



Summary of Working Group 4 QCD and Hadronic Final States

Daniel Britzger, Konstantinos Kousouris, Vladimir Braun

DIS 2014

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects

April 28 – May 2, 2014

Wide range of new results



In total 27 contributions

- ~7 theory talks
- Contributions from 8 experiments
- LHC experiments often presented several analyses together



Very fruitful common session with WG2

Wide range of physics

- Jet production
- Photon and associated production
- Charged particle production
- Underlying event
- ...



Not all results could be covered in this short summary

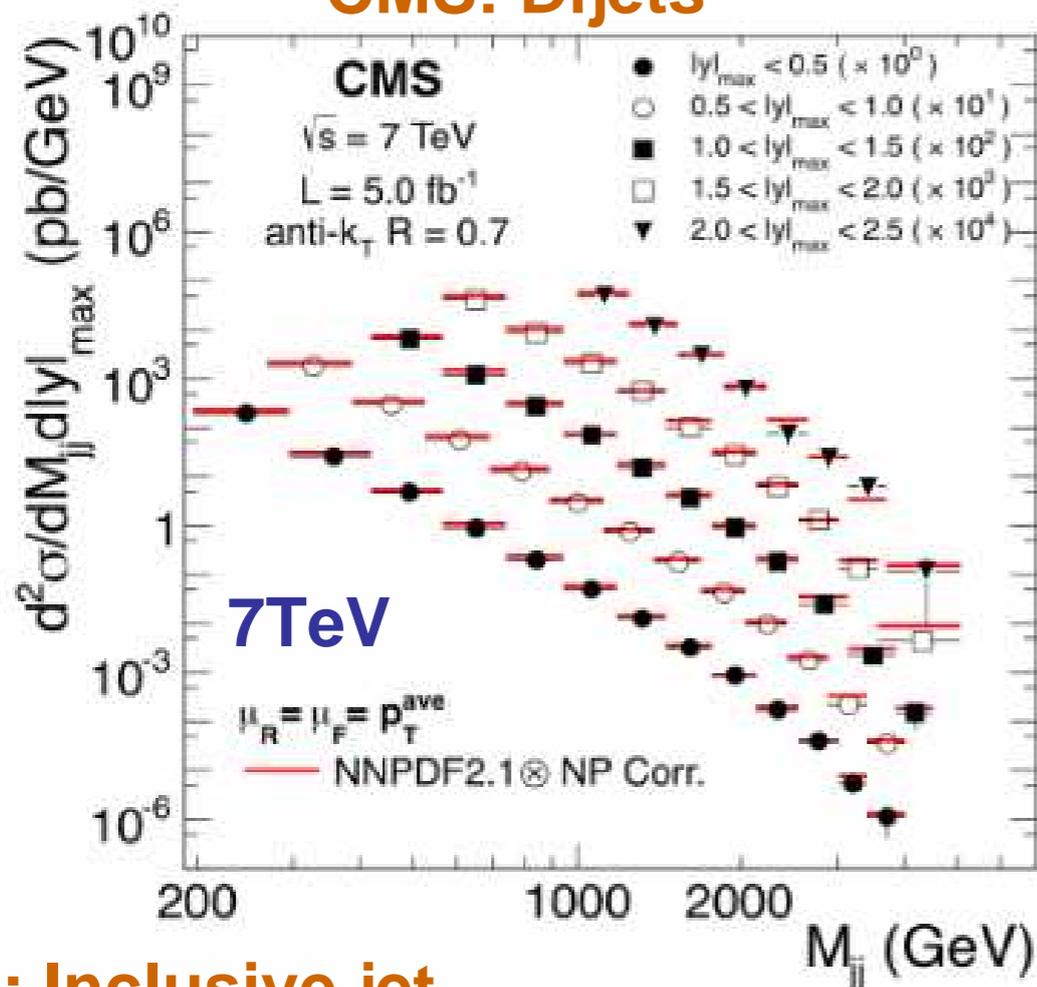
Please excuse if your favorite result is missing



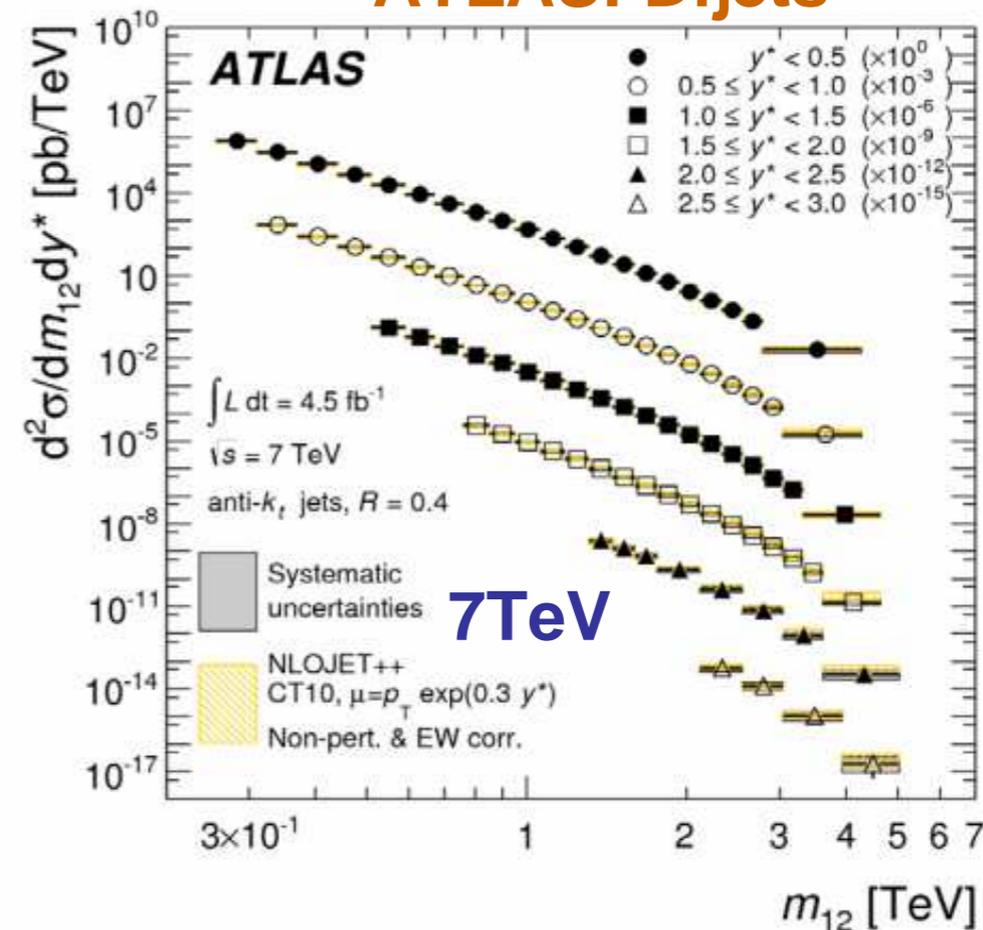
Jet production at LHC

P. Kokkas
G. Vardanyan

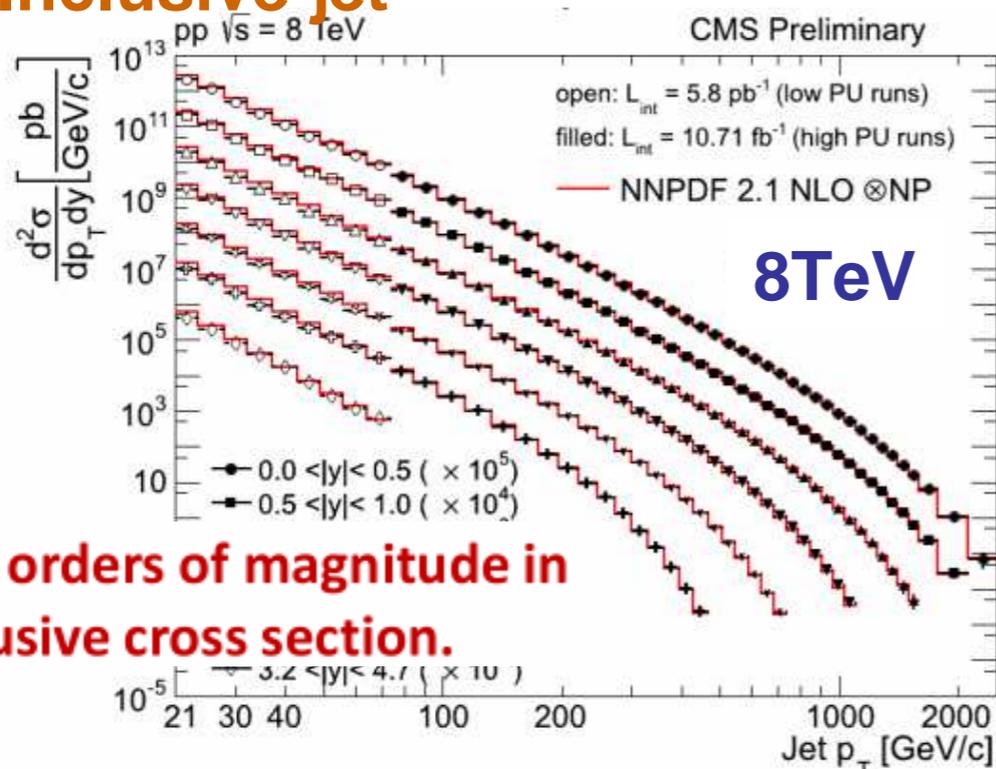
CMS: Dijets



ATLAS: Dijets



CMS: Inclusive jet



Over 14 orders of magnitude in the inclusive cross section.

Dijet mass from $\sim 5\text{fb}^{-1}$ from both experiments

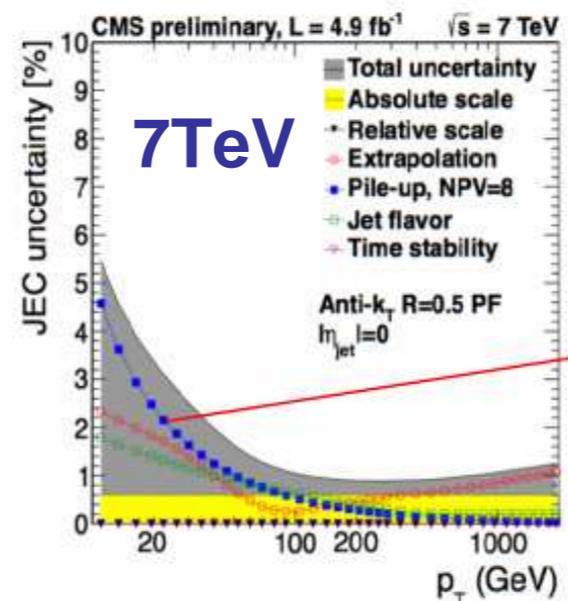
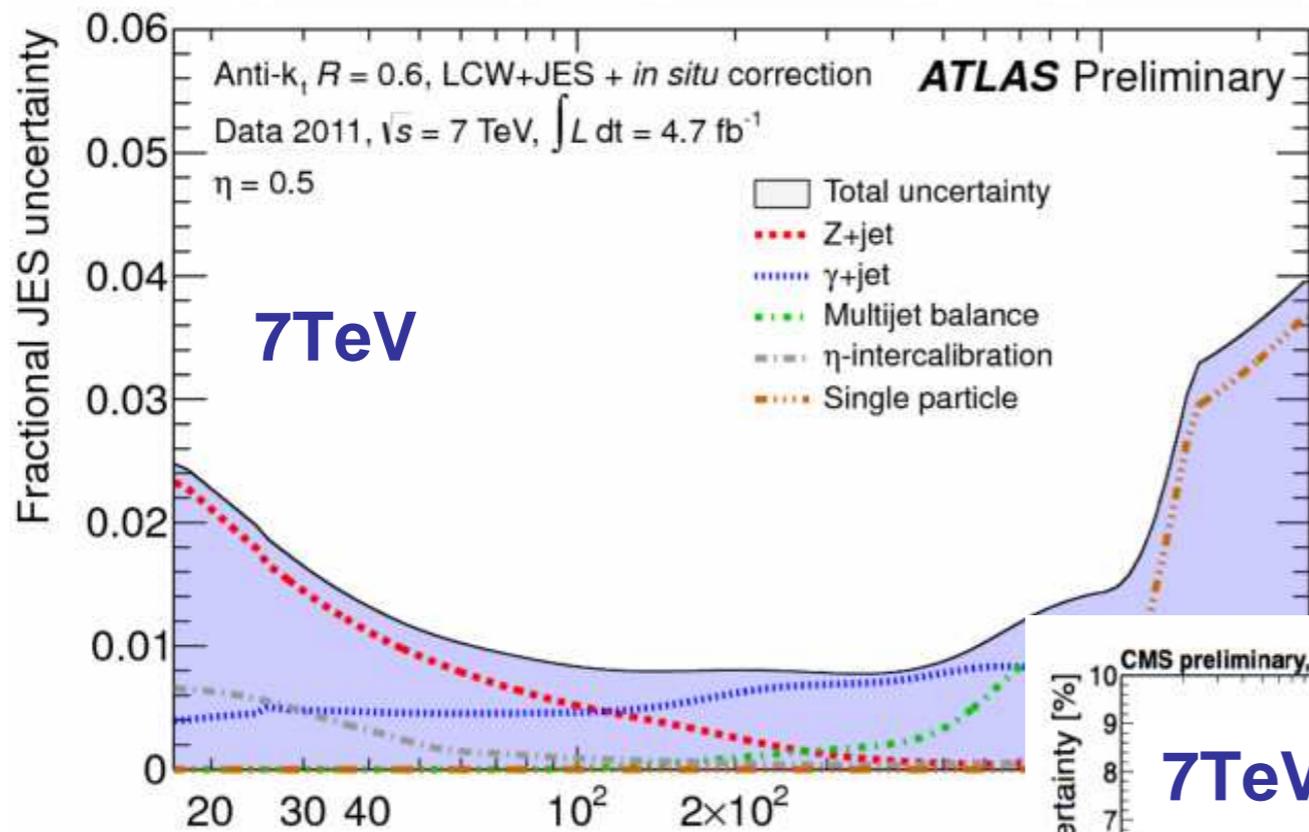
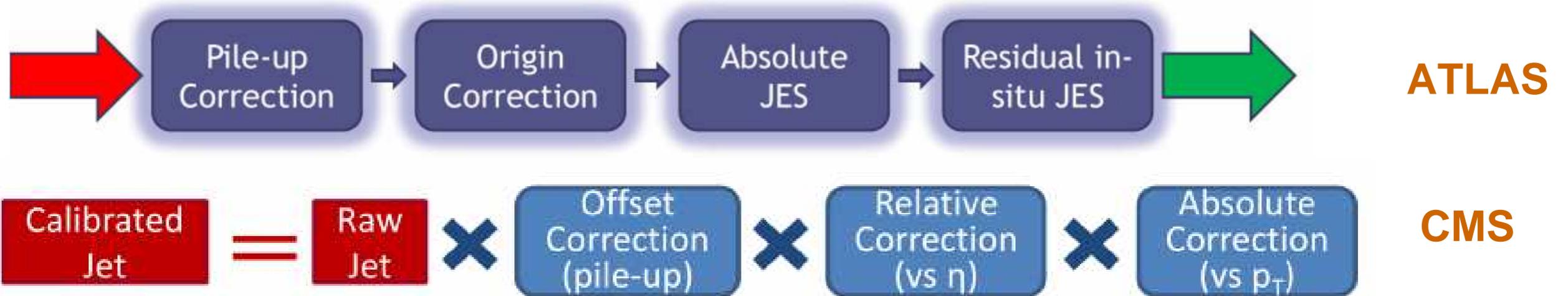
- EW corrections $O(\alpha_s^2)$ become important for $M_{12} > 1 \text{ TeV}$ and are used
- Hadronisation and UE corrected for

CMS inclusive jet:

- Low- p_T from low PU runs (5.8pb^{-1})

Experimental benefits for jet measurements

P. Kokkas
G. Vardanyan



High-pile-up effects at low p_T

Jet measurements benchmark for jet energy scale uncertainty

Sophisticated methods

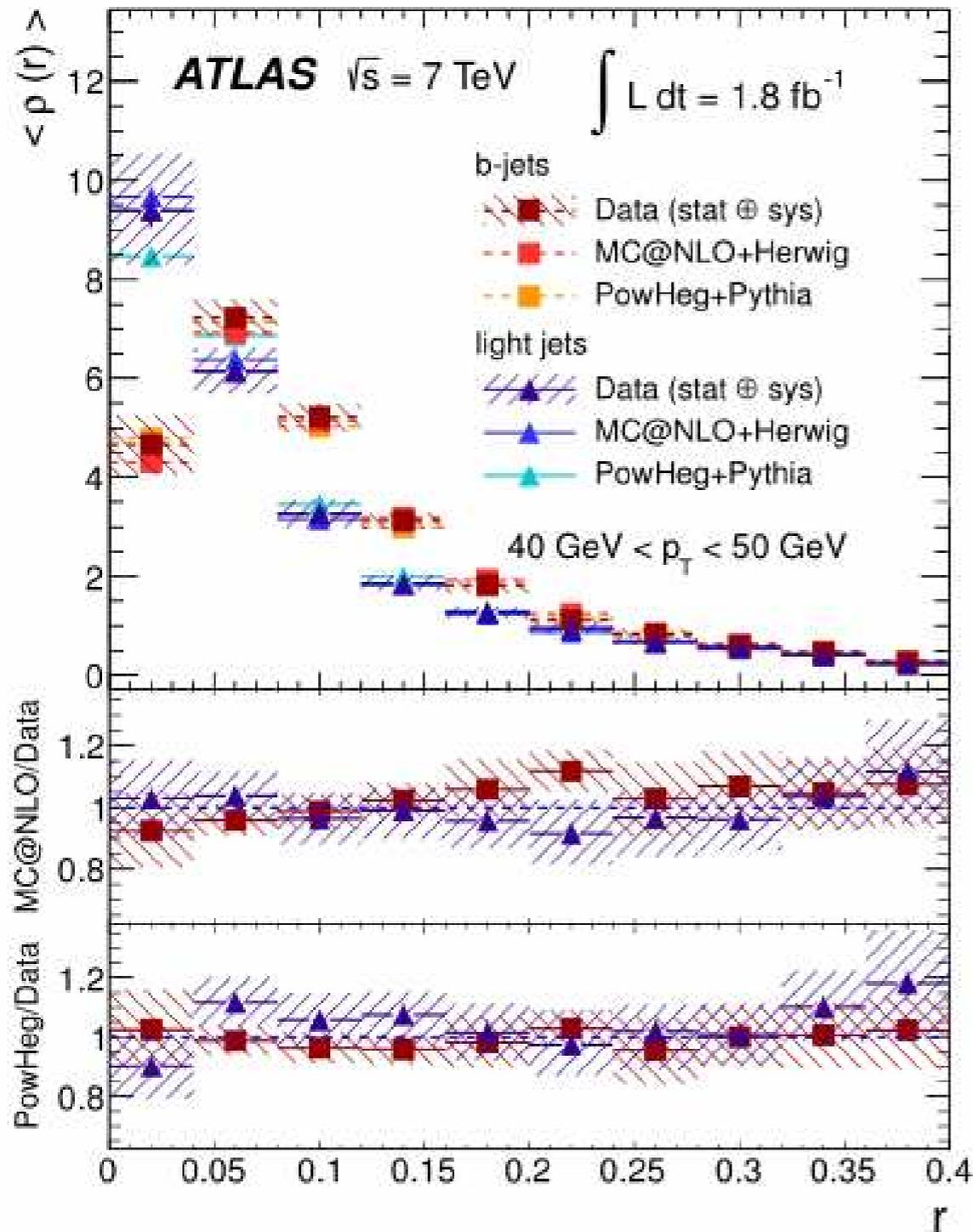
Multiple methods combined over jet kinematic spectra

Large uncertainties often from unfolding, despite good MC Models and well understood data

unfolding

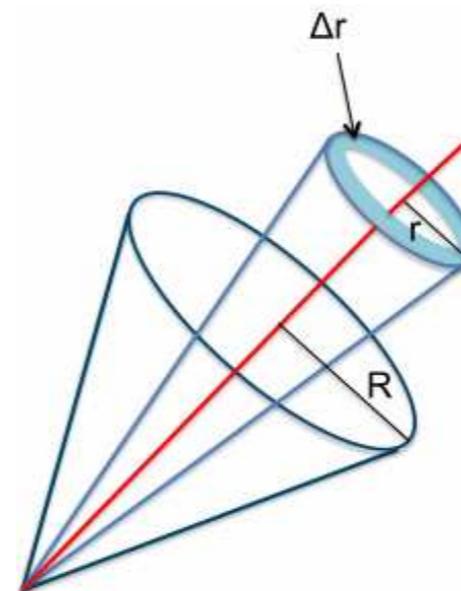
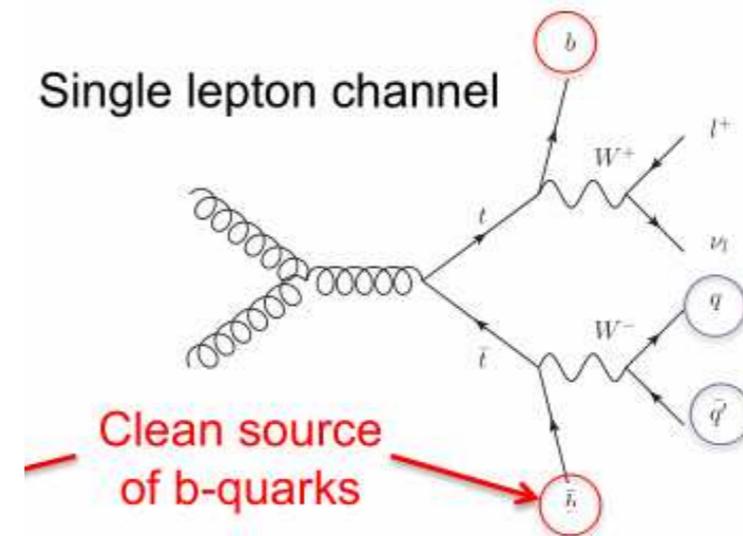
Insights into jets (ATLAS)

$40 < p_T < 50 \text{ GeV}$



Jet properties of hadronically decaying massive particles

Top quark pair events in single lepton channel



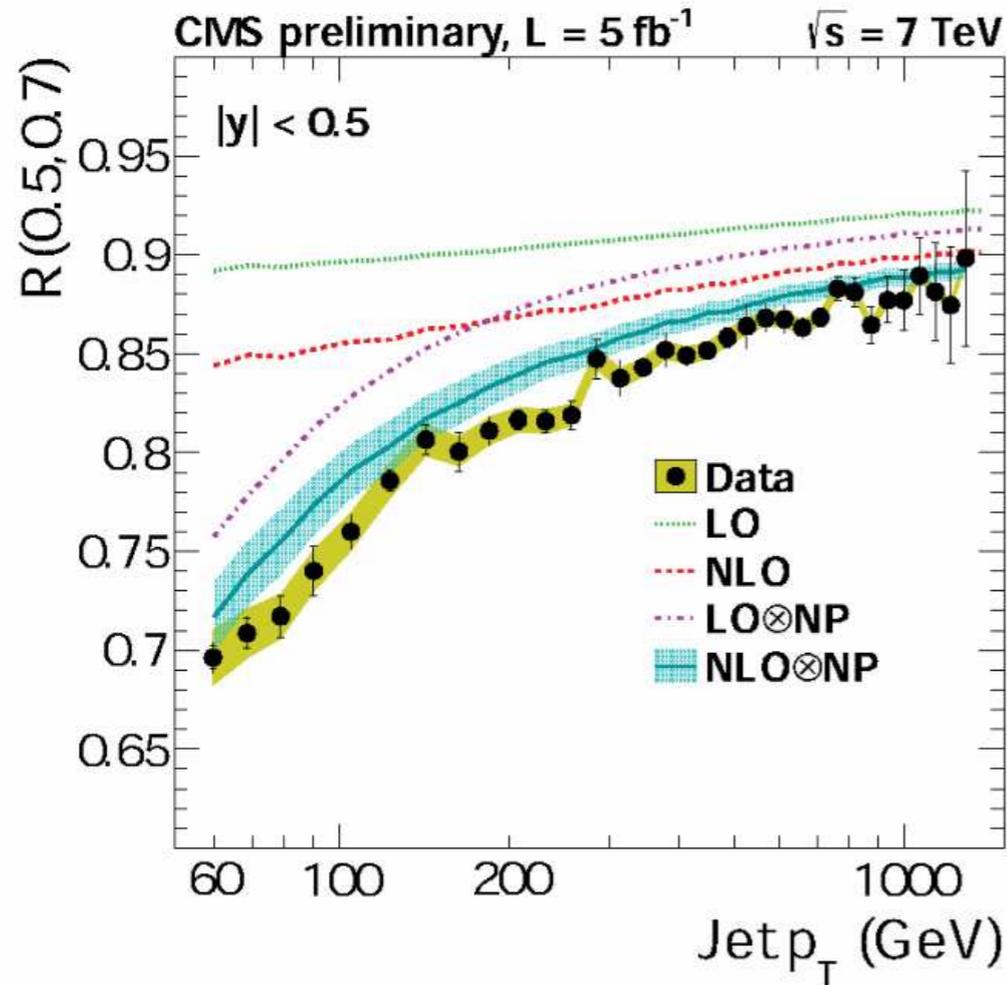
• Differential:

$$\rho(r) = \frac{1}{\Delta r} \frac{p_T \left(r - \frac{\Delta r}{2}, r + \frac{\Delta r}{2} \right)}{p_T(0, R)}$$

Further Jet Measurements (CMS)

P. Kokkas

AK5/AK7 cross section ratio



Sensitive to collinear radiation

Best description obtained from

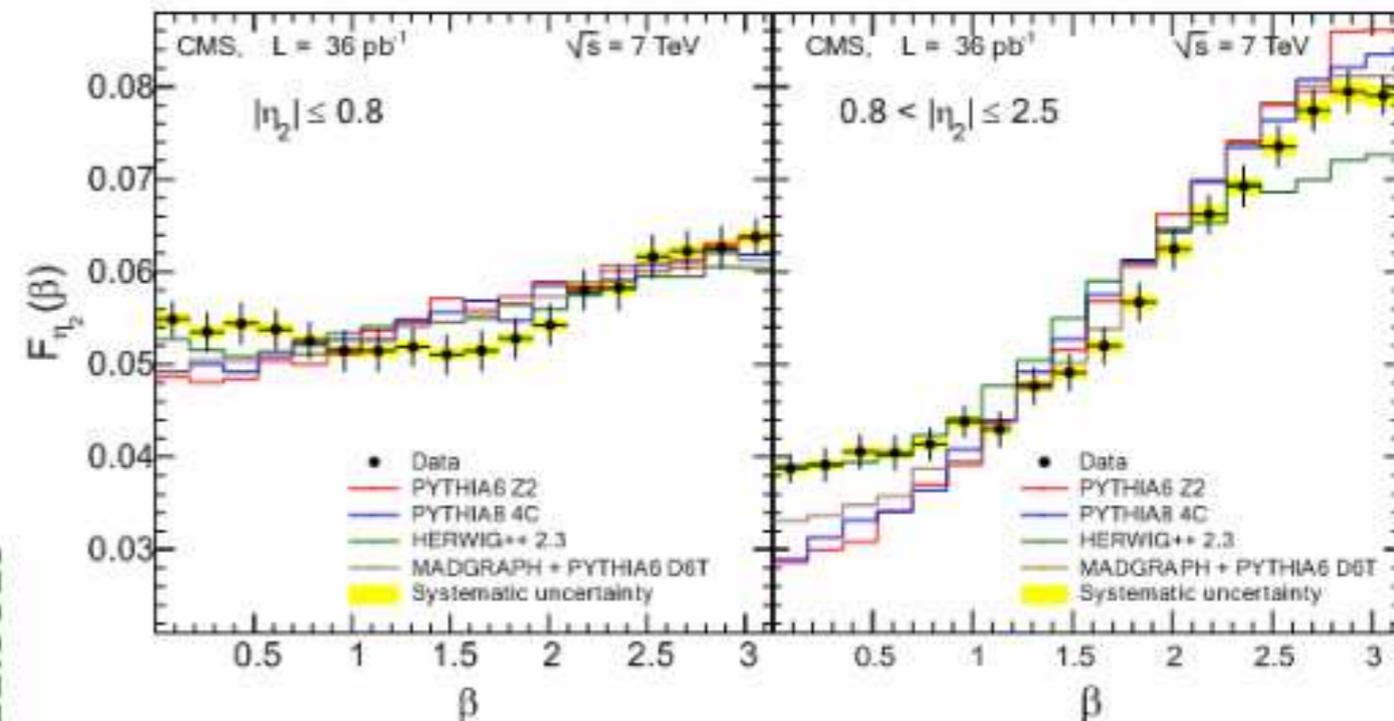
- NLO calculations fail to describe this observable
- NLO+PS (POWHEG+PYTHIA)
- Pythia6 Z2 gives also good description

Color coherence effects measured

- Study 3-Jet events where two leading exhibit a back-to-back topology .
- The observable β is defined as the azimuthal angle of the 3rd jet with respect to the 2nd in (η, ϕ) space:

$$\tan \beta = \frac{|\Delta \phi_{23}|}{\Delta \eta_{23}} \quad \Delta \phi_{23} = \phi_3 - \phi_2$$

$$\Delta \eta_{23} = \text{sign}(\eta_2) \cdot (\eta_3 - \eta_2)$$



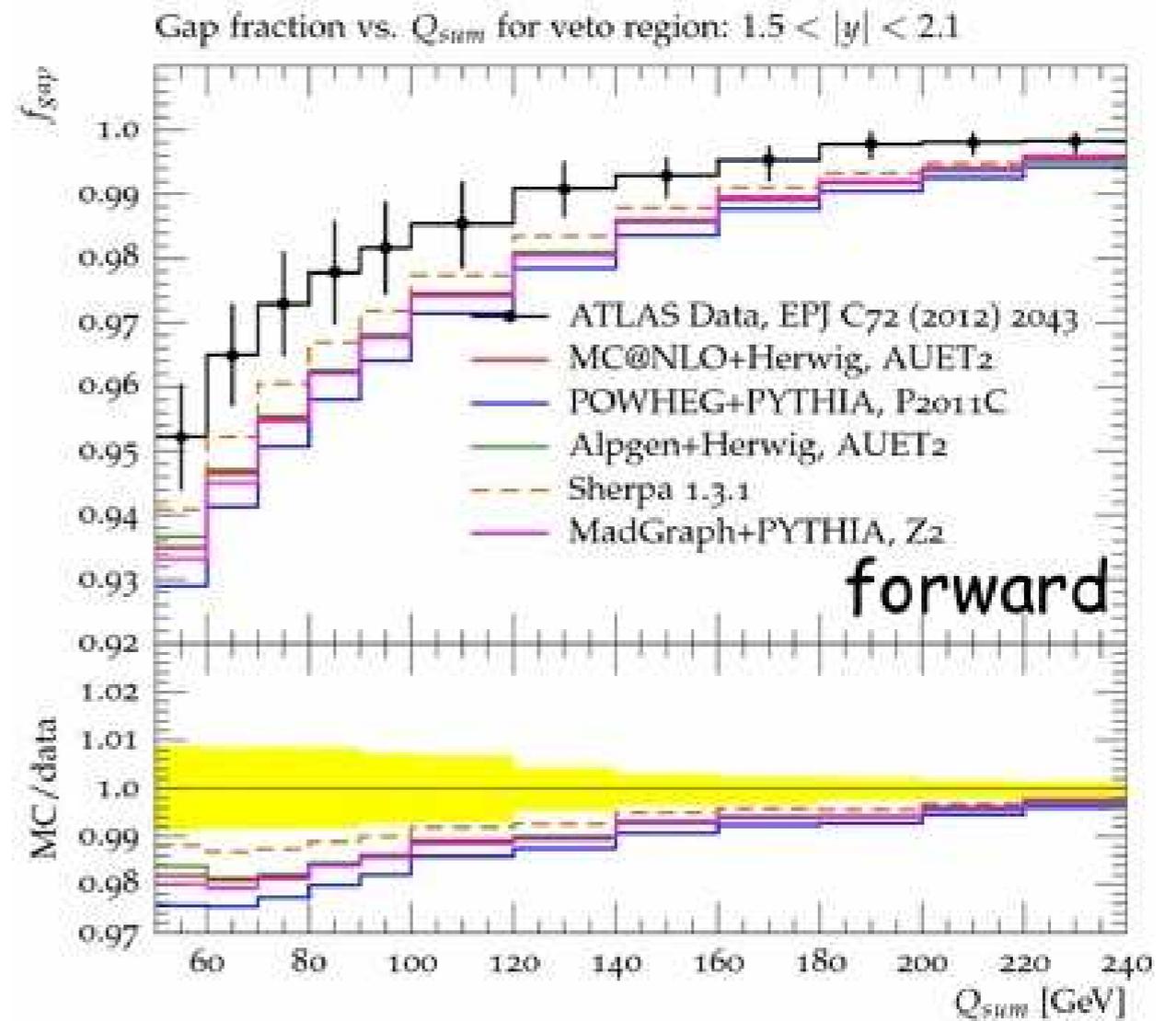
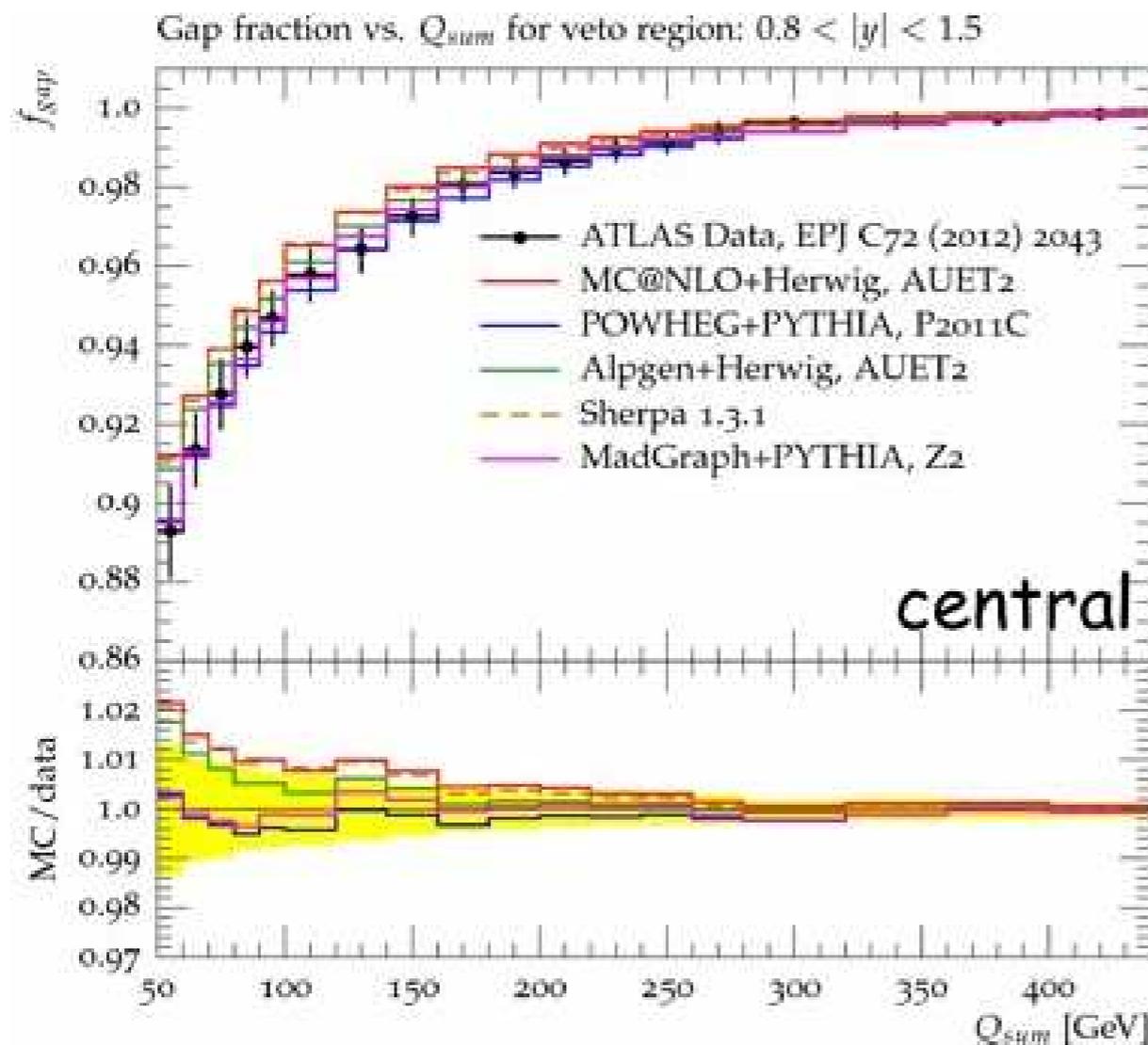
Top quark pairs with extra jet (ATLAS)

L. Bellagamba

Top-pairs with extra jet

$$f(Q_{sum}) = \frac{n(Q_{sum})}{N} \longrightarrow \text{all hard emission}$$

- Measured in two y regions
- Important to constrain model uncertainties for $t\bar{t}$ production
- All generators have difficulties in describing data in forward region



Charged particles (LHCb)

Low pile-up run data

At least one charged particle

$$2.0 < \eta < 4.8$$

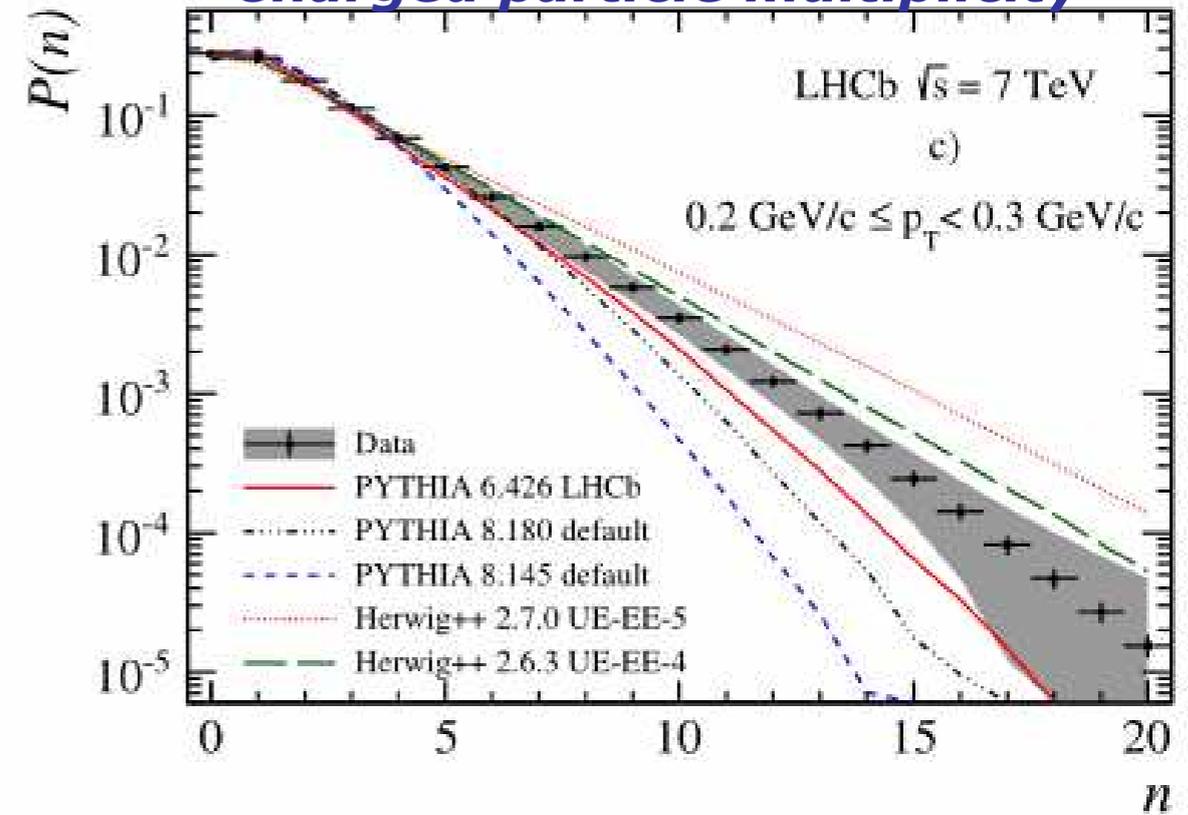
$$p > 2 \text{ GeV}/c$$

$$p_T > 0.2 \text{ GeV}/c$$

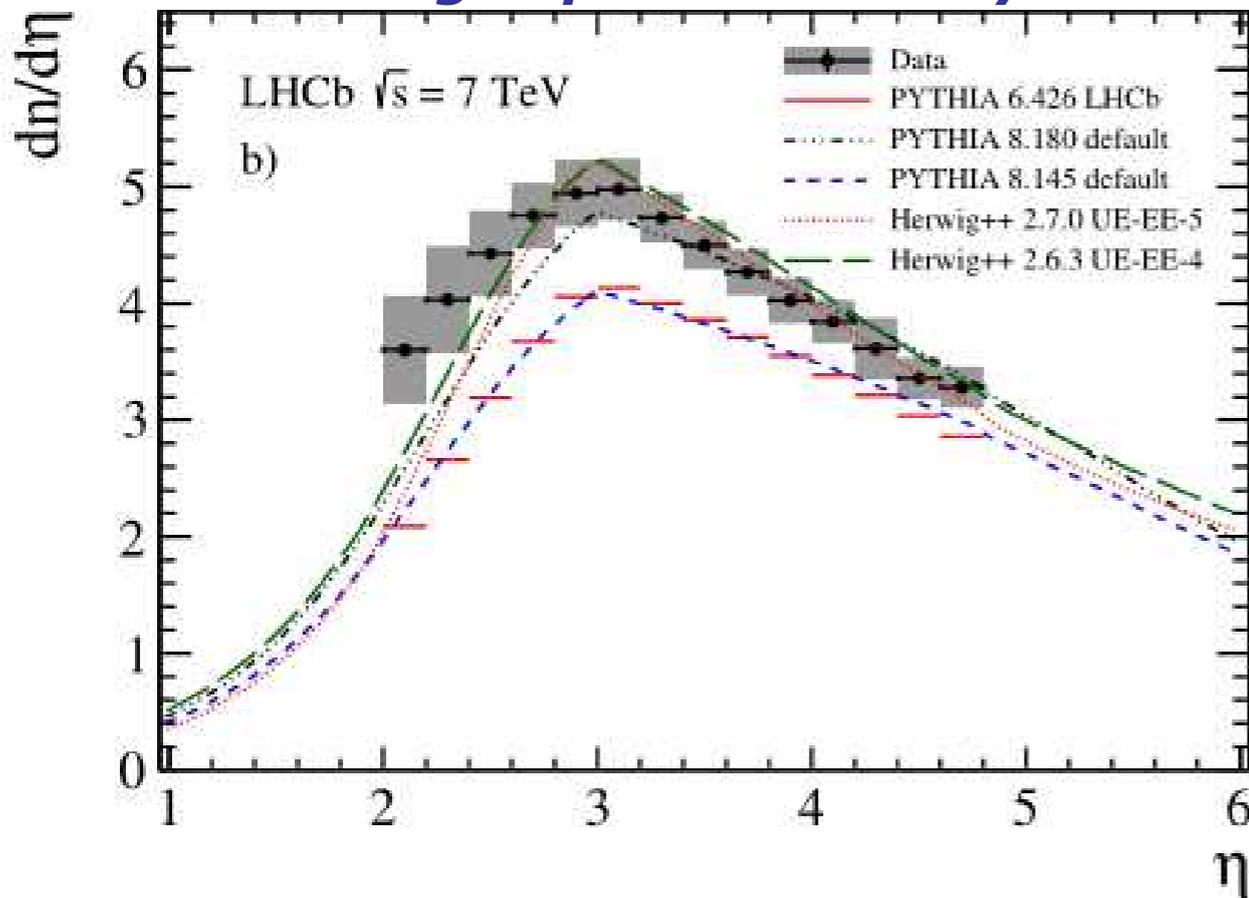
- Charged particle multiplicites in bins of p_T
- Charged particle densities

Data available in Rivet

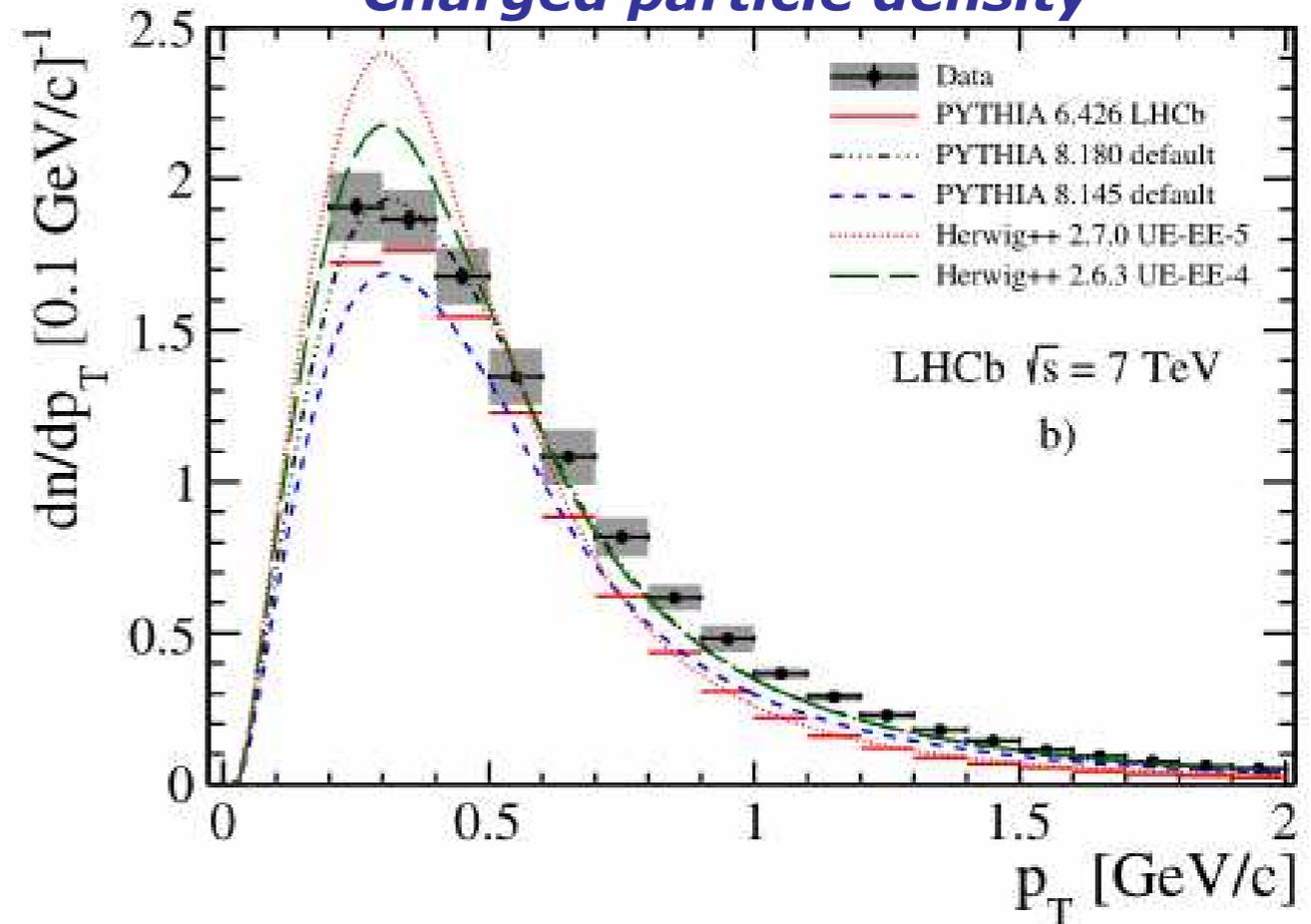
Charged particle multiplicity



Charged particle density

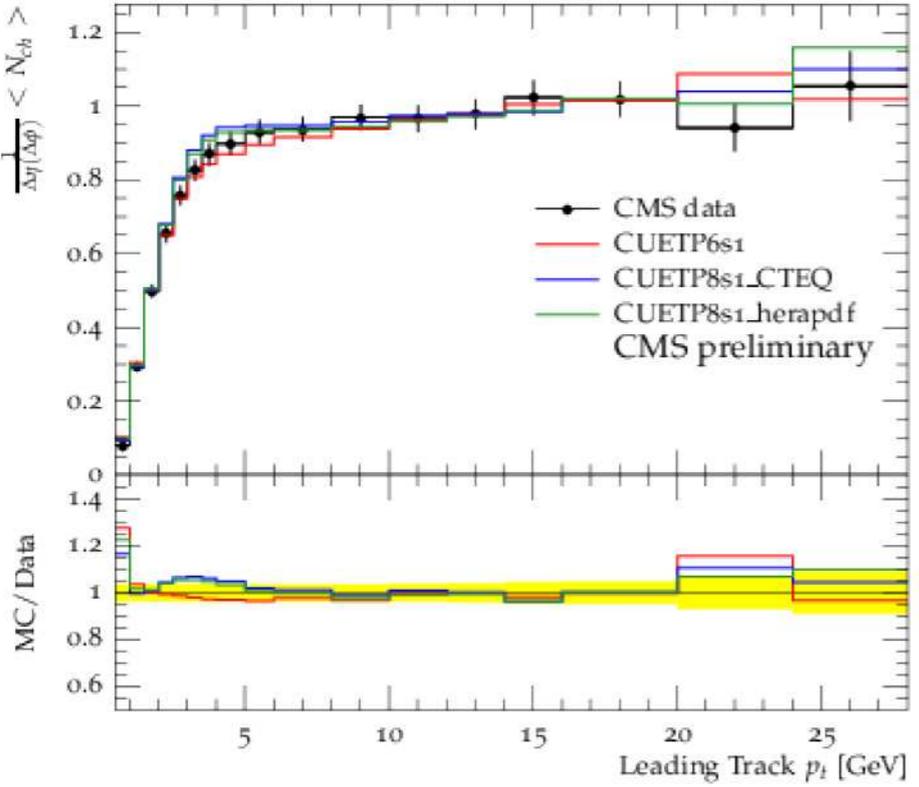
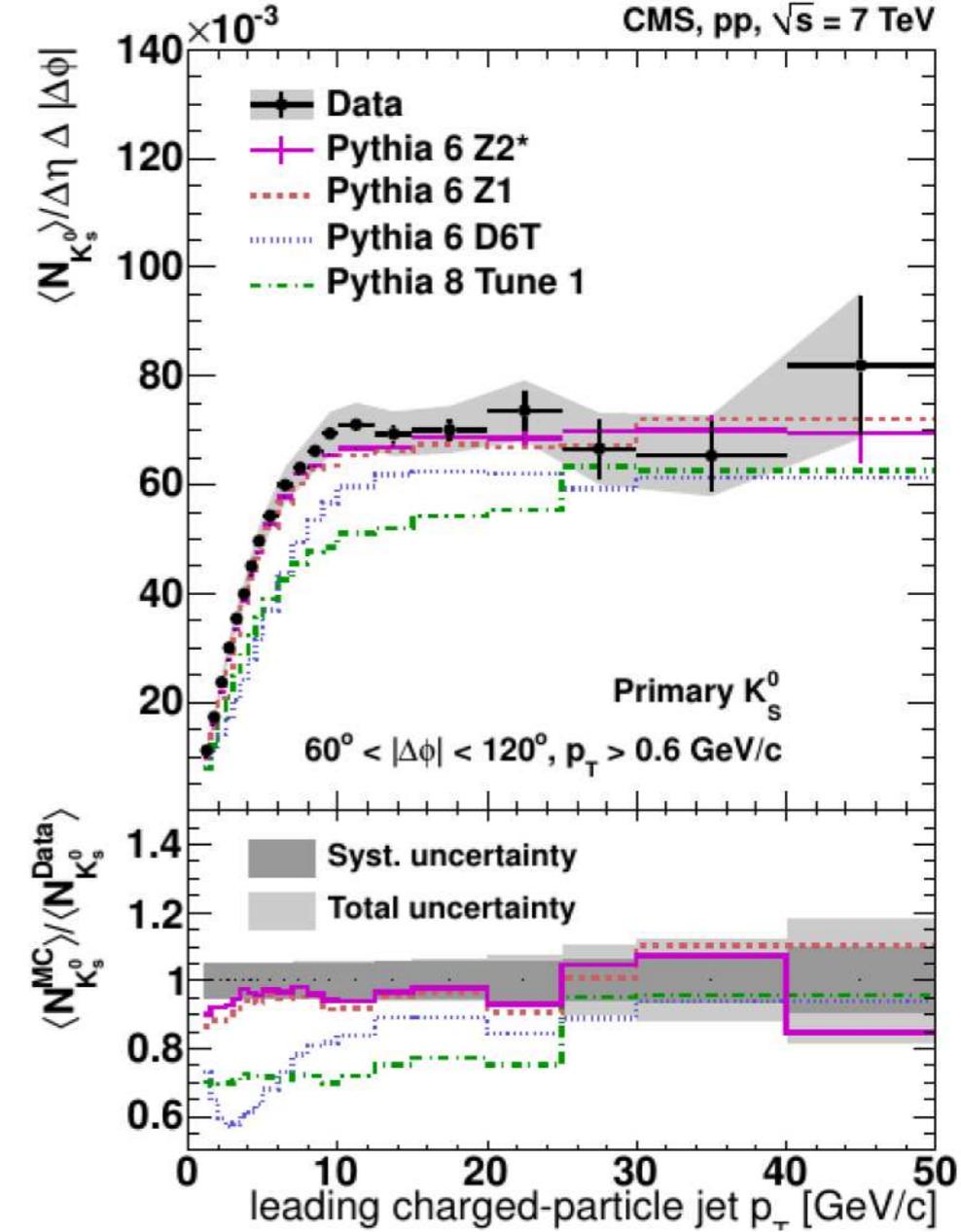
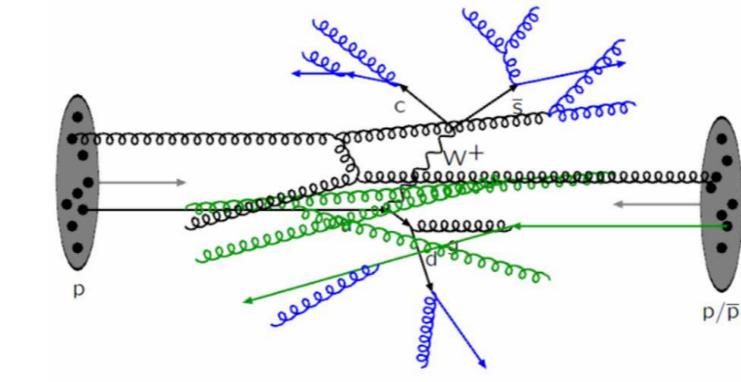
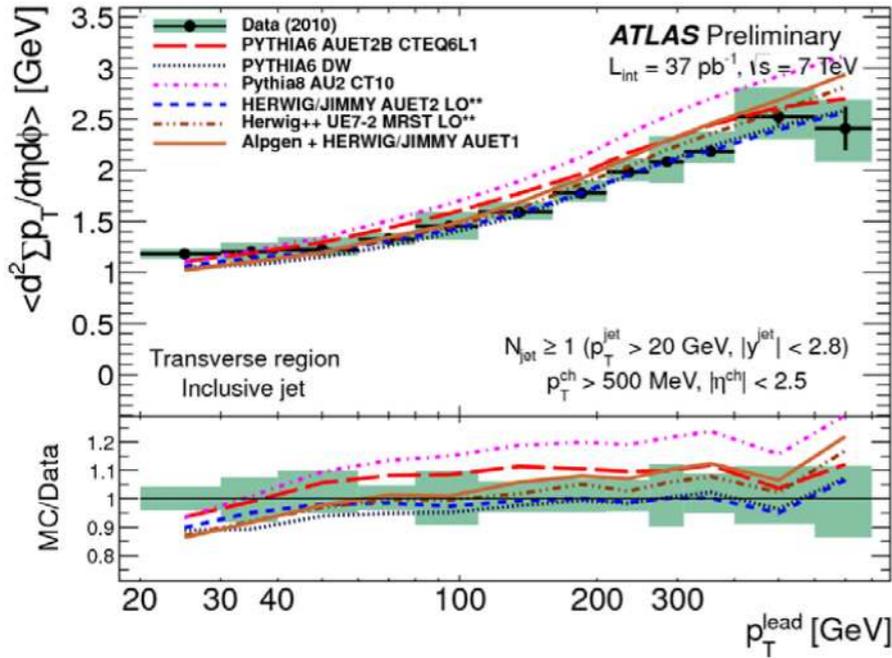


Charged particle density



Underlying event measurements (ATLAS, CMS)

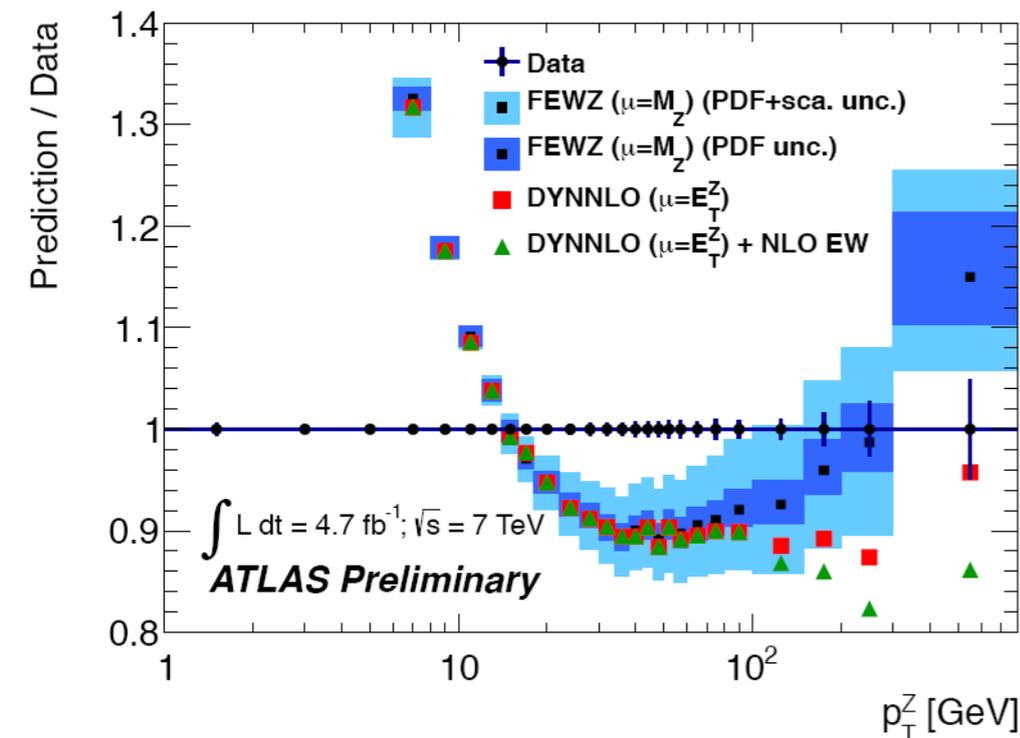
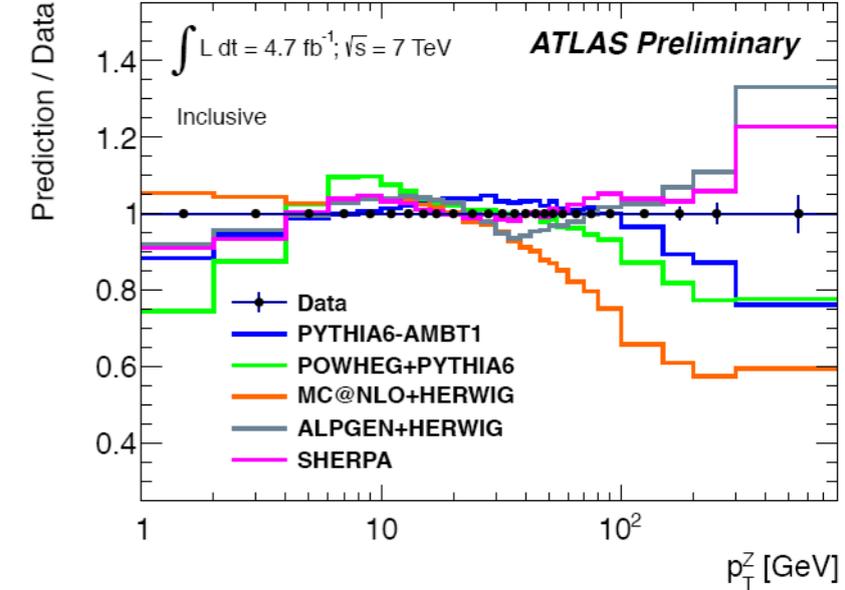
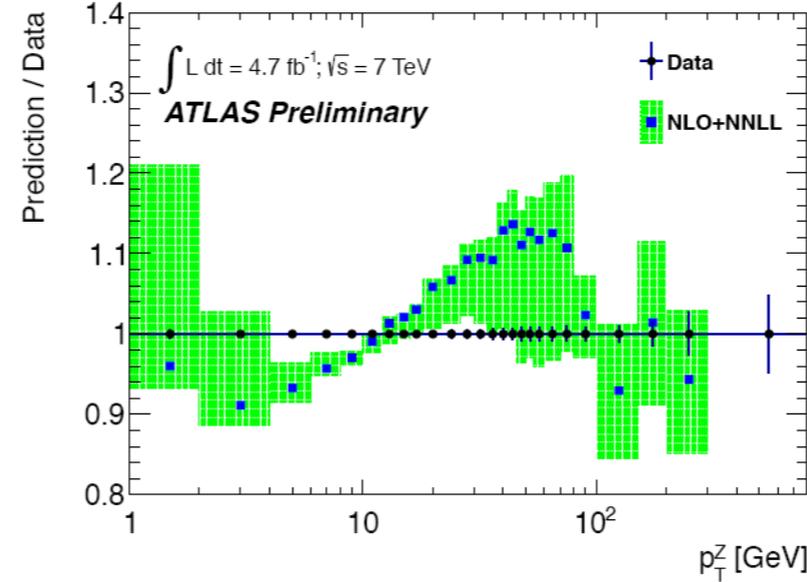
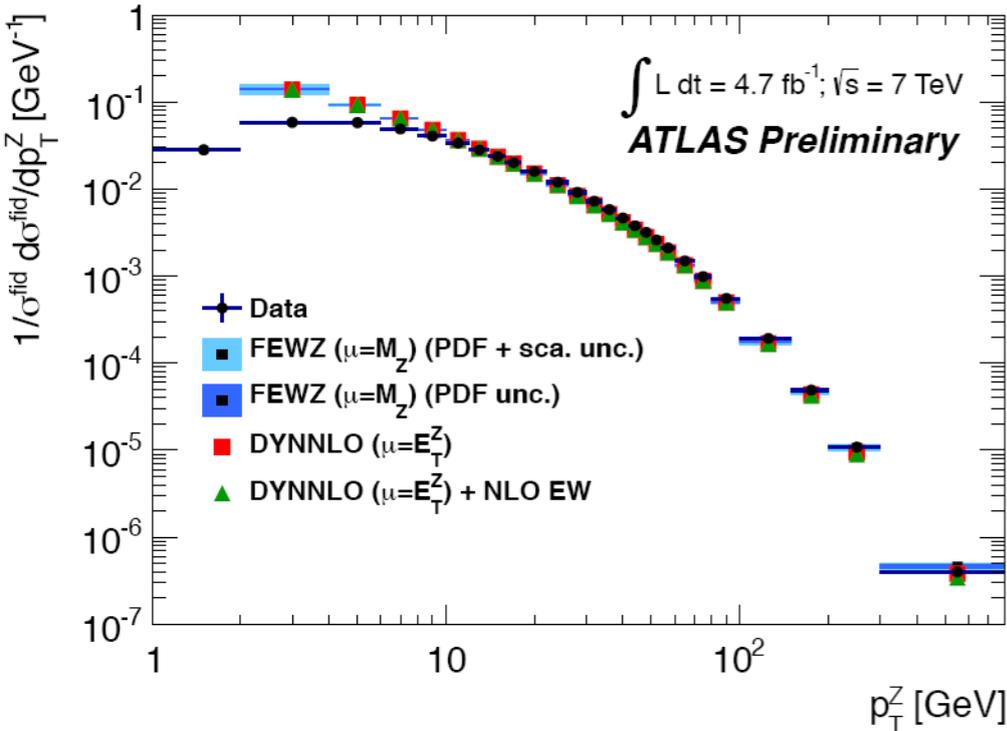
A. Minaenko
T. Frueboes
P. Gunnellini



- ▶ precise measurements of the UE activity at LHC have been made
- ▶ pre-LHC tunes fail to describe the data
- ▶ both CMS and ATLAS are deriving new tunes (using LHC and Tevatron data) that yield better agreement
- ▶ despite the new tunes, strangeness is badly modeled

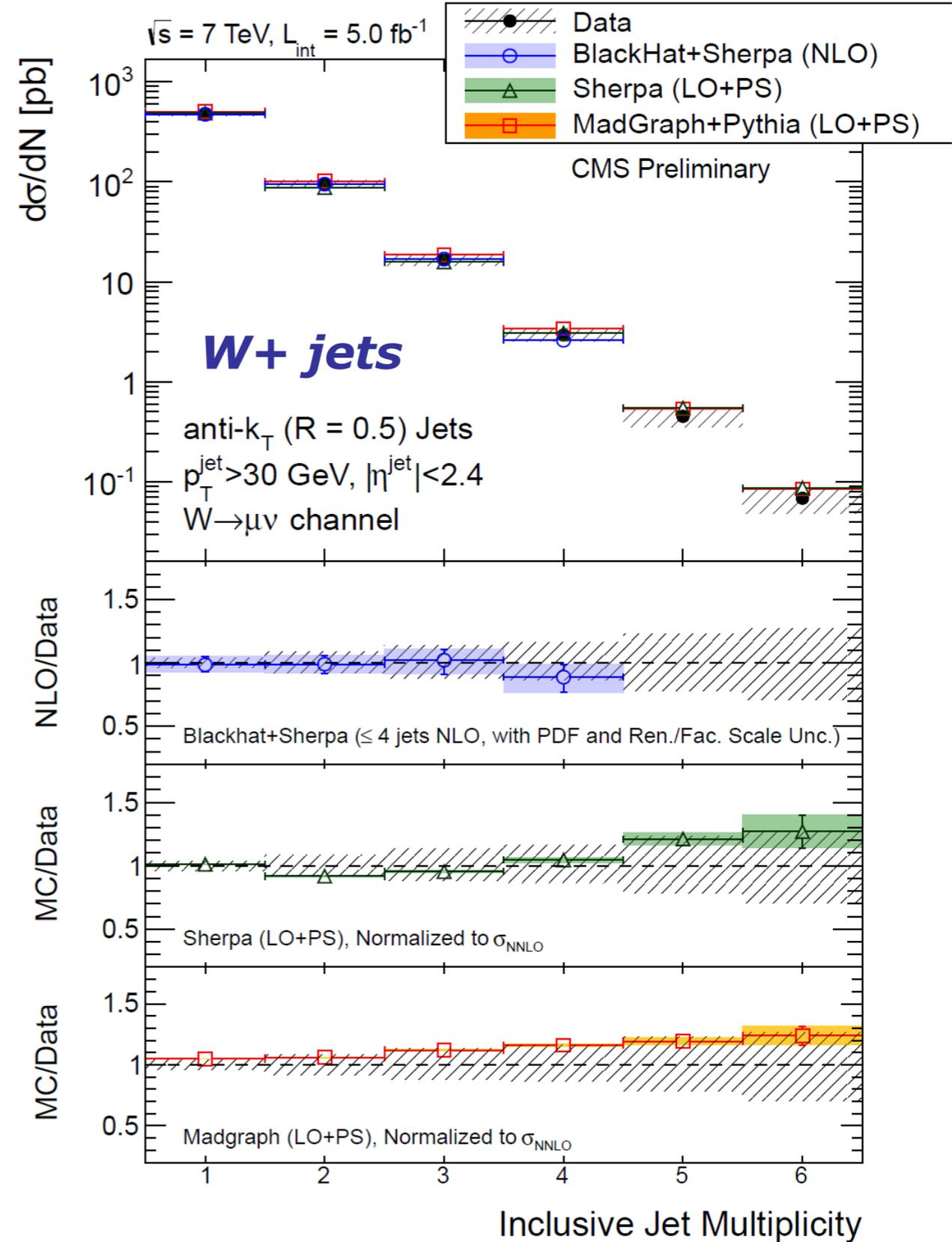
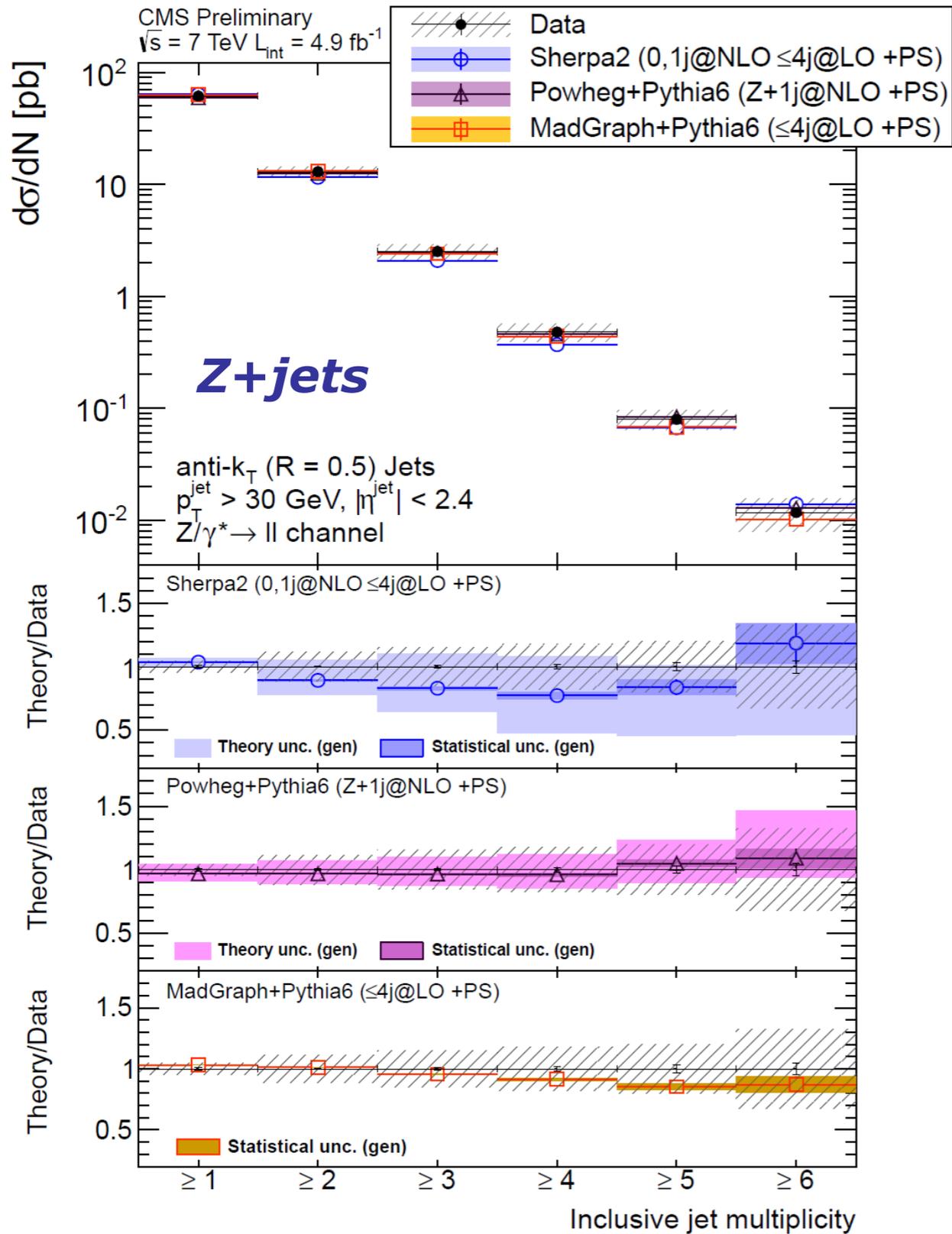
Transverse momentum of Z: $p_T(Z)$ (ATLAS)

H. Martinez Bruzal



- ▶ Z pt distribution sensitive to QCD dynamics
- ▶ new ATLAS measurement
 - ▶ from 1 to 800 GeV
 - ▶ great experimental precision
- ▶ NNLO calculations describe the data within 20%
- ▶ NLO + NNLL calculations and MC generators with parton shower provide better description

V+Jets in CMS



Z+2jets (VBF) electroweak production

[CMS-FSQ-12-035](#) new!

- 8 TeV measurement of EW production of Z + 2 jets (see back-up for the previous study @7 TeV)
- Signal extraction by MVA discrimination (I) and dijet Fisher discriminant fit (II)
- MADGRAPH for event generation with CTEQ6L1 PDF
- VBFNLO program for NLO calculations
- **The measured cross section is in agreement with theoretical value (239 fb)**

By MVA method in dimuon channel:

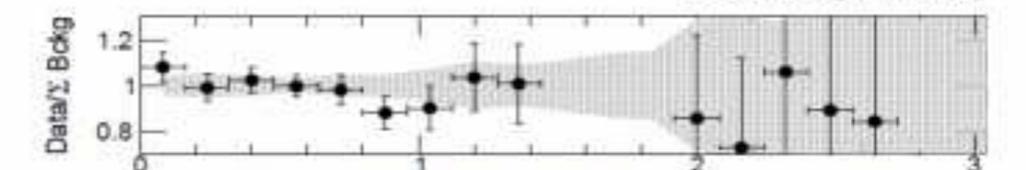
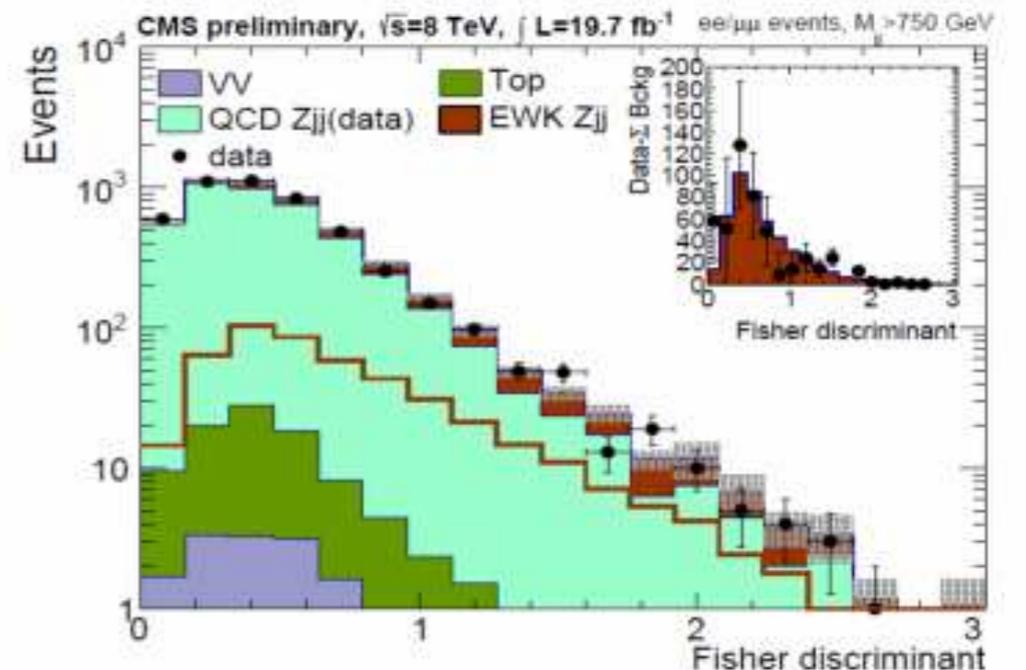
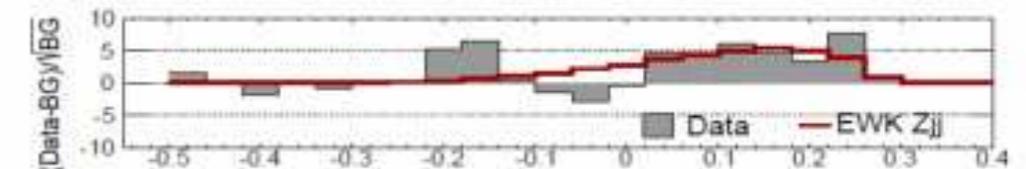
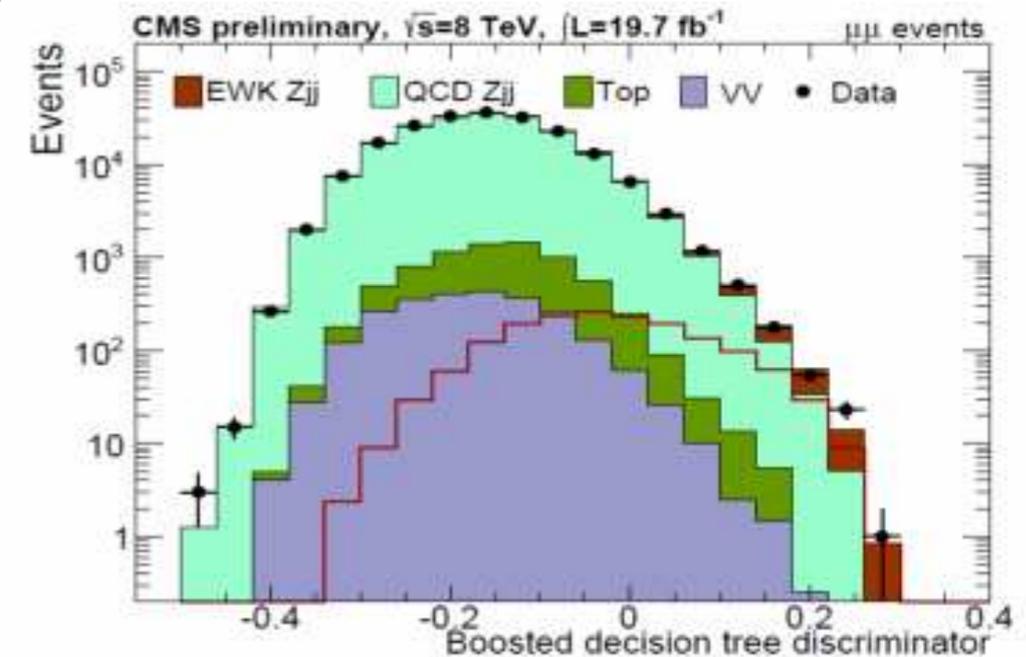
$$\sigma(\text{EWK } ll + jj)_I = 191 \pm 29_{\text{stat}} \pm 39_{\text{syst}} \text{ fb}$$

By dijet analysis in dimuon and dielectron channels:

$$\sigma(\text{EWK } ll + jj)_II = 303 \pm 29_{\text{stat}} \pm 57_{\text{syst}} \text{ fb}$$

Combined result (by using Best Linear Unbiased Estimator technique) in dimuon channel:

$$\sigma(\text{EWK } lljj) = 226 \pm 26_{\text{stat}} \pm 35_{\text{syst}} \text{ fb}$$



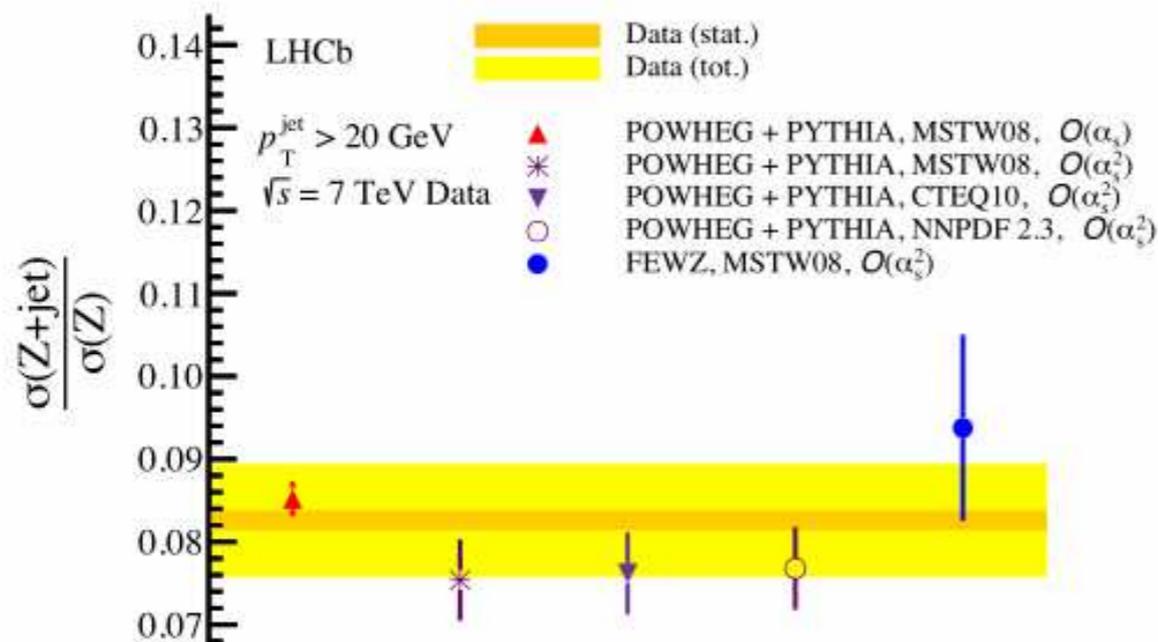
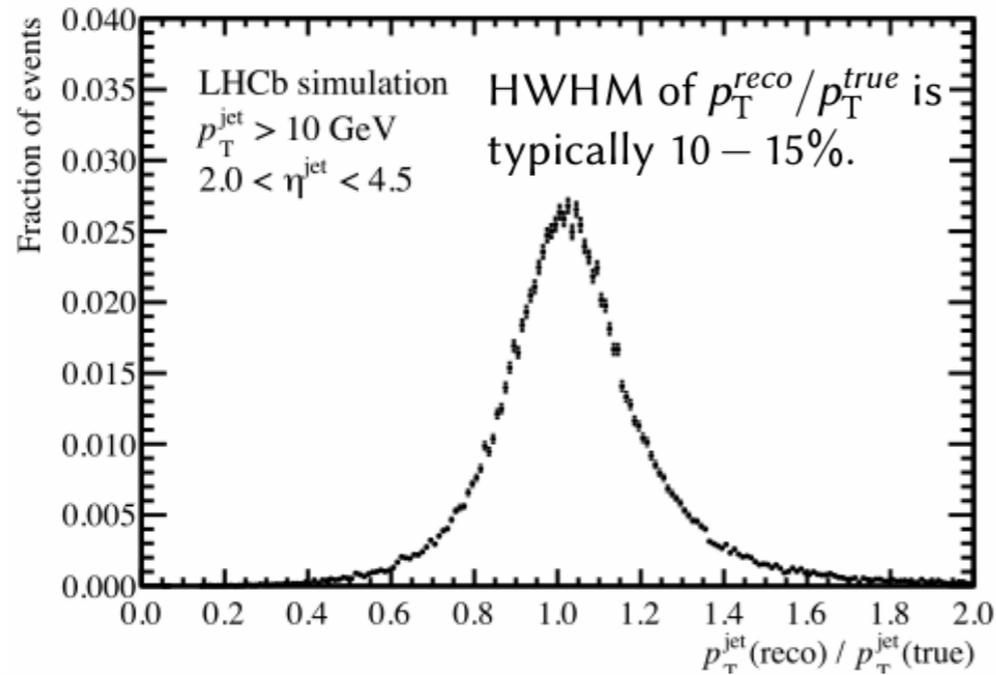
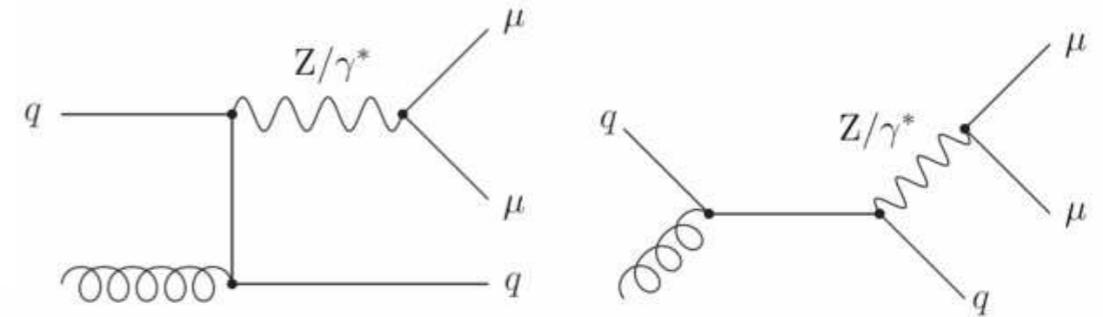
Signal extracted from the fit to the discriminator shapes

Z+jets in LHCb

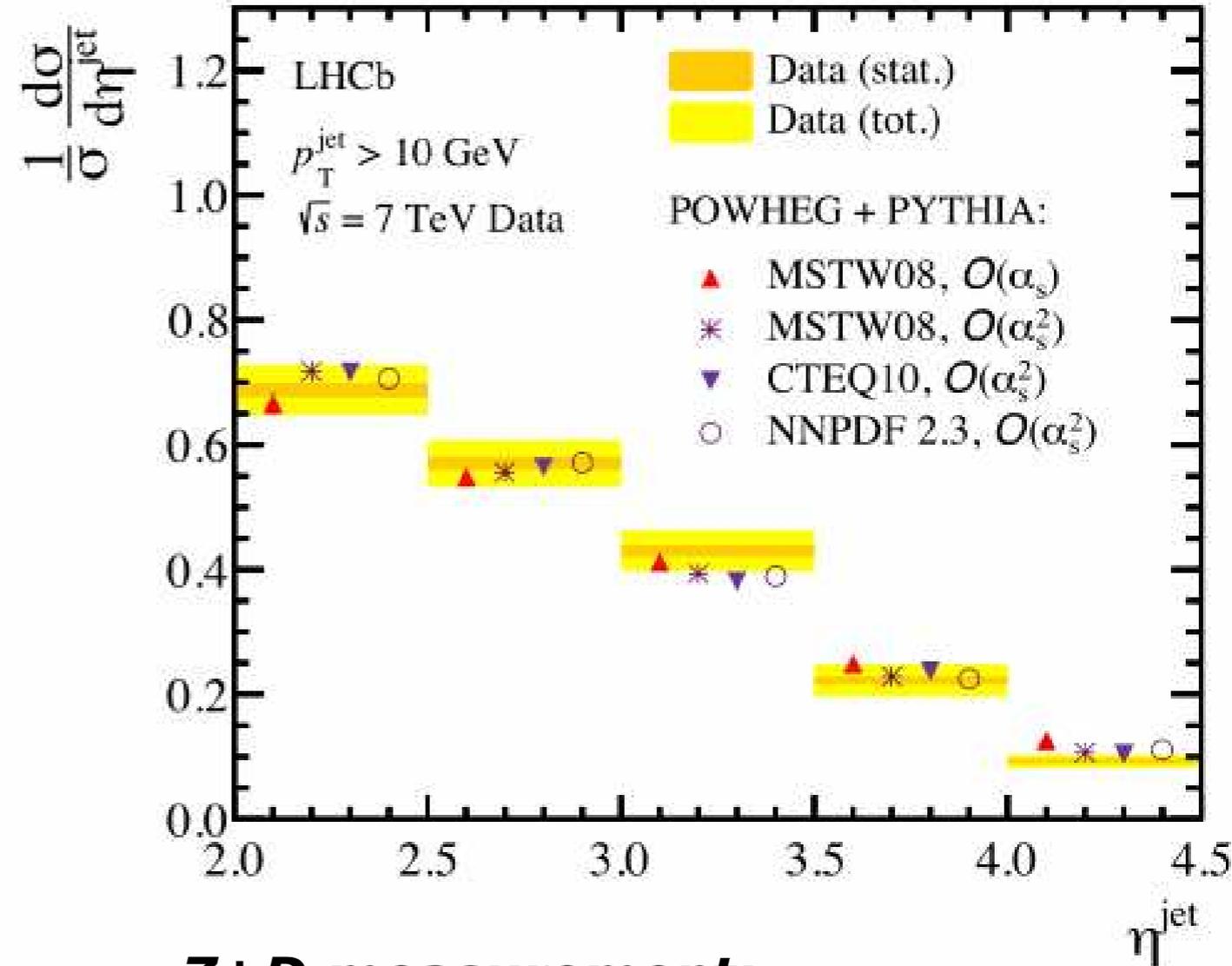
M. Sirendi

New Player: First jet measurement in LHCb

Particle-flow with calorimeter energy deposits



Data not corrected for UE and hadronization



Z+D measurement:

7 Z+D⁰ events measured

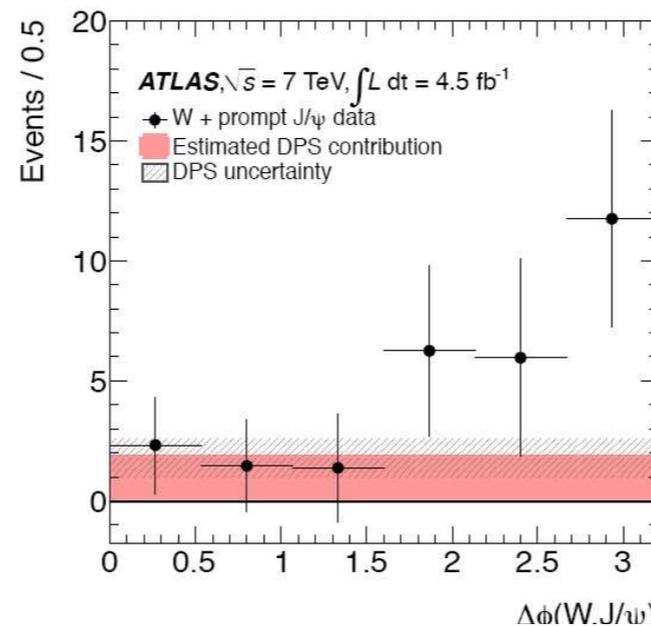
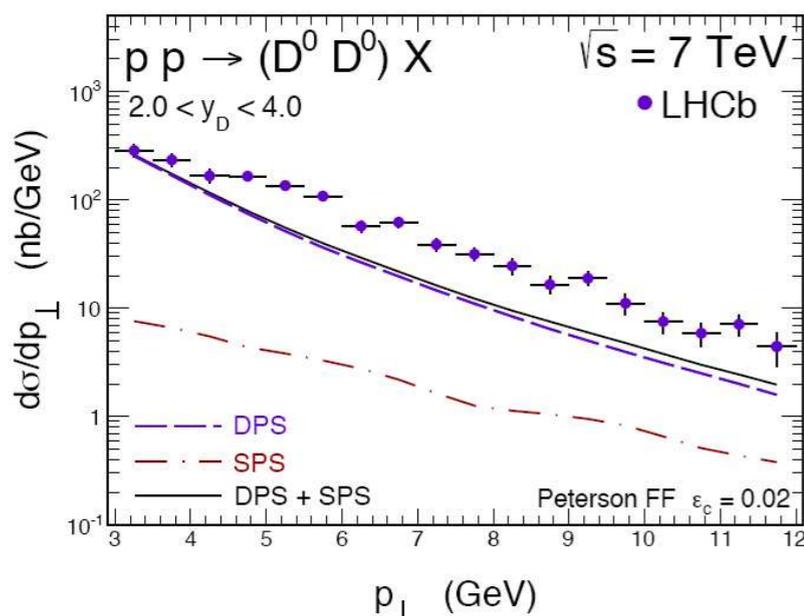
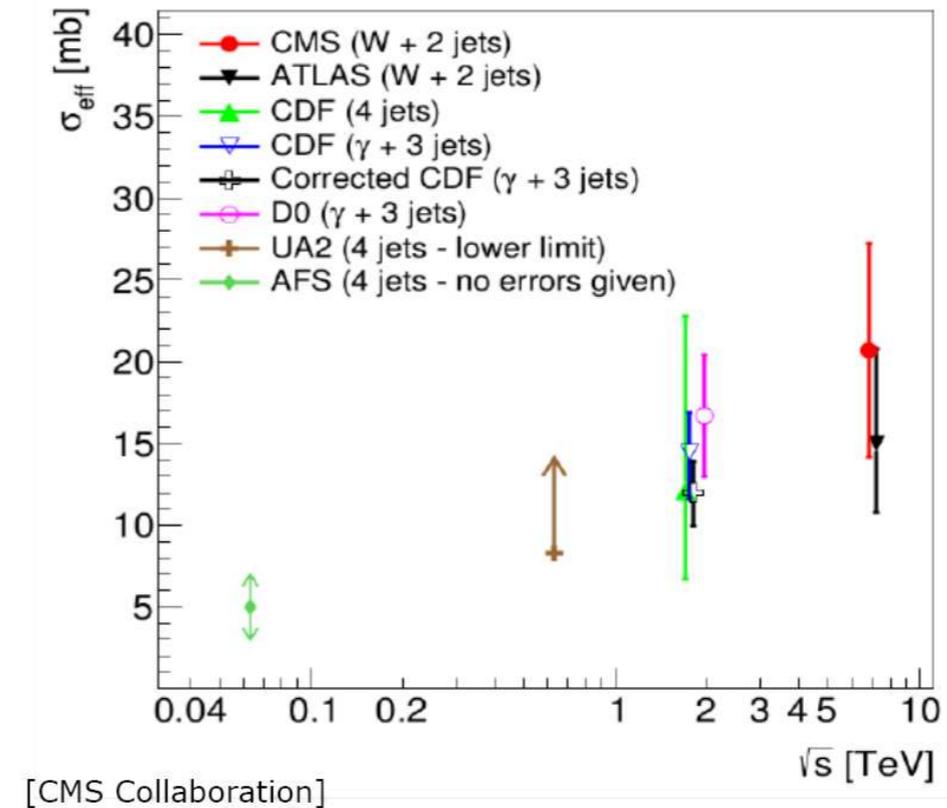
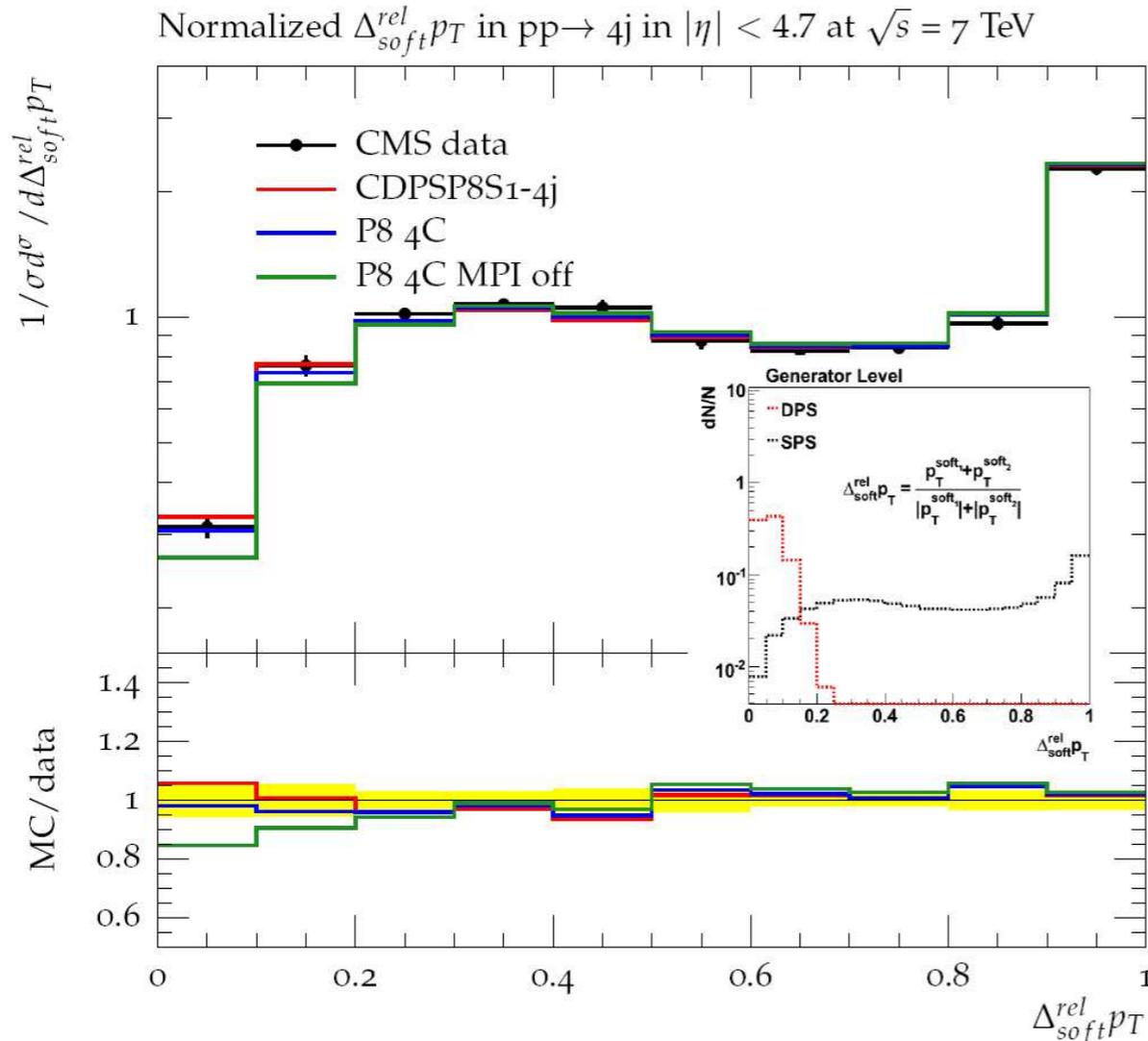
4 Z+D⁺ events measured

-> 5.1 σ

-> More statistics

Double Parton Scattering (CMS, ATLAS)

H. Arnold
A. Grebenyuk
P. Gunnellini
A. SZCZUREK



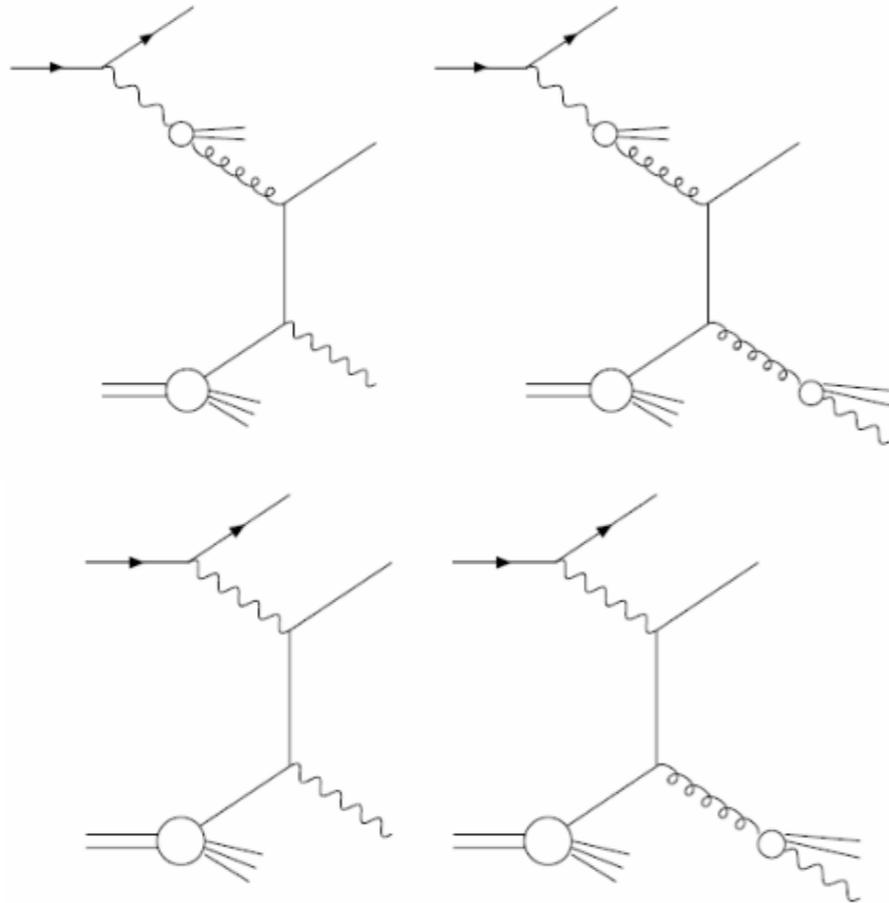
▶ DPS increasingly interesting at LHC
 ▶ several final states suitable for DPS observation

- ▶ W+jj (ATLAS, CMS)
- ▶ W+J/ψ (ATLAS)
- ▶ double meson production (very prominent final state: DPS is dominant !!)
- ▶ new measurements of σ_{eff} confirm approximate value of ~ 15 mb

Photons in Photoproduction (ZEUS)

Prompt photons in photoproduction

- Inclusively
- With accompanying jet



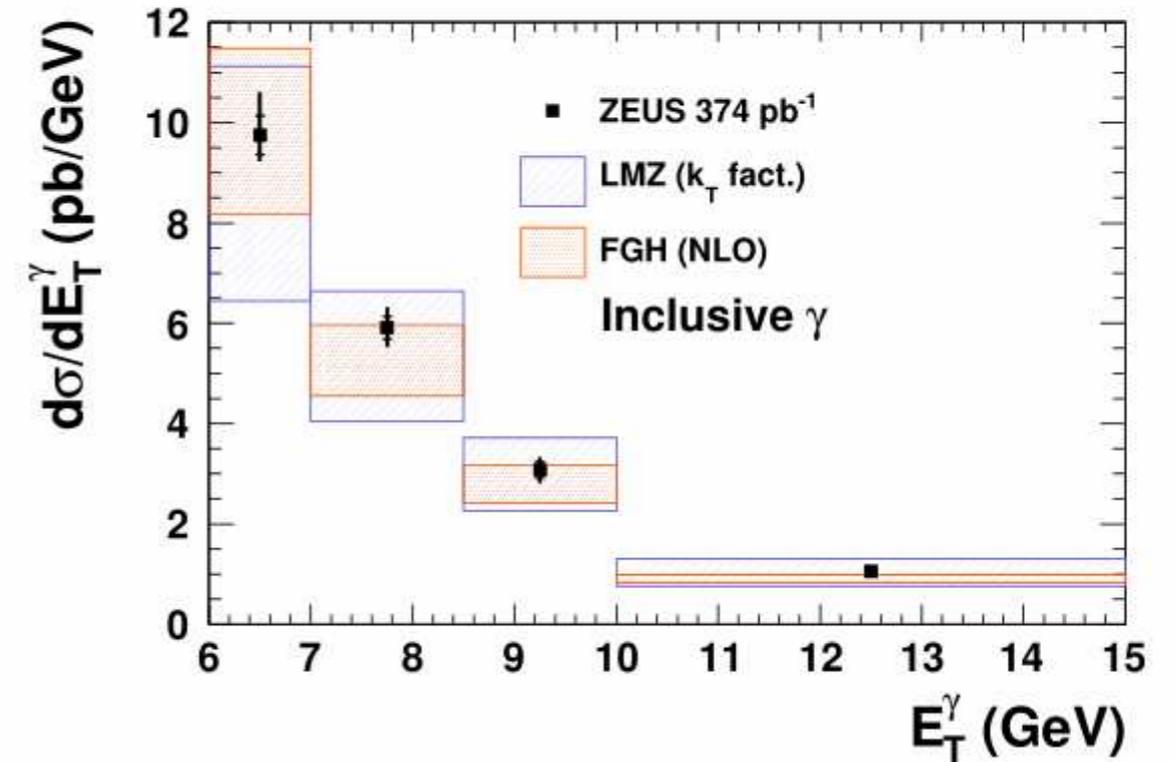
pQCD predictions in NLO

- Good description of data

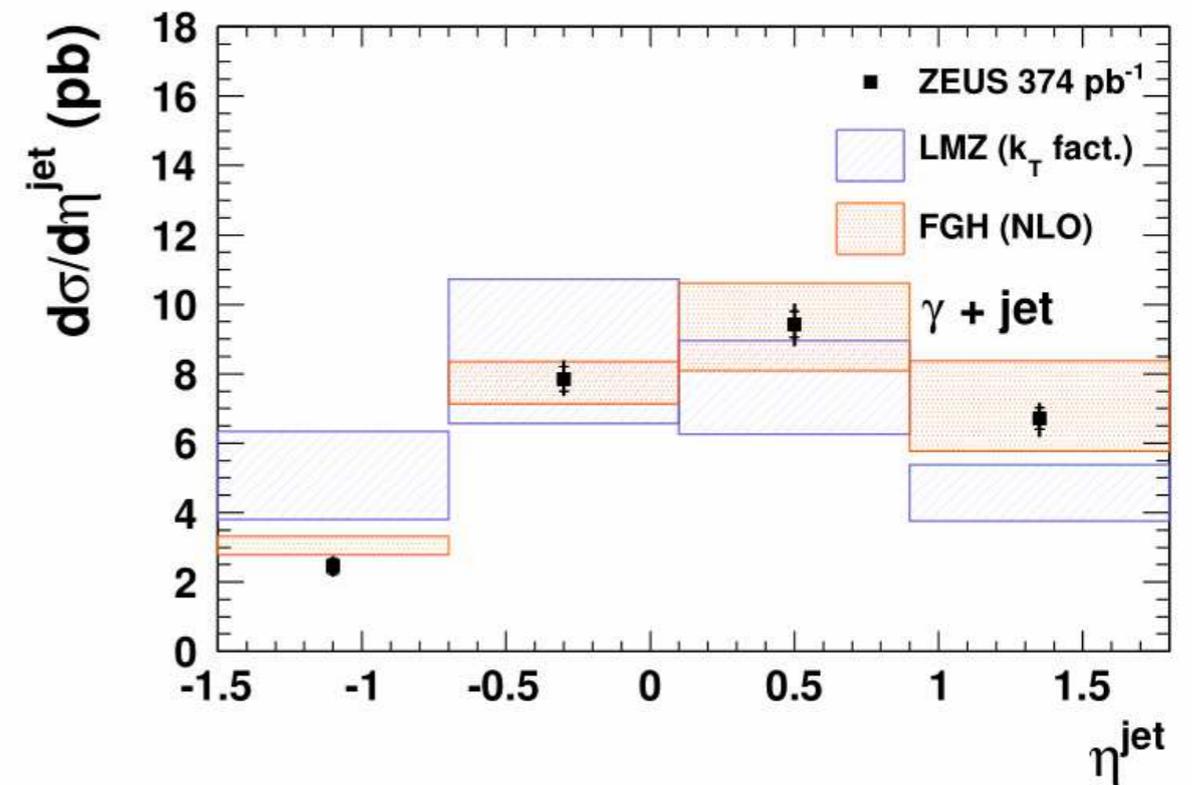
K_T factorization calculations

- few deficits in η^{jet}

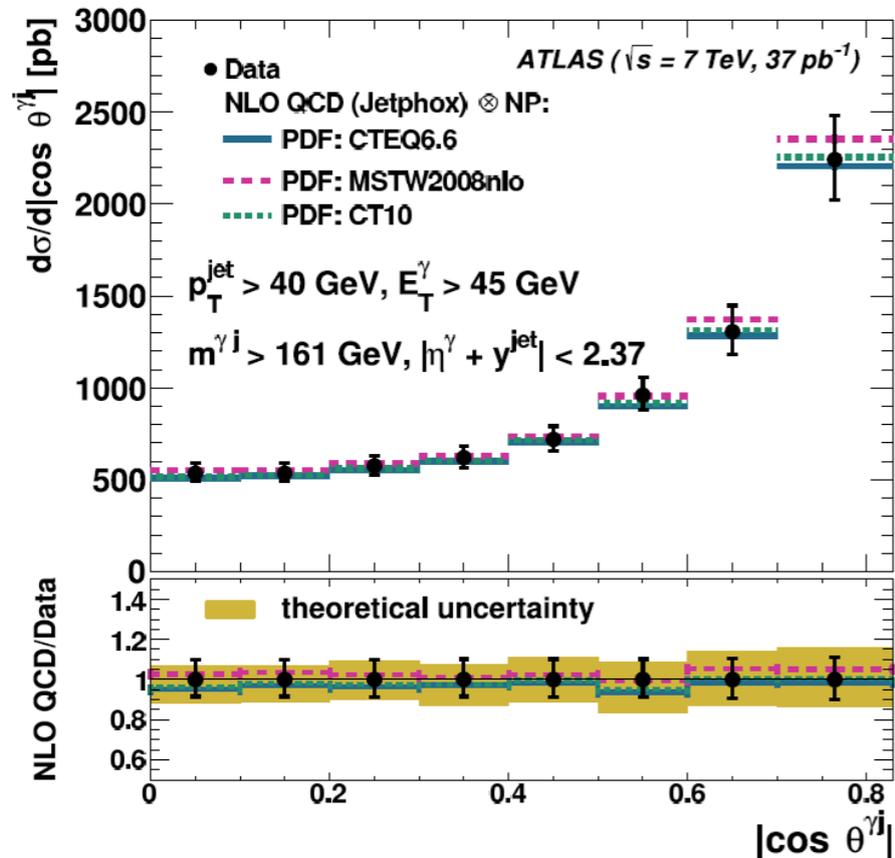
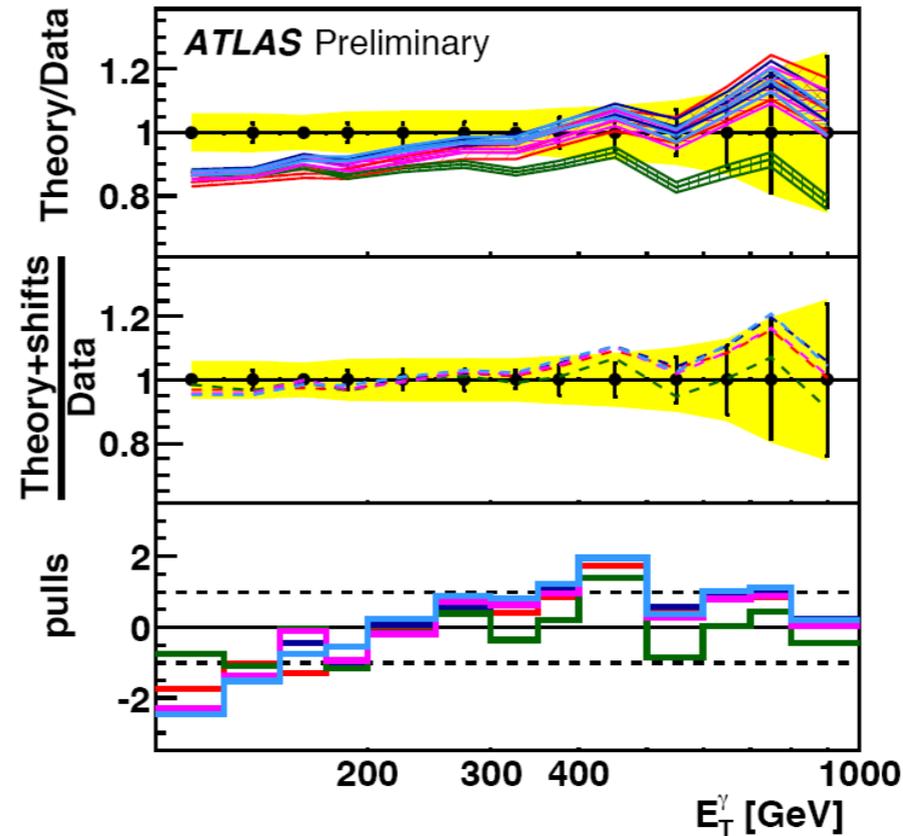
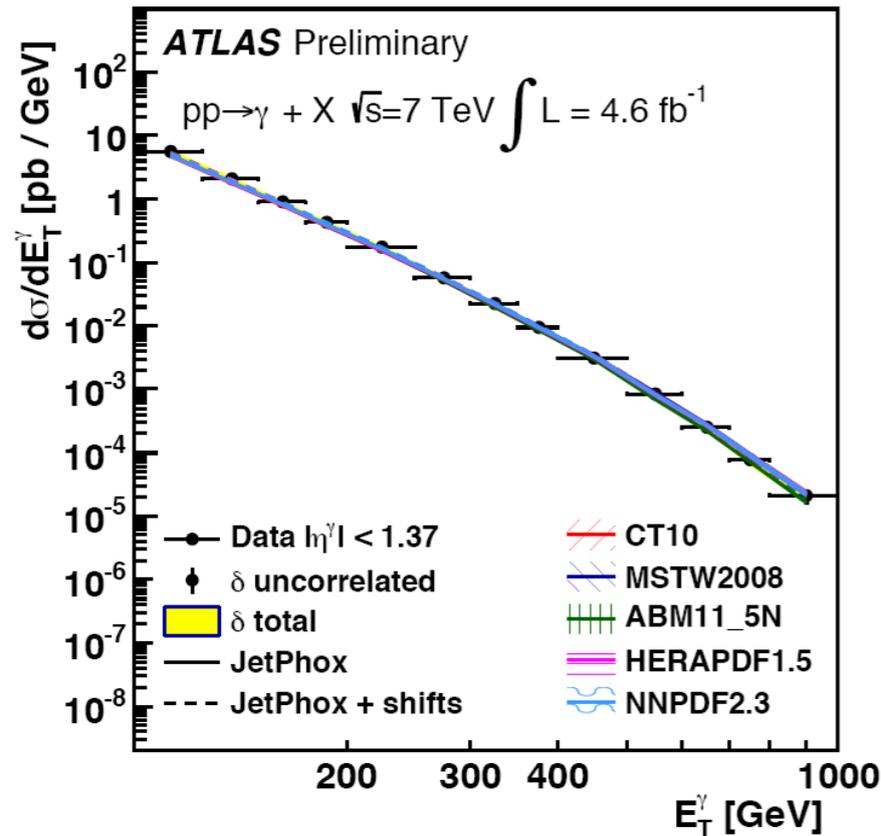
ZEUS



ZEUS



Photons at LHC (ATLAS)



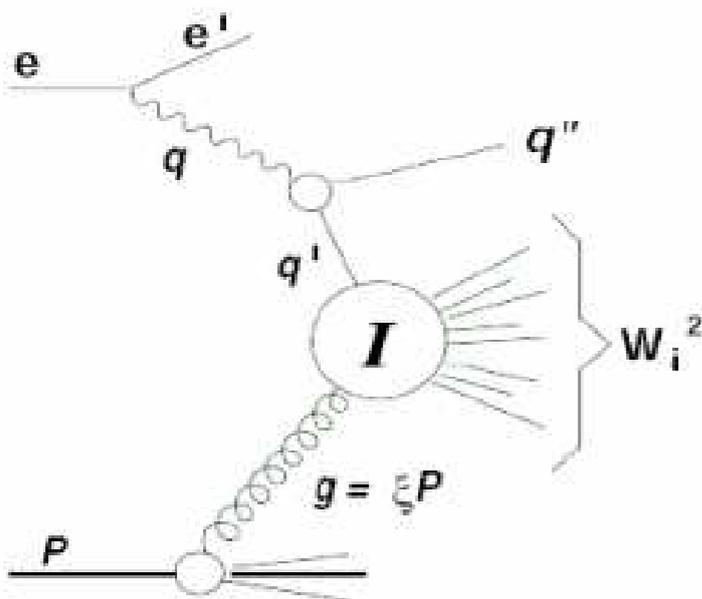
- ▶ most precise measurement of inclusive photon and photon + jet production with 7 TeV data
- ▶ NLO QCD predicts the p_T spectrum with relative accuracy
 - ▶ but tension with the various PDF sets
- ▶ measurement can be used to constrain the gluon PDF, but large scale uncertainty (NNLO needed)
- ▶ photon + jet dynamics reproduced well NLO

Search for QCD Instantons (H1)

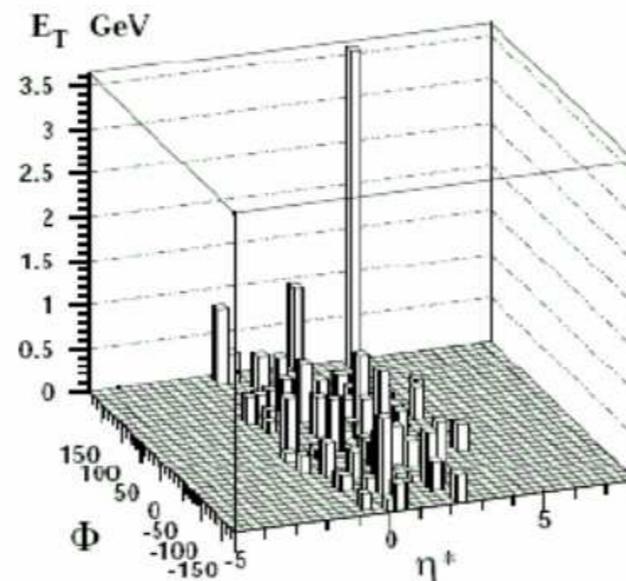
P. Sopicki

Search for QCD instantons at HERA

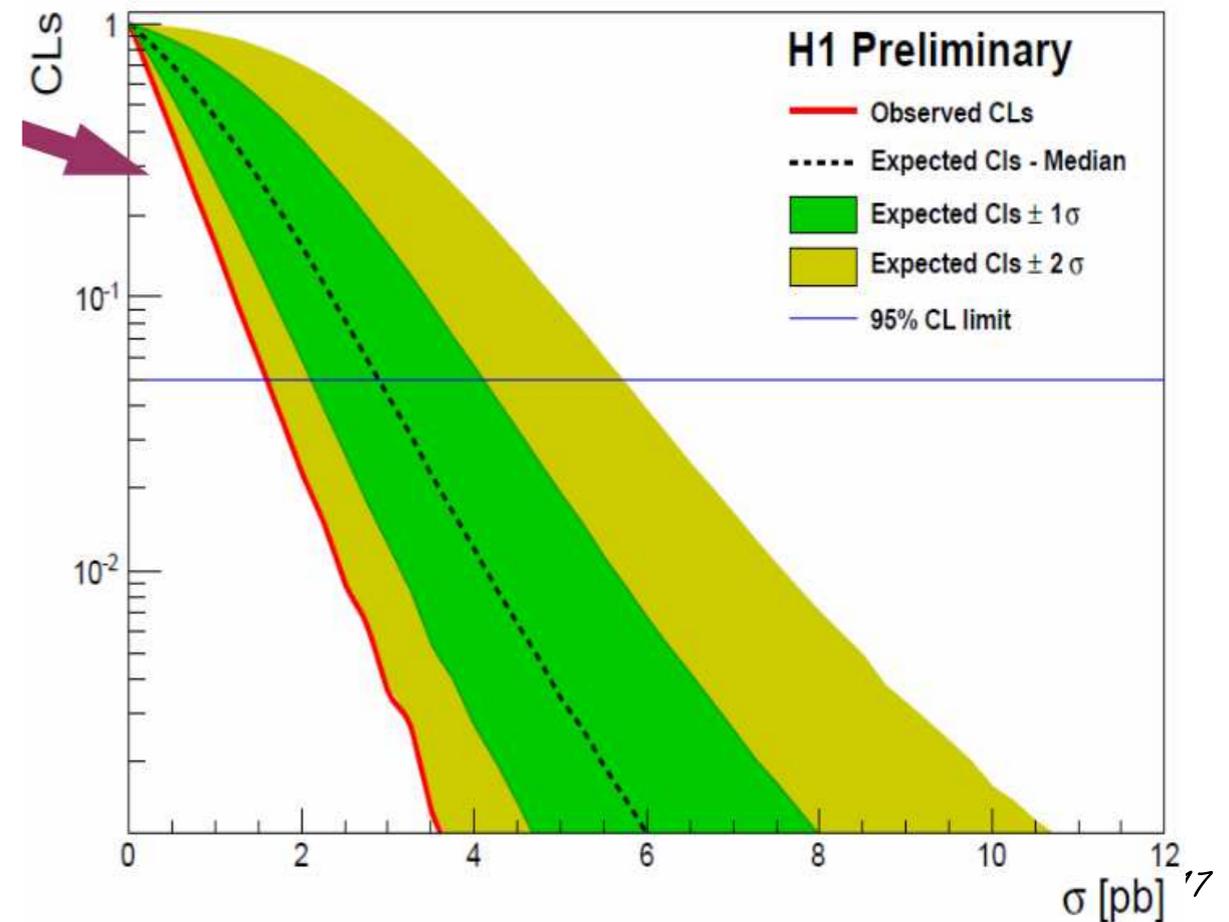
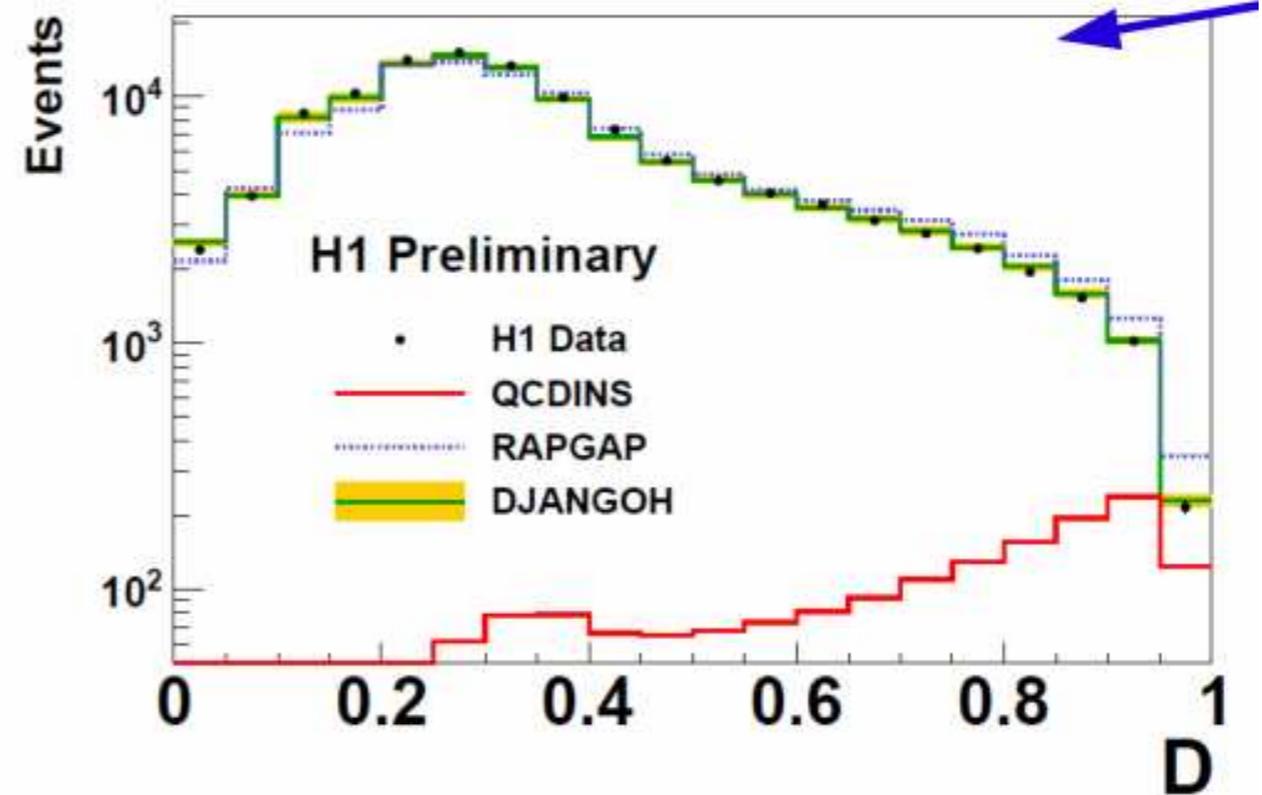
- Instantons are solution to Yang-Mills equation of motion
- Ringwald-Schremp MC event generator employed



'Typical event'
(η, ϕ) - plane: hadronic CMS



PDERS discriminator



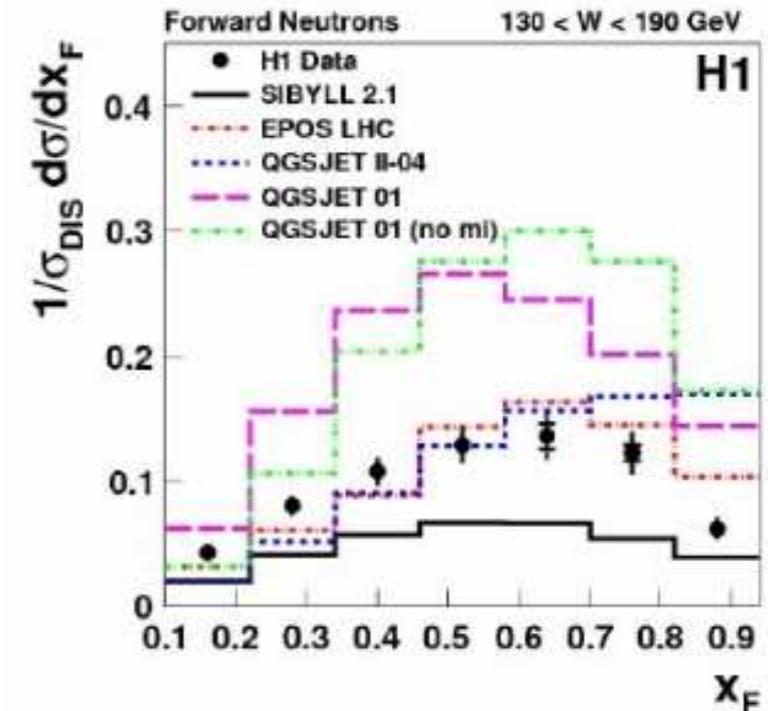
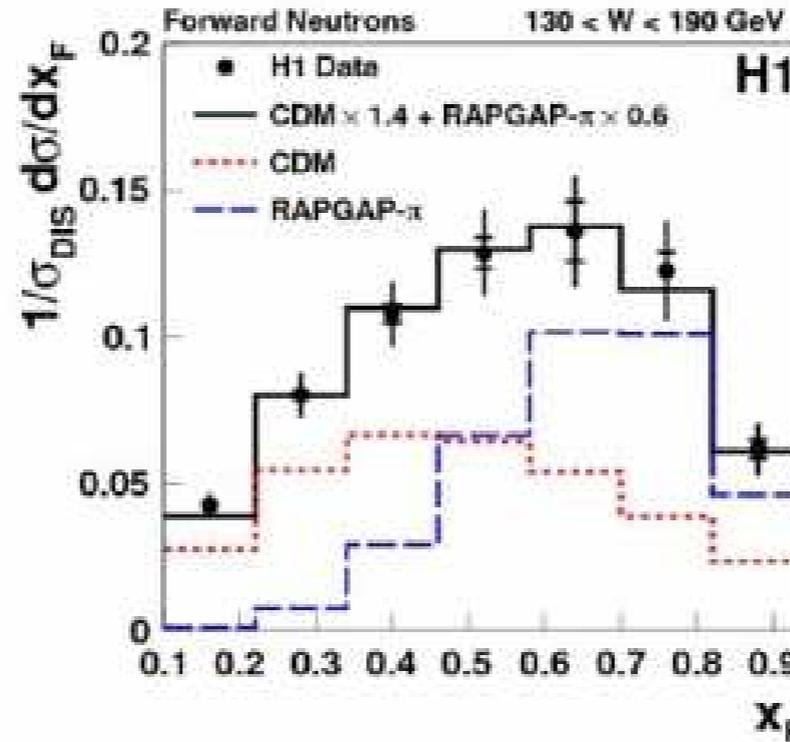
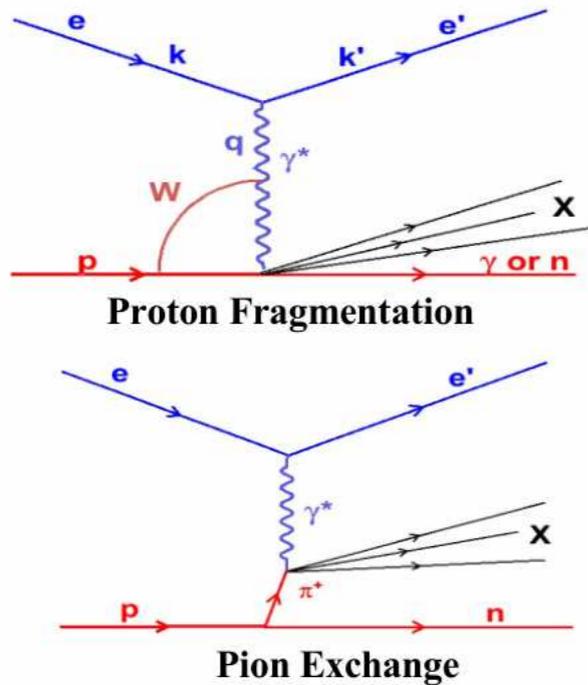
Data are consistent with background and no evidence for QCD Instantons is observed

Upper limit of 1.6pb set

Feynman Scaling in Photon and Neutron Production (H1)

J. Olsson

Very forward: $\eta > 7.9$



Feynman-x variable

$$x_F = 2p_{||}^*/W = p_{||}^*/p_{||,max}^*$$

Photons

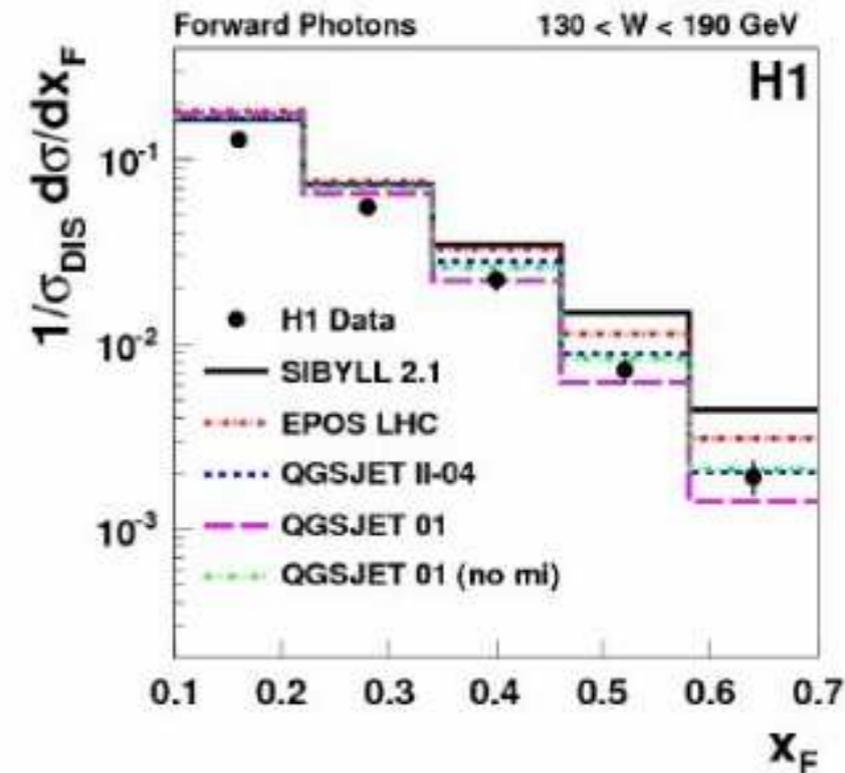
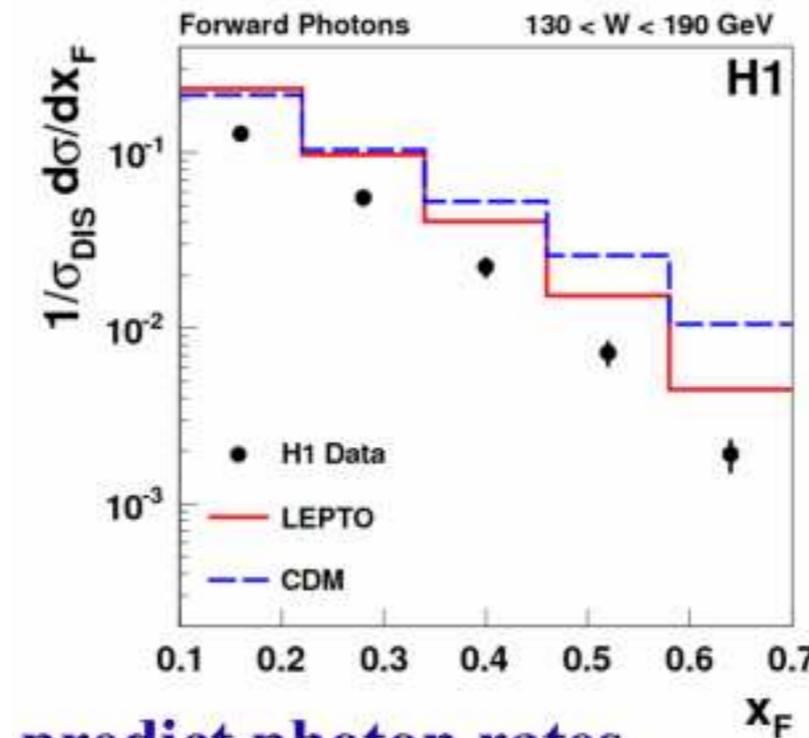
- from proton fragmentation (π^0 decay)

Neutrons

- from proton fragmentation and pion exchange

Compare to

- ep MC Models
- Cosmic Ray Models

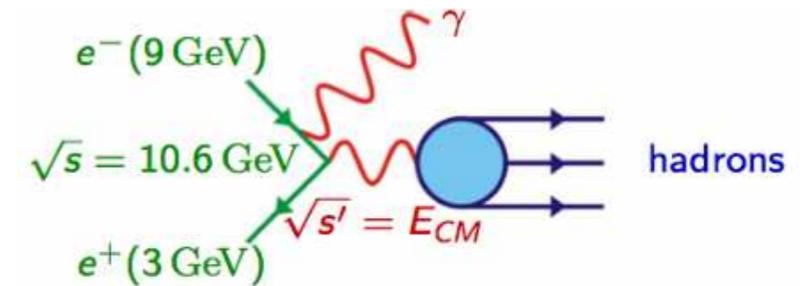


Light meson production in Babar: $e^+e^- \rightarrow \pi^+\pi^-$

G. CIBINETTO

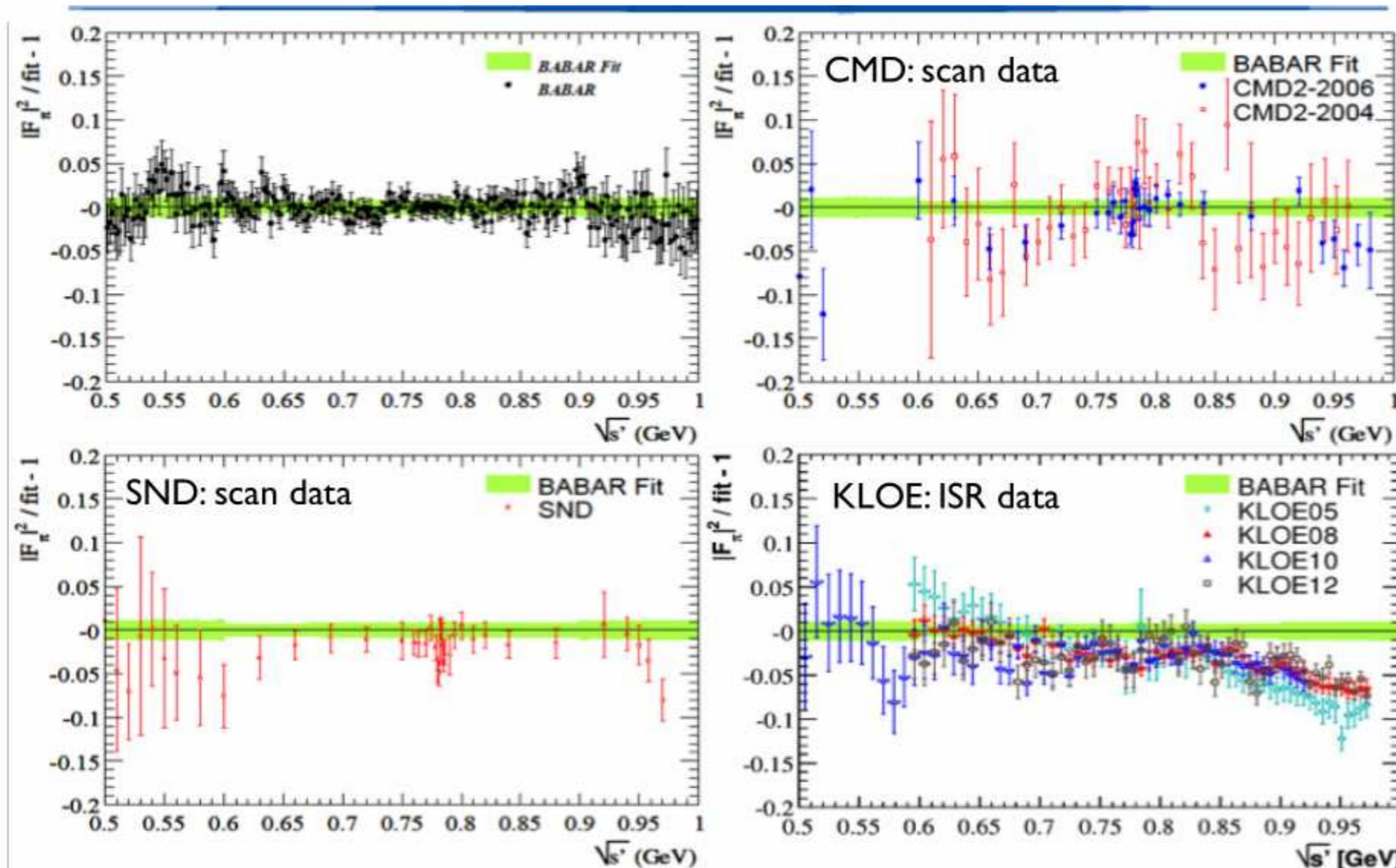
Hadronic cross sections accessible via initial-state radiation

- 232 fb⁻¹ of data analysed
- Compare fitted cross section to other measurements



Further results on $e^+e^- \rightarrow K^+K^-$

- Results on $a_\mu^{KK,LO}$ about 2.6 times better than previous world average



Theory presentations

Antoni SZCZUREK

Double charmed meson production at the LHC. Single- versus double-parton scattering mechanism

Hannu PAUKKUNEN

LHC data challenges the contemporary parton-to-hadron fragmentation functions

Medley JACK

High Energy Jets at the LHC

Krzysztof KUTAK

Azimuthal decorrelations in forward central dijets production at LHC within high energy factorization

Hans VAN HAEVERMAET

Higgs boson as a gluon trigger

Alexander Thomas GORITSCHNIG

Hard exclusive J/Ψ photoproduction off a proton

Jean-Philippe LANSBERG

Associated-quarkonium production

The inclusive h^+h^- production at the LHC

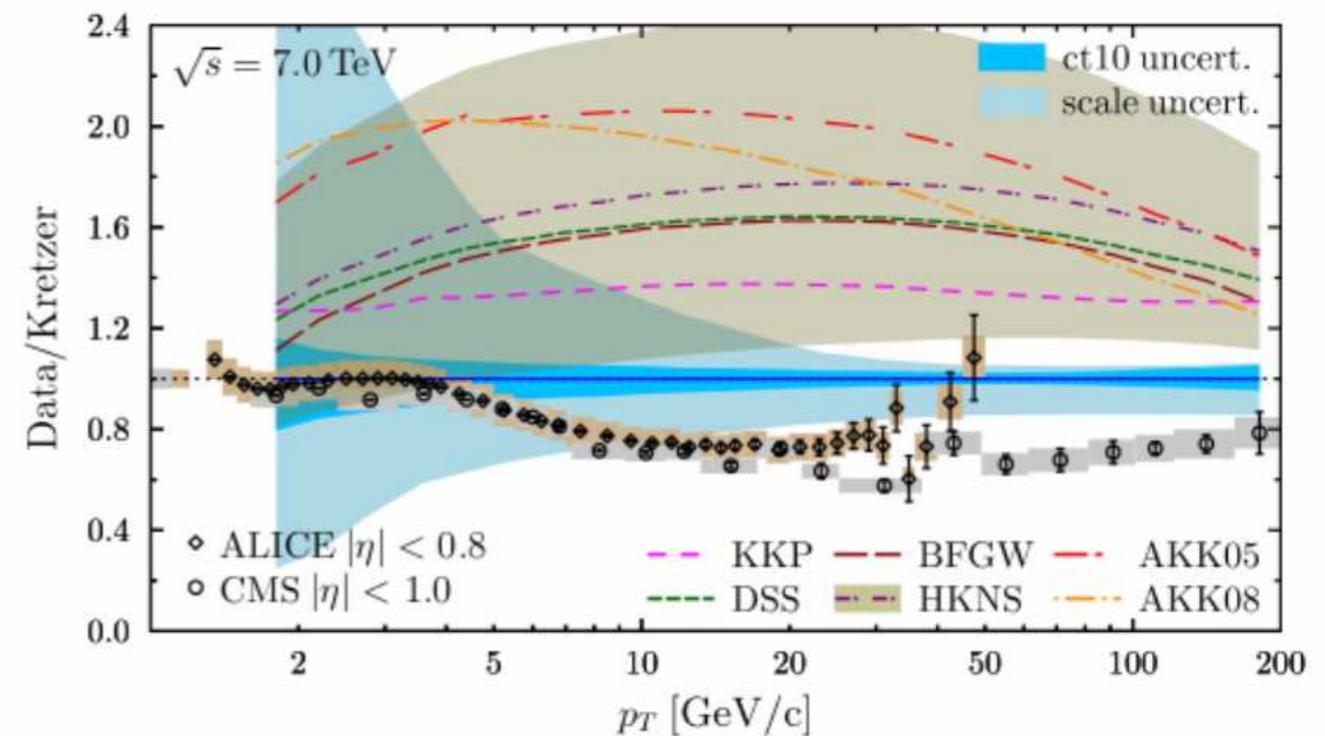
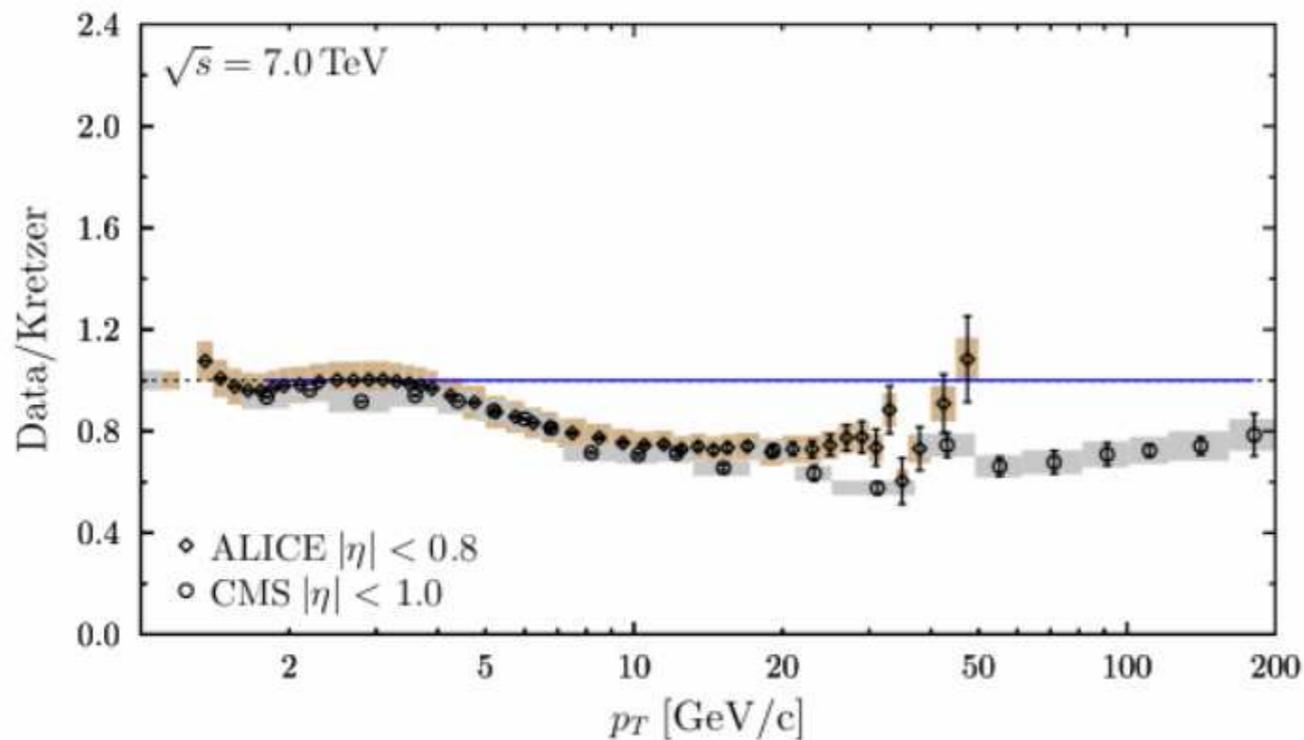
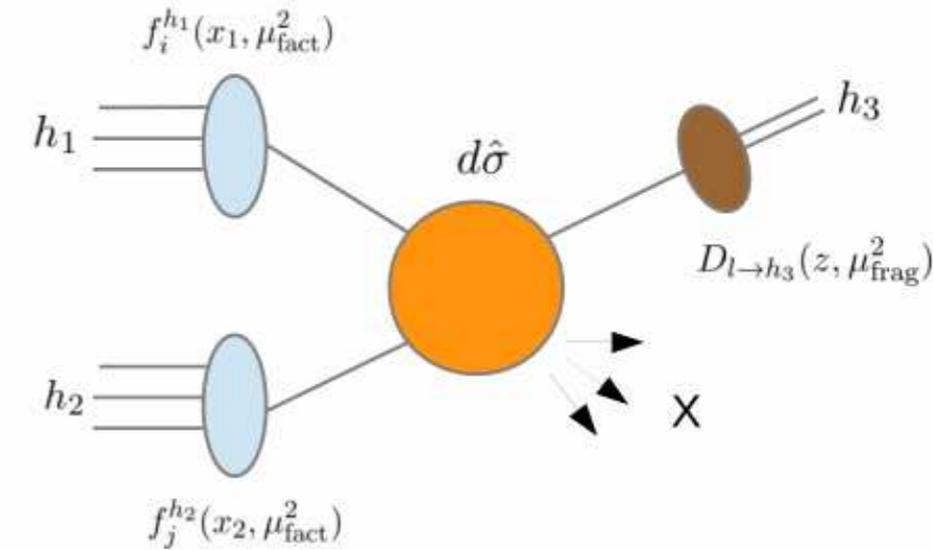
H. Paukkunen

Detailed analyses of inclusive charged hadron production spectra

- NLO calculations overshoot data by CMS and ALICE
- ALICE and CMS data compatible

Compare contemporary Fragmentation Function

- Only a smallish PDF uncertainty
- Enormous scale uncertainty at small p_T – moderate at large p_T
- The other FFs disastrously overshoot the data



None of the current sets of NLO FFs can optimally describe the LHC and Tevatron charged particle measurements

High energy factorization

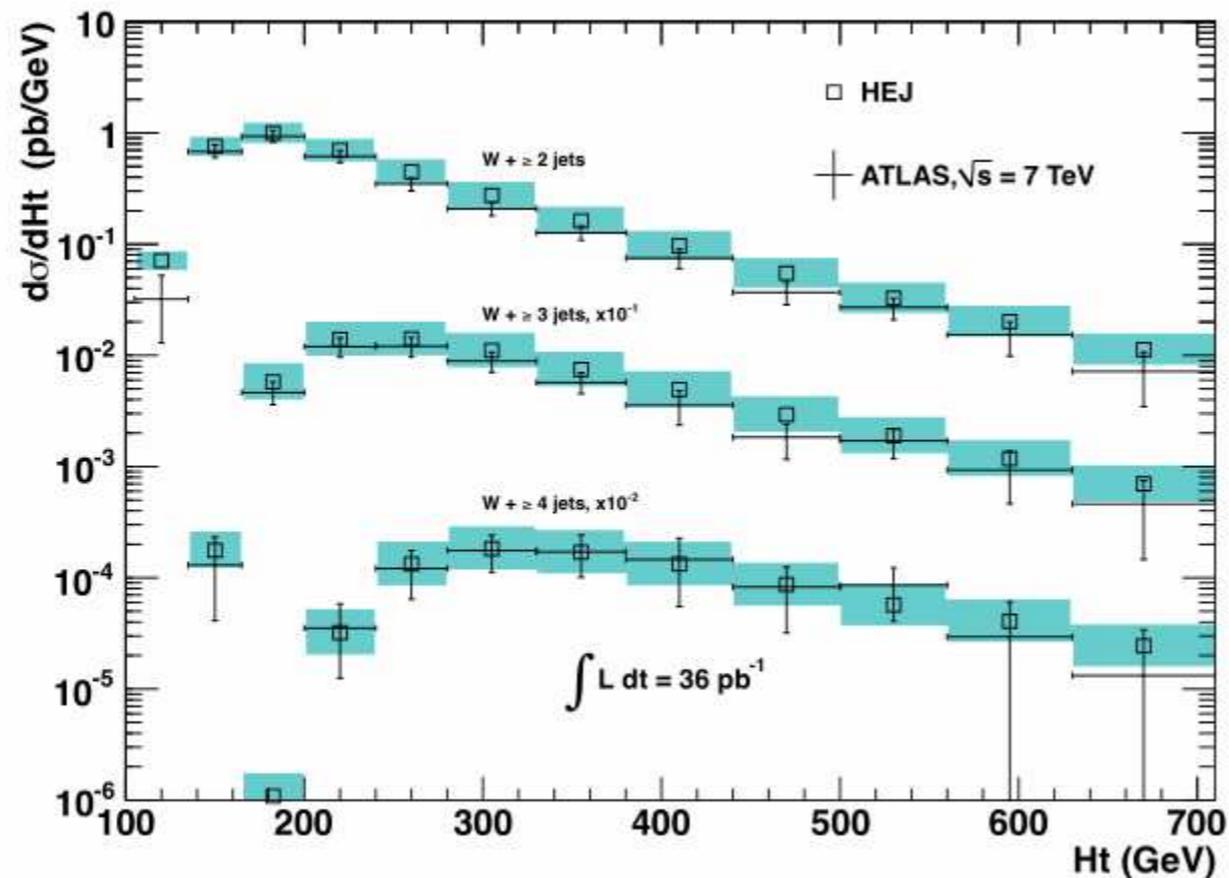
M. Jack
K. Kutak

Updated calculations in framework of high energy factorization

- Based on BFKL equations

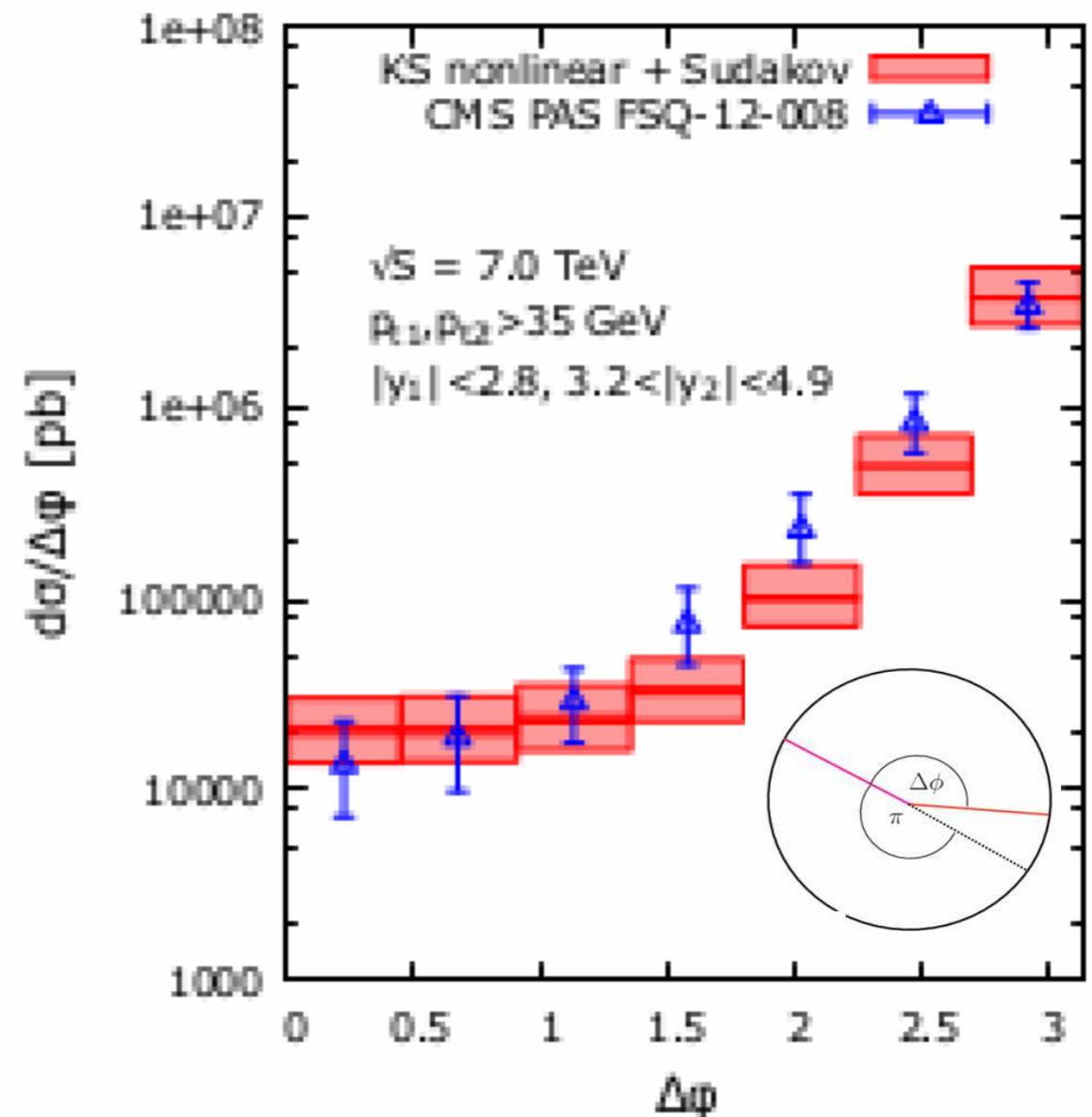
High energy jets

- Wide range of processes can be described
- Newly added extra configurations which are not resummed to 4 jets
- New predictions for W+jets (2,3,4 jets)



Azimuthal decorrelations of dijets

- Dijets p_T spectra already available
- Including Sudakov effects from LxJet



Higgs as a gluon trigger

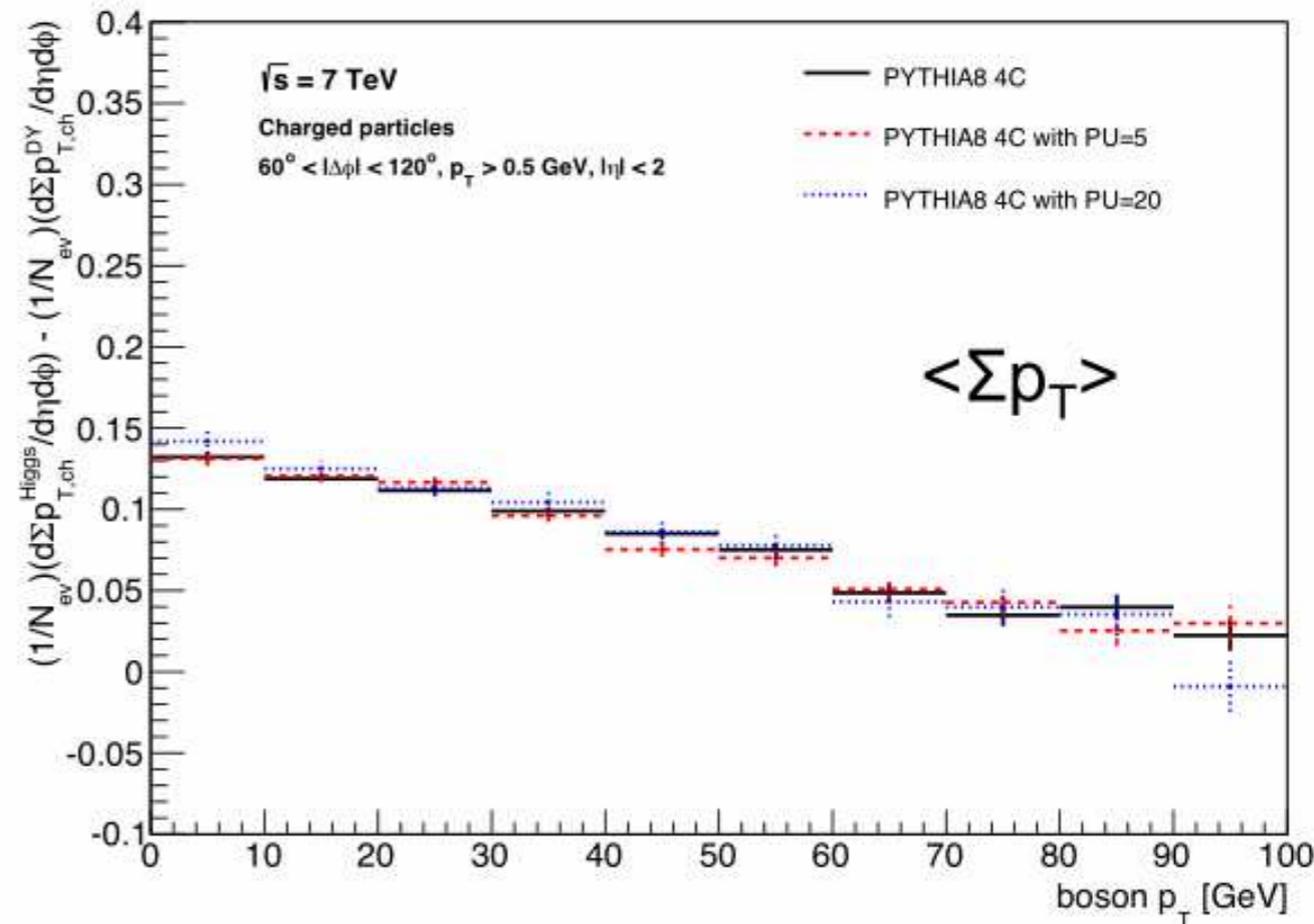
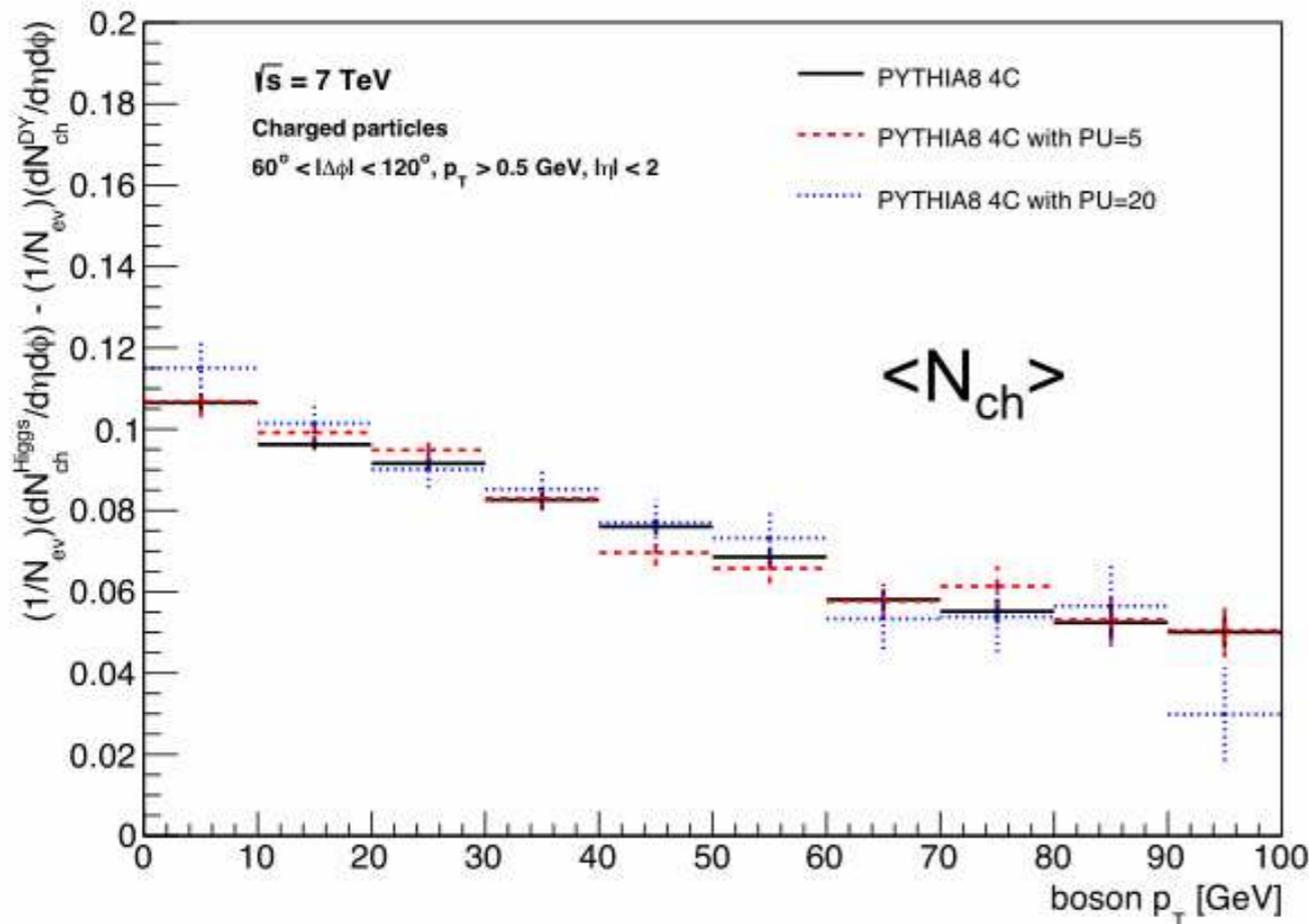
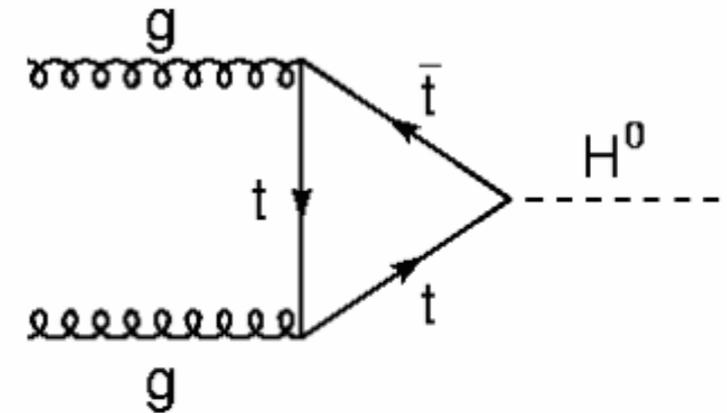
Proposed measurement for high-pile up environments

- High pile-up runs -> High Luminosity

Compare Higgs and Drell-Yan production in same mass range

- Difference in soft gluon resummation
- Measure gluon induced effects directly
- Ratio is stable in high PU environments

UE will still be measurable in high pile-up environments



Hard exclusive J/Ψ (and Φ) photoproduction off a proton

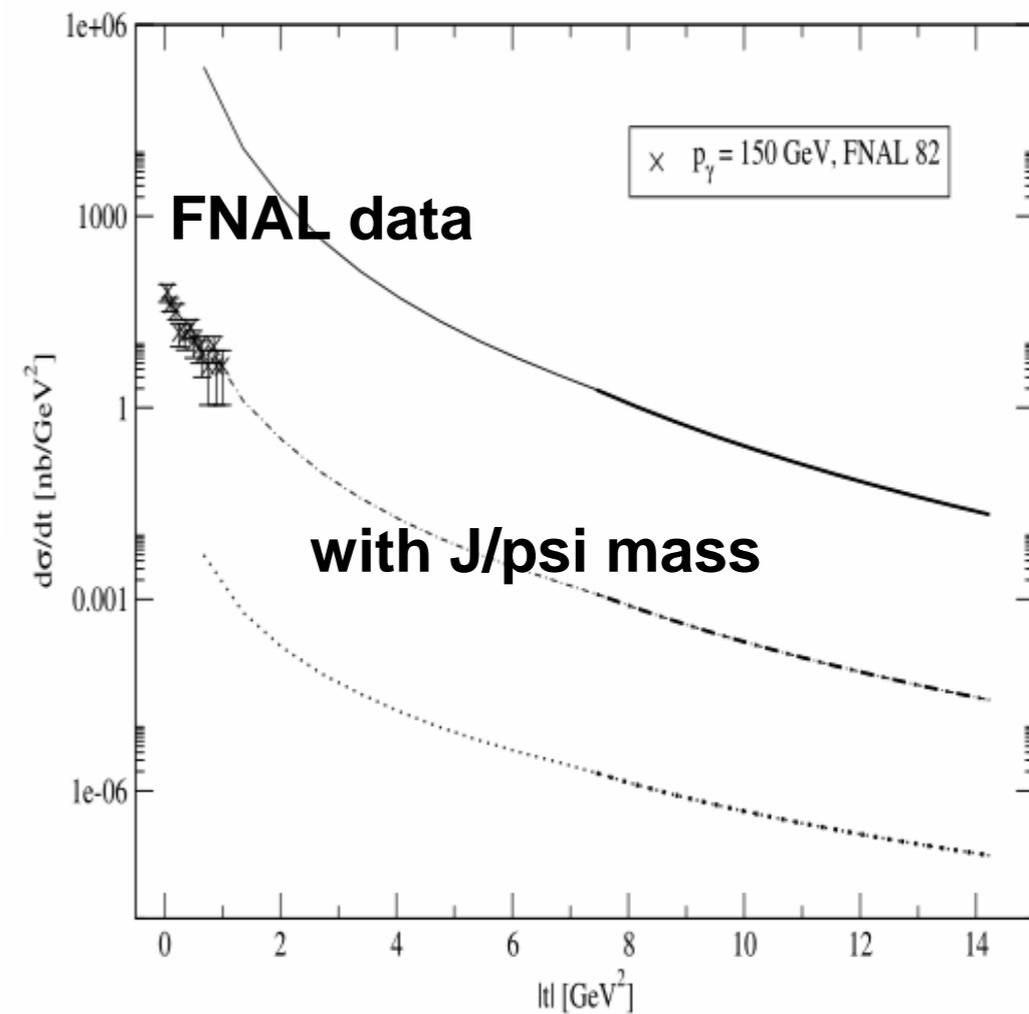
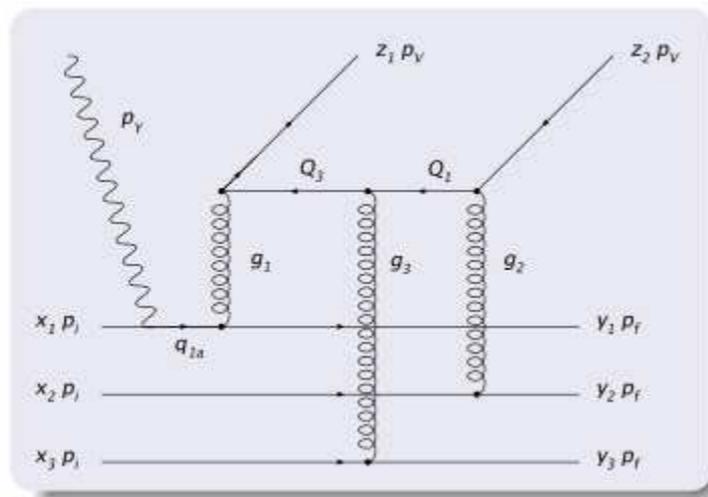
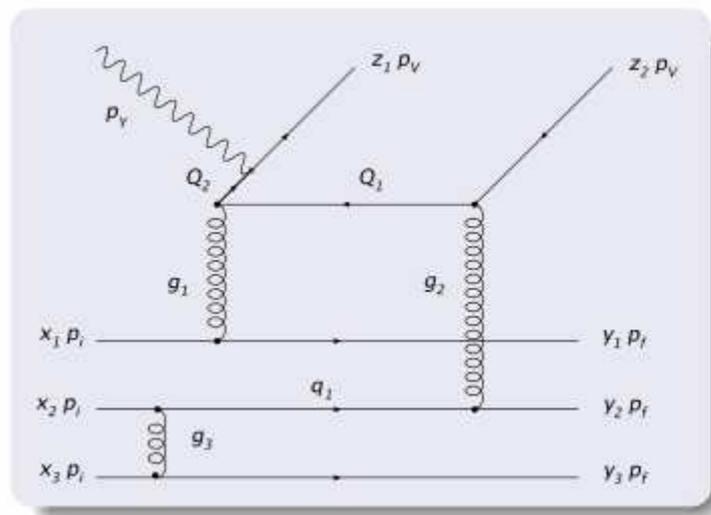
Investigate J/psi in photoproduction at large four-momentum transfer |t|

$$\gamma(p_\gamma) p(p_i) \rightarrow J/\Psi(p_\Psi) p(p_f)$$

at large four-momentum transfer $|t| = |(p_f - p_i)^2|$.

Heavy charm-quark mass sets hard energy scale

- pQCD is applicable
- Work within collinear approximation



Finite c-mass

longitudinally and transversely polarized J/Ψs can be produced.

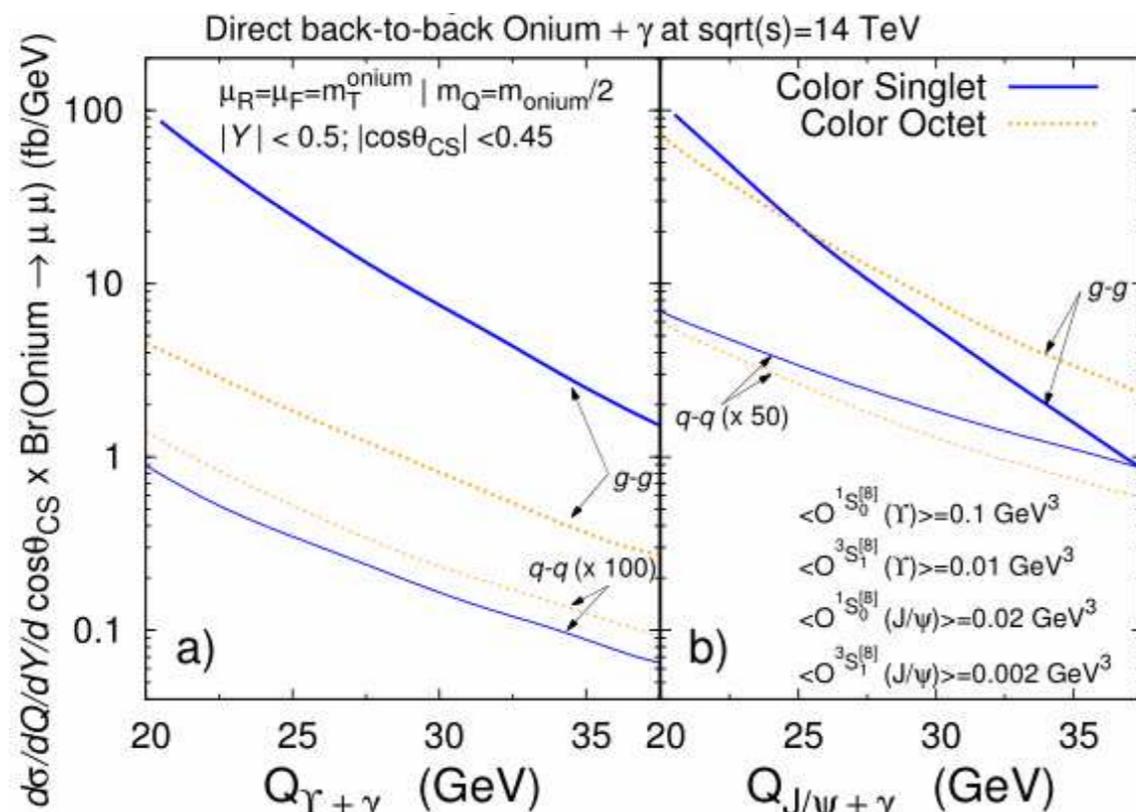
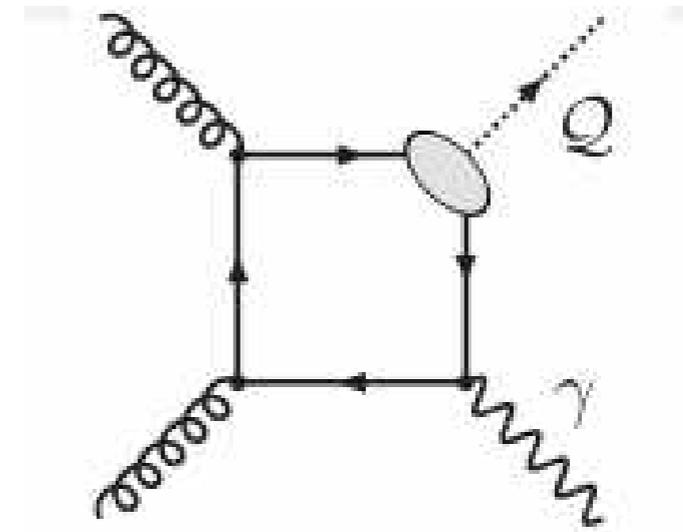
• predictions for $d\sigma_{\gamma p \rightarrow J/\Psi p}/dt$ at $p_\gamma^{(lab)} = 150 \text{ GeV}$

Enormous amount of Associated-quarkonium processes calculated

- Quarkonium pair
 - b-tagged jet
- Quarkonium + isolated photon
- Quarkonium + W boson
- Quarkonium + Z boson
- Quarkonium + hadron
- J/Psi + charm

Quarkonium + isolated photon

- Both back-to-back and isolated
- Back-to-back limits DPS contribution



- Unique candidate to pin down gluon TMDs
 - gluon induced
 - colorless final state
 - small QCD corrections

WG4 Conclusions

- In our working group we had: Great new results, friendly discussions and fantastic quality of all the presentations !
- We saw an impressive performance of the experiments and the theory in many corners of QCD
- Overall a very remarkable description of data by theory and/or models

DIS 2014

XXII. International Workshop on
Deep-Inelastic Scattering and Related Subjects

Warsaw, April 28 - May 2, 2014



Many thanks to all the speakers !!!

**And to everybody who has
contributed to the results**

Study of the K_{e4} decay mode properties

* 1.11 millions of reconstructed $K^{\pm} \rightarrow \pi^+\pi^-e^{\pm}\nu$ / $K_{e4}(\pm-)$ / and
 ~65000 of $K^{\pm} \rightarrow \pi^0\pi^0e^{\pm}\nu$ / $K_{e4}(00)$ / decays (2003+2004 data).

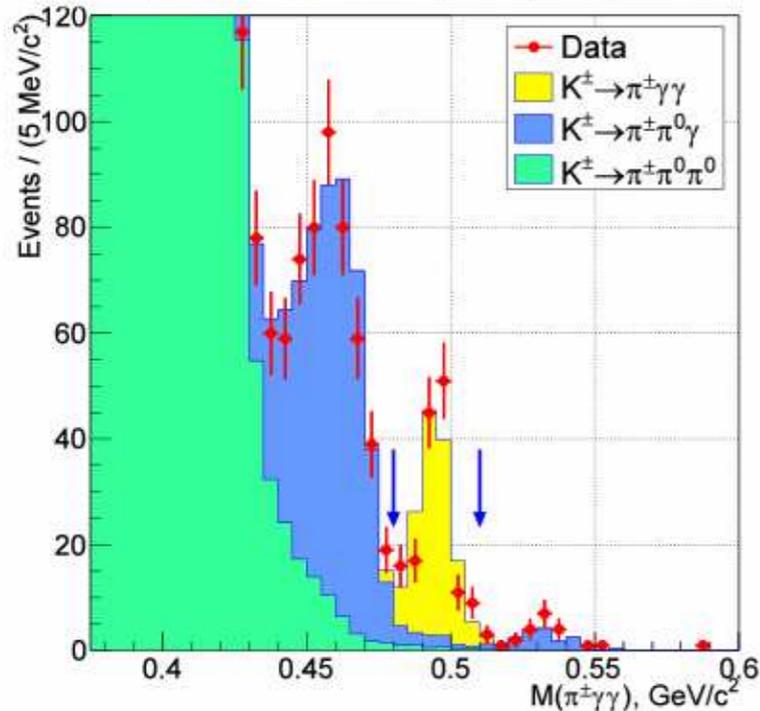
* Improved branching fractions:

$Br K_{e4}(\pm-) = (4.257 \pm 0.035) \times 10^{-5}$ [Phys.Lett. B715 (2012) 105] (3 times better/PDG)

$Br K_{e4}(00) = (2.552 \pm 0.035) \times 10^{-5}$ [preliminary] (13 times better/PDG)

Measurement of the rare decay $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$

NA48/2 (2003, 2004)
 [Phys. Lett. B730 (2014) 141]



NA62 R_K -phase (2007)
 [Phys. Lett. B732 (2014) 65]

