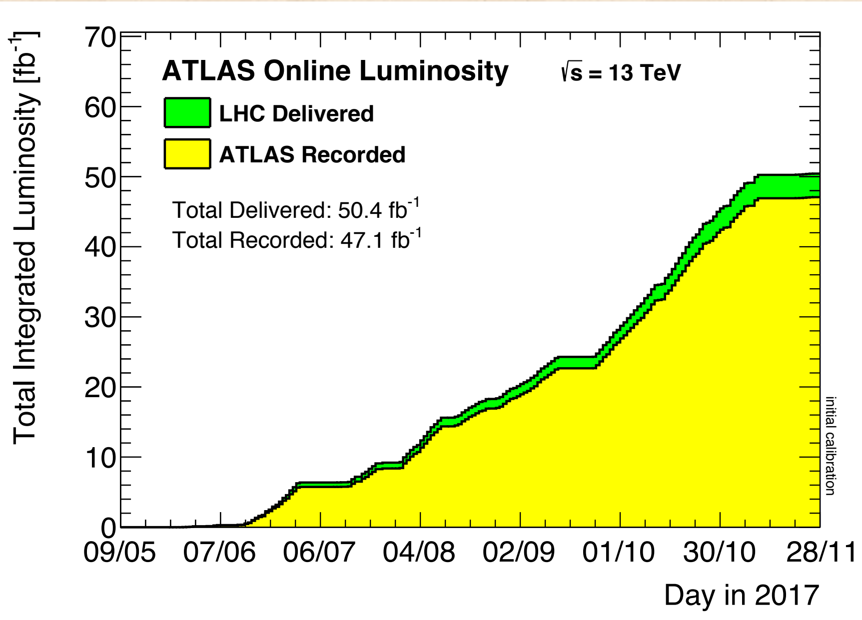
Standard Model and Heavy Ion Physics in CMS and ATLAS

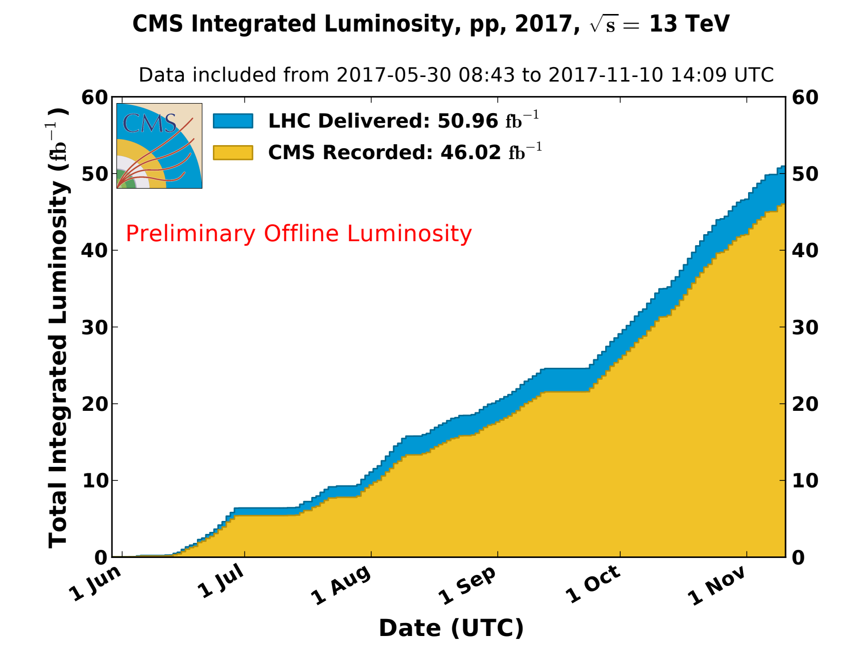
Yi Chen for the CMS and ATLAS collaborations

56th International Winter Meeting on Nuclear Physics

Jan 26, 2018

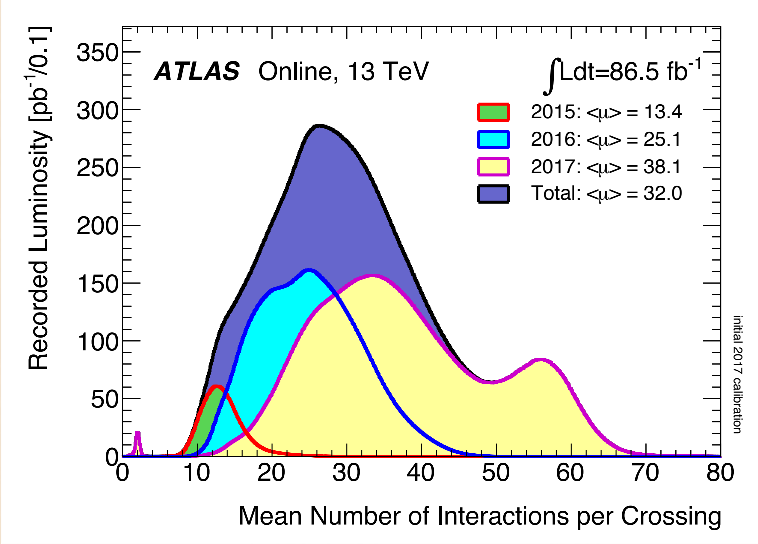
2017

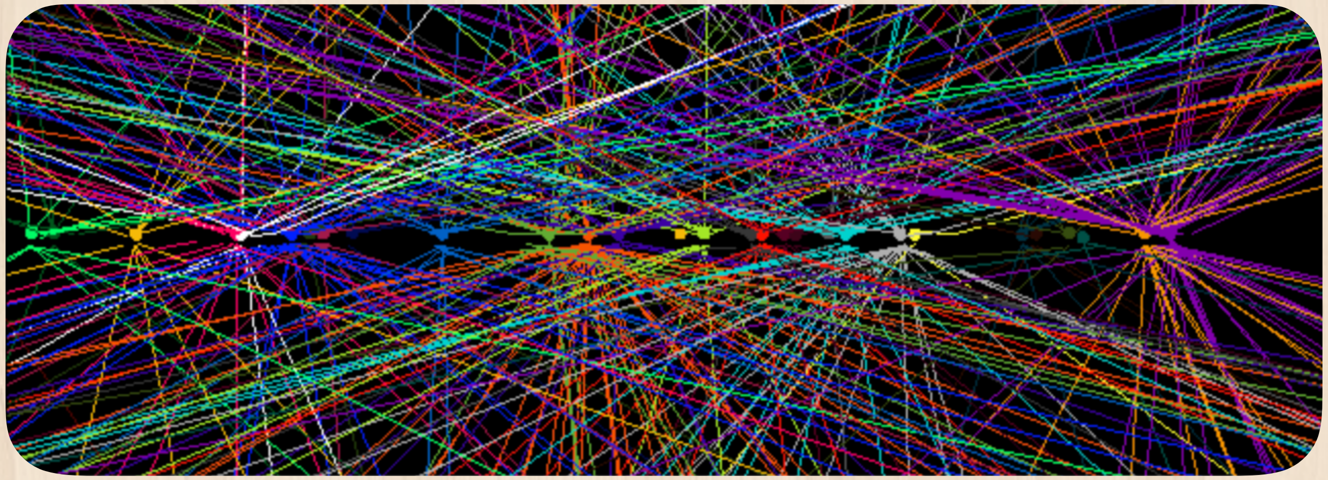




LHC delivered ~50 fb^{-1} to both experiments

A great (challenging) and rewarding year!

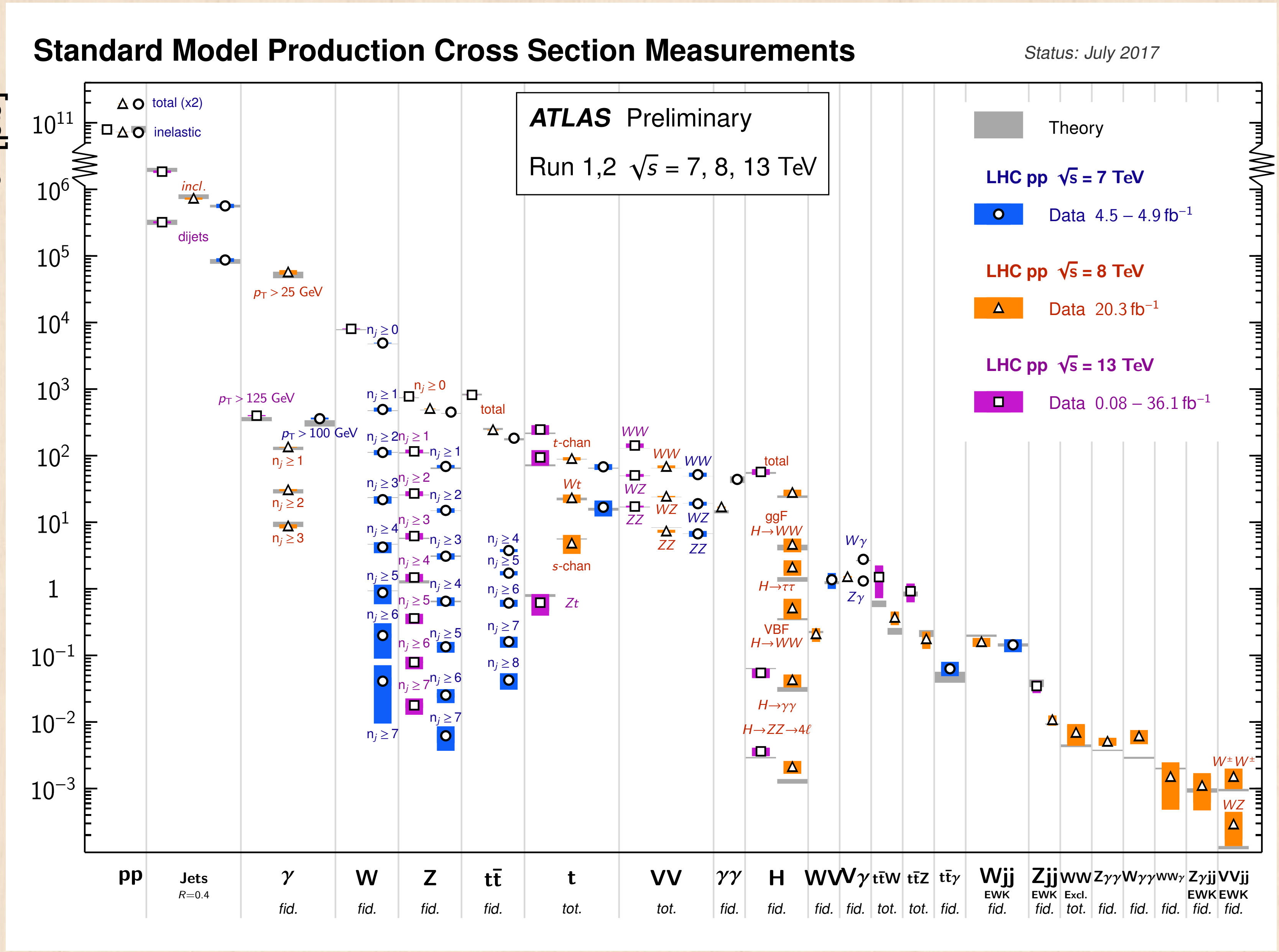




Standard Model Highlights

* Only a few selected topics shown here

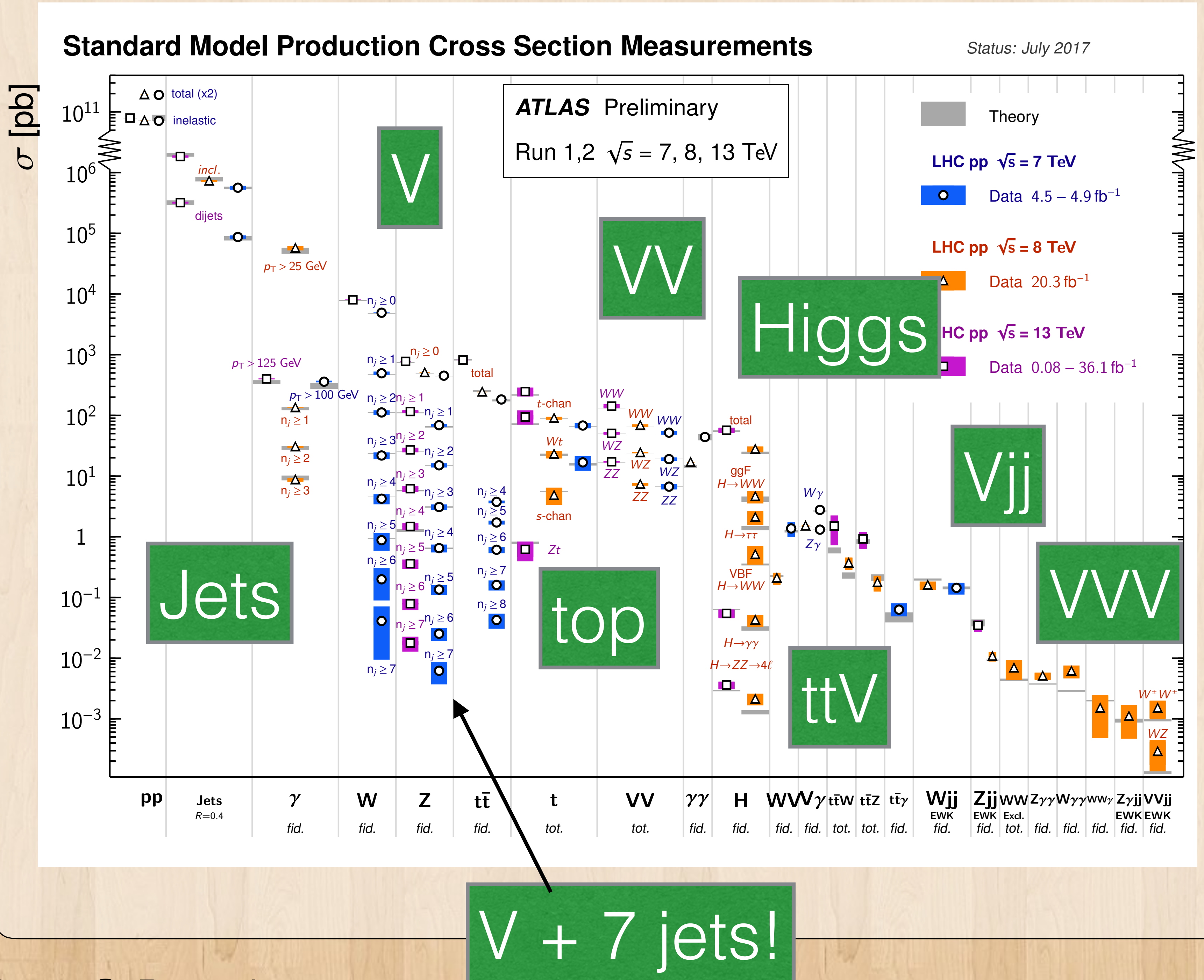
Standard Model at LHC



A rich program: measurement of standard model processes in hadron collider

Also serves as foundational studies for many beyond standard model searches

Cross Sections

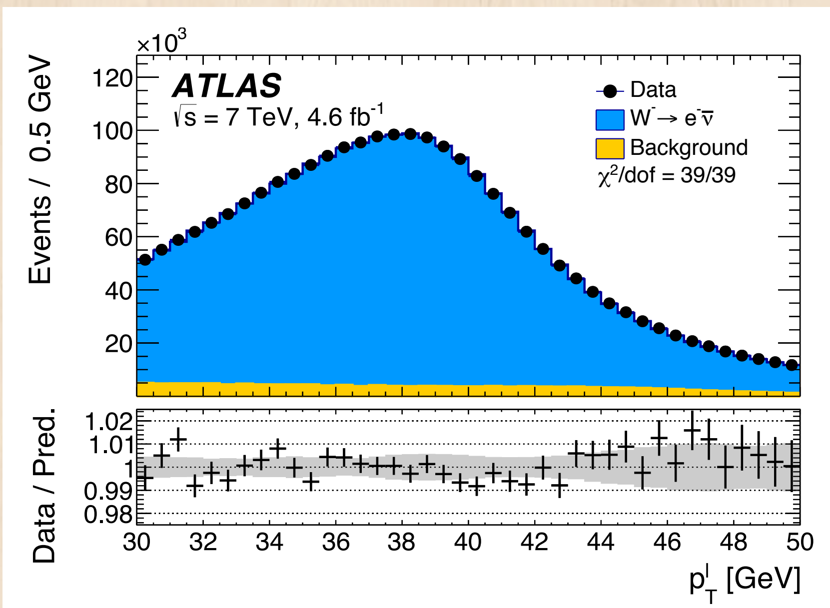


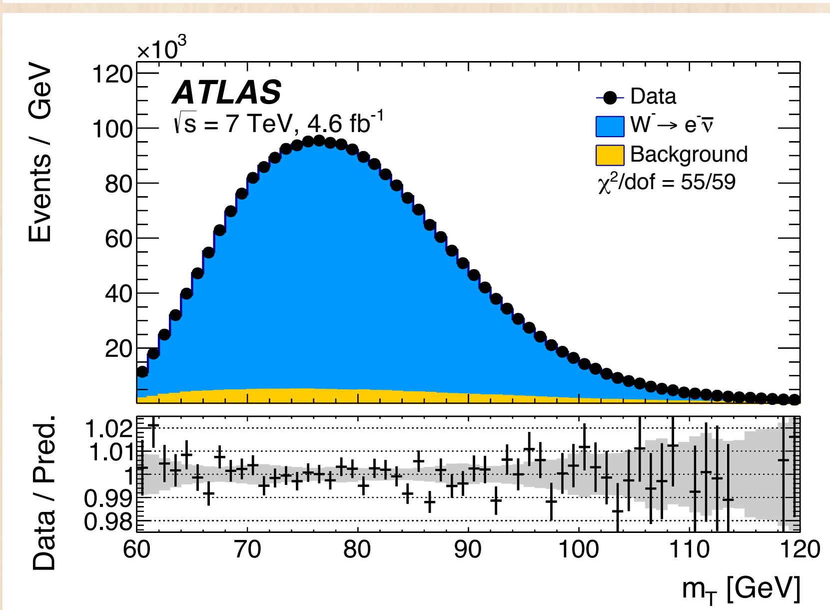
Results span many orders of magnitude of cross sections

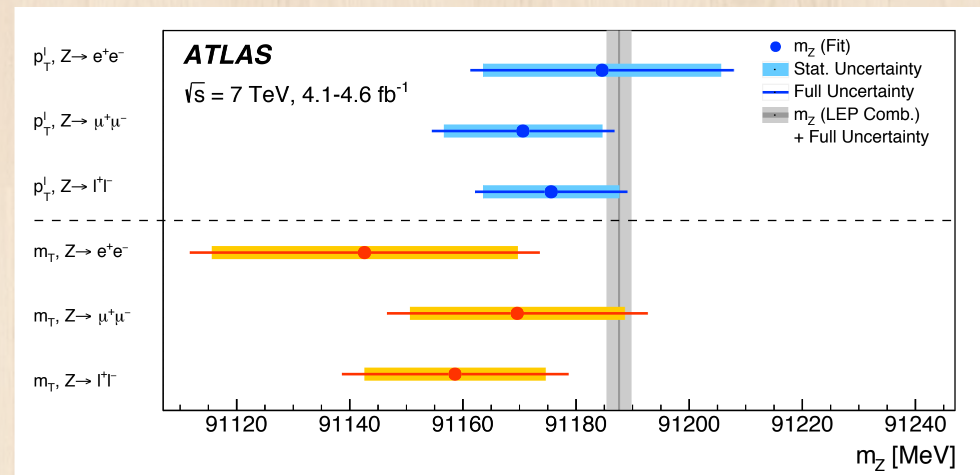
Measurement across many different sectors: jets, V, VV, top, Higgs, …

W Mass Measurement

Fit to m_T and lepton P_T distributions







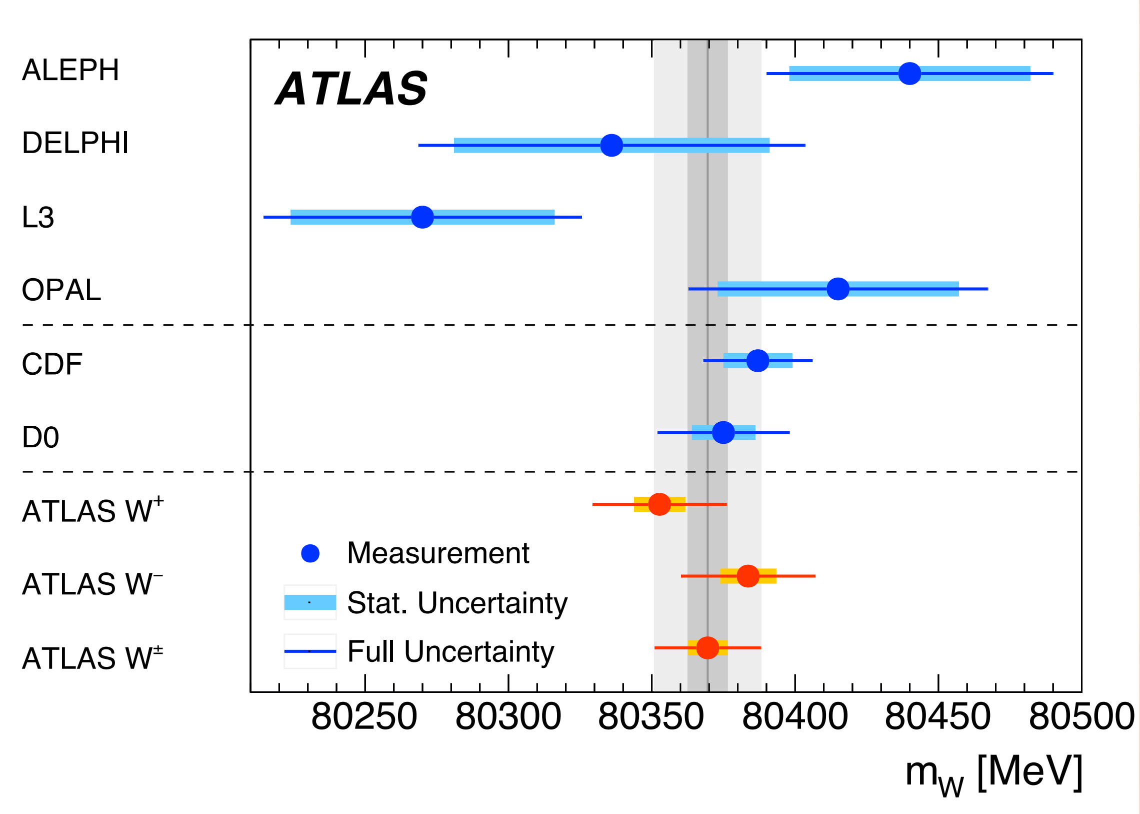
Method validated with Z events

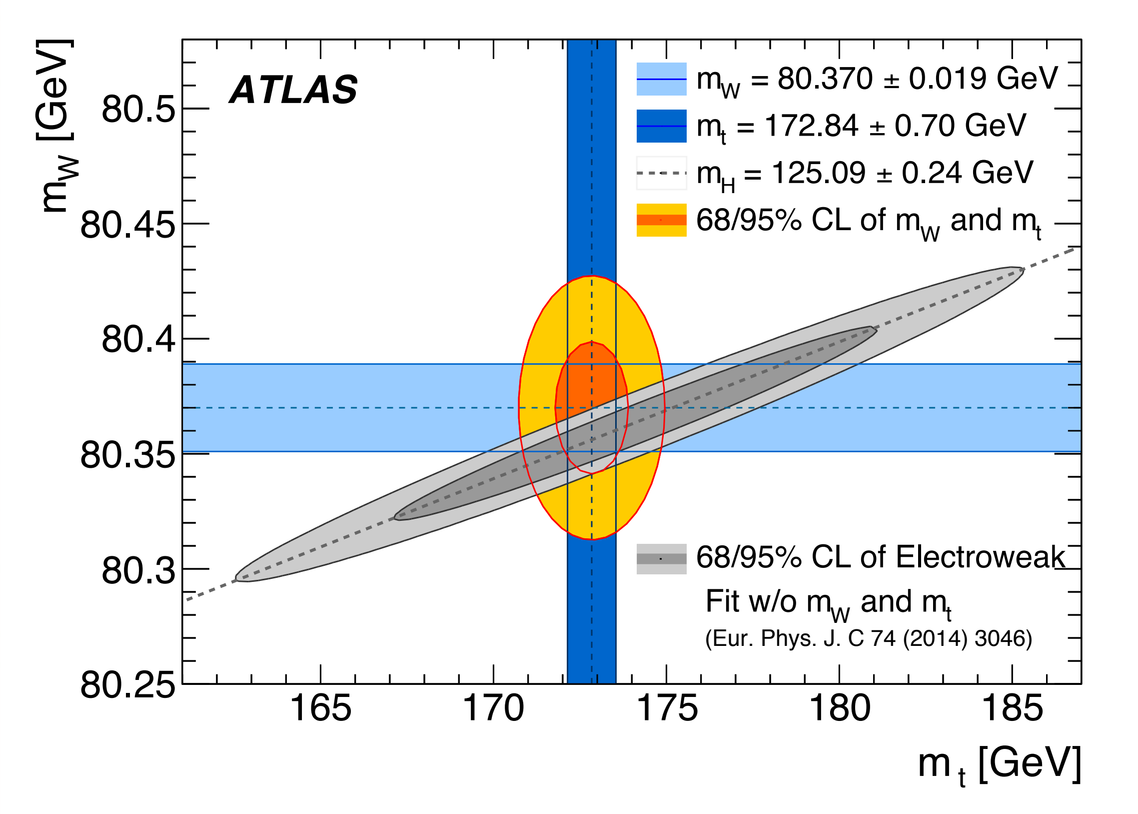
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Largest uncertainty comes from QCD modeling and PDF

W Mass Measurement

Incredible work in understanding the detector and controlling systematics





Uncertainty ~19 MeV!

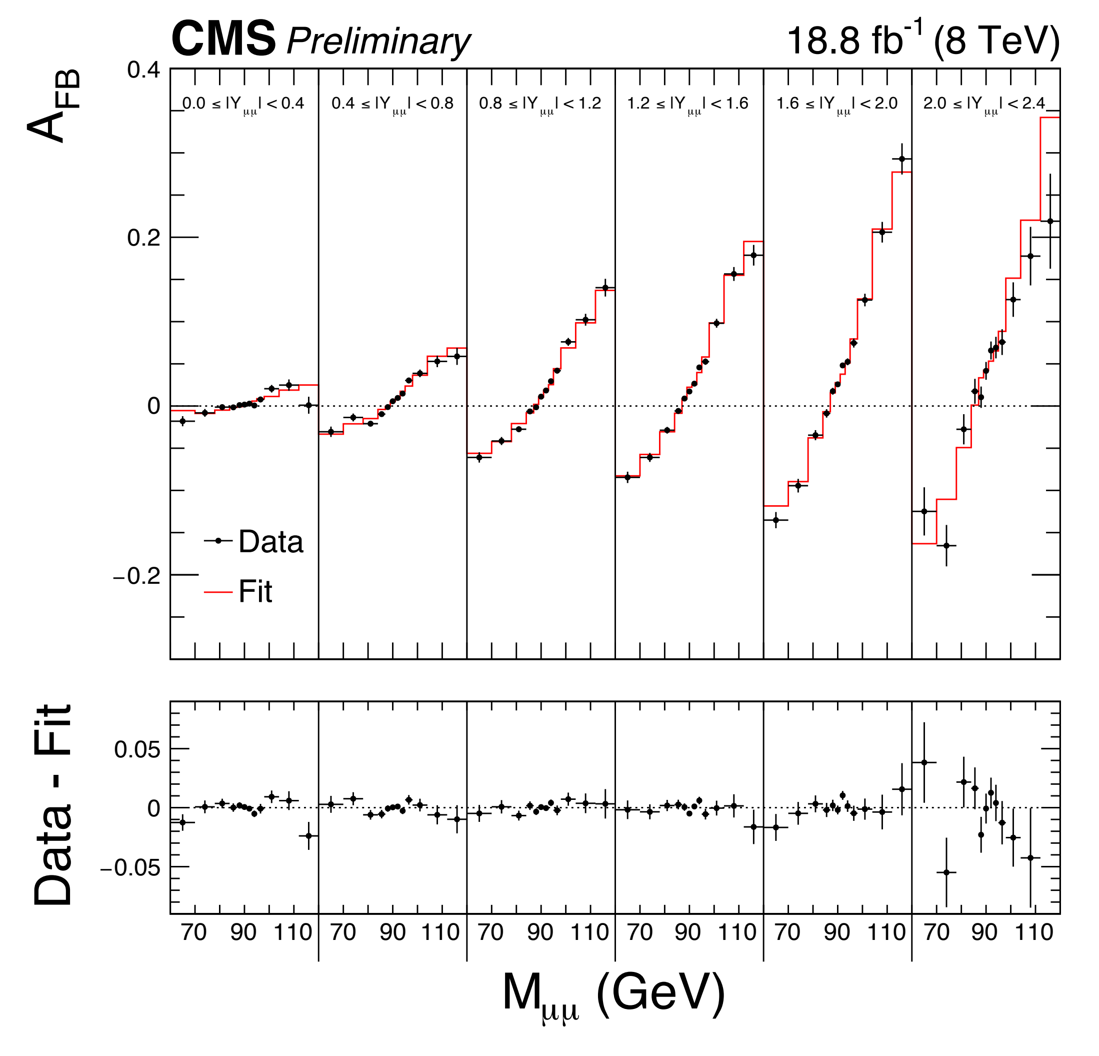
Precision similar to previous best measurement

Weak mixing angle

Measurement of the mixing angle using forward-backward asymmetry of Drell-Yan events (full 8 TeV)

Vector and axial currents interfere

Asymmetry as a function of mass and pseudorapidity provide measurement on the angle



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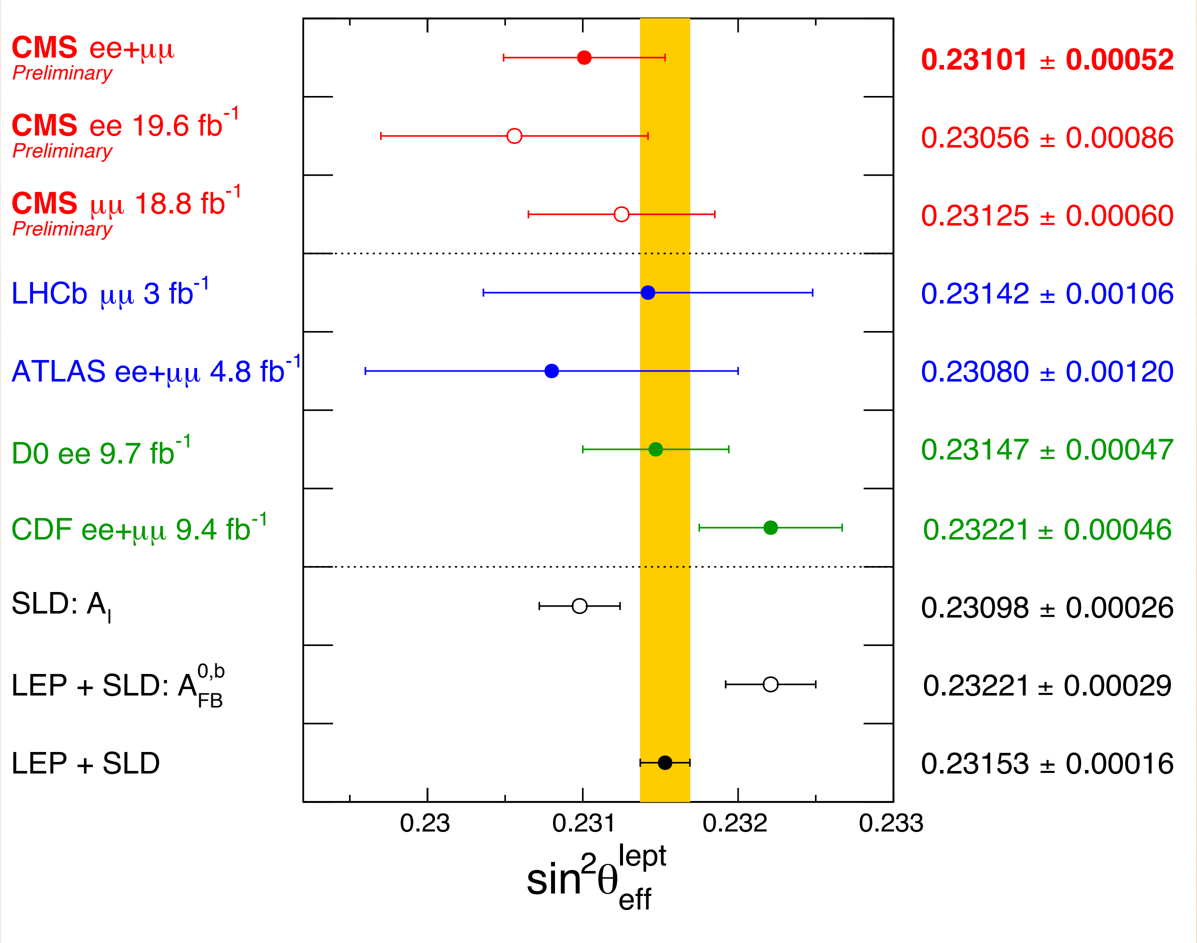
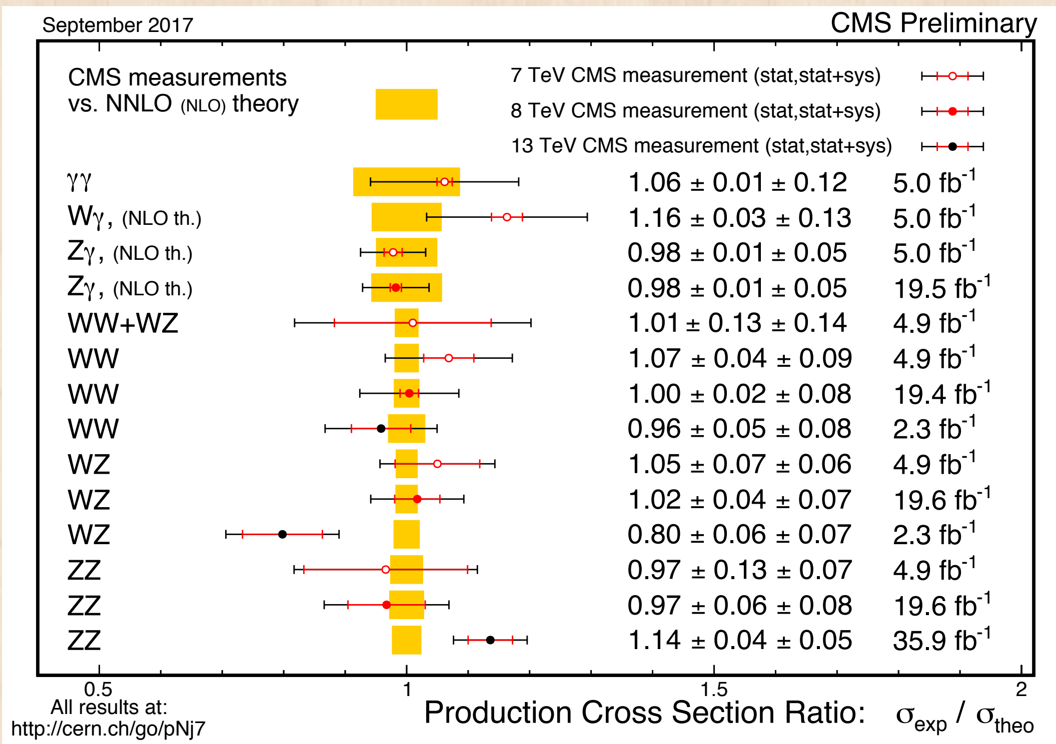
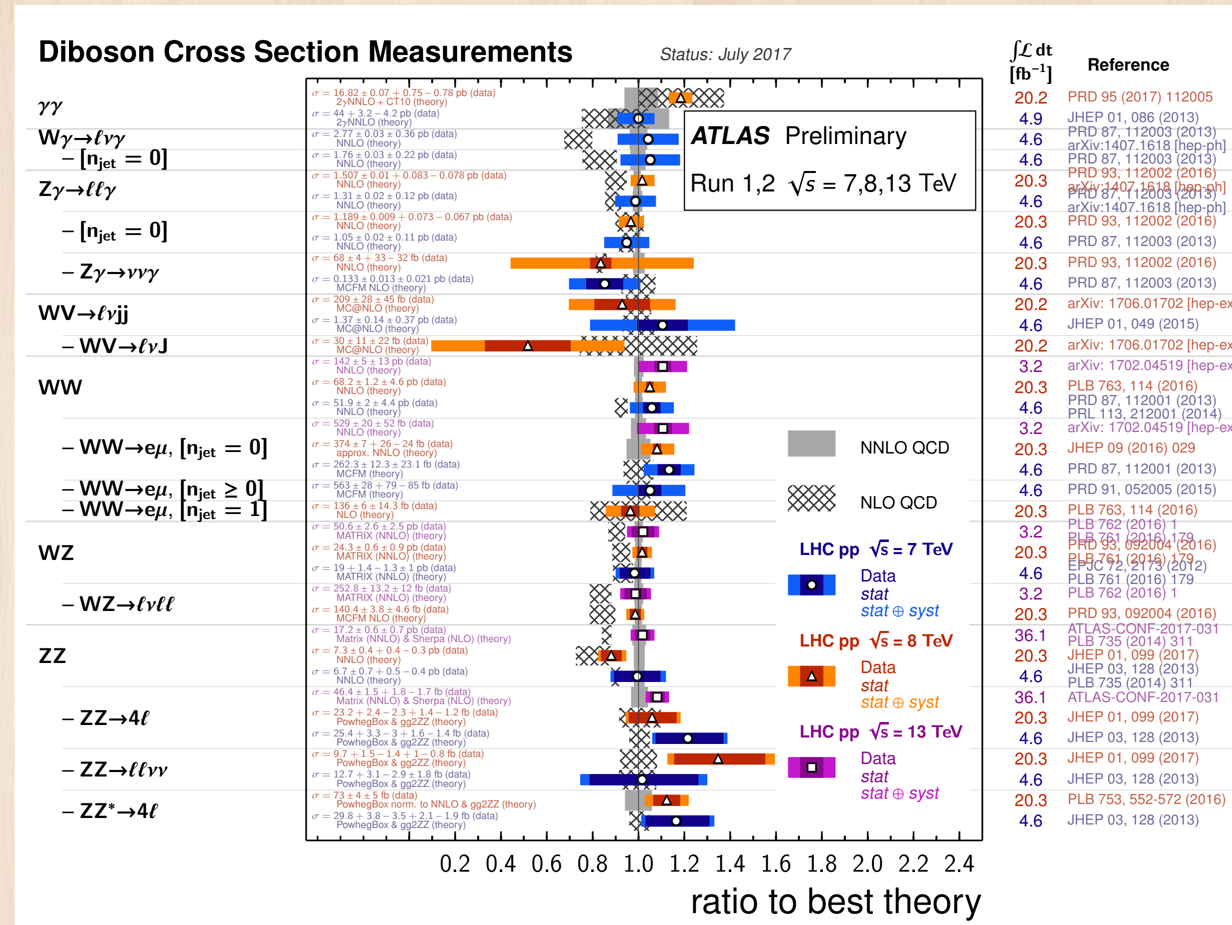


Multi-Boson Productions



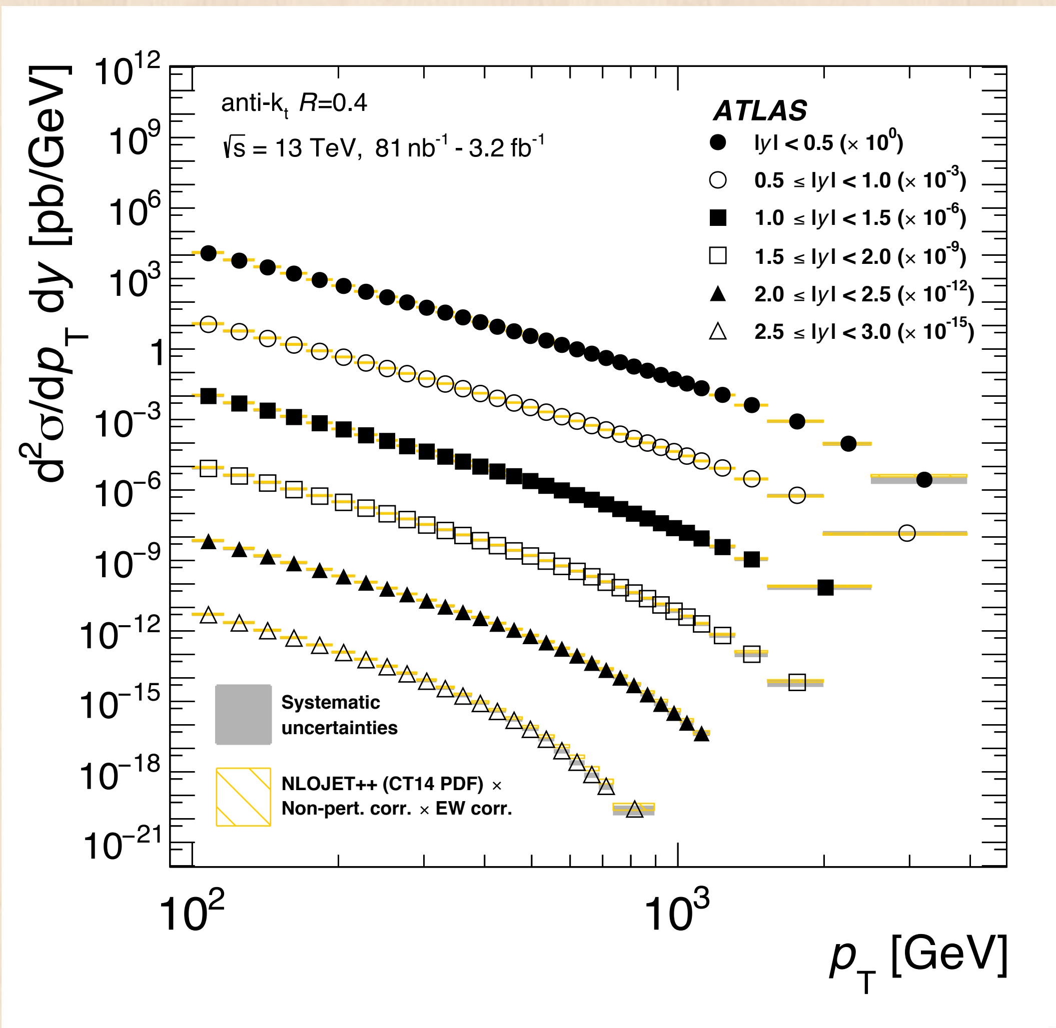


Important test of electroweak sector standard model

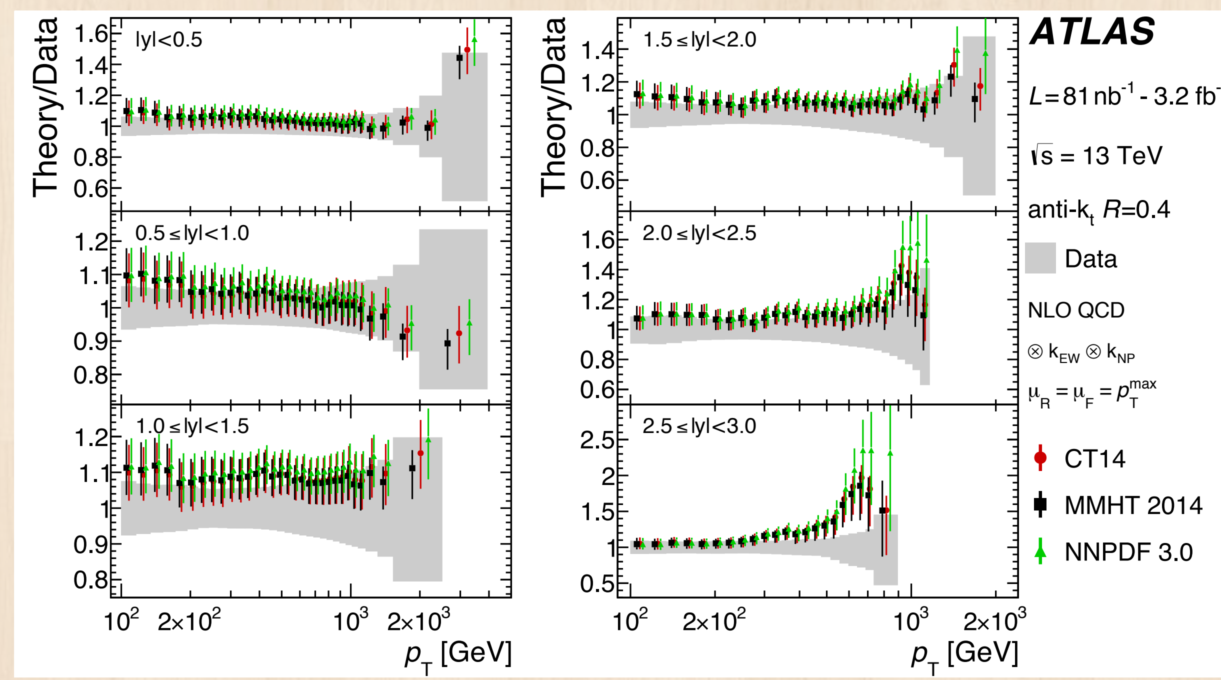
Stringent limits on anomalous gauge couplings

Irreducible background to many new physics searches and Higgs to VV measurements

Jets



Jet cross sections measured in a wide range of momentum

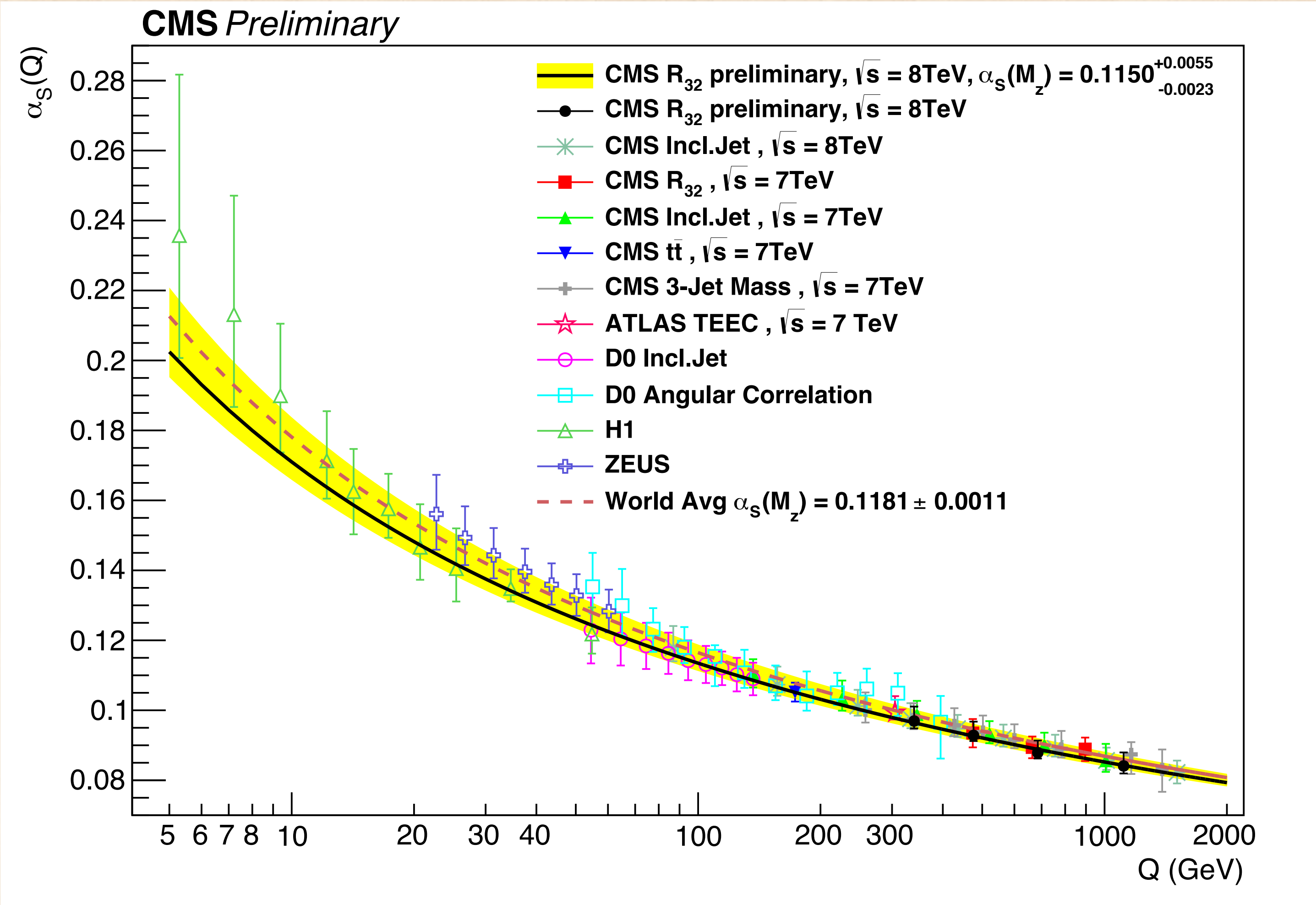


Demonstrates excellent capability for jets in LHC

Allows to constrain PDF

Strong coupling constant

Determination of α_s from jet cross sections

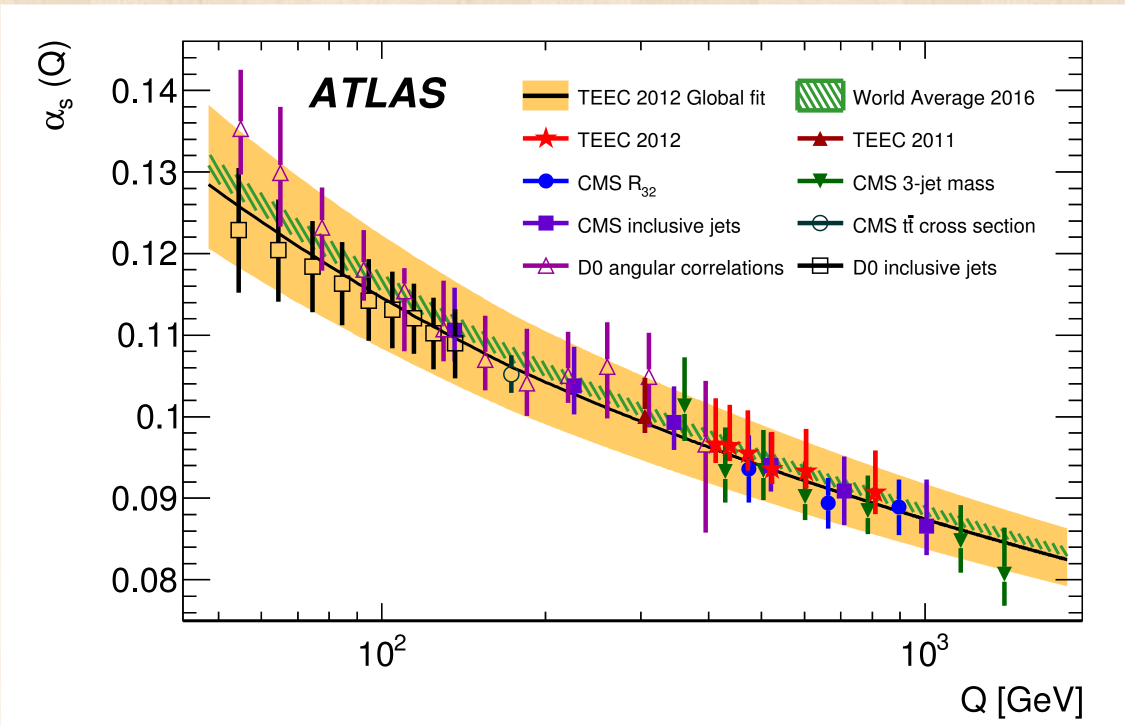


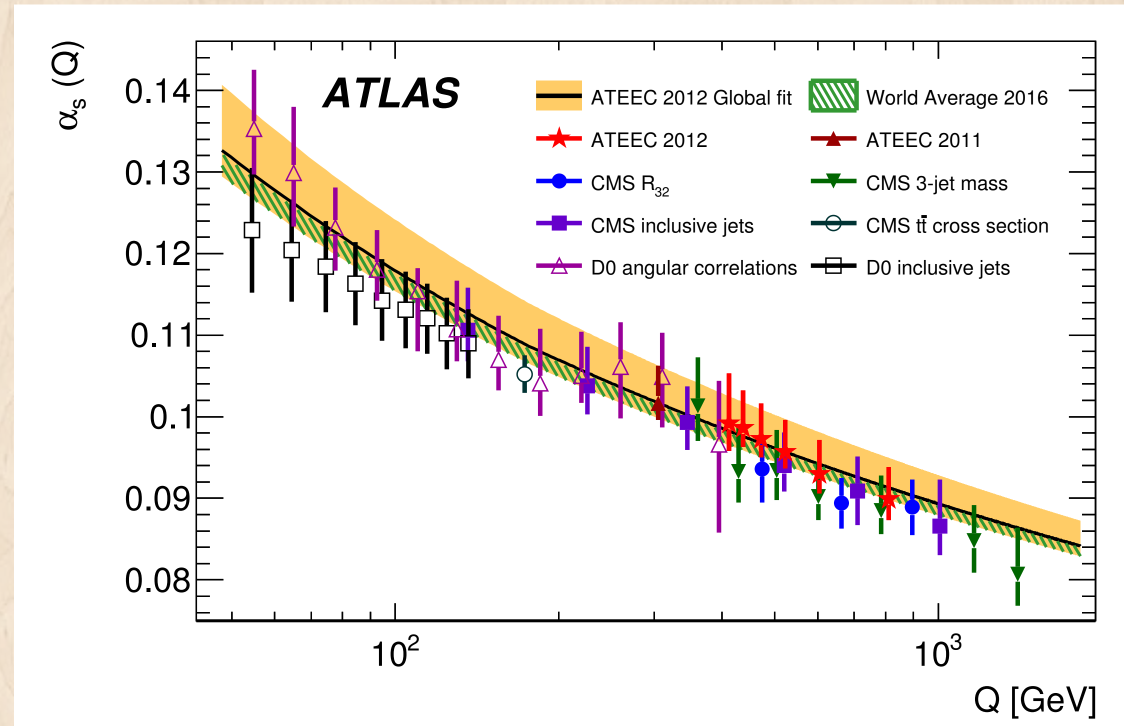
Ratio of 3-jet and 2-jet cross sections

Many experimental uncertainties cancel in the ratio

$$\alpha_s(M_Z) = 0.1150^{+0.0055}_{-0.0023}$$

Strong coupling constant





TEEC: Energy weighted angular distribution of jet pairs

ATEEC: forward-backward asymmetry of TEEC

Sensitive to α_s at NLO — precision test of pQCD

$$\text{TEEC: } \alpha_s(m_Z) = 0.1162 \pm 0.0011(\text{exp.})^{+0.0076}_{-0.0061}(\text{scale}) \pm 0.0018(\text{PDF}) \pm 0.0003(\text{NP})$$

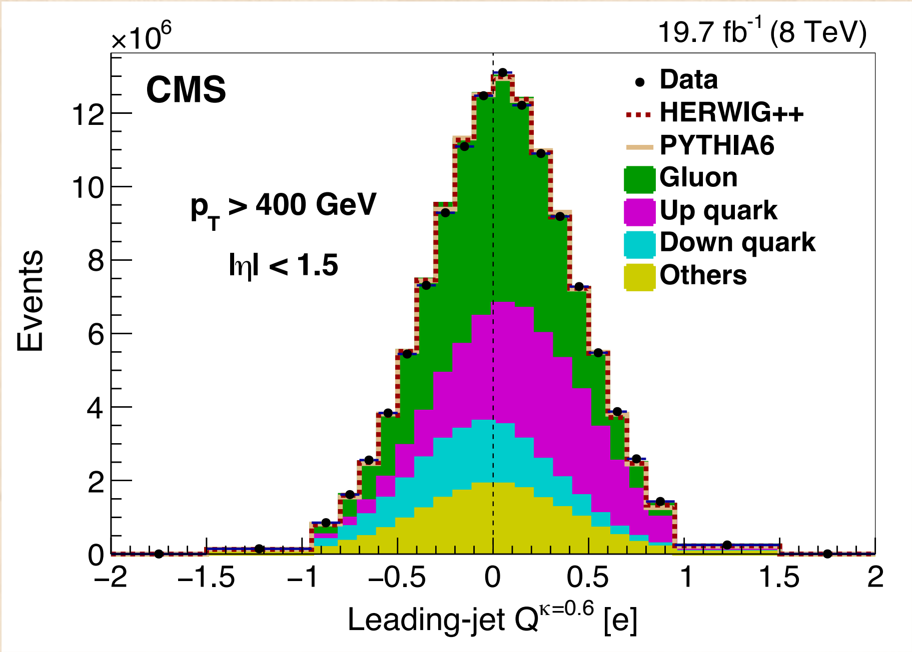
$$\text{ATEEC: } \alpha_s(m_Z) = 0.1196 \pm 0.0013(\text{exp.})^{+0.0061}_{-0.0013}(\text{scale}) \pm 0.0017(\text{PDF}) \pm 0.0004(\text{NP})$$

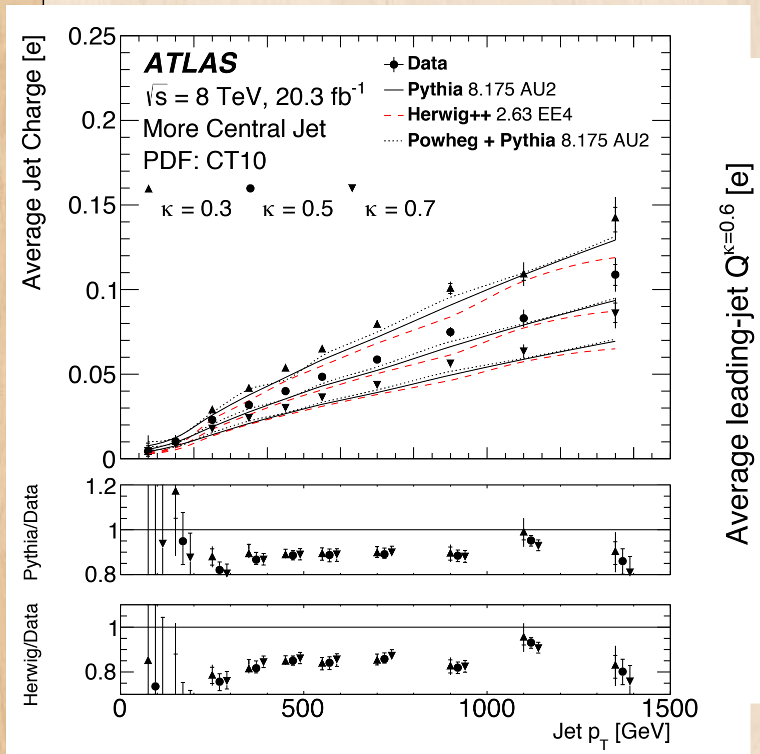
CMS-SMP-15-003: JHEP 10 (2017) 131
ATLAS-STDM-2014-17: Phys. Rev. D 93, 052003 (2016)

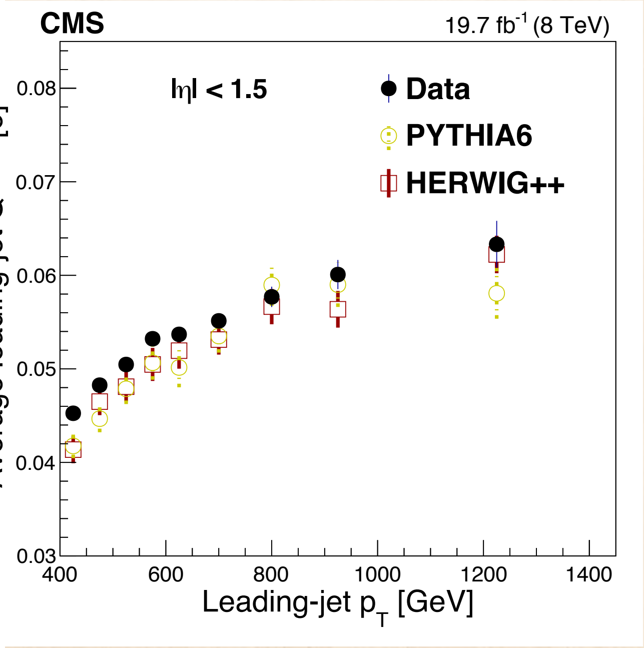
Jet Charge

Weighted average of track charges inside a jet

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





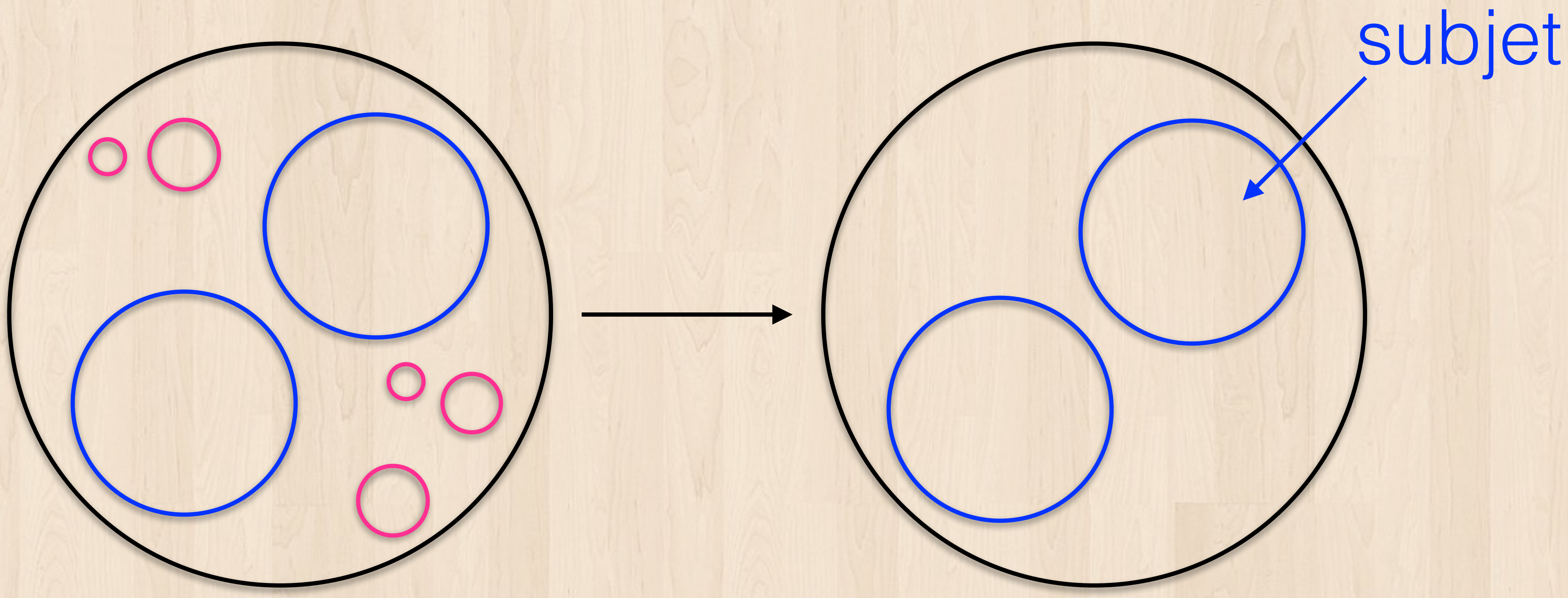


Larger jet PT —> larger fraction of contribution from valence quark

Sensitive to PDF and modeling of fragmentation process

Jet Substructure

Grooming: Clean up soft component of the jets
and isolate the hard structure



Jet Substructure

- Soft drop / mMDT algorithm: sequentially removes subjets with small momentum fraction

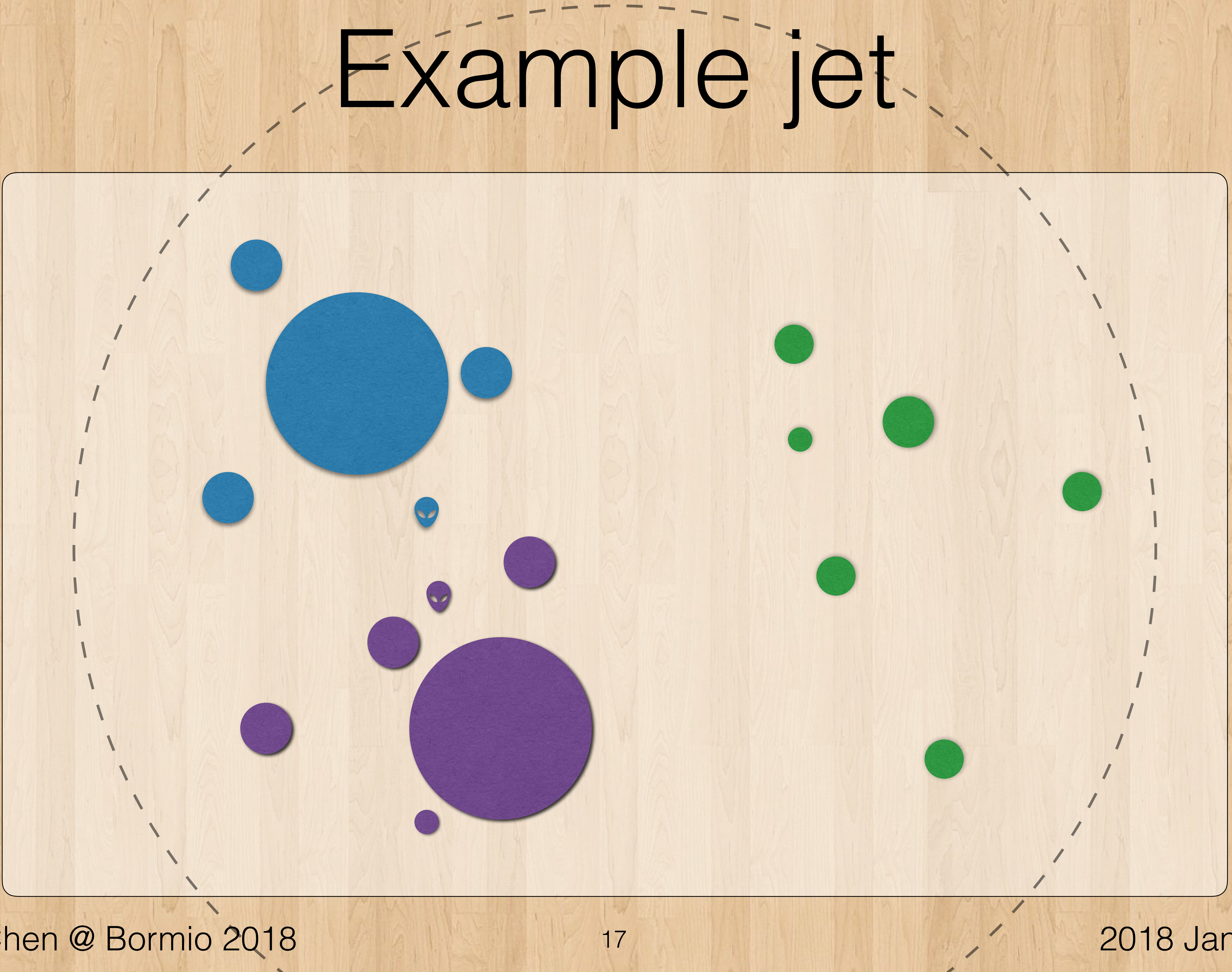
$$z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\mathrm{cut}} \left(\frac{\Delta R}{R}\right)^{\beta}$$

- Flat grooming on momentum fraction (z_{cut} = 0.1, β = 0.0)

- Settin
weak n the
core of the jet (z_{cut} = 0.5, β = 1.5)

Grooming allows to remove soft component that is harder to model

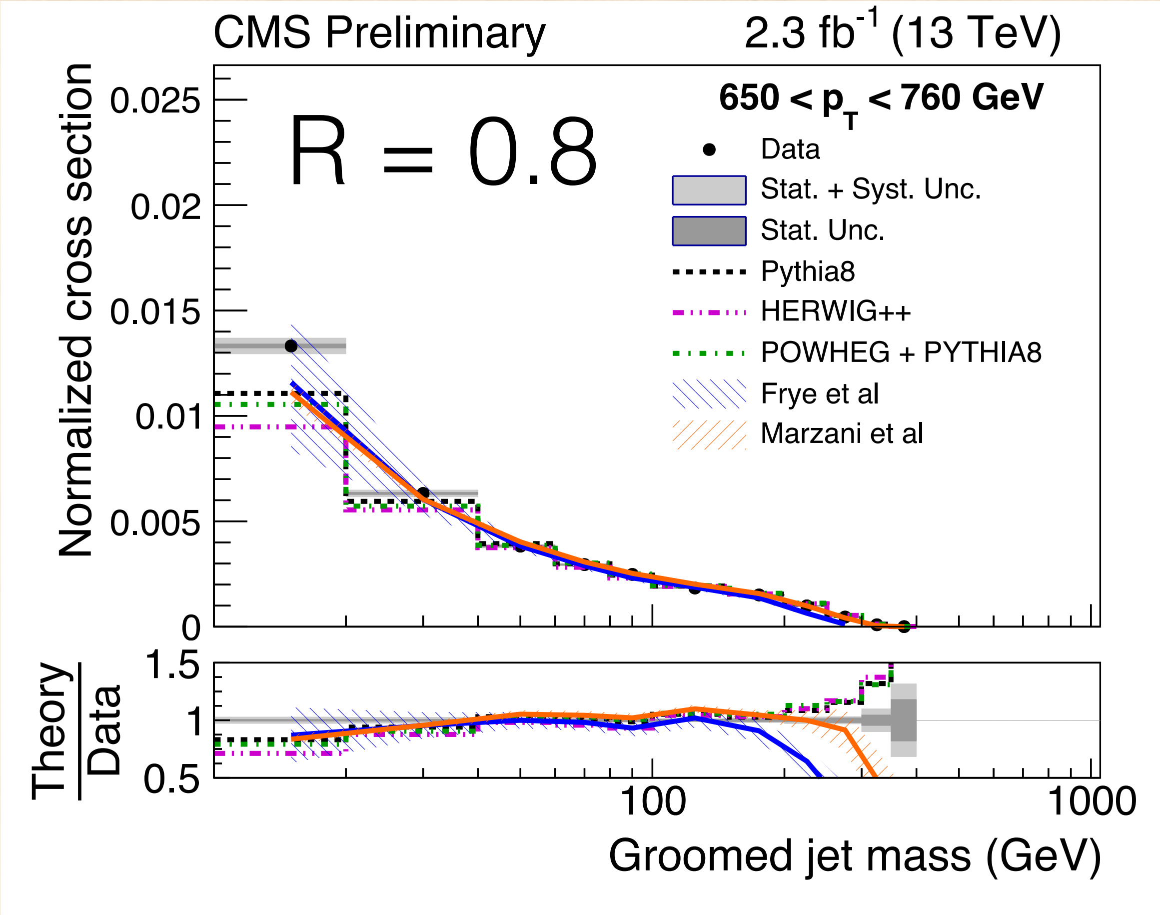
Example jet

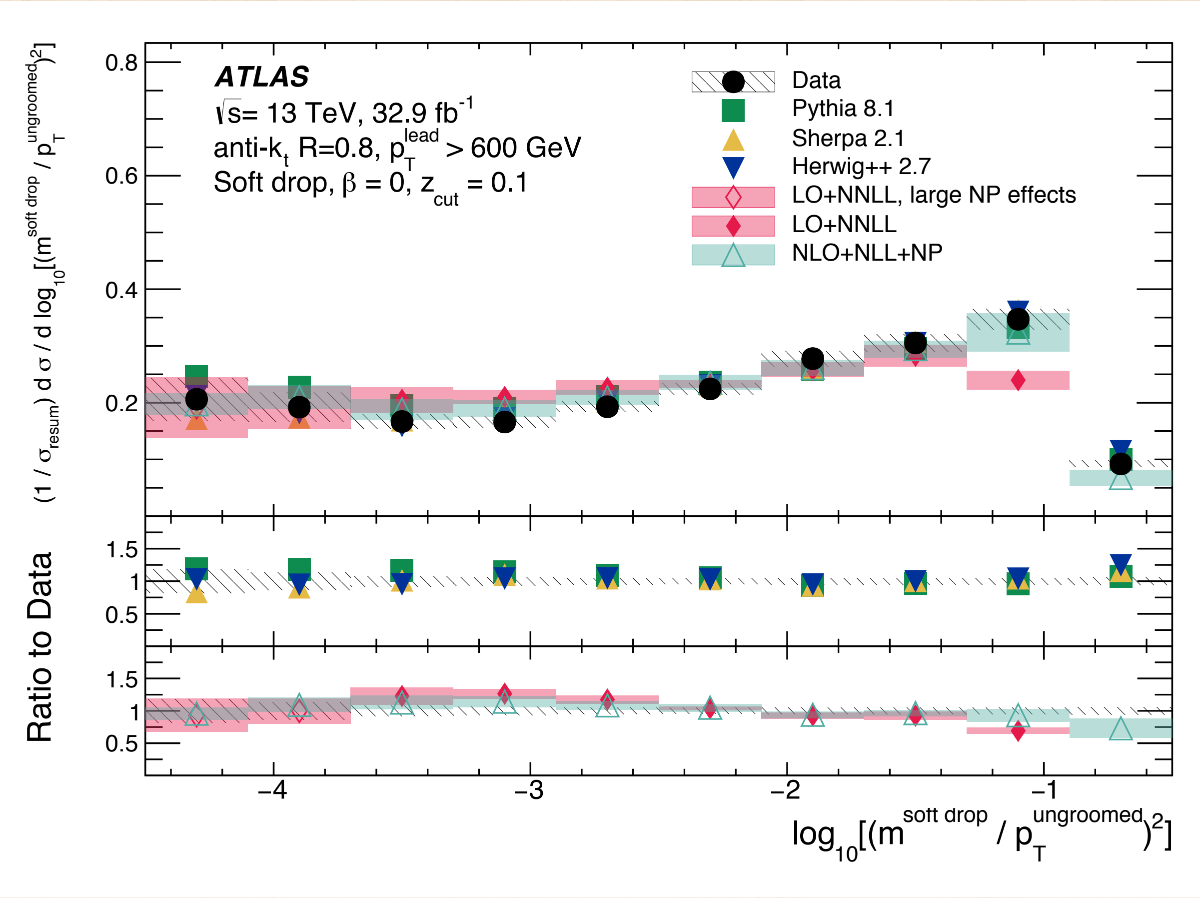


ATLAS-STDM-2017-04: 1711.08341
CMS-PAS-SMP-16-010

Jet Substructure

Unfolded groomed mass distribution in dijet events

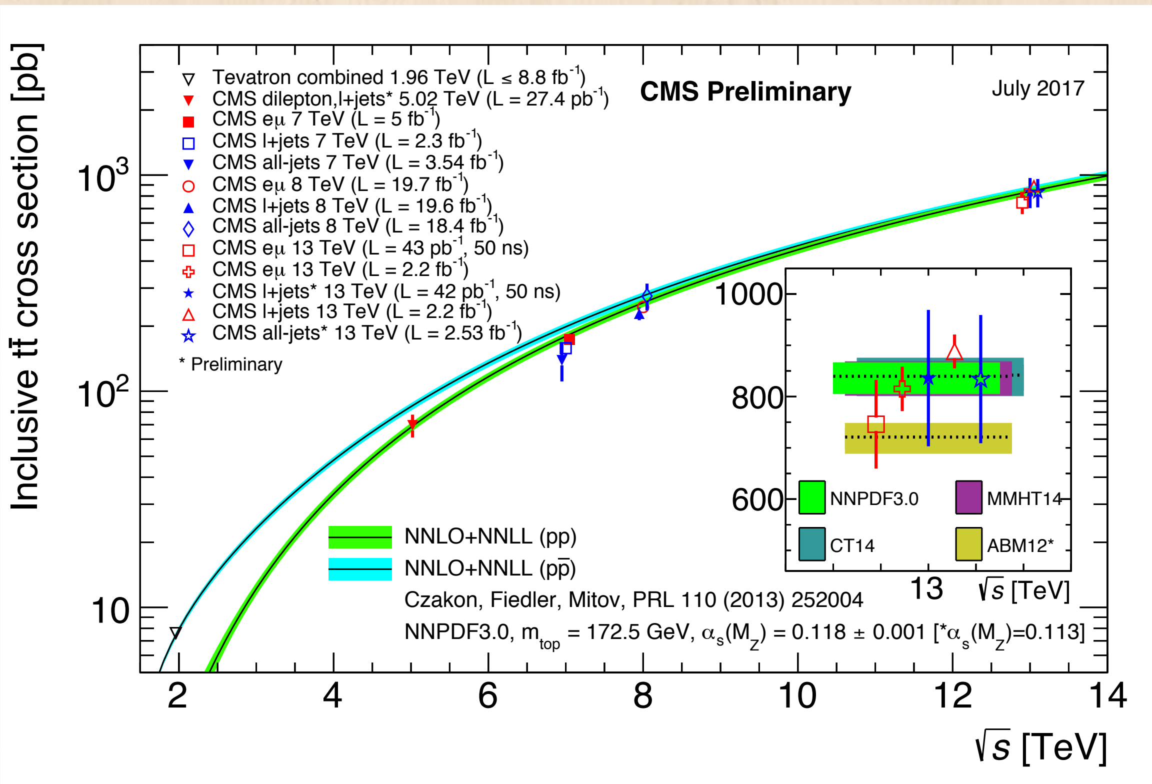


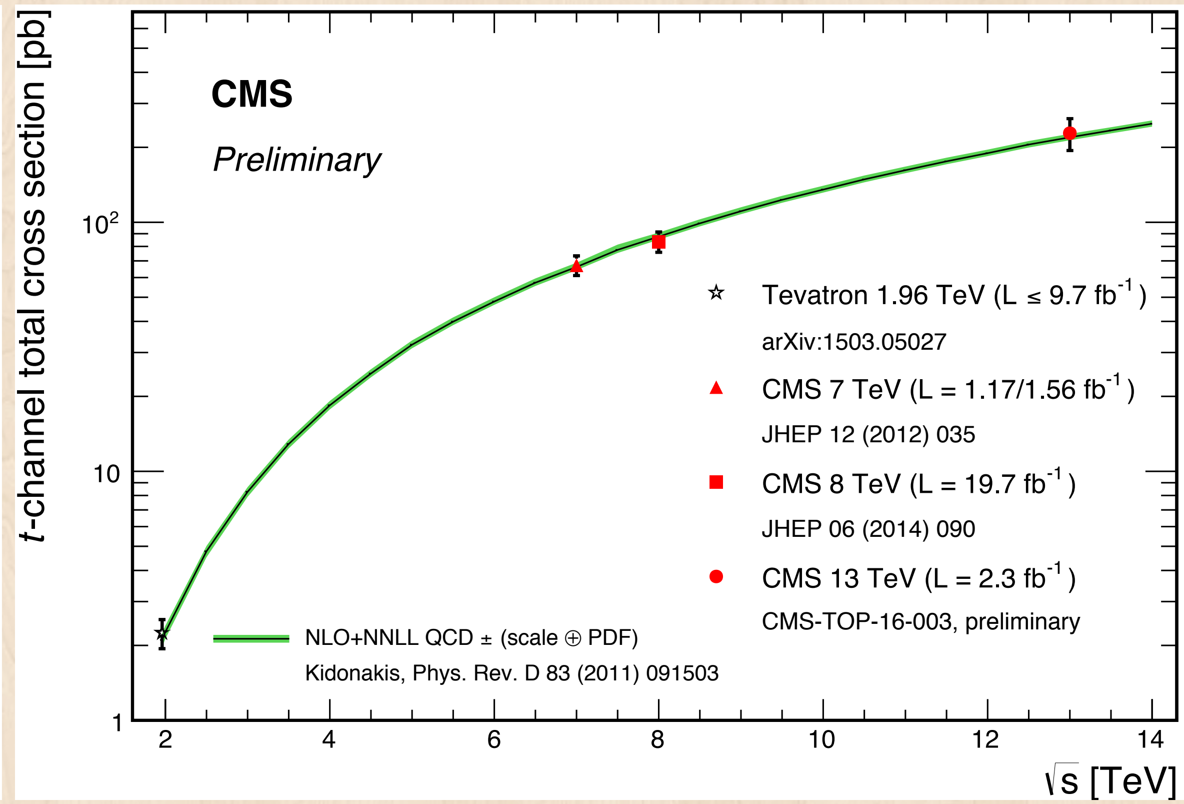


Calculations agree well in moderate mass region

Top measurements

LHC produces large amount of top quarks

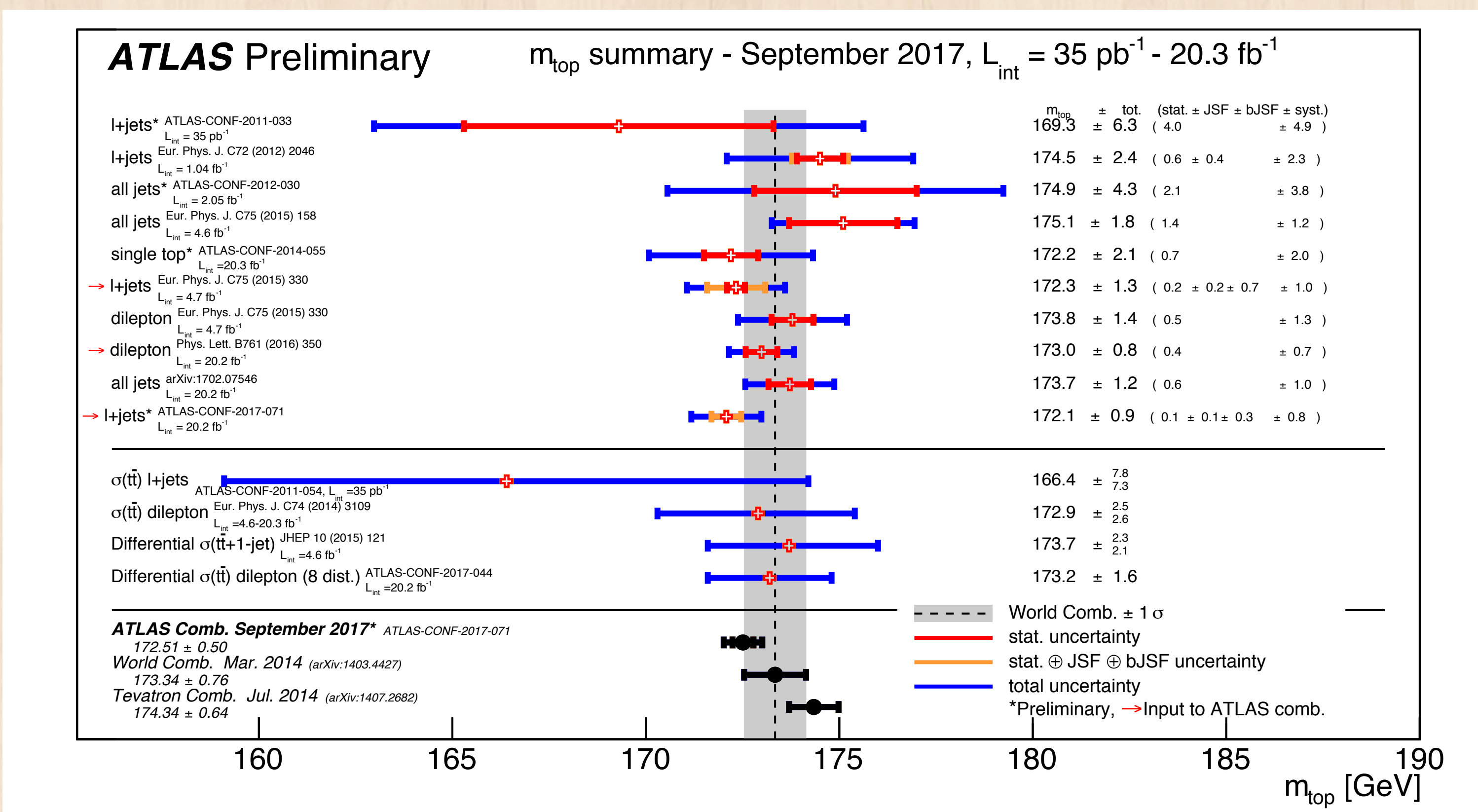


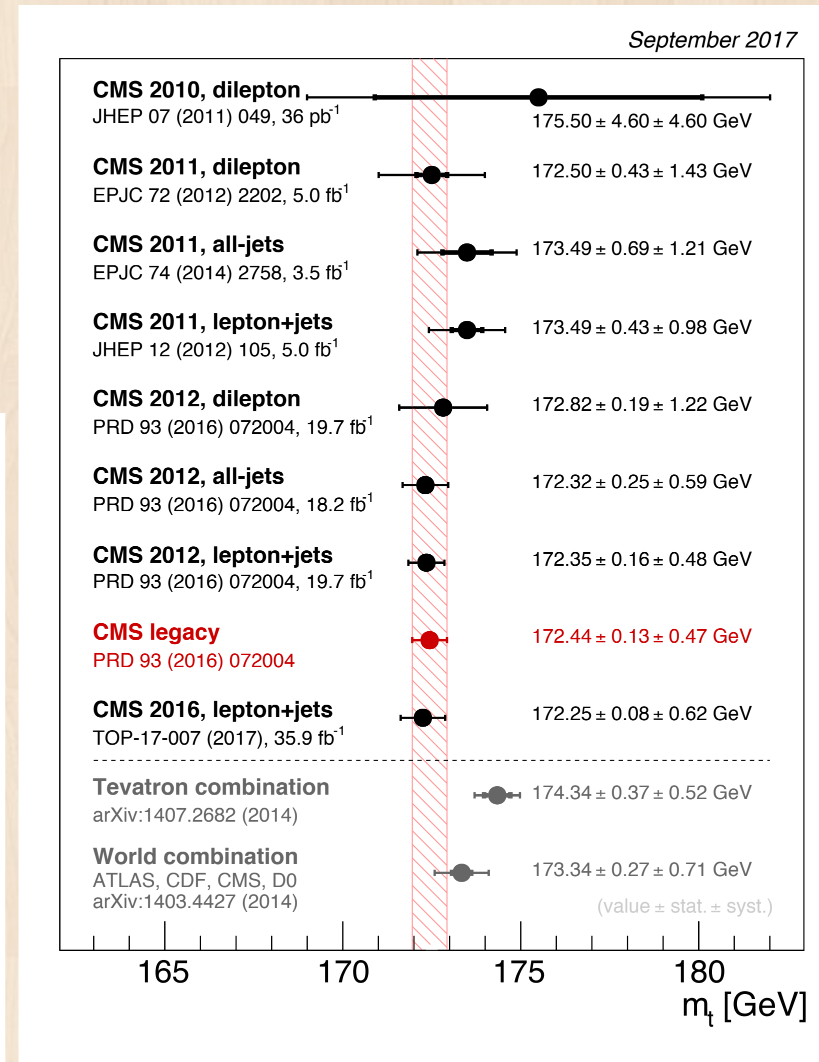


Many top-related measurements: cross section, ttW, ttZ, ttjj, tZq, top mass, W helicity, …

Top mass

Mass of top quark determined with great precision!





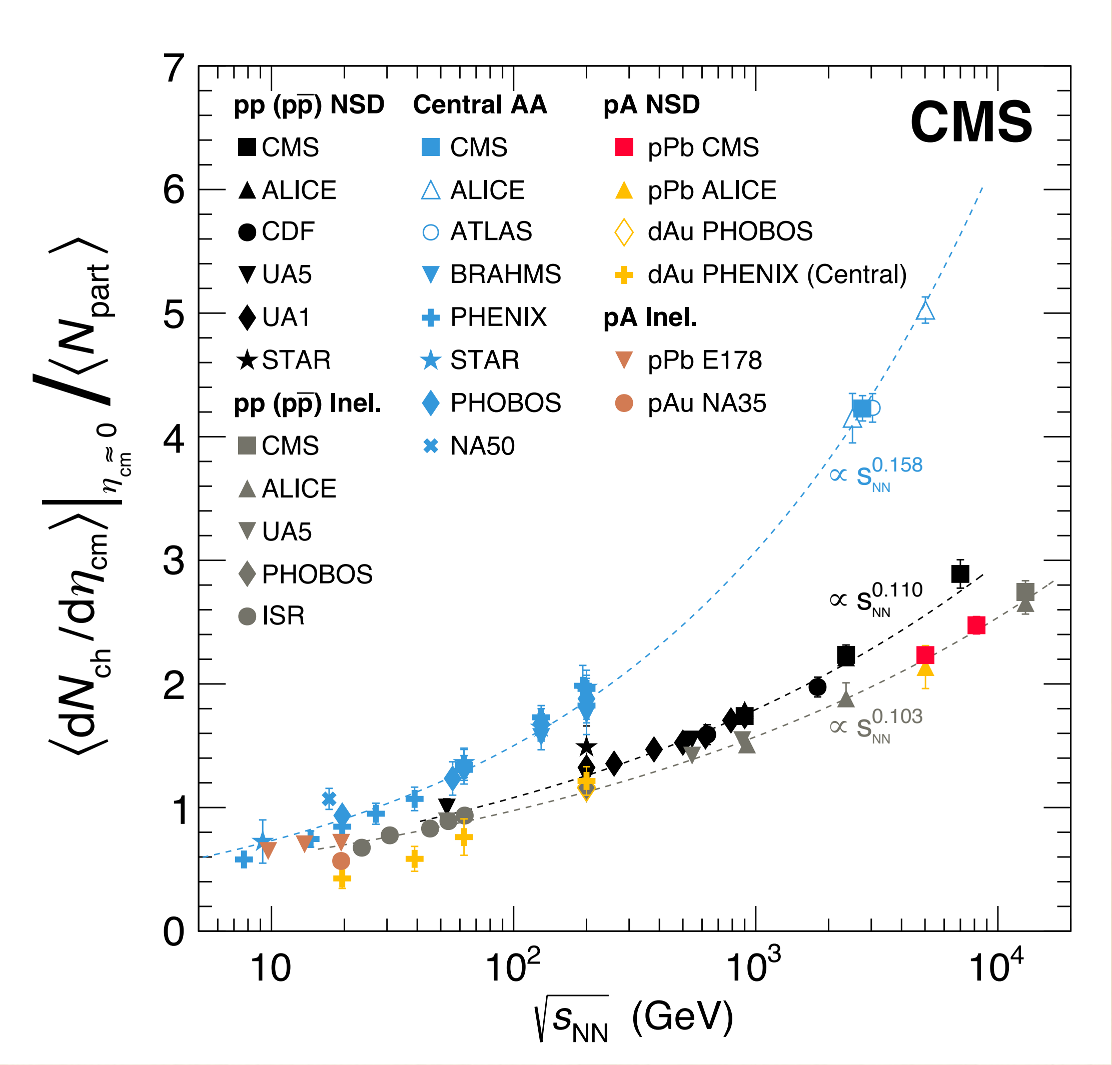
Precision < 0.5%

Heavy Ion Highlights

Mostly CMS results
For overview of ATLAS results:
Laura Havener, 17:45, 2018 Jan 23

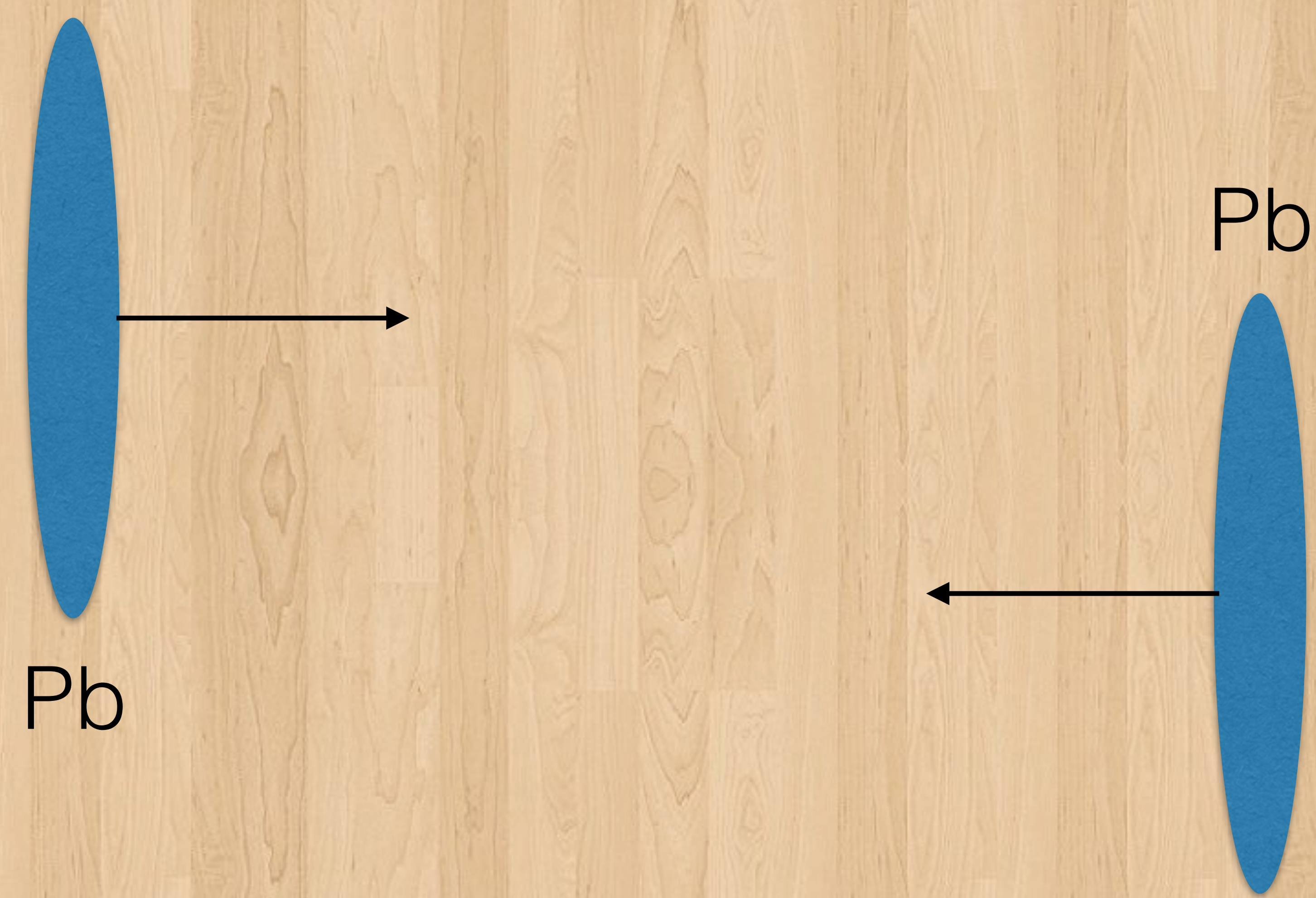
Data collected in CMS

E (TeV)	5.02	8.16	5.44
pp	330 pb^{-1}	-	-
pPb	0.5 nb^{-1}	185 nb^{-1}	-
PbPb	~450 μb^{-1}	-	-
XeXe	-	-	2 μb^{-1}



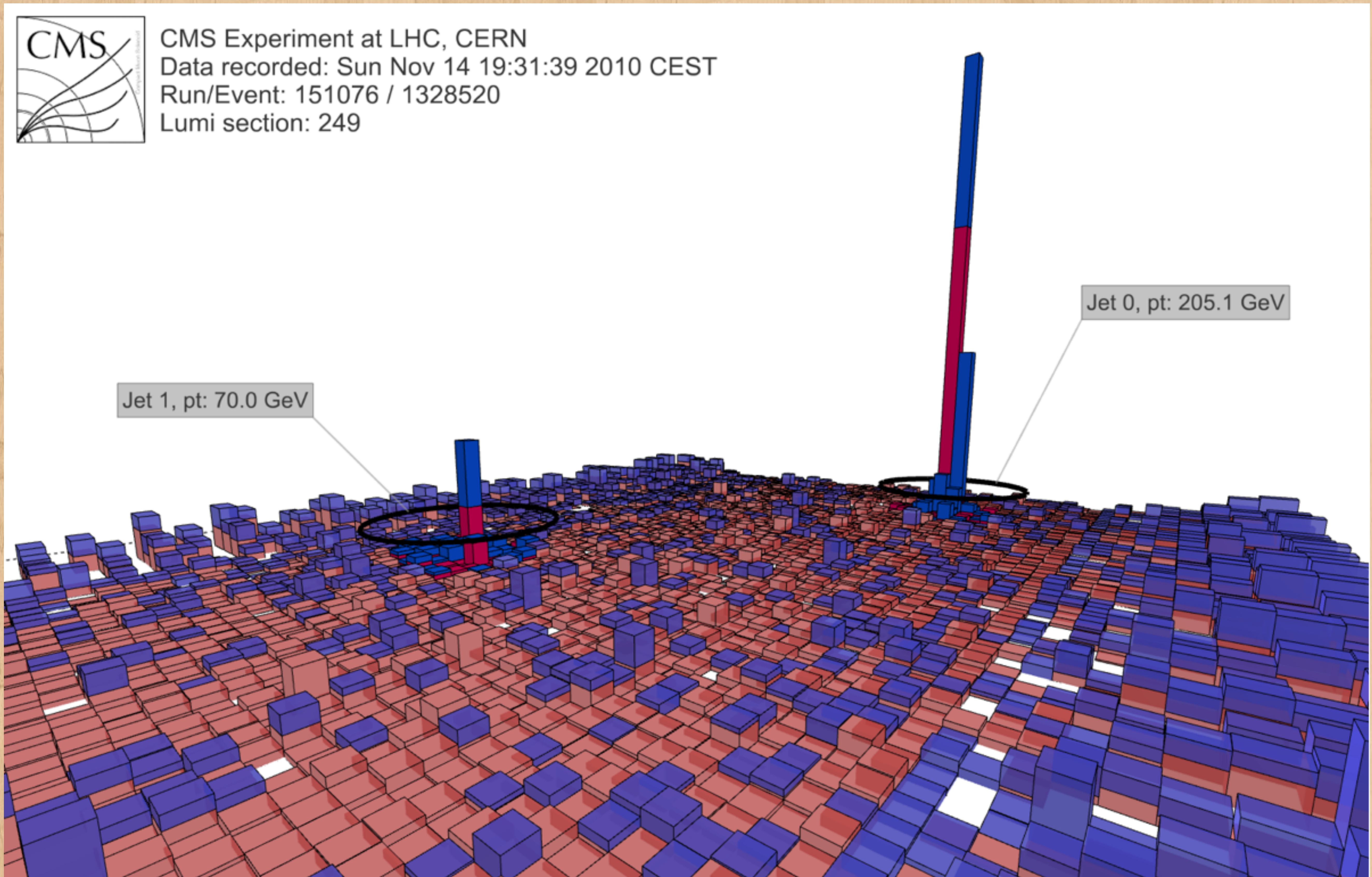
A lot of data accumulated

Allows precision measurement of heavy ion physics



Centrality: 0% = head on
100% = grazing


hello
Hot QCD
medium


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

Some questions

How does the medium evolve?

How do high energy objects lose energy?

What about initial state?
Can we say something about the nuclear PDF?

Do we see similar phenomena in smaller systems?
p+Pb, pp

Any interesting new phenomena?

Measurements

Single hadrons

Particle correlations

Quarkonium

Top

Jets

Ultra-peripheral collisions

Chiral magnetic effect

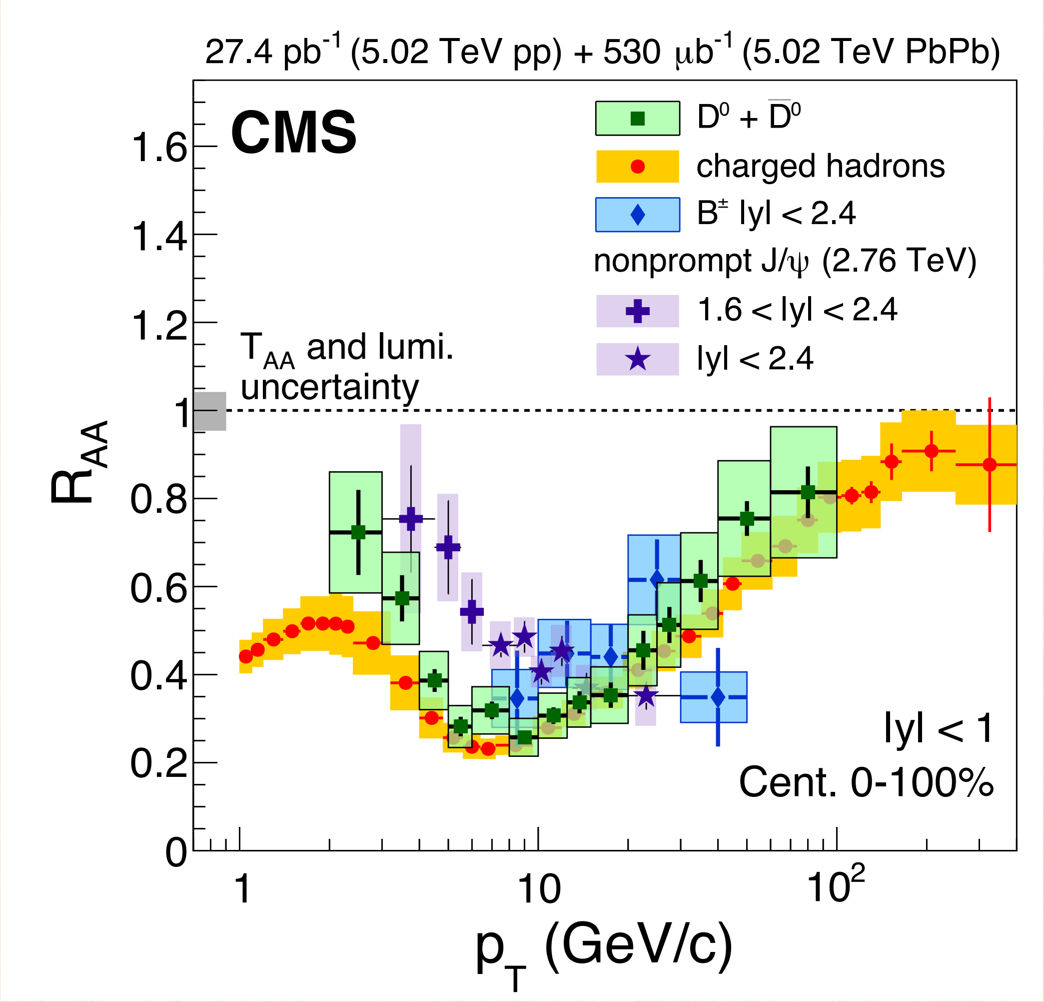
Nuclear modification factor

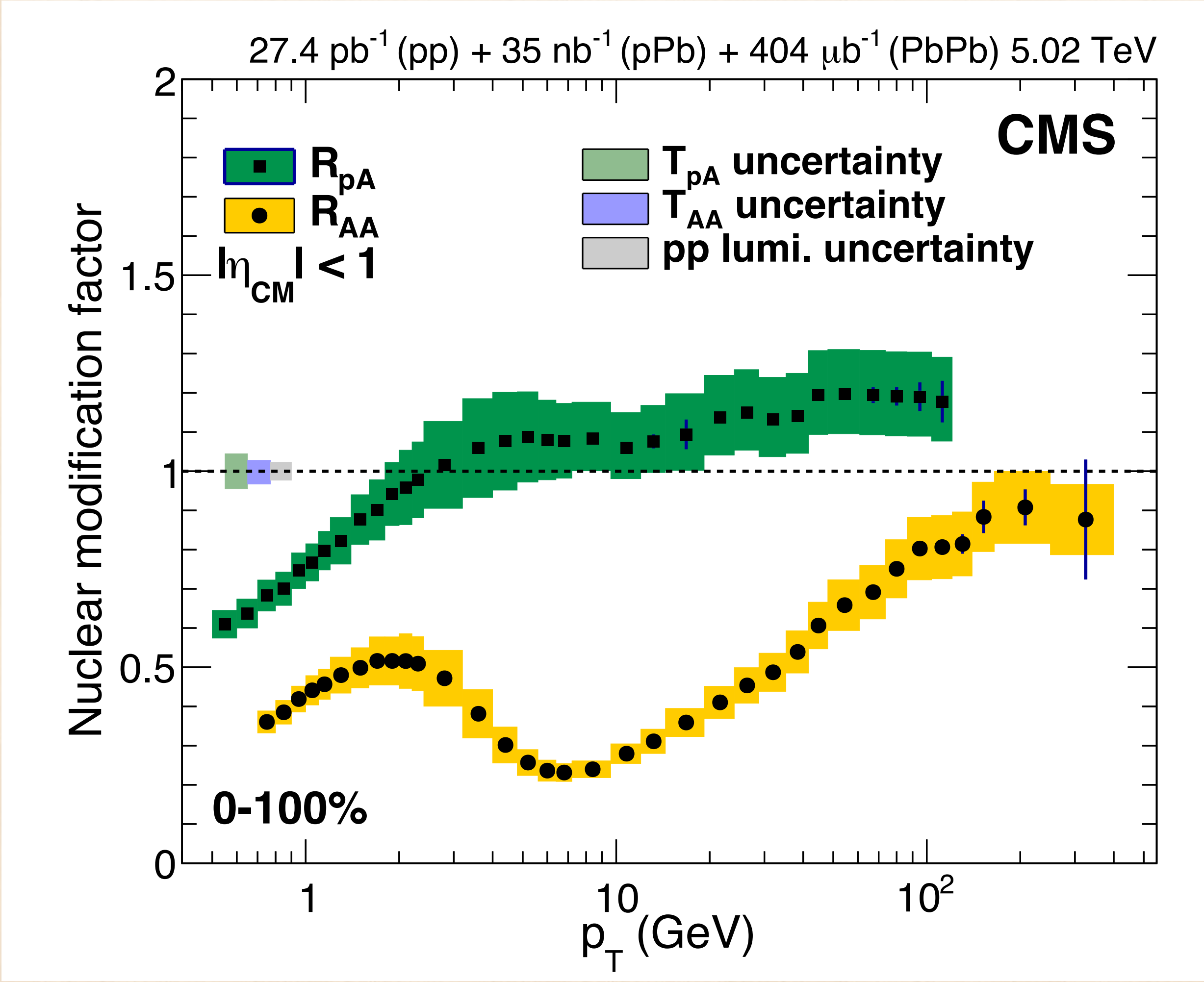
Modification on particle spectra in AA collision is characterized by the nuclear modification factor R_{AA}

$$R_{AA} \equiv \frac{d\sigma_{AA}/dX}{N_{\text{collisions}} d\sigma_{pp}/dX}$$

Ratio of spectra between what is observed in AA and what is seen in pp, scaled by number of expected binary nucleon collisions

Nuclear modification factor



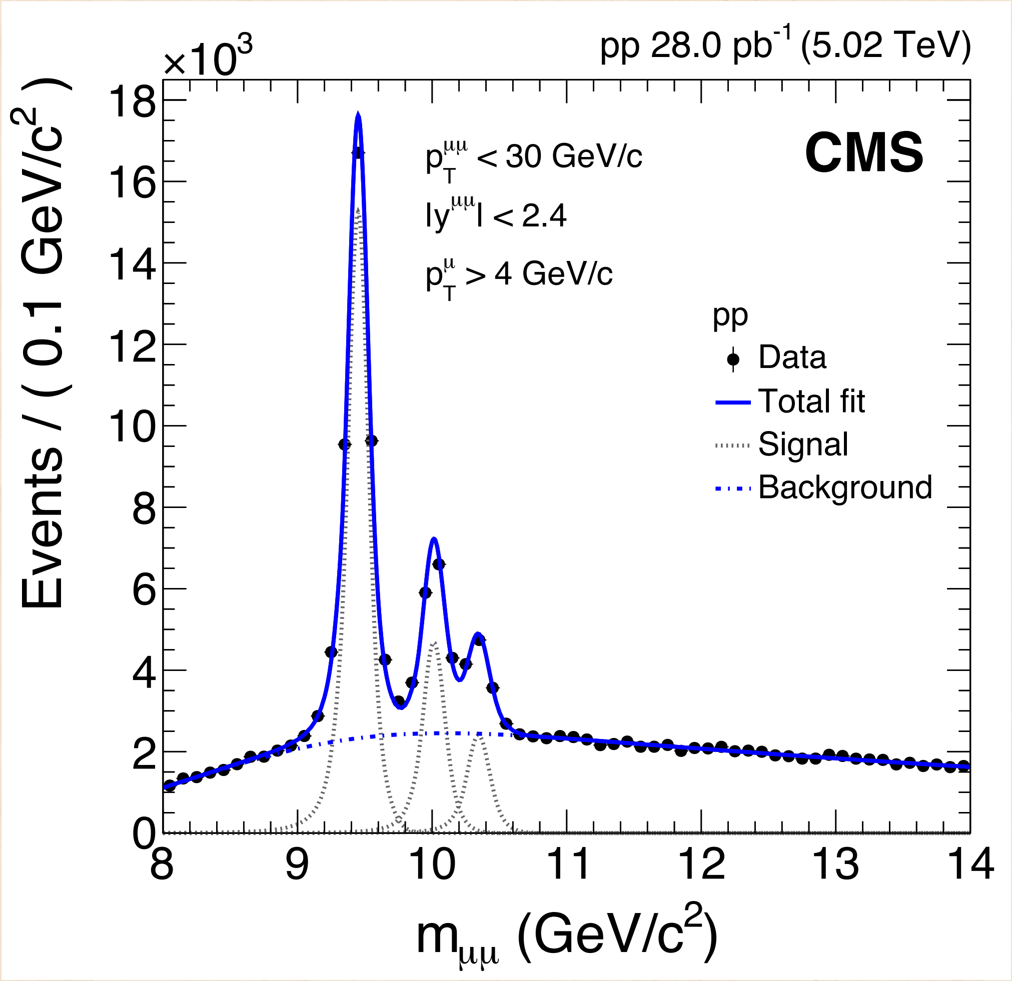


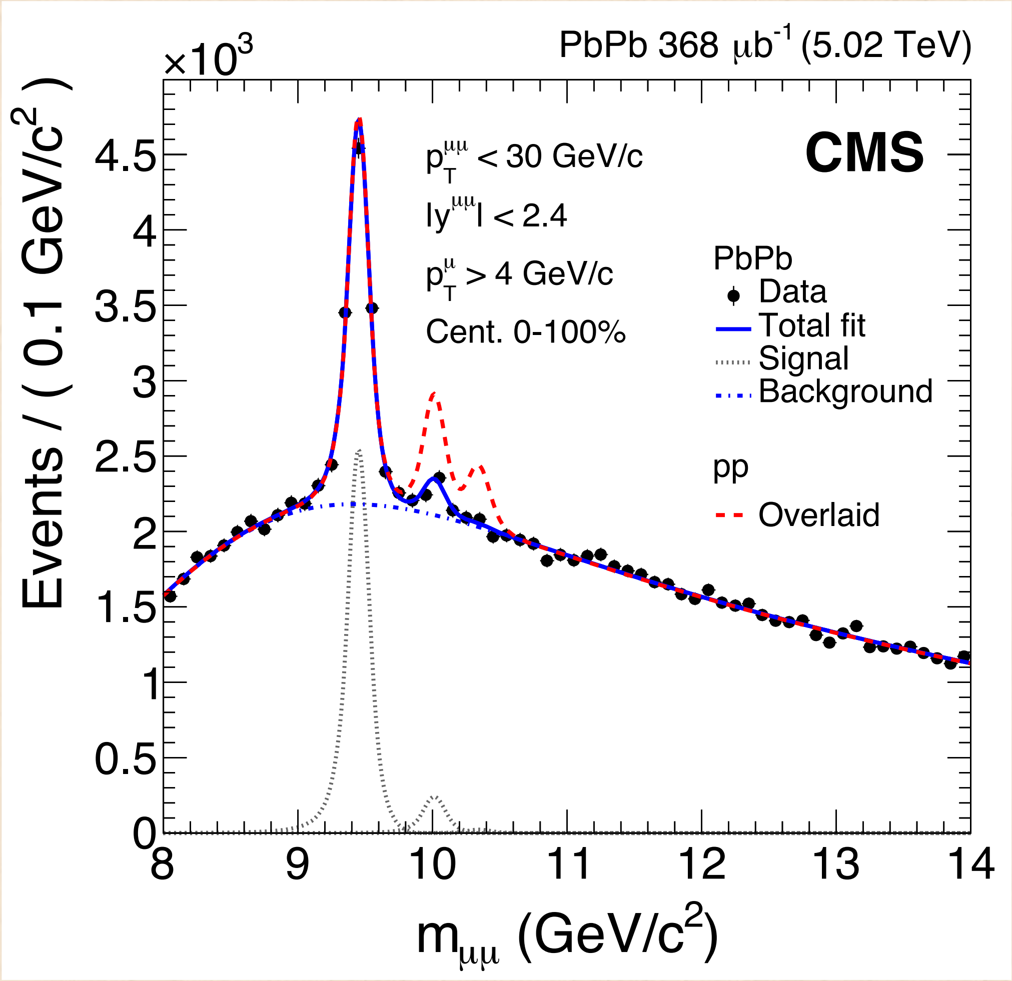
In PbPb, above ~10 GeV R_{AA} seems to converge

Electroweak objects are not modified on the other hand

Quarkonium

Increasing amount of suppression is observed for higher mass states —> sequential melting vs. recombination





Quarkonium

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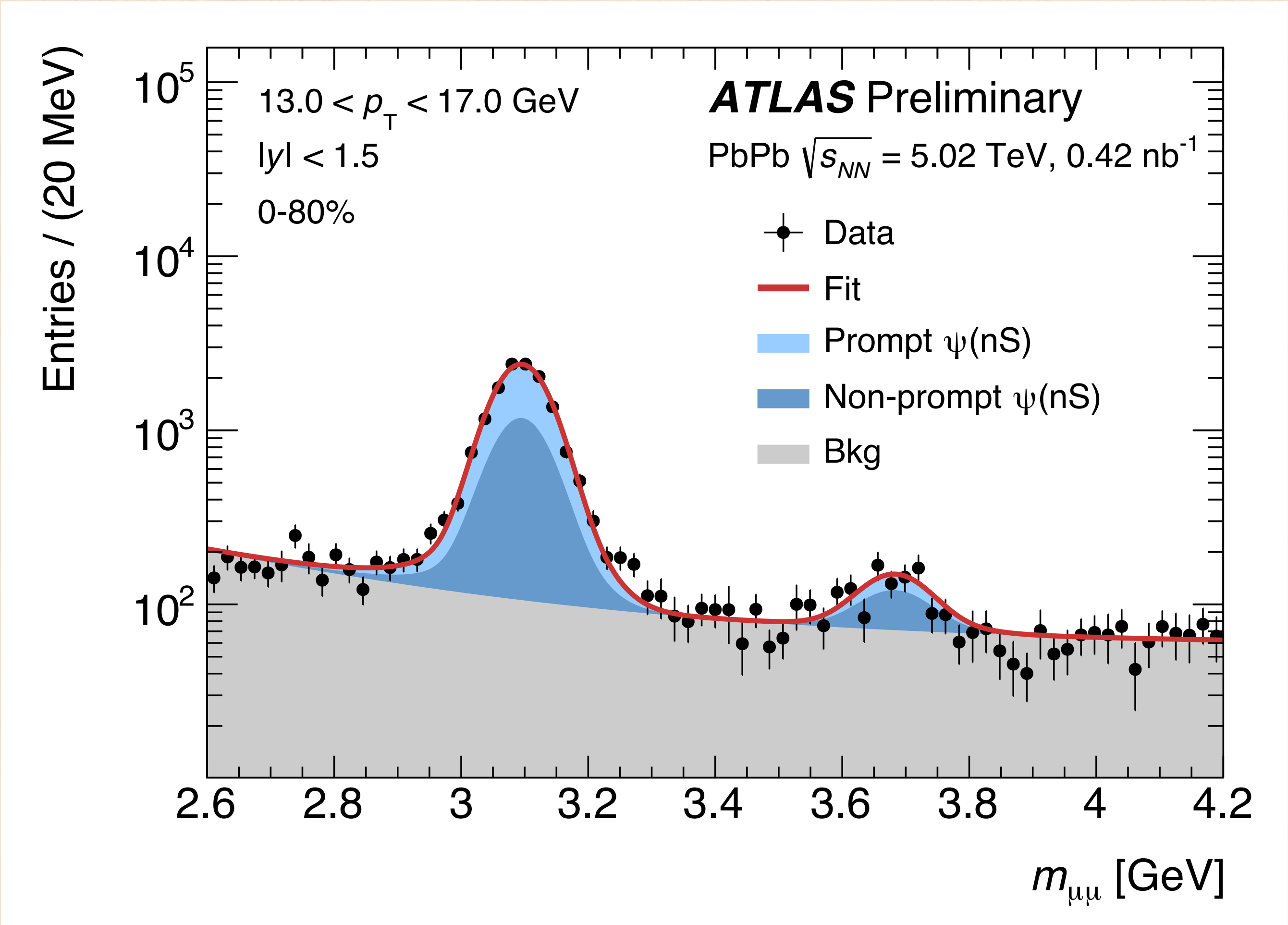
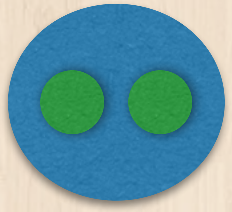
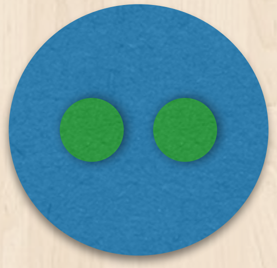


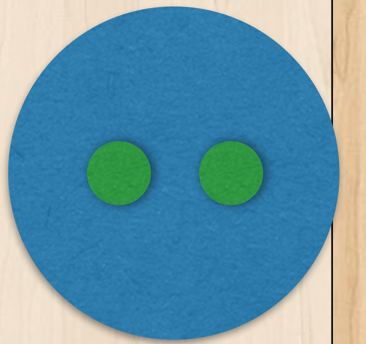
1S



2S

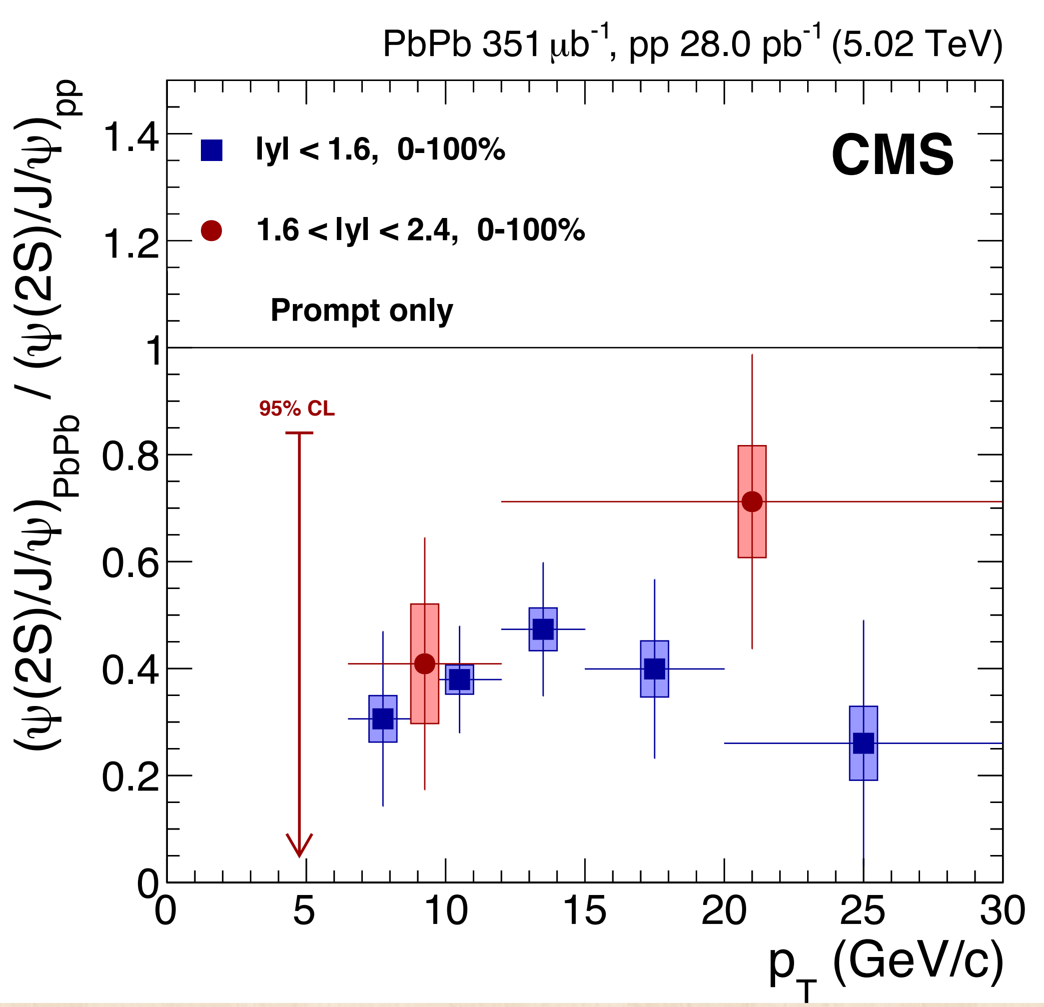


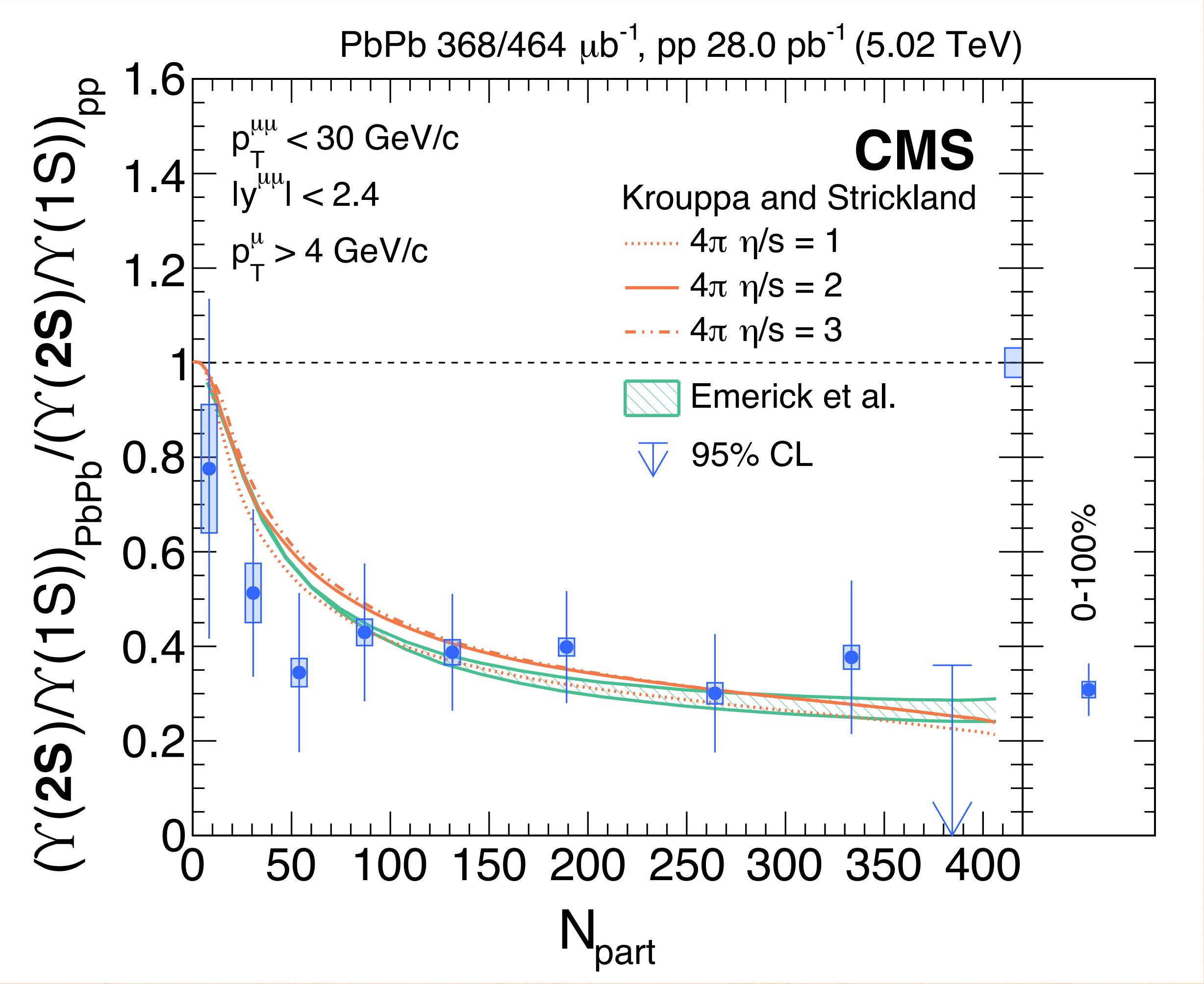
3S



CMS-HIN-16-008: 1706.05984
CMS-HIN-16-004: PRL 118 (2017) 162301

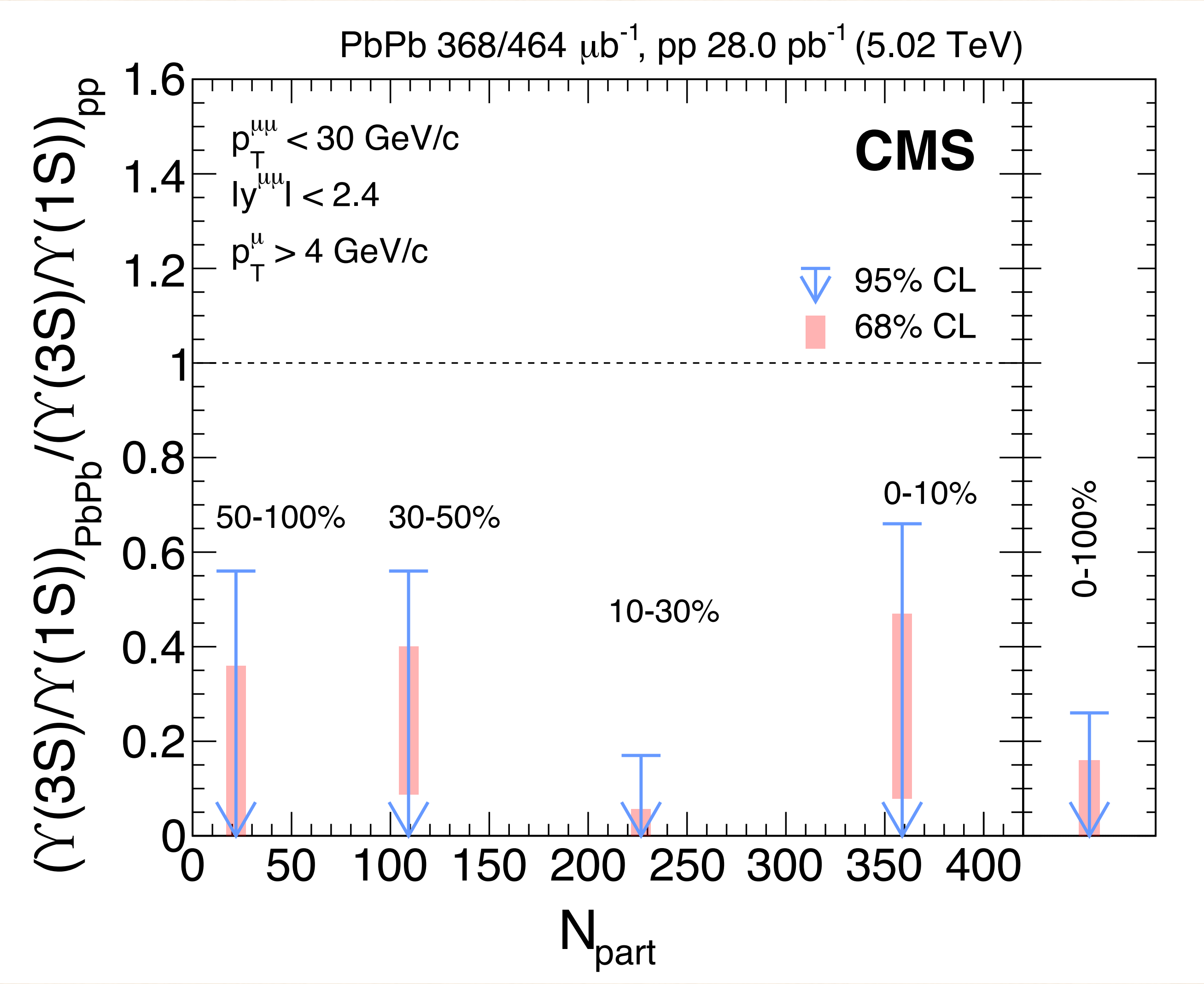
Quarkonium





Strong relative suppression observed for 2S states compared to lowest mass 1S state for J/psi and Y

Quarkonium



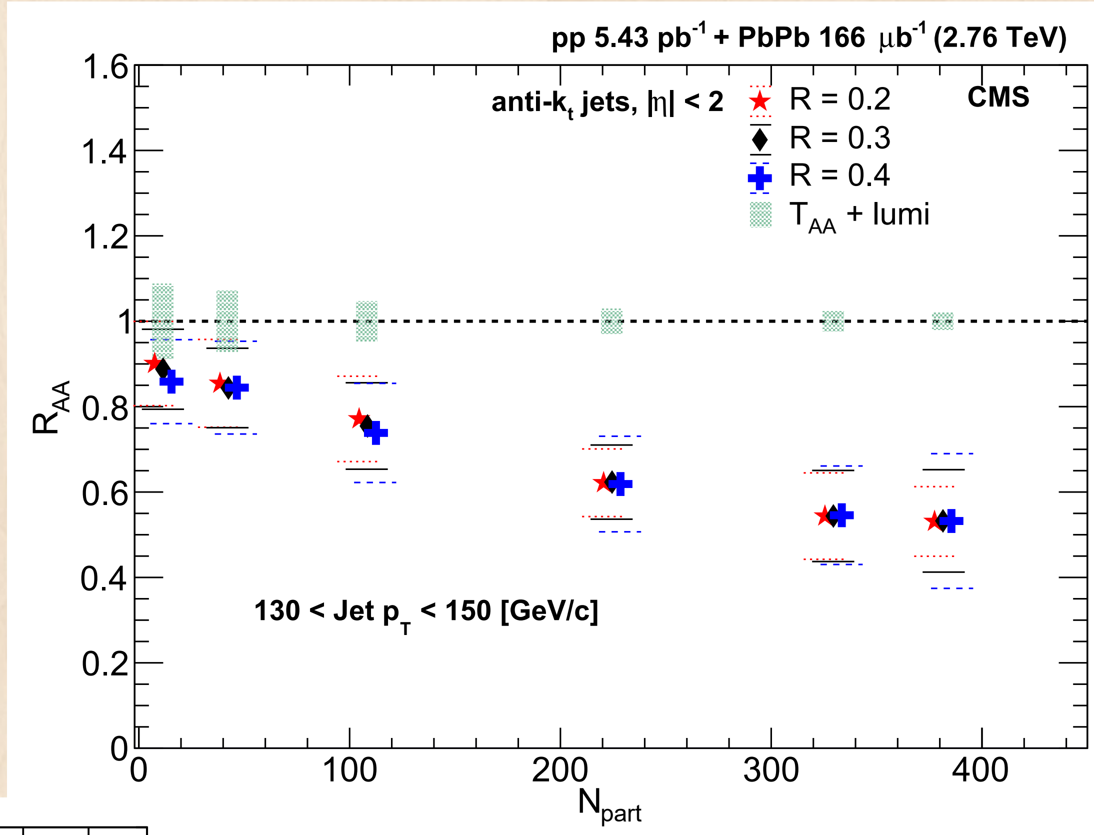
No sign of Y(3S) so far in PbPb collisions

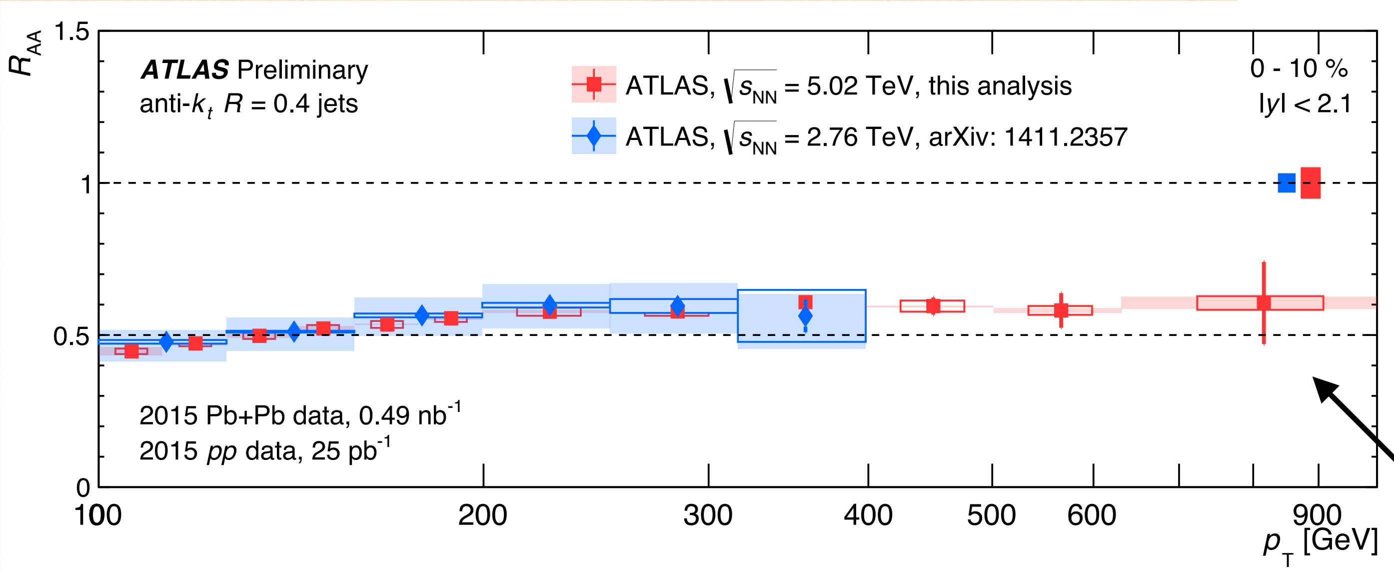
ATLAS-CONF-2017-009
CMS-HIN-13-005: PRC 96, 015202 (2017)

Jet R_{AA}

Jets are suppressed

No strong dependence on radius parameter between 0.2, 0.3 and 0.4



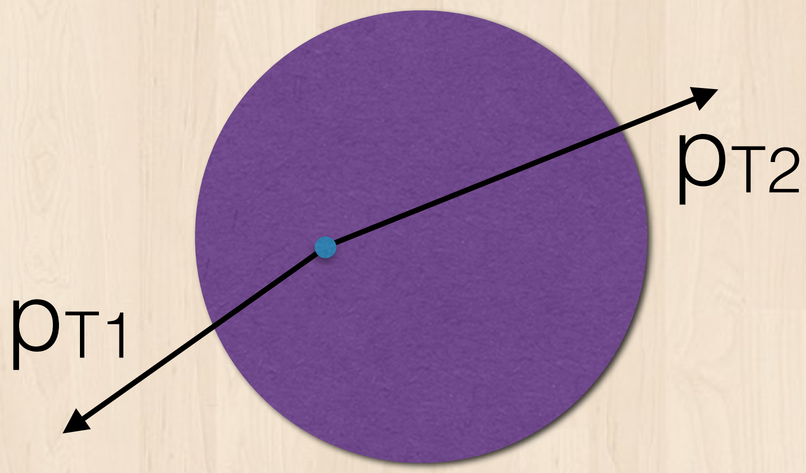


R_{AA} roughly flat for high P_T jets in the measured range

Up to TeV!

ATLAS-HION-2012-11: PLB 774 (2017) 379

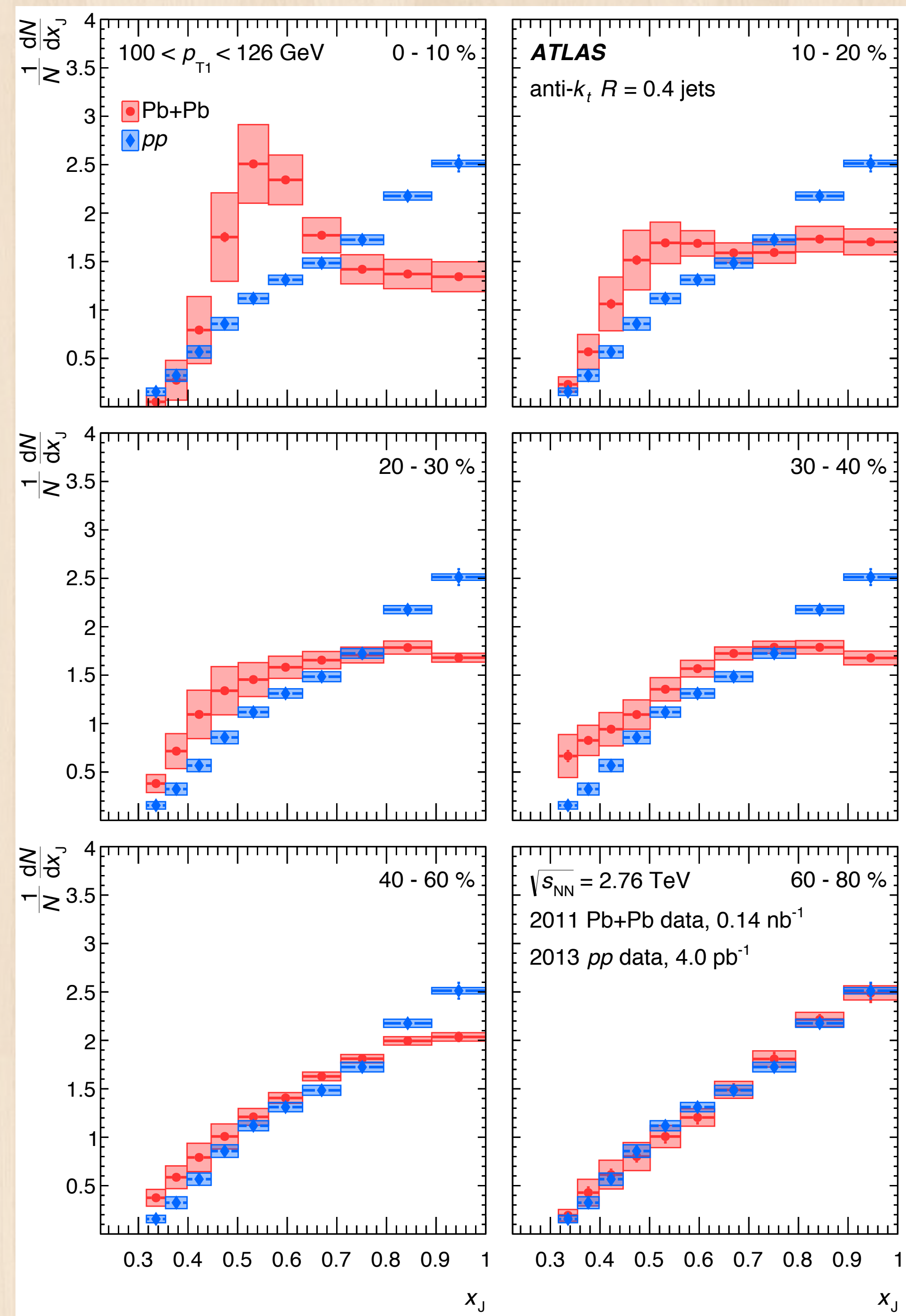
Dijet imbalance



Imbalance measured with dijet events

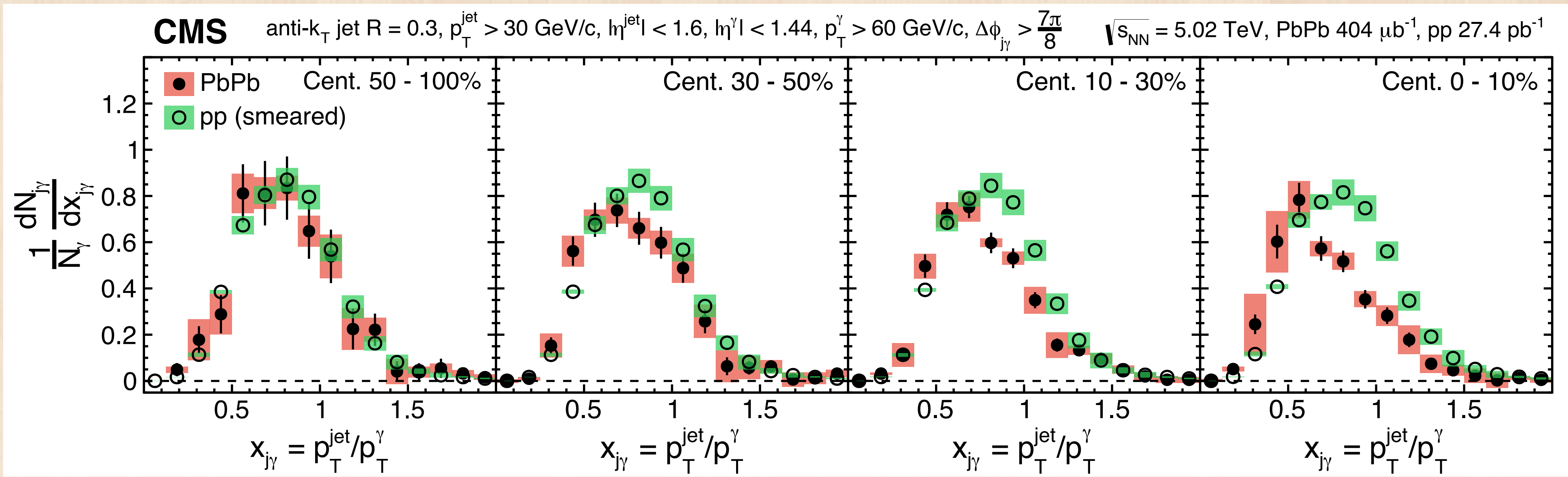
$$x_J = \frac{p_{T,2}^{\text{jet}}}{p_{T,1}^{\text{jet}}}$$

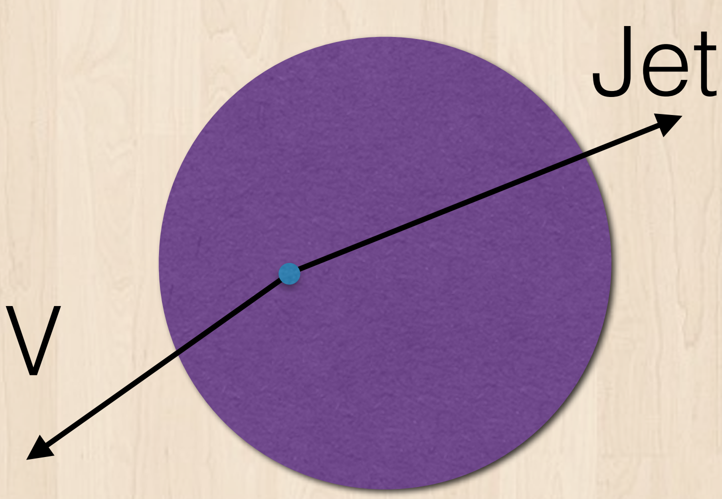
Larger momentum imbalance observed in central collisions



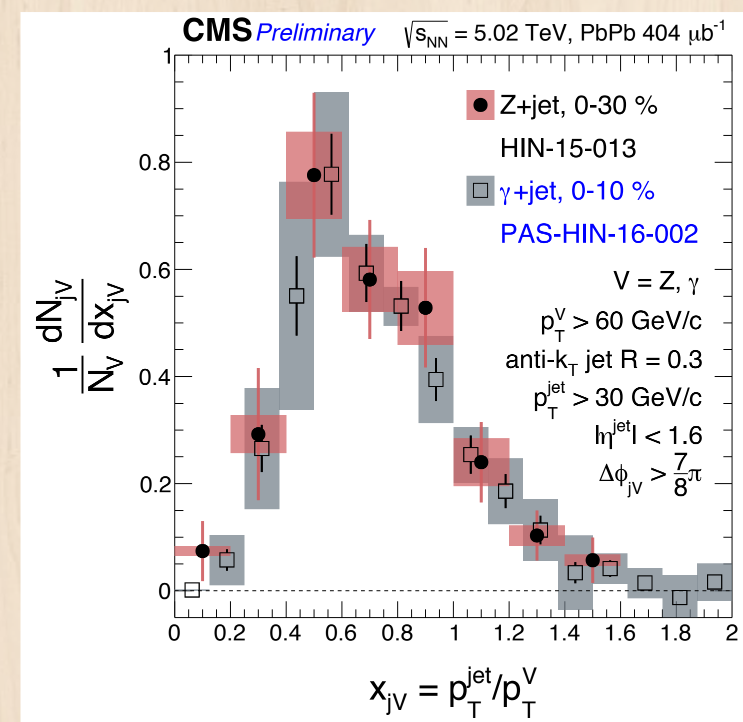
CMS-HIN-16-002: 1711.09738
CMS-HIN-15-013: PRL 119 (2017) 082301

V+Jet





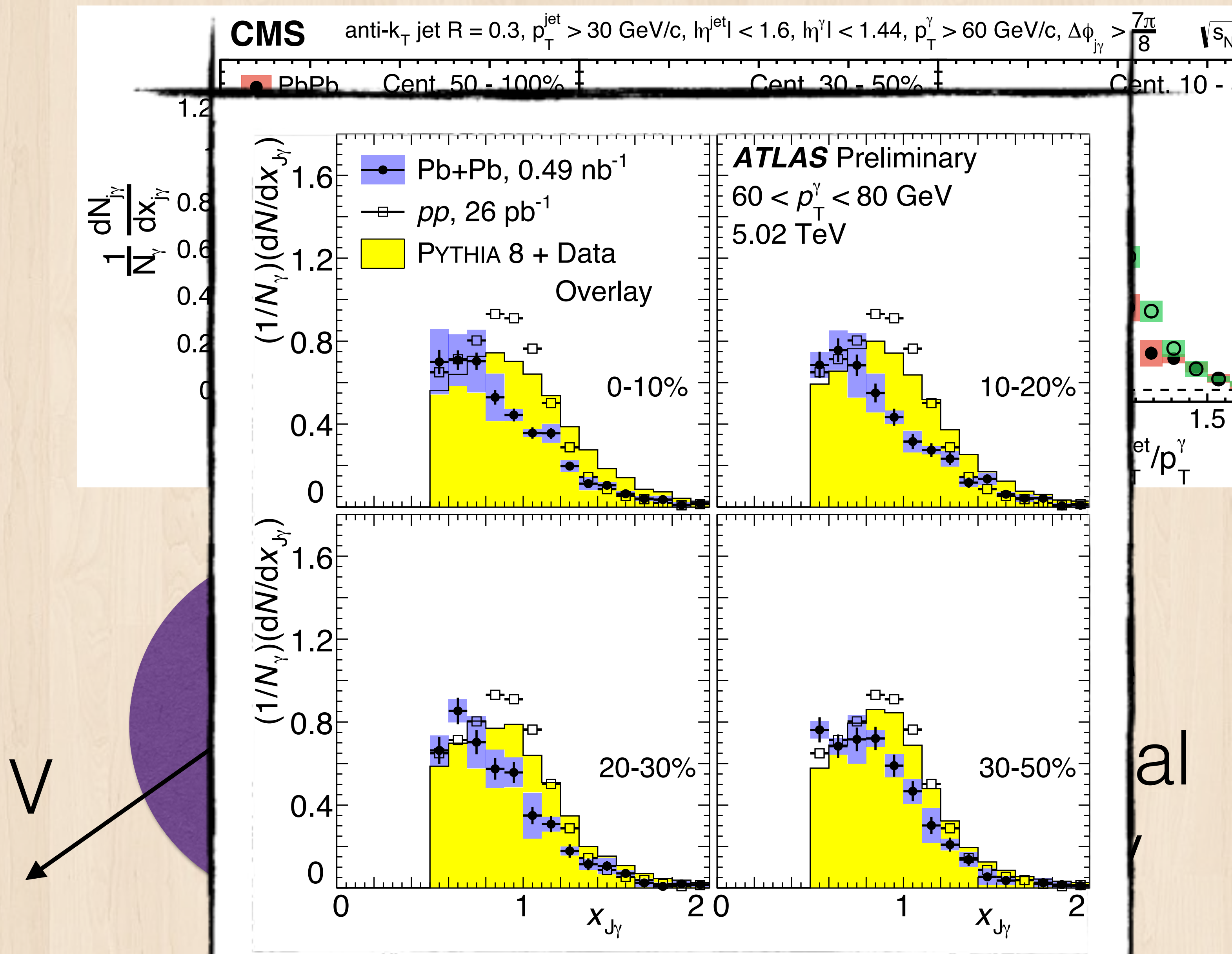
Photon and Z boson can be used to tag initial parton energy



More energy lost in central collisions

V+Jet

CMS-HIN-16-002: 1711.09738
CMS-HIN-15-013: PRL 119 (2017) 082301
ATLAS-CONF-2016-110



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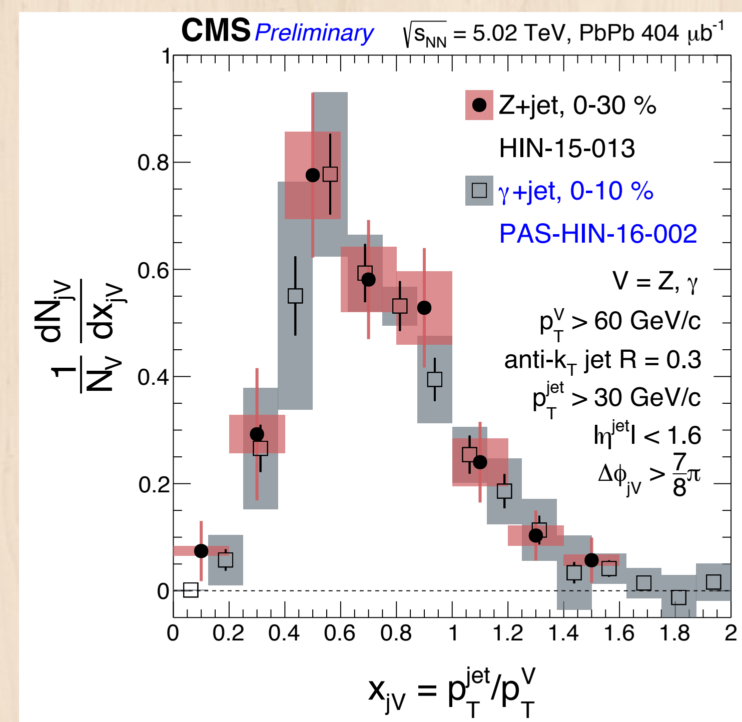
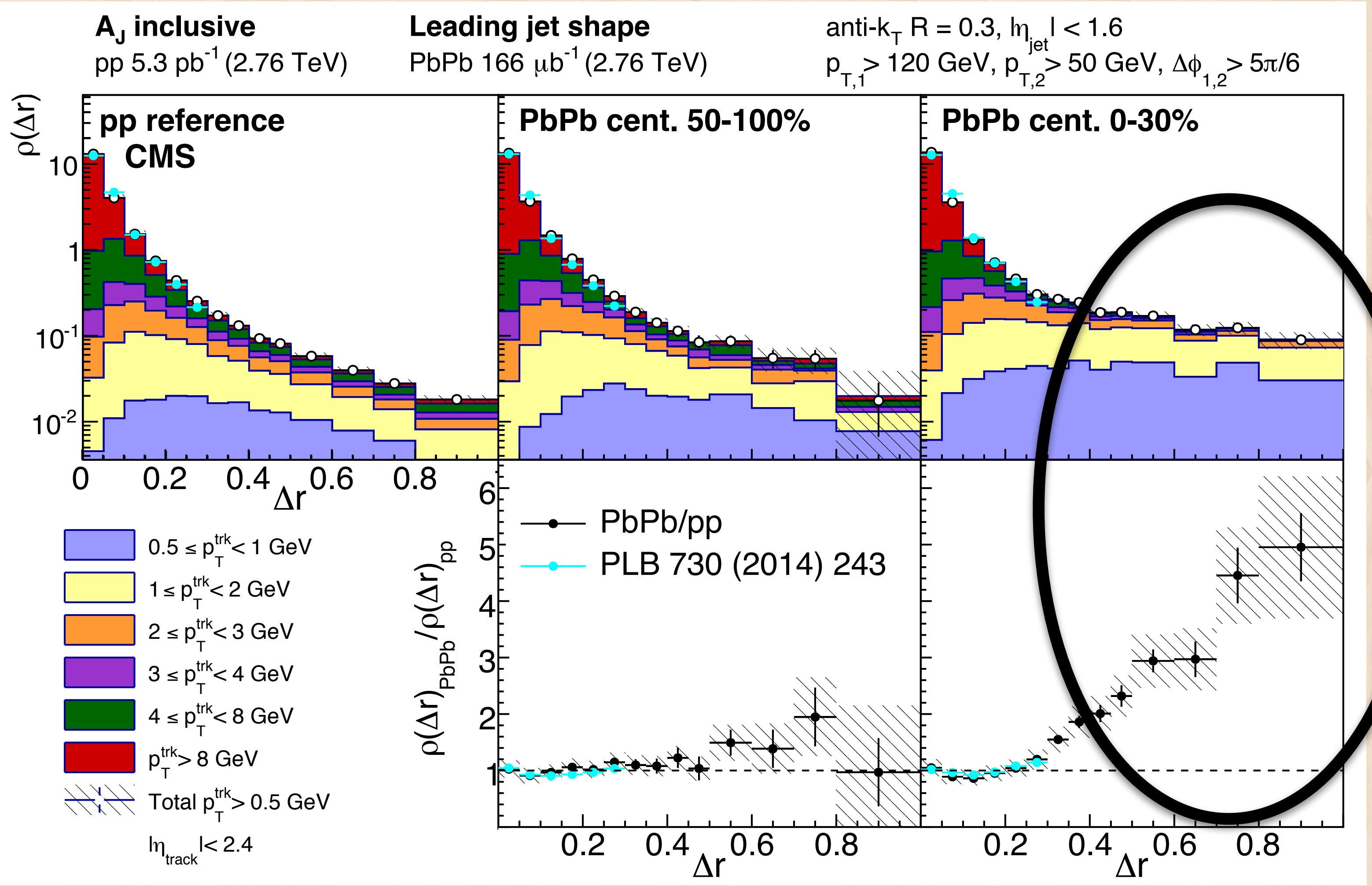


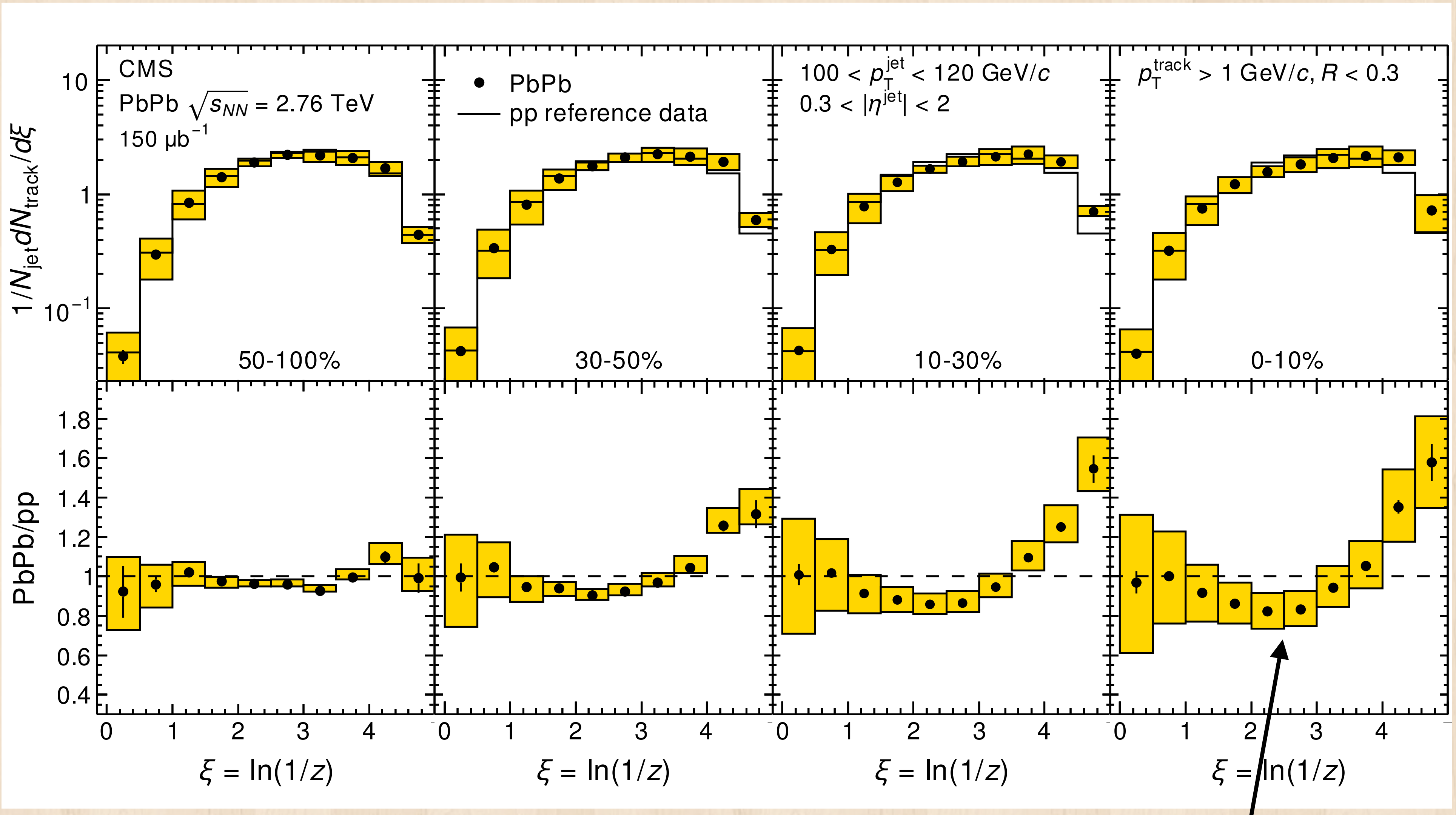
How are jets modified?



Energy carried by charged particles around jet axis

A lot more low-energy charged particles at large ΔR

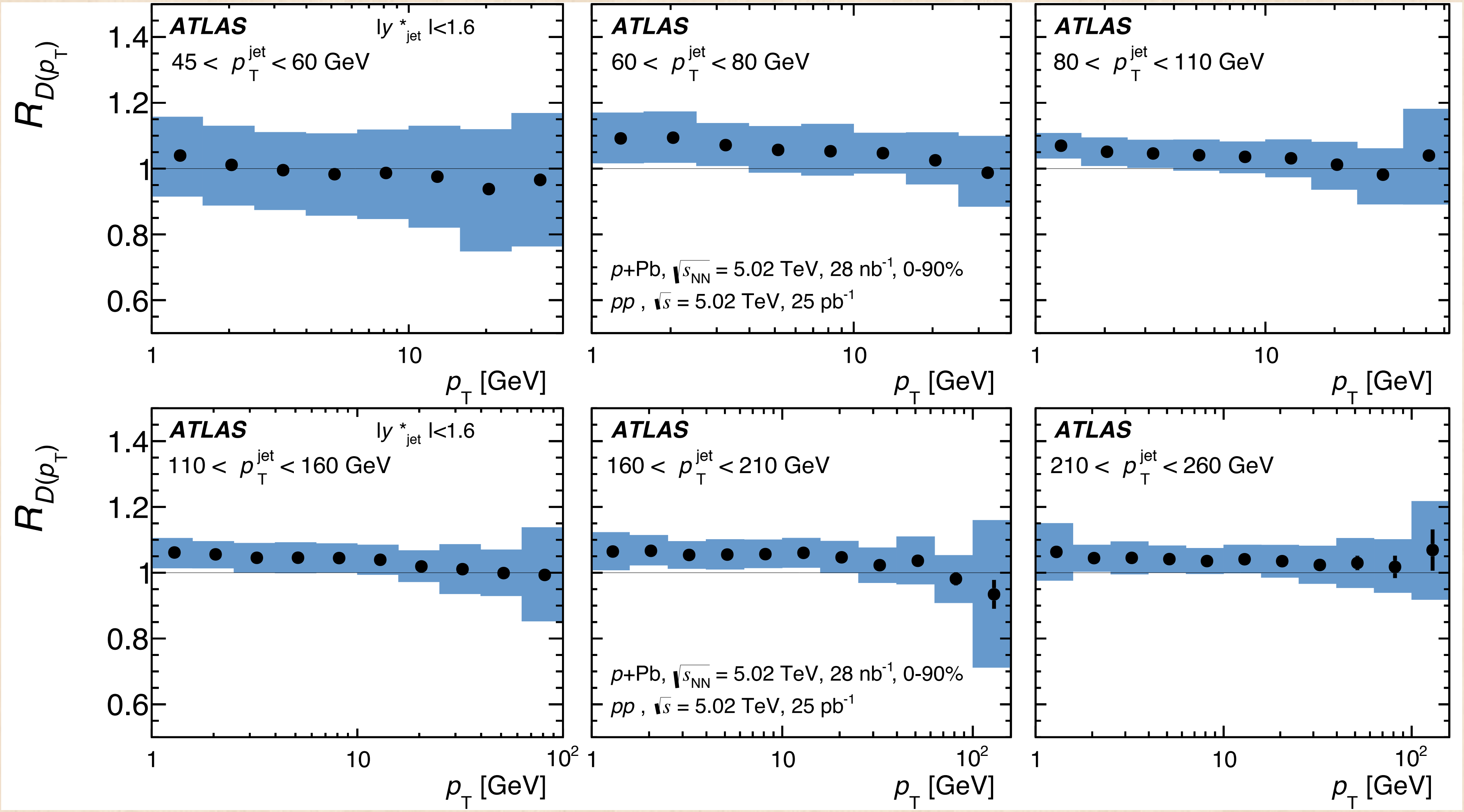
How are jets modified?



Relative suppression of moderate momentum tracks

$$\xi = -\ln z,\ z = p_{||}^{\text{track}} / p^{\text{jet}}$$

How are jets modified?



In p+Pb no significant modification is observed

Jet Substructure

- Soft drop / mMDT algorithm: sequentially removes subjets with small momentum fraction

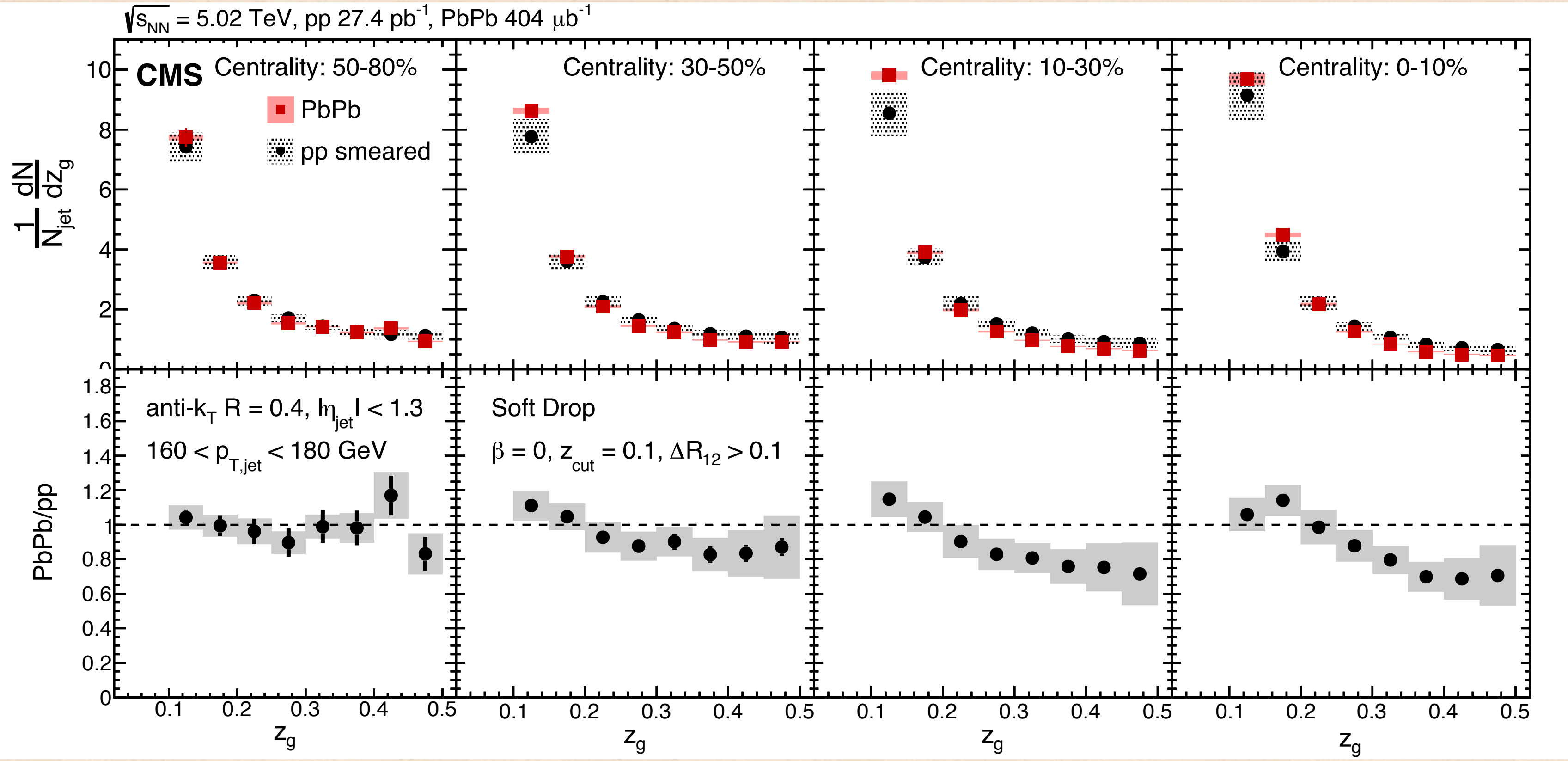
$$z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\mathrm{cut}} \left(\frac{\Delta R}{R}\right)^{\beta}$$

- Setting 1: **Angle-independent** grooming on momentum fraction (z_{cut} = 0.1, β = 0.0)

- Setting 2: Stronger grooming at larger angle, weaker grooming at small angle —> focus on the **core** of the jet (z_{cut} = 0.5, β = 1.5)

Jet Substructure

Modification observed in both momentum sharing between subjet and jet mass



z_{cut} = 0.1
β = 0.0

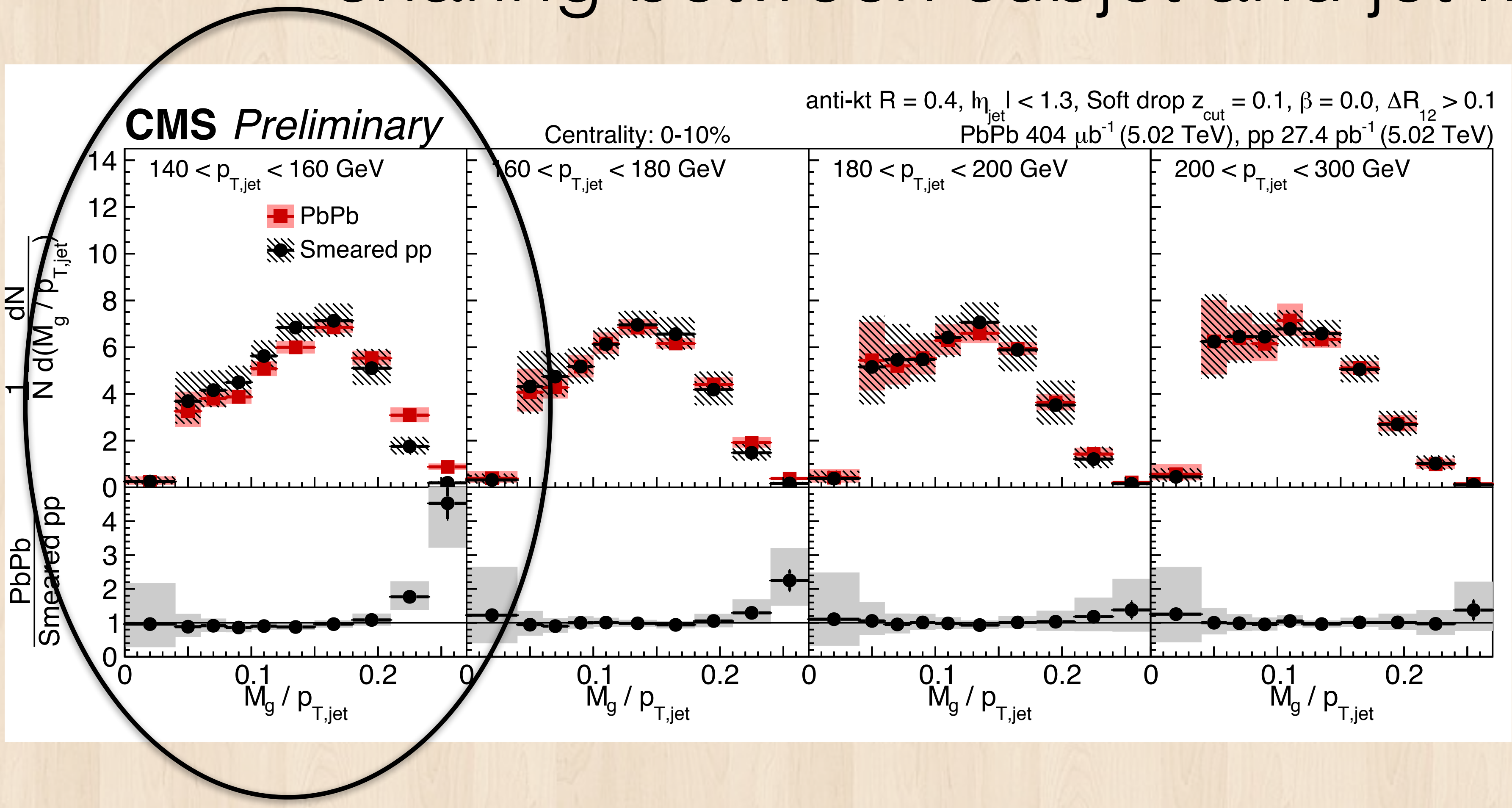
angle-independent

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

There are more jets with imbalanced subjets

Jet Substructure

Modification observed in both momentum sharing between subjet and jet mass



$z_{cut} = 0.1$

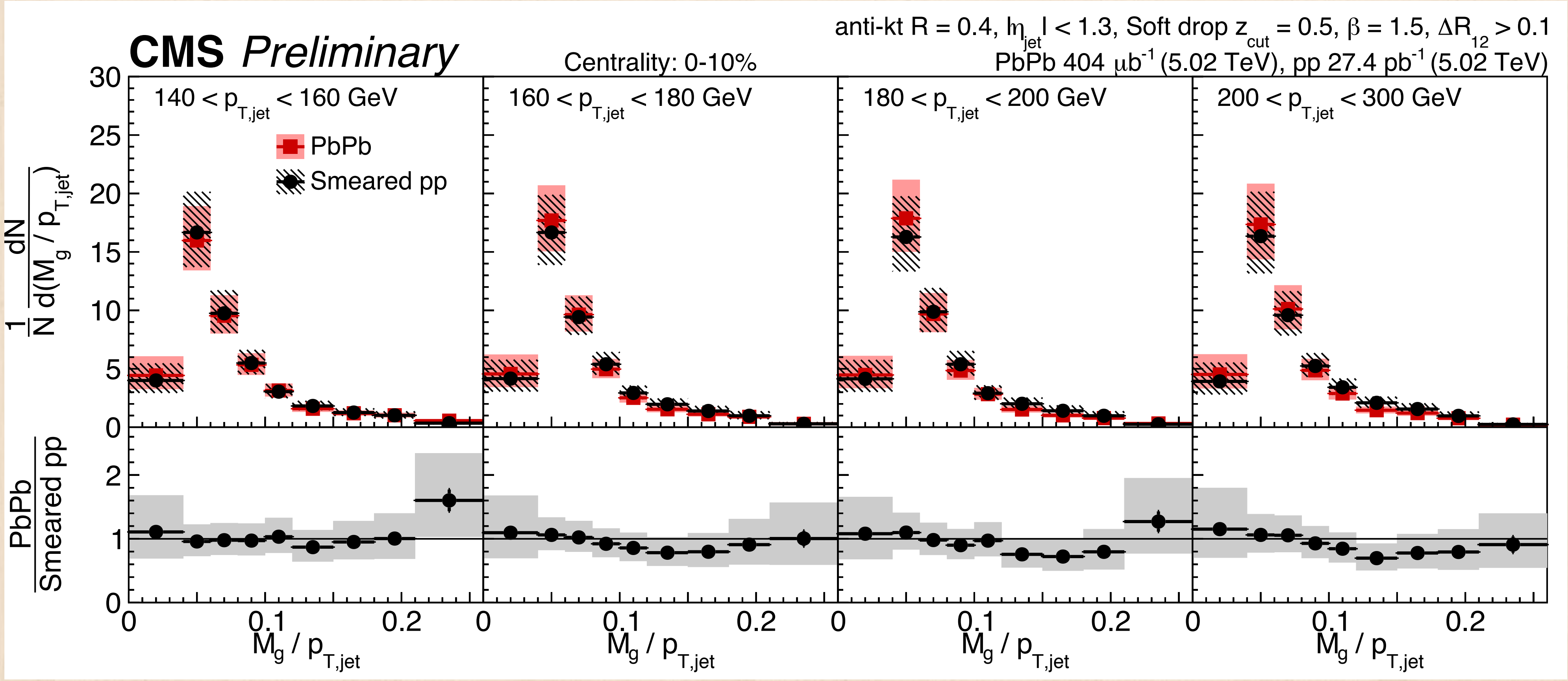
$\beta = 0.0$

angle-independent

…and larger groomed mass

Jet Substructure

Modification observed in both momentum sharing between subjet and jet mass



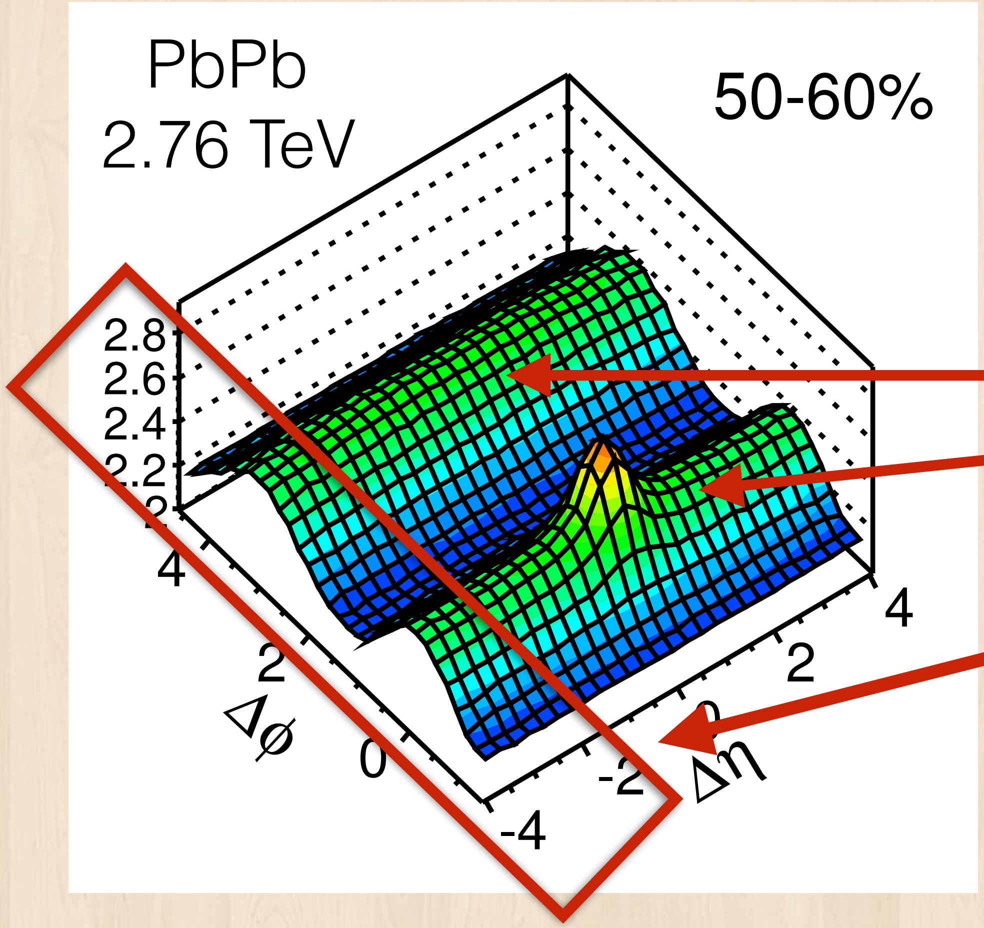
Zcut = 0.5
β = 1.5

Jet core

but the jet core is (within uncertainty) not modified

Collective behavior

"Ridge" in two-particle correlation



Initial state (geometry/interaction) + hydrodynamical evolution

Jet peak

Fourier decomposition (after subtraction)

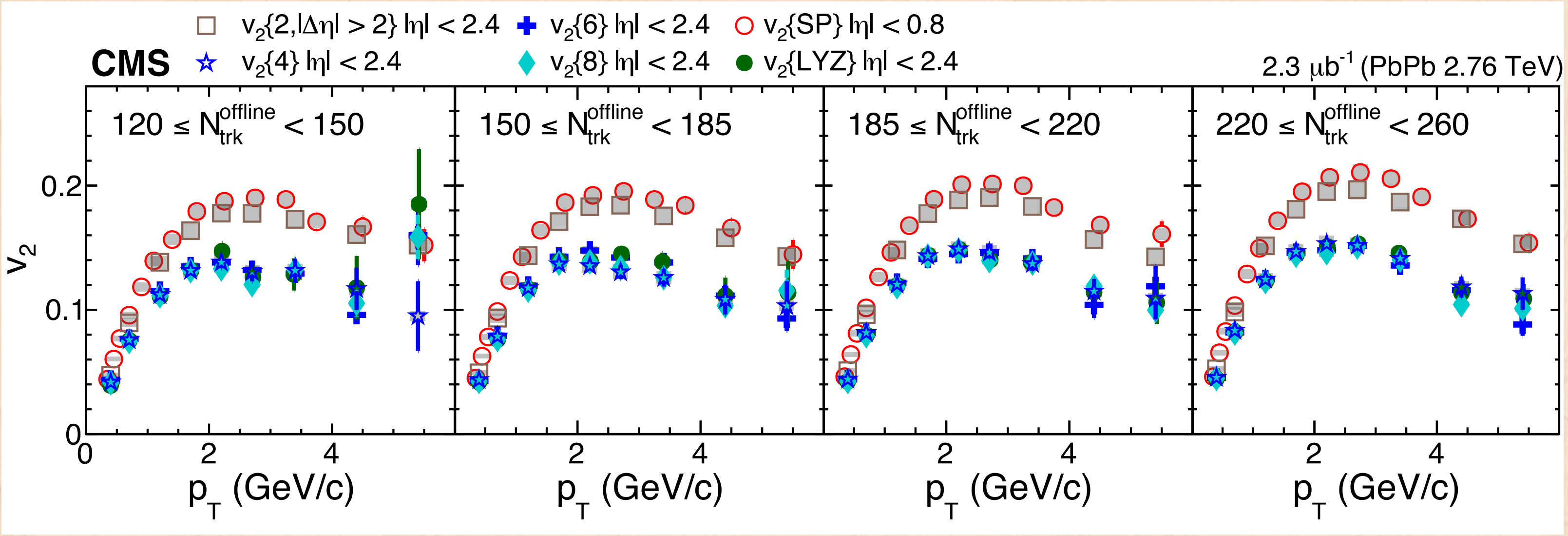
$$f(\Delta\phi) = \sum_n v_n \cos(n\Delta\phi)$$

Observed in PbPb, pPb and **high multiplicity pp**

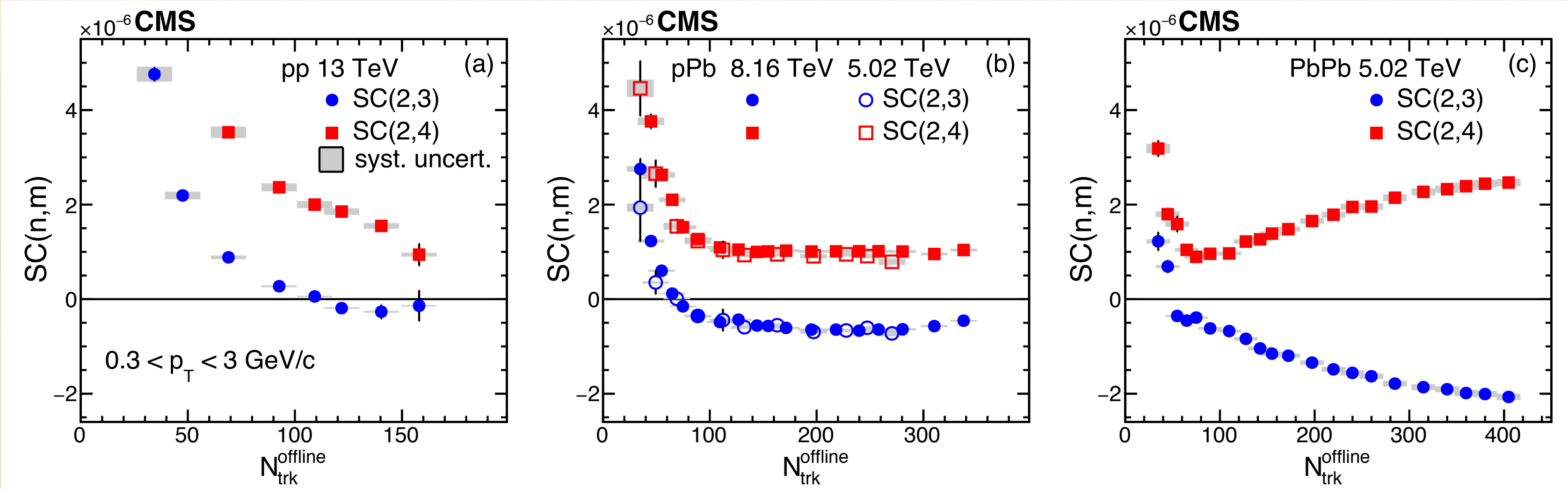
CMS-HIN-16-022: 1709.09189
CMS-HIN-15-008: 1710.07864

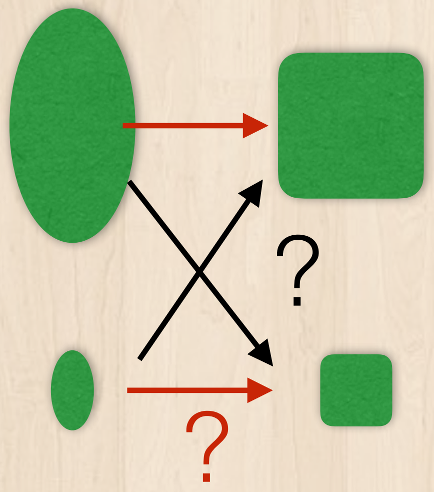
Collective behavior

Detailed analysis on v_n coefficients



multi-particle correlations





Correlation between v_n directly probes the initial state

$$\mathrm{SC}(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

CMS-HIN-16-022: 1709.09189
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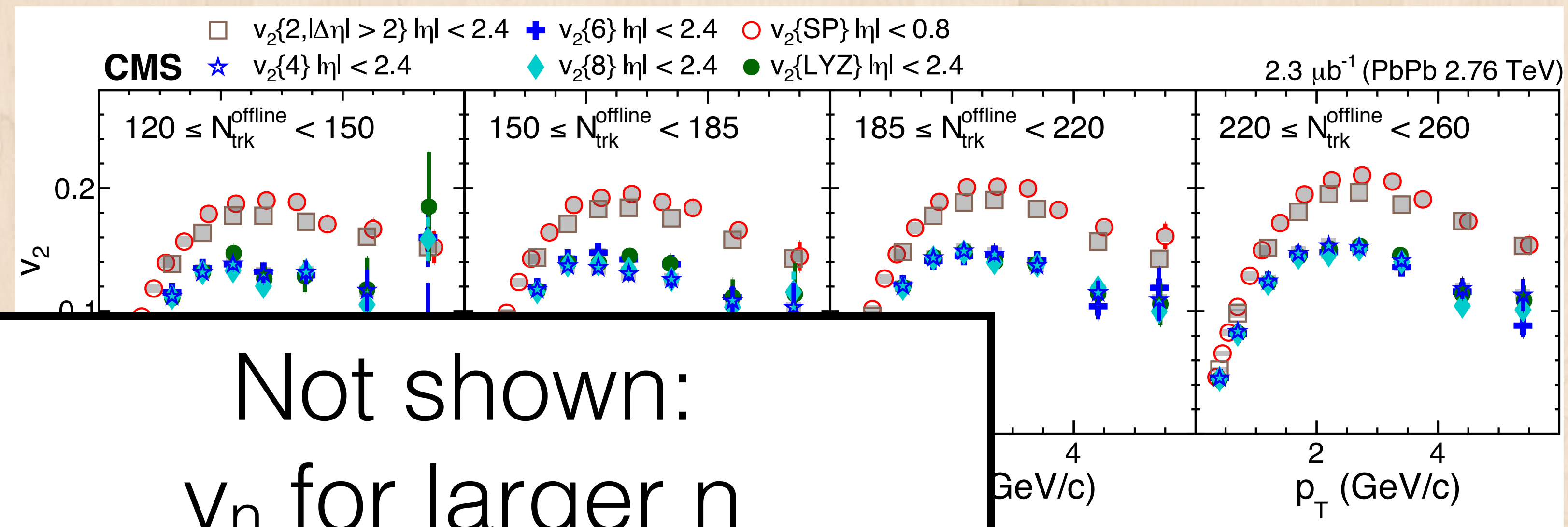
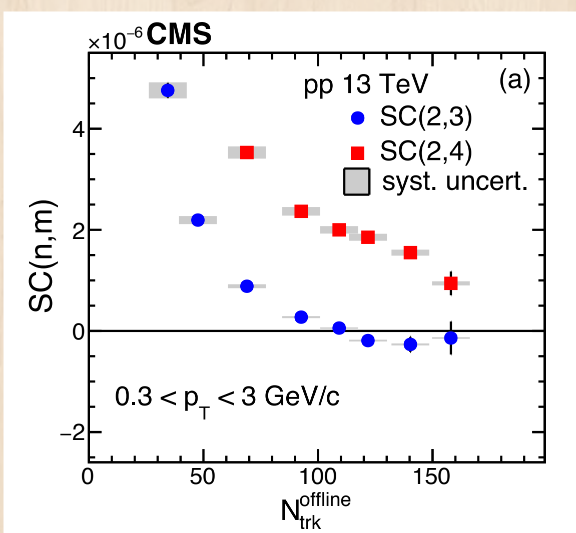
Collective behavior

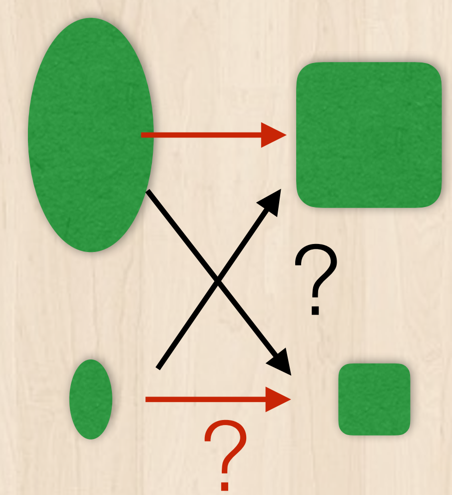
Detailed analysis on v_n coefficients



multi-particle correlations



Not shown:
v_n for larger n
linear vs. non-linear flow
flow decorrelation
flow in small systems
...

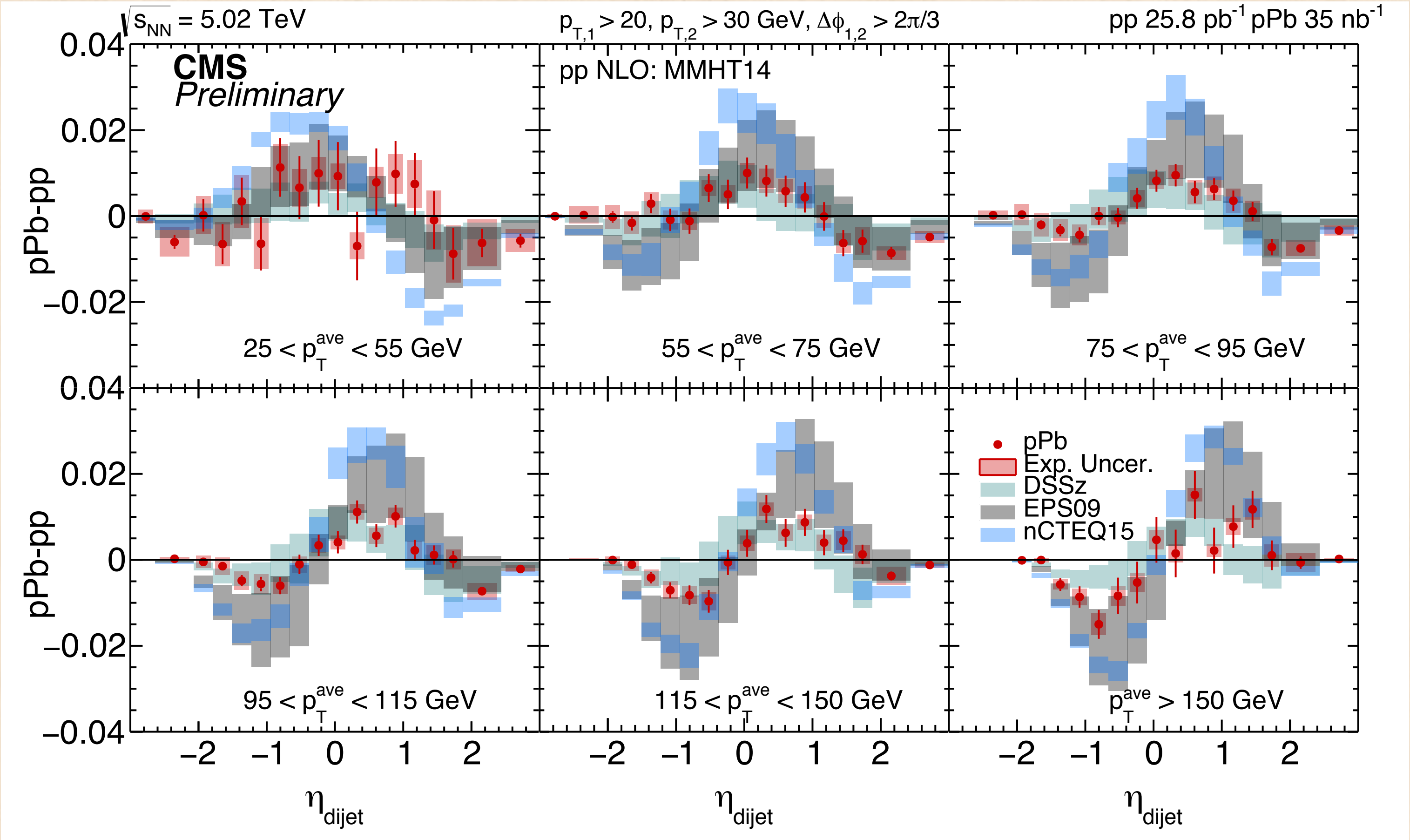


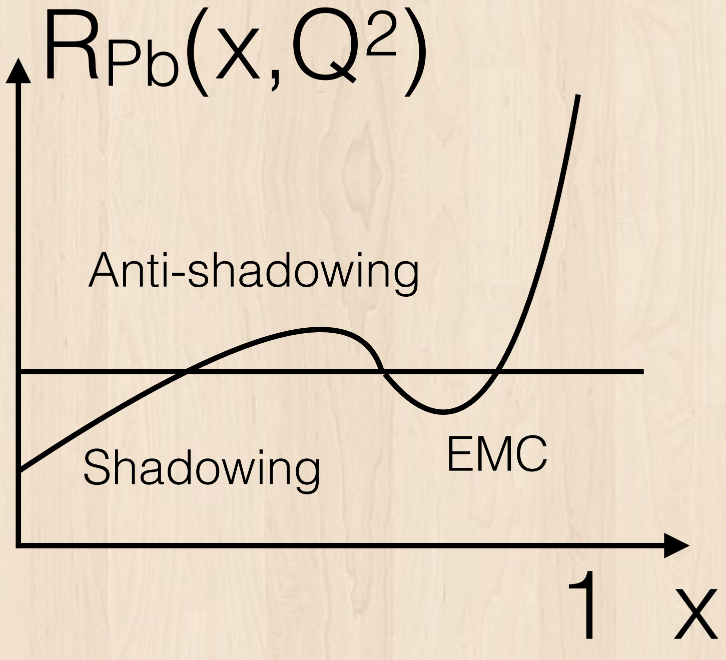
Correlation between v_n directly probes the initial state

$$\mathrm{SC}(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

Nuclear PDF

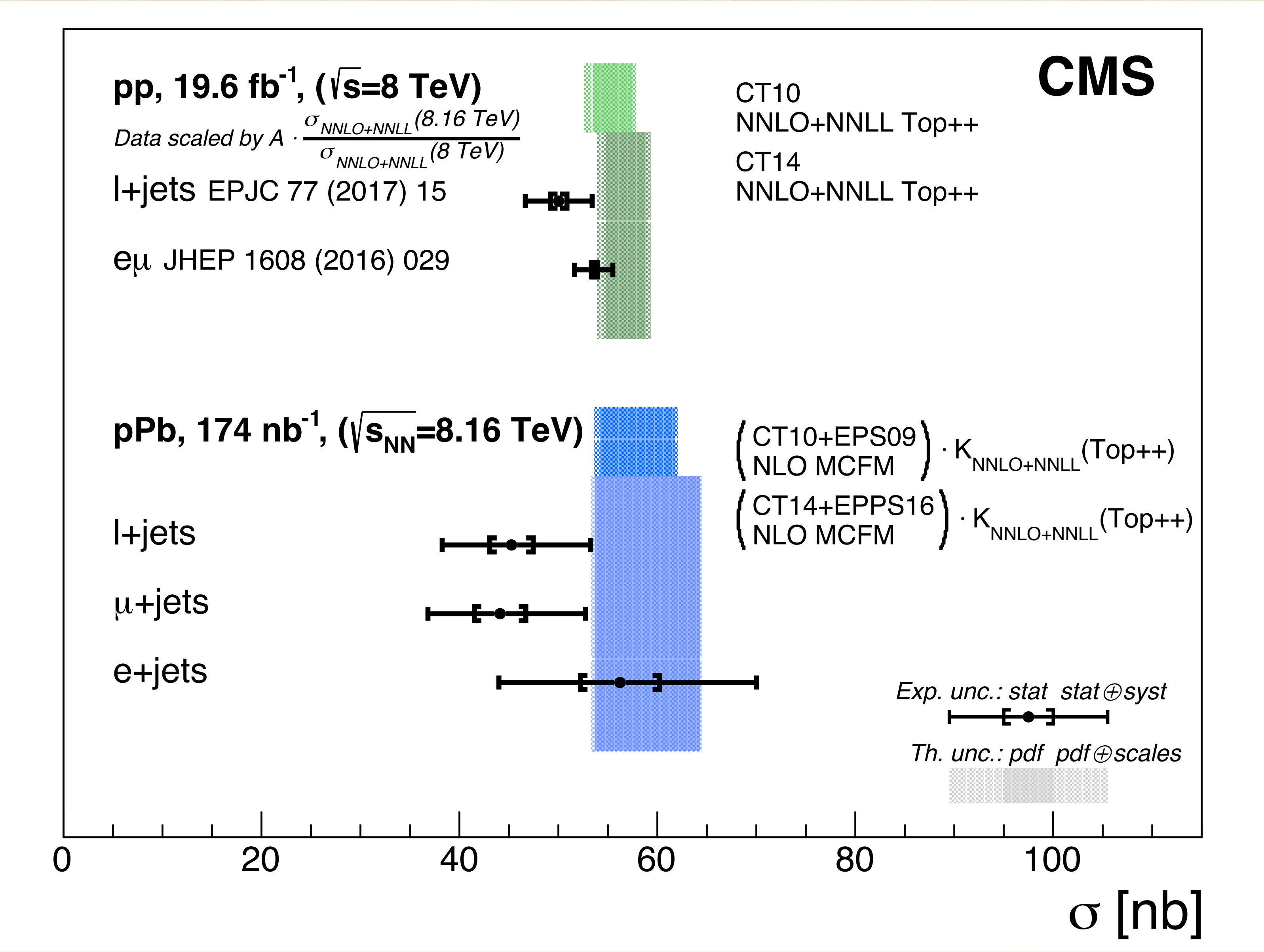
Nuclear PDF can be constrained with p+Pb collision

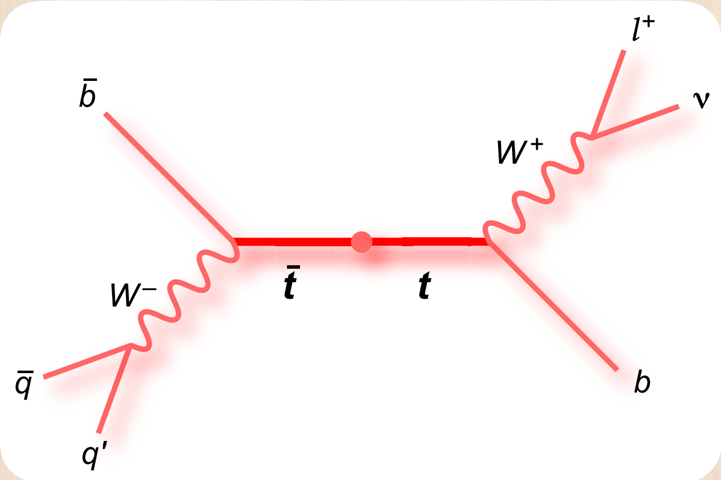




Measurement of dijet pseudorapidity distribution

Observation of top

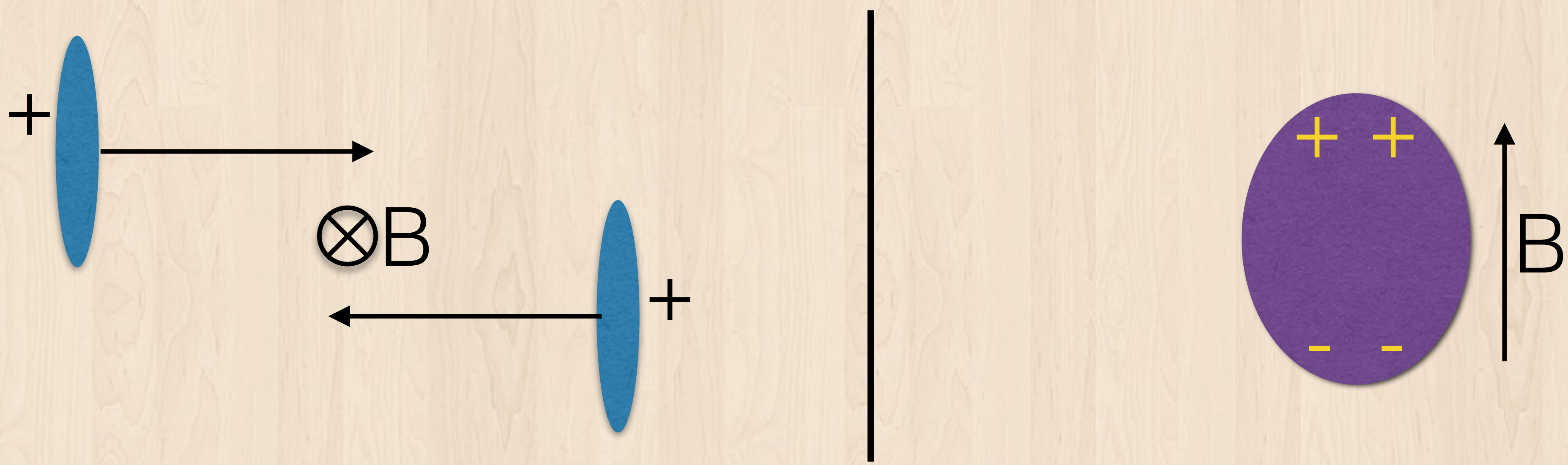




Top production is observed for the first time in p+Pb!

Chiral magnetic effect

Strong magnetic field created in PbPb collisions



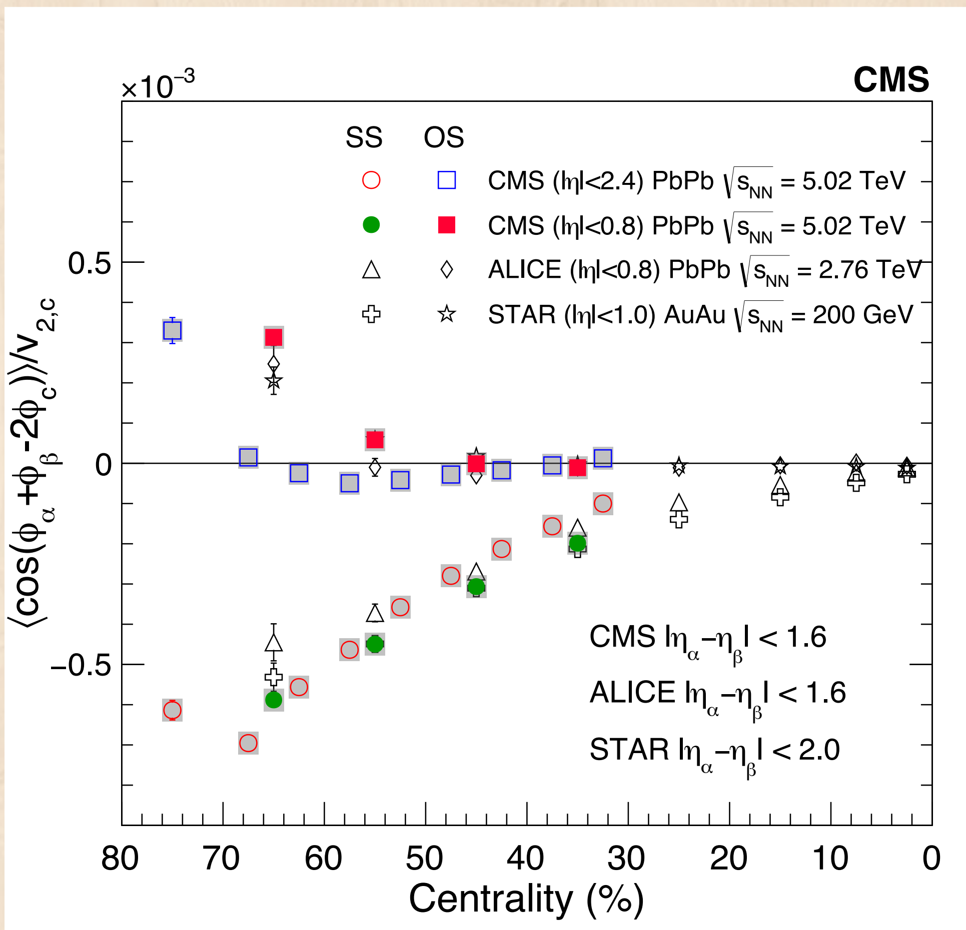
The magnetic field could induce electric current due to chiral imbalance —> charge separation

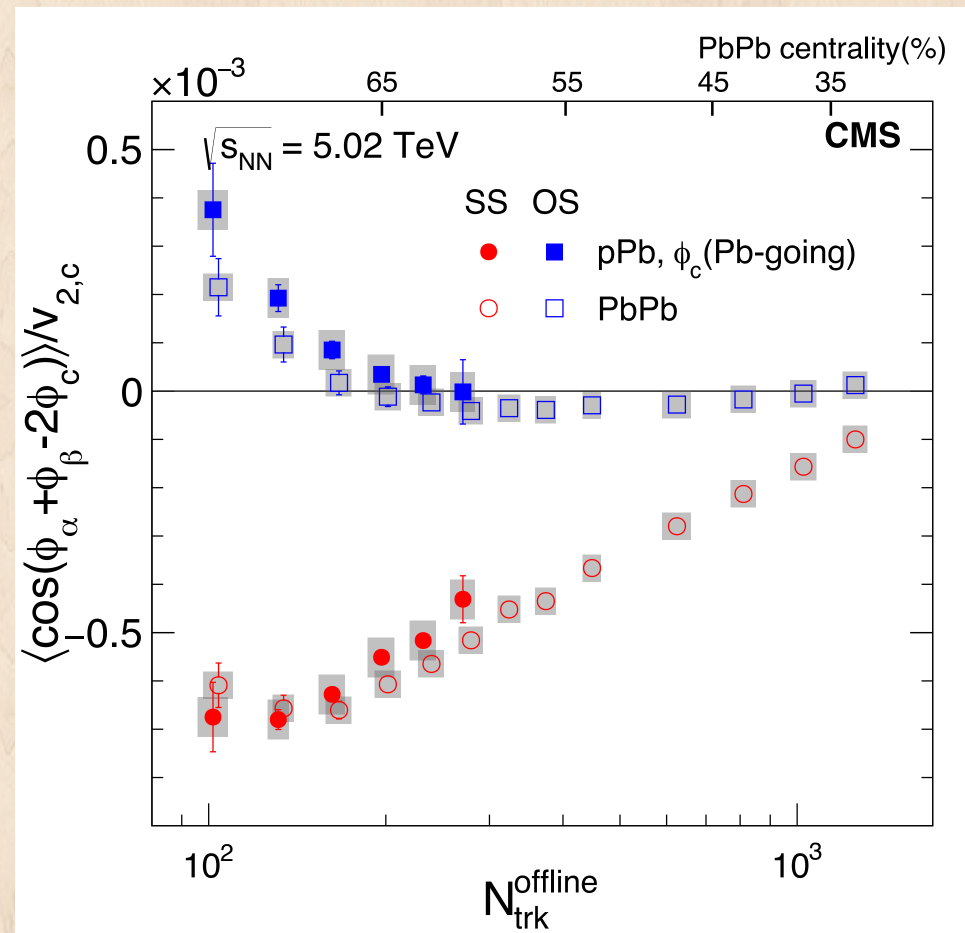
Signature: different correlation between same sign and opposite sign particles

CMS-HIN-16-009: PRL 118 (2017) 122301

Chiral magnetic effect

We observe the signature we are looking for





The lack energy and collision system dependence suggest that some other mechanisms also contribute

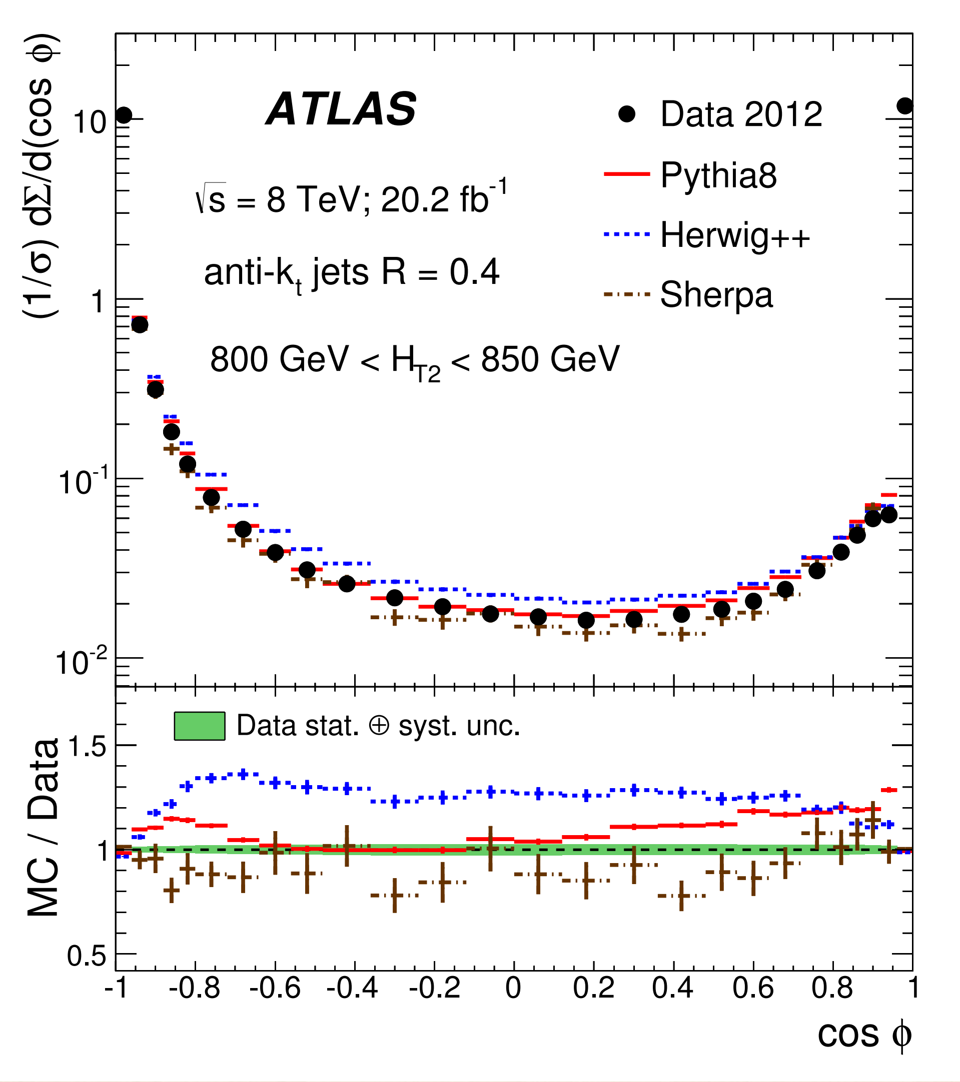
Summary

- LHC Run 2 is going well! We expect a lot more pp collision data at 13 TeV by the end of 2018.
- At the end of 2018 another PbPb run is expected, greatly increasing in statistics in both experiments
- Experiments have been performing very well and produced huge range of results in standard model and heavy ion physics
- Exciting times ahead for heavy ion and standard model physics in the next few years!

Backup Slides Ahead

TEEC

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

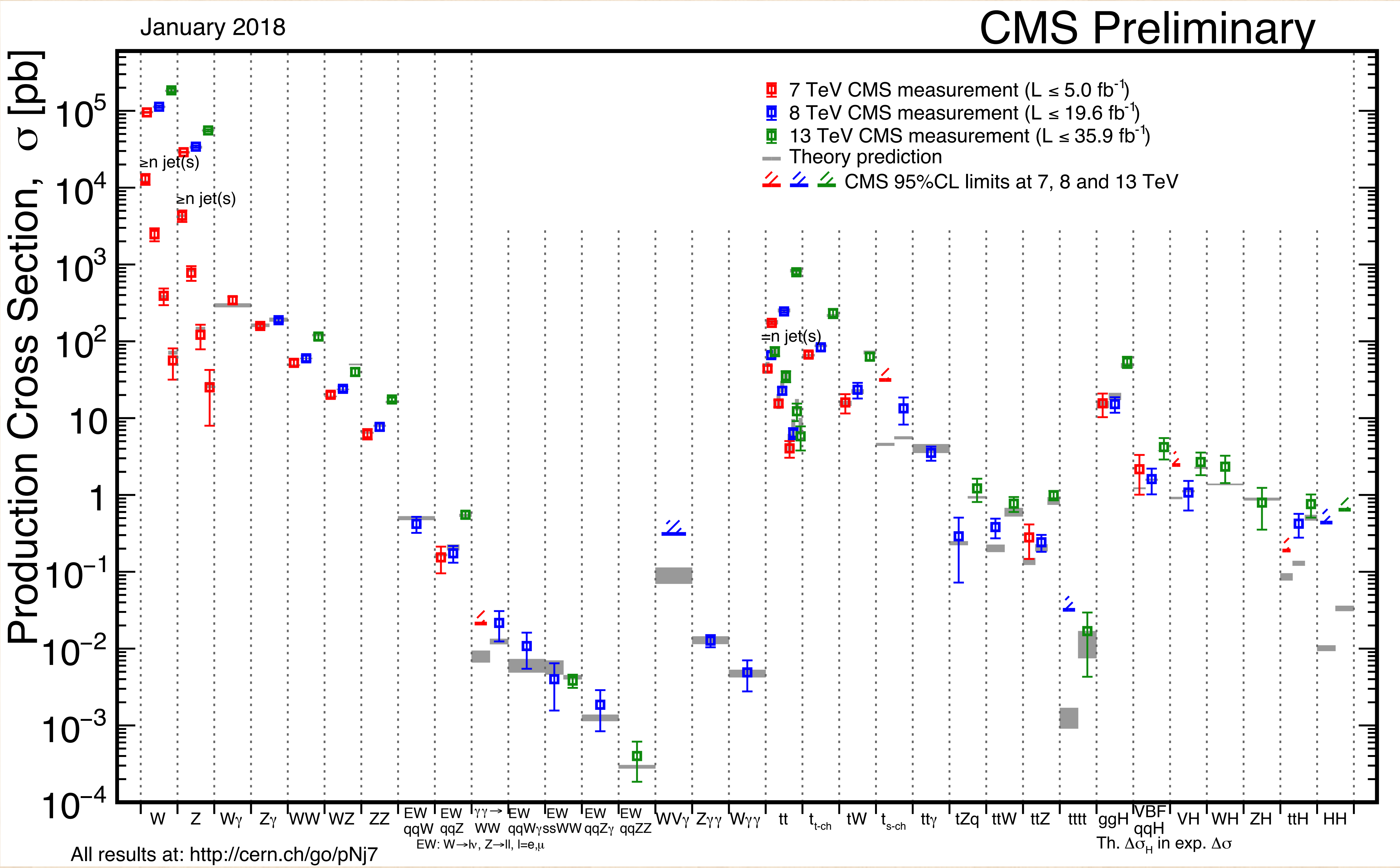


Weak mixing angle

$$A_{\mathrm{FB}}^{\mathrm{true}}(M) = \frac{6a_\ell a_\mathrm{q}(8v_\ell v_\mathrm{q} - Q_\mathrm{q} K D_\mathrm{M})}{16(v_\ell^2 + a_\ell^2)(v_\mathrm{q}^2 + a_\mathrm{q}^2) - 8v_\ell v_\mathrm{q} Q_\mathrm{q} K D_\mathrm{M} + Q_\mathrm{q}^2 K^2 (D_\mathrm{M}^2 - \Gamma_\mathrm{Z}^2 / M_\mathrm{Z}^2)},$$

where $K = 8\sqrt{2}\pi\alpha / G_\mathrm{F} M_\mathrm{Z}^2$, and $D_\mathrm{M} = 1 - M_\mathrm{Z}^2 / M^2$.

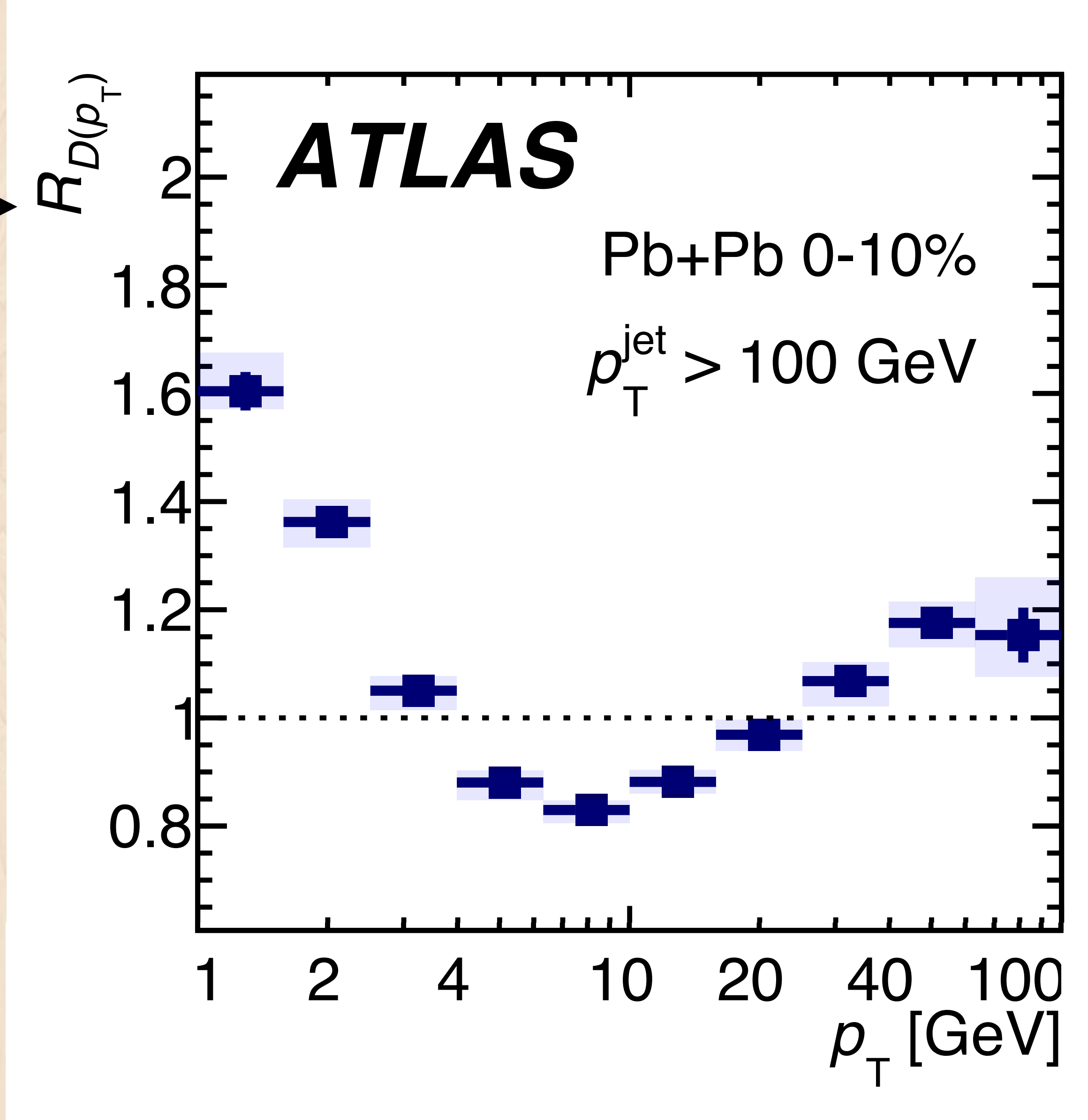
CMS Cross Sections



How are jets modified?

Ratio of track transverse momentum distribution inside jet cone between PbPb and pp reference

Relative suppression of moderate P_T tracks compared to low P_T



Grooming Profiles