Jet and photon physics

Marco Peruzzi
Institute for Particle Physics - ETH Zurich

on behalf of the ATLAS and CMS collaborations

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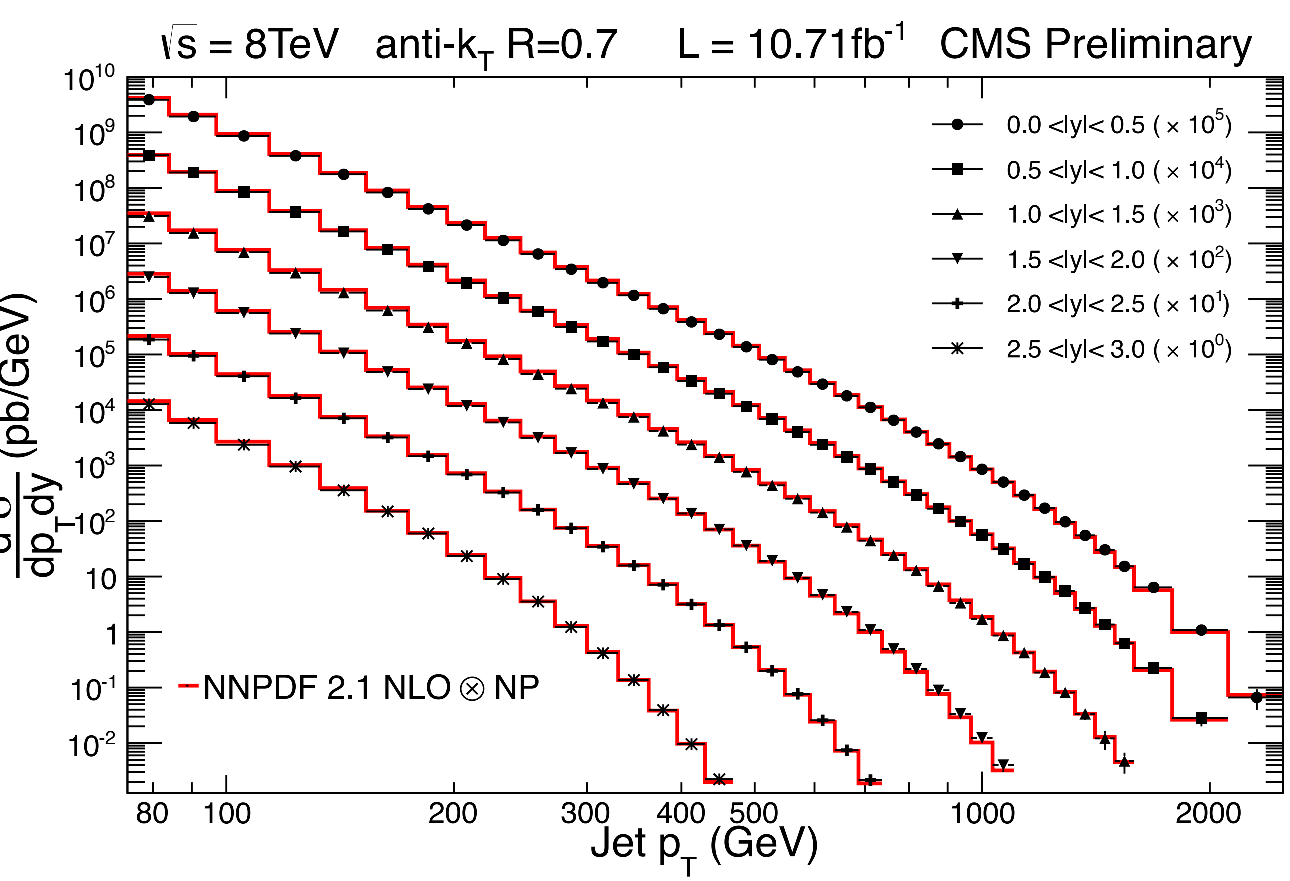
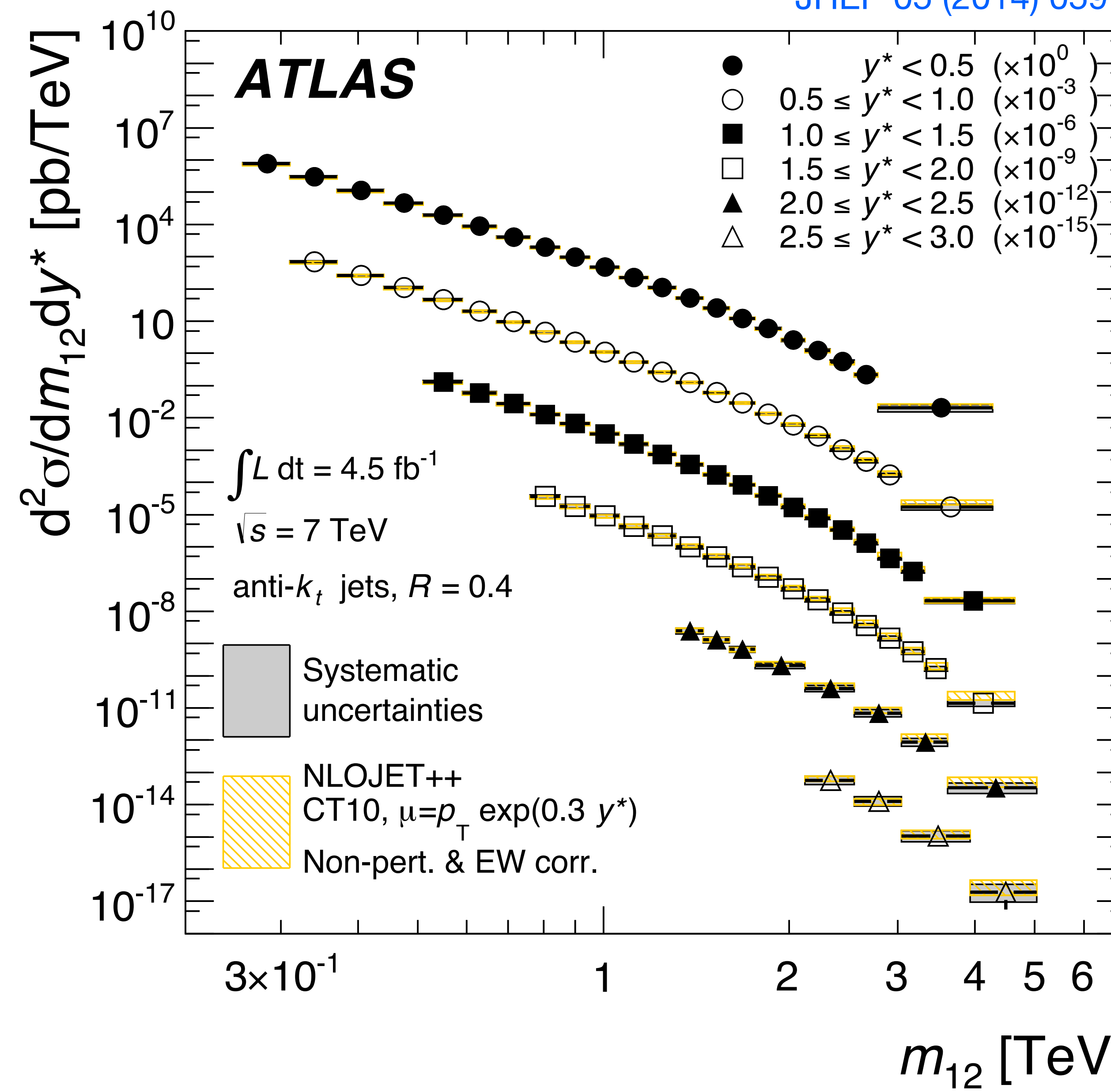
A great success!

- Differential jet cross section predicted over many orders of magnitude
  - NLO fixed-order calculation + NP and EW corrections



CMS-PAS-SMP-12-012

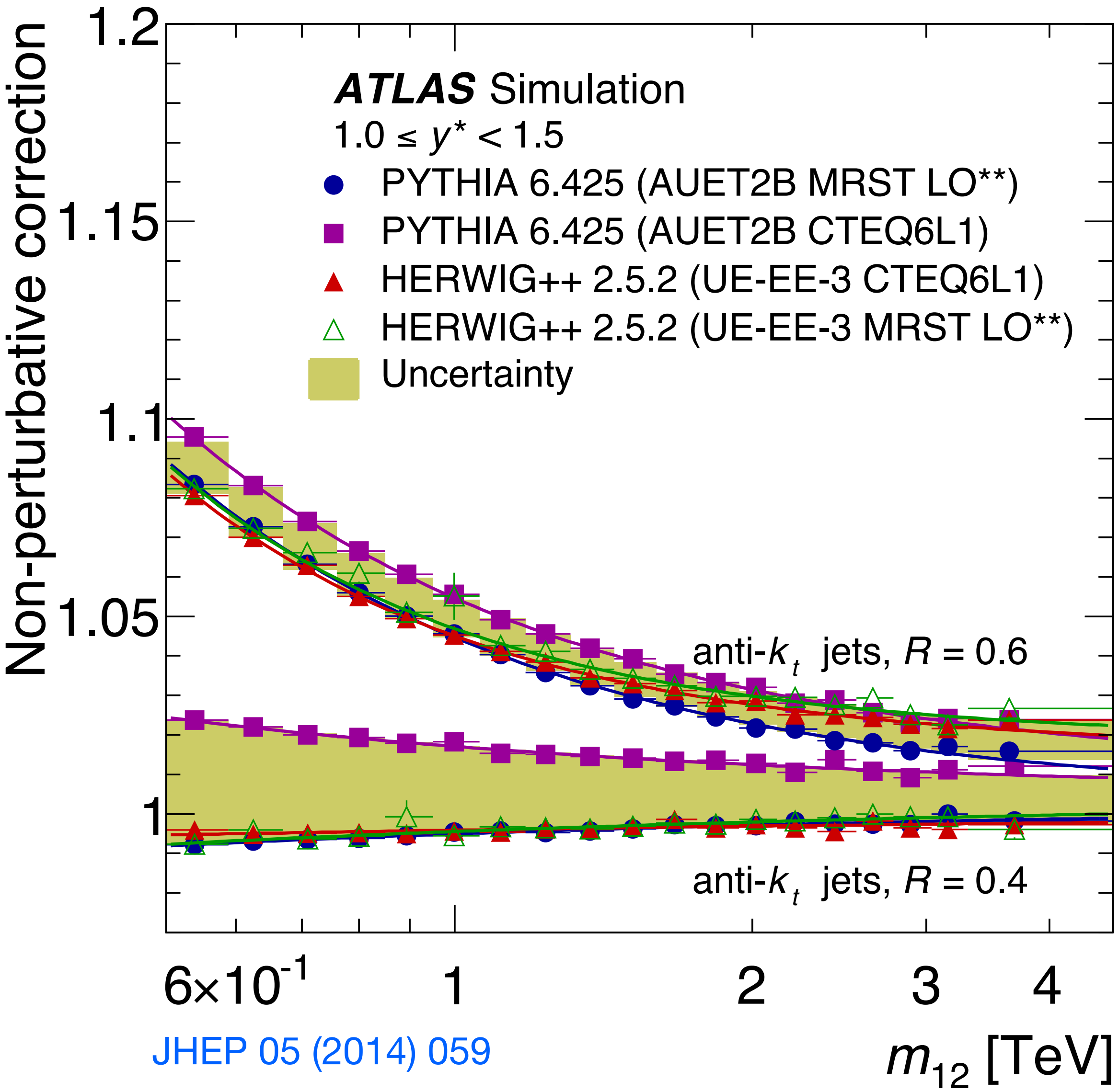
JHEP 05 (2014) 059



- Jet energy scale is the main experimental uncertainty (10-30% of the cross section)
- Theory: main uncertainties PDF / scale

Non-perturbative frontier

❖ Non-perturbative corrections: from fixed-order parton-level to particle-level predictions



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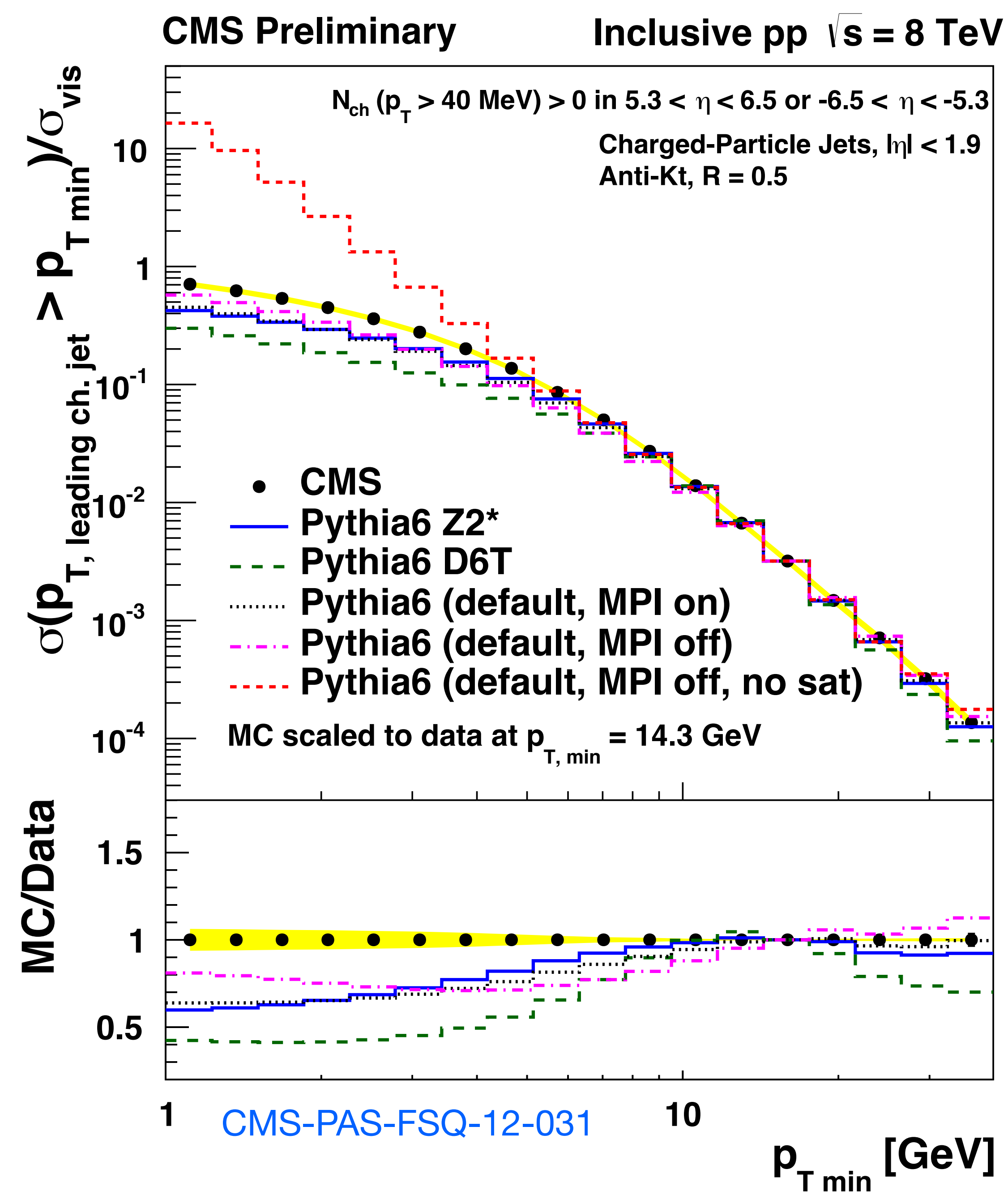
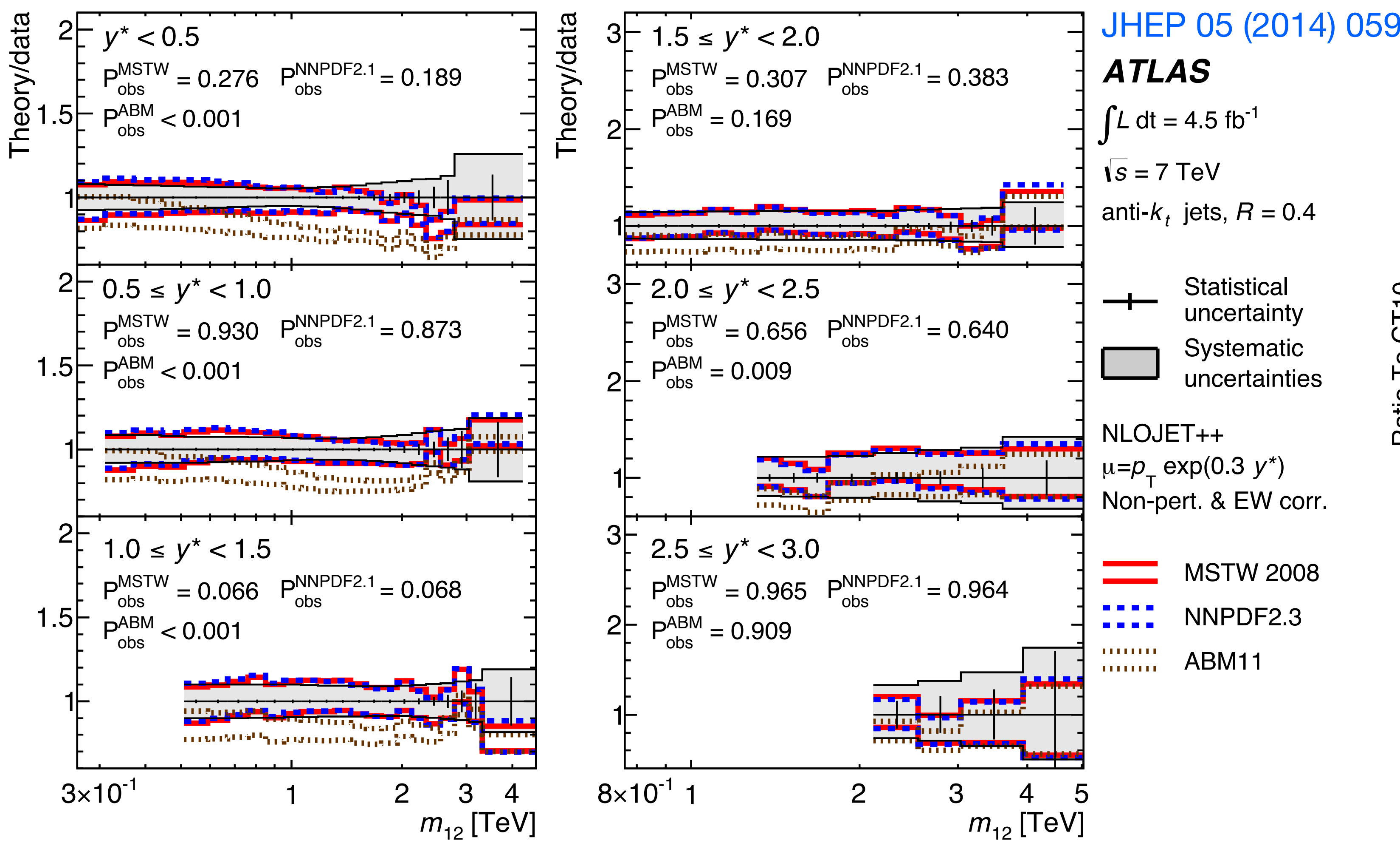
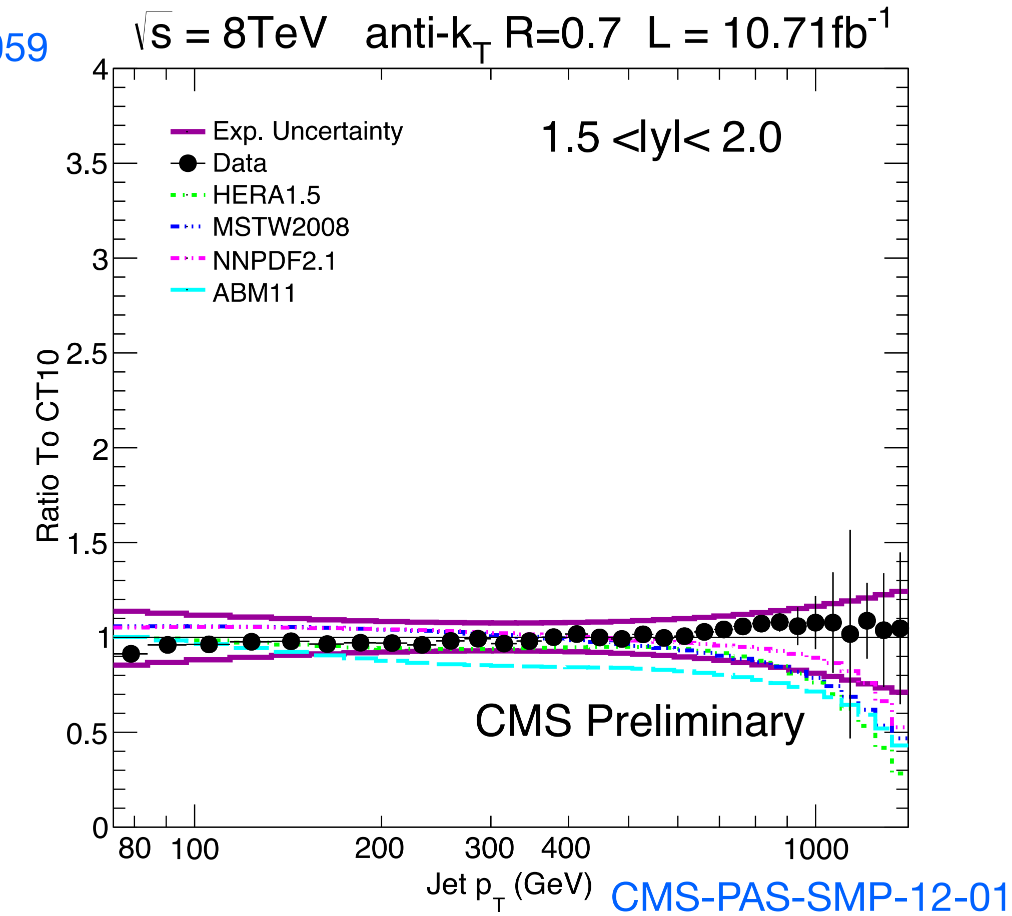


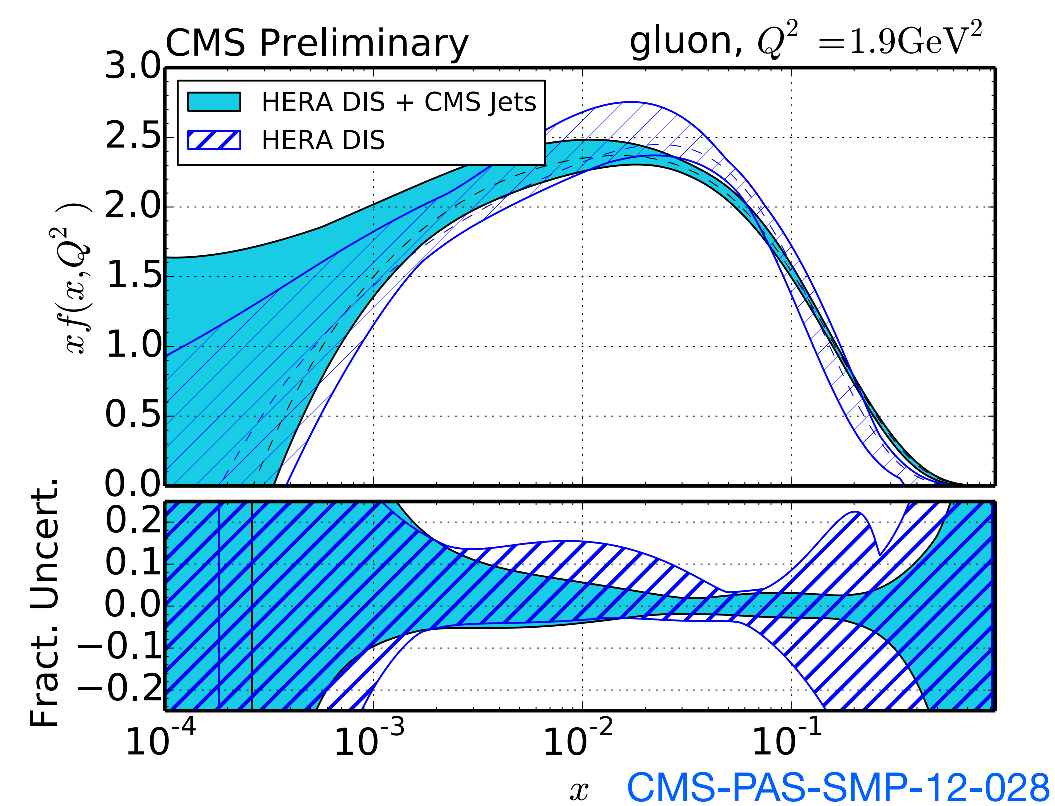
CMS-PAS-FSQ-12-031

❖ Low-p_T leading jet sensitive to UE, MPI model and saturation effects

PDF sensitivity

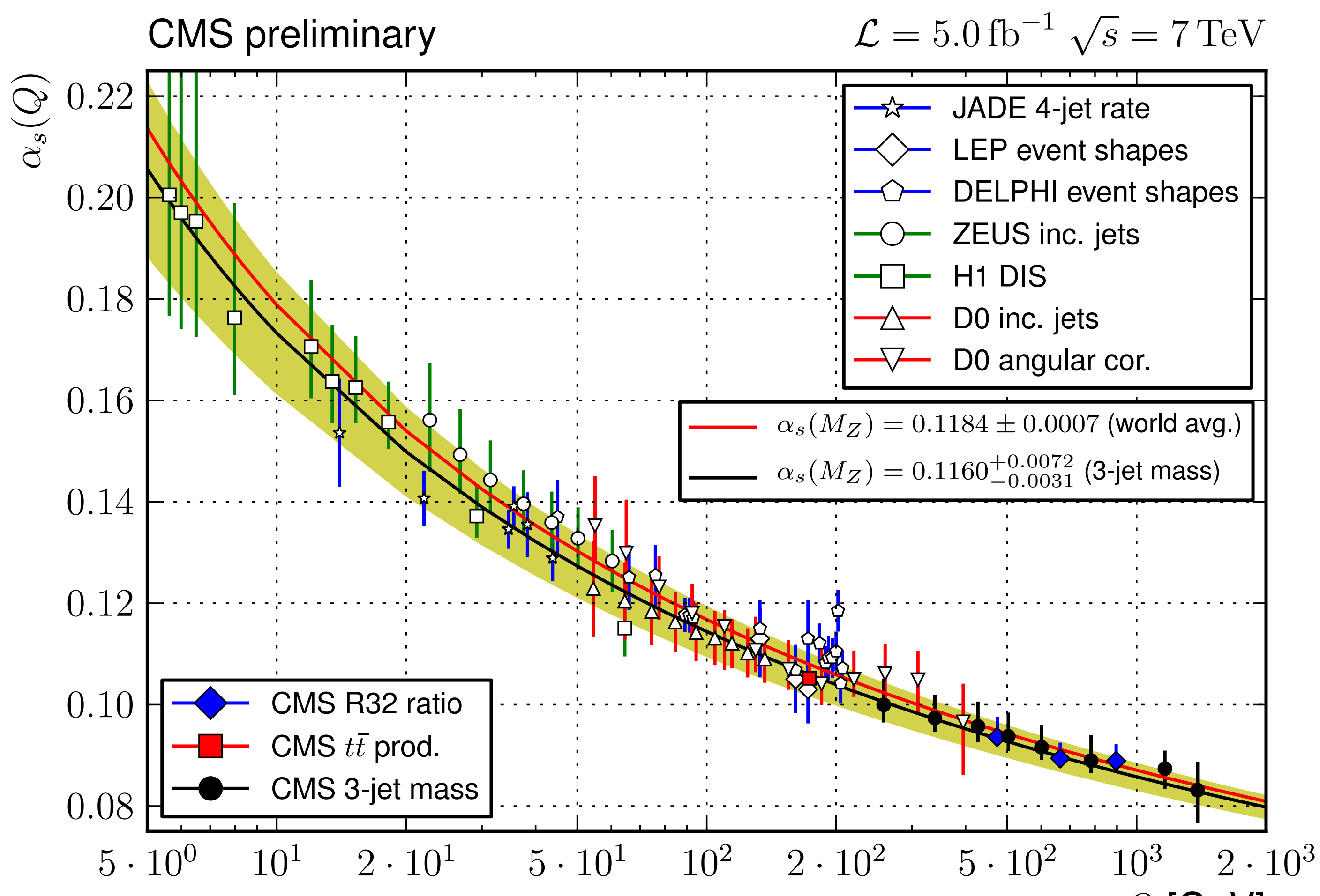




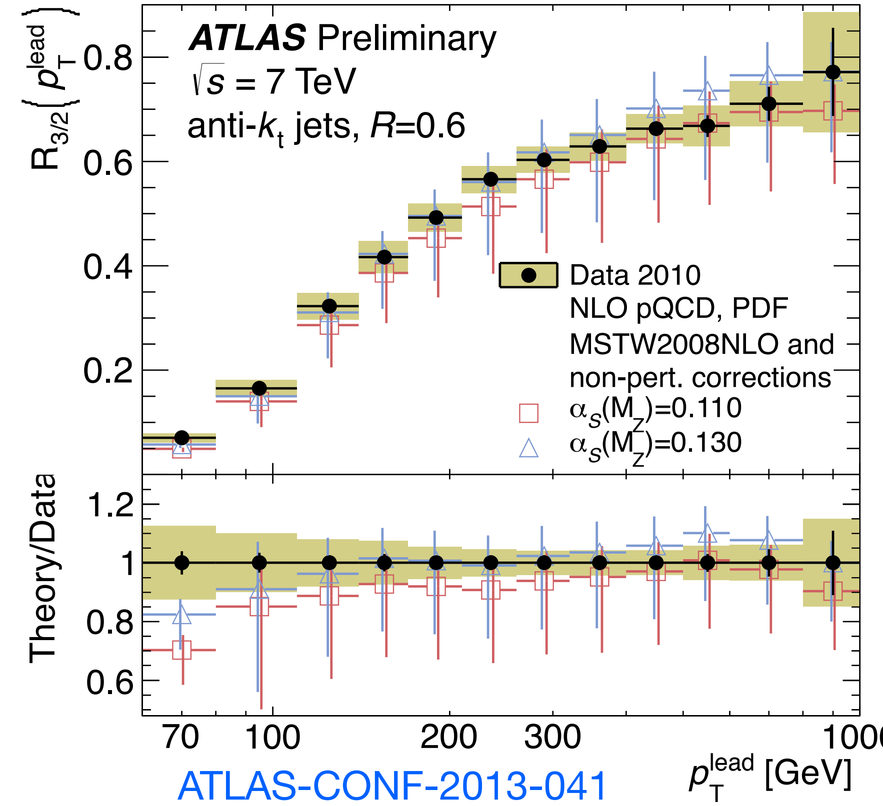


- High-p_T cross section sensitive to PDFs
- Probing gluon content at high *x*
  - uncertainties reduced including LHC data
  - data favour larger contribution

Strong coupling constant



CMS-PAS-SMP-12-027



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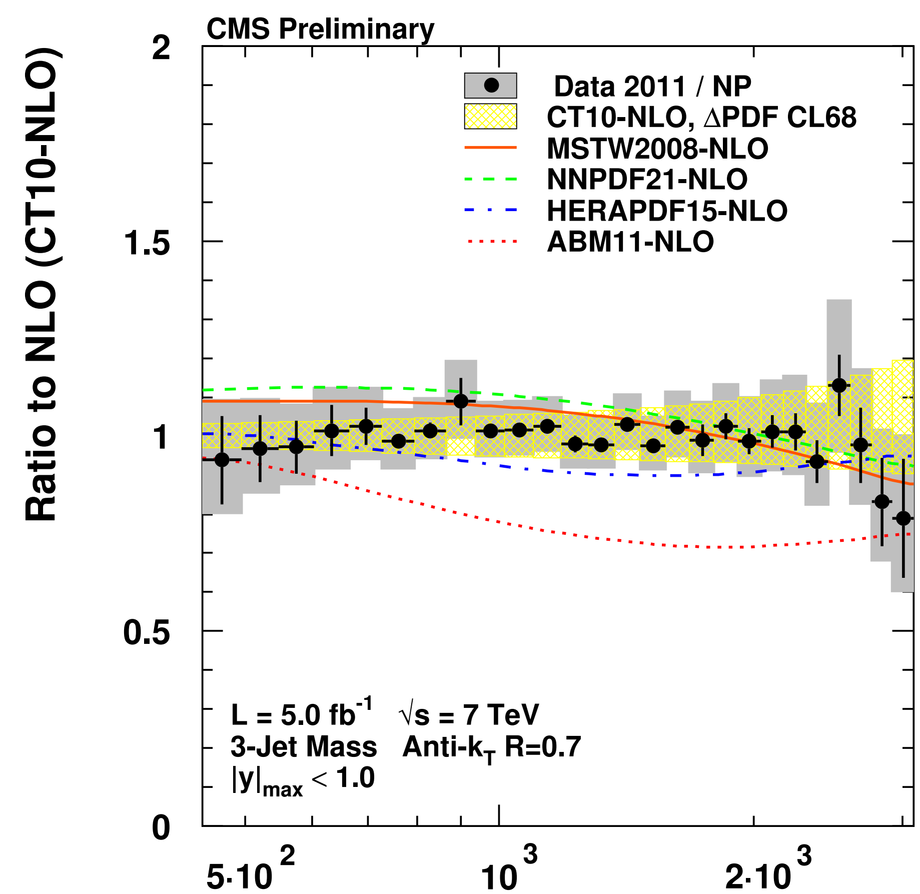
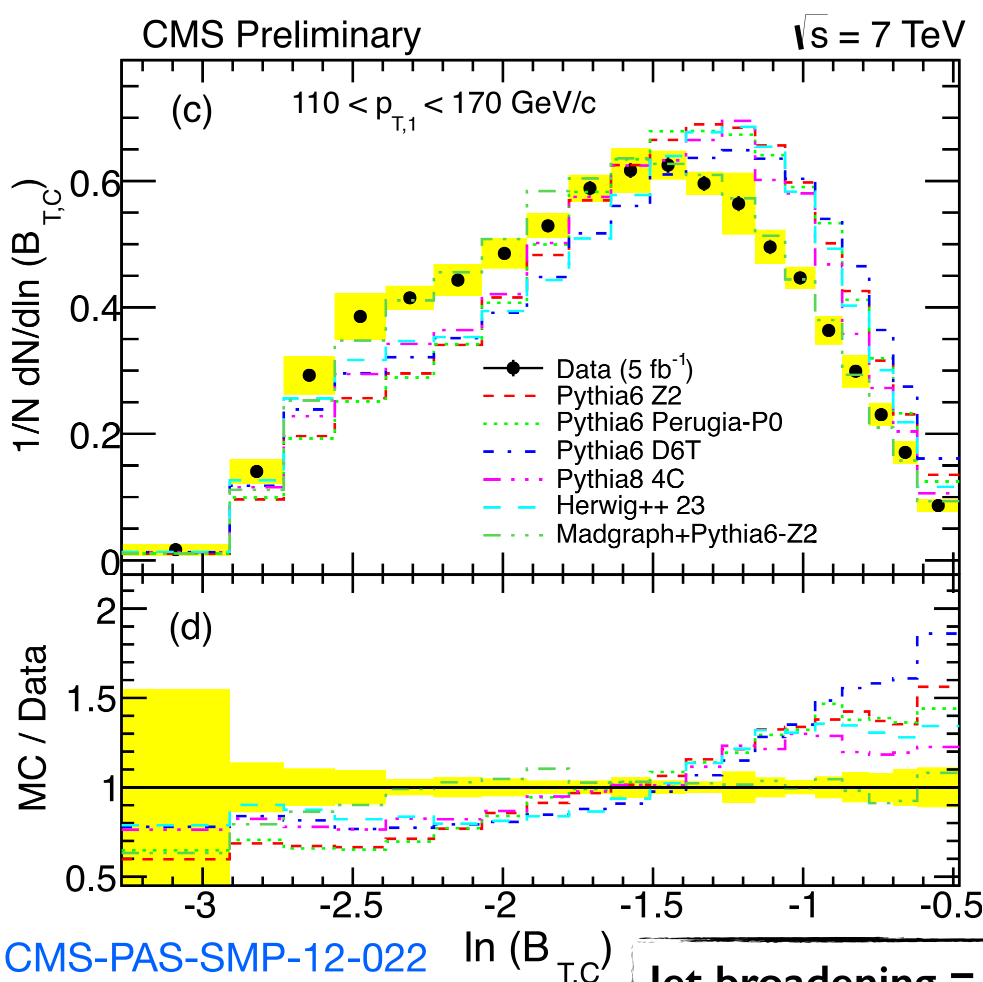


CMS-PAS-SMP-12-027

- $R_{3/2}$ and three-jet mass constrain α_S up to the TeV scale
- Energy scale dependence nicely in agreement with RGE evolution

Event shapes

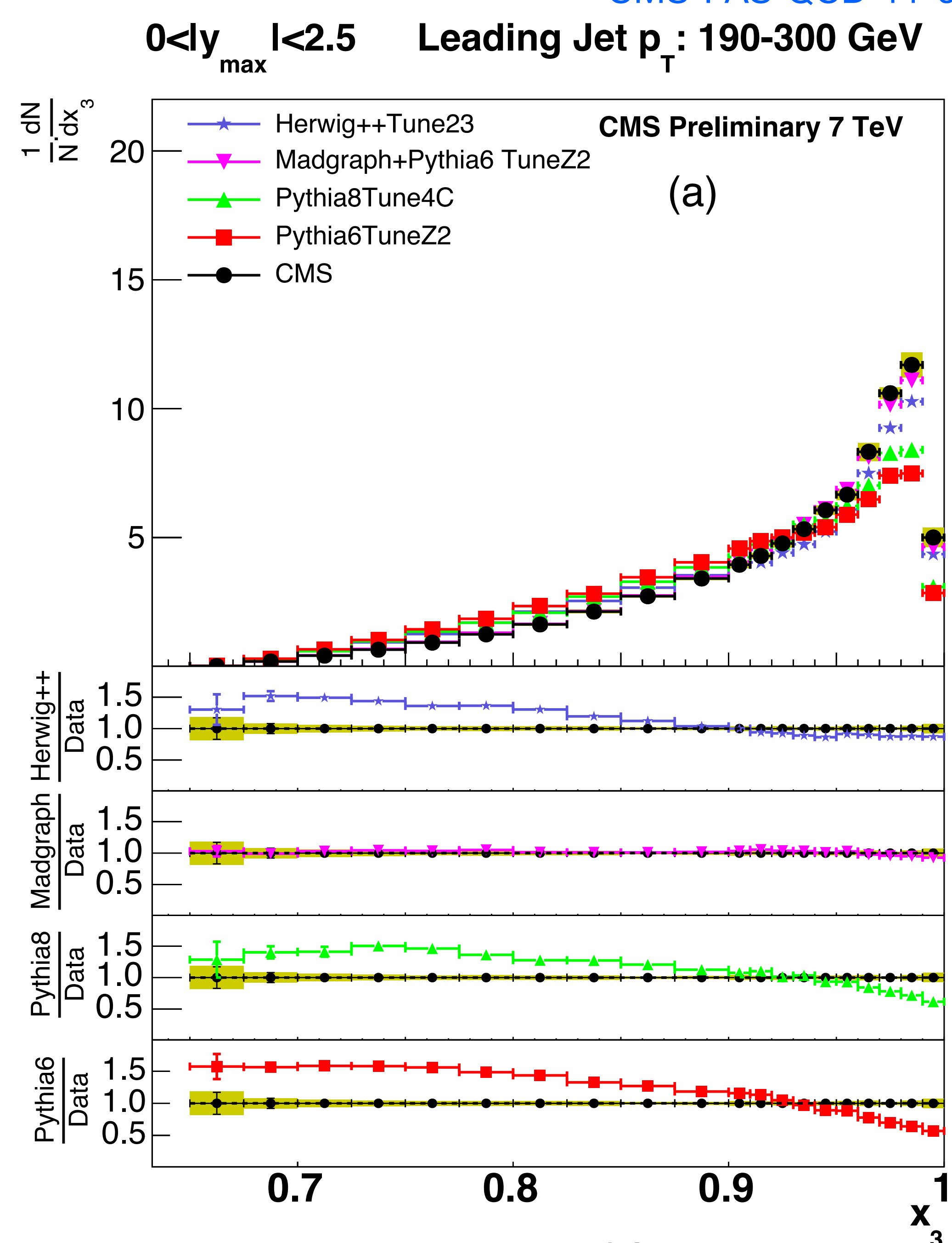
- Multi-jet events: more than a 2 -> 2 process!
- Topological variables sensitive to approximate treatment of higher-order effects
- Madgraph describes well event shapes (ME includes multi-parton final states)



CMS-PAS-SMP-12-022

Jet broadening = spread of jets around transverse thrust axis
Insensitive to hadronization

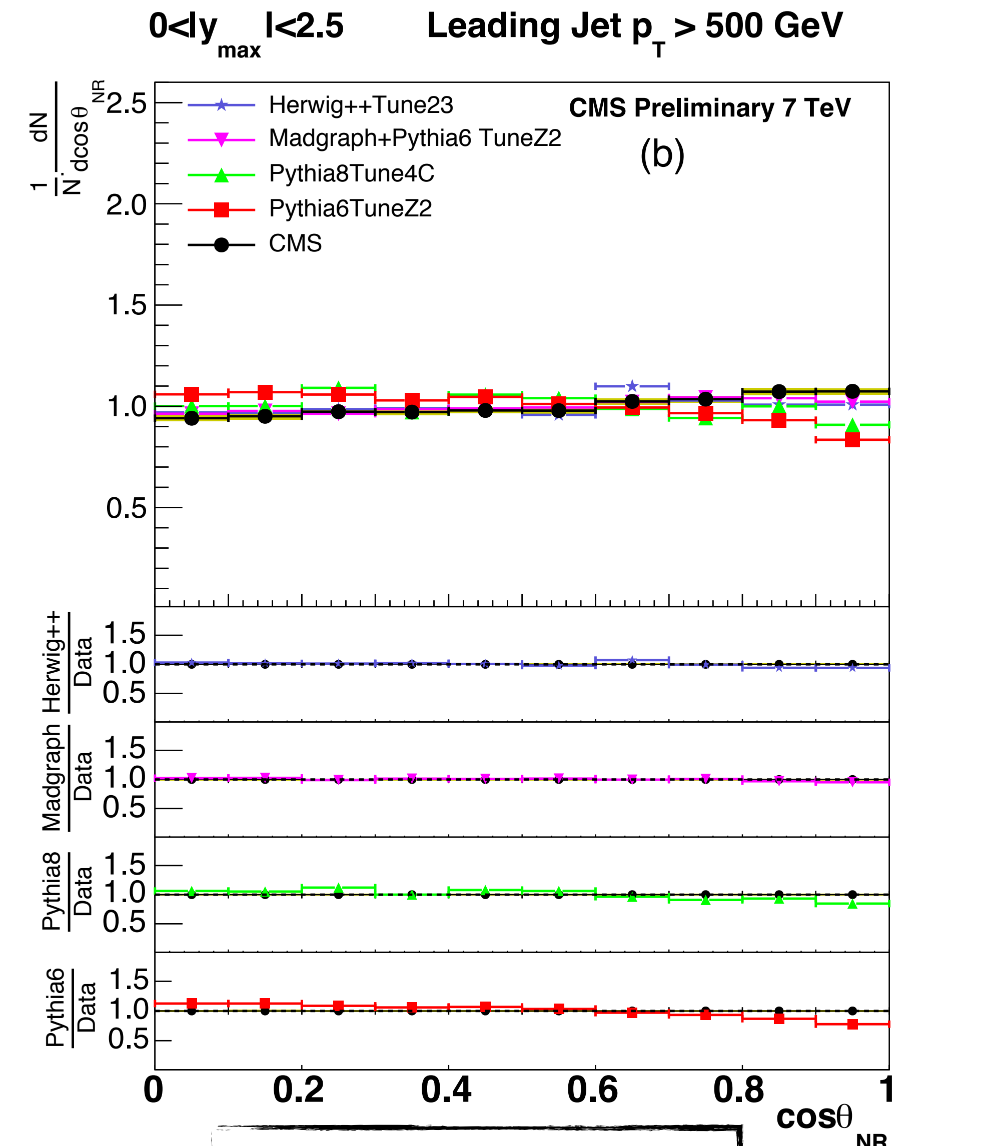
CMS-PAS-QCD-11-006



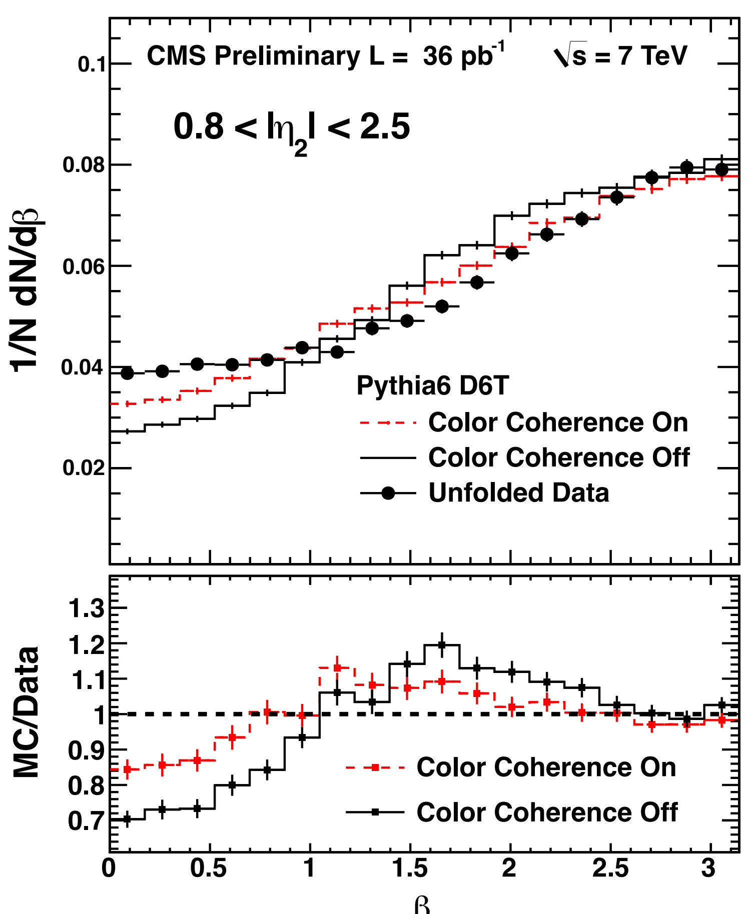
p_T of leading jet normalized to $\sqrt{\hat{s}}$

Event shapes

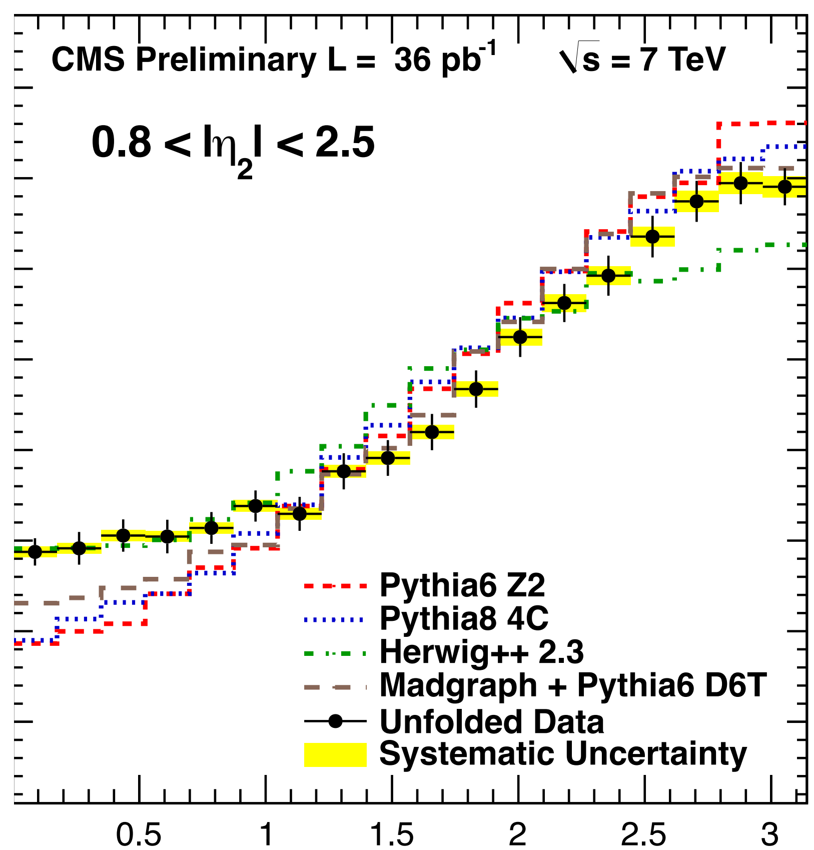
CMS-PAS-QCD-11-006



- Color coherence: soft radiation between color-connected final-state partons
  - third jet emitted close to di-jet event plane
  - data support larger effect than in MC



arXiv:1311.5815

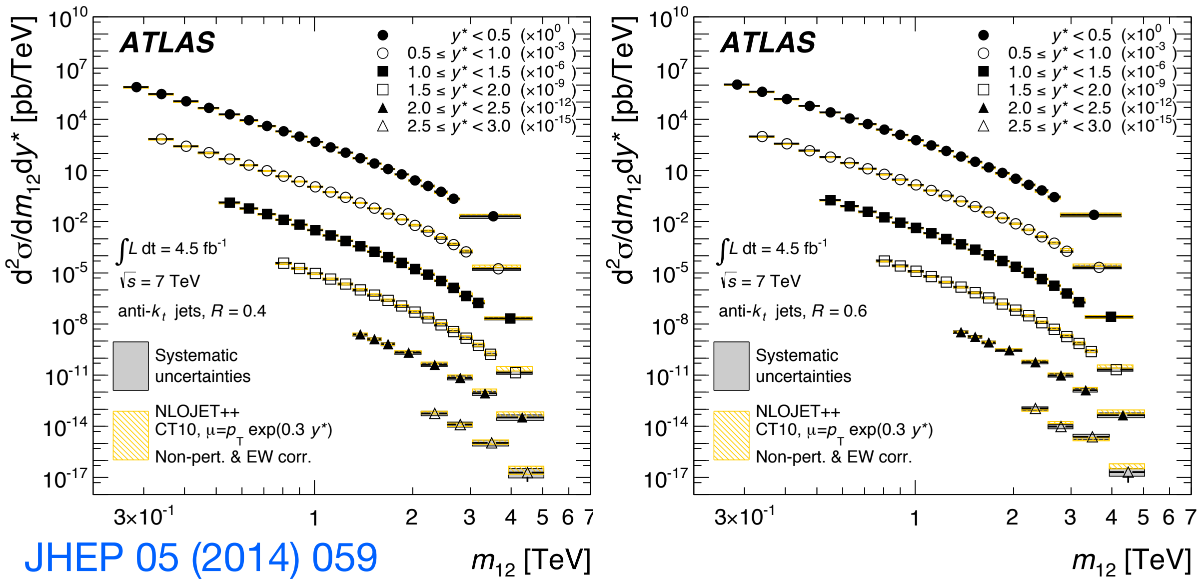


$\beta = \Delta\varphi / \Delta\eta$ between third and second jet

θ_{NR} = angle between $(p_1\text{-}p_2)$ and $(p_3\text{-}p_4)$

- Soft jets from parton splitting
- Angular distributions probe parton shower

Jet size



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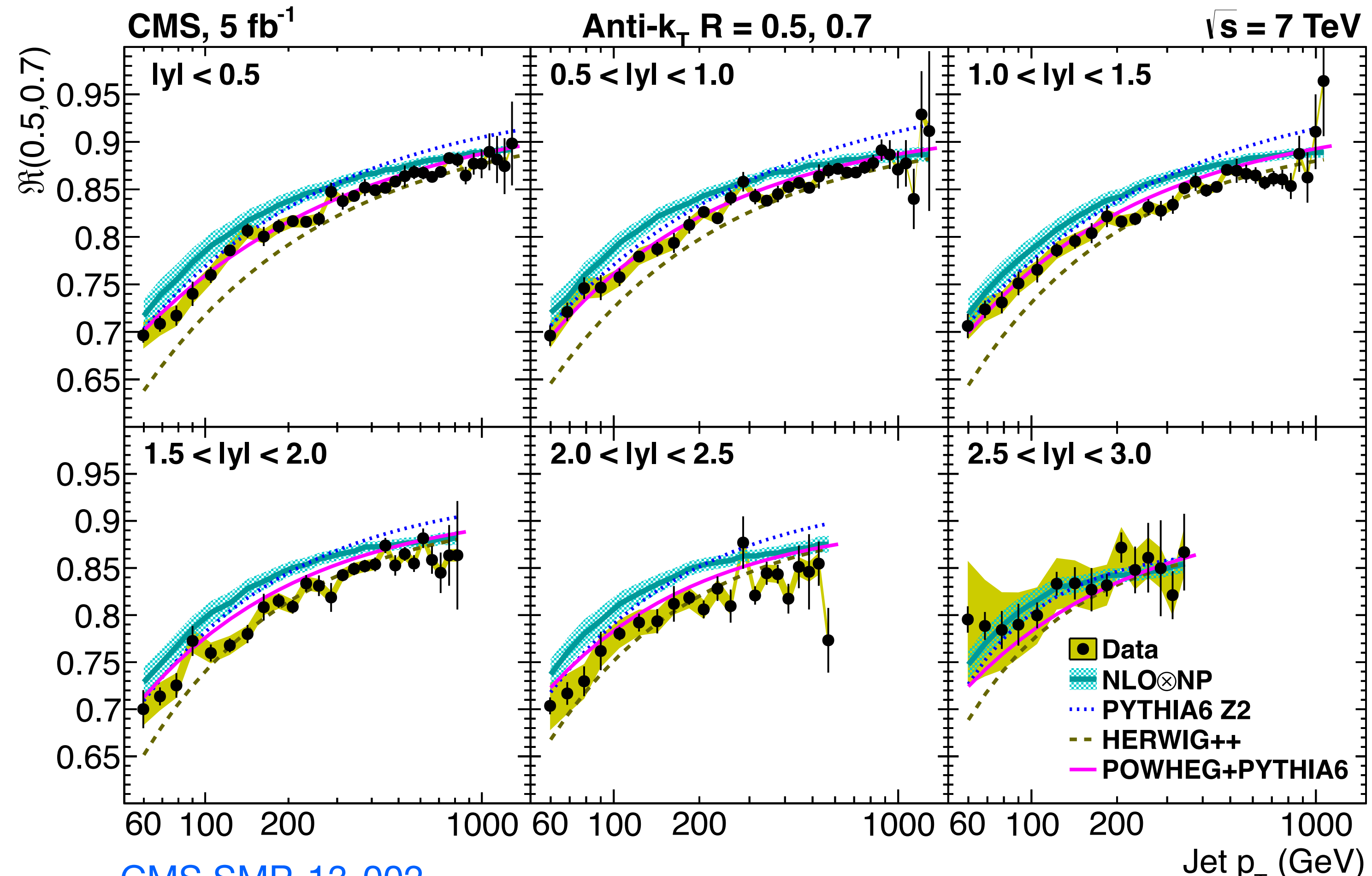
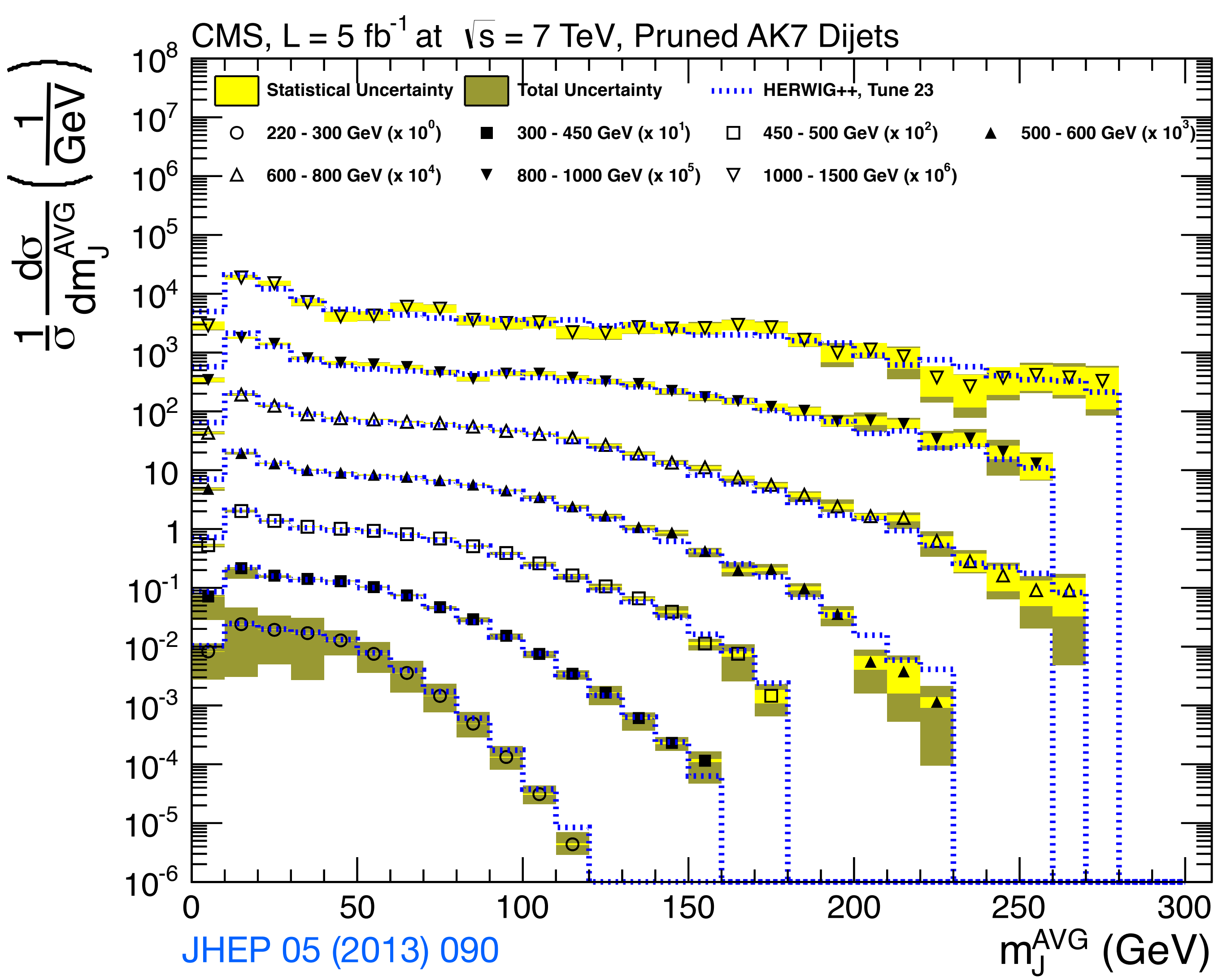


CMS SMP-13-002

- ❖ Jet measurements with different size parameters
- ❖ AK5/AK7 ratio sensitive to collinear radiation
  - ✦ PYTHIA does well in low-p_T region (NP effects)
  - ✦ HERWIG describes high-p_T substructure
- ❖ Jet size choice is a trade-off:
  - ✦ collinear radiation losses
  - ✦ non-perturbative effects
  - ✦ pileup and UE energy

Pileup effect on jets

- Pileup energy contribution to jets subtracted using jet area methods
- Intense research activity on substructure quantities: e.g. mass



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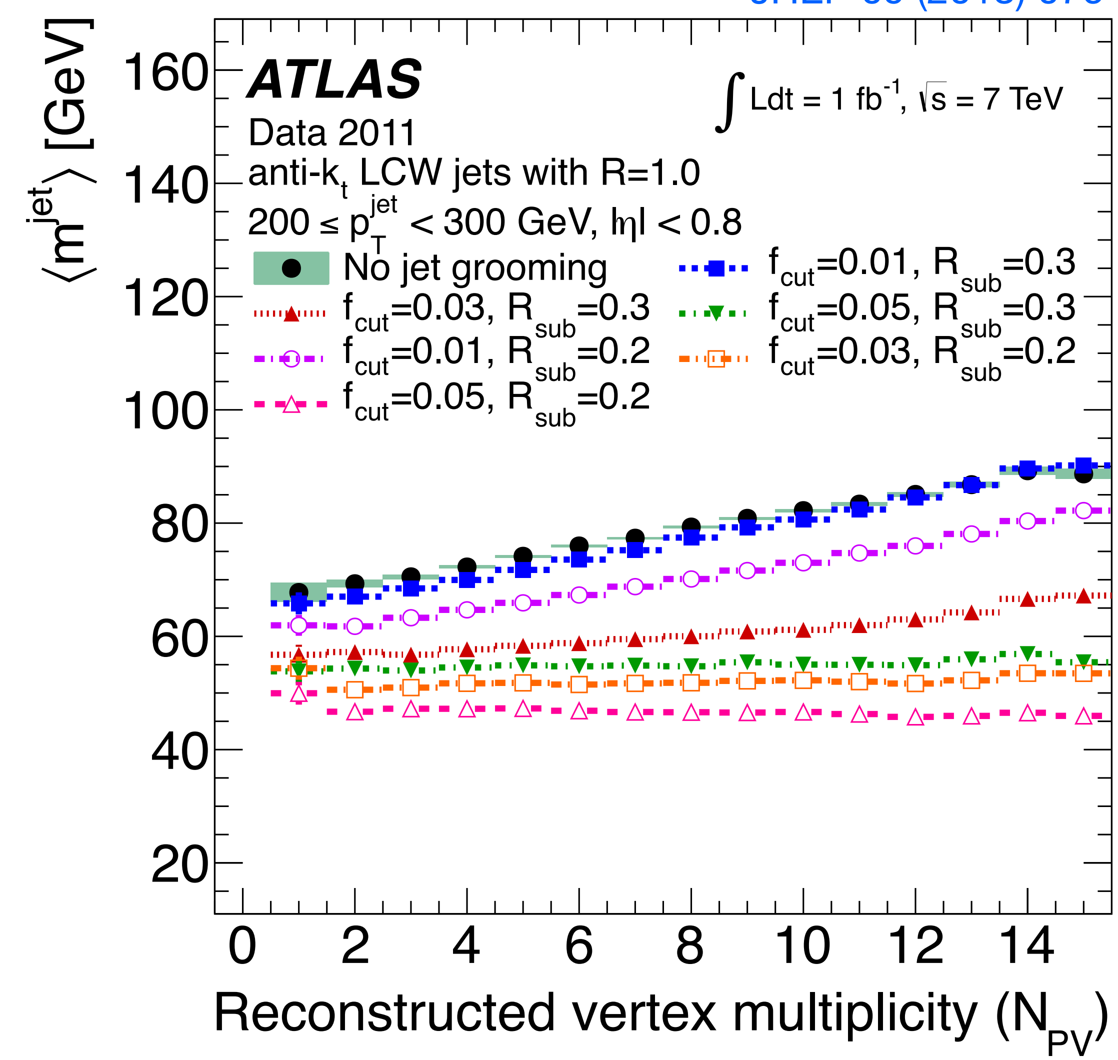
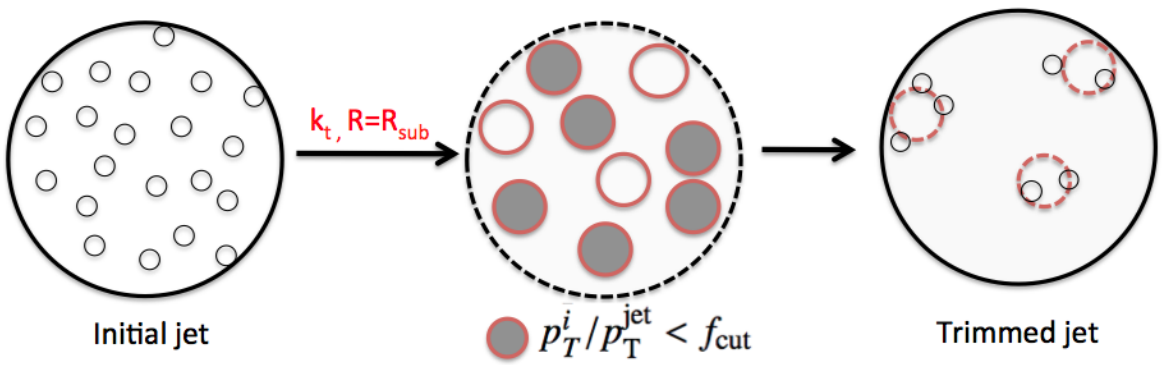


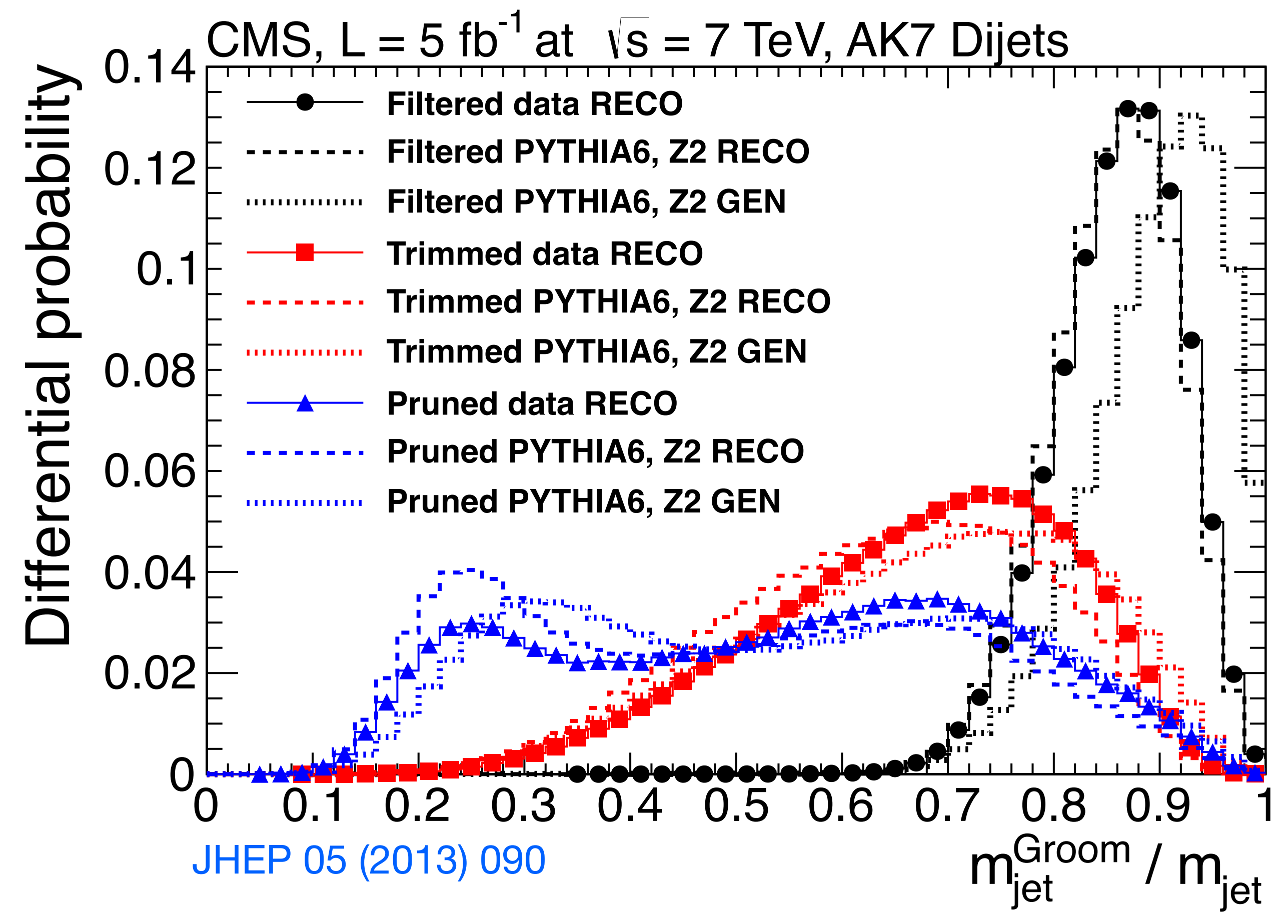
- Solution: apply cleaning on jet constituents
- Pileup dependency strongly reduced

Jet grooming techniques

- Filtering:
  - keep only the 3 leading sub-jets

- Trimming:
  - remove soft sub-jets

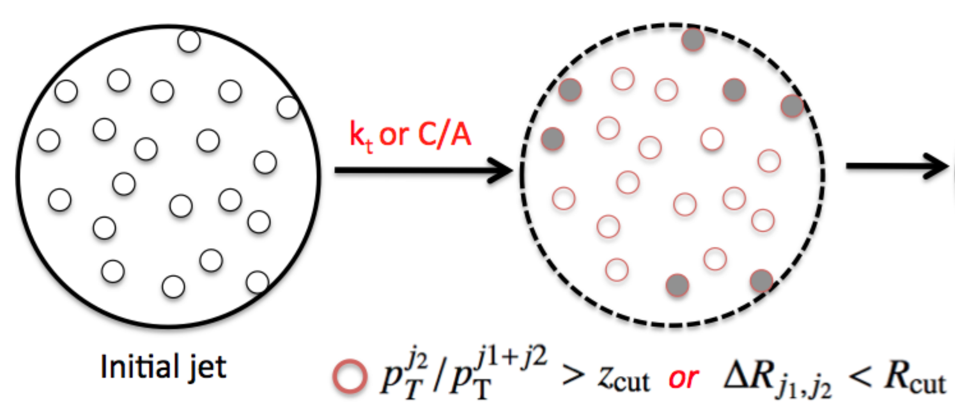




JHEP 05 (2013) 090

- Separation of hard-core jets from symmetric gluon splittings

- Pruning:
  - reject soft and wide-angle radiation at each clustering step



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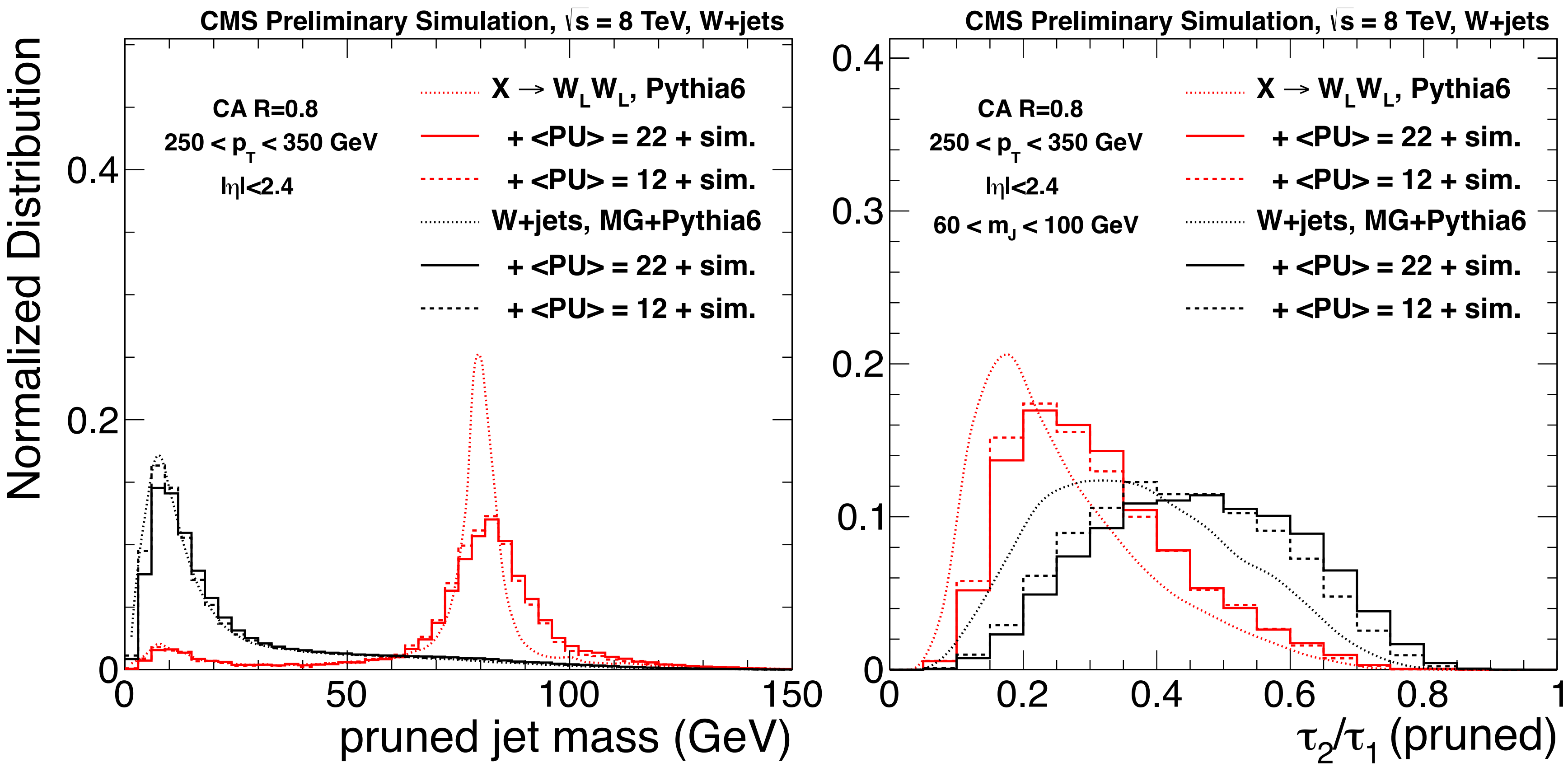
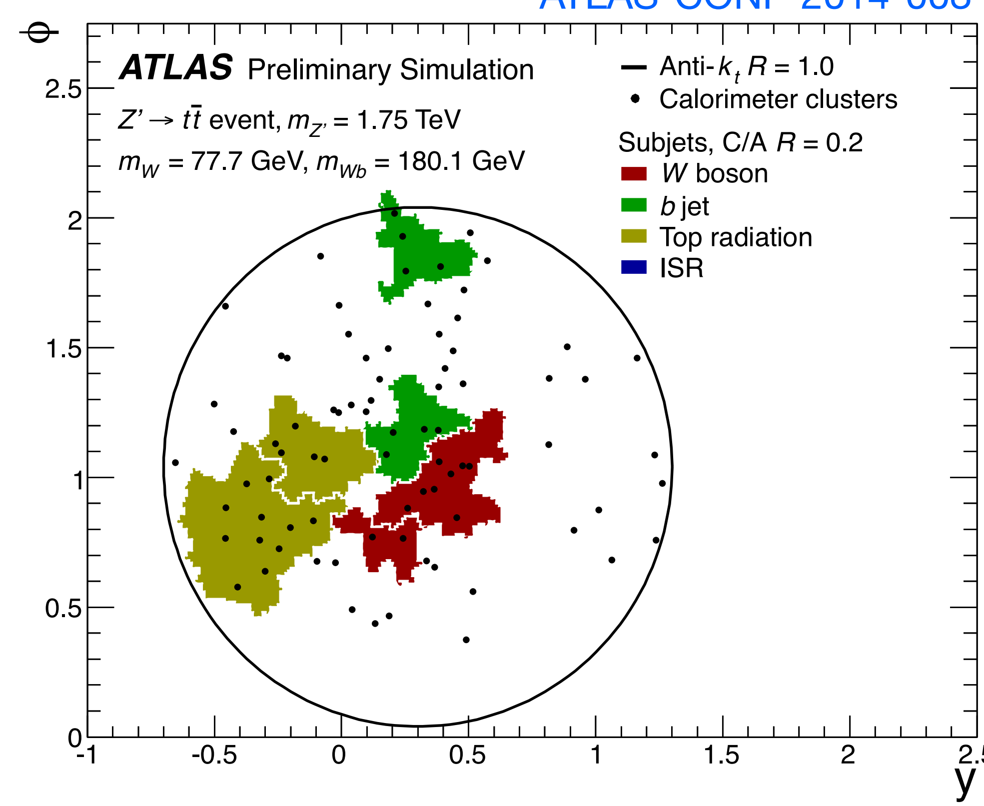
Tagging boosted decays



CMS-PAS-JME-13-006

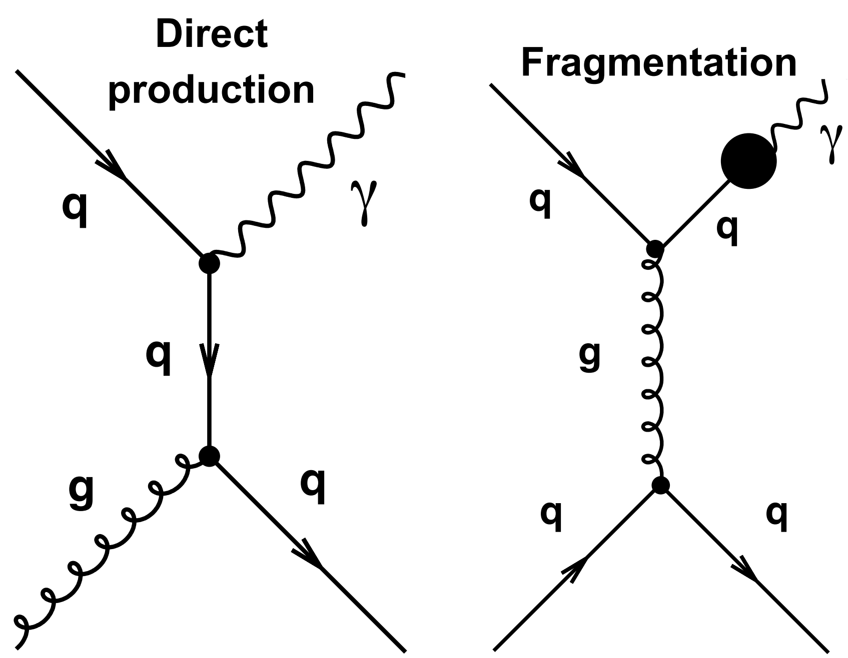
- Pruned mass used for tagging boosted W/top
  - more sub-jet and clustering-history variables improve discrimination

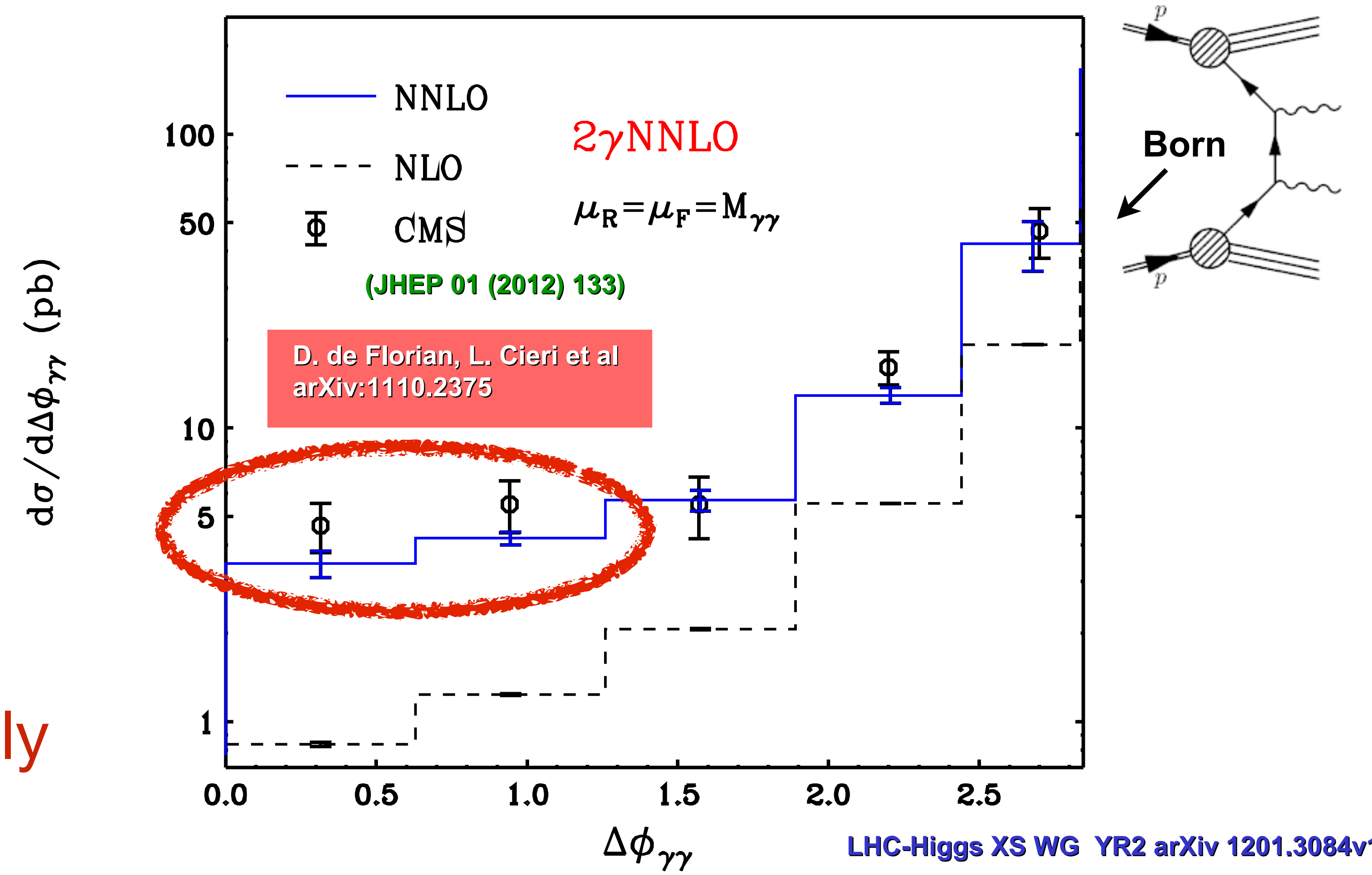
ATLAS-CONF-2014-003



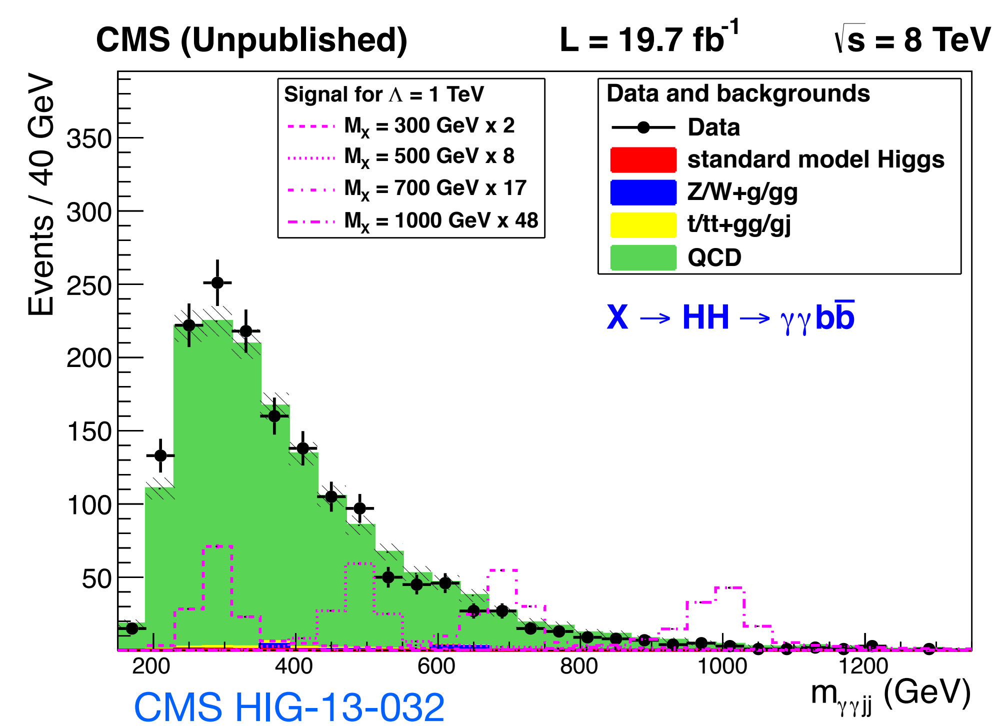
- Shower deconstruction method
  - probability-weighting shower histories compatible with reconstructed sub-jets

Photon production

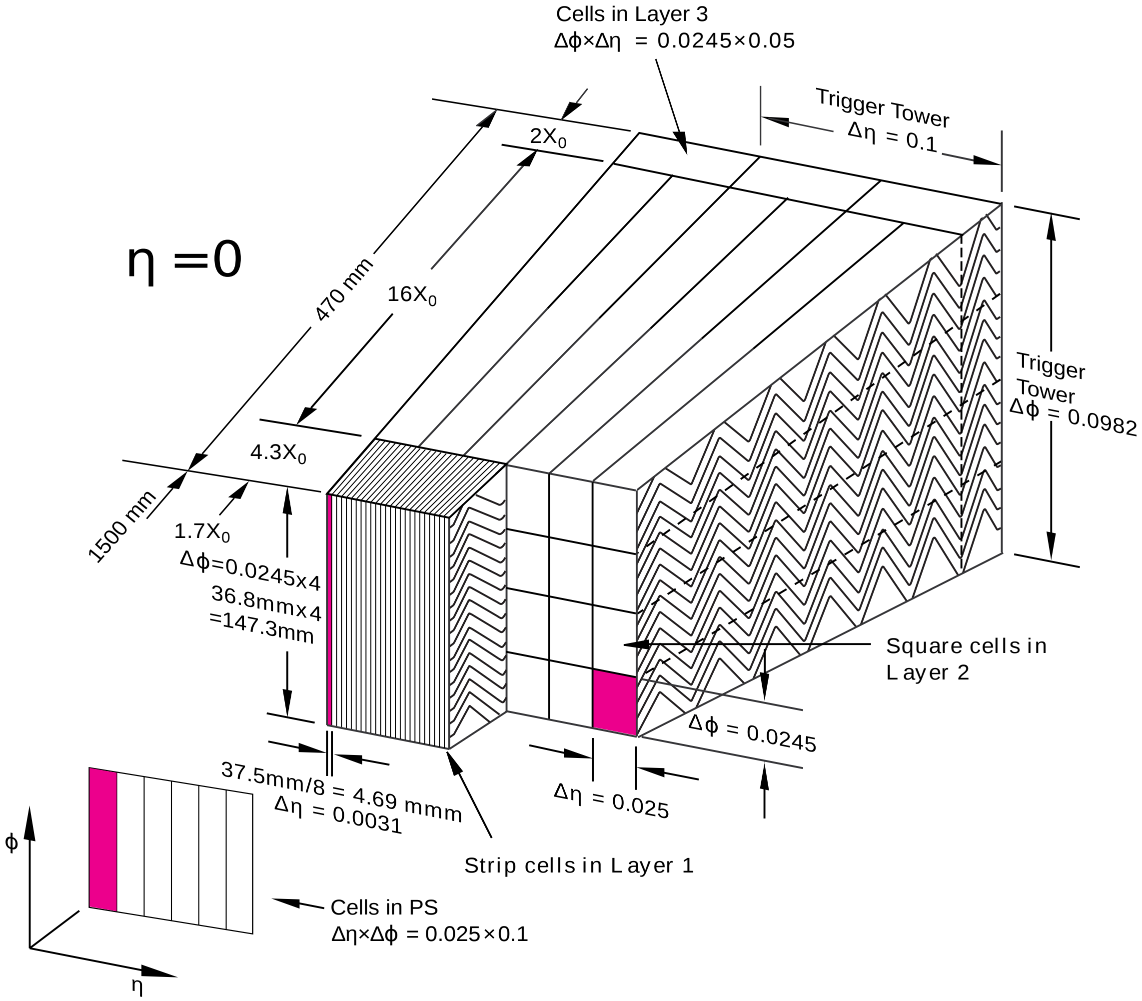


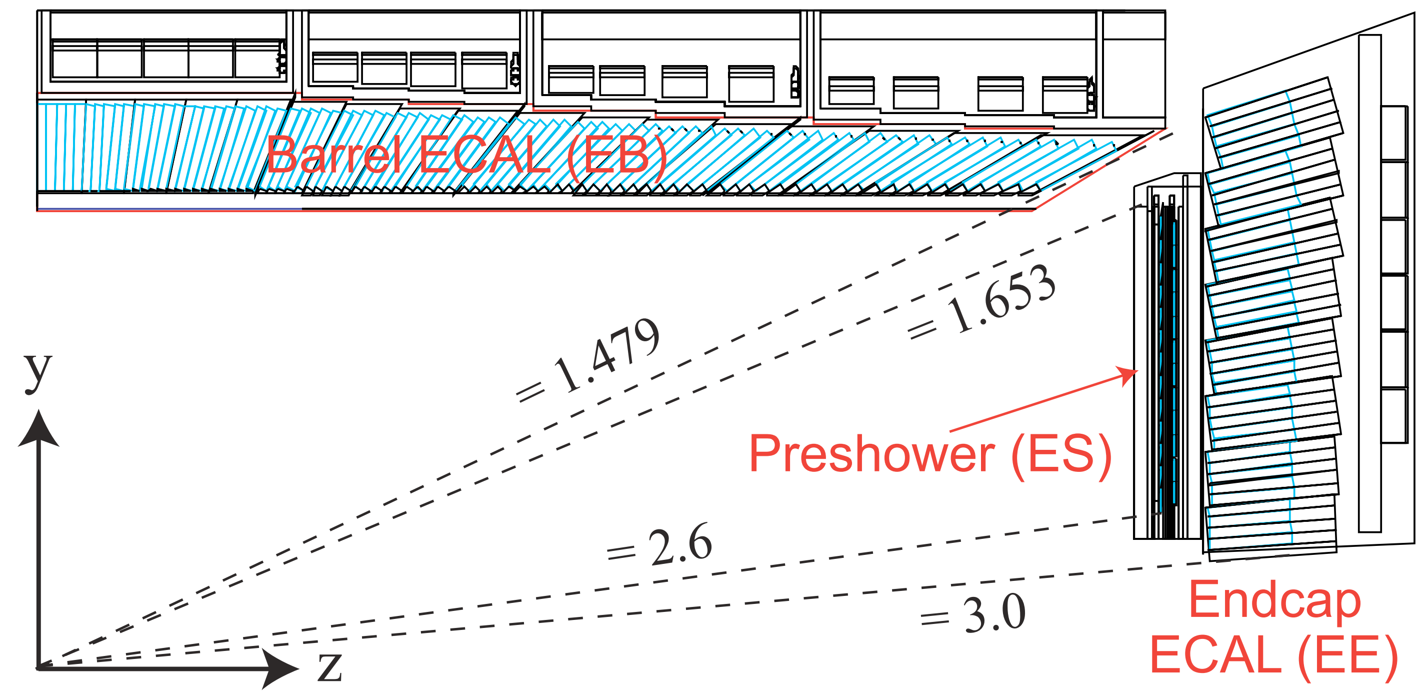


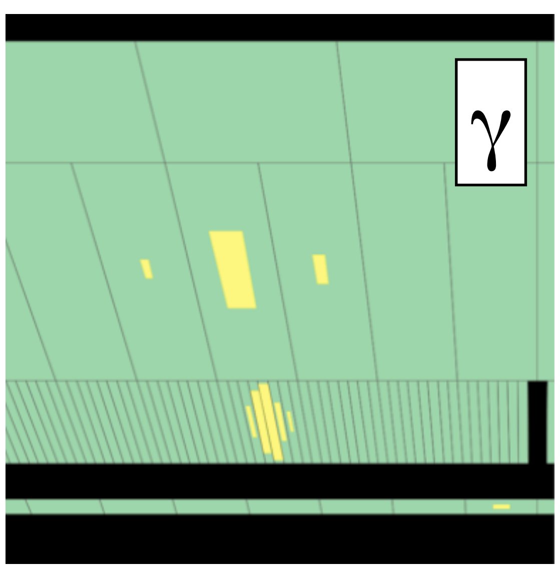
- Photon production tests directly the hard scattering in pQCD
- qg channel dominates at the LHC
- Parton fragmentation to photon contributes in some regions
- Strong sensitivity to NNLO phenomenology from diphoton differential cross section
- Background in searches for new physics

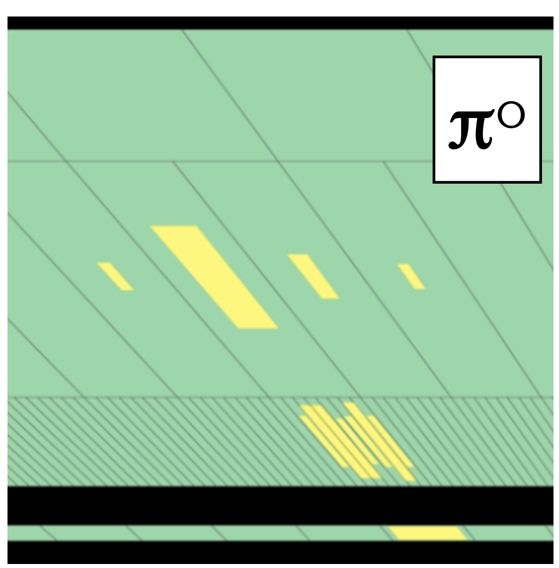


Photon reconstruction



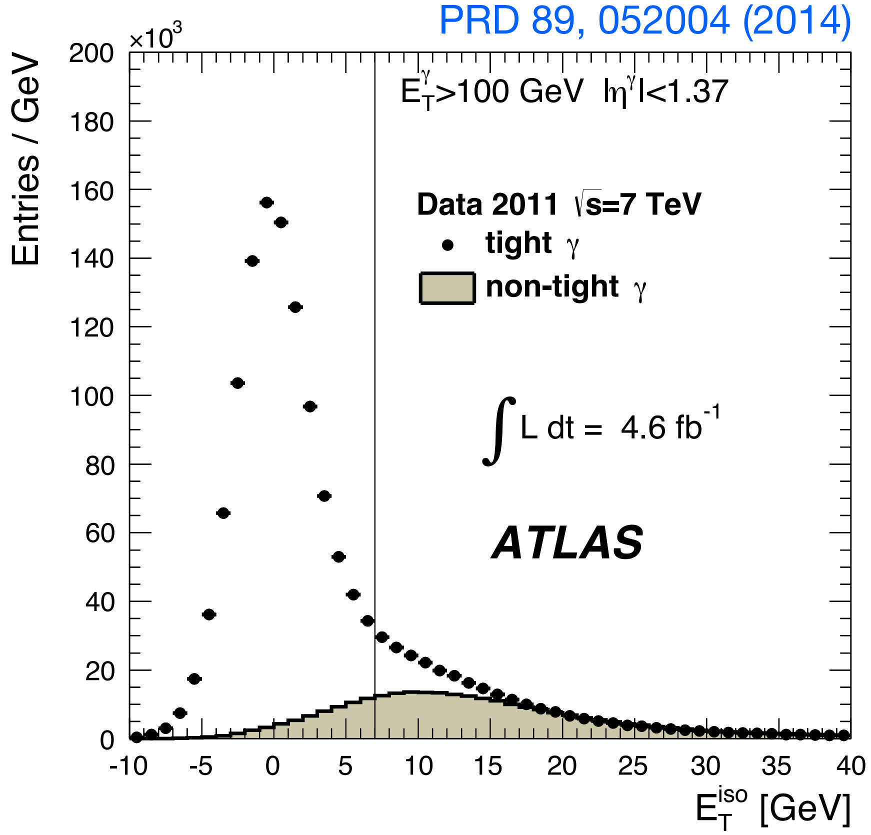


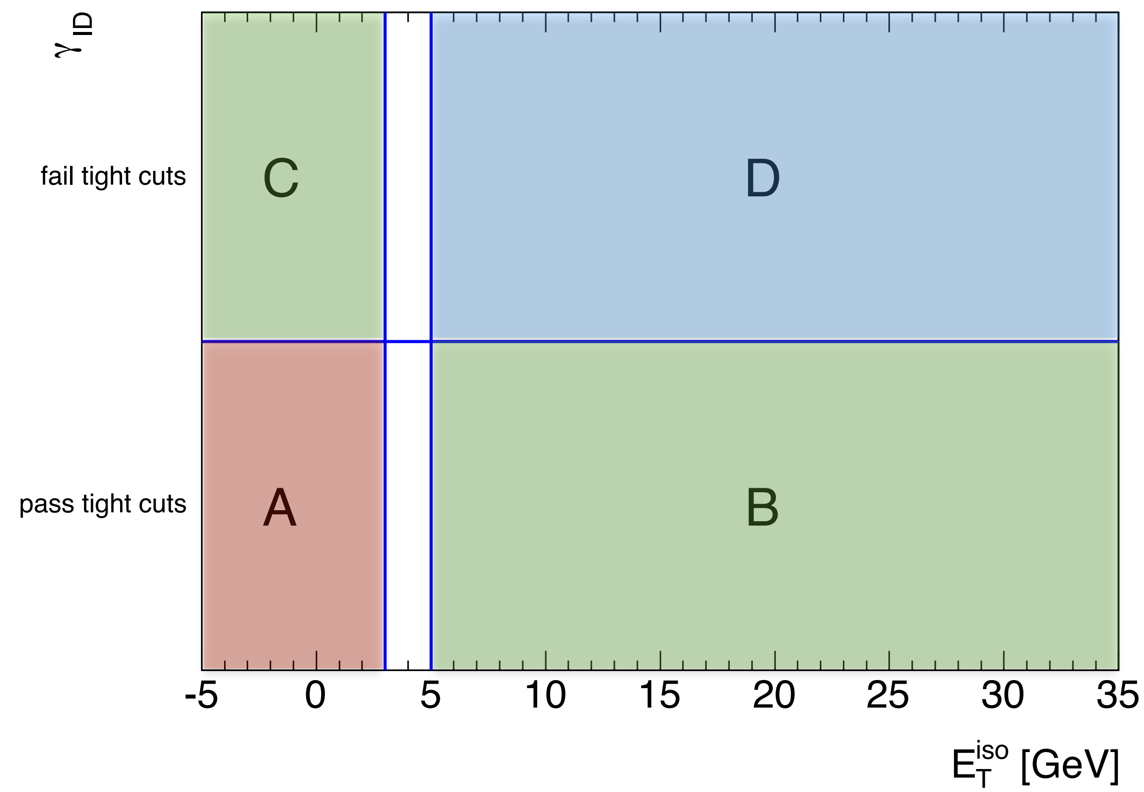


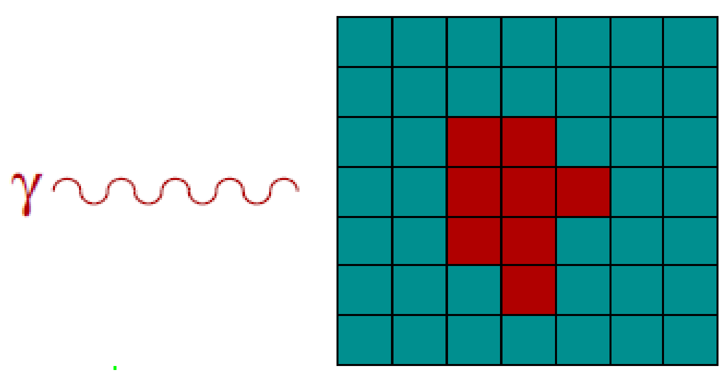


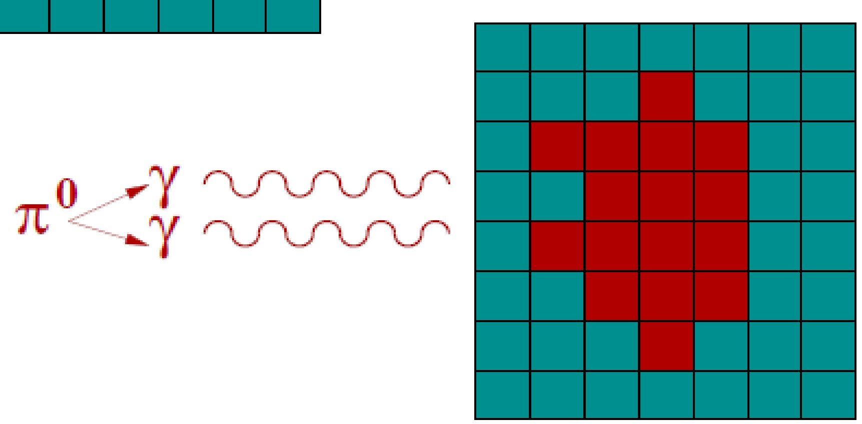
- Electromagnetic shower
- High-granularity calorimeter cells clustered to reconstruct energy deposit
- Background from boosted neutral mesons collimated diphoton decays, reconstructed as single photon

Background subtraction



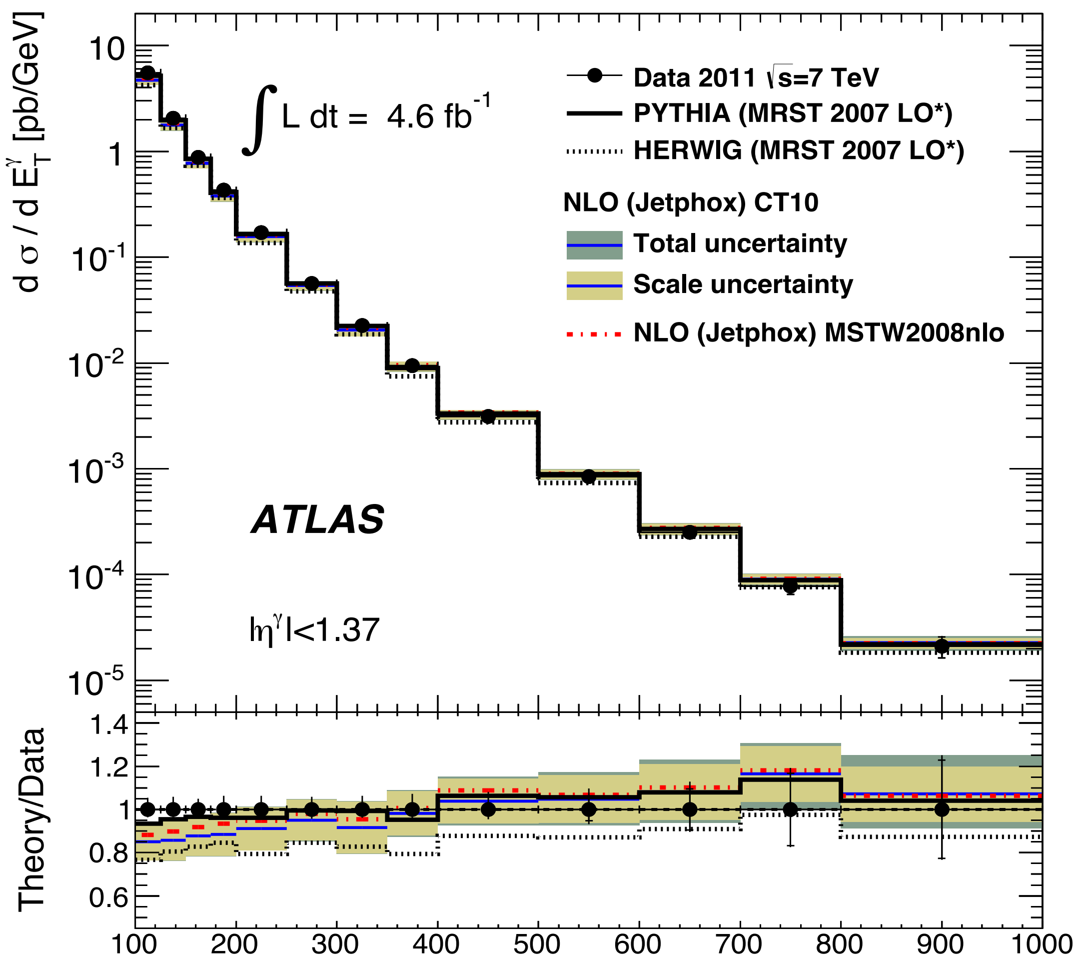




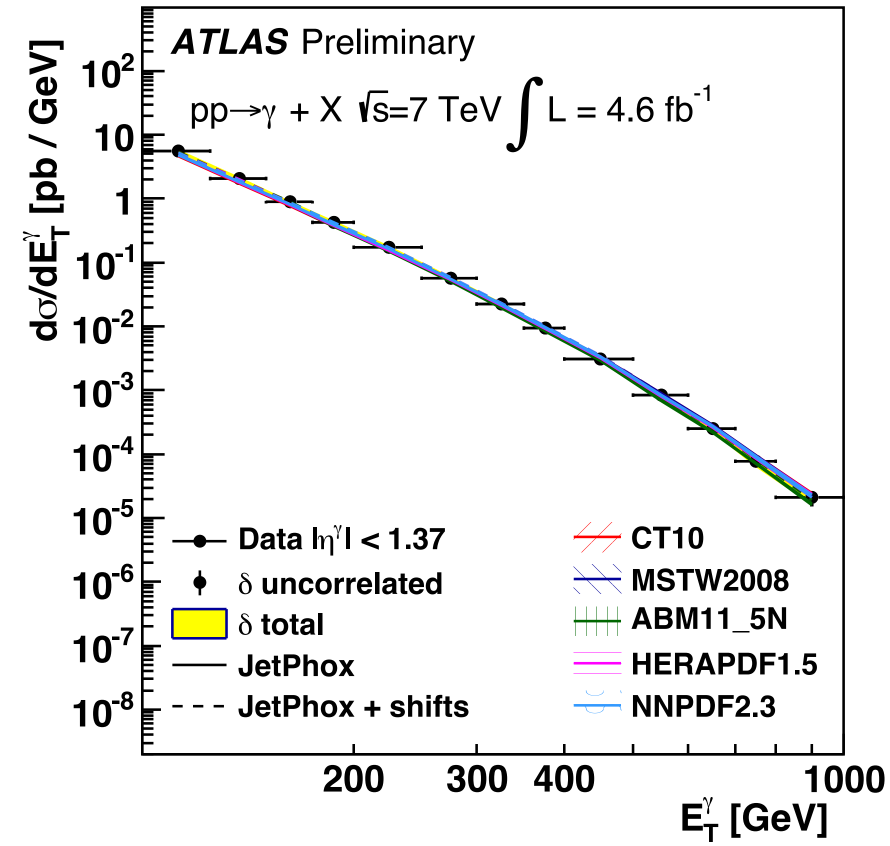


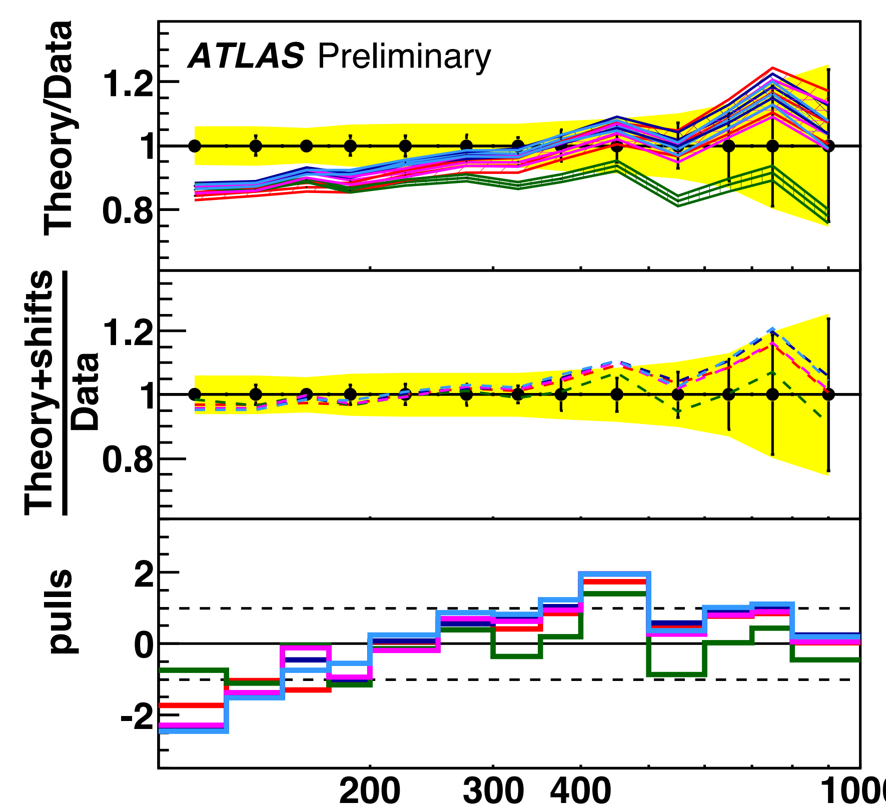
- Key concepts:
  - **shape of em shower**
  - **isolation energy**
- Variables de-correlated
  ➠ **sideband methods**
- Background subtracted on statistical basis

PDF sensitivity



PRD 89, 052004 (2014)

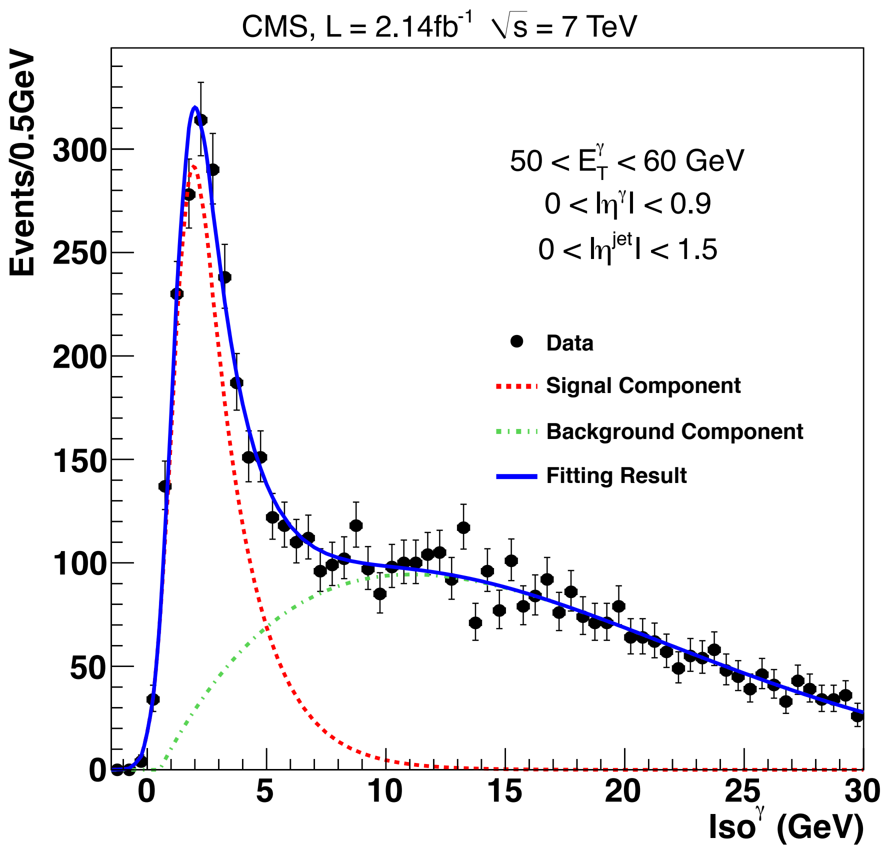


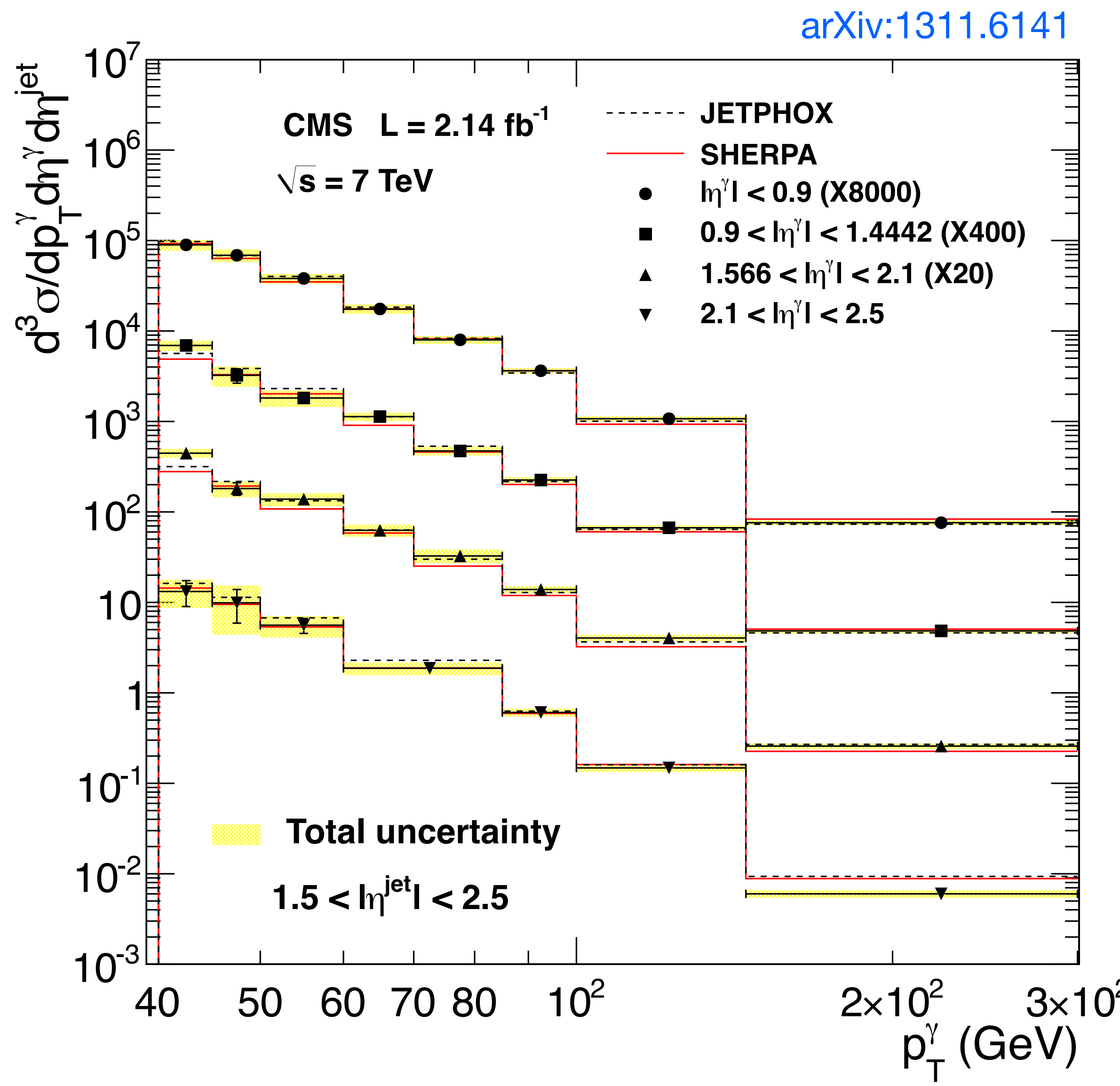


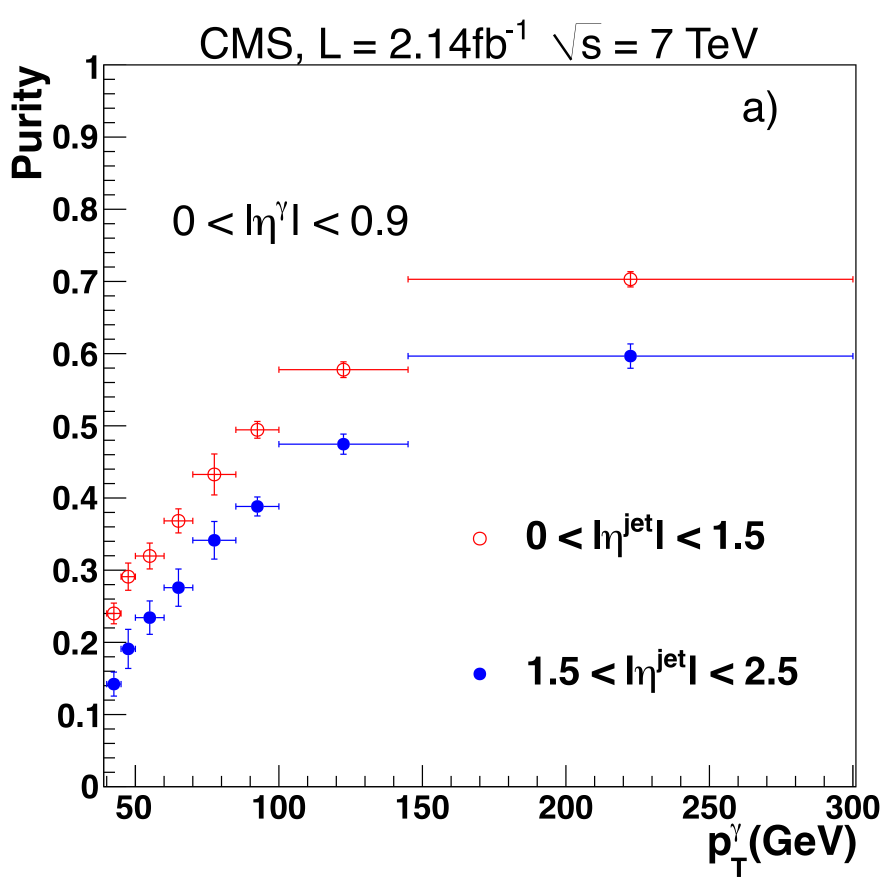
ATL-PHYS-PUB-2013-018

- Inclusive photon cross section in agreement with NLO prediction
- Sensitivity to PDF investigated, limited by scale uncertainty

Photon + jet production

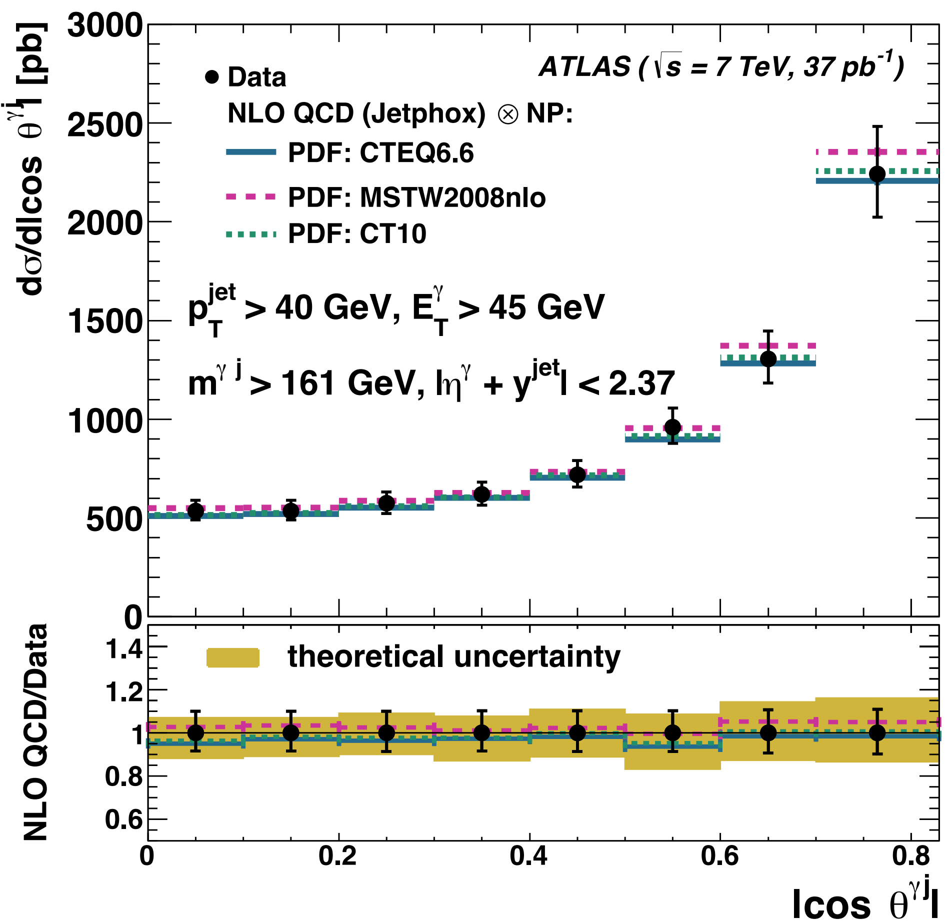




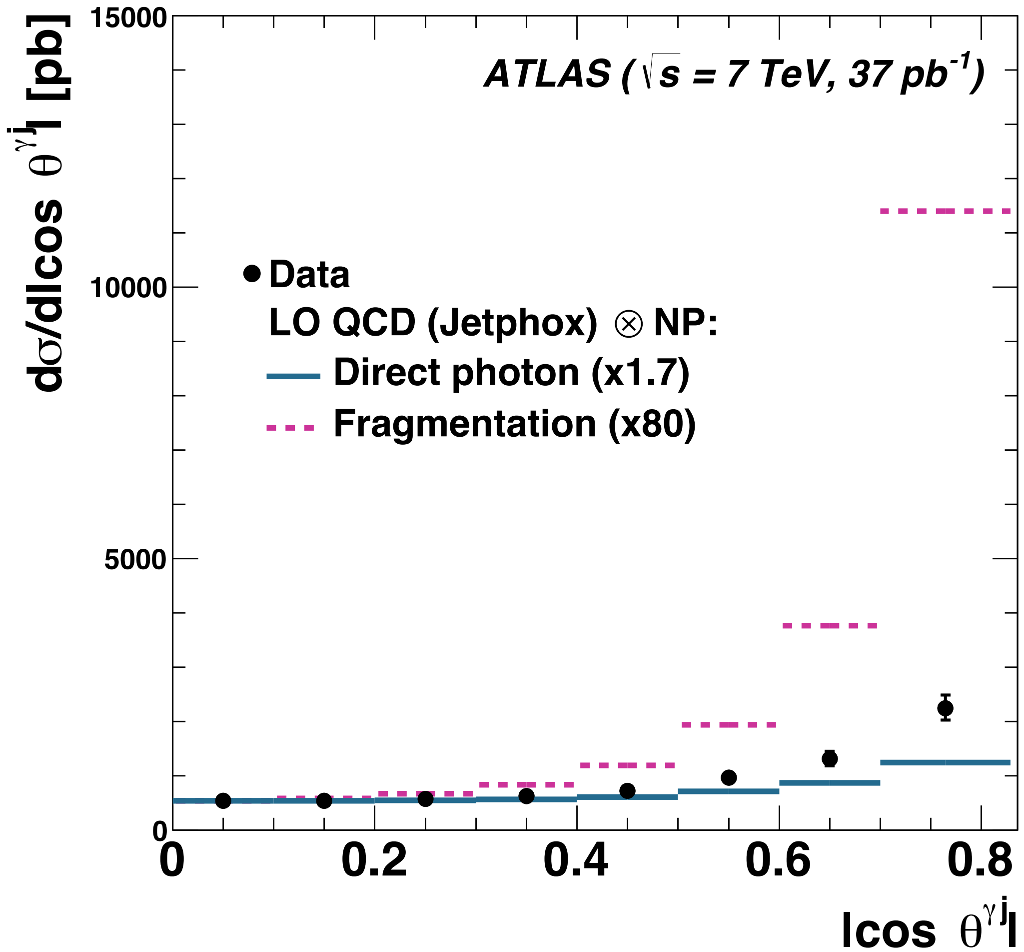


- ❖ Isolation template fit to extract signal
- ❖ Purity is increasing with p_T
- ❖ Very good agreement with NLO calculation

Photon + jet dynamics



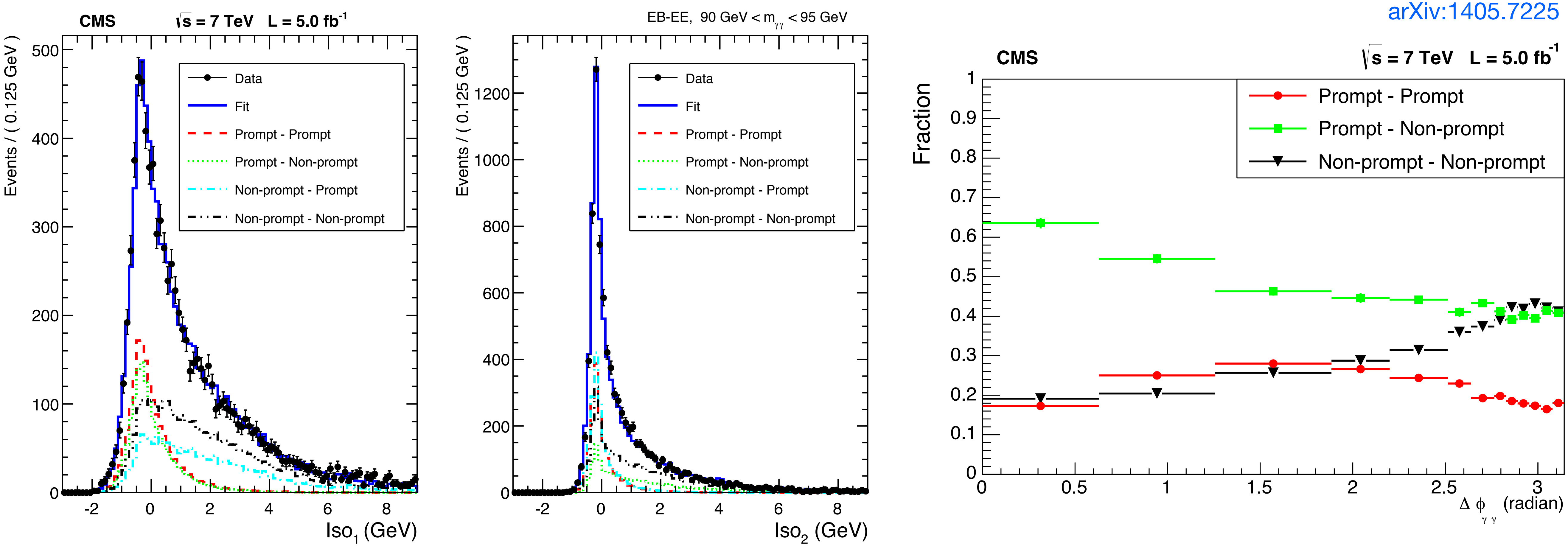
Nucl. Phys. B 875 (2013) 483



- Angular distributions probe pQCD production diagrams
- Relative enhancement of fragmentation in corners of the phase space
- Small uncertainties, very good agreement with NLO theory

Diphoton measurement

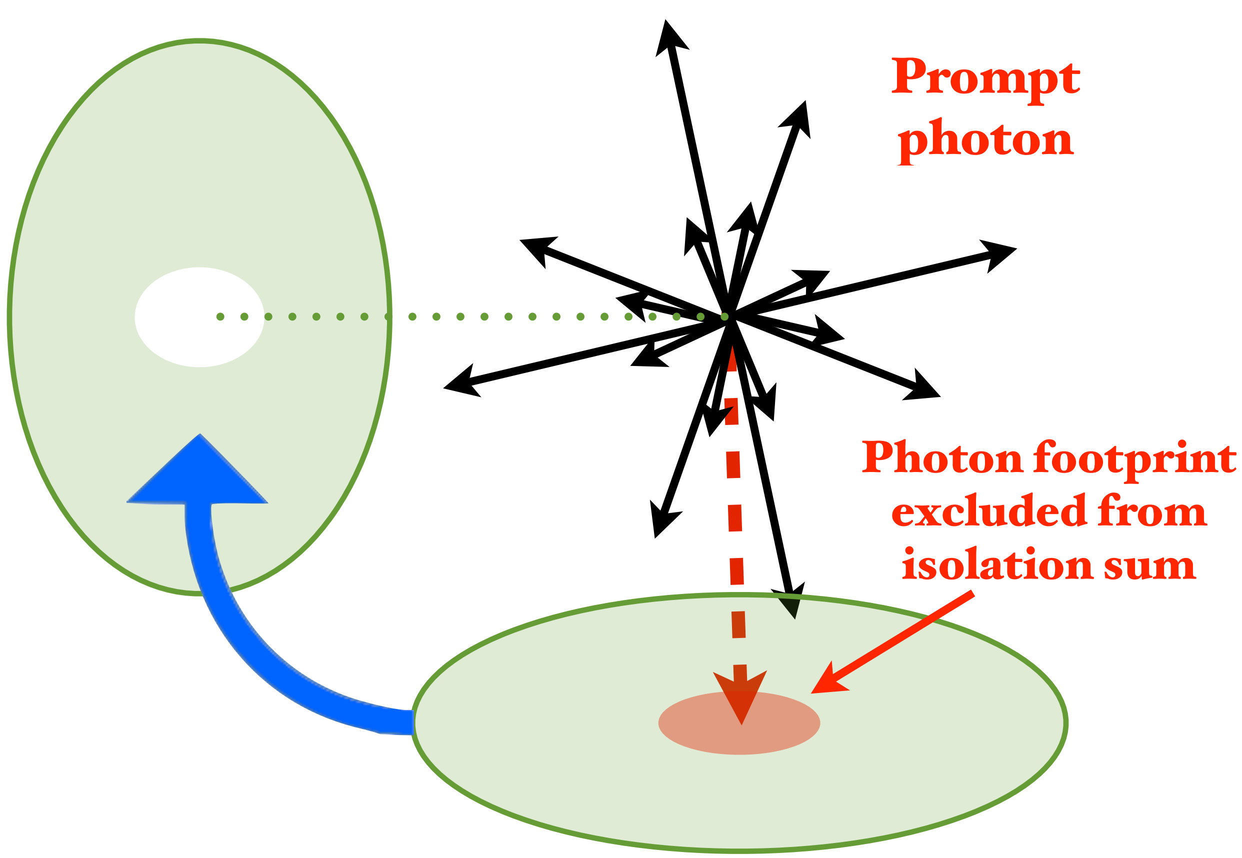
arXiv:1405.7225

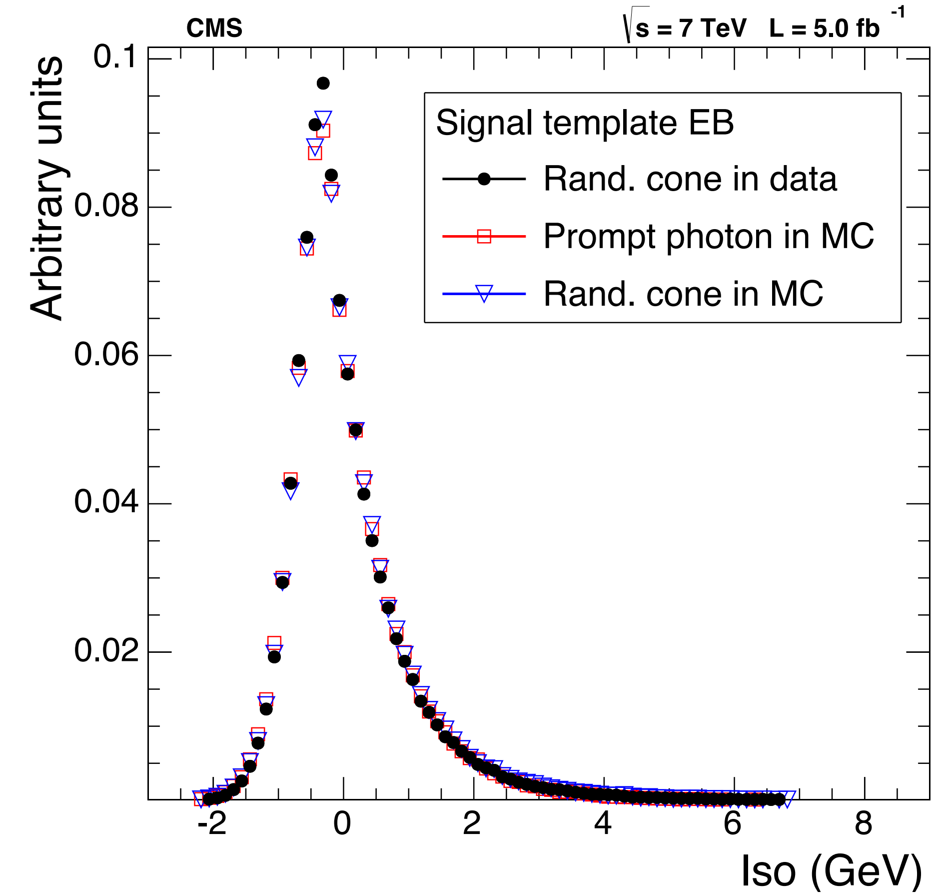


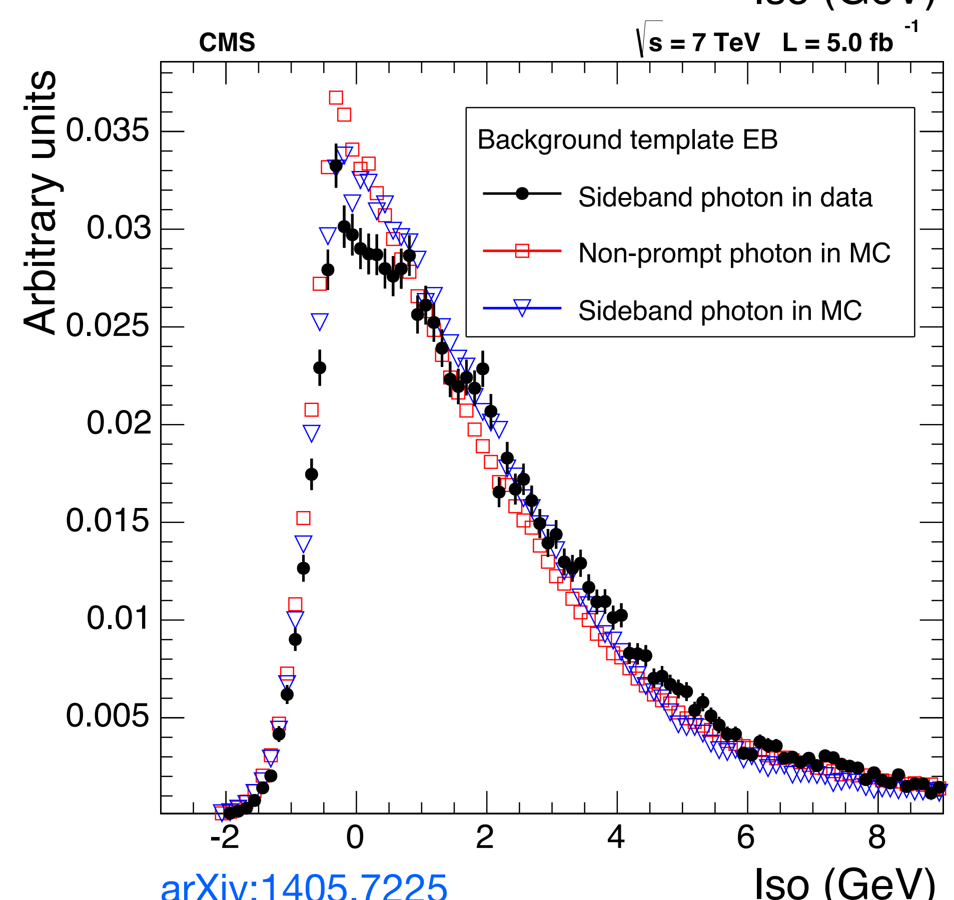
- Separate prompt diphoton component from photon+jet, di-jet
- **Two-dimensional template fit**: isolation as discriminating variable
- Robust **data-driven template building** methods
- Correlation between isolation sums taken into account

Isolation templates in data

- Isolation templates built from data:
  - random-cone technique for signal (isolated photons)
  - shower shape sideband for background
- Very successful closure of the method, leading to small uncertainties

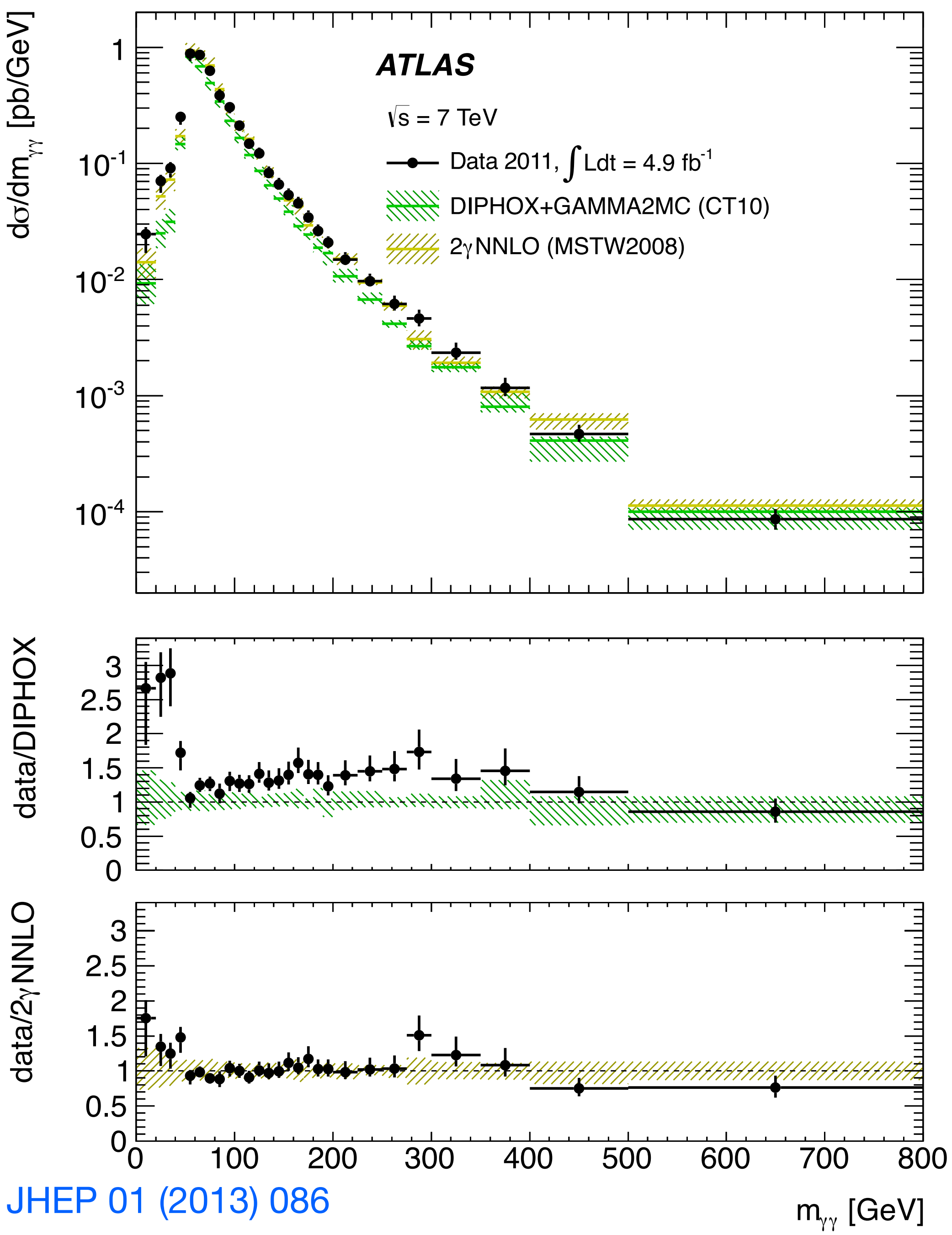






arXiv:1405.7225

NNLO pQCD sensitivity



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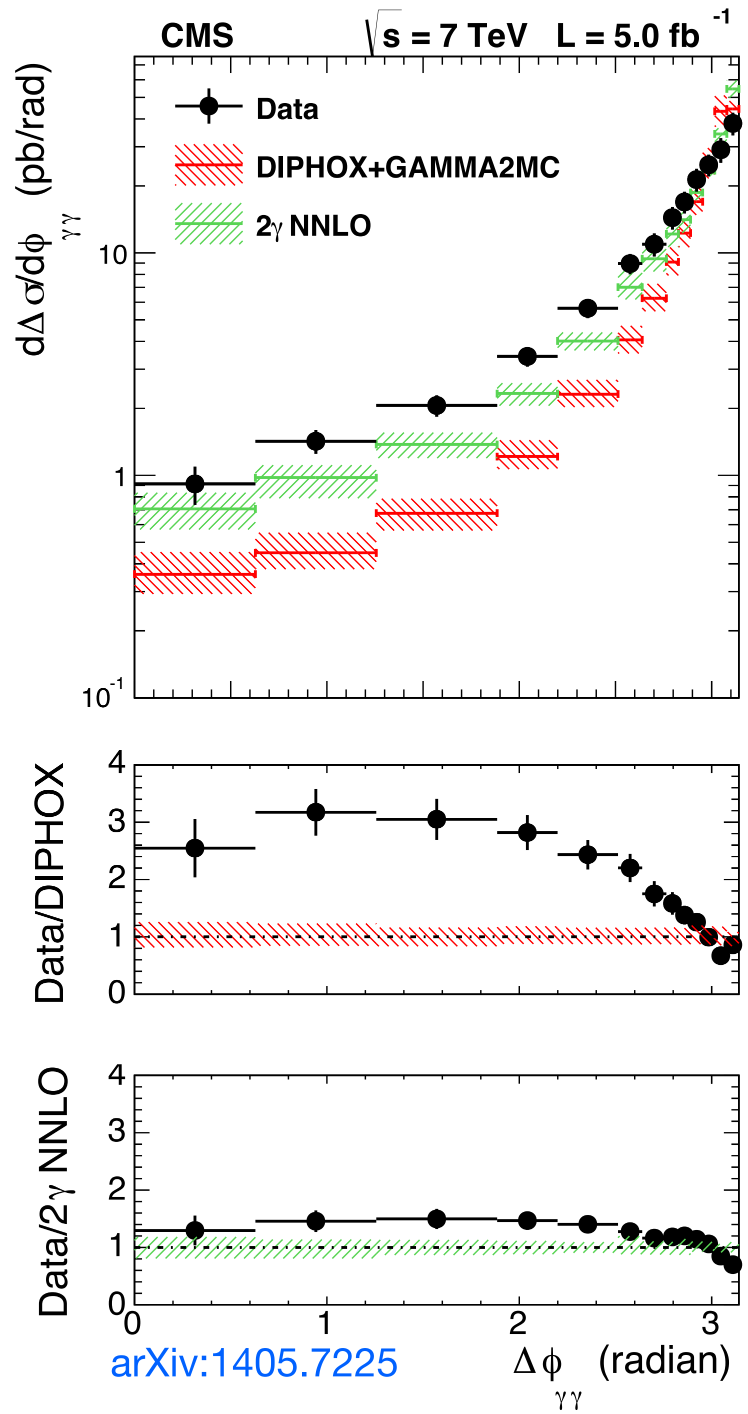
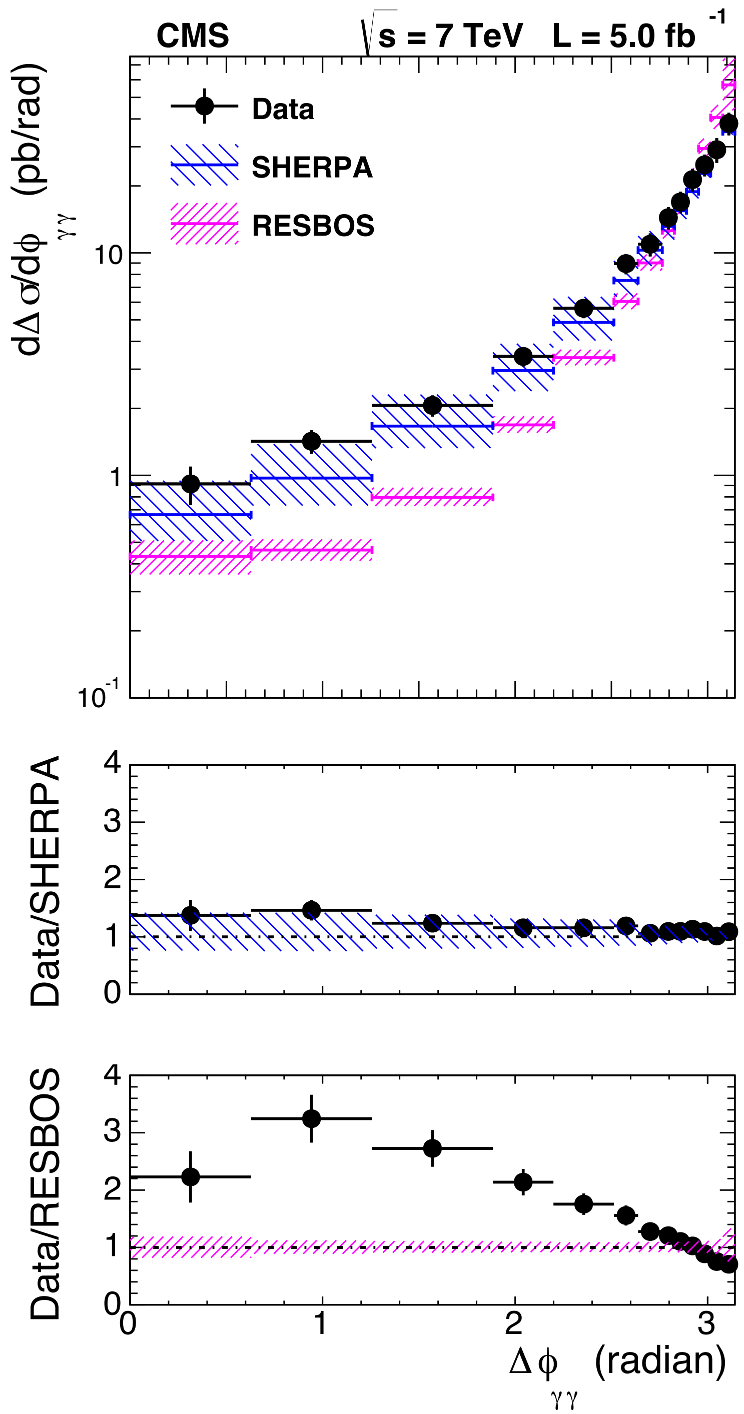


arXiv:1405.7225



- **NNLO calculation is needed to describe low-$m_{\gamma\gamma}$, low-$\Delta\varphi_{\gamma\gamma}$ region**
- **SHERPA** also in good agreement with the data

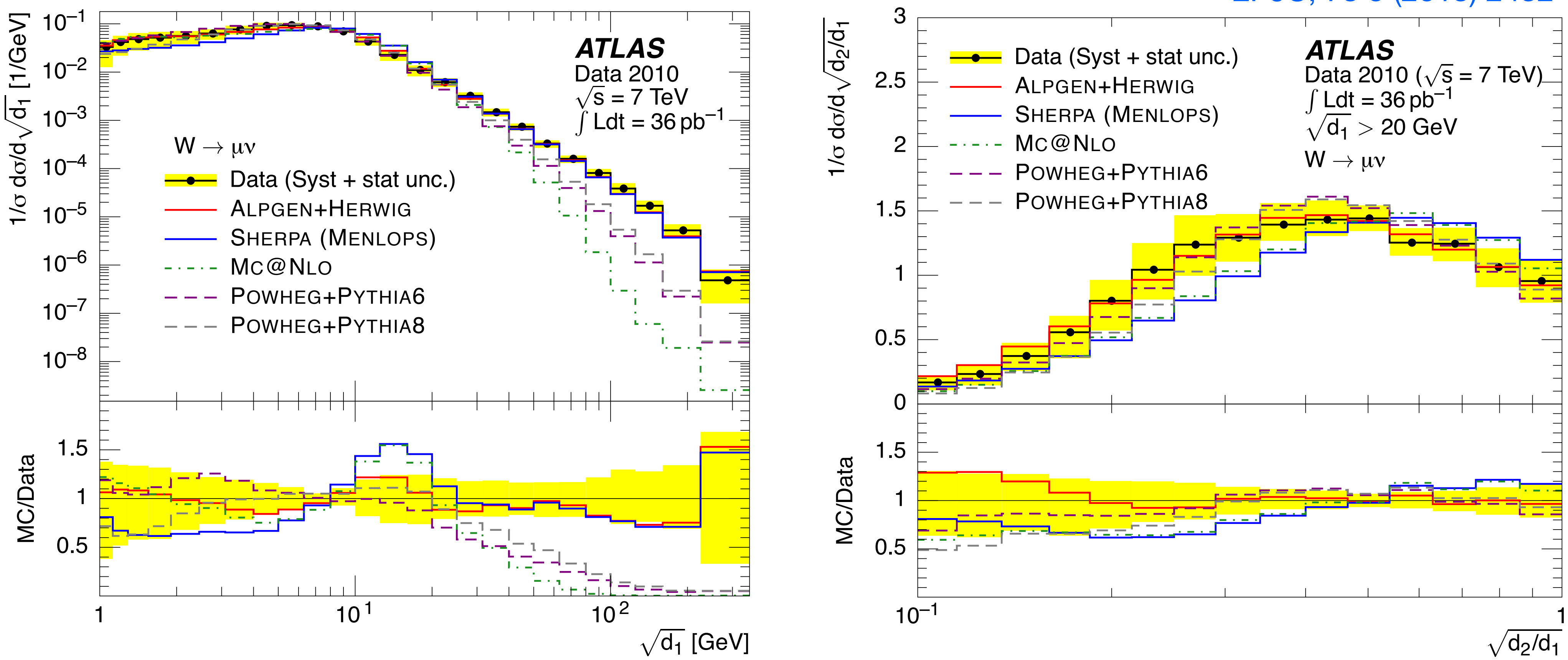
Conclusions

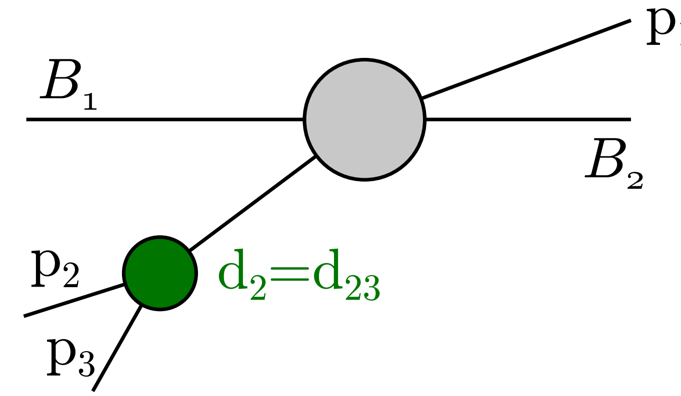
- Jet production is predicted very successfully in QCD
- ATLAS and CMS achieve strong performance in jet and photon reconstruction, even in challenging pileup conditions
- Valuable physics input to α_S and PDF fits
- Multi-jet observables probe various aspects of QCD radiation
- Jet substructure methods useful to withstand pileup and tag boosted heavy object decays
- Diphoton measurements stringently test NNLO phenomenology

Backup slides

Splitting scales

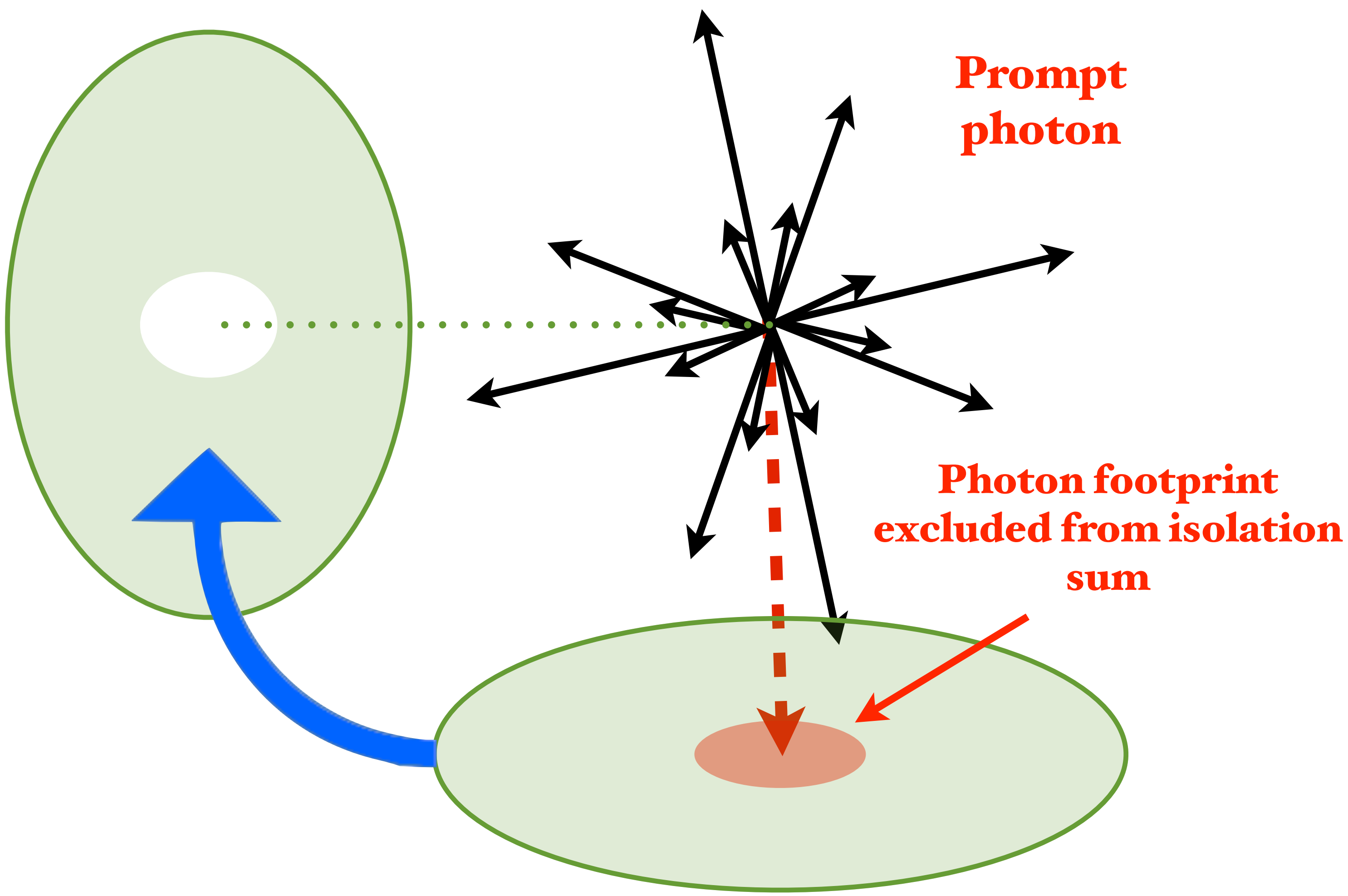
EPJC, 73 5 (2013) 2432





- Measurement of k_T splitting scales
  - value of k_T metric at k-th last clustering
  - hard tail described by ME generators
  - soft region sensitive to hadronization and MPI
  - ratio ~ 1 = subsequent emissions at the same scale

Random cone method



- Procedure (event-by-event):
  - rotate the isolation cone in φ by a random angle
  - check that no other photon or jet is nearby
  - underlying activity does not change (same η)
  - build the template from this isolation sum away from the photon candidate