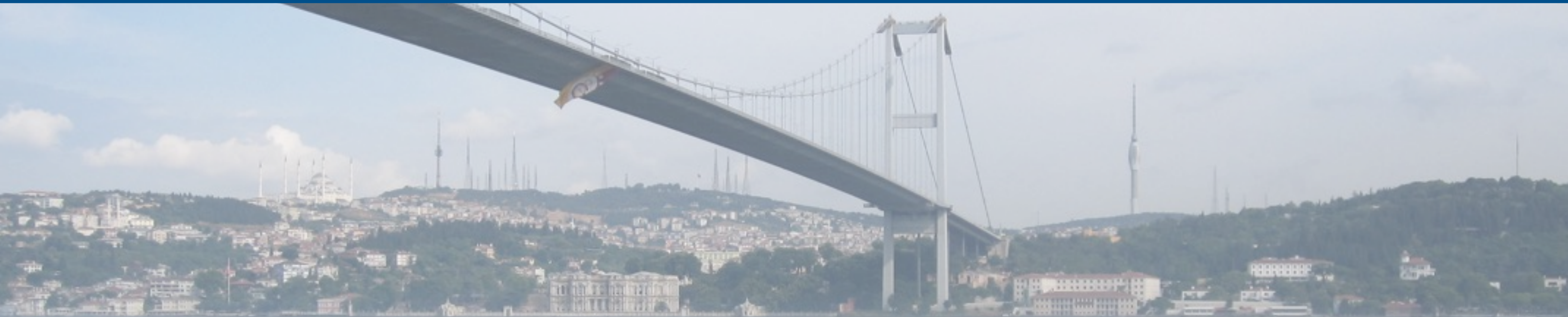
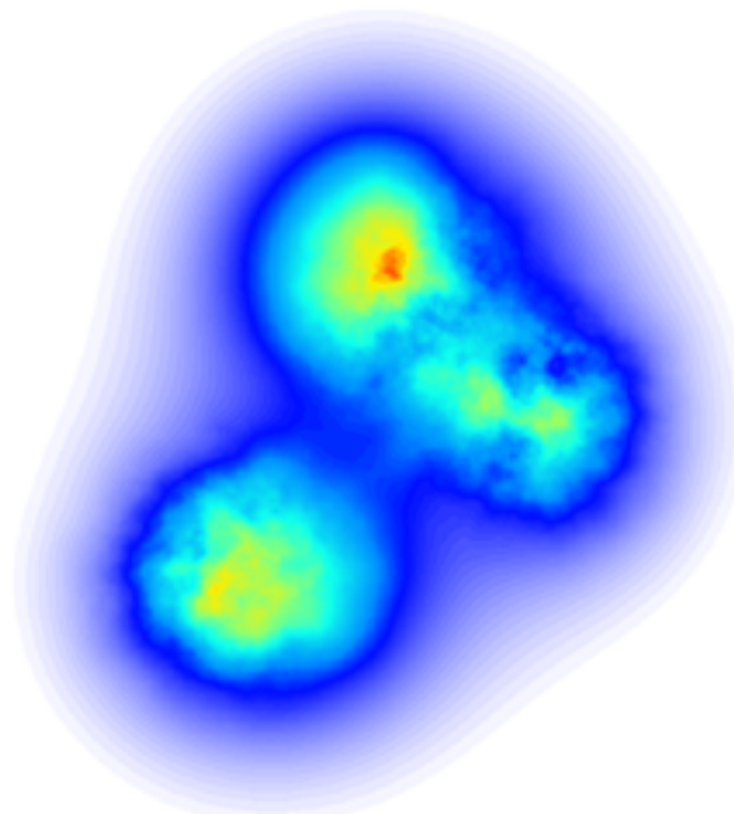


Jet measurements at the LHC

Mikko Voutilainen, U. Helsinki and Inst. of Physics

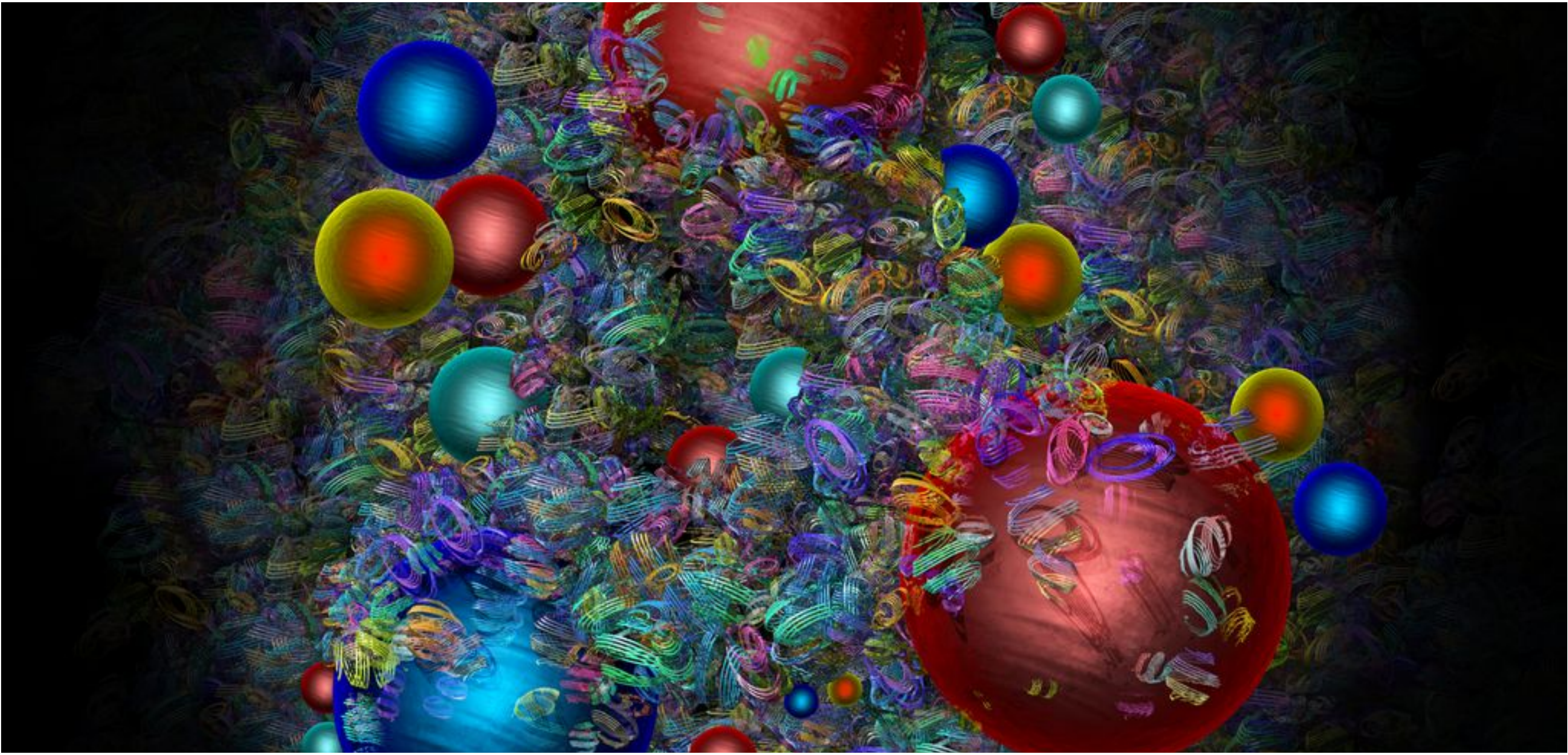
Overview

- Introduction 10’
  - Proton structure: PDFs, αs
  - New physics searches with jets
  - Jets experimentally
- Jet measurements 10’
  - Inclusive jets (PDFs, αs; CI+ED)
  - Dijet azimuthal decorrelations (ISR; Jet+X)
  - B jets (g>bb; H>bb)
  - Jet shapes (FSR; boosted t, H, Z/W)
- Gluons 5’
  - Discovery (PETRA 3-jet)
  - Challenges in definition (Les Houches)
  - Challenges in identification (P8 vs H++, jet topics)
  - Challenges in calibration (P8 vs H++)
  - Prospects for a measurement
- New physics searches with jets 5’
  - high dijet mass
  - low dijet mass
  - top quark mass and vacuum stability
- Conclusions 1’



Gluon density of a proton at high energy, **PRL 117, 052301 (2016)**.

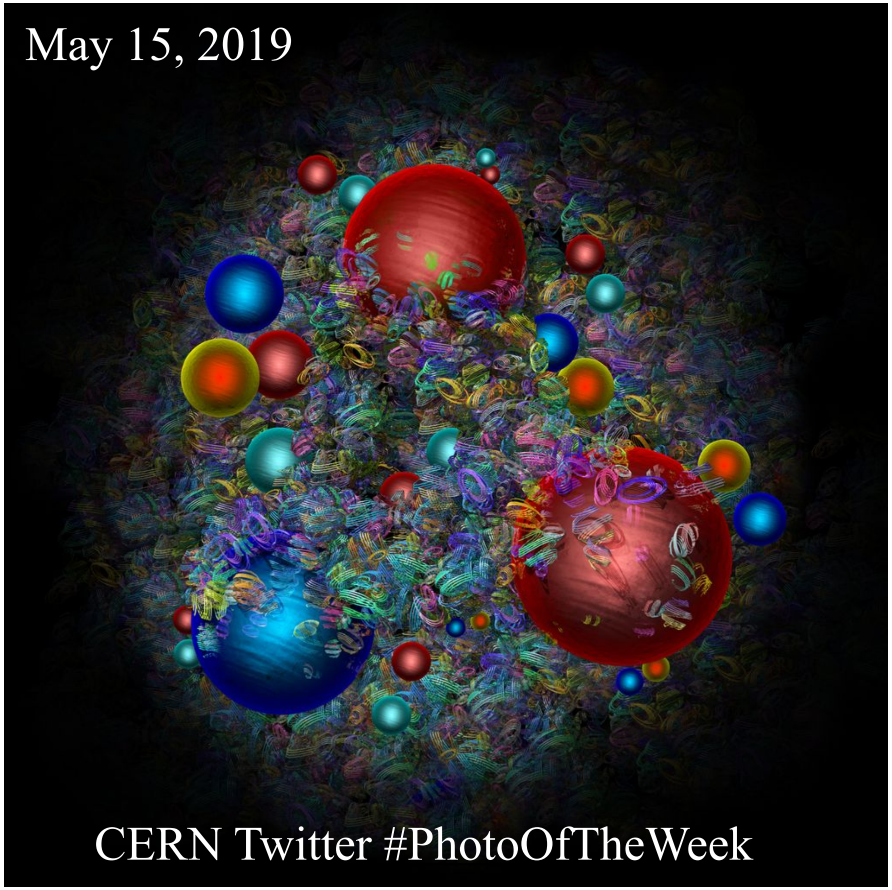
Introduction

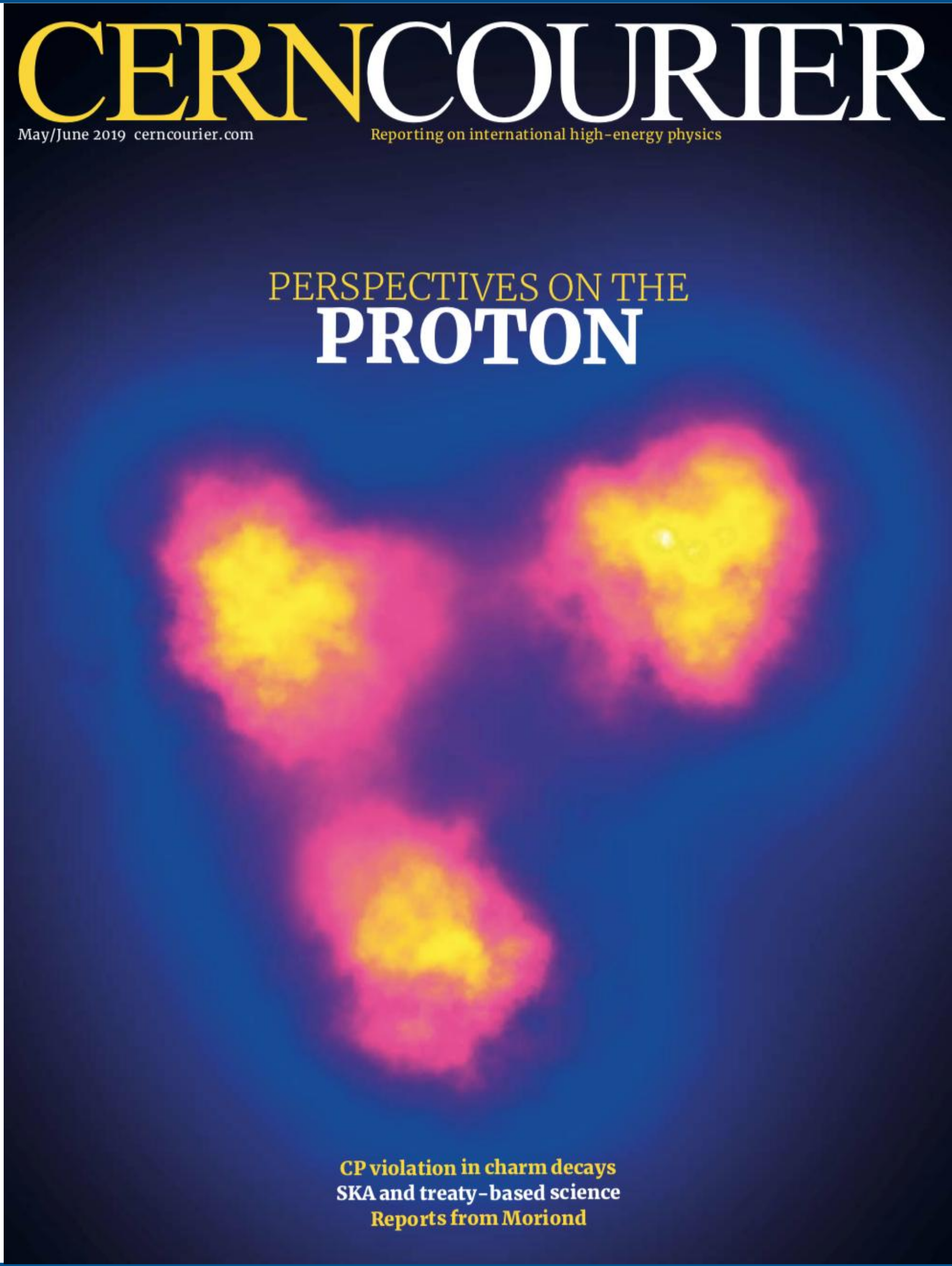


CERN Twitter #PhotoOfTheWeek

Proton structure

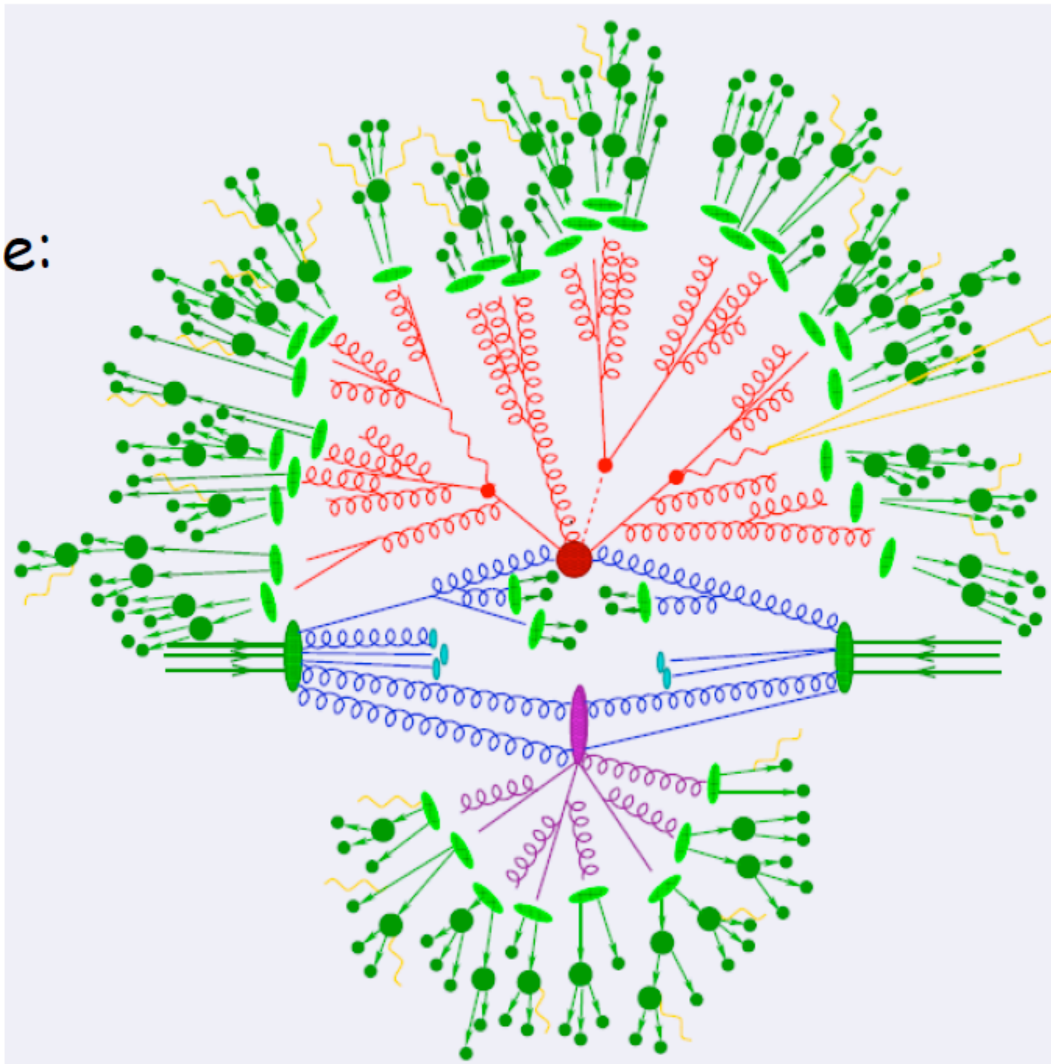
- One clear motivation for jet measurements is to better understand **protons**
- LHC collides these *en masse*, jets are background to everybody else's searches
- Precise modelling of pp collisions, and of jets, prerequisite for LHC physics programme

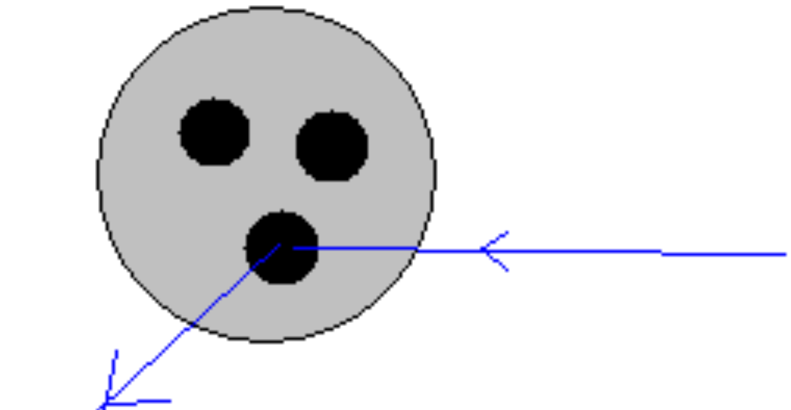




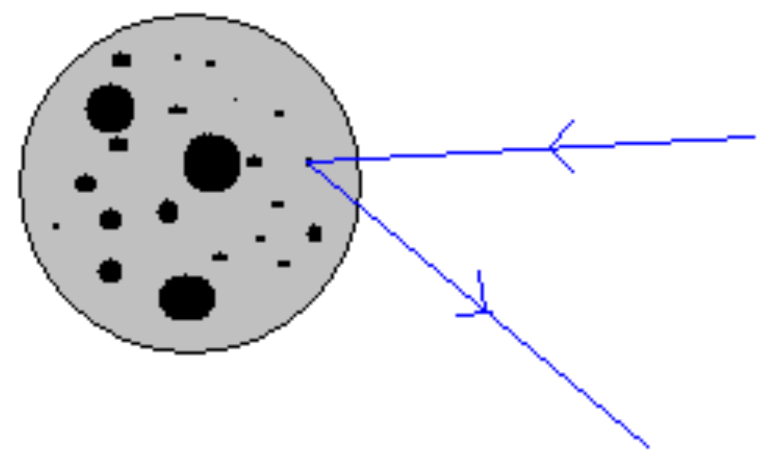
Calculating jet rates

- Jet rate calculations factorize into convolution of matrix elements (Feynman diagrams) with proton structure functions, plus parton shower and multiple interactions modelling





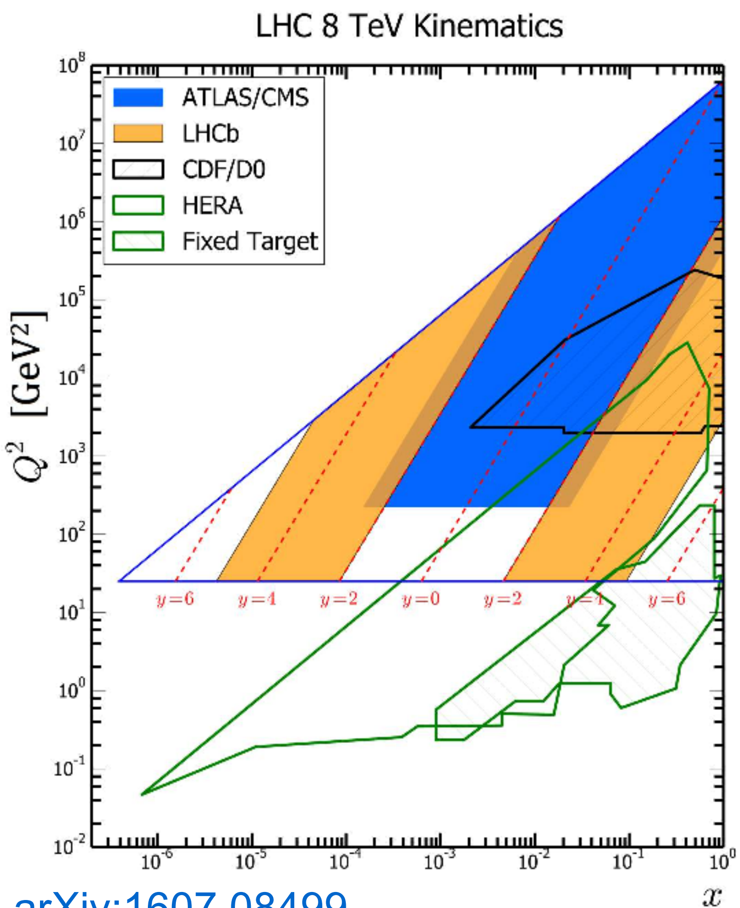
- Proton looks quite different depending on the energy scale



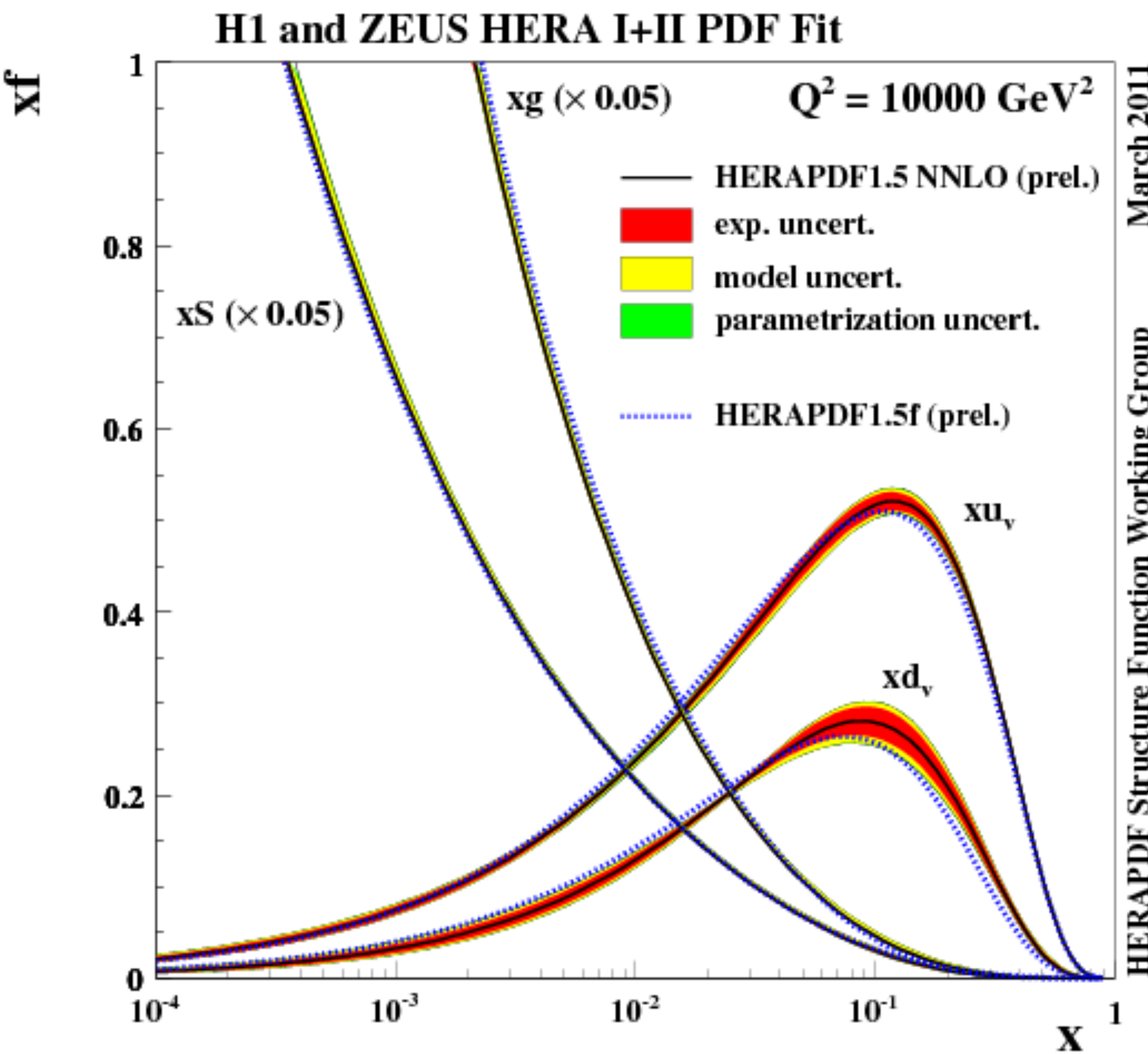
- For robust experimental observables, essential physics already captured by the ME

Parton distributions

- Parton distribution functions (PDFs) largely constrained by HERA data (ep collider)
- Least known part is gluon PDF at high Bjorken **x** and high Q^2
- LHC jets can cover this well



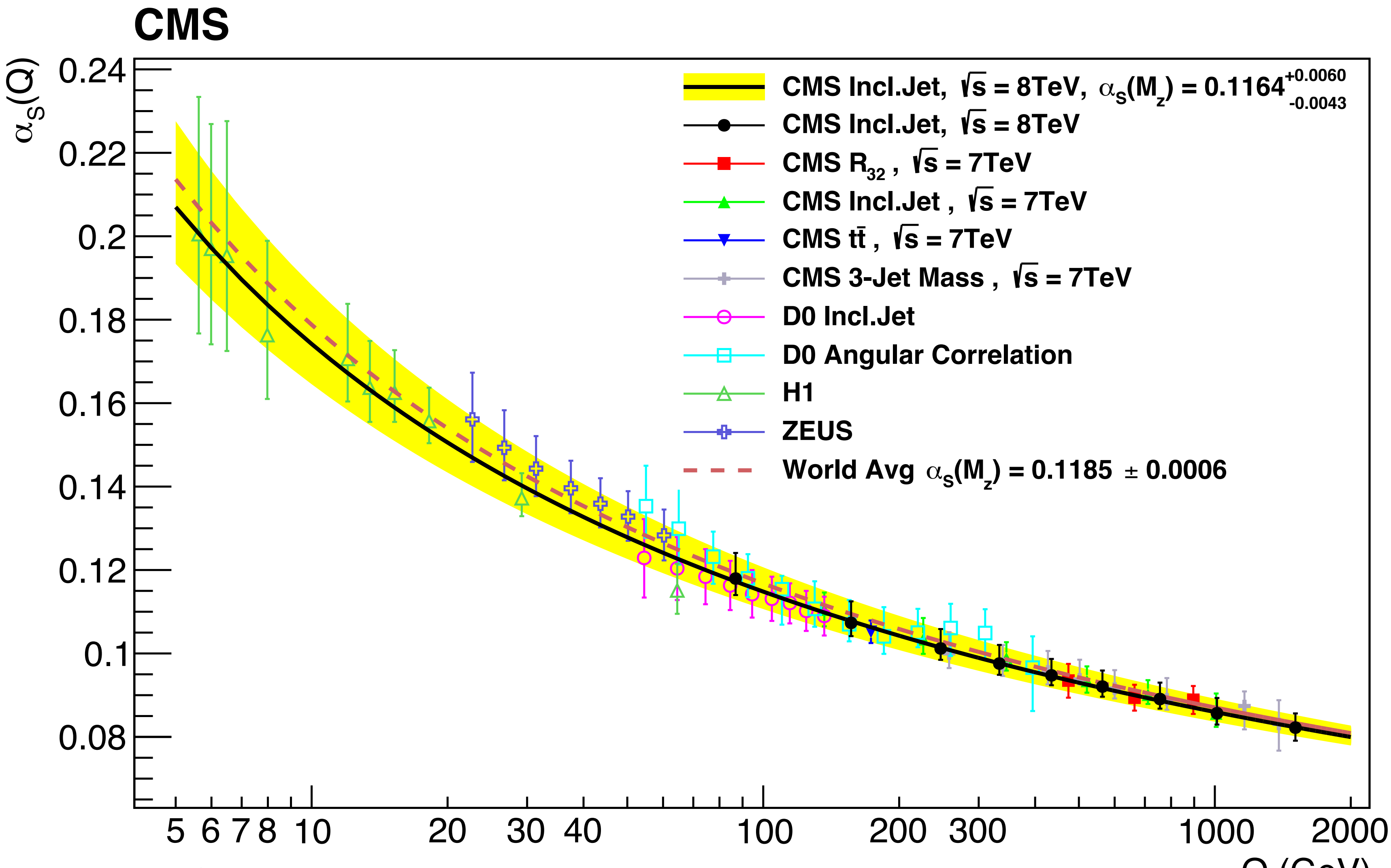
arXiv:1607.08499



review: arXiv:1111.5452

Strong coupling α_s

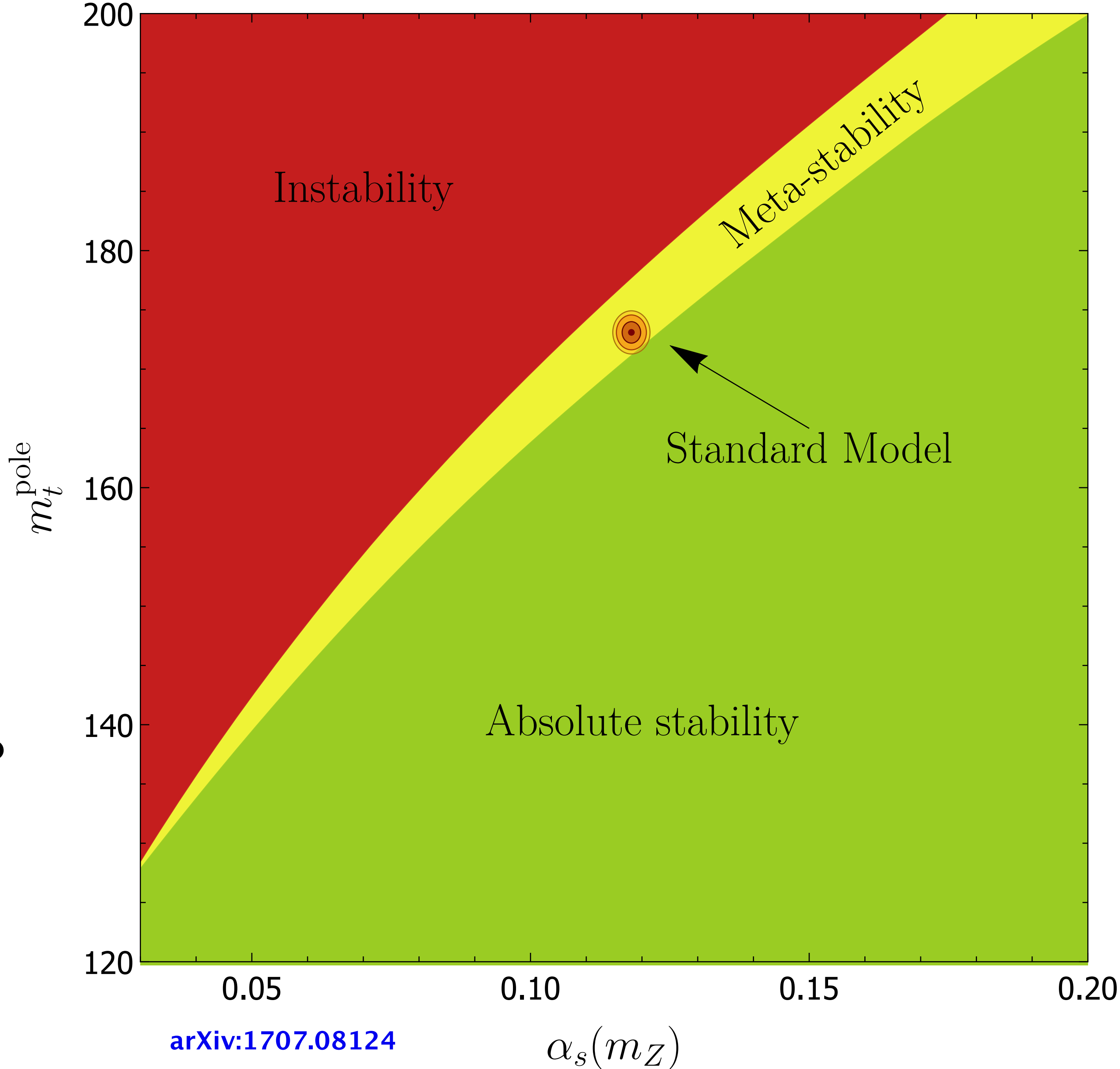
- Matrix element calculations proportional to strong coupling α_s at different orders $(\alpha_s)^n$
- Strong force becomes weaker at high energies, making perturbative calculations feasible
- Inclusive jet and 3-jet measurements test running of α_s to highest energy scales



CMS SMP summary plots

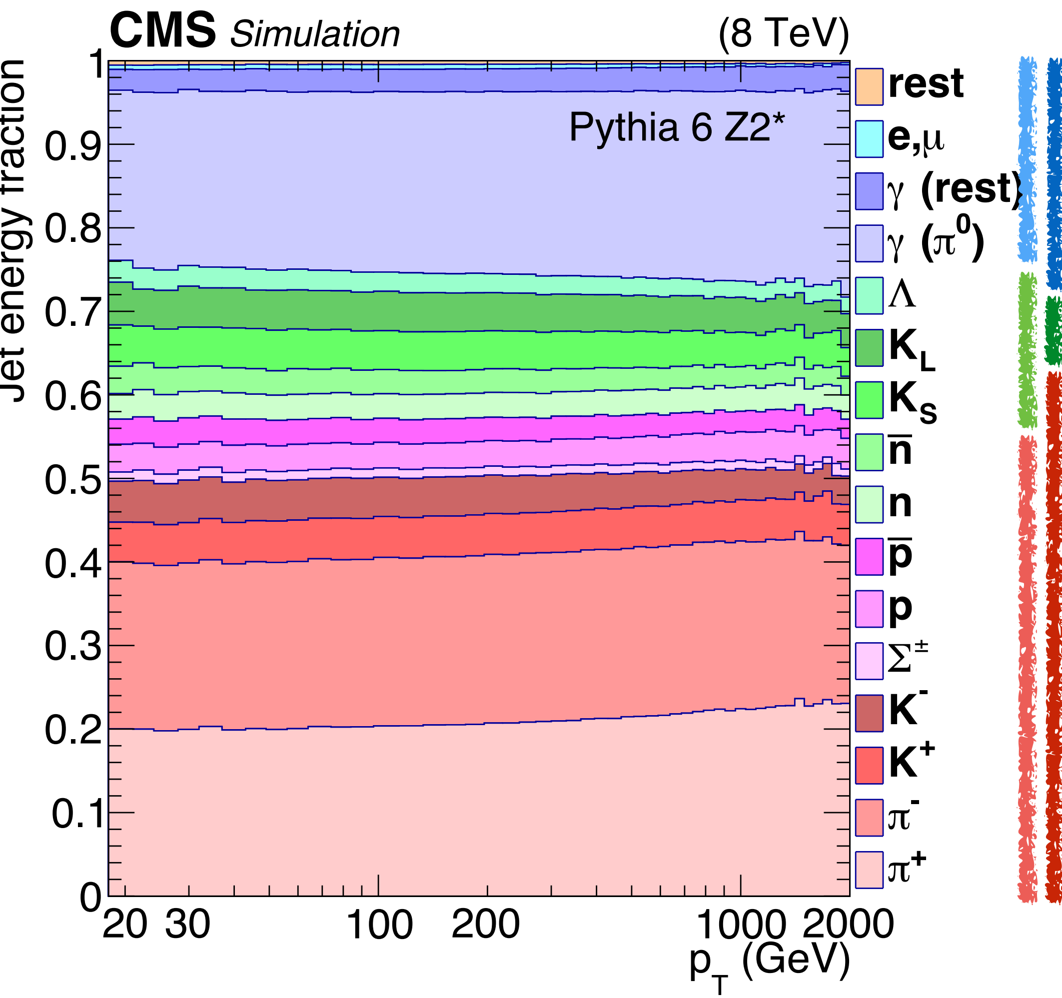
New physics with jets

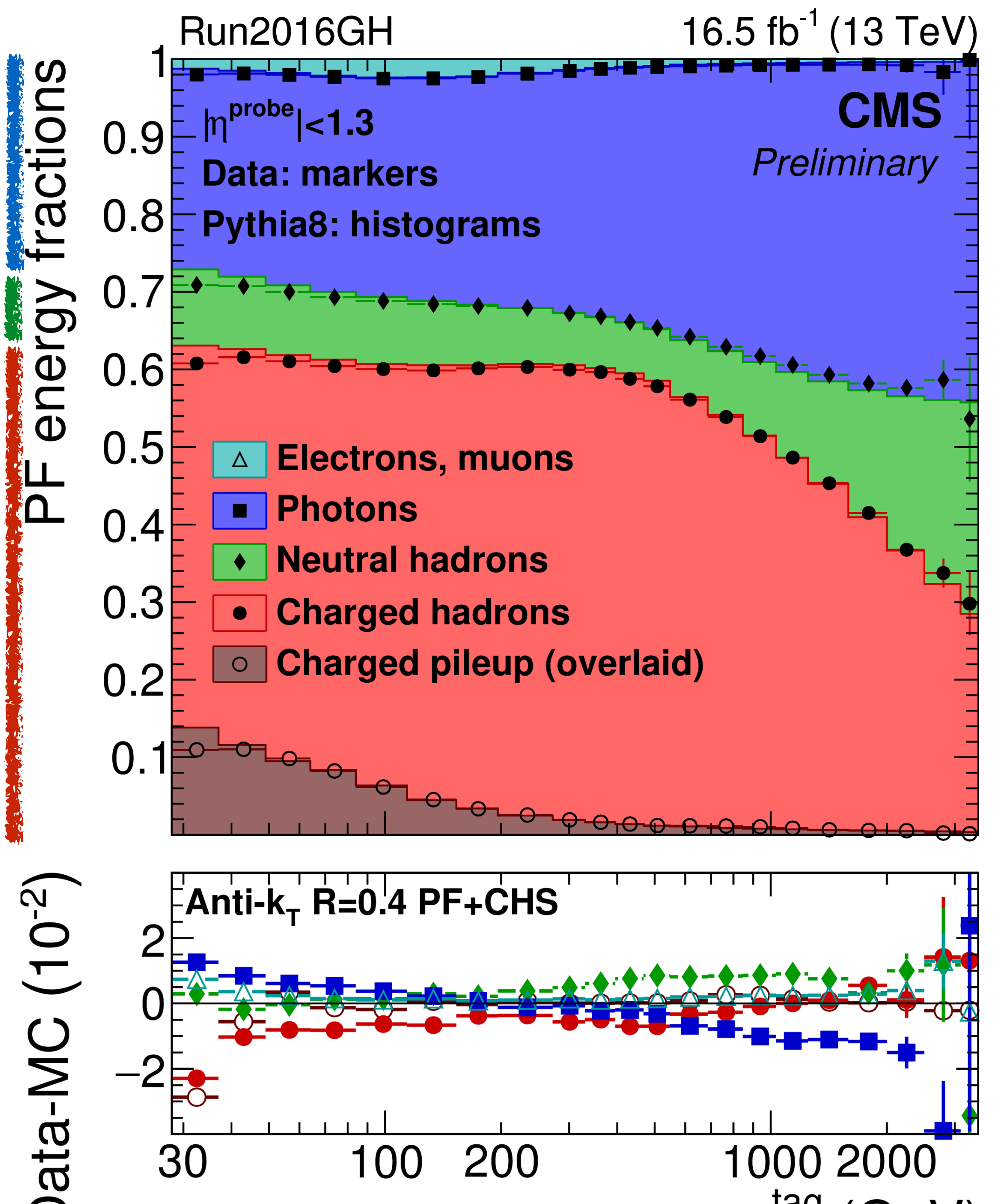
- Jets are background to many searches, but also a direct signal, e.g. X>qq
- Vacuum stability has deep connection to jets
  - strong coupling α_s controls all jet observables
  - most precise m_t from jet kinematic measurements
  - if new physics, possible it decays to jets (X>qq,gg,qg)
- Going deeper into the rabbit hole, all paths lead to gluons (more on that later)



arXiv:1707.08124

Jet composition





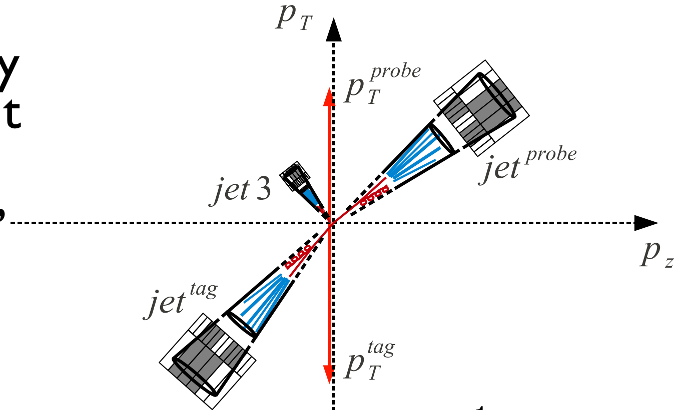
- Quarks/gluons shower into tens of particles, whose detector response varies by type
- Jet composition differs subtly for quarks and gluons, and depends on MC model

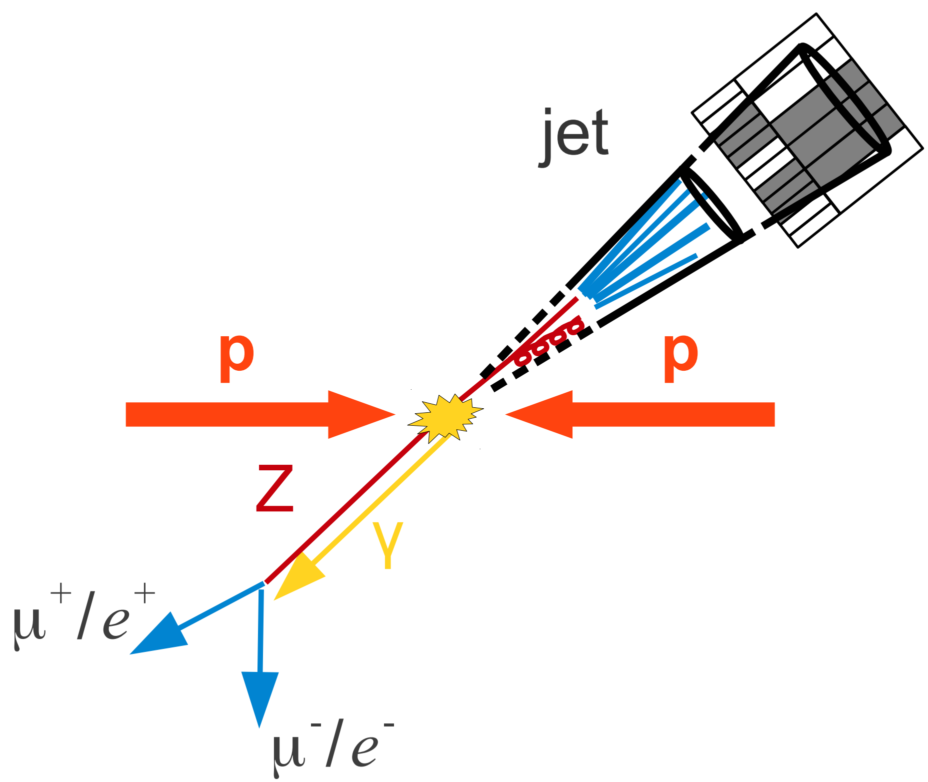
arXiv:1607.03663

DP 2018/028

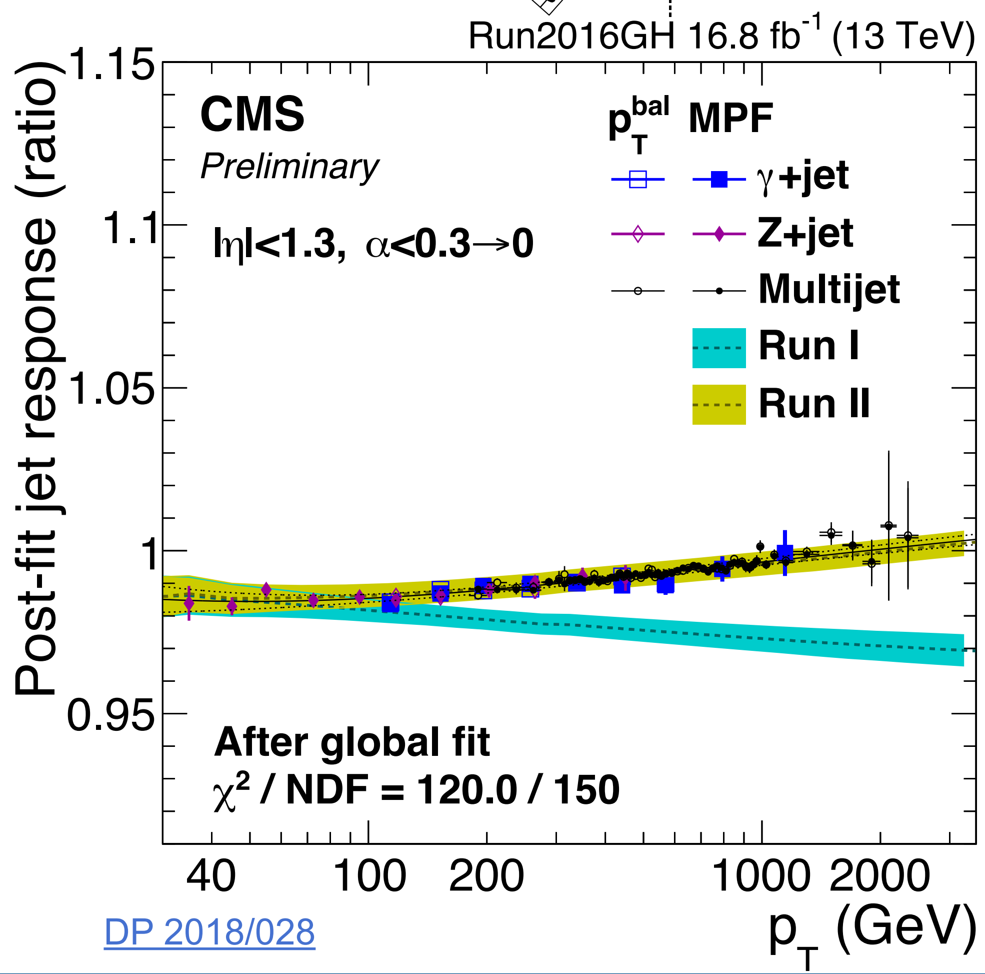
Calibrating jets

- Jets are calibrated against a well-measured reference object by enforcing transverse momentum conservation in the full event
- Combination of multiple channels (Z>μμ, Z>ee, γ, central jet, multijet recoil) allows for full phase space coverage
- Residual data/MC corrections typically at percent-level





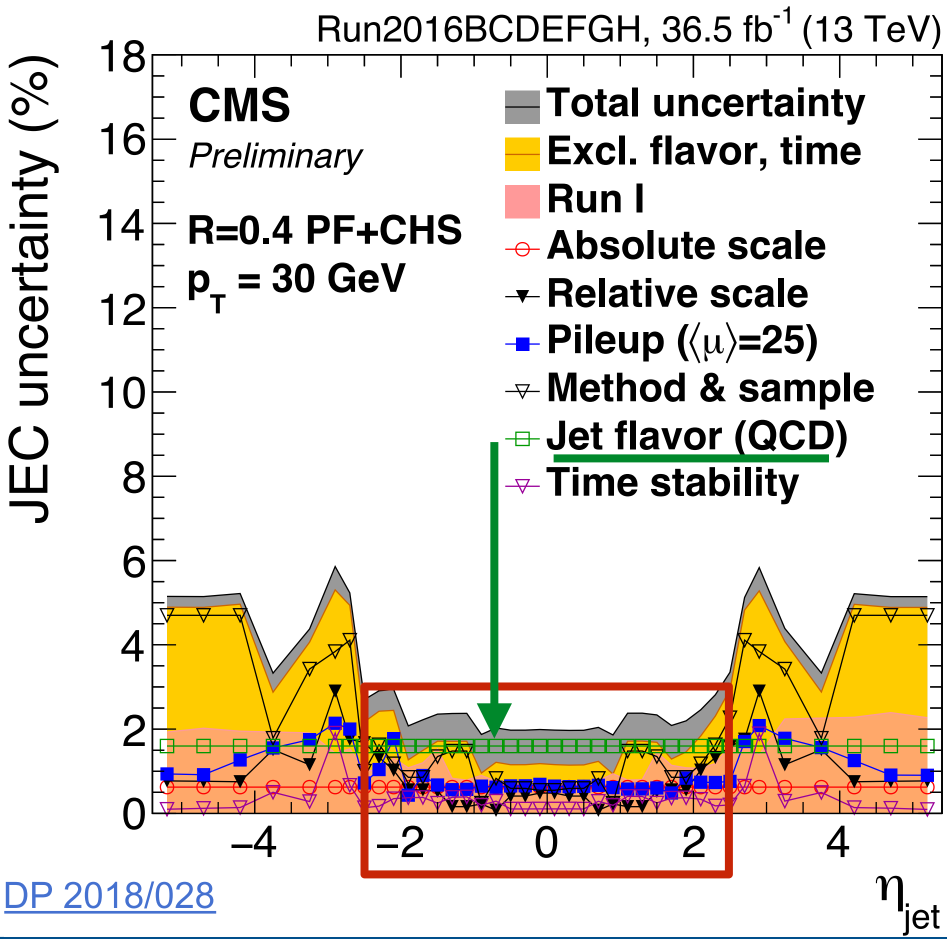
DP 2018/028

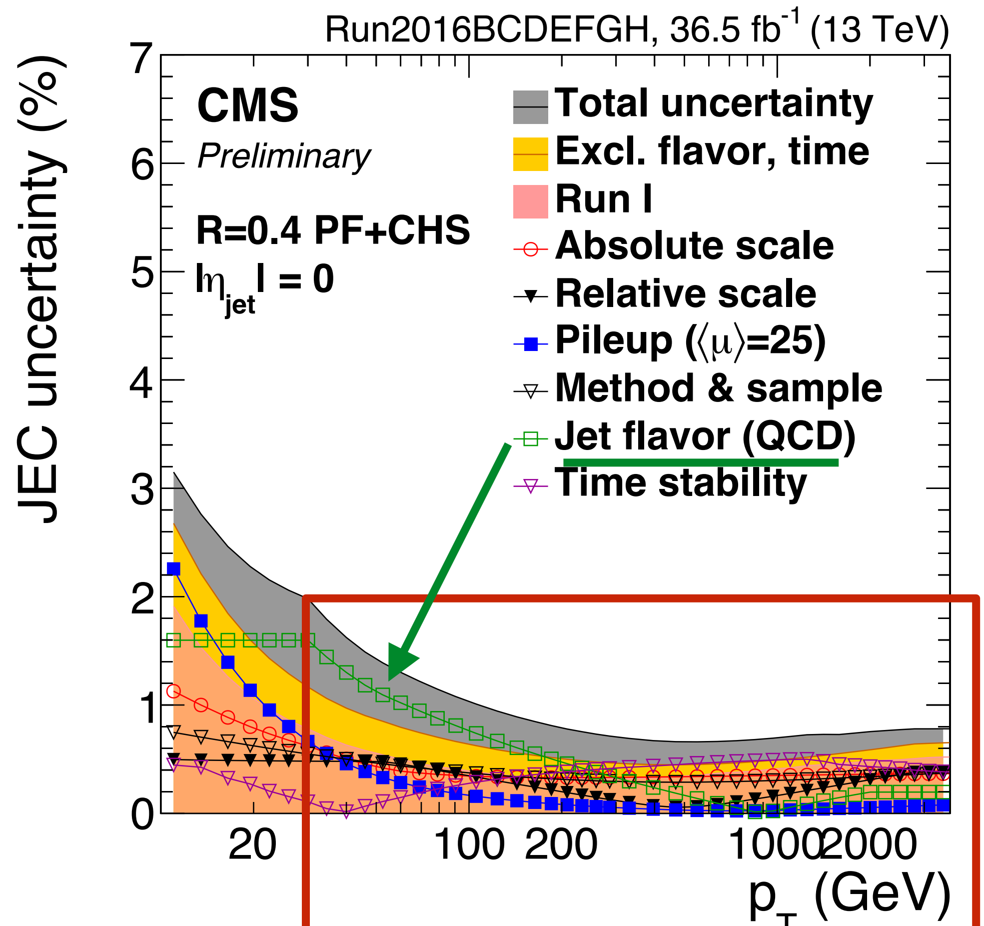


DP 2018/028

Jet uncertainties

- CMS uncertainties at 13 TeV 1–3% at $|\eta|<2.5$ and $p_T>30$ GeV; similar on ATLAS for GSC
- Dominant uncertainty is due to gluon jet response in "Jet flavor (QCD)"
  - same uncertainty as in Run I, **very similar on ATLAS**: comes from jet fragmentation modelling
- Future progress will come from better parton shower + fragmentation modelling => data

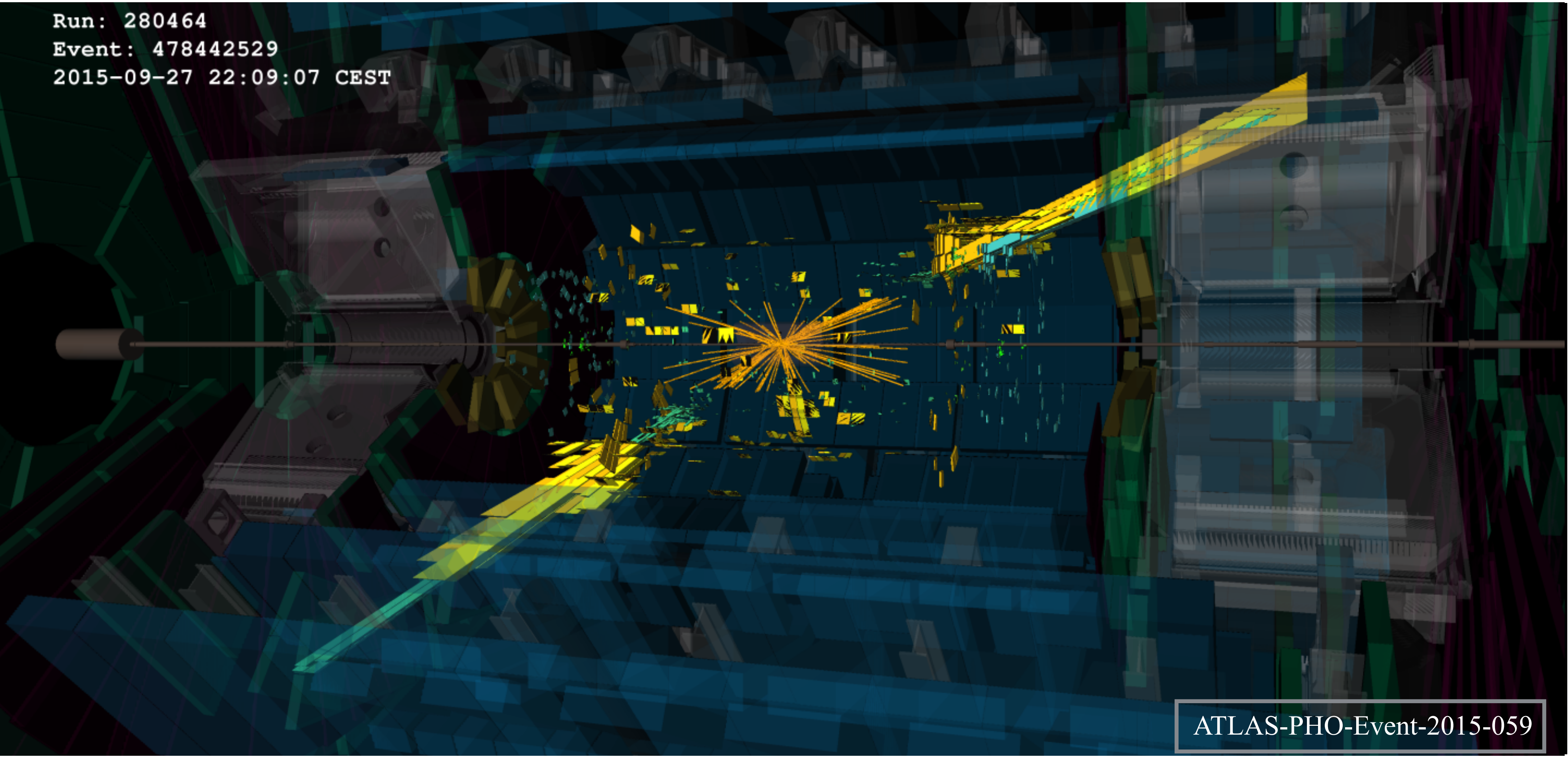




DP 2018/028

Jet measurements

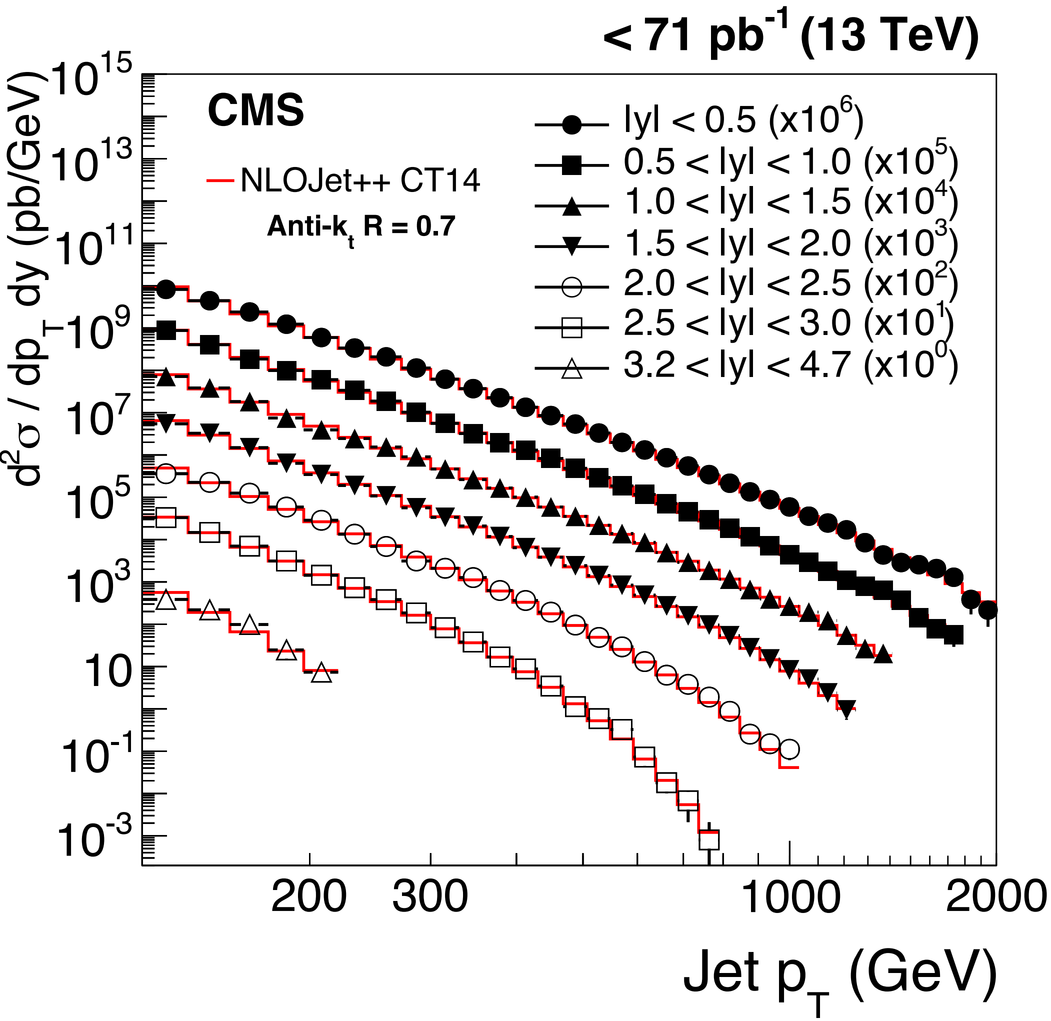
https://twiki.cern.ch/twiki/bin/view/AtlasPublic



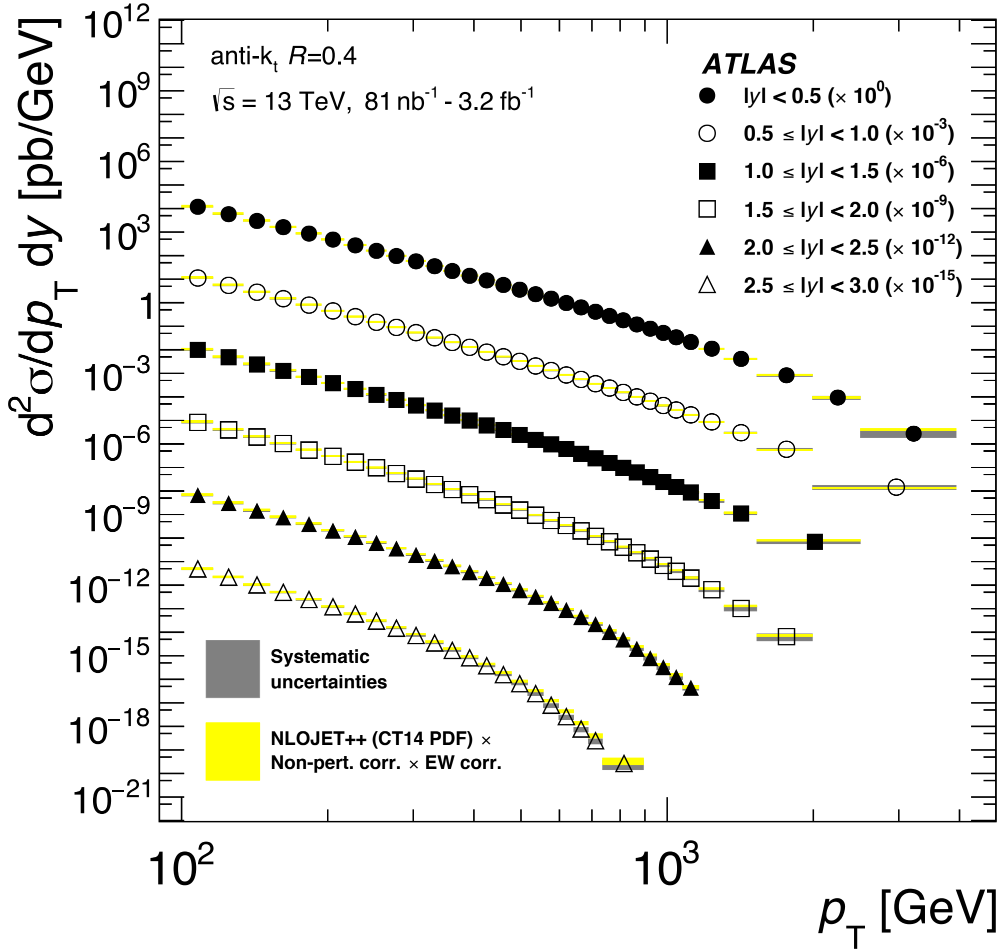
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Inclusive jets

- Inclusive jet production is one of highest cross section processes at the LHC
- Measurements versus p_T typically span more than 10 orders of magnitude
- Several measurements by both CMS and ATLAS (**13 TeV**, 8 TeV, 7 TeV, 2.76 TeV)



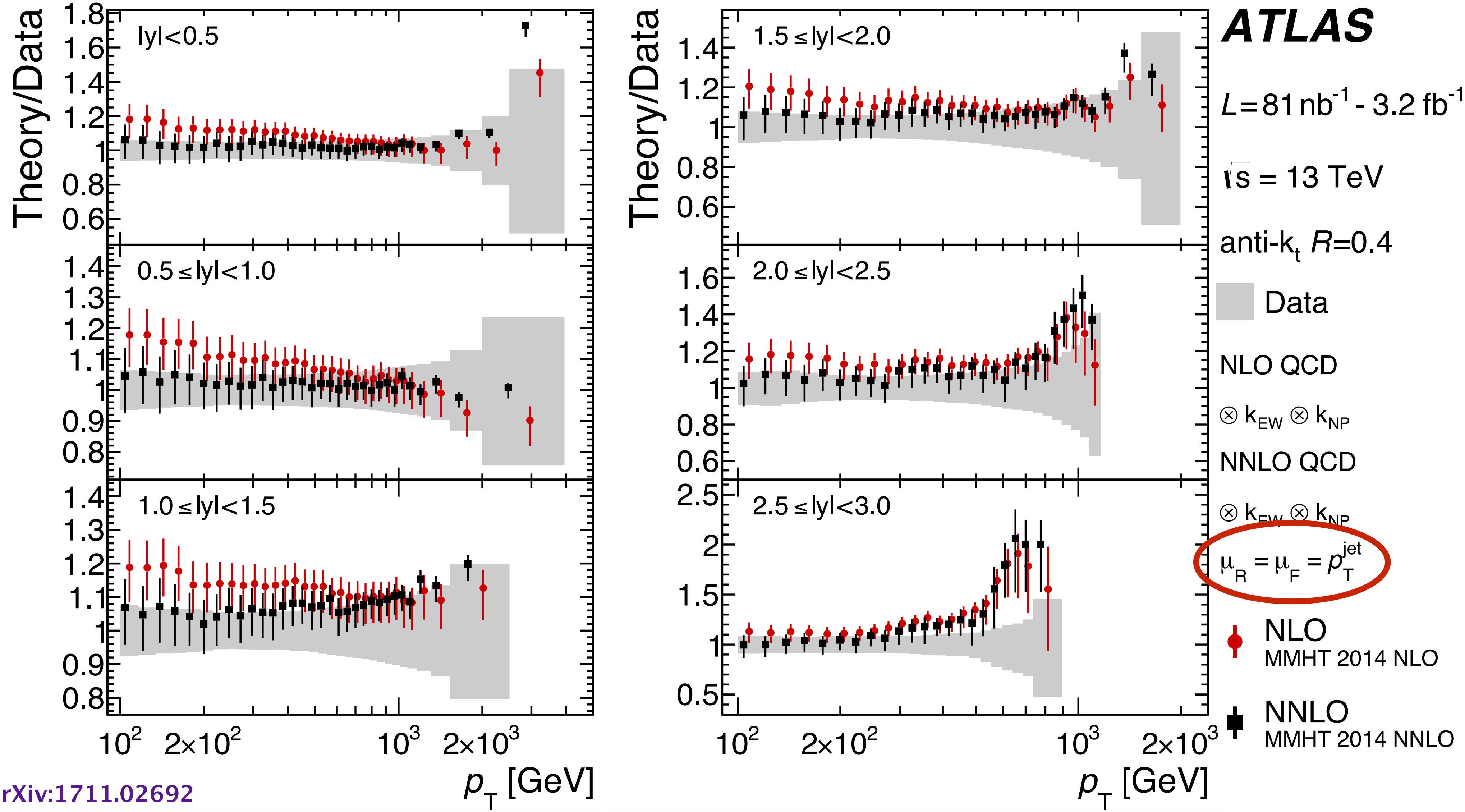
arXiv:1605.04436



arXiv:1711.02692

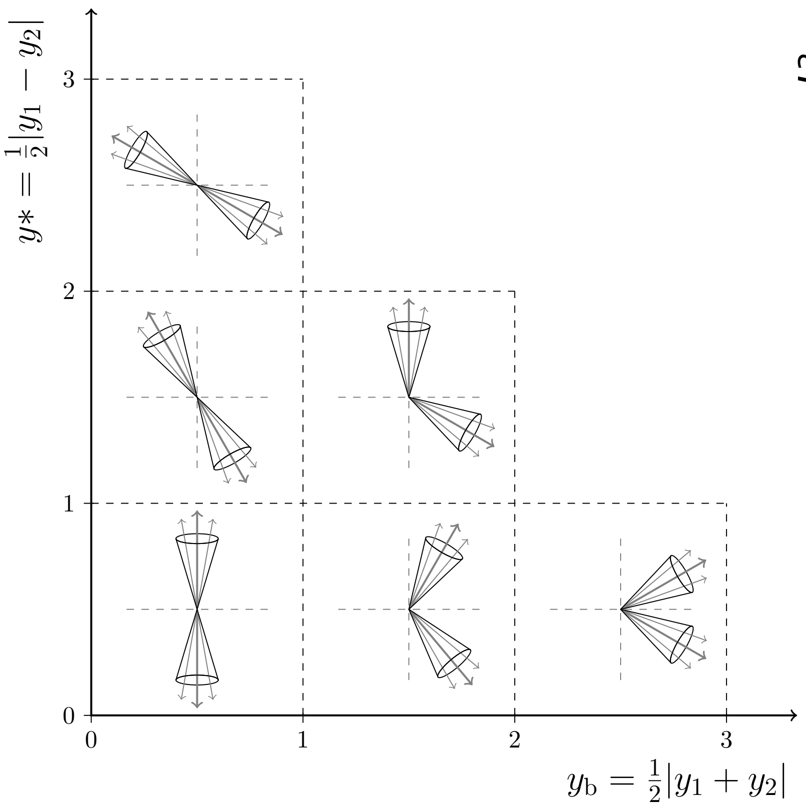
Inclusive jets vs NNLO

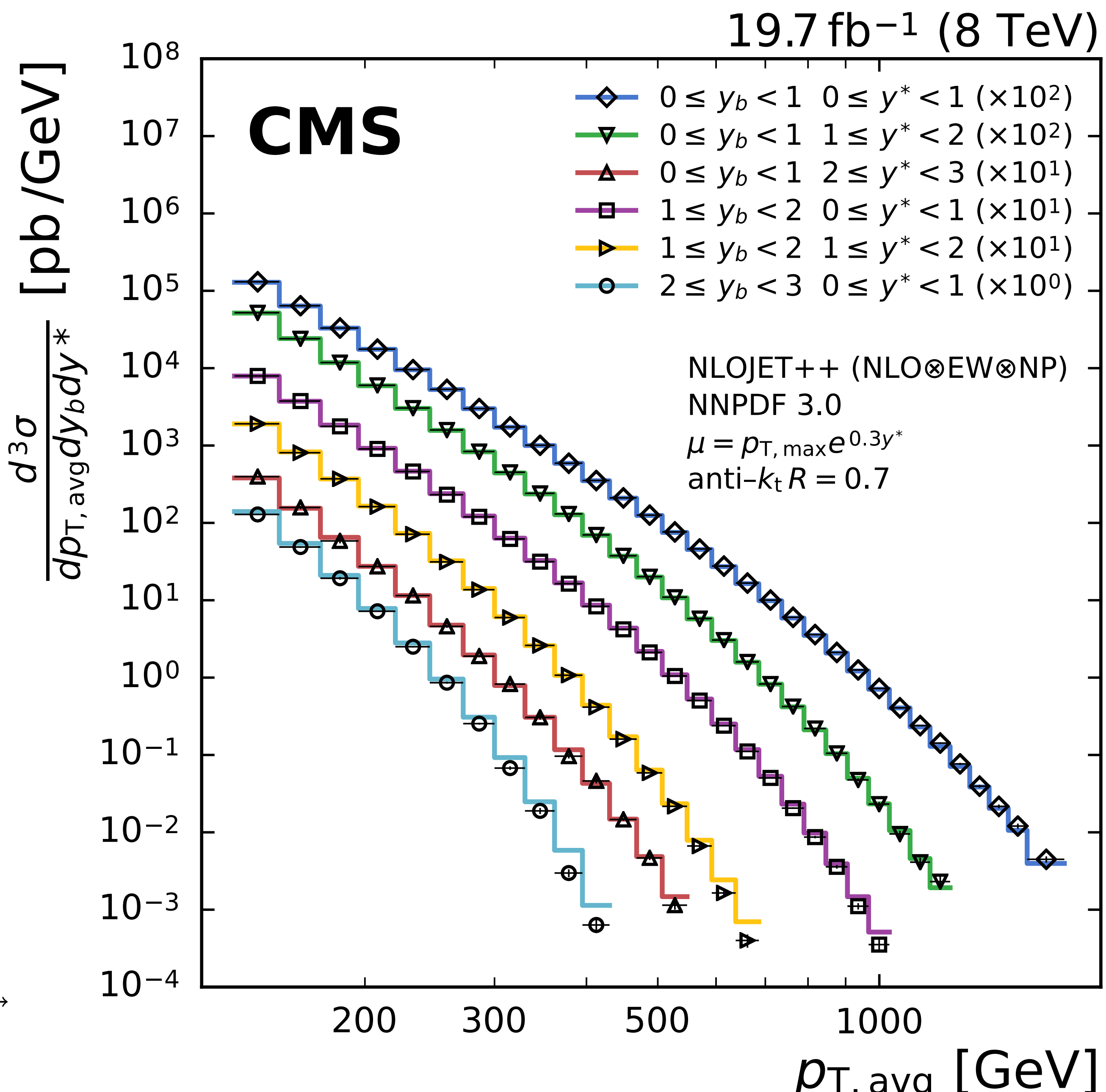
- Data generally in agreement for small R=0.4 with new state-of-the-art NNLO calculations
- Large NNLO sensitivity to scale choice (p_T^{jet} vs p_T^{max}); now mostly settled from theory side



arXiv:1711.02692

- CMS 8 TeV dijet measurement is arguably the single most precise LHC jet measurement
- Benefits from the best Run I calibrations and techniques
- Triple-differential cross section improves PDF & α_s sensitivity



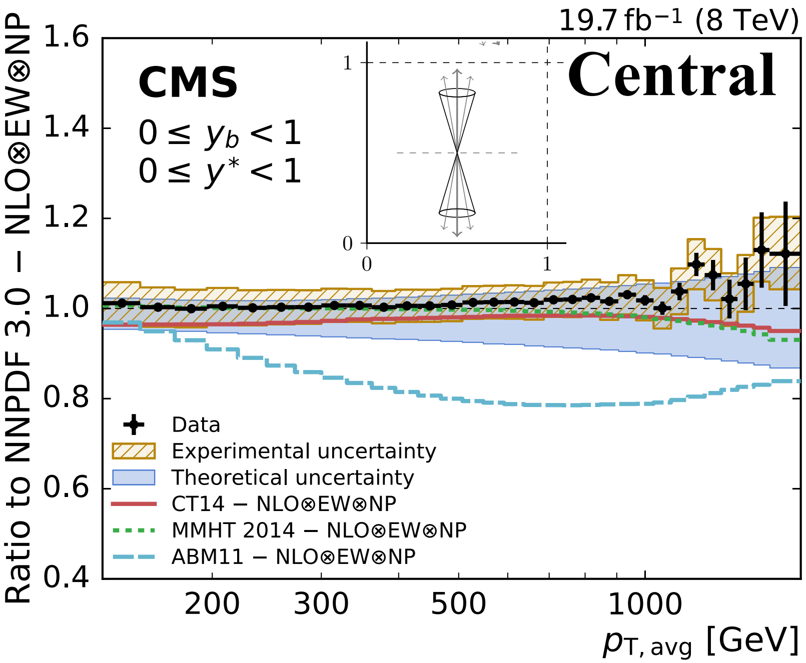


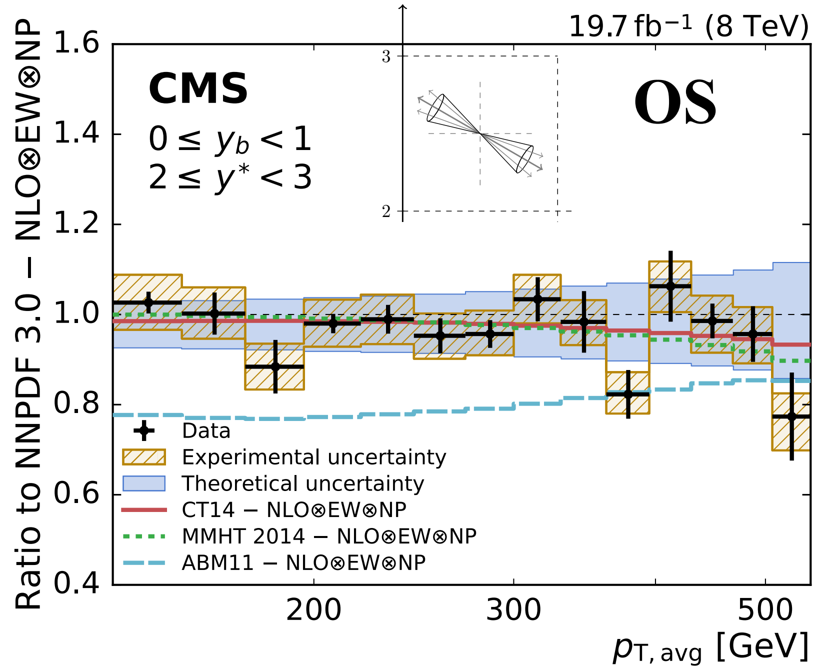
arXiv:1705.02628

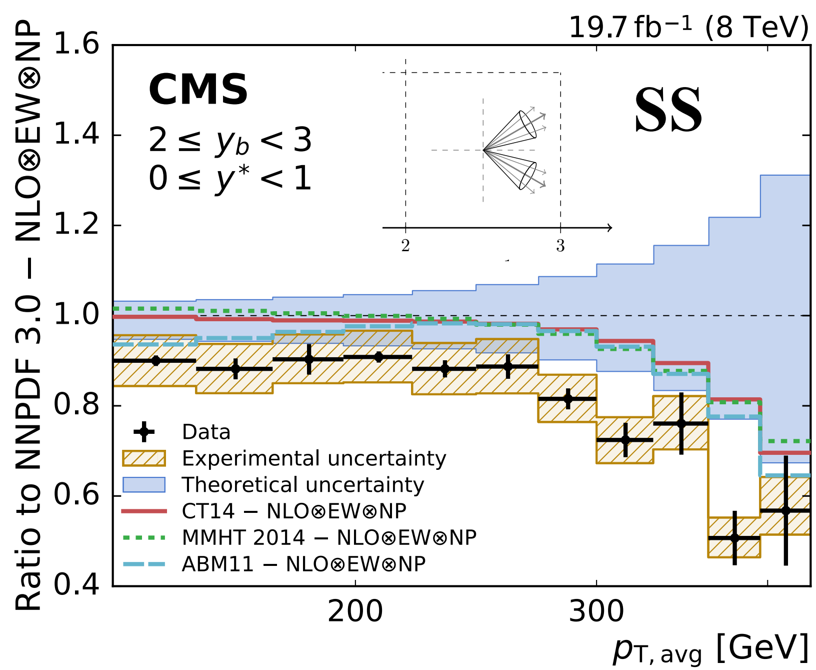
Dijets

- Centrally produced dijets well-modelled
- Classifying dijet events by same-side versus opposite-side enhances sensitivity to PDFs
- OS dominated by qq>jets, SS by **g**q>jets ($\mathbf{x_g}$<x_q),
  - Central also some **g**q>jets ($\mathbf{x_g}$>x_q)

$\alpha_S(M_Z)$ = 0.1199 ± 0.0015 (exp) −0.0020 +0.0031 (theo)





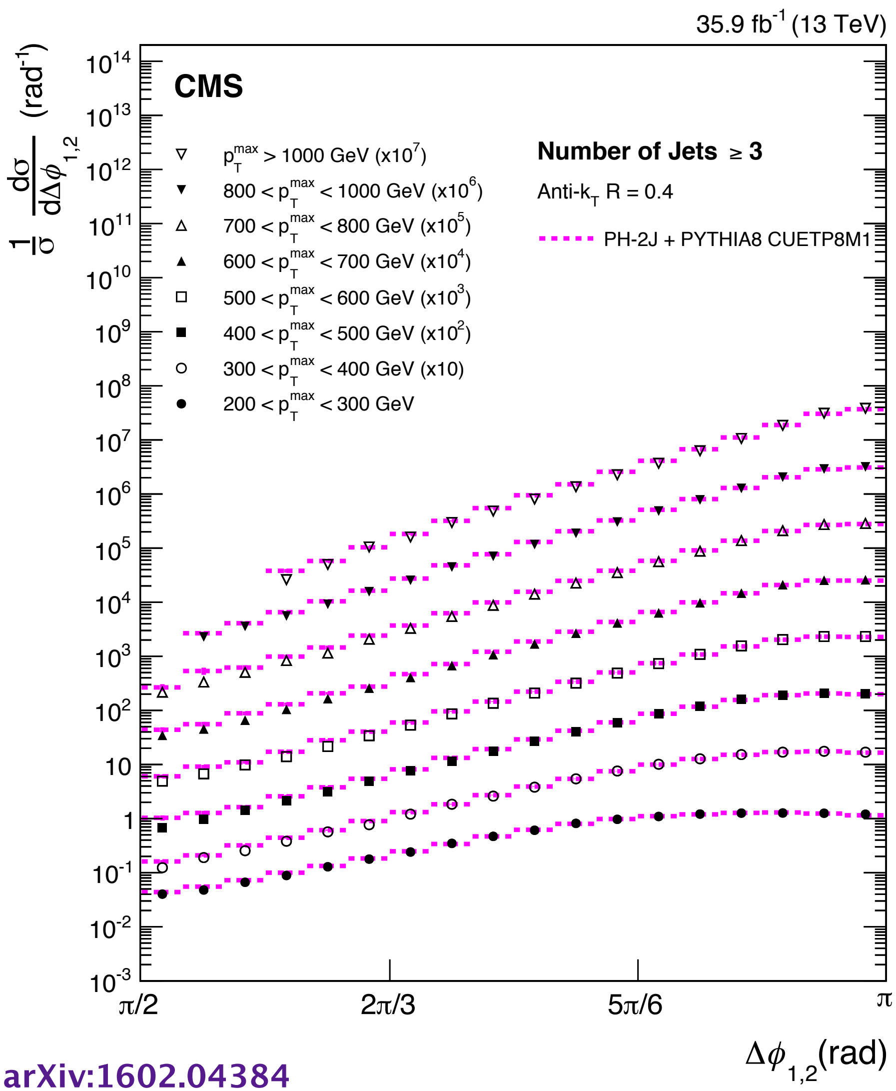


HEPData entry in the works

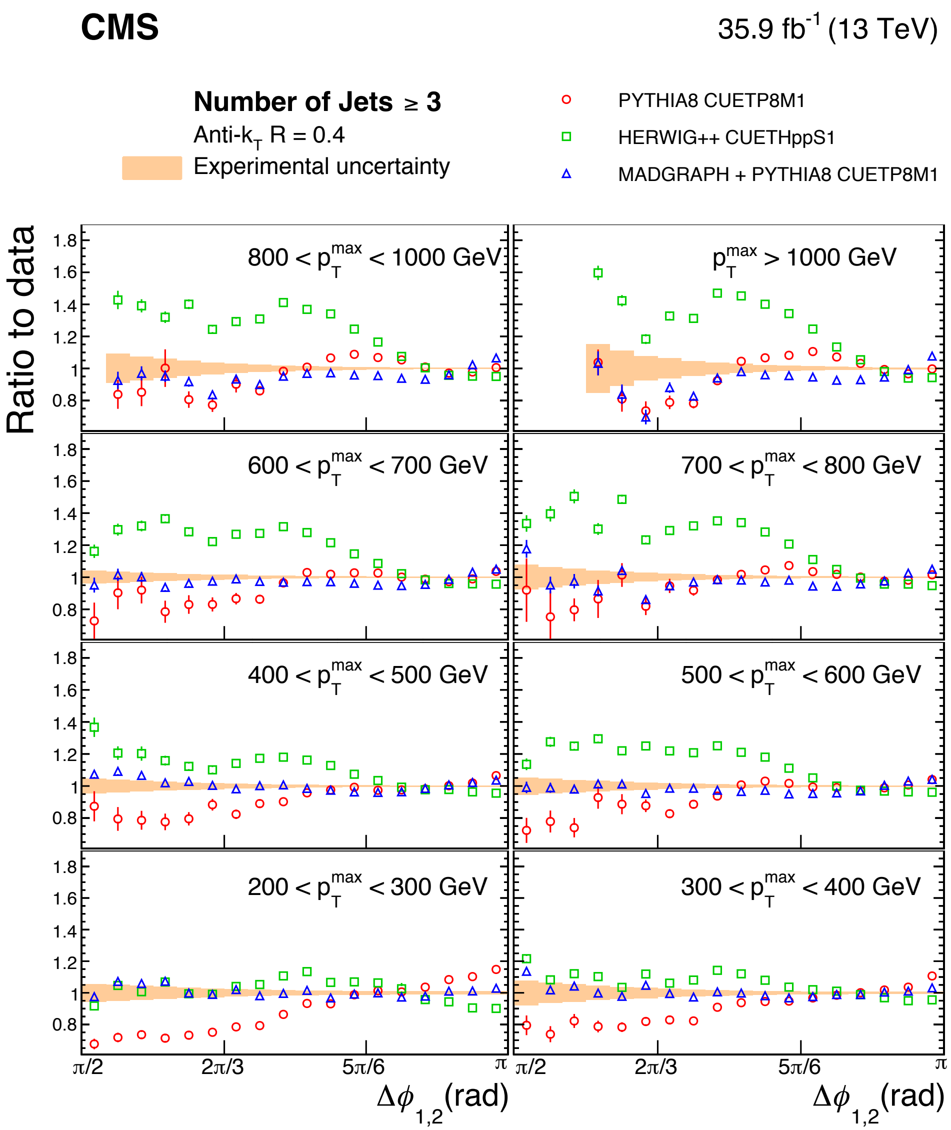
arXiv:1705.02628

Azimuthal decorrelations

- Dijet azimuthal decorrelations sensitive to additional jet production
- Initial state radiation (ISR) reduces dijet angle from back-to-back configuration ($\Delta\varphi=\pi$)
- Multileg MC generators (MadGraph) do generally well here, NLO ok for $\Delta\varphi>5\pi/6$



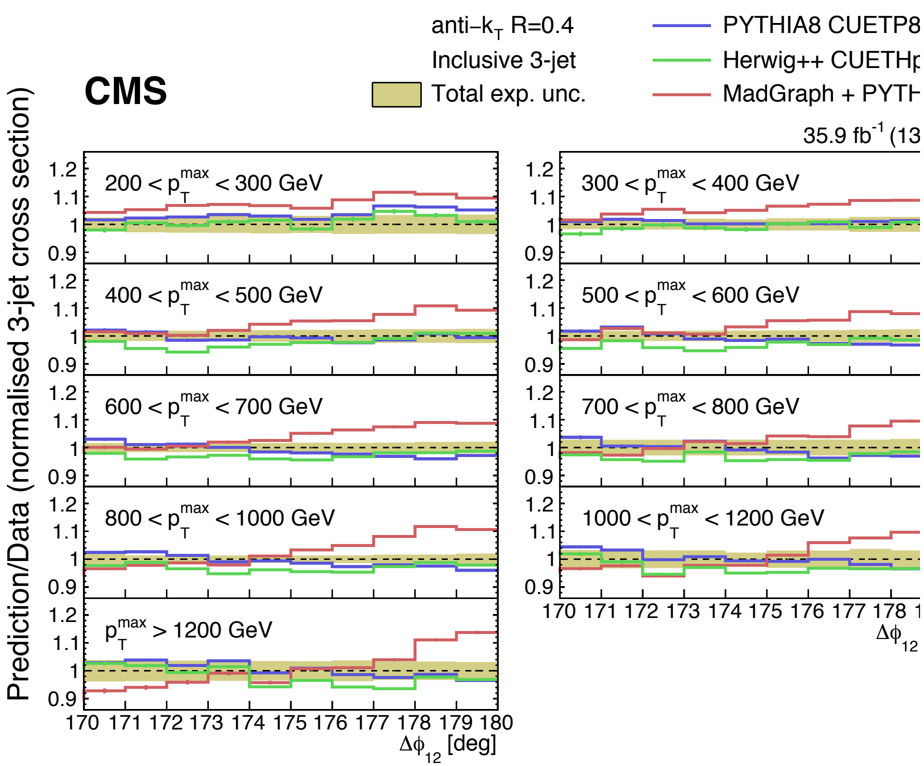
arXiv:1602.04384

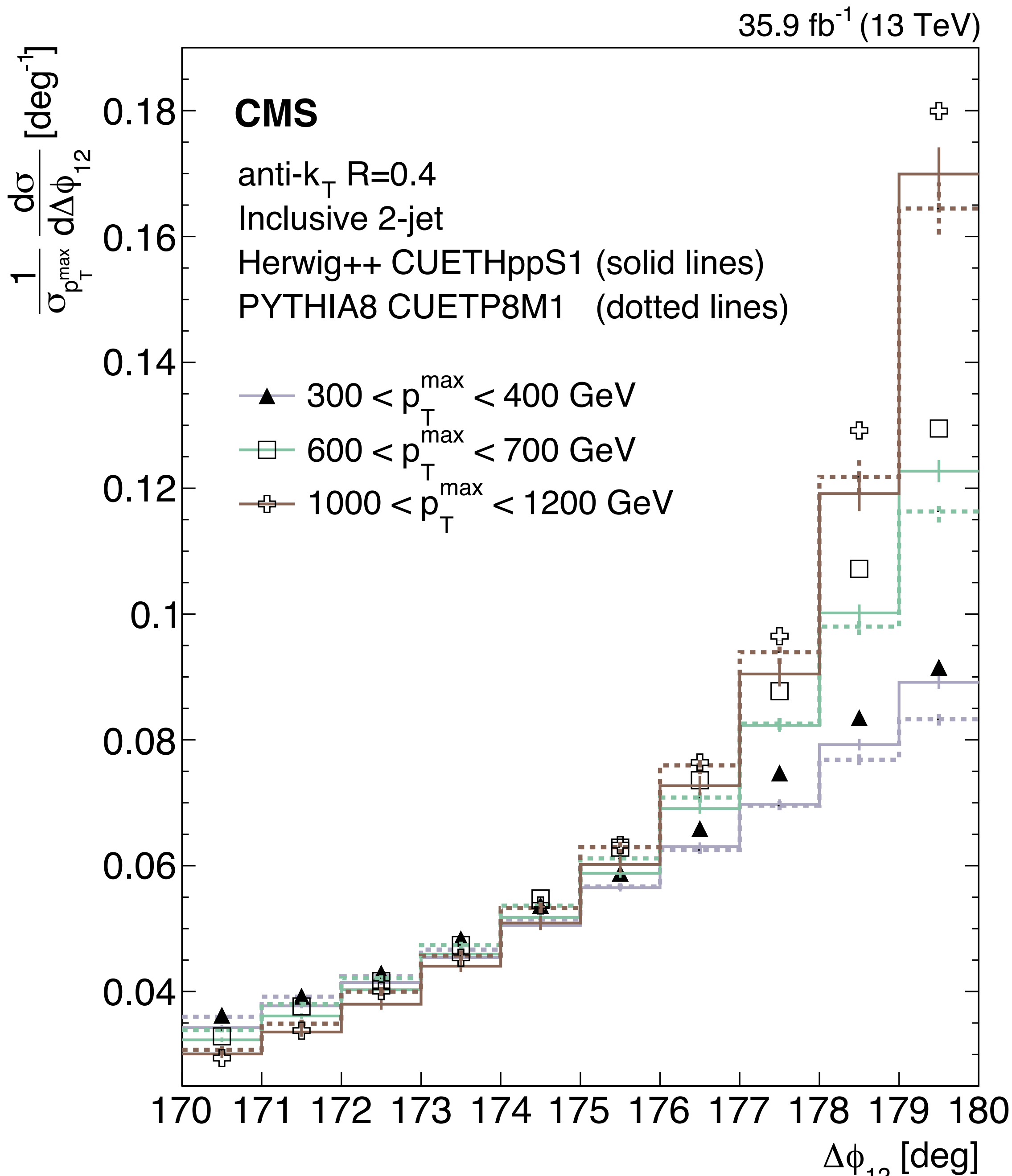


arXiv:1602.04384

Azimuthal decorr. zoomed

- Zooming into back-to-back region at the limit of detector resolution
- Measurement probes multiple scales from soft to hard
- Here even MadGraph exhibits some differences, especially for inclusive 3-jet case (inclusive 2-jet on the right)



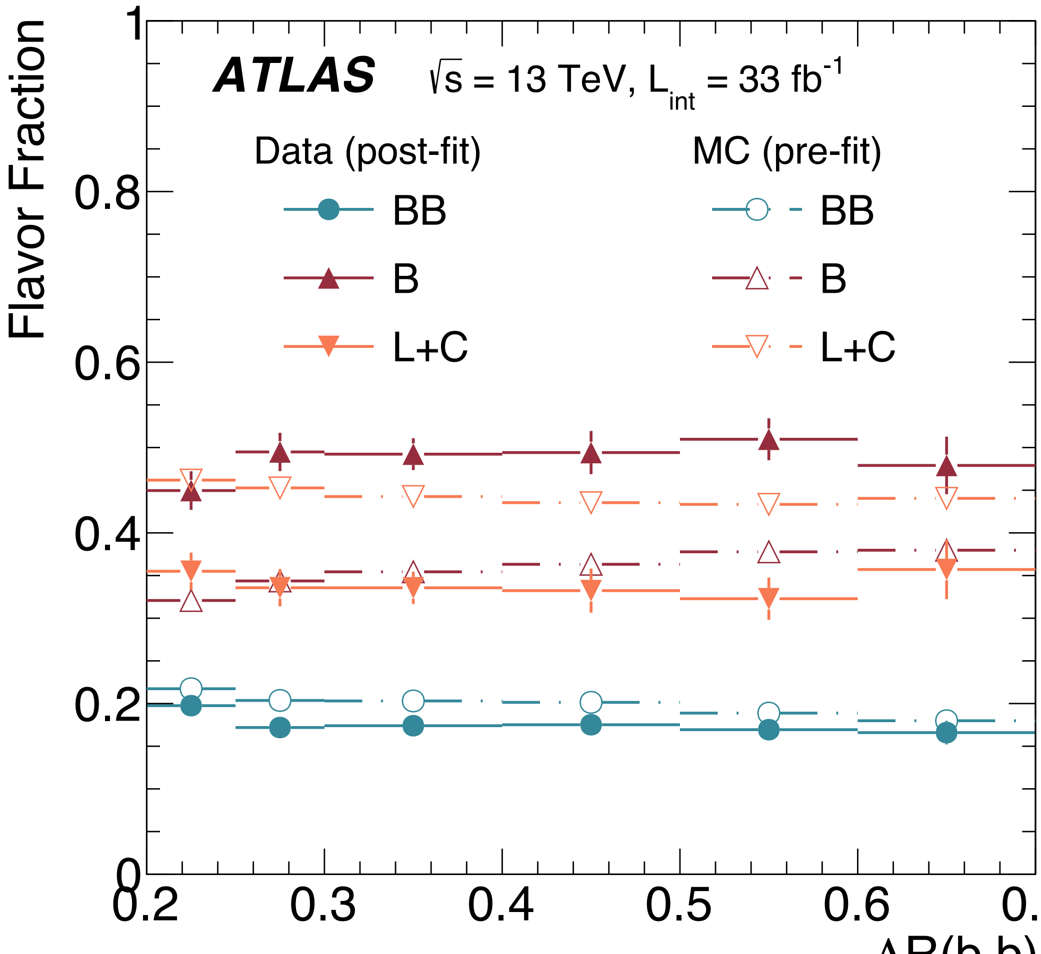


arXiv:1902.04374

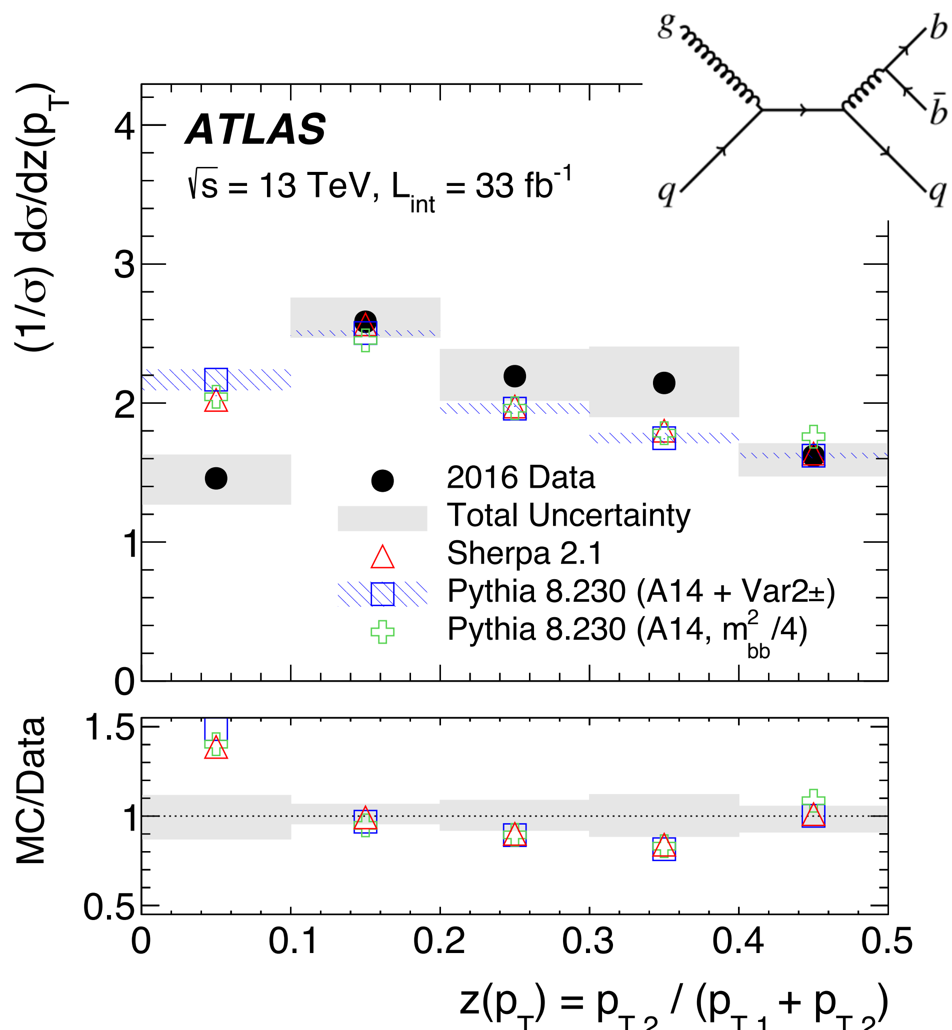
arXiv:1902.04374

B-jet production

- B-jet fraction is about 2–4% of inclusive jets, dominated by g>b$\underline{b}$ splitting (GS) at high p_T
- GS has often small b$\underline{b}$ separation, which ATLAS studies with R_{sub}=0.2 subjets within R=1.0
- MC mismodels e.g. B (single b or $\Delta R(b,\underline{b})<0.2$) vs L+C fractions and fragmentation $z(p_T)$



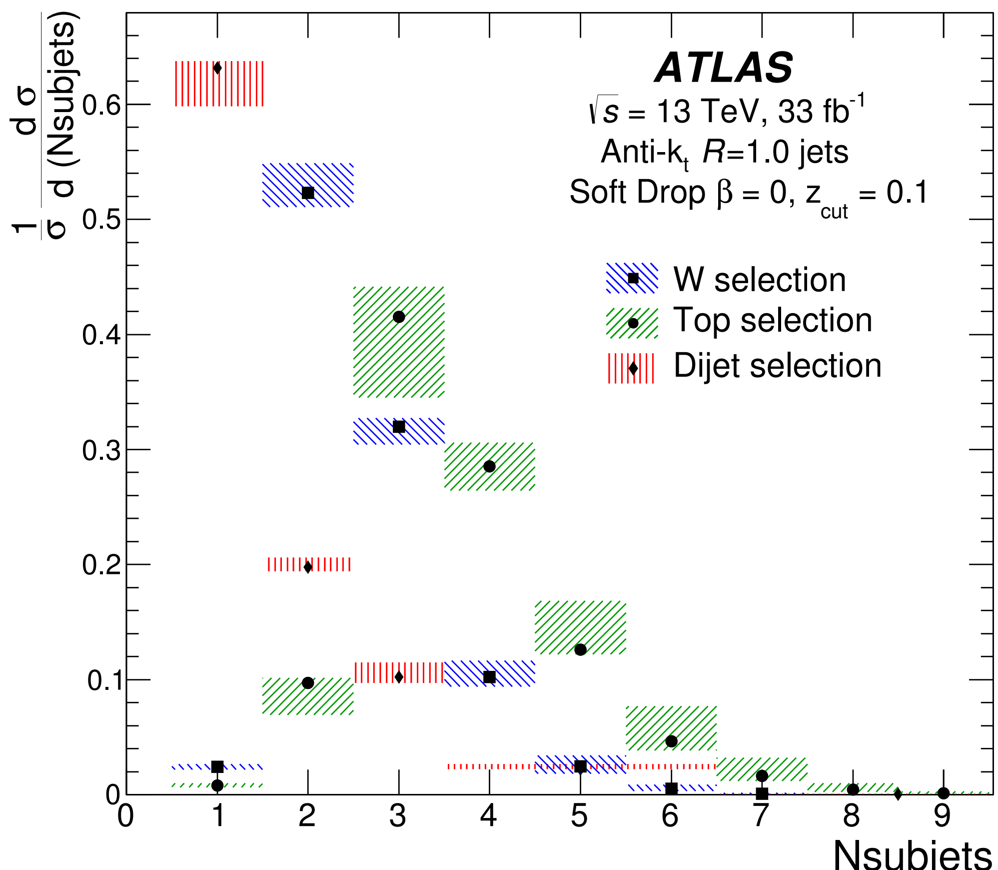
arXiv:1812.09283



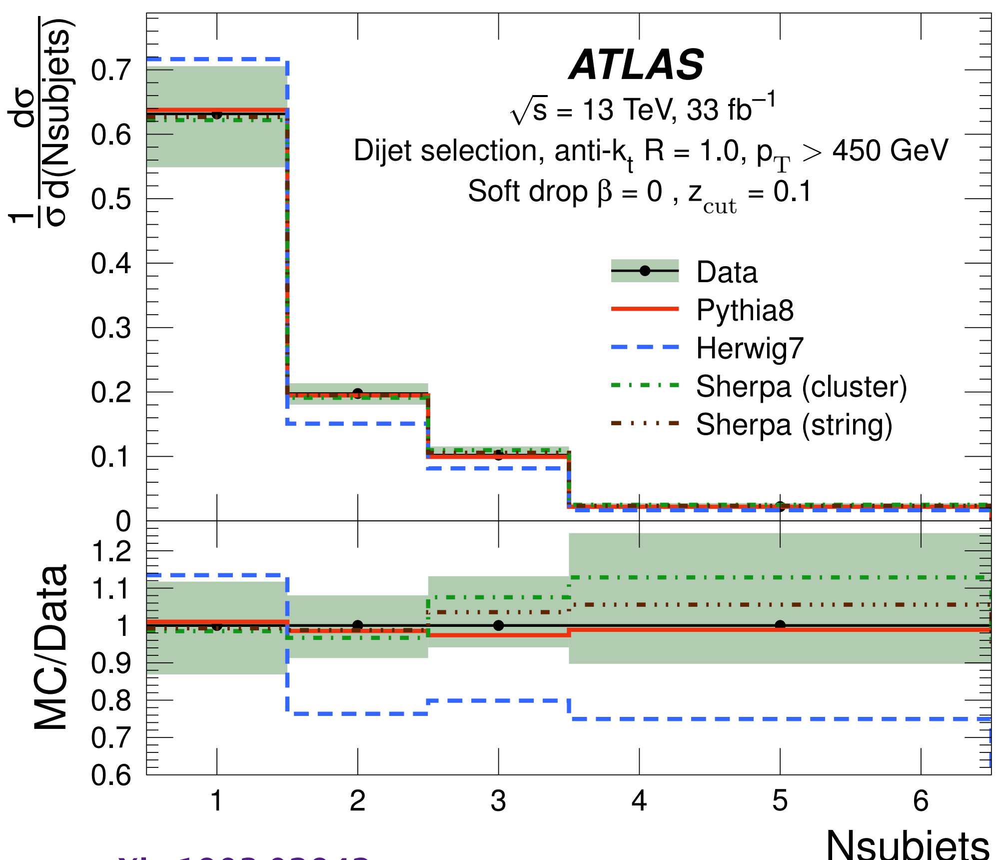
arXiv:1812.09283

Jet shapes

- Jets from boosted W/Z, t, h are a hot topic at the LHC
- Number of subjets and (groomed) jet mass are important variables to separate QCD jets
- Many other shape variables also studied in detail by ATLAS

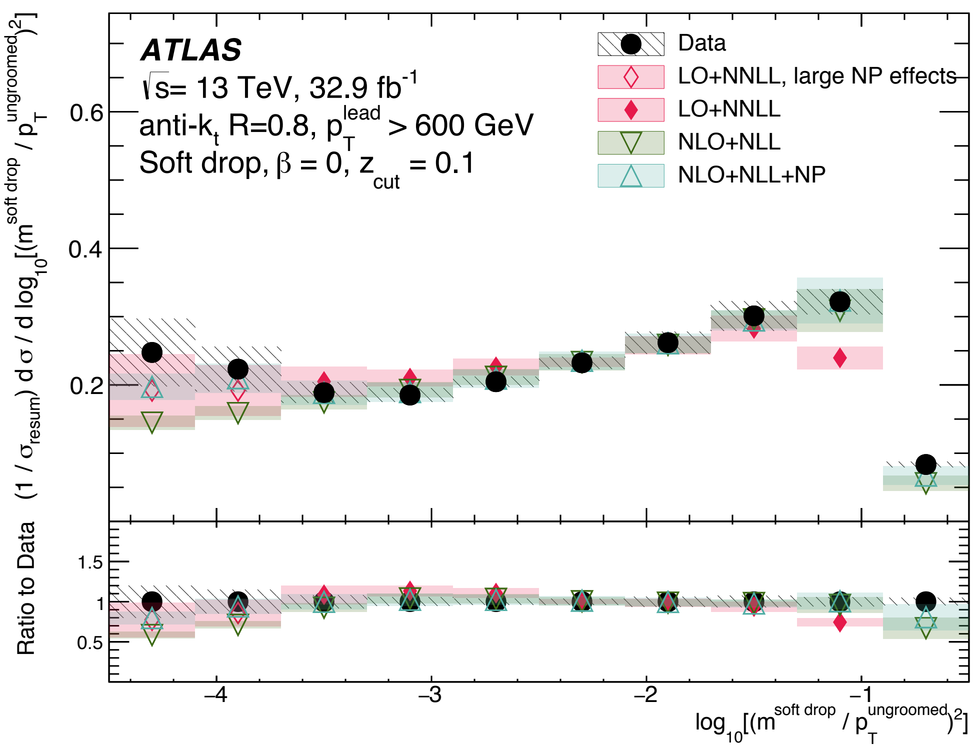


arXiv:1903.02942

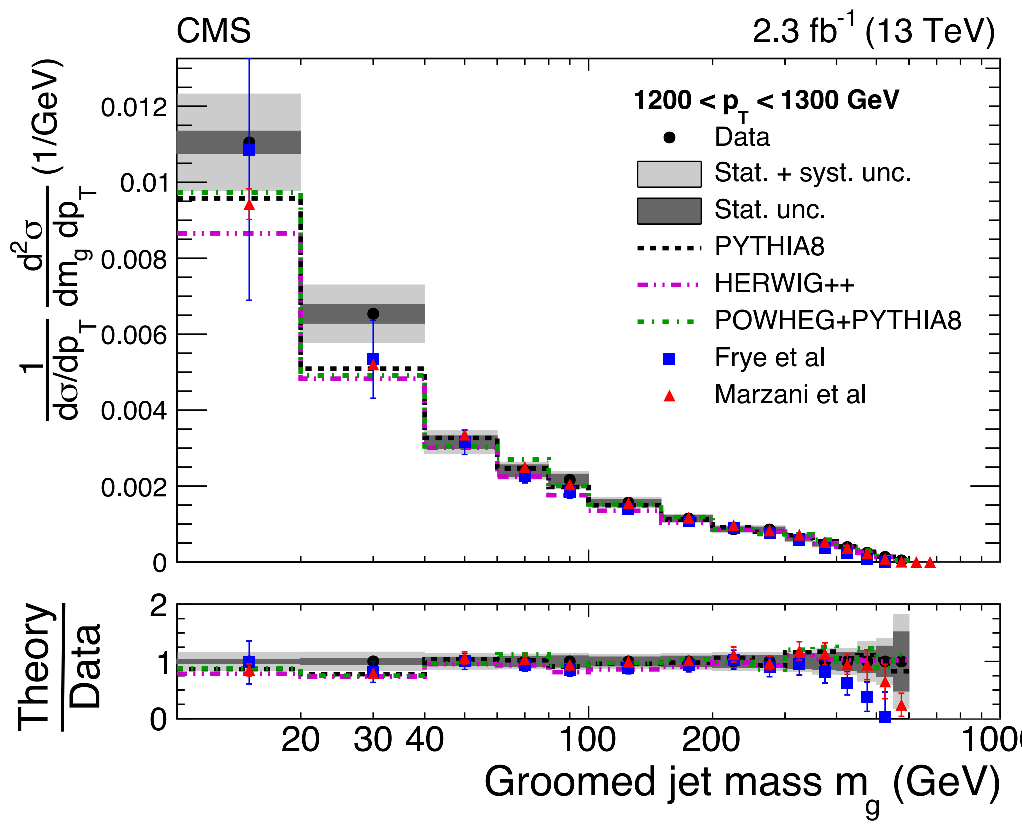


arXiv:1903.02942

- Jet mass is important discriminator between boosted Z/W, t, h jets, and new resonances
- pQCD predictions now available for mass of groomed QCD jets (background shape)
- Recent measurements from both ATLAS and CMS



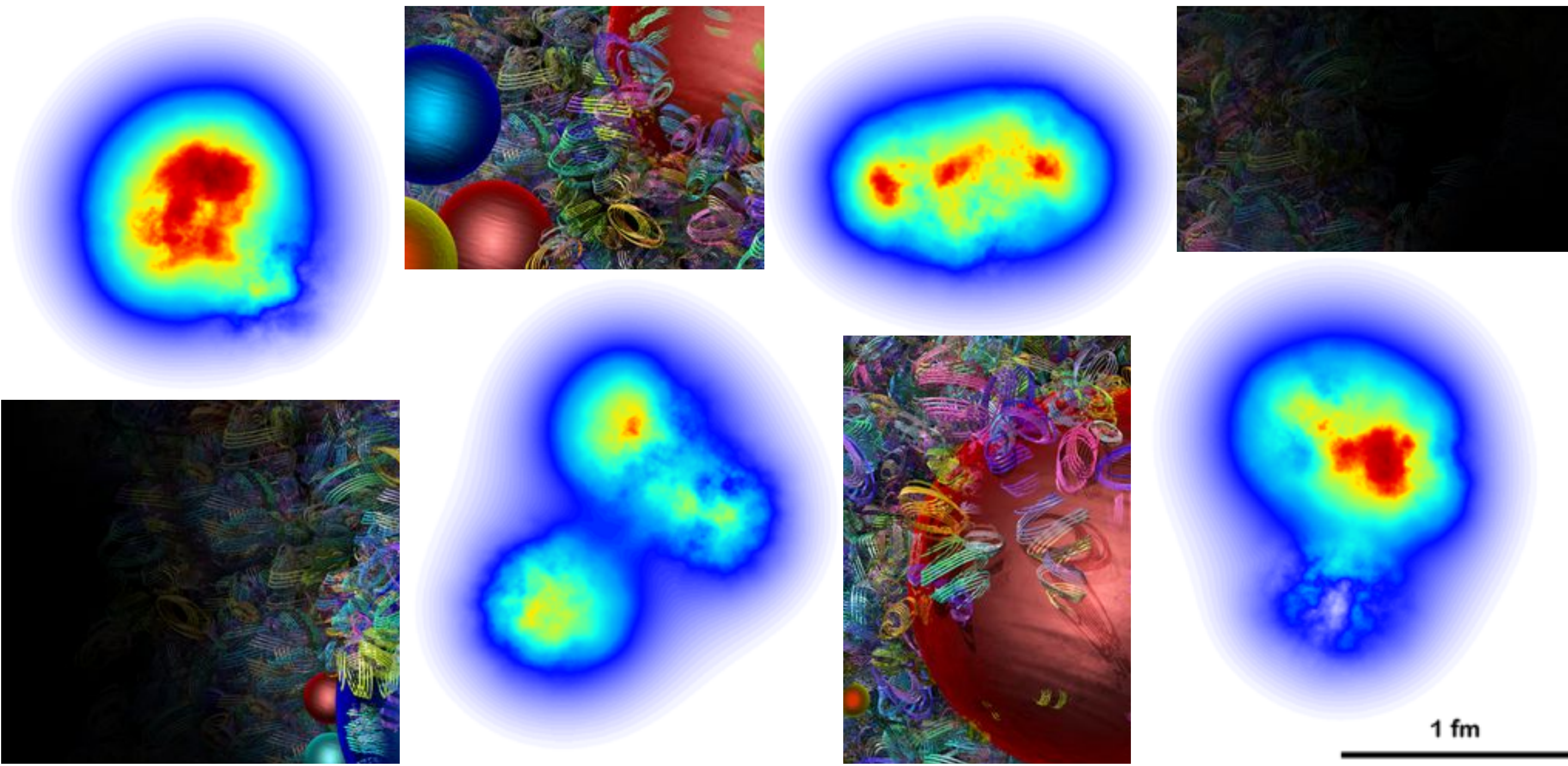
arXiv:1711.08341



arXiv:1807.05974

Gluons

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



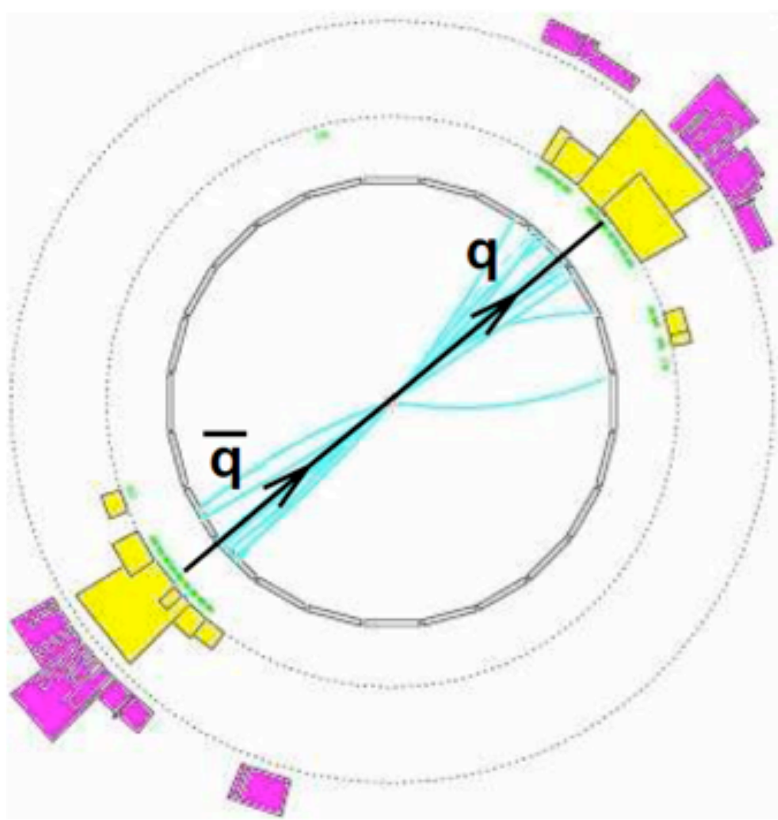
H. Mäntysaari and B. Schenke, **Phys. Rev. Lett. 117, 052301 (2016)**.

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

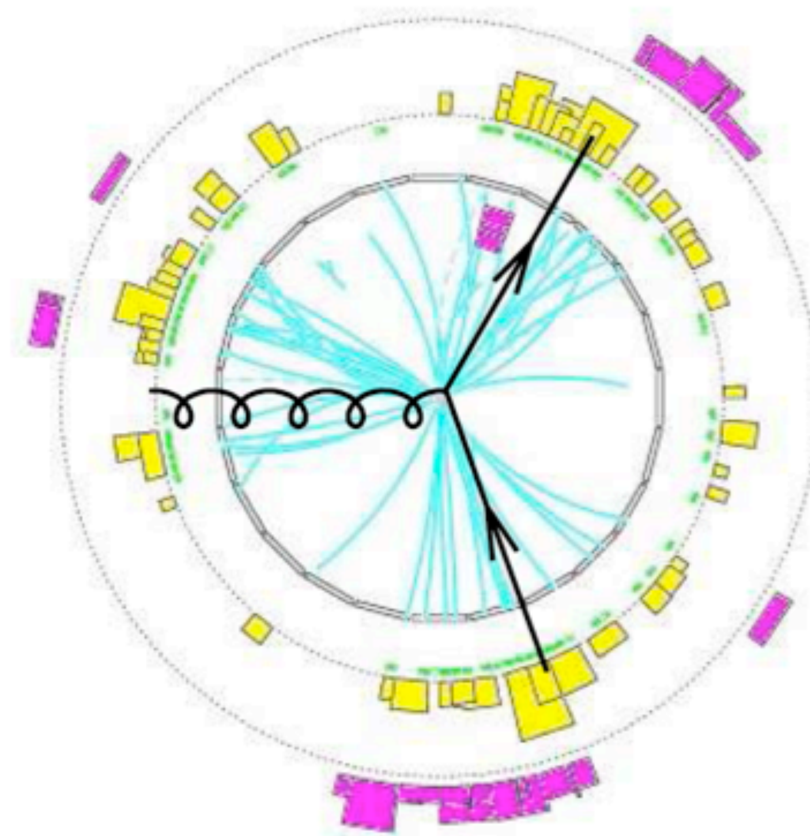
Discovery of gluons

- Gluons discovered at DESY in 1979 by TASSO and other experiments at PETRA [1]
- Evident as 3-jet events in e^+e^- collisions

[1] https://arxiv.org/abs/1409.4232



Jets are what we see.
Clearly(?) 2 jets here

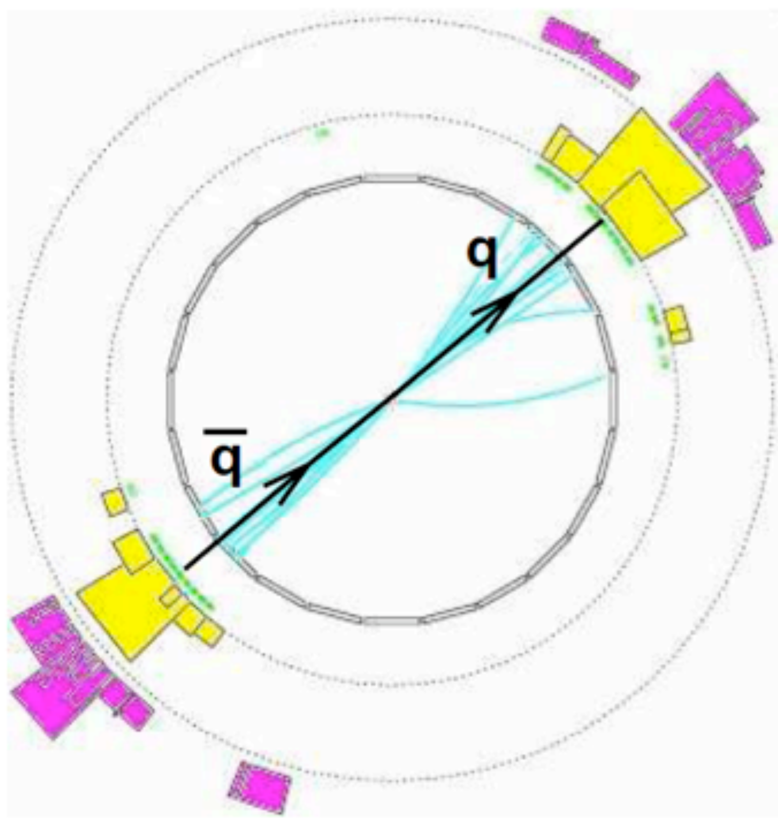


How many jets do you see?

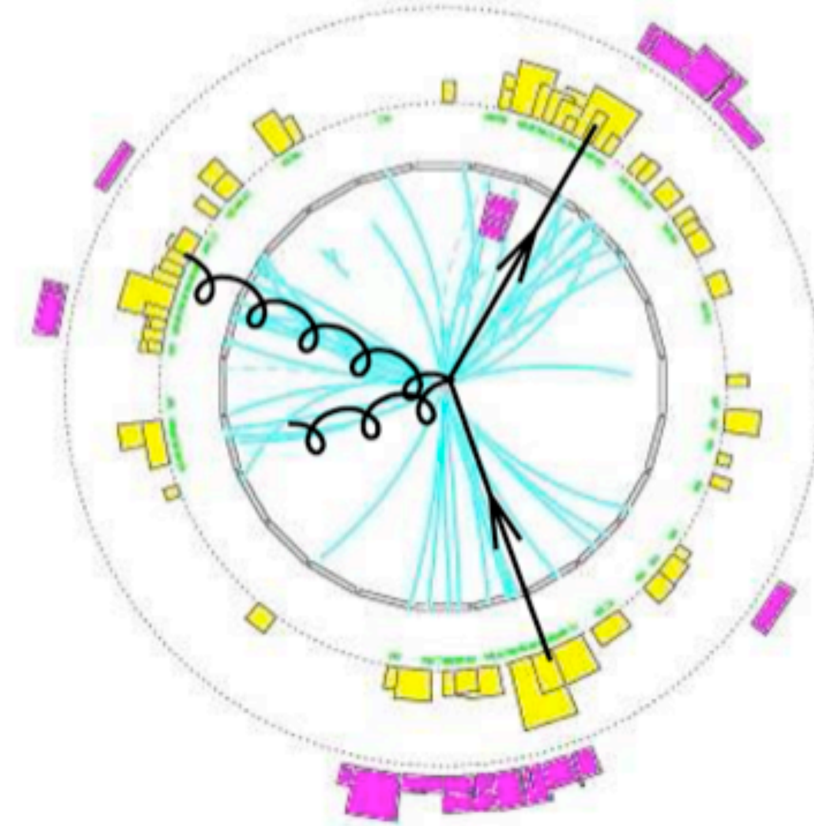
From G. Salam, Towards Jetography

Ambiguity of gluons

- Yet what amounts to a gluon jet remains a bit slippery concept
- Parton shower is g>gg branchings with g>qq splittings, so answer depends on pQCD order



Jets are what we see.
Clearly(?) 2 jets here



How many jets do you see?

From G. Salam, Towards Jetography

arXiv:1704.03878

What is a Quark Jet?

From lunch/dinner discussions

Ill-Defined ↓ **Well-Defined**

What people sometimes think we mean ↑ **What we mean**

Quark as noun

A quark parton

A Born-level quark parton

The initiating quark parton in a final state shower

An eikonal line with baryon number 1/3
and carrying triplet color charge

A quark operator appearing in a hard matrix element
in the context of a factorization theorem

A parton-level jet object that has been quark-tagged
using a soft-safe flavored jet algorithm (automatically
collinear safe if you sum constituent flavors)

Quark as adjective

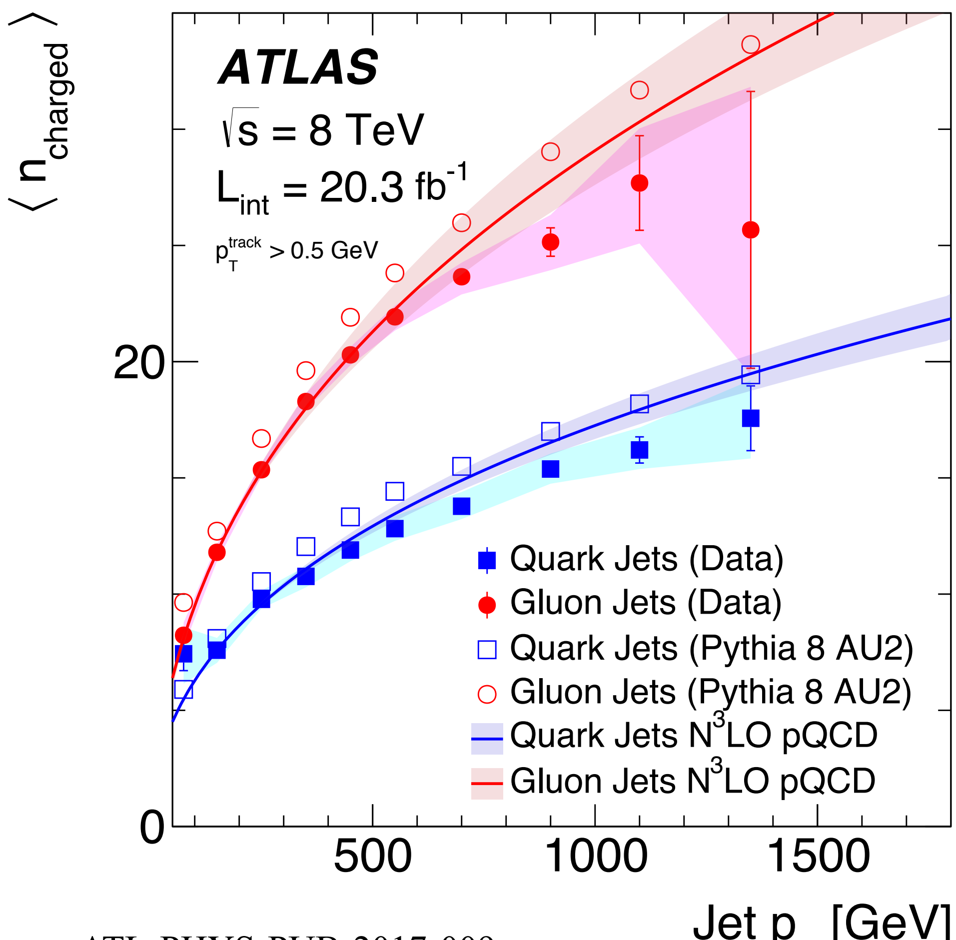
A phase space region (as defined by an unambiguous
hadronic fiducial cross section measurement) that yields
an enriched sample of quarks (as interpreted by some
suitable, though fundamentally ambiguous, criterion)

Gluon-jet identification

- Suitable observables for gluon identification are e.g. N_{ptcl}, jet width, hardest particle p_T

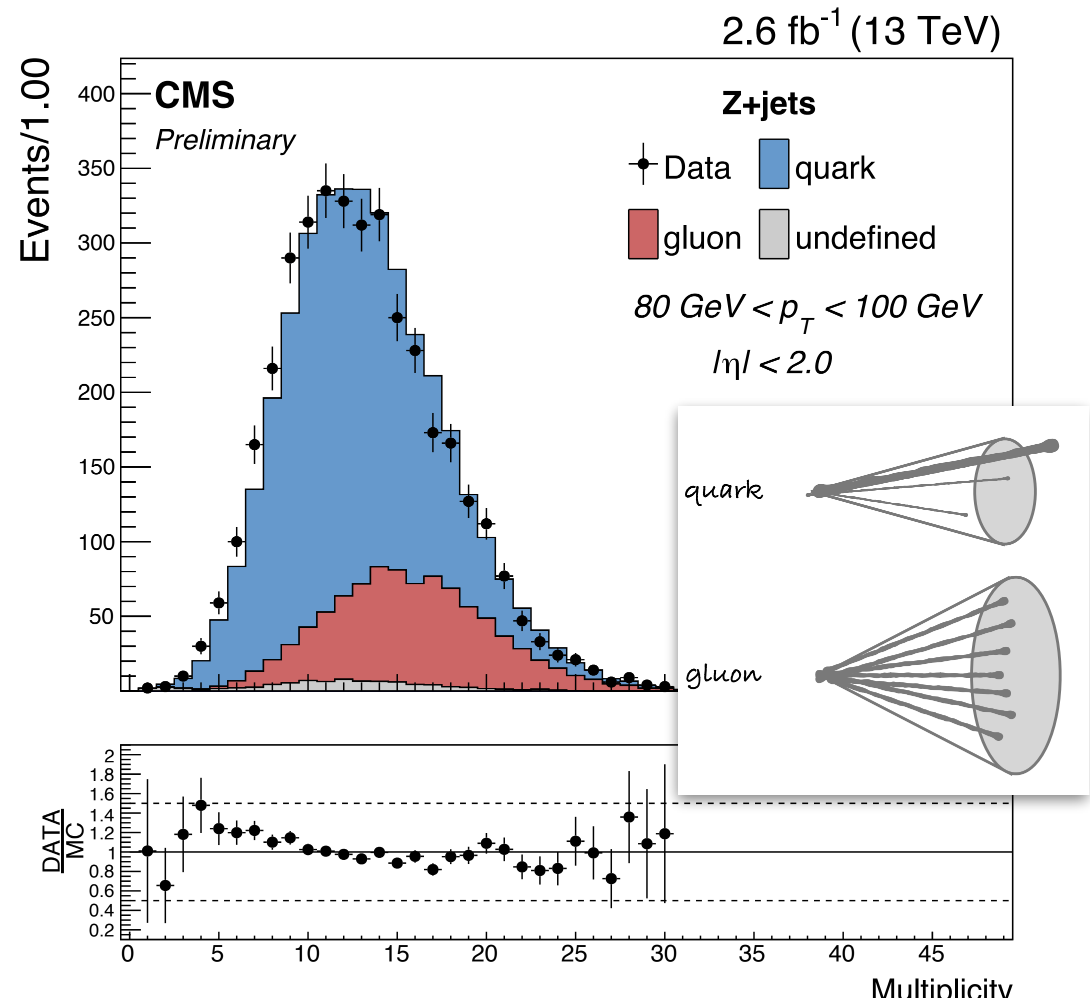
8 TeV ref. CMS-PAS-JME-13-002

- Requires non-perturbative QCD, difficult to model, but can reweigh based on data
  - Dijet, γ+jet and Z+jet channels each have different quark/gluon fractions
  - Quark/gluon more similar in data than in Pythia 6 (or Pythia8), but less similar than in Herwig++



ATL-PHYS-PUB-2017-009

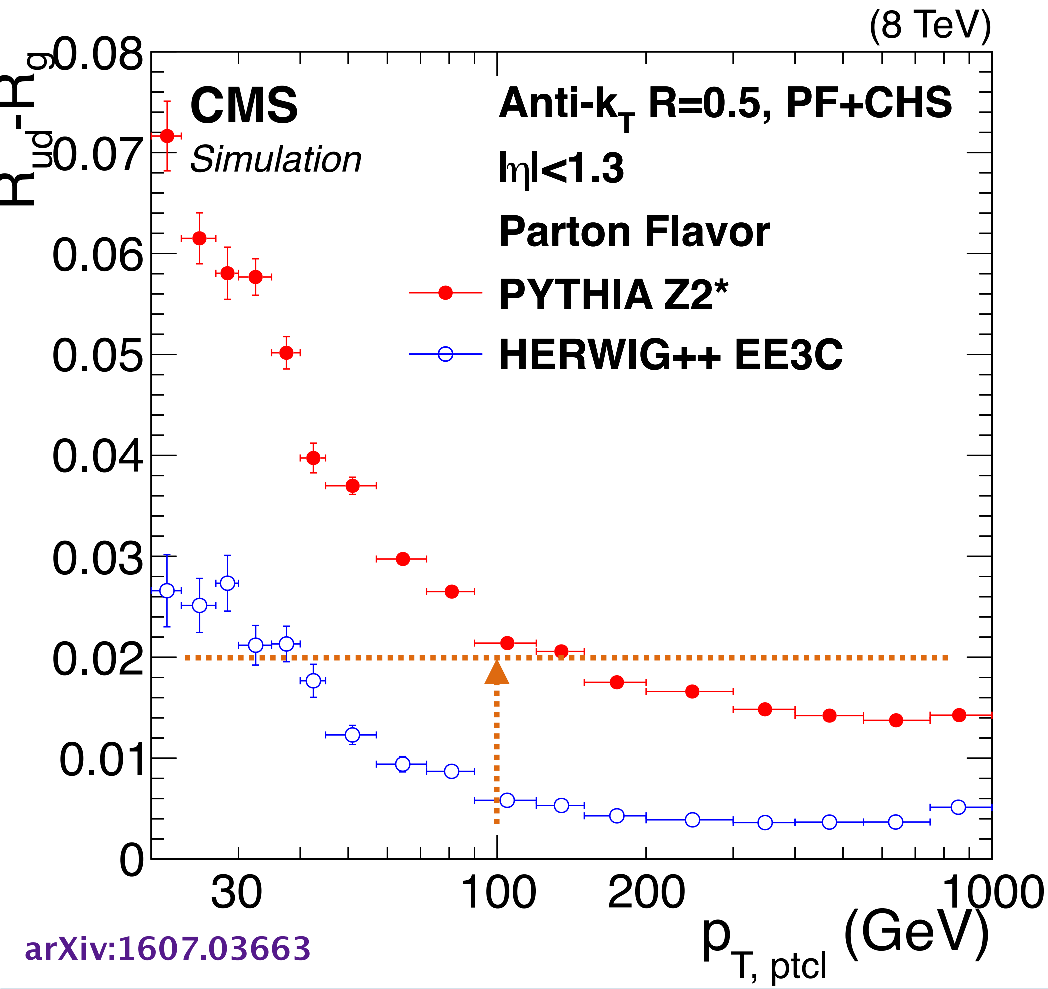
(also: ATL-PHYS-PUB-2017-017 arXiv:1405.6583)



CMS-DP-2016-070

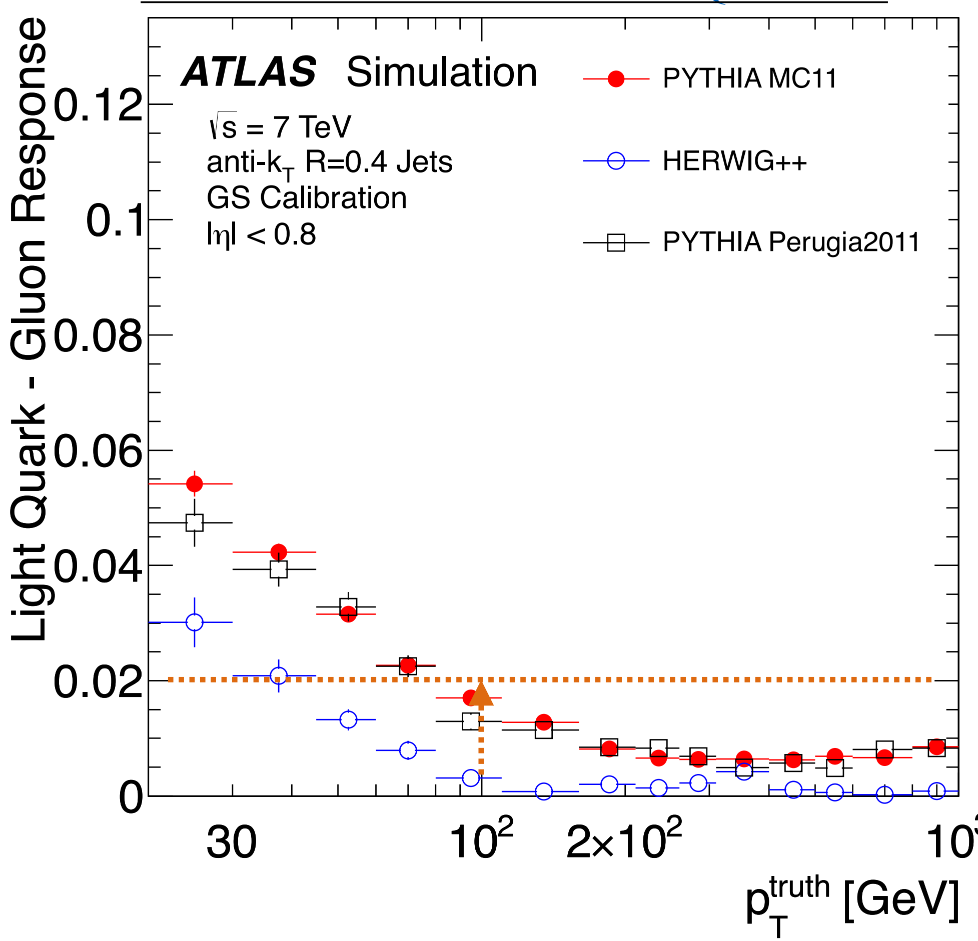
Gluon-jet calibration

- Both ATLAS and CMS calibrate gluon jets with Pythia MC, uncertainties vs Herwig++
- CMS Particle Flow (PF) and ATLAS Global Sequential (GS) calibration both use tracks
- Observed, highly correlated, quark/gluon difference from fragmentation to neutral hadrons?



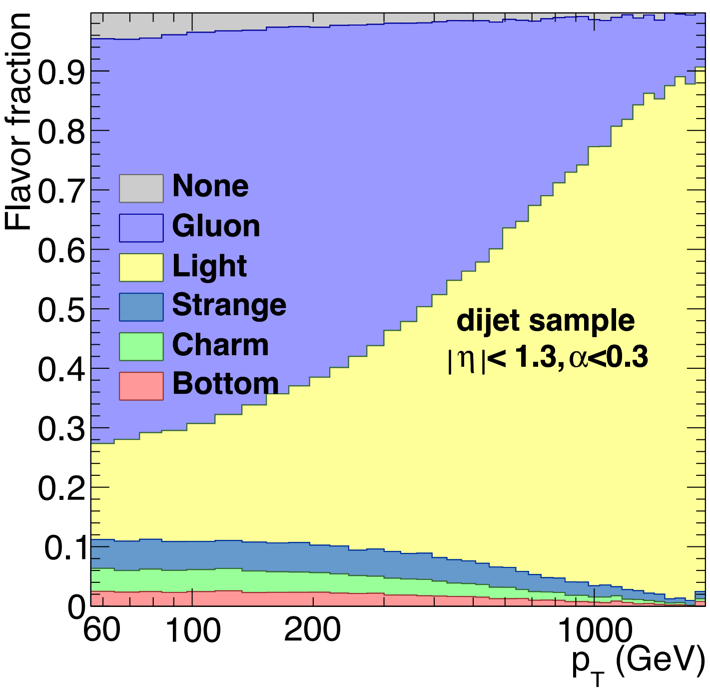
arXiv:1607.03663

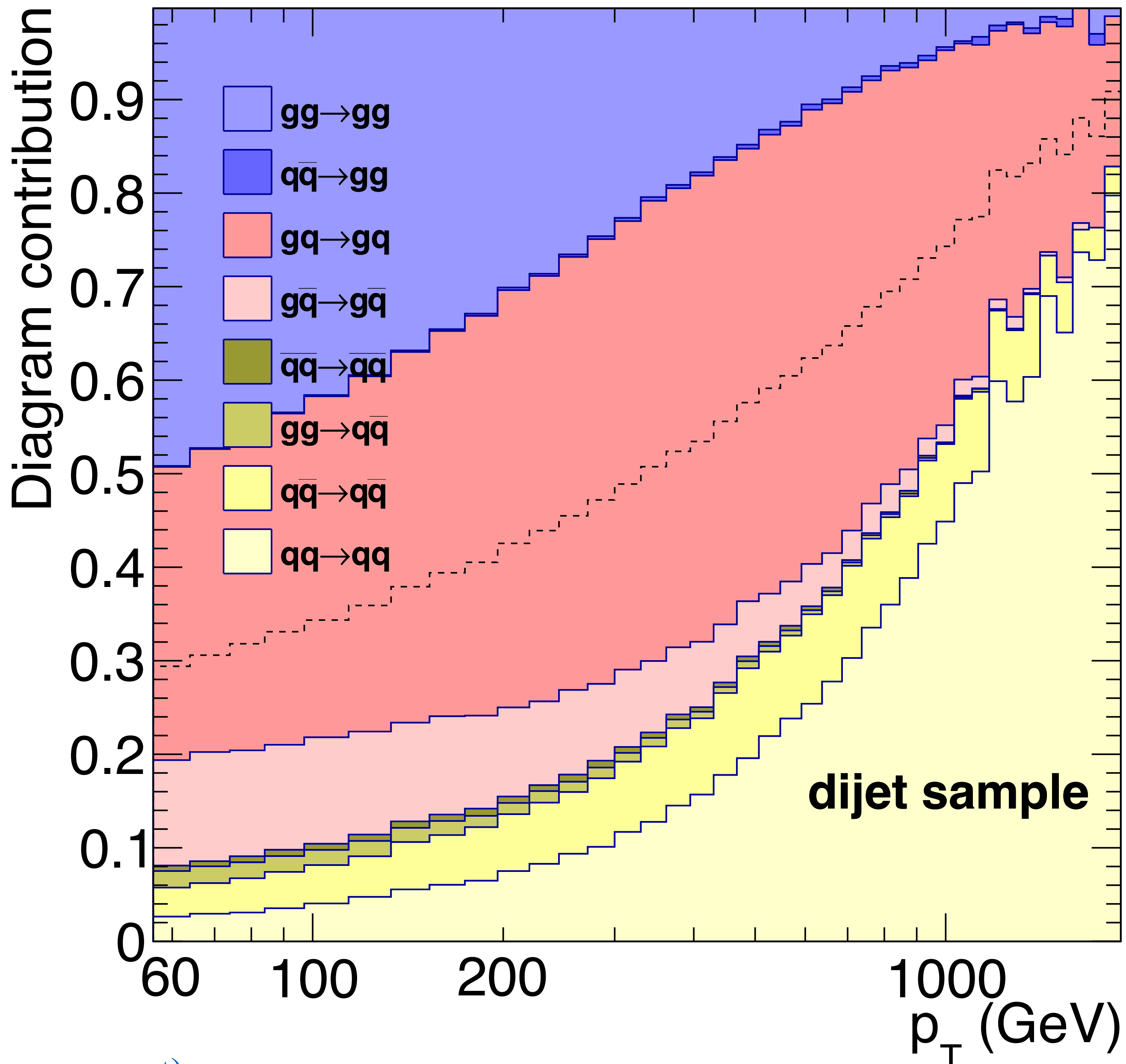
AtlasPublic/JetEtmissJetPerformanceQuarkGluon



Gluon-jet fraction

- High p_T gluon-jet production mostly from $gq_v > gq_v$ scatter
- Sensitivity to high-x gluon PDF could be enhanced with gluon-jet tagging
- Requires robust data/MC scale factors for gluon ID and response + (N)NLO theory

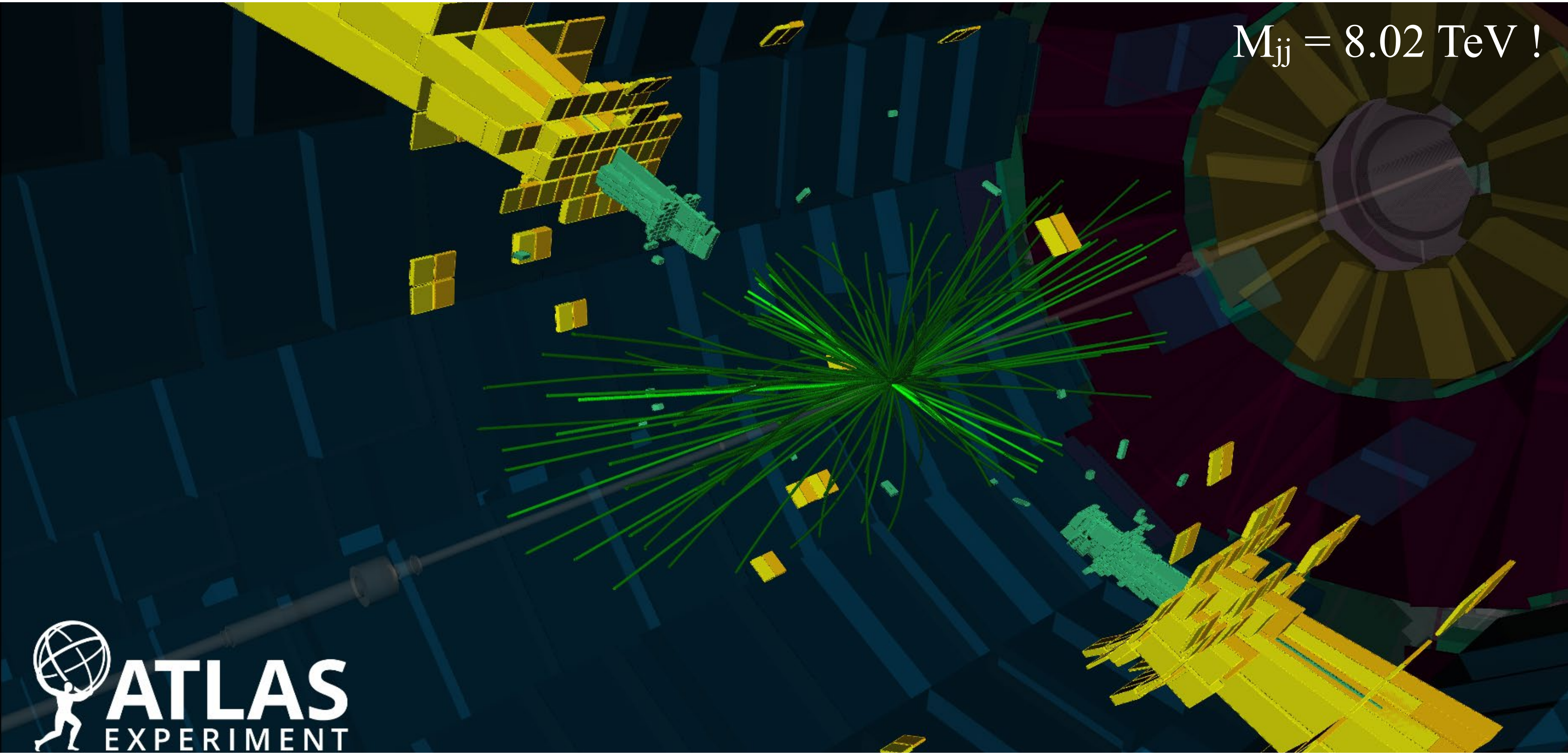




A. Abhishek, MSc Thesis (available on request)

New physics

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

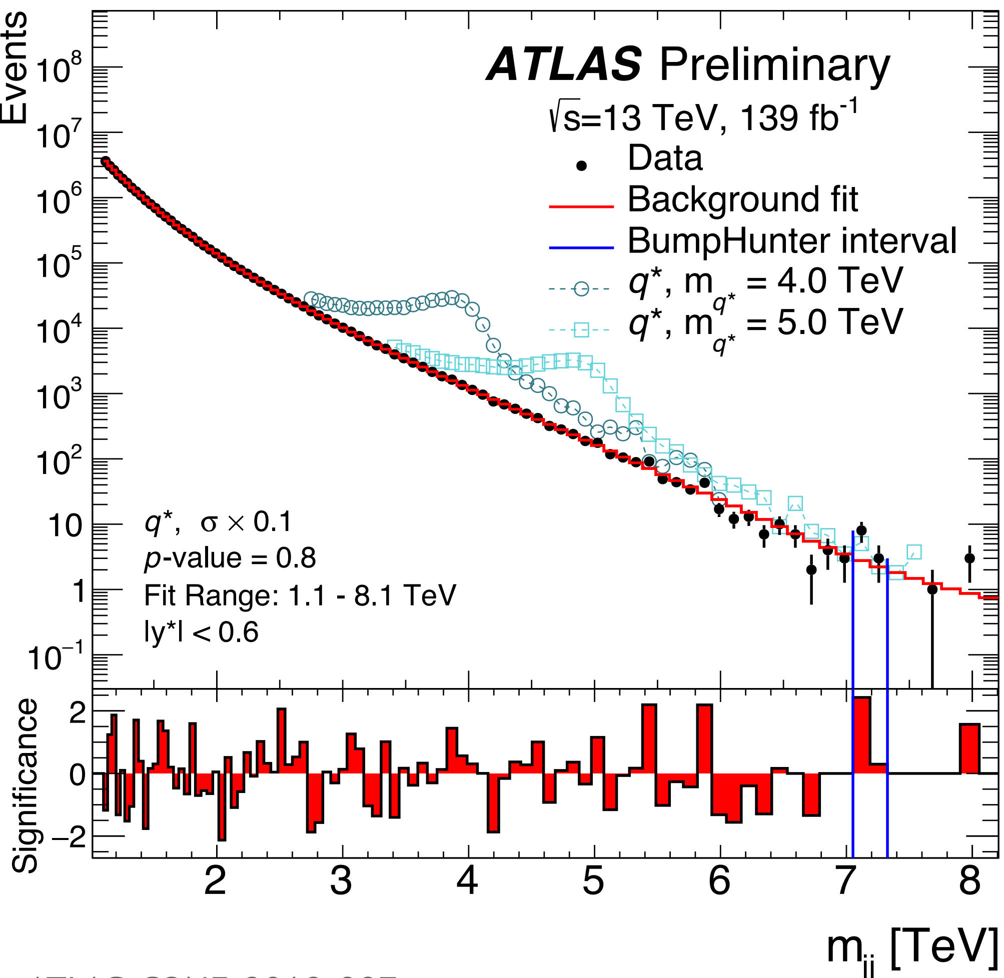


http://cms-results.web.cern.ch/cms-results/public-results/publications/

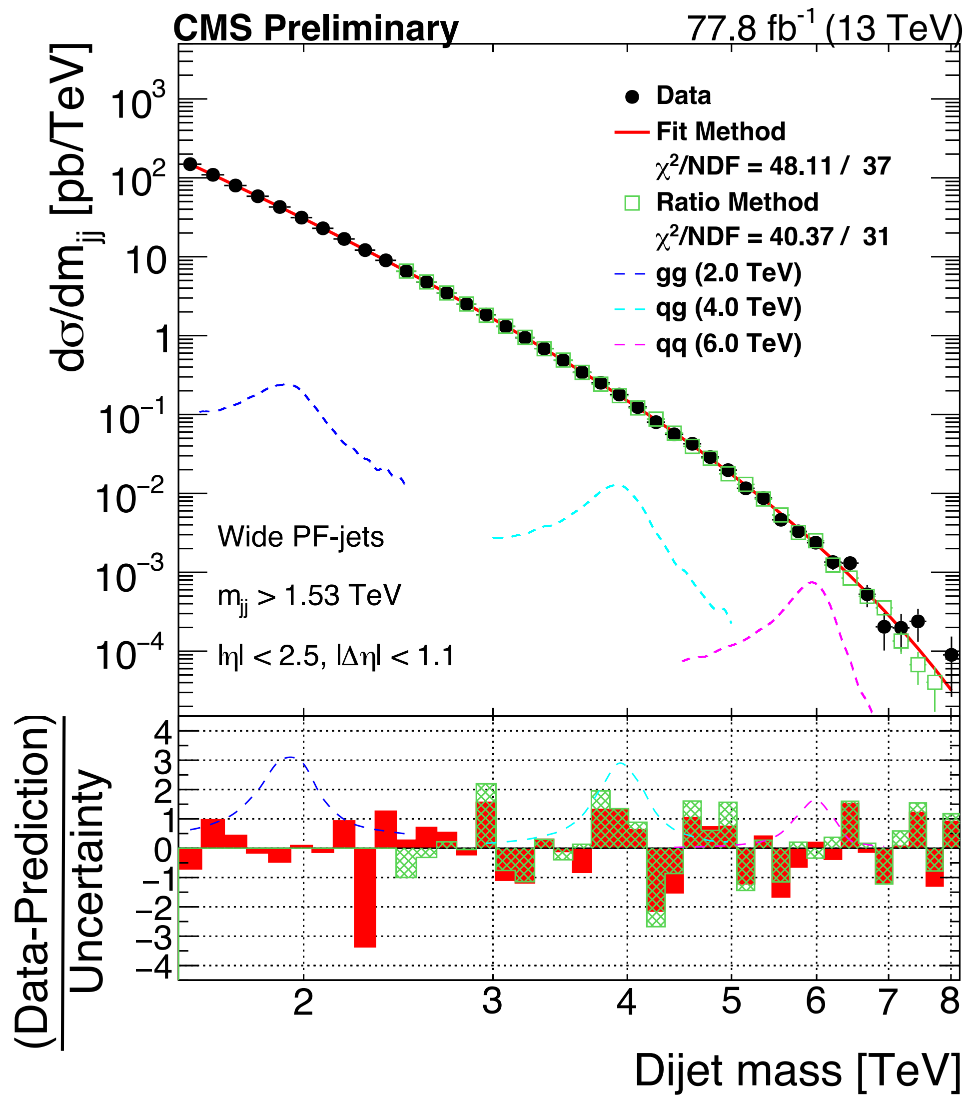
High dijet mass

- ATLAS and CMS both scan dijet mass spectrum for resonances
- No evidence for new physics, both now have highest M_{jj} at 8 TeV

LHCP highlight



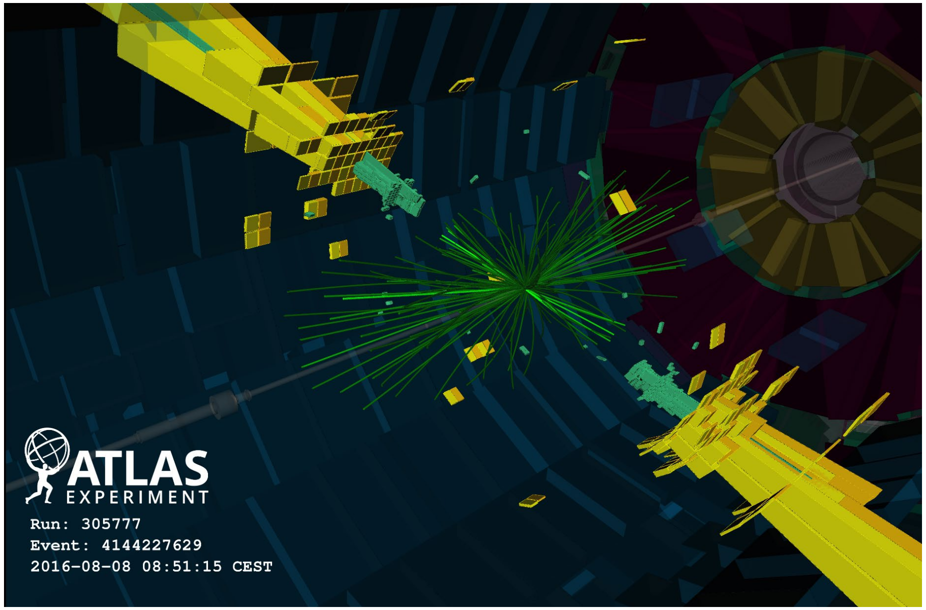
ATLAS-CONF-2019-007

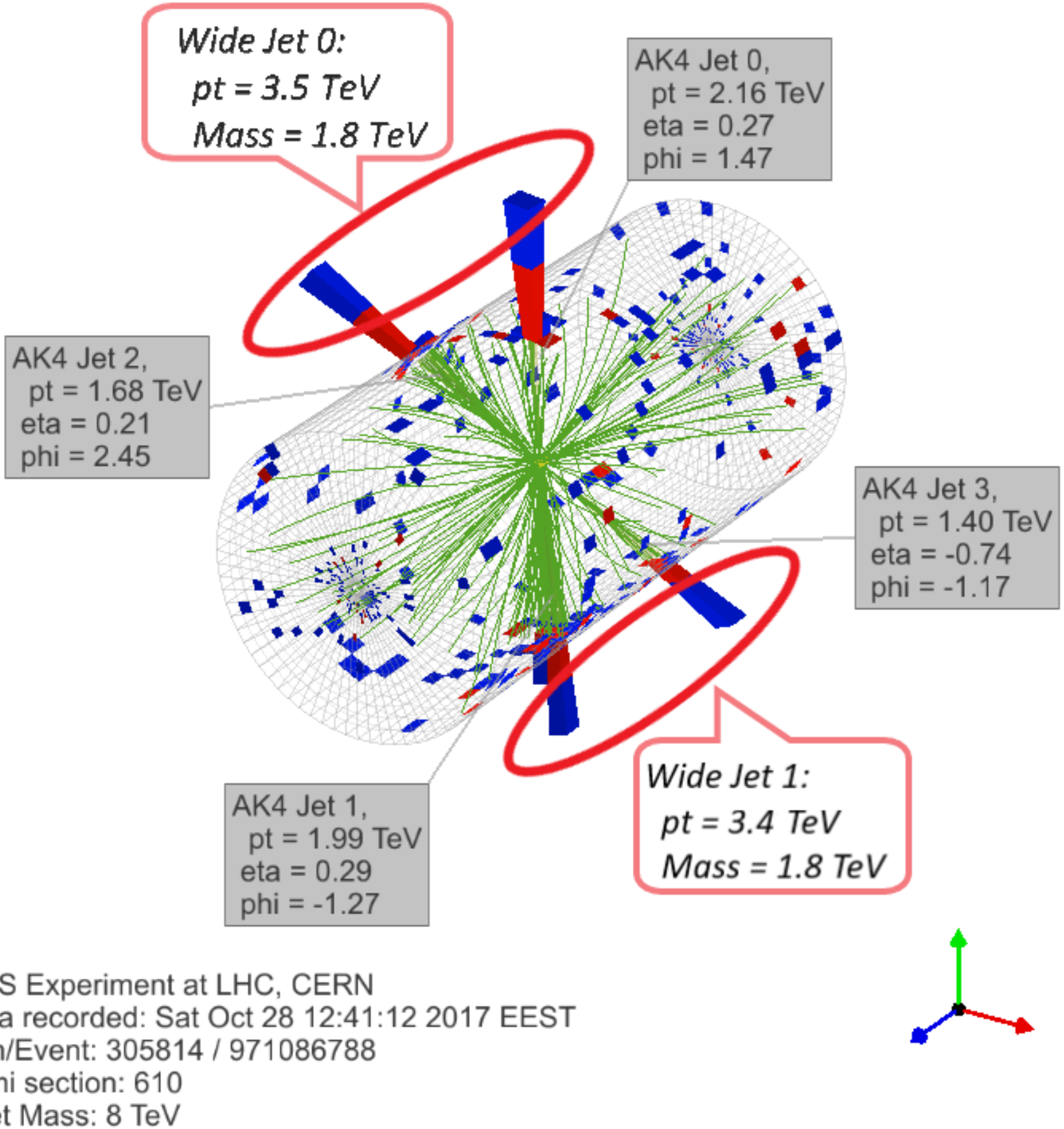


CMS-PAS-EXO-17-026

8 TeV dijet mass events

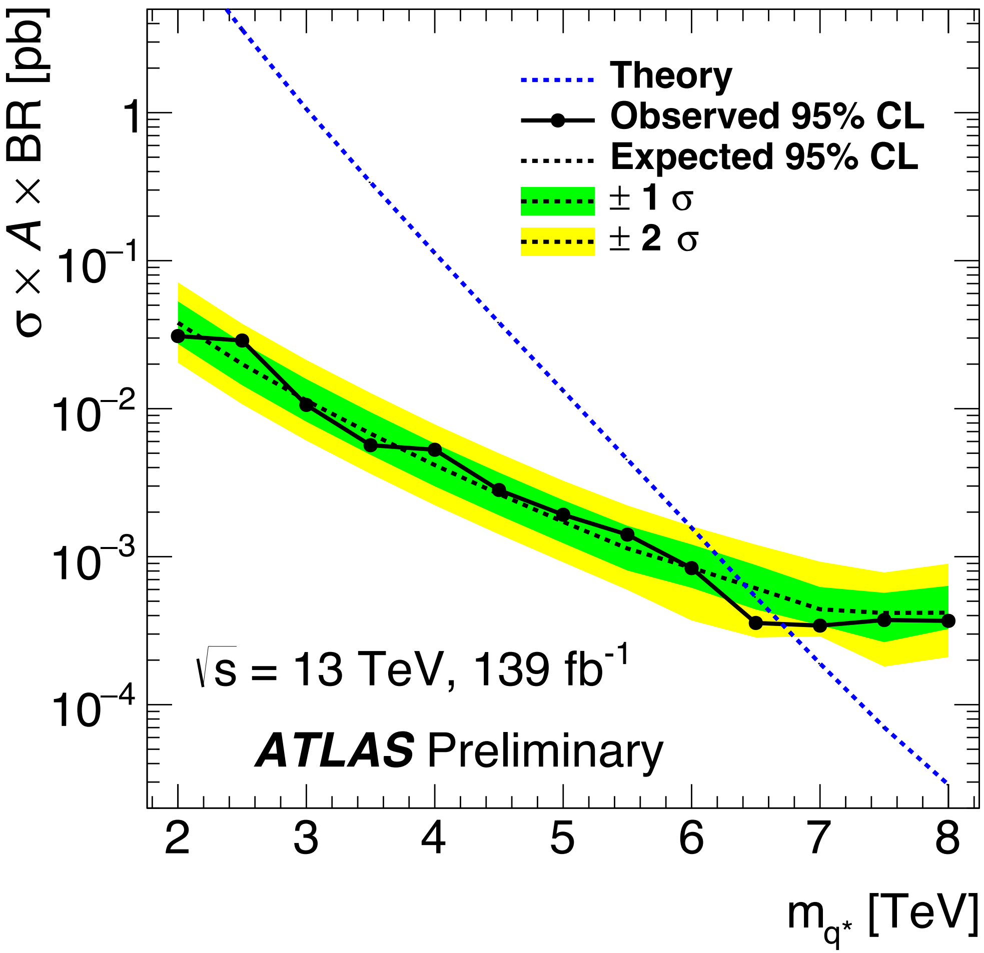
- Both CMS and ATLAS highest M_{jj} dijet events are quite spectacular
  - most common event type is two narrow jets back-to-back
- CMS event is particularly curious, as it is composed of two wide jets with mass m_j=1.8 TeV each
  - rare event type (MadGraph<<1%), but MC could underestimate rate
  - 2nd highest M_{jj}=7.9 TeV is regular dijet





Exclusion limits

- Dijet data can rule out a number of quark-quark, quark-gluon, gluon-gluon resonances
- At 7–8 TeV sensitive to axigluon/coloron models, scalar diquarks, strings, excited quarks
- No significant deviations present anywhere, but 8 TeV expected limits still high



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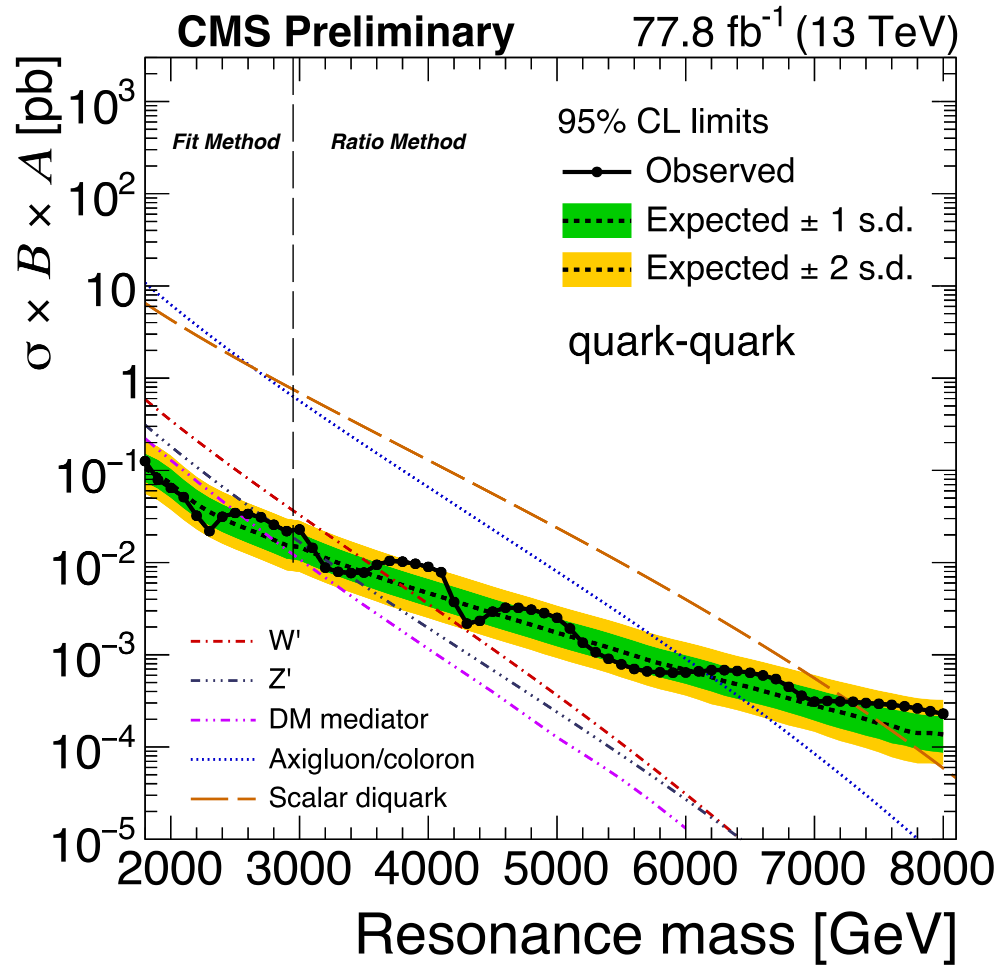
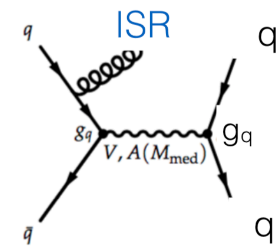


CMS-PAS-EXO-17-026

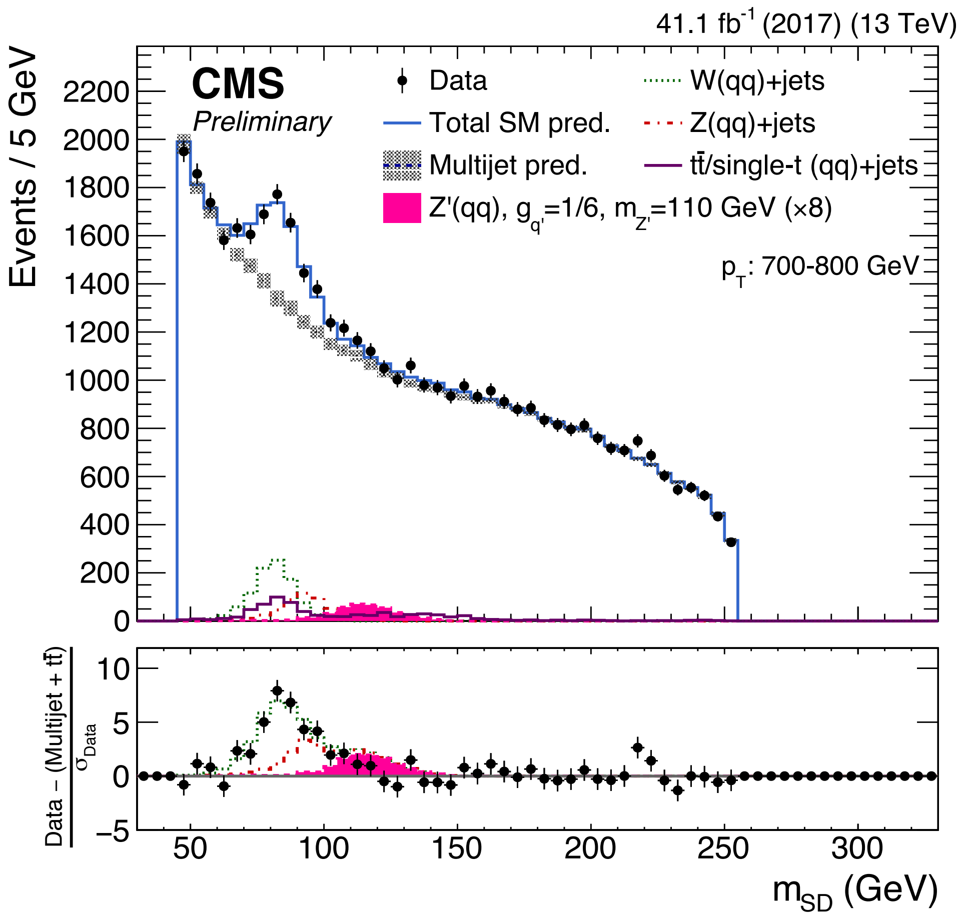
Low mass dijets

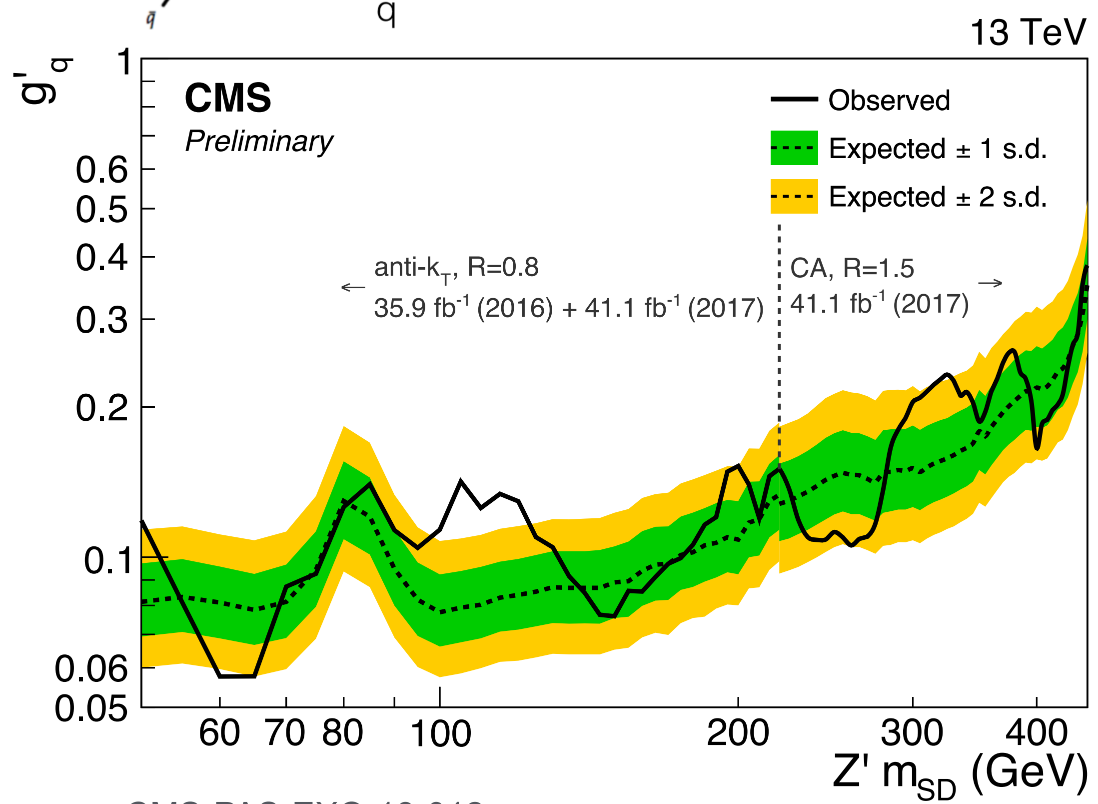
- Low mass dijet resonances accessible with trigger-level analysis ("scouting") and hard ISR
  - scouting stores only partial information (e.g. 1 kB vs 1 MB for full event) on-line with low prescale
  - hard ISR causes resonance to be boosted into a single jet, which is analysed with jet substructure
- Both are impressive techniques; can e.g. reconstruct Z/W>qq resonance!



boosted resonance

LHCP highlight



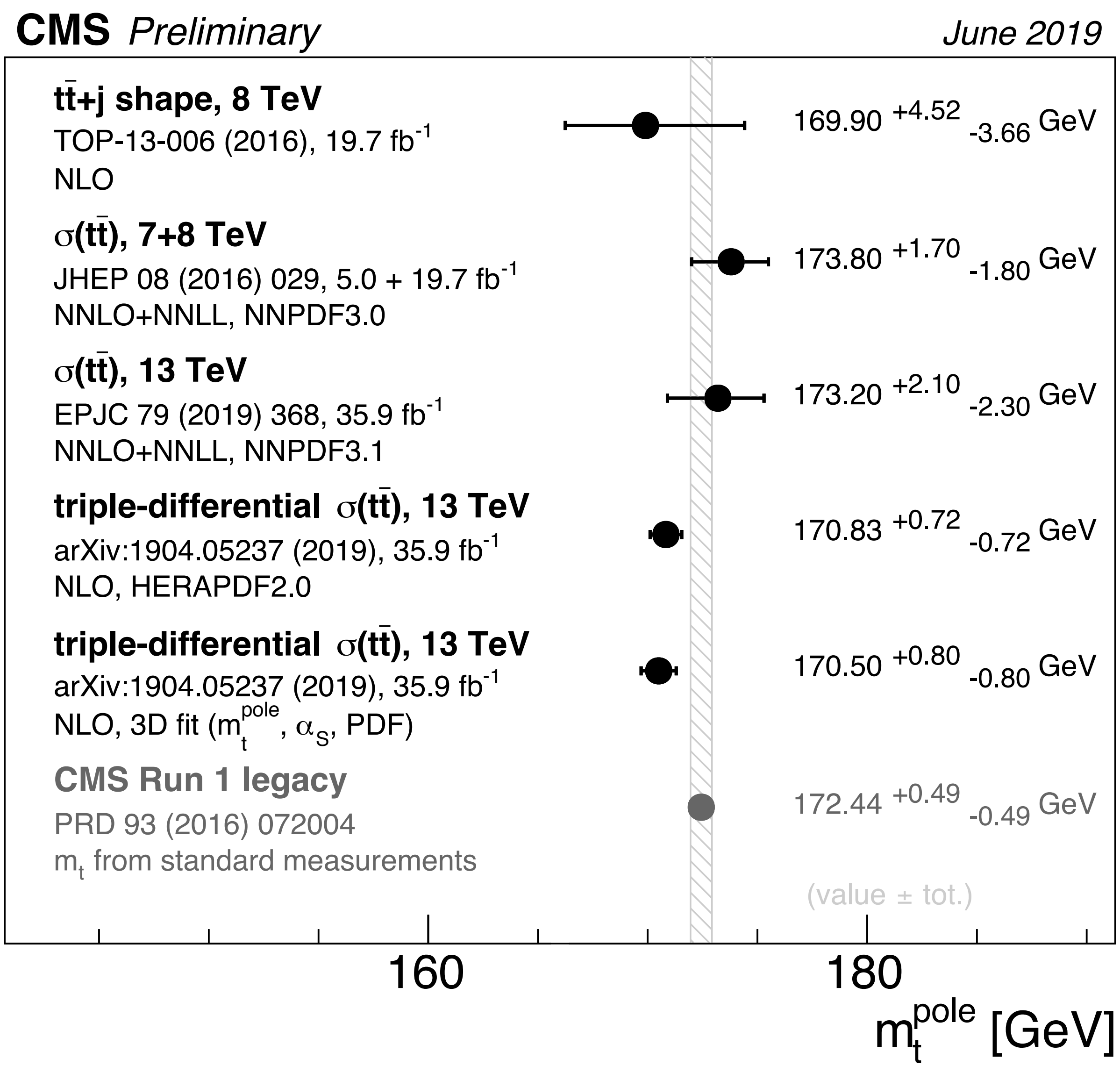


CMS-PAS-EXO-18-012

Top quark mass

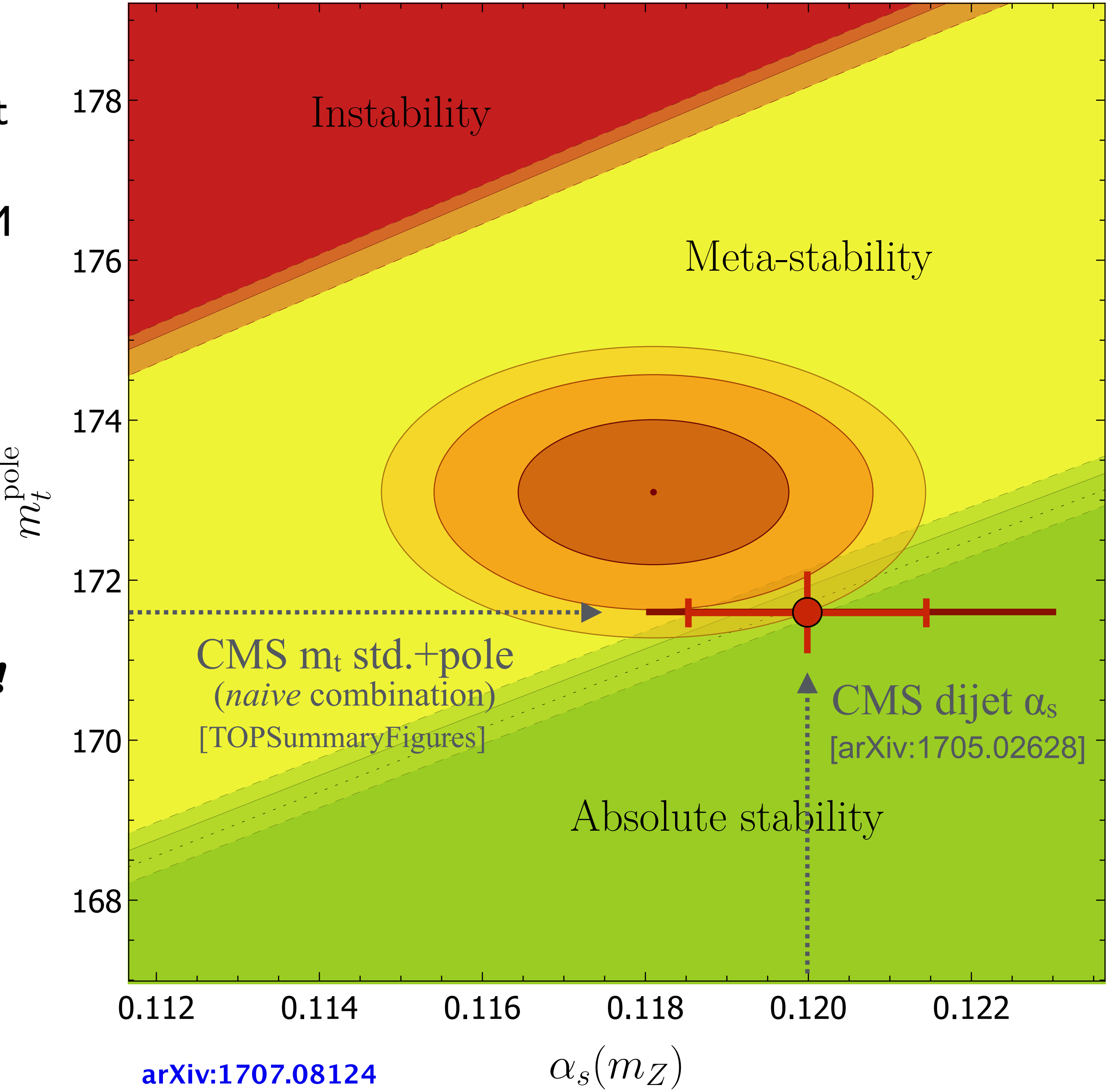
- Standard measurements of m_t rely on kinematic reconstruction from jets (and lepton, MET), compared to MC simulation
  - particularly sensitive to b-jet scale and final state radiation (gluons)
- Ambiguity between MC mass parameter and theoretical pole mass m_t^{pole} of O(0.5 GeV)
- Triple differential $t\bar{t}$ cross section now of comparable precision
  - ***naive*** combination with 0.5 GeV m_t^{MC}-m_t^{pole} uncertainty 171.6 GeV

Top quark production gg>tt, decay t>Wb, W>qq + W>lv



Planck scale?

- There is now non-negligible chance that new experimental measurements will converge at (α_s=0.120, m_t=171.6 GeV)
- No new physics required in SM (and none seen so far), and EW vacuum is stable up to the Planck scale
- Dark matter to be explained, but axions offer an elegant alternative to SUSY / WIMP
- ***Need more precise jet measurements to confirm!***

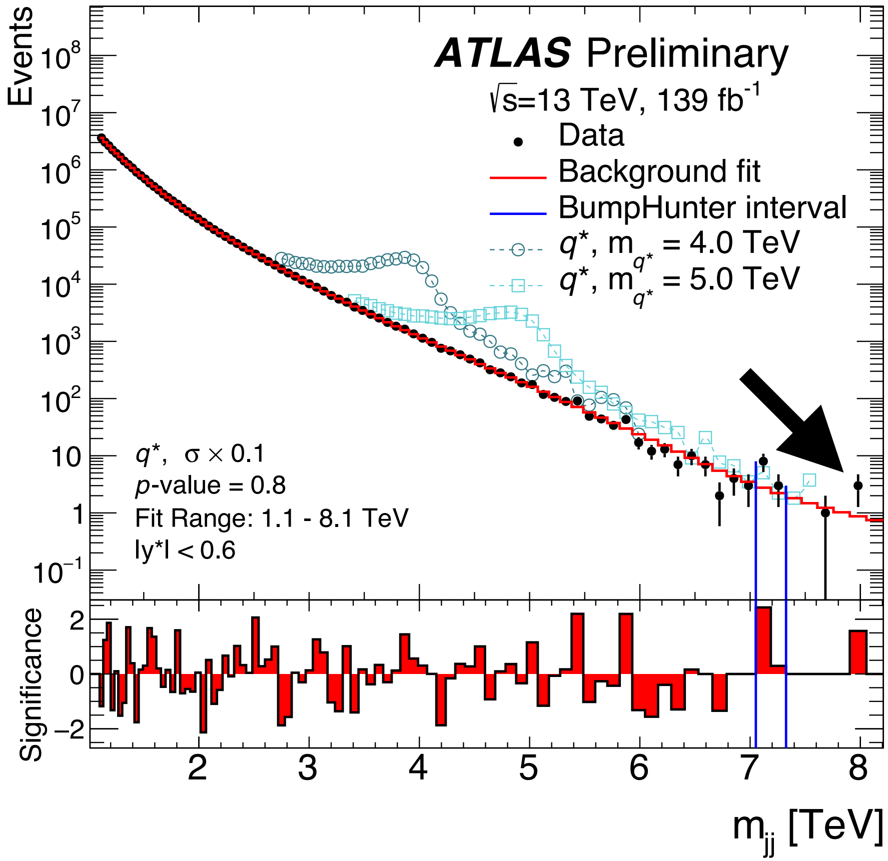


arXiv:1707.08124

Conclusions

- Jets offer great prospects for precision measurements and new physics searches
  - Hints of new resonances at the highest energies ?
  - Or converging to vacuum stability limit, ruling out all new physics below Planck scale?
- Jet measurements will tell! The beauty (quark) and the beast (gluons, FSR) are the key

The big LHC jet showdown



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