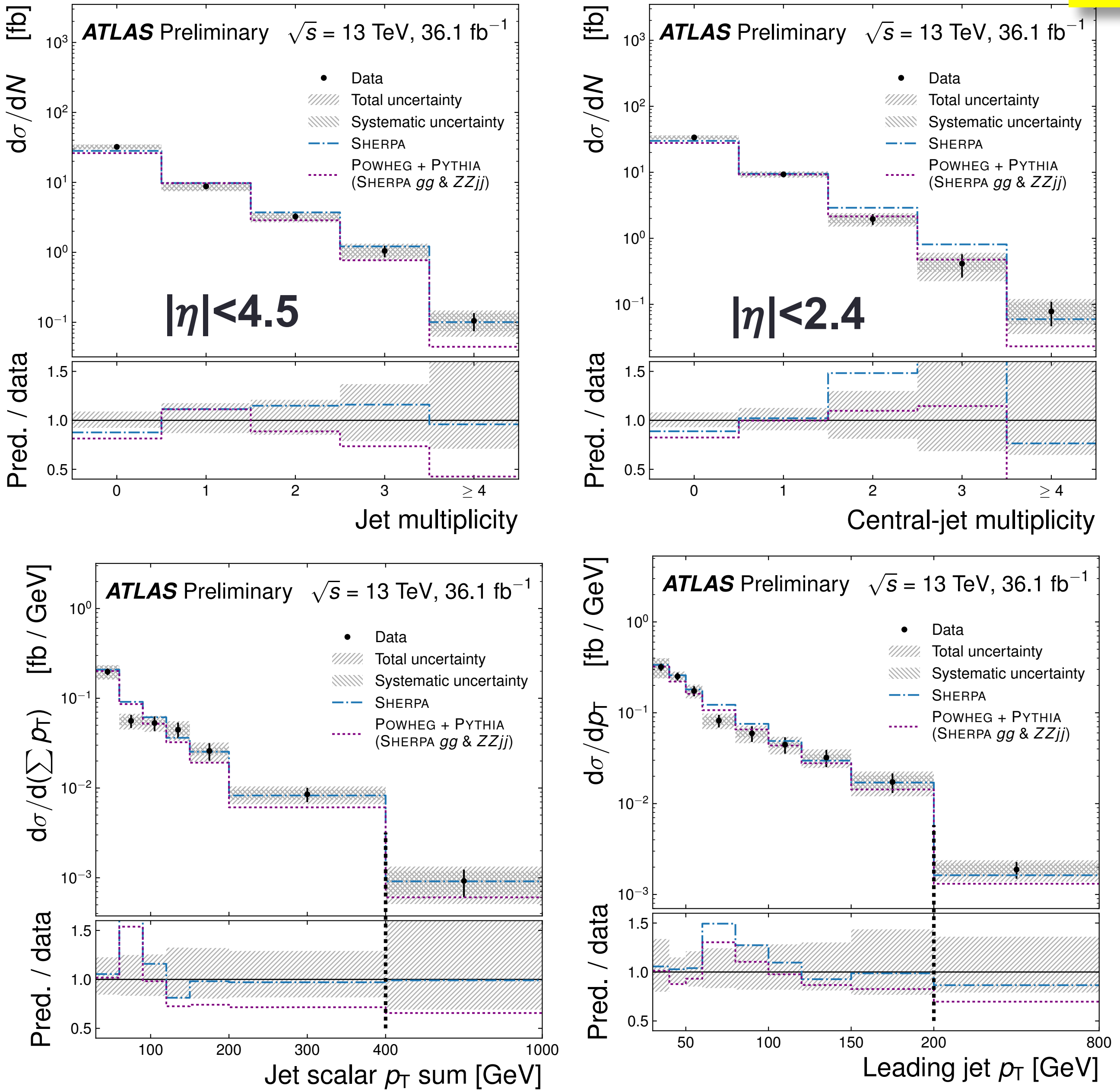
- CMS dijets: use of $p_{T(ave)}*e^{0.3y*}$
  - correlate p_T and rapidity
  - compensation for scale induced instabilities at high rapidity differences?



see ideas in PRL 69 (1992) 1496

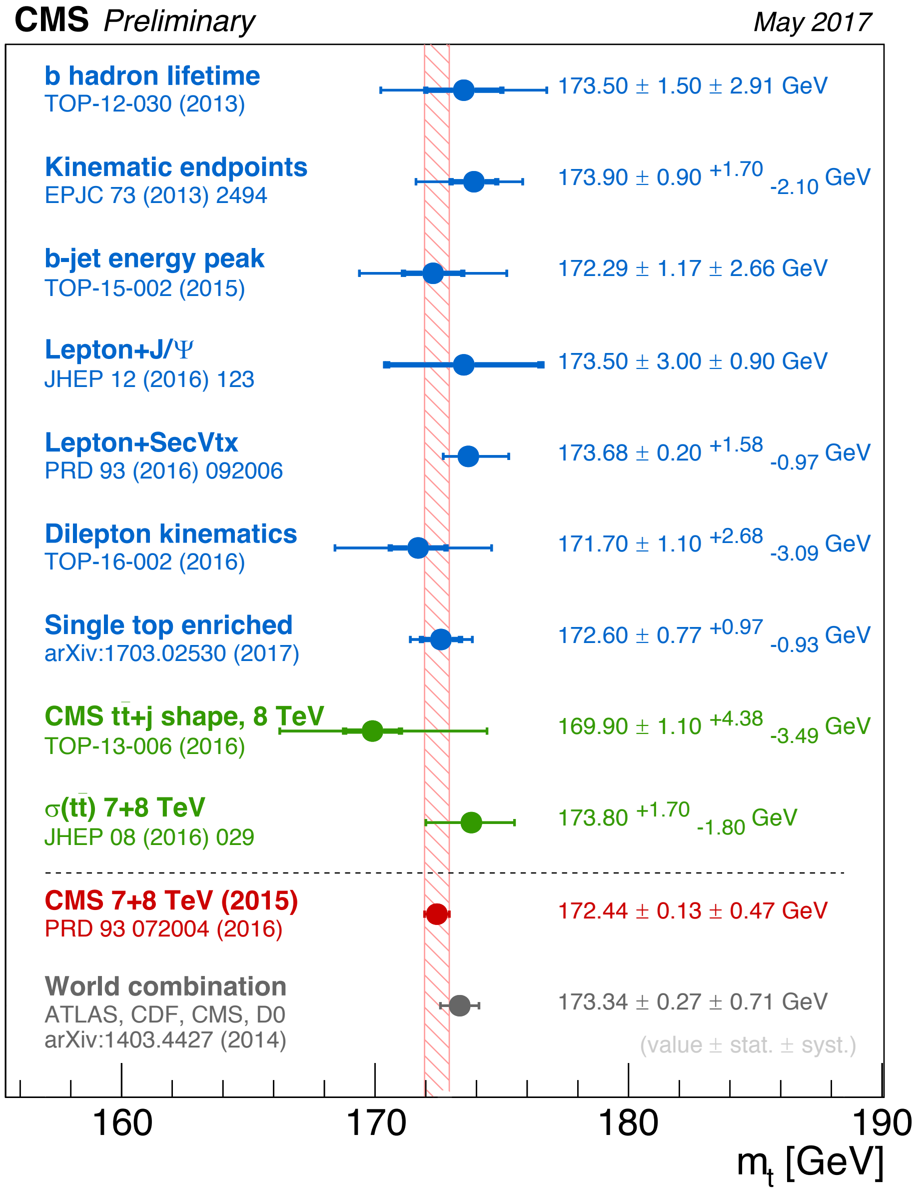
ZZ+jets differential distributions

ATLAS-CONF-2017-031



- Statistics still a limiting factor
- Theory uncertainty in unfolding and JES main systematic sources
- Reasonable overall data/MC agreement

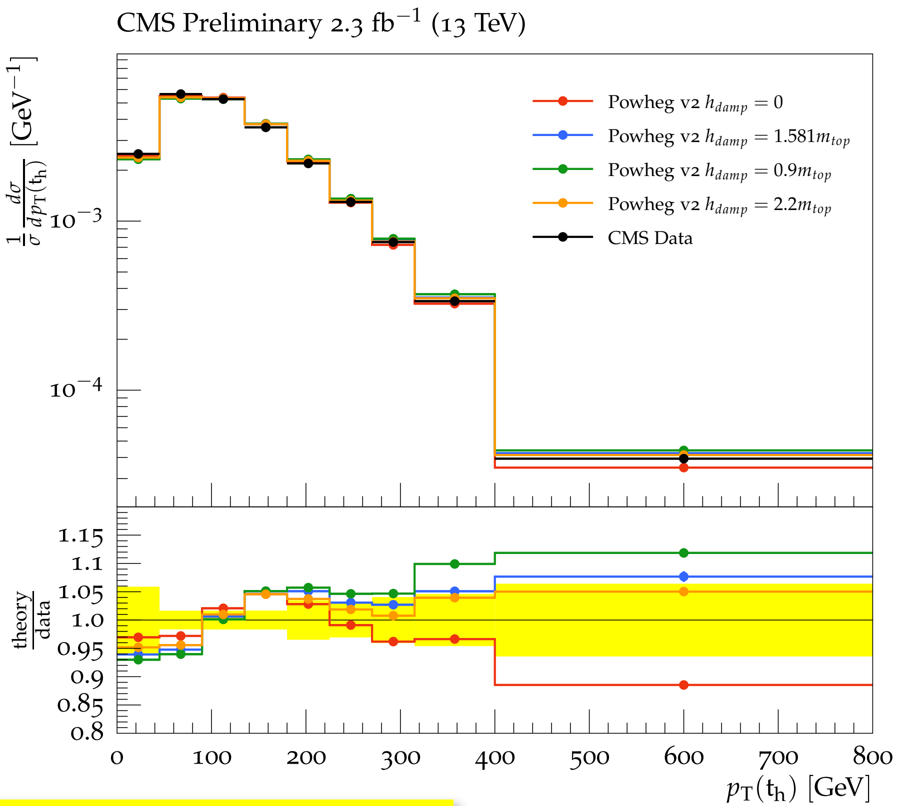
Top mass: alternative approaches



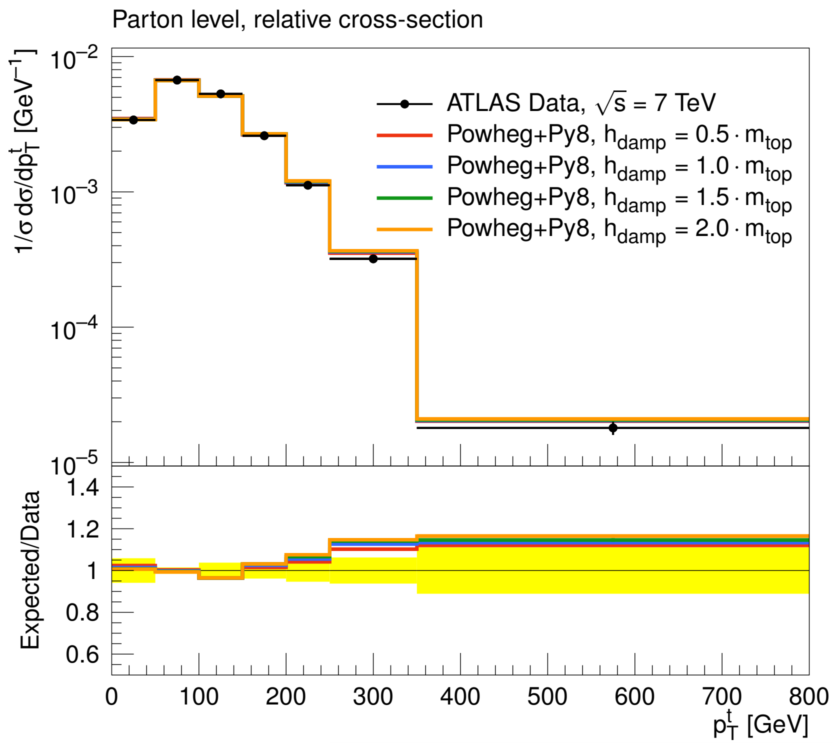
CMS-PAS-TOP-15-012

- QCD interpretation issue of the main top mass measurements with direct kinematic reconstruction
- 2 possible strategies:
  - precise MC calibration vs m_t^{pole}
  - e.g. PRL 117, 232001 (2016)
- use alternative methods less dependent on this calibration

Top quark spectra modelling



CMS-PAS-TOP-16-021



ATL-PHYS-PUB-2016-020

- Extensive studies to tune NLO+PS to reproduce top pair kinematics
  - main parameters: h_{damp} (POWHEG damping for high p_T emission, related to ME-PS matching) and α_S^{ISR} in PS ISR
  - non tt observables checked to avoid inconsistencies in other topologies
  - improvements can be obtained