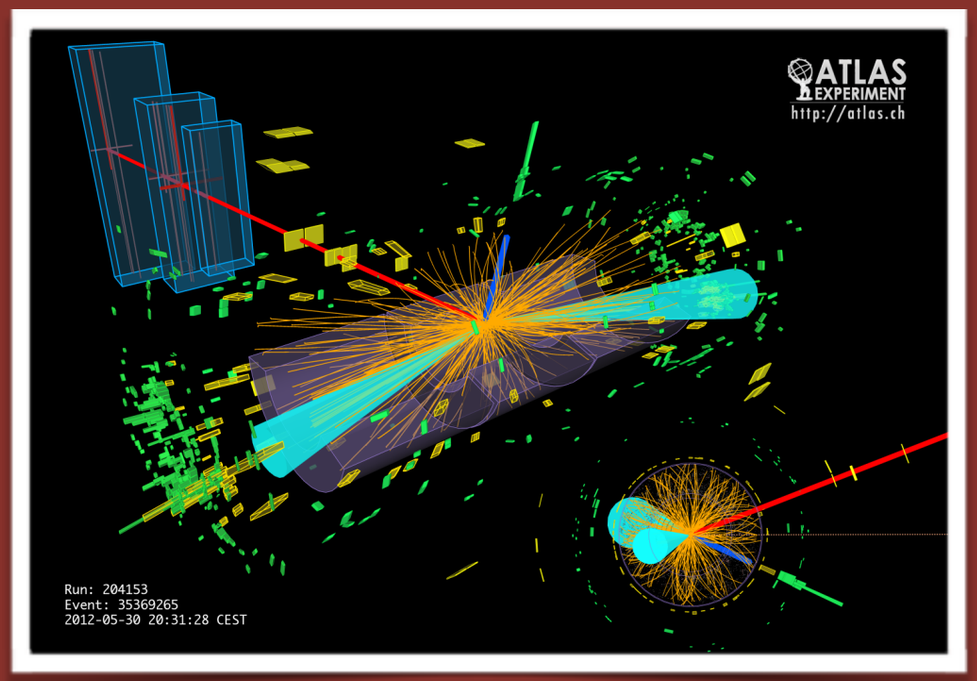
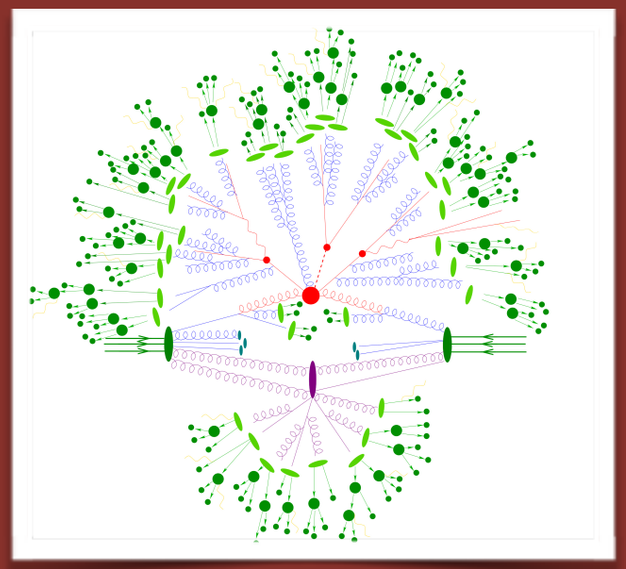
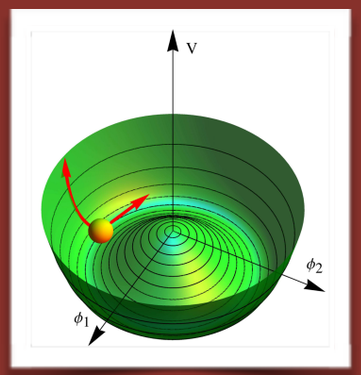






ATLAS QCD measurements for Higgs studies and New Physics searches

Manuel Proissl on behalf of the ATLAS collaboration
University of Edinburgh

QCD@Work 2014
International Workshop on QCD, Theory and Experiment
16-19 June, 2014 - Giovinazzo (Bari, Italy)

THE UNIVERSITY of EDINBURGH

Introduction

Precision QCD measurements

Constrain PDFs

understand

- Higgs cross-sections
- SM backgrounds

…

…

Constrain BSM Models

- Exp. boundaries

…

TeV scale

Test / Tune MC predictions

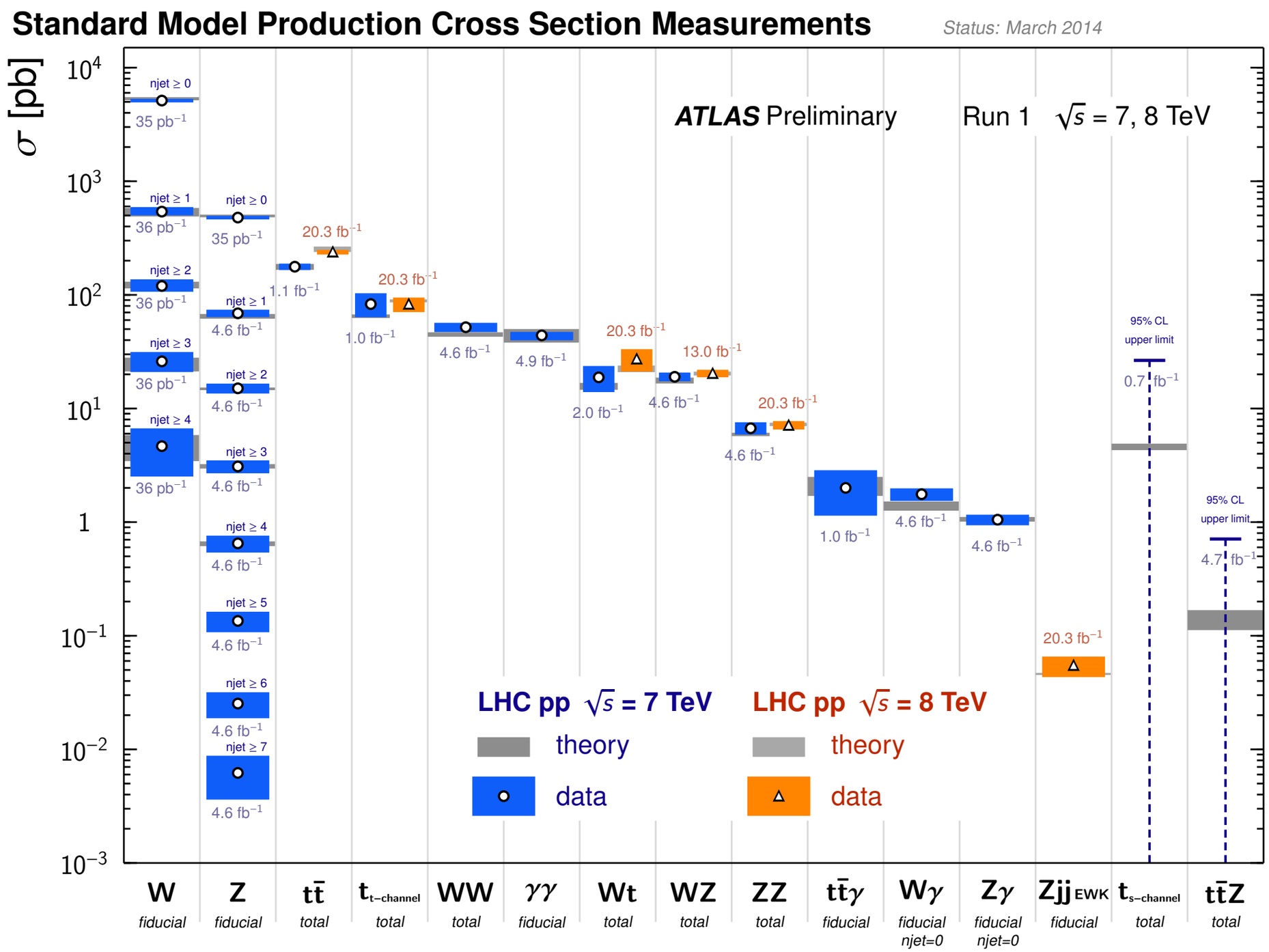
- SM backgrounds
- Underlying event …

Test pQCD calculations

- Parton showers …

Data Analysis — Detector level → Particle level ← Parton level — **Theory Prediction**

Introduction



Generally, good agreement between experiment & theory!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Summary_plots

Introduction

- SM processes are important backgrounds in **Higgs analyses**.
- Any deviations from SM expectation: hint to **new physics**.

IN THIS TALK

Hard QCD

- **Reminder: Higgs production and PDFs**
- **Photon, Di-Photon and Photon+Jet Production**
- **Jet, Dijet cross sections and Jet Shapes**
- **W/Z + Jet Production**
- **Prompt W + J/Ψ Production**

Predicted through perturbative QCD

Soft QCD

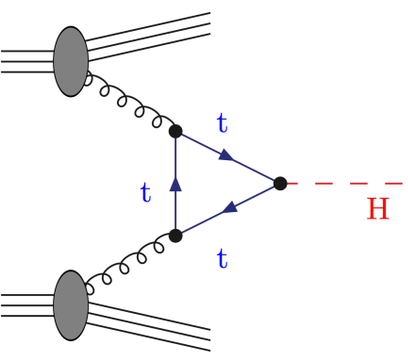
- **Underlying Event**
- **Φ(1020) Meson Production**

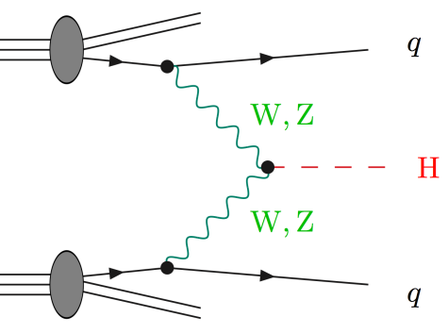
Non-perturbative effects of QCD

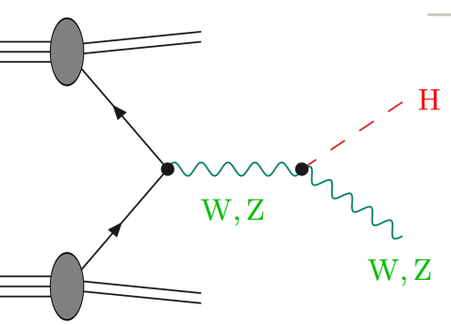
Hard QCD

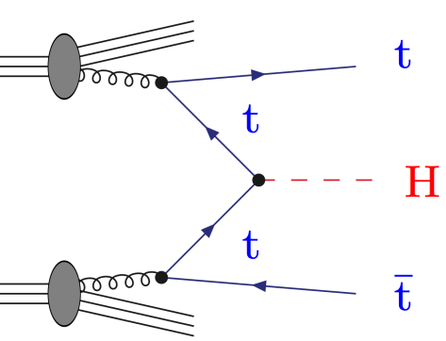
Higgs Production & PDFs

Process	Main IS Contrib.	σ: PDF (+α_S)
ggF	gluon-gluon, $0.001 < x < 0.1$	5.6% (6.6%)
VBF	quark-antiquark	3.0%
VH	quark-antiquark	2.8% (WH)
ttH	gluon-gluon $x \sim 0.1$	7.7%









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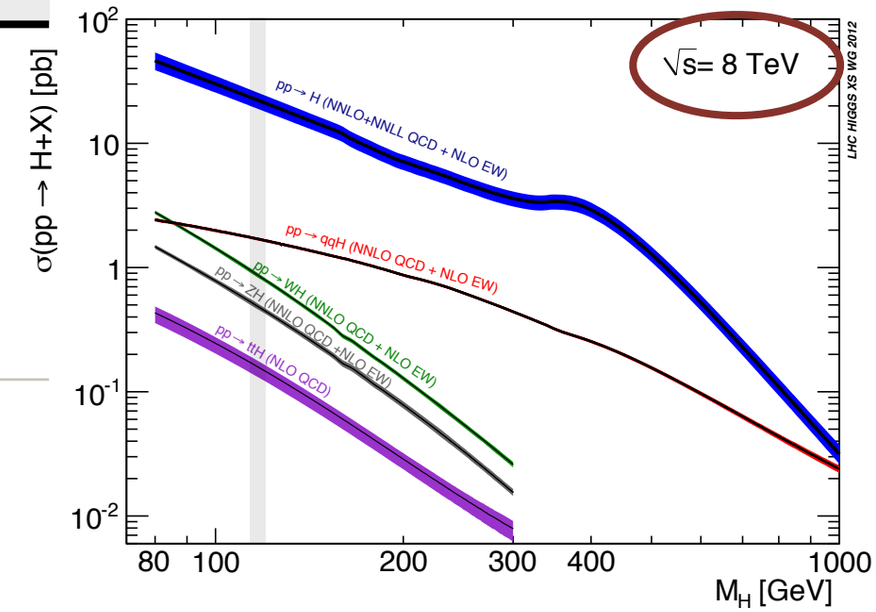
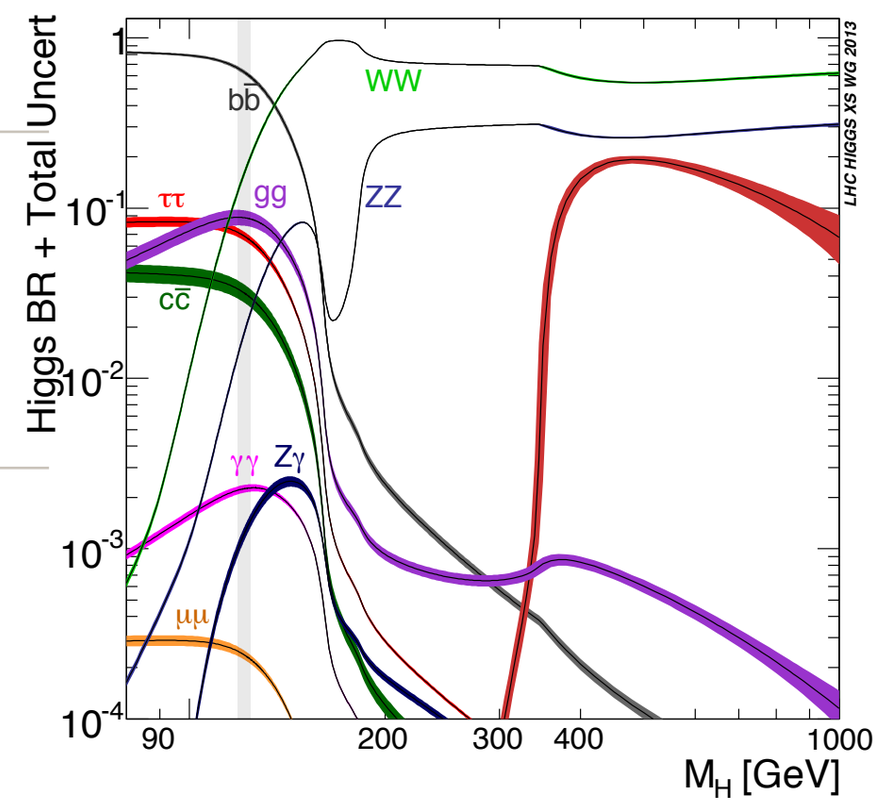
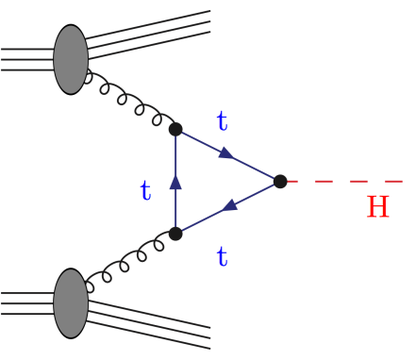
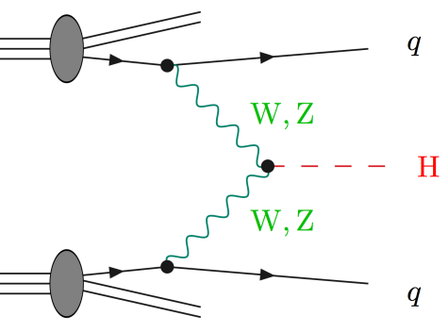
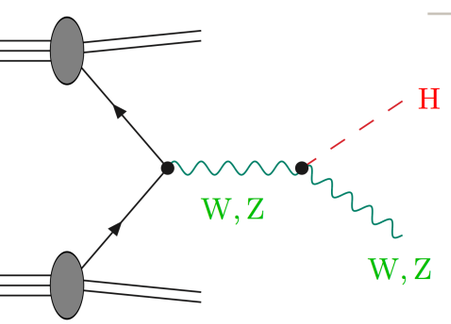


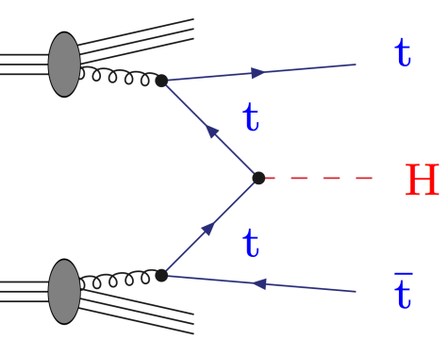


Higgs Production & PDFs









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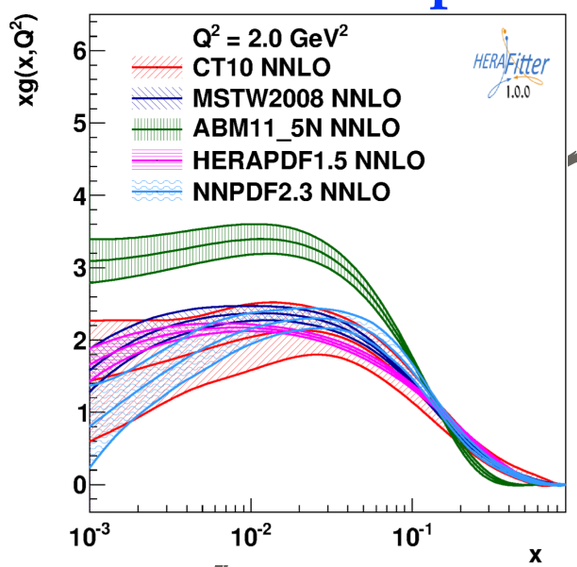
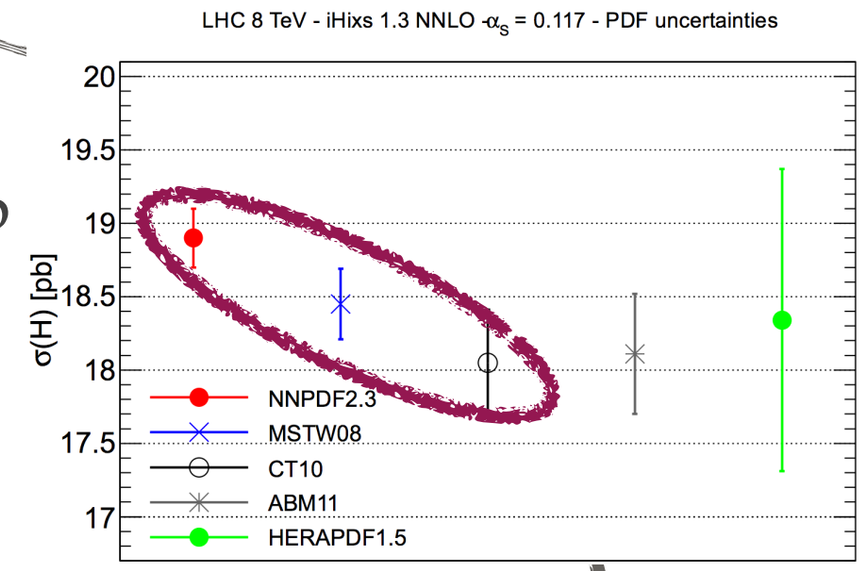
- PDF4LHC prescription; evaluated with NNLO PDF
- NNLO PDF envelope (CT10, MSTW2008, NNPDF2.3)
- **ggF PDF uncertainty**: a *dominant* theory uncert. - once N^{3}LO complete probably largest one.
- **Expected to limit interpretation of Higgs cross section measurement end of LHC Run-2.**

Higgs Production & PDFs: ggF

Gluon PDF Spread

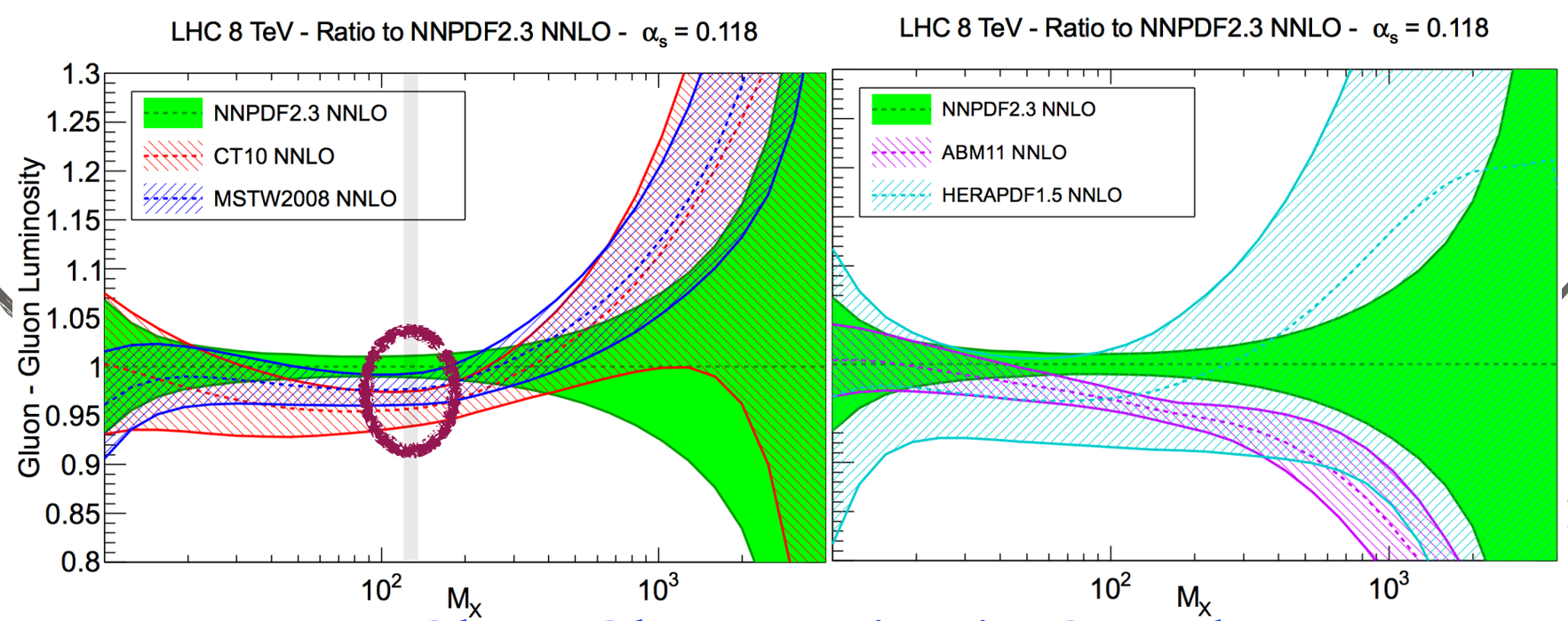


gg→H cross section Spread



- Gluon-Gluon lumi. do not overlap at M_H = 125 GeV
- Uncert. from each PDF set ~3-4%
- PDF uncert. envelope: ~7%

- **Constraints from data needed!**



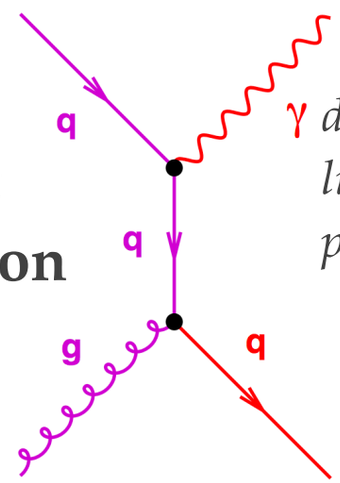
M_X>1TeV large uncert. → relevant for BSM searches and charact. of heavy resonances!

Gluon-Gluon Luminosity Spread

Photon production

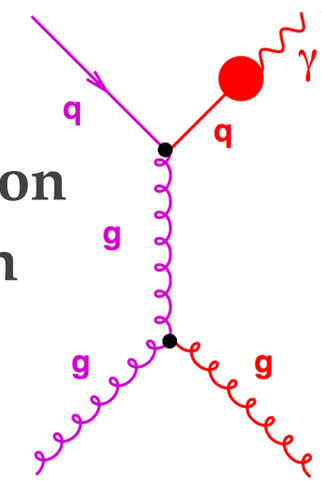
- *Prompt* photon production tests hard scattering in pQCD
- There are 2 mechanisms high-pT prompt photons can be produced:

Direct Production



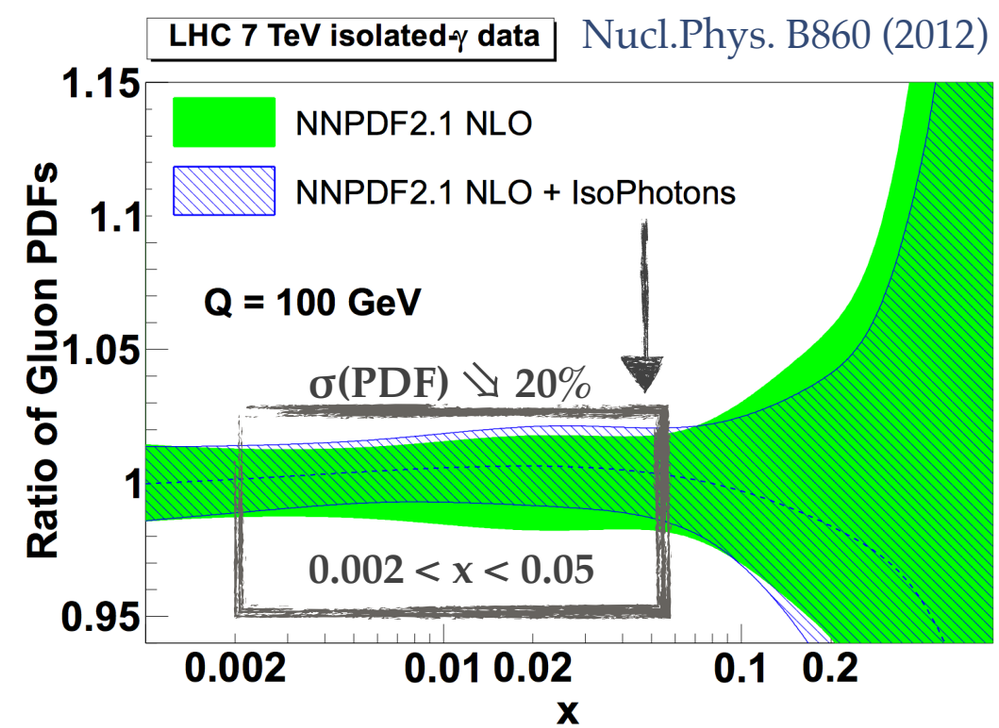
directly emitted from point-like coupling to hard parton-parton vertex

Fragmentation Production



originates from collinear fragmentation of final-state parton

- Compton-like **qg → qγ dominates** at LHC
- Potential to **constrain gluon PDF**
- Probe *photon fragmentation* contribution
- **Understand photon background** in Higgs (H→γγ) and BSM searches



Phys. Rev. D 89, 052004 (2014)

Photon production

Cross section measurement at 7 TeV:

- **Isolated photons**: $E_T^{iso} < 7$ GeV within a $\Delta R < 0.4$ cone
- Require $E_T^{\gamma} > 100$ GeV and $|\eta^{\gamma}| < 2.37$ (excluding crack region)

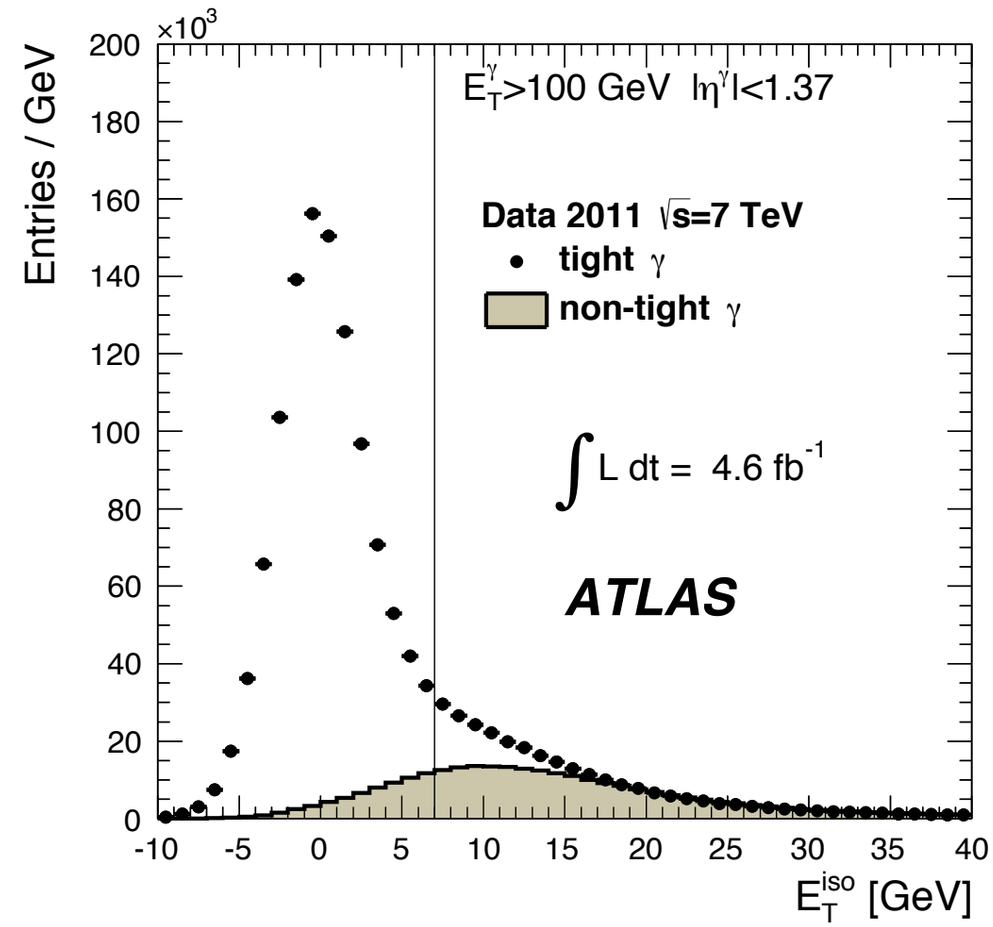
- Total systematic uncertainty below 6-7%

- Scale uncertainty 12 - 20% (var. μ_R, μ_F, μ_f)

- PDF uncertainty 5% ($E_T^{\gamma} = 100$ GeV) to 15% ($E_T^{\gamma} \sim 900$ GeV) {via CT10 52 eigenvector sets}

- α_s uncertainty 4.5% (var. around $\alpha_s = 0.118$)

- Detector effects corrected (bin-by-bin method)

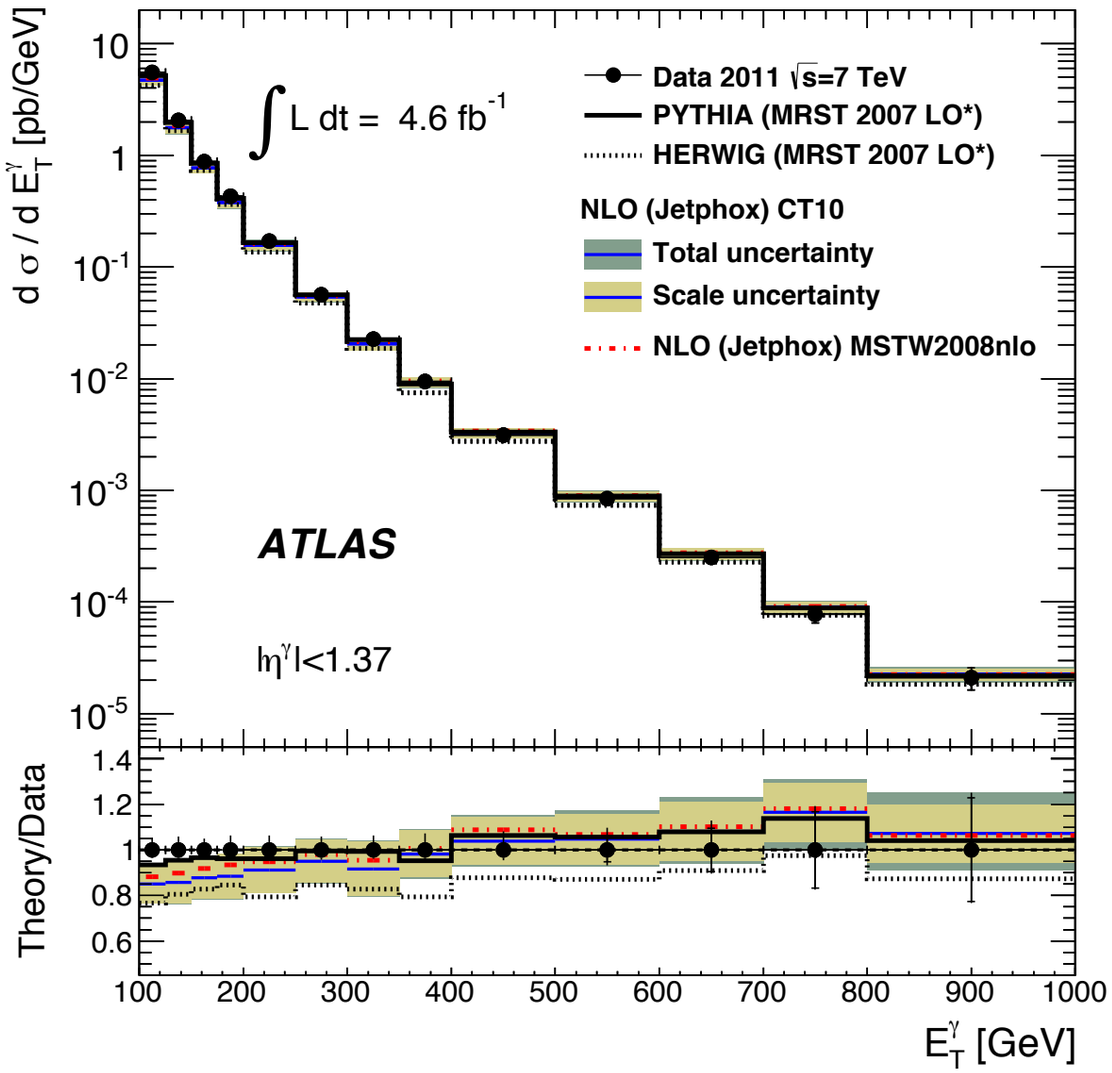


Jetphox: **NLO QCD** calculation incl. direct & frag. contribution.

PYTHIA / HERWIG: **LO MC** incl. direct & frag. production (γ emission in parton shower).

Phys. Rev. D 89, 052004 (2014)

Photon production

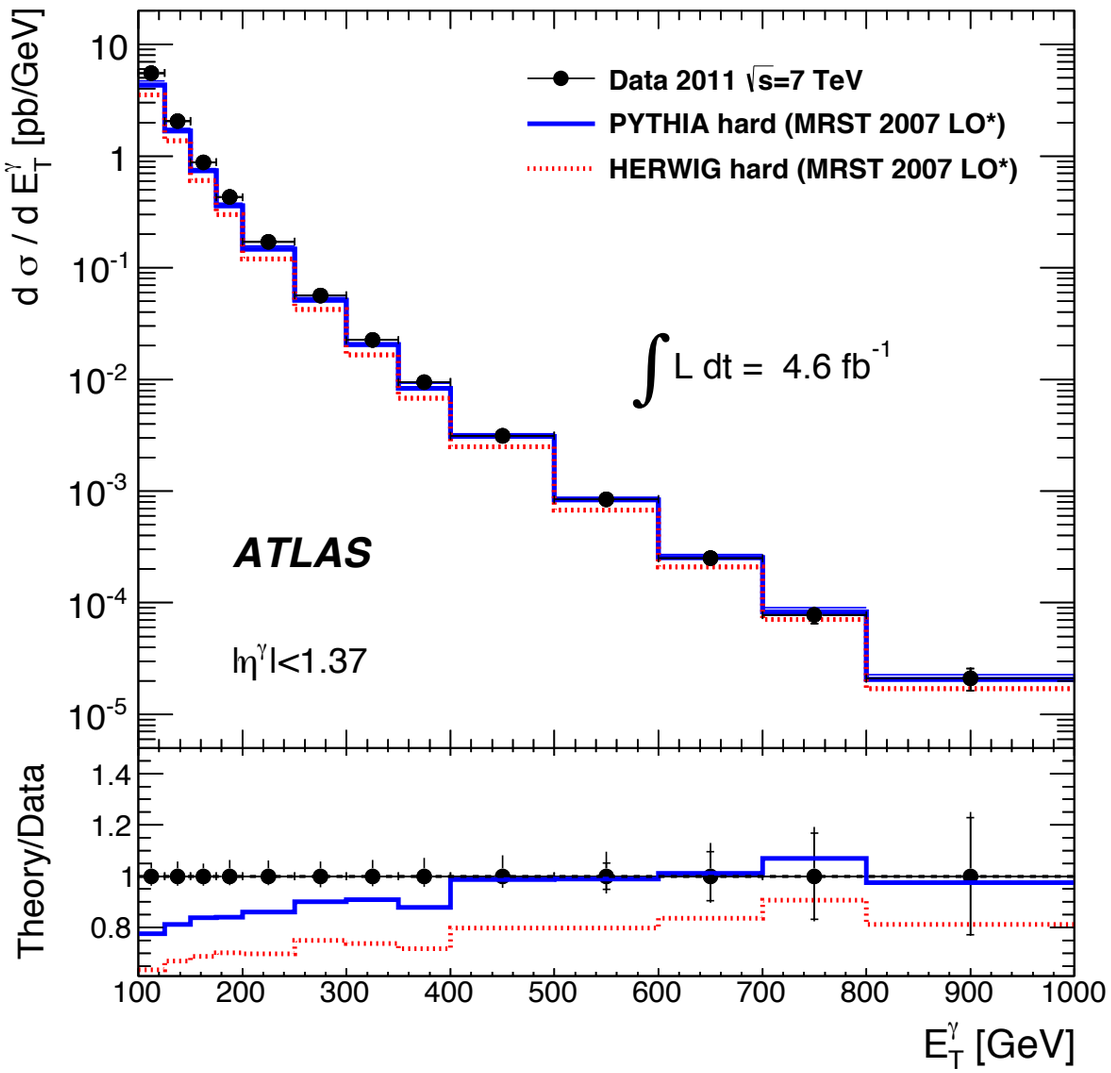


- **NLO** (Jetphox) **overall agreement**, except at low E_T^{γ} (dominated by frag. photons)
  - Large PDF uncertainties > 700 GeV (constraints from measurement?)
  - Scale uncertainties most important at $200 < E_T^{\gamma} < 600$ GeV
- **LO** PYTHIA describes the data fairly well
- **LO** HERWIG ~ 10 - 20% lower than data

σ(pb)	CENTRAL |η| < 1.37	FORWARD 1.52 < |η| < 2.37
ATLAS	236 ± 2 (stat) +13/-9 (syst) ± 4 (lumi)	123 ± 1 (stat) +9/-7 (syst) ± 2 (lumi)
CT10 NLO	203 ± 25	105 ± 15
MSTW2008NLO	212 ± 24	109 ± 15
LO PYTHIA	224	118
LO HERWIG	187	99

Phys. Rev. D 89, 052004 (2014)

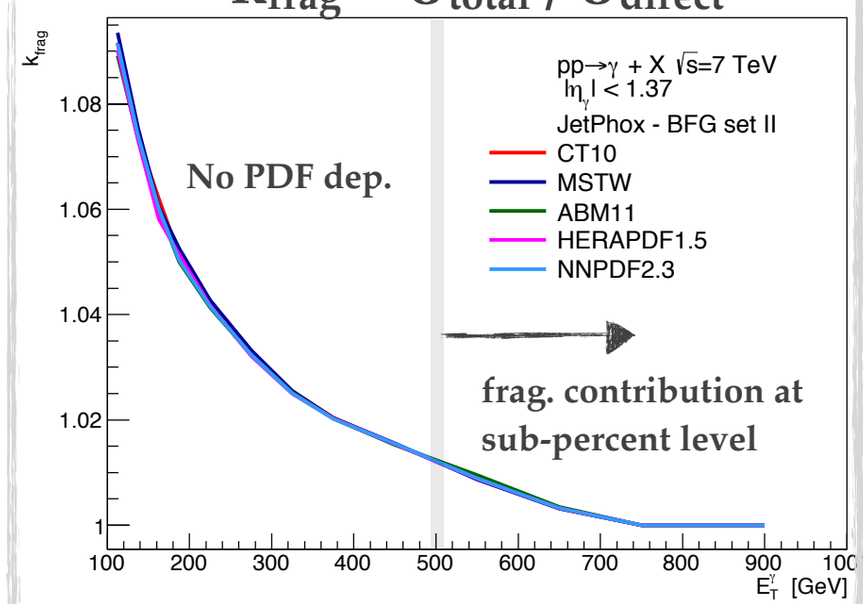
Photon production



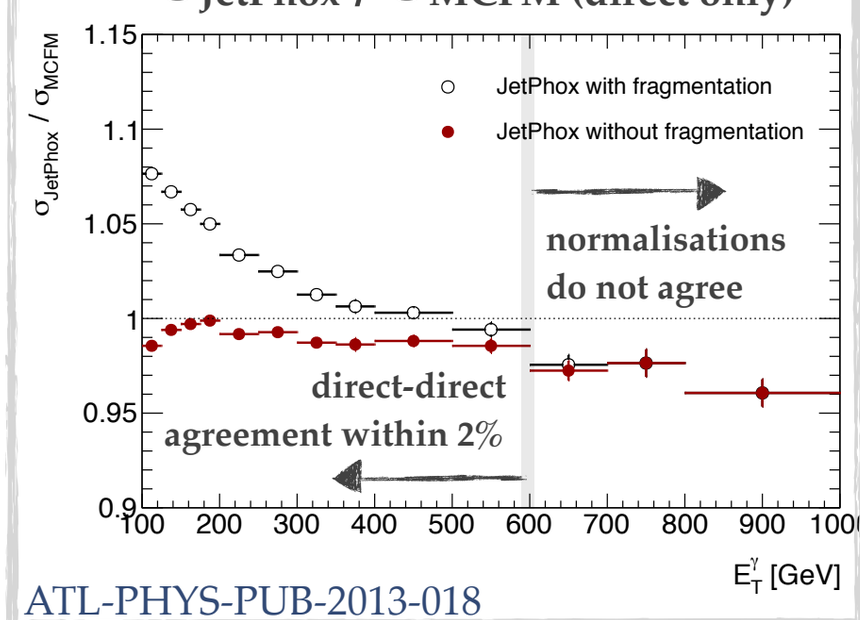
- **LO** PYTHIA / HERWIG (direct production only) **20% lower than data** at low E_T^γ ⇒ higher-order fragmentation terms important
- Better agreement at high E_T^γ ⇒ less frag. contrib.

Expect. Fragmentation

$k_{frag} = \sigma_{total} / \sigma_{direct}$



$\sigma_{JetPhox} / \sigma_{MCFM}$ (direct only)



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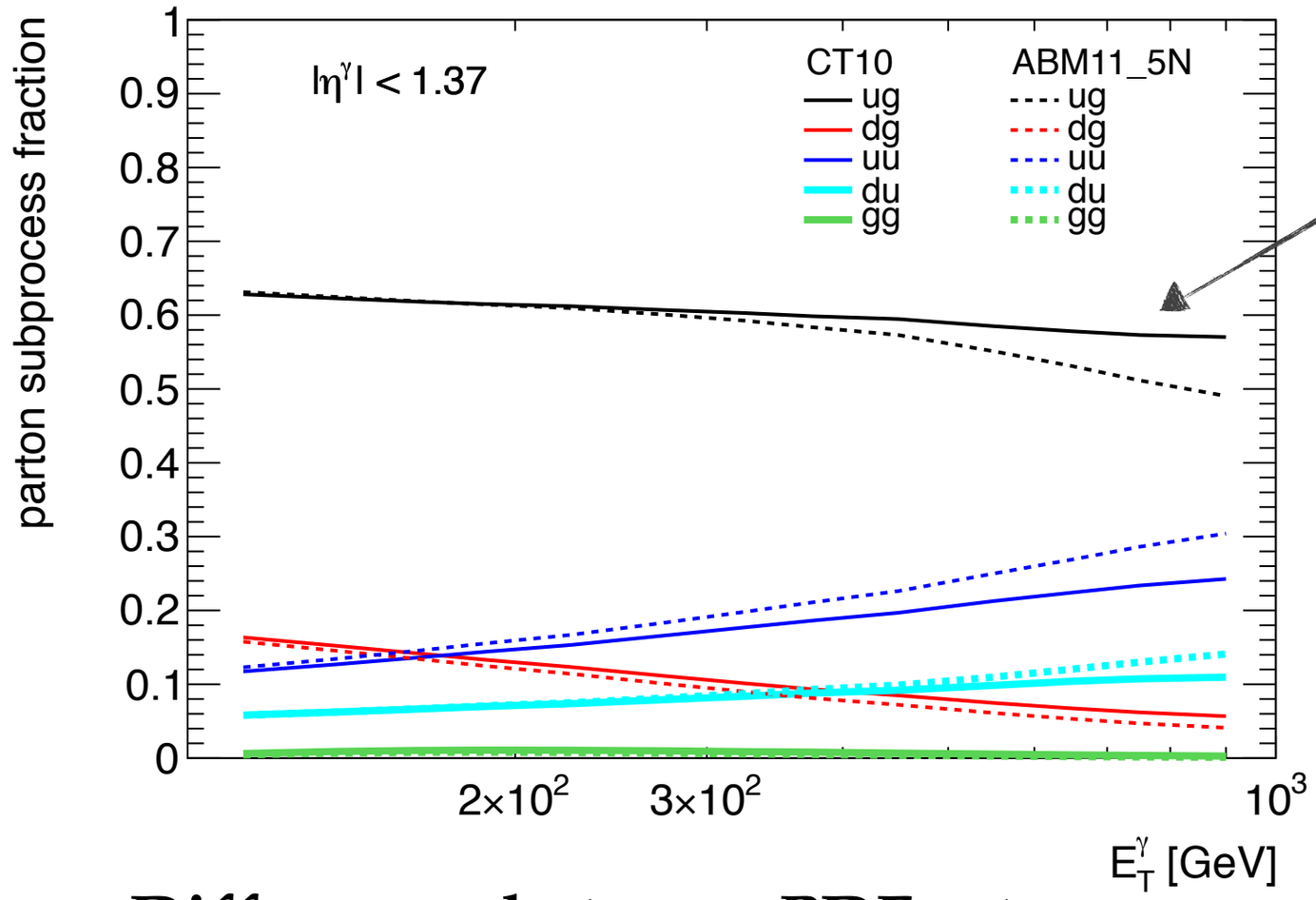
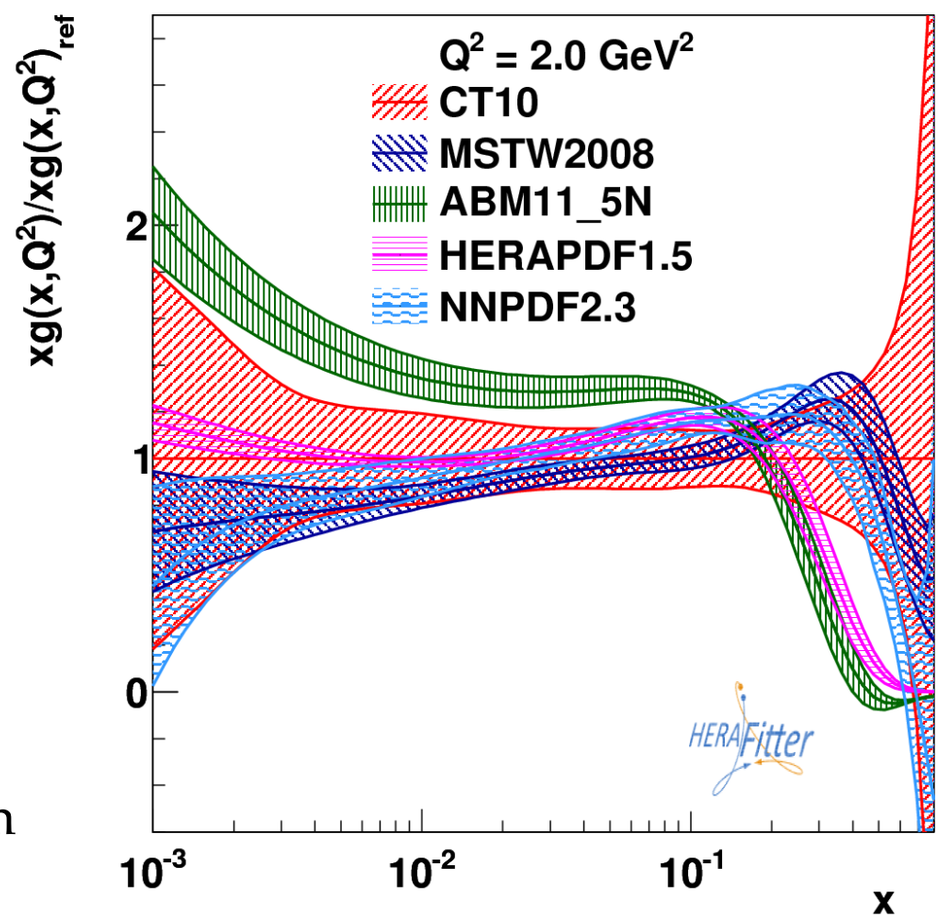
Photon production



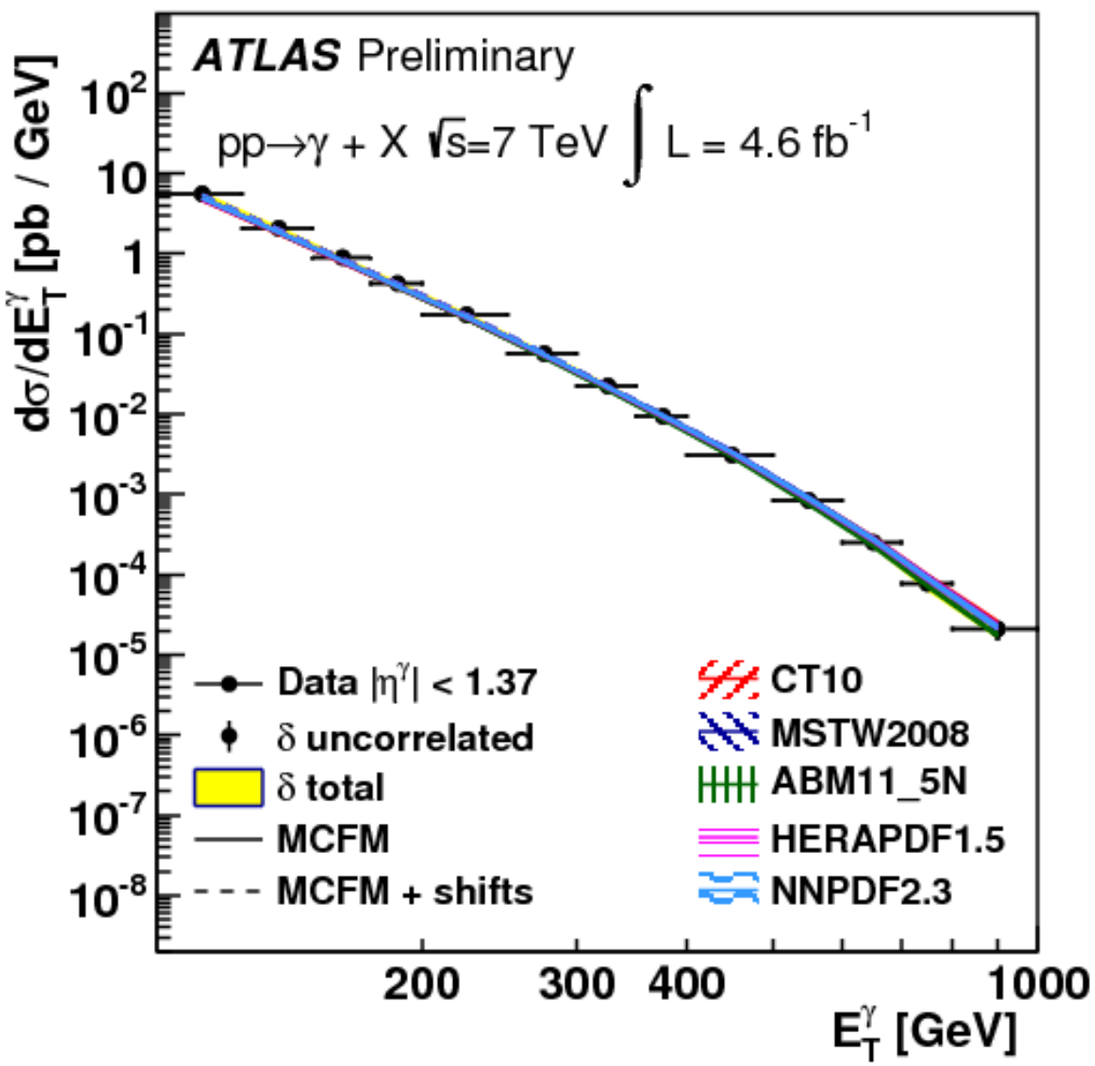
- Inclusive prompt γ production: ***u-g process*** dominated
  - Larger u-type quark charge and prevalence in the proton
  - **Sensitive to gluon PDF**

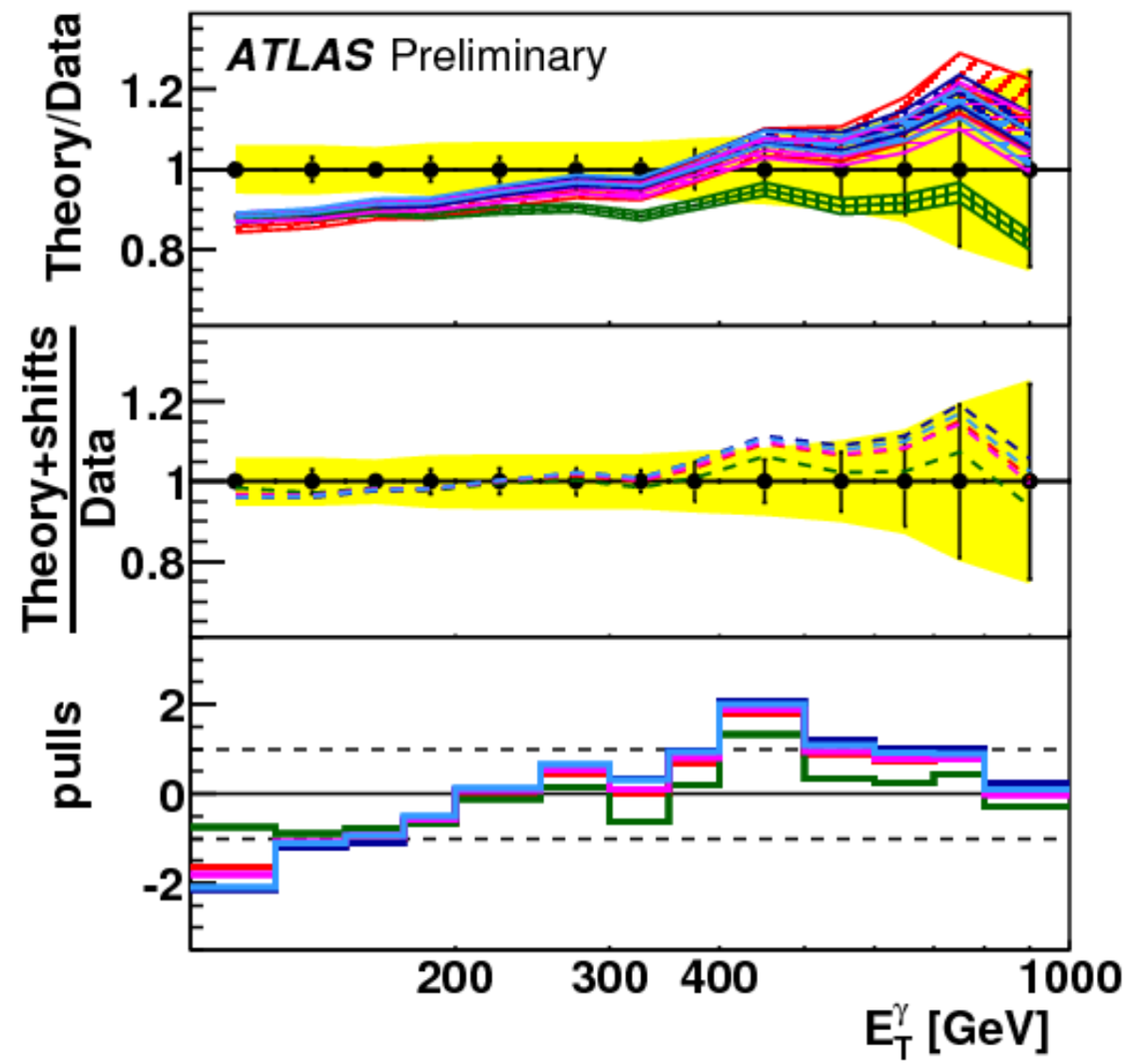


- **Differences between PDF sets**
- Potential to constrain gluon PDF (both shape and uncertainty)
- ABM11_5N softer gluon distrib. at high x
  ⇒ contrib. from processes with gluons in IS smaller at high E_T^γ compared to CT10.

Photon production

- **Tensions** between data and theory for various PDF sets
- Sensitivity to PDF limited by **large scale uncertainties**: dominant at intermediate E_T^{γ}, where data is most precise ⇒ **NNLO necessary**





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Photon+Jet production

- **Kinematics** and **dynamics** of γ+jet system can be studied
  - Insights into fragmentation contributions

Photon + Jet Selection

1 Photon

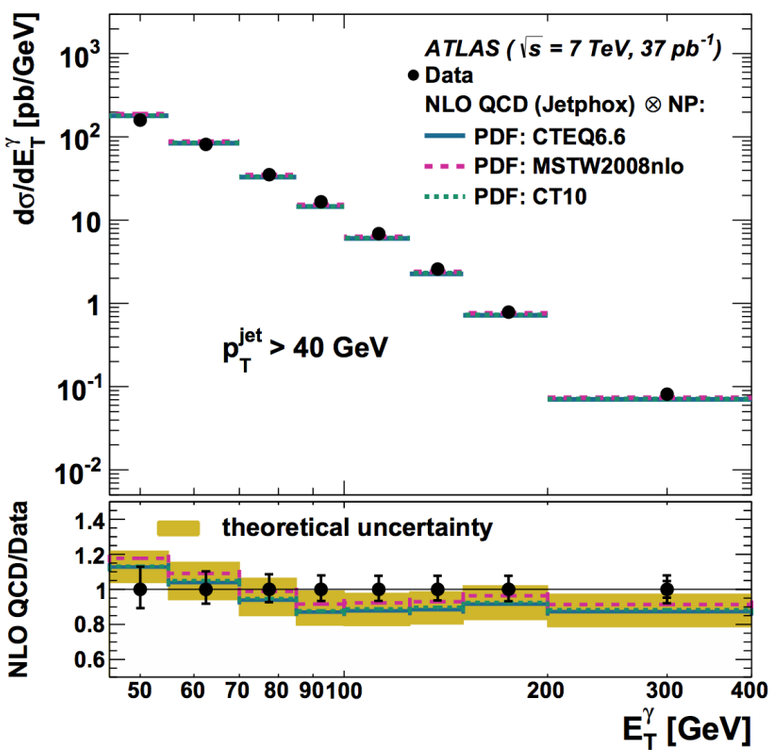
- **Isolated**: $E_T^{iso} < 4$ GeV within a $\Delta R < 0.4$ cone
- Require $E_T^{\gamma} > 45$ GeV and $|\eta^{\gamma}| < 2.37$ (excluding crack region)

1 Jet

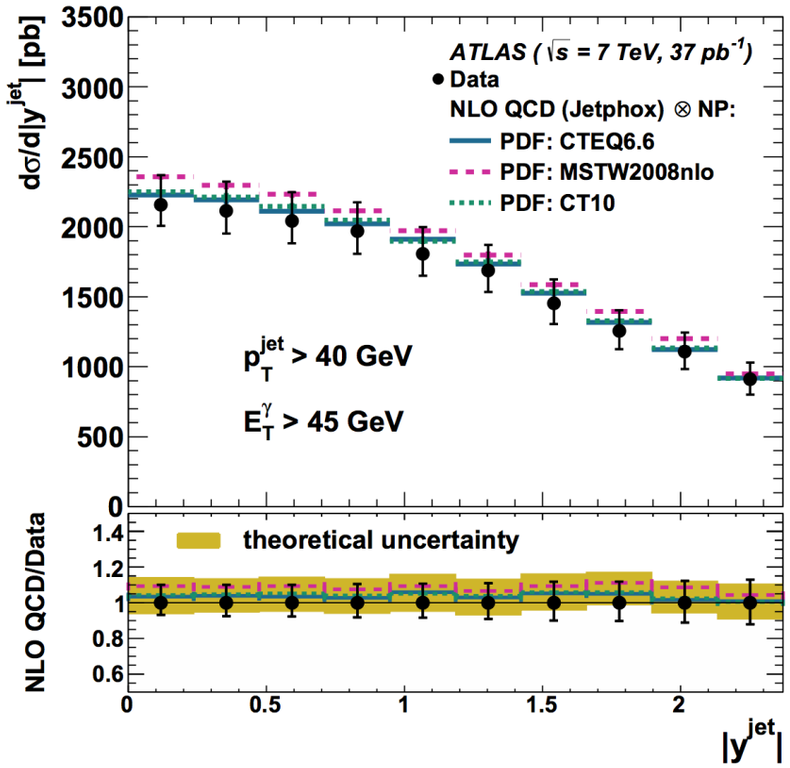
- anti-k_t jet with $R = 0.6$ with $p_T > 40$ GeV
- **Leading jet** at $|y^{jet}| < 2.37$
- $\Delta R(\gamma, \text{jet}) > 1.0$

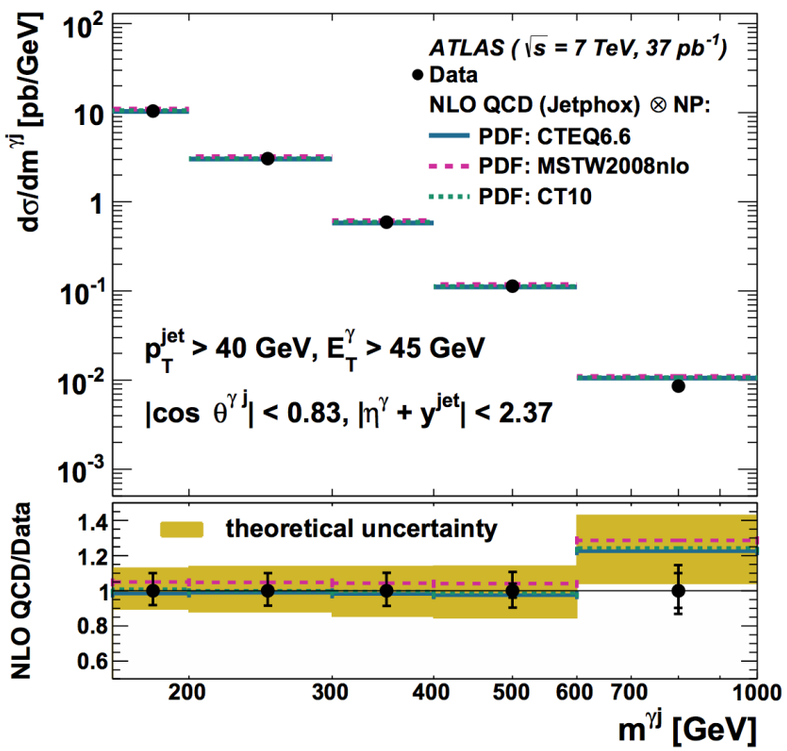
Nucl. Phys, B 875 (2013) 483-535

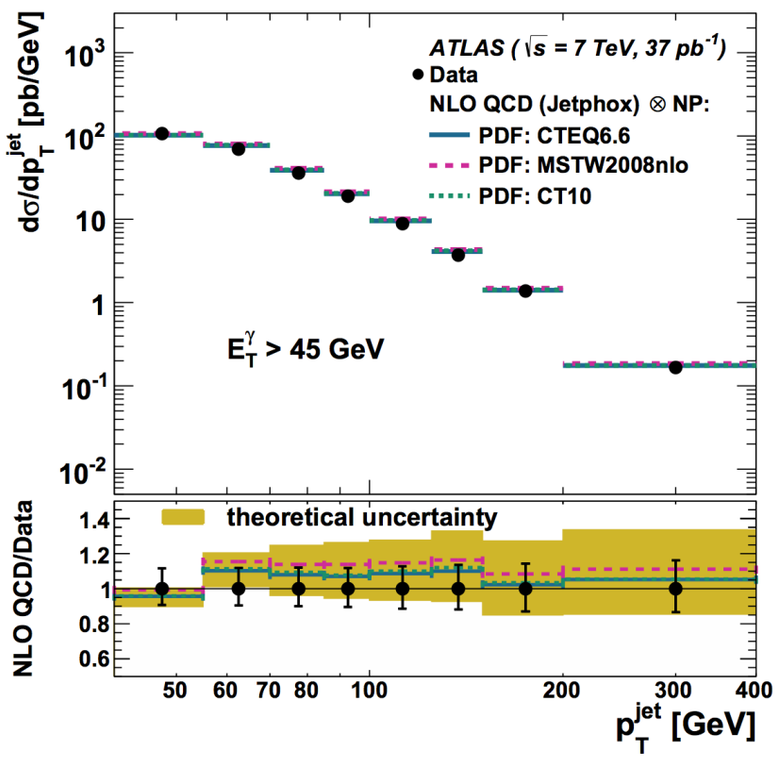
Photon+Jet production

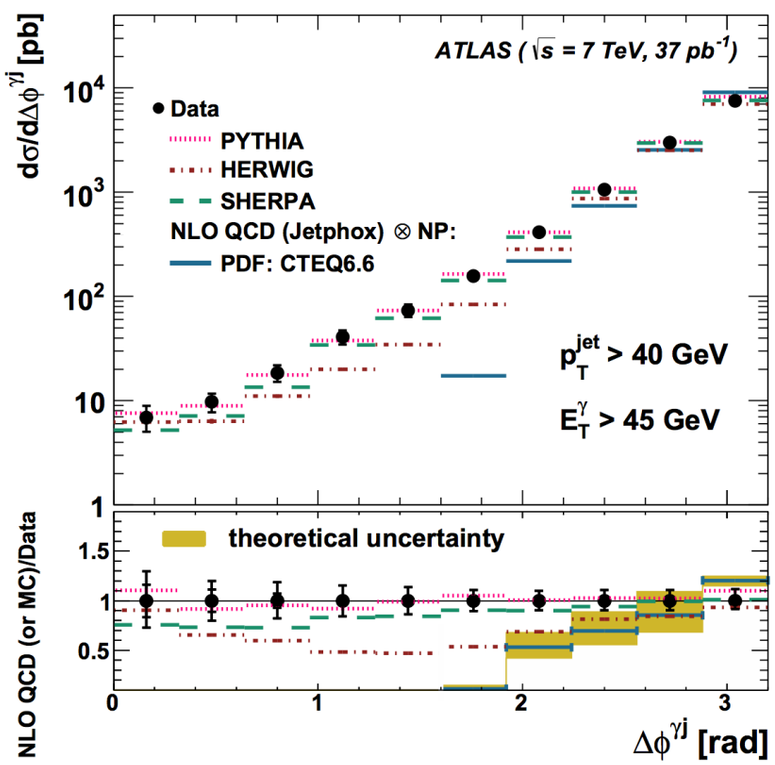


- **Good agreement in most variables!**
- MSTW2008NLO ~5%>CT10
- NLO: $\Delta\Phi^{\gamma j} > \pi/2$
  - Only PYTHIA agrees









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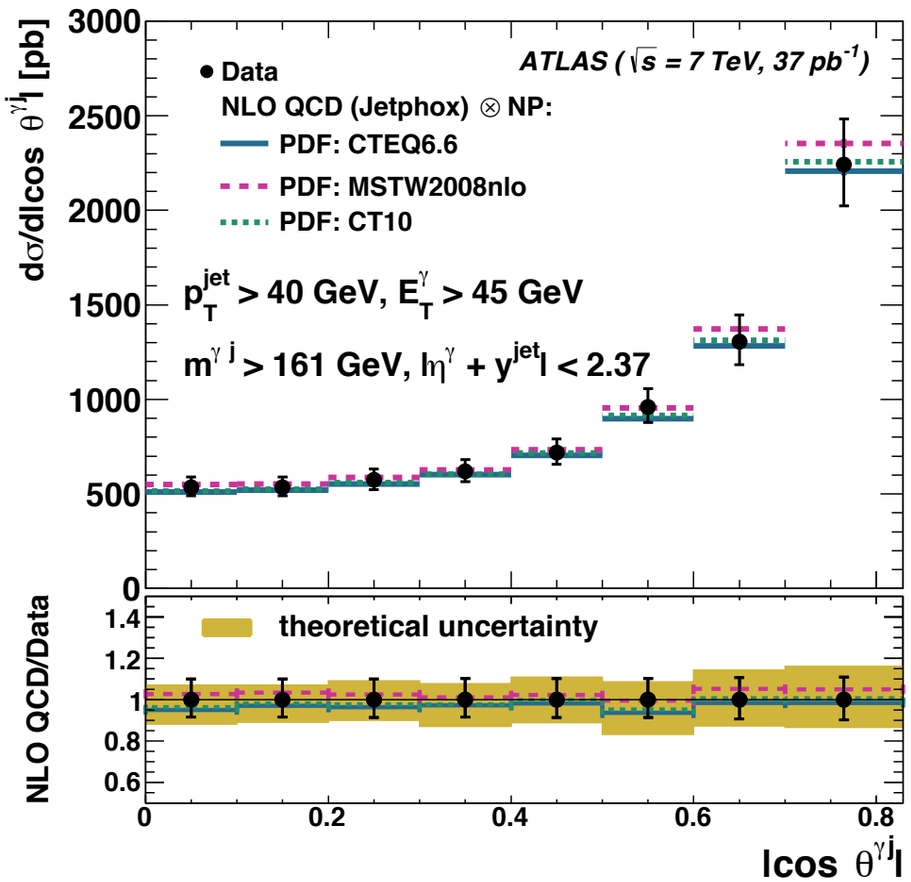
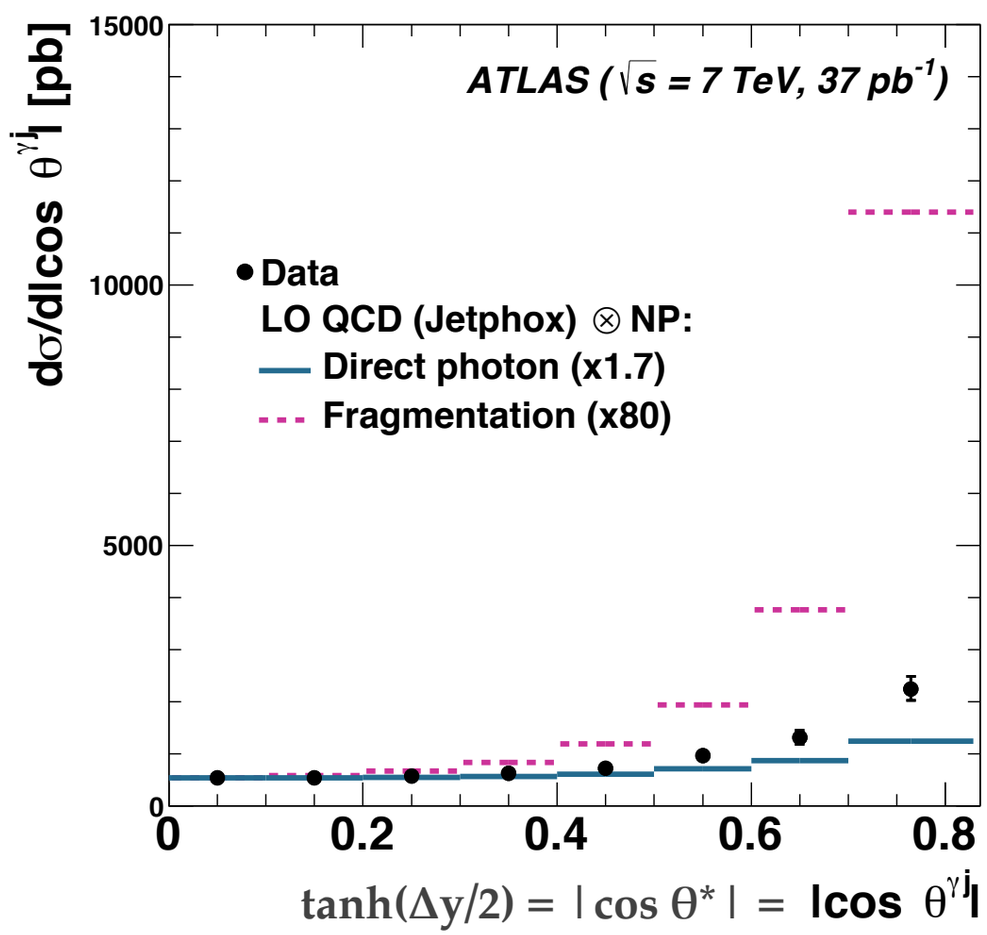
Photon+Jet production

- **Angular distribution** $|\cos\theta^{\gamma j}|$ sensitive to **spin of exchanged particle**
- Small uncertainties, **good agreement with NLO** Jetphox





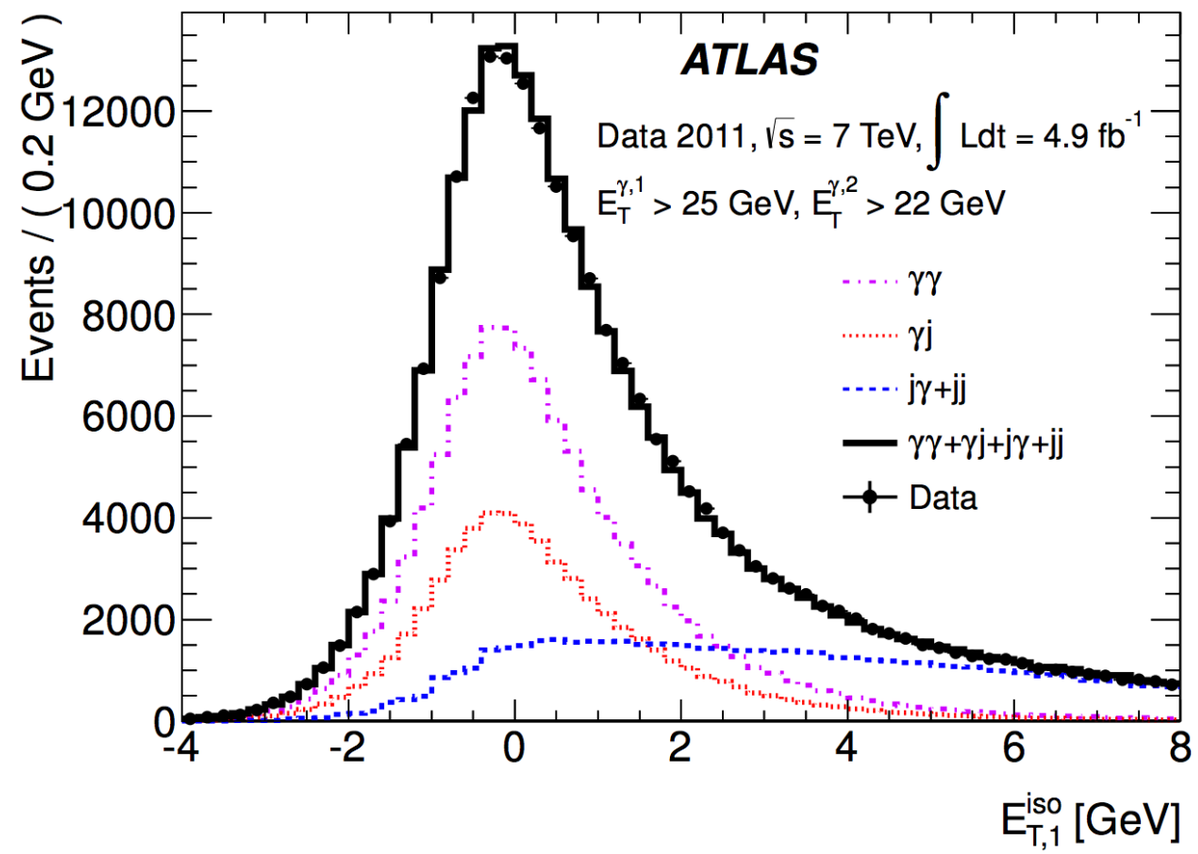
- Relative **fragmentation enhancement** in corners of phase space
- **Shape** of <u>direct production much closer to data</u> than fragmentation photons (*consistent: dominance of processes in which exchange particle = quark*)

Di-Photon production

- **Key to understand** backgrounds for **Higgs (H→γγ)** and **BSM searches** (e.g. graviton decays predicted in Universal Extra-Dimension models).

- **Photon selection:**
  - 2 isolated photons: $E_T^{iso} < 4$ GeV within a $\Delta R < 0.4$ cone
  - Require $E_T^{1/2} > 25$ / 22 GeV
  - Separated by $\Delta R(\gamma_1,\gamma_2) > 0.4$

- Remove **jet-jet & γ-jet background**
  - 2D Template Fit with leackage correction
  - 2 x 2D Sidebands Method



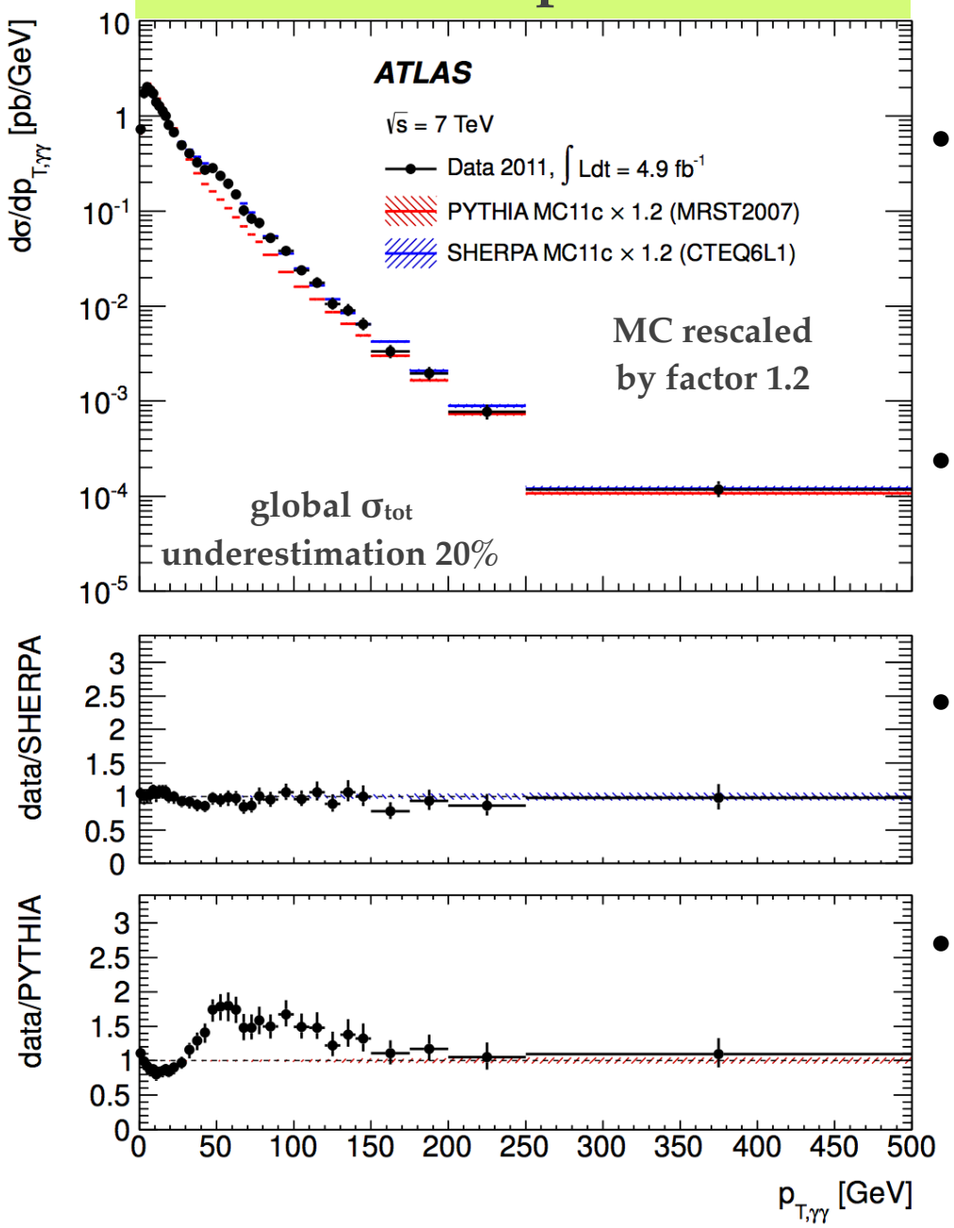
DIPHOX+GAMMA2MC (**NLO**) and **2γNNLO** (**NNLO**) calculations.

PYTHIA / SHERPA: **LO MC**

Di-Photon production

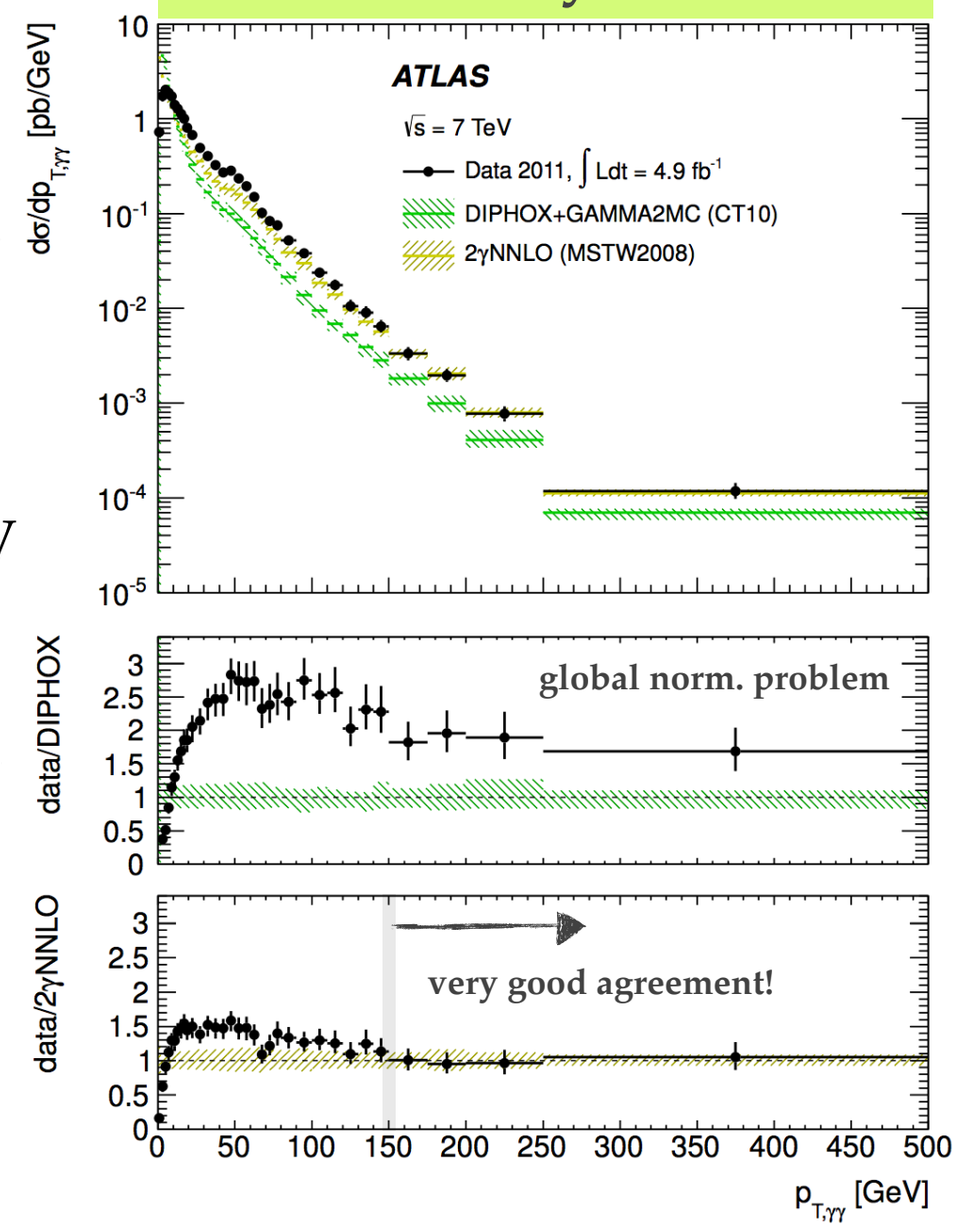
- Cross section variables studied: $m_{\gamma\gamma}$ (backup), $\mathbf{pT_{\gamma\gamma}}$, $\mathbf{\Delta\Phi_{\gamma\gamma}}$, $\mathbf{\cos\theta^*_{\gamma\gamma}}$

Data to MC predictions



- SHERPA does better **shape modelling** than PYTHIA
- **Good agreement** by 2γNNLO: $p_T > 150$GeV
- Fragmentation comp. significant: 20-150GeV
- Divergence at low p_T needs soft gluon reΣ

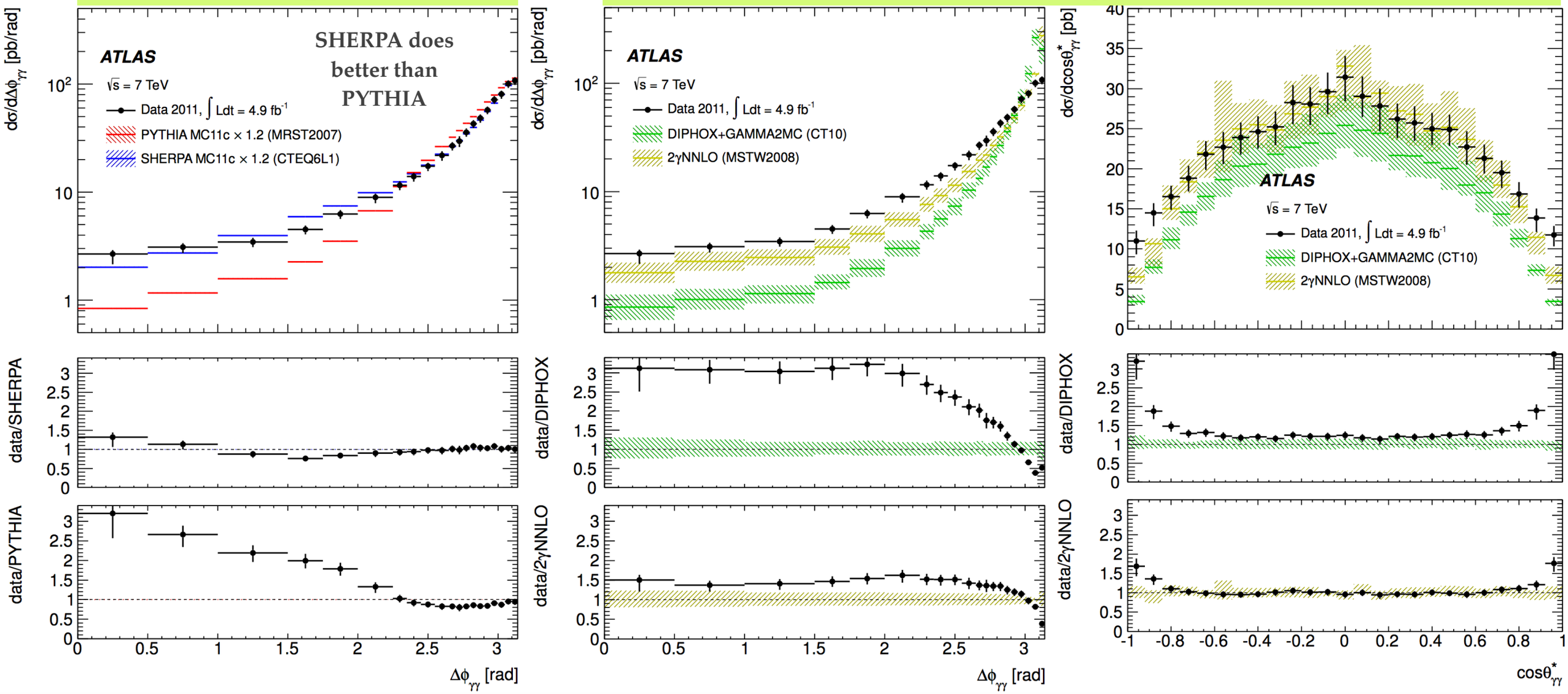
Data to Theory calculation



Di-Photon production

- NNLO better than NLO description
  - Excess at $\Delta\Phi_{\gamma\gamma} \sim \pi$: no soft gluon resummation
  - High $|\cos\theta^*_{\gamma\gamma}|$: NNLO misses fragmentation contribution

Data to MC predictions | **Data to Theory calculation**



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Inclusive Jet cross sections

- **Test pQCD** to shortest accessible distances
  - Information on strong coupling & proton structure

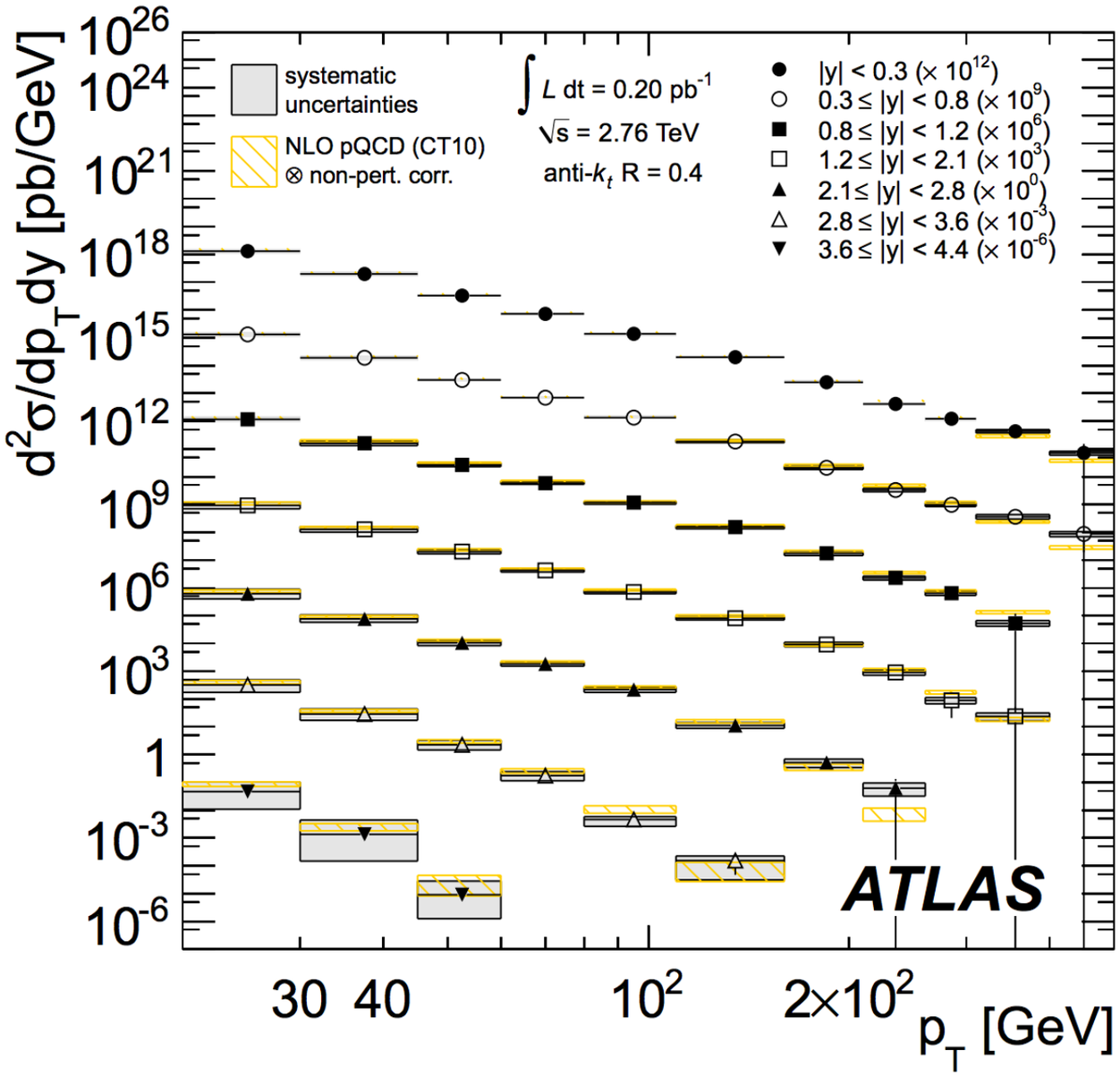
- Latest measurement at **2.76 TeV** with 0.20 pb^{-1} compared to **7 TeV**

- Jet Energy Scale (JES) main experimental uncertainty

  (2.5% central 60<p_T<800GeV to 14% forward p_T<30GeV)

NLOJet++ (fixed-order **NLO pQCD**) with non-perturbative corrections.

POWHEG⊗PYTHIA: **NLO MC**



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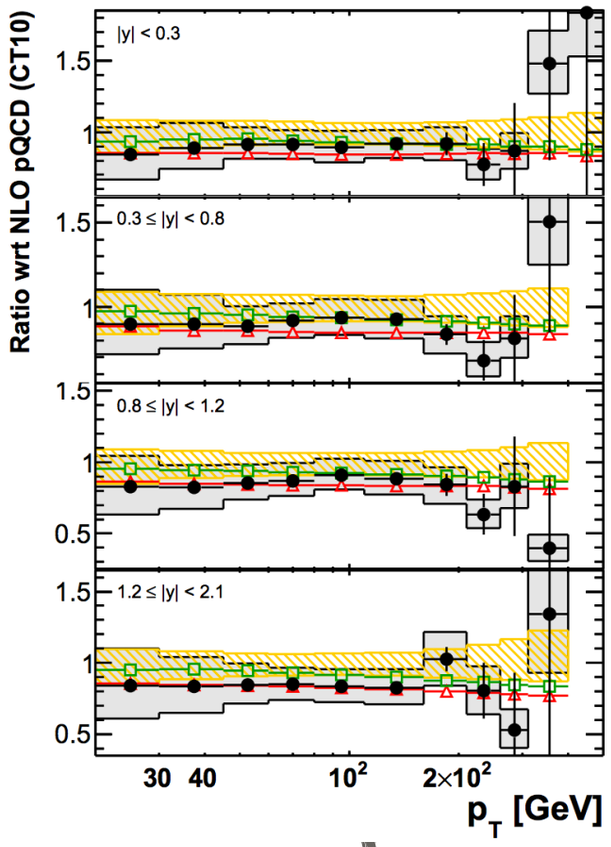
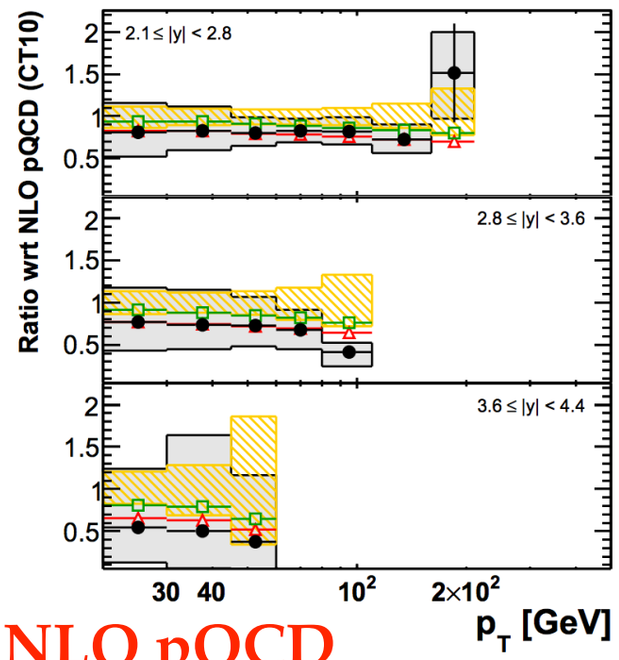
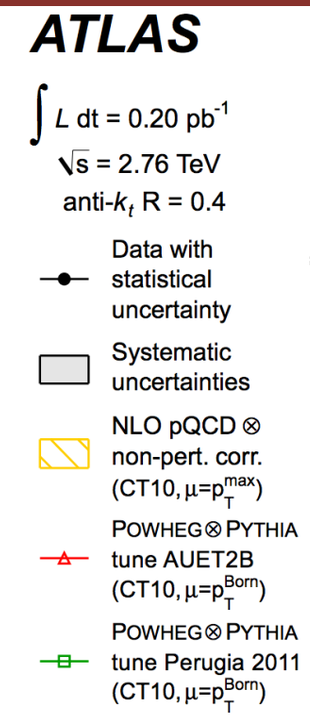
Inclusive Jet cross sections



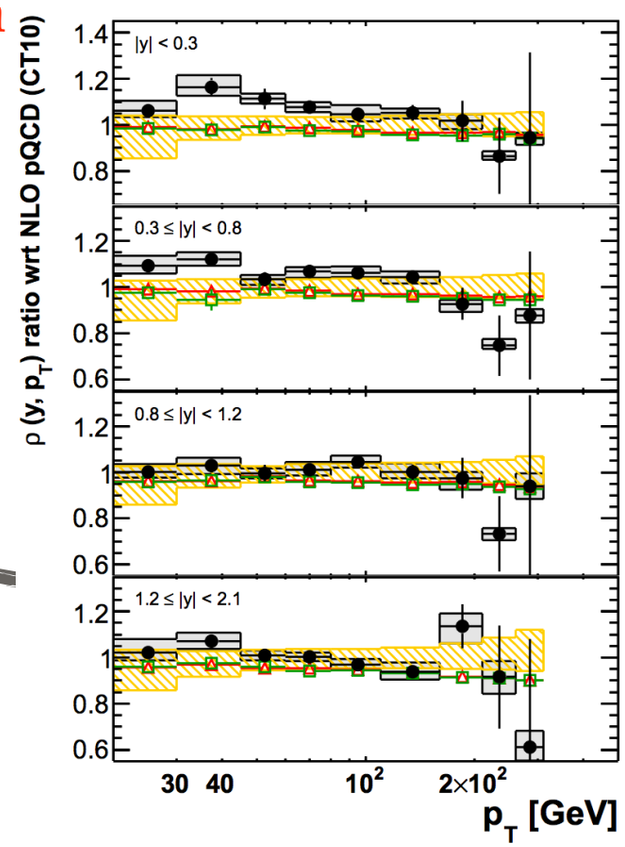


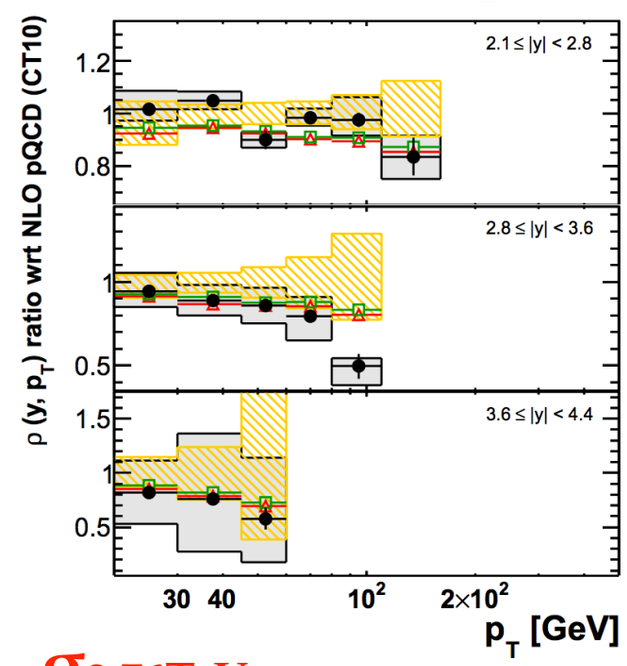
NLO pQCD

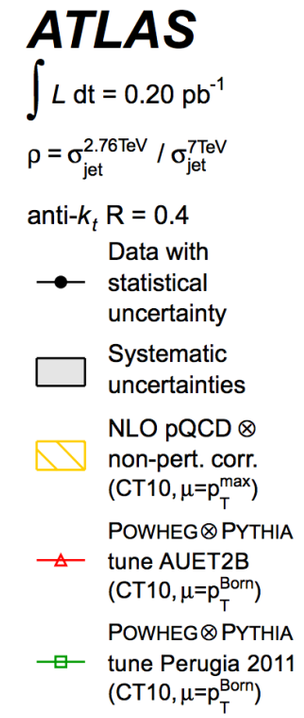
2.76 TeV data



Correlated Uncertainties Reduced !







$$\frac{\sigma_{2.76TeV}}{\sigma_{7TeV}}$$

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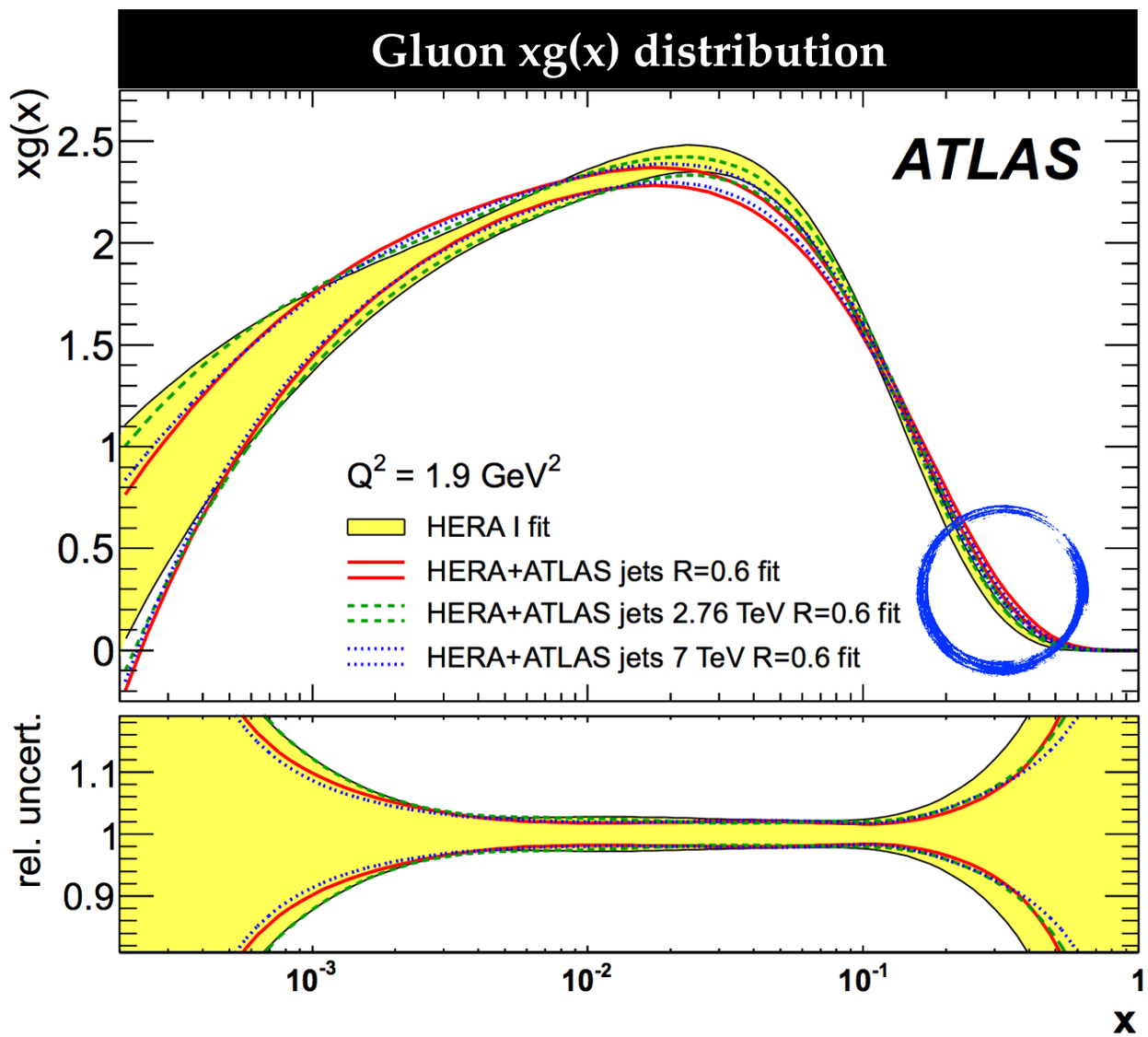
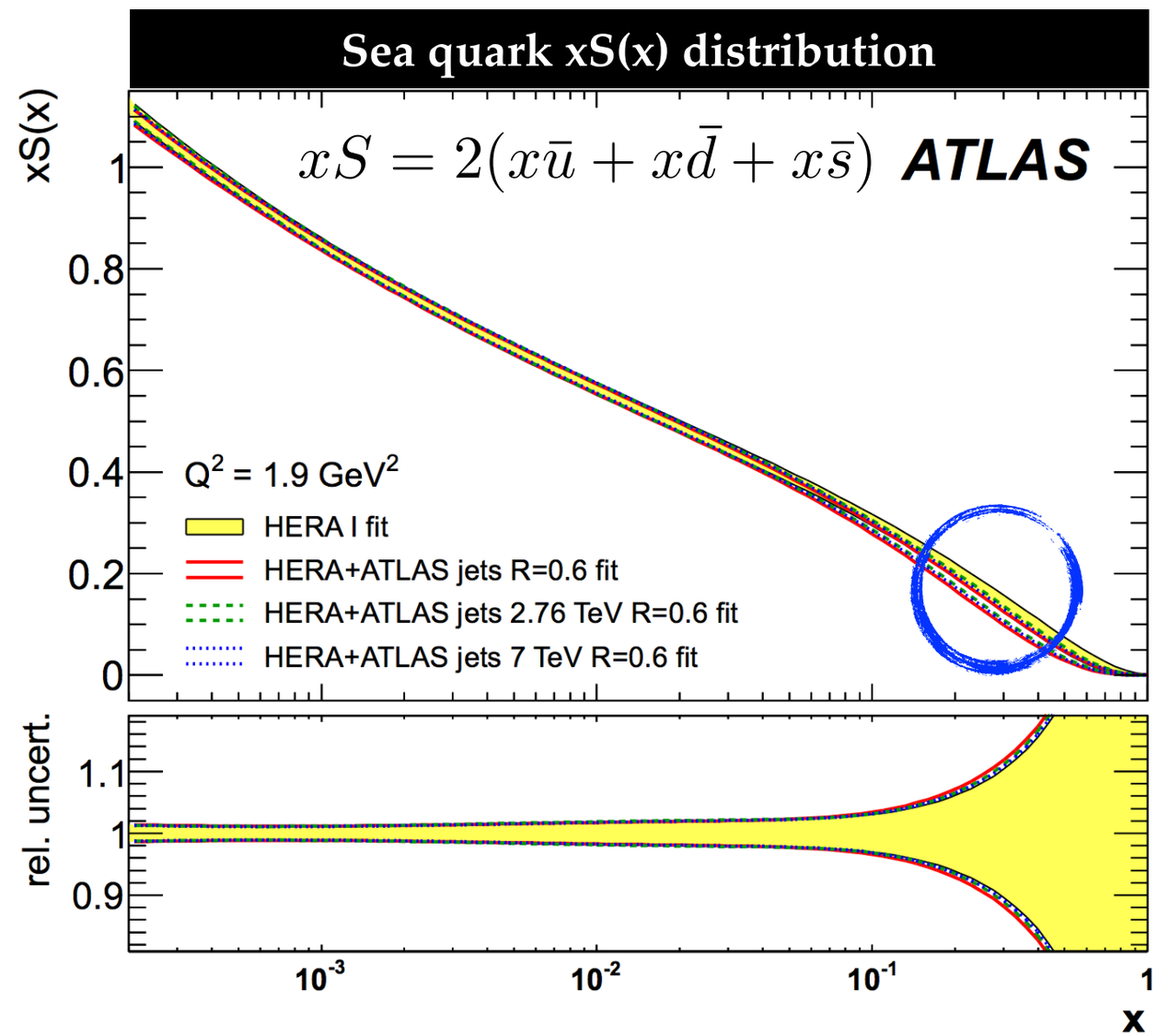
Inclusive Jet cross sections

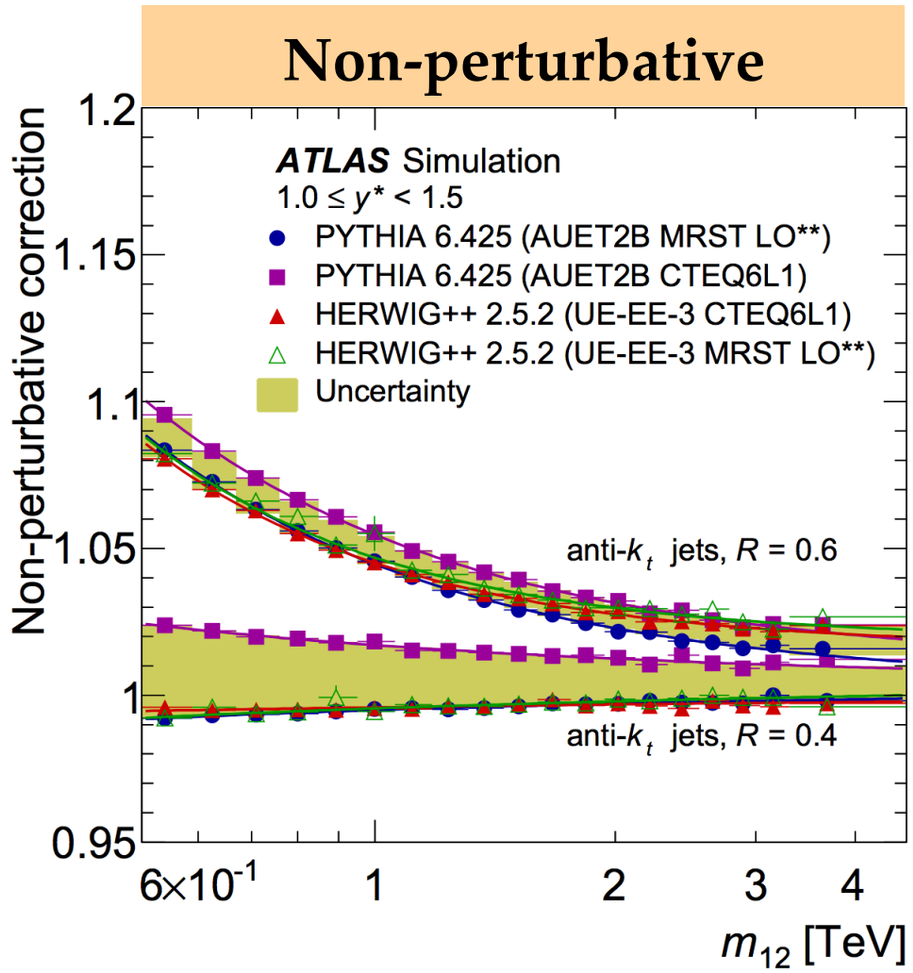
- **NLO PDF fit**: HERA I & ATLAS 2.76 TeV and 7 TeV data
  - Improved sensitivity from correlated uncertainties
- **Impact at high x**: (1) **harder gluon** xg(x) distribution *(reduced uncertainty)*
  (2) **softer sea quark** xS(x) distribution *(rel. uncert. larger)*

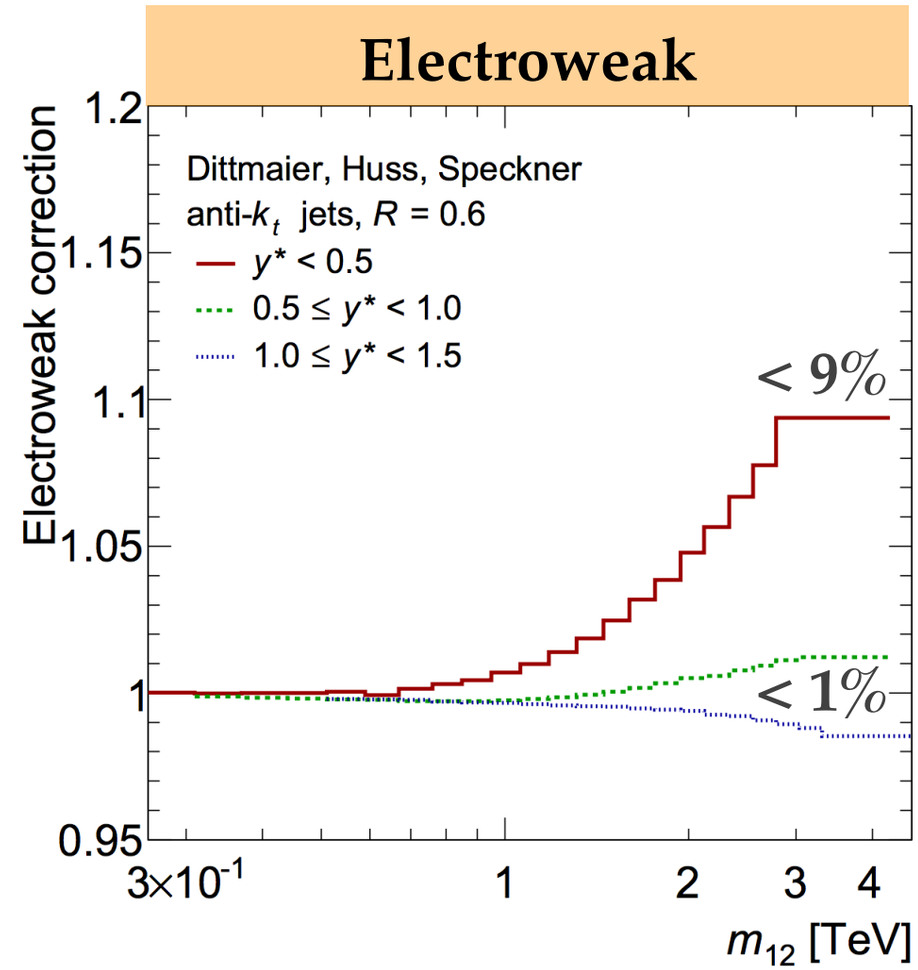




Dijet cross sections

- **NLO QCD** (NLOJet++) with corrections:





Selection

2 leading jets

- rapidity separation $y^* = |y_1 - y_2| / 2$
- dijet mass up to $m_{12} < 5$ TeV

Note:
Compared to previous results: increased statistics & improved JES

Dijet cross sections

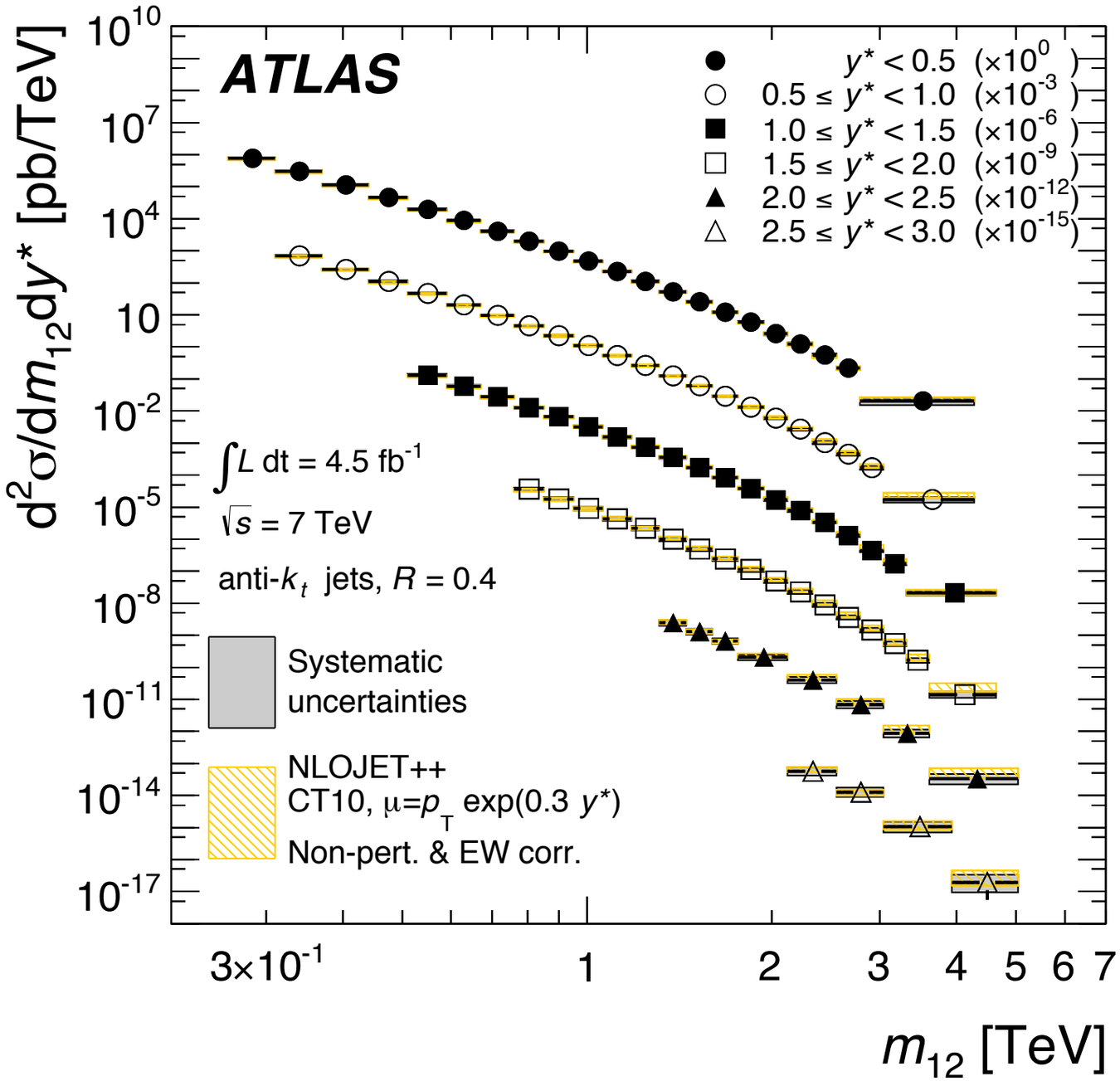
- **Double differential cross section** as a function of dijet mass and y*

- **Agreement** over almost 8 orders of magnitude!

- Jet Energy Scale (JES): dominant exp. uncertainty

- **Constrain gluon PDF at large x**

- Unfolded cross section <u>sensitive to new physics</u>

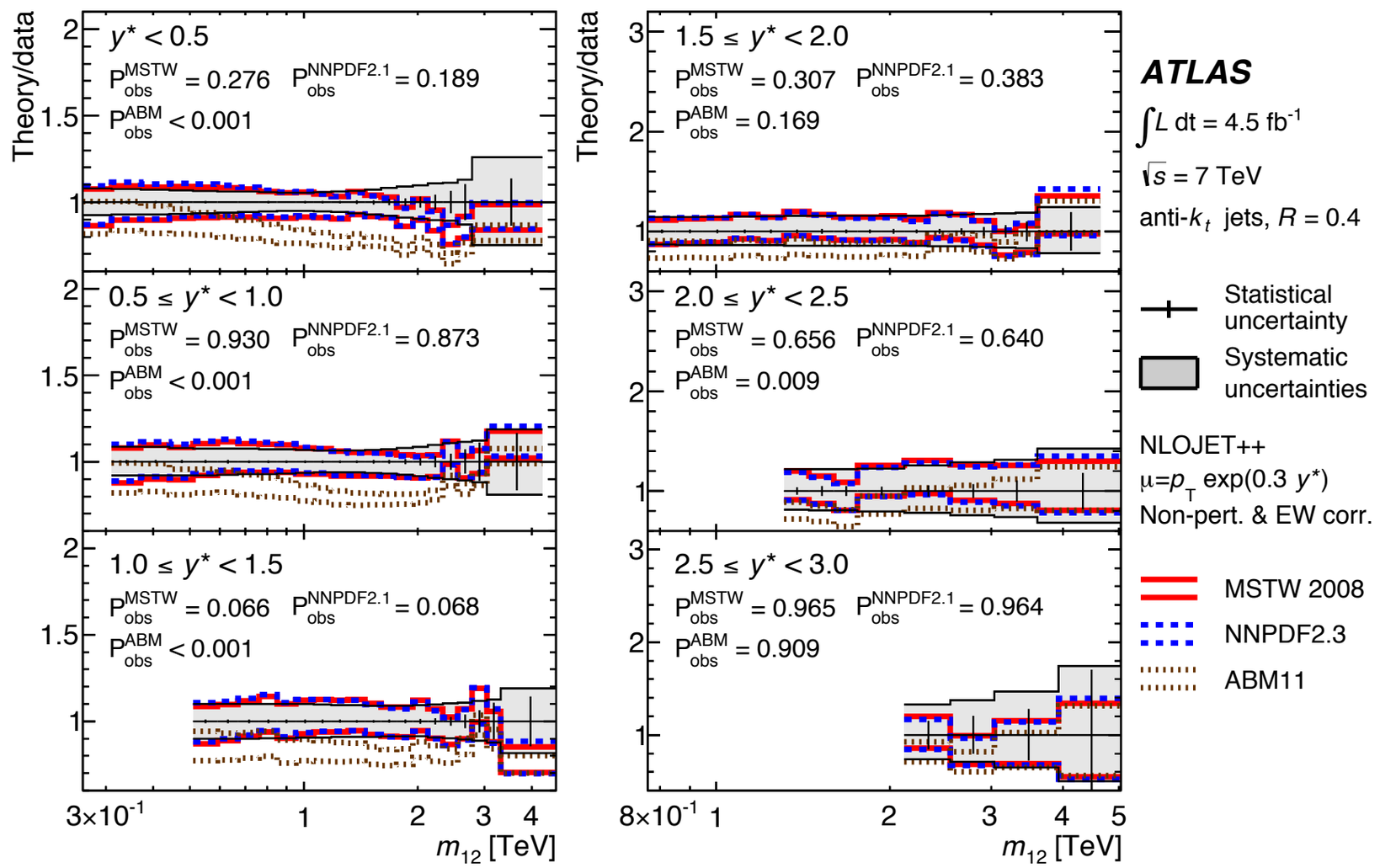


Dijet cross sections

- Overall good agreement with **theory predictions**!
- Data agreement with MSTW2008 and NNPDF2.3
- Tensions with HERAPDF1.5 (backup) and ABM11 observed.

PDF set	y^* ranges	mass range (full/high)	P_{obs} $R = 0.4$	P_{obs} $R = 0.6$
CT10	$y^* < 0.5$	high	0.742	0.785
	$y^* < 1.5$	high	0.080	0.066
	$y^* < 1.5$	full	0.324	0.168
HERAPDF1.5	$y^* < 0.5$	high	0.688	0.504
	$y^* < 1.5$	high	0.025	0.007
	$y^* < 1.5$	full	0.137	0.025
MSTW 2008	$y^* < 0.5$	high	0.328	0.533
	$y^* < 1.5$	high	0.167	0.183
	$y^* < 1.5$	full	0.470	0.352
NNPDF2.1	$y^* < 0.5$	high	0.405	0.568
	$y^* < 1.5$	high	0.151	0.125
	$y^* < 1.5$	full	0.431	0.242
ABM11	$y^* < 0.5$	high	0.024	$< 10^{-3}$
	$y^* < 1.5$	high	$< 10^{-3}$	$< 10^{-3}$
	$y^* < 1.5$	full	$< 10^{-3}$	$< 10^{-3}$

Some phase space regions have $P_{obs} < 5\%$ to be described by some PDF sets.



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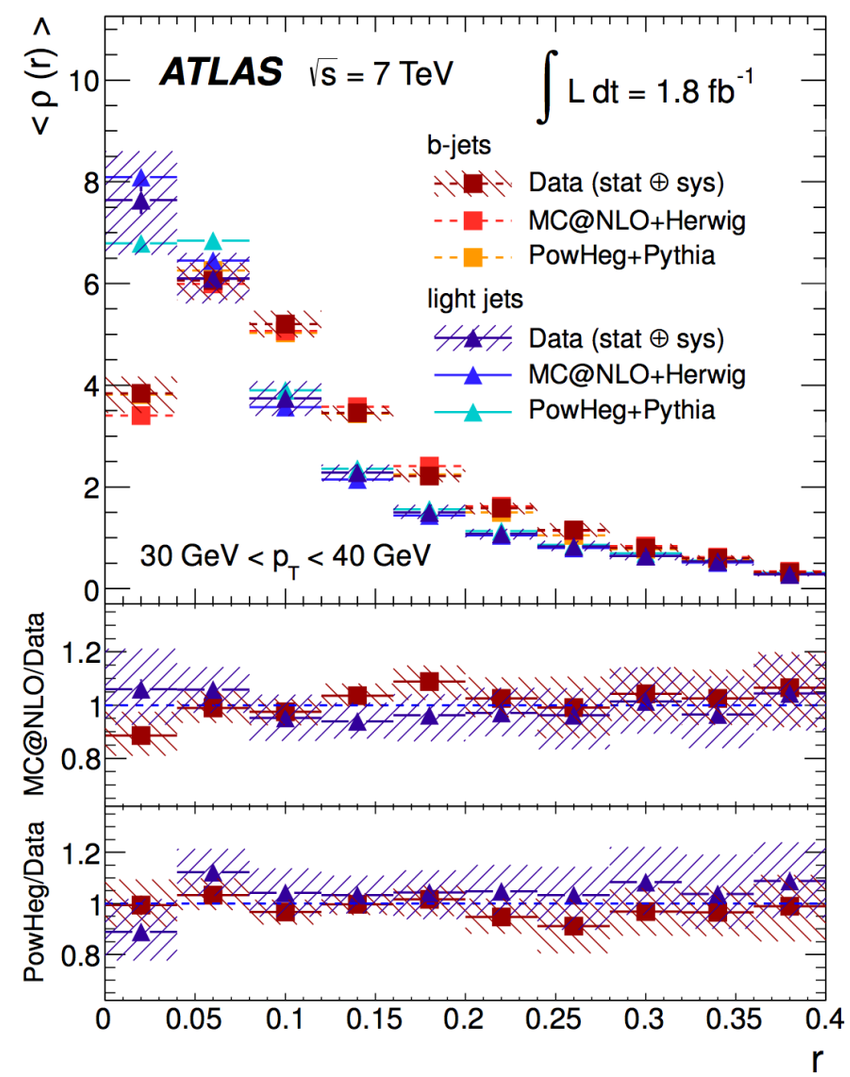
Jet shapes in top-quark pair events

- **Jet shapes**, *norm. p_T flow as function of distance (r) to jet axis*, can probe the **parton shower and hadronization evolution**.

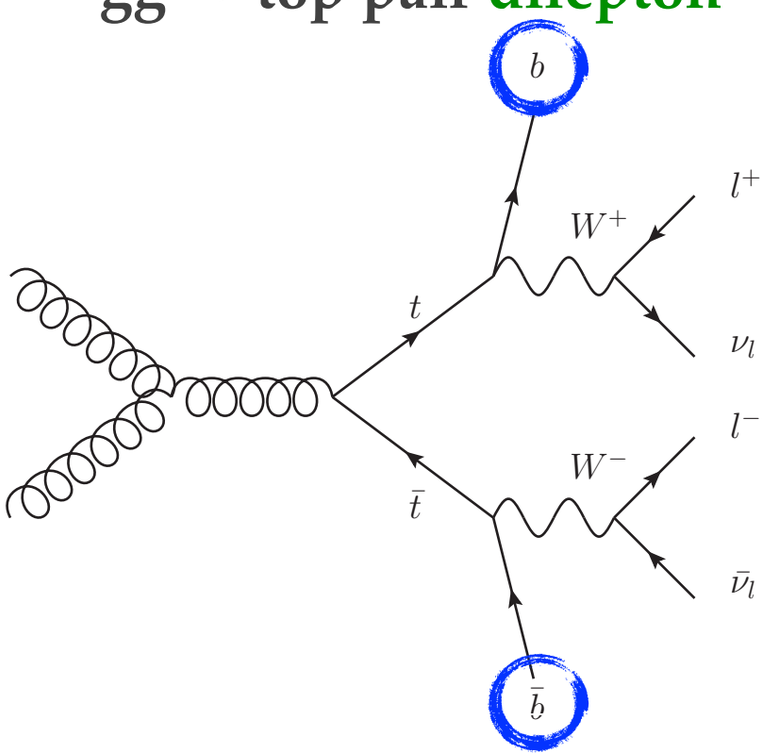
- Strongly jet **p_T dependent**

- b-jets are *wider* than light jets

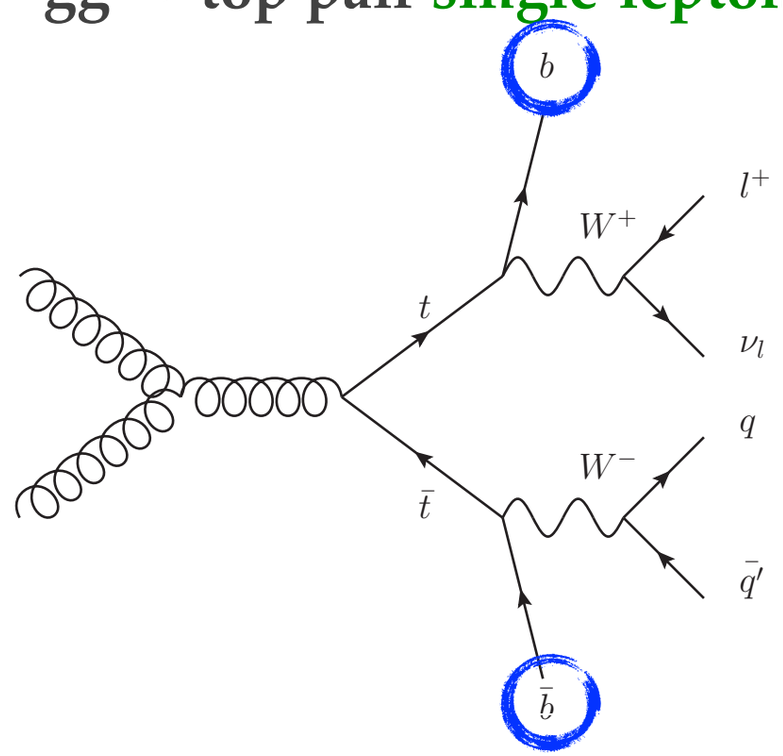
$$\rho(r) = \frac{1}{\Delta r}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$



gg → top pair dilepton



gg → top pair single-lepton



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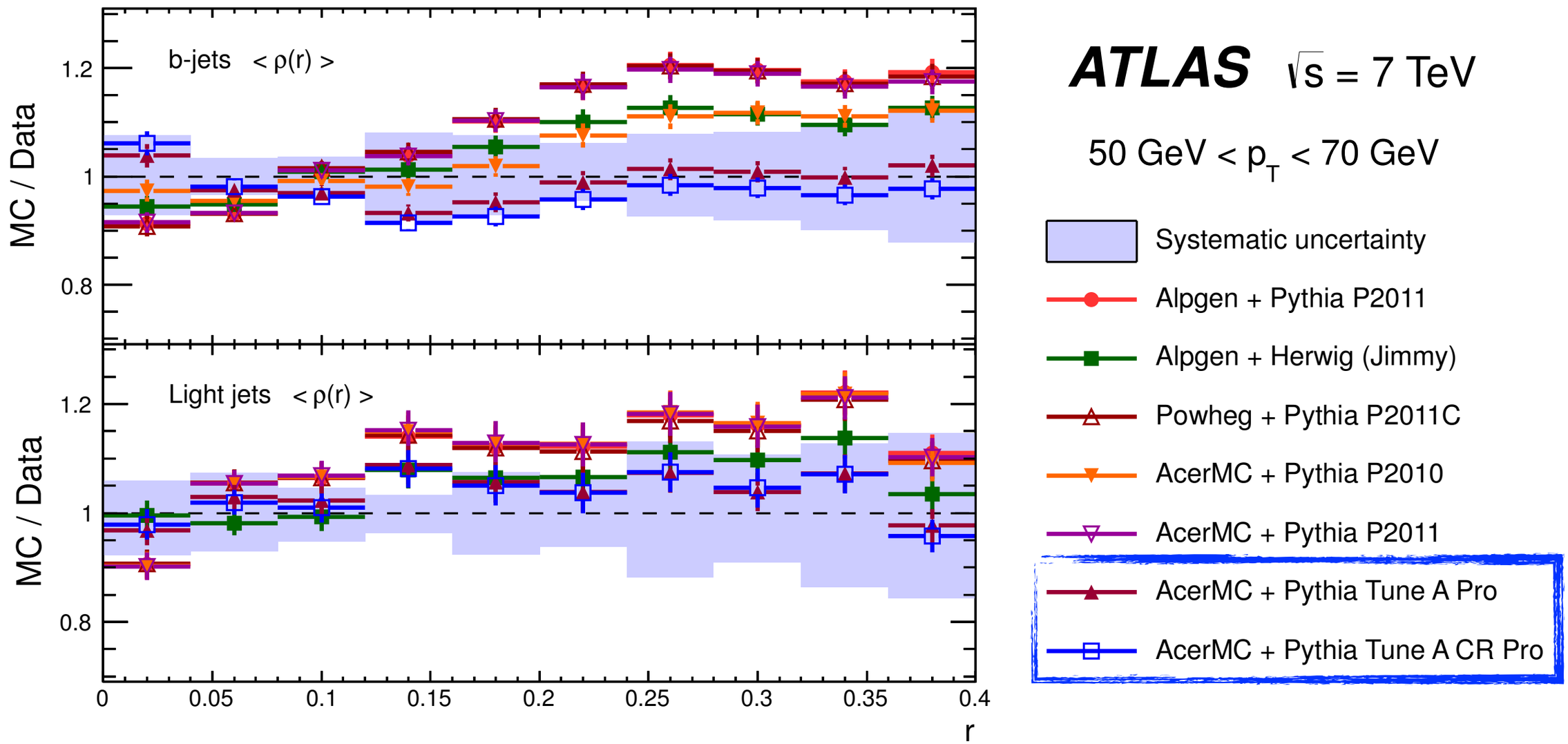
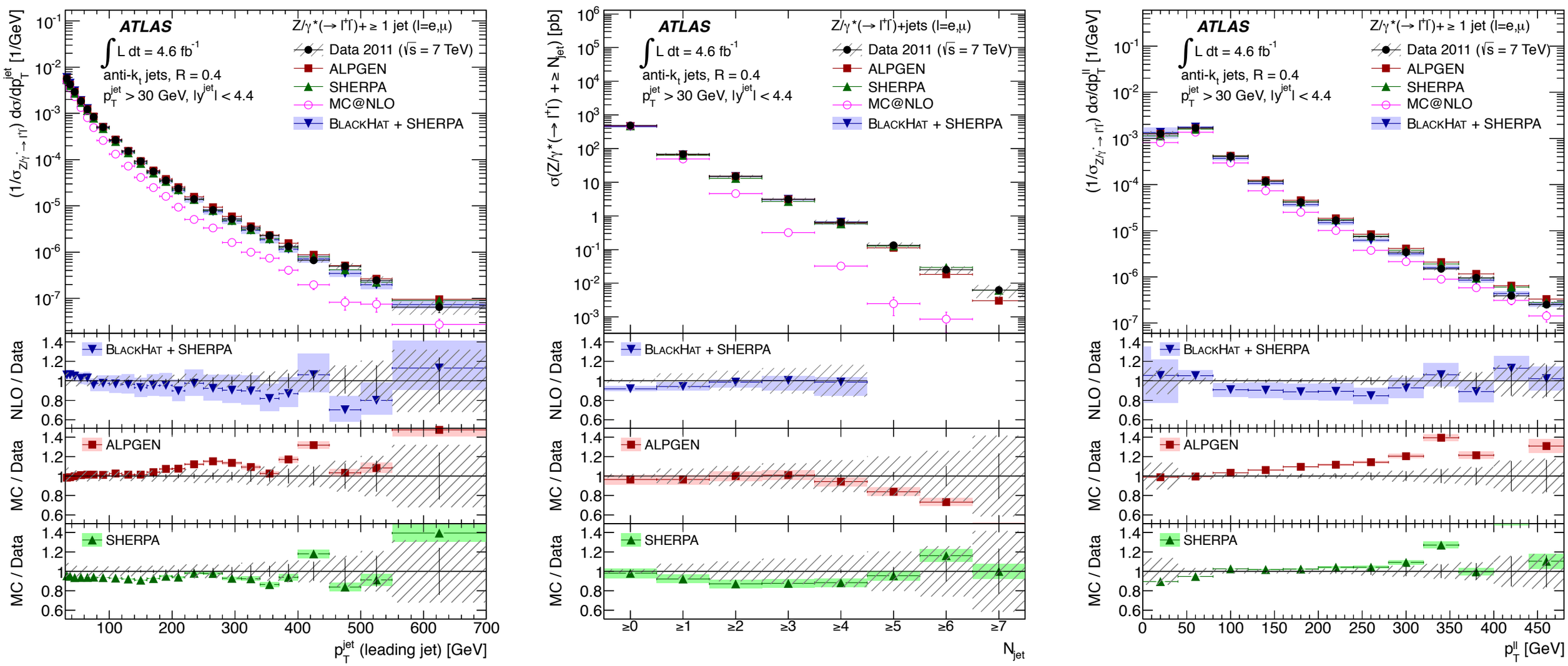
Jet shapes in top-quark pair events

- Most evaluated **MC** generators **overpredict the observable**
- Best data description: AcerMC + Pythia Tune A



W/Z + jets production

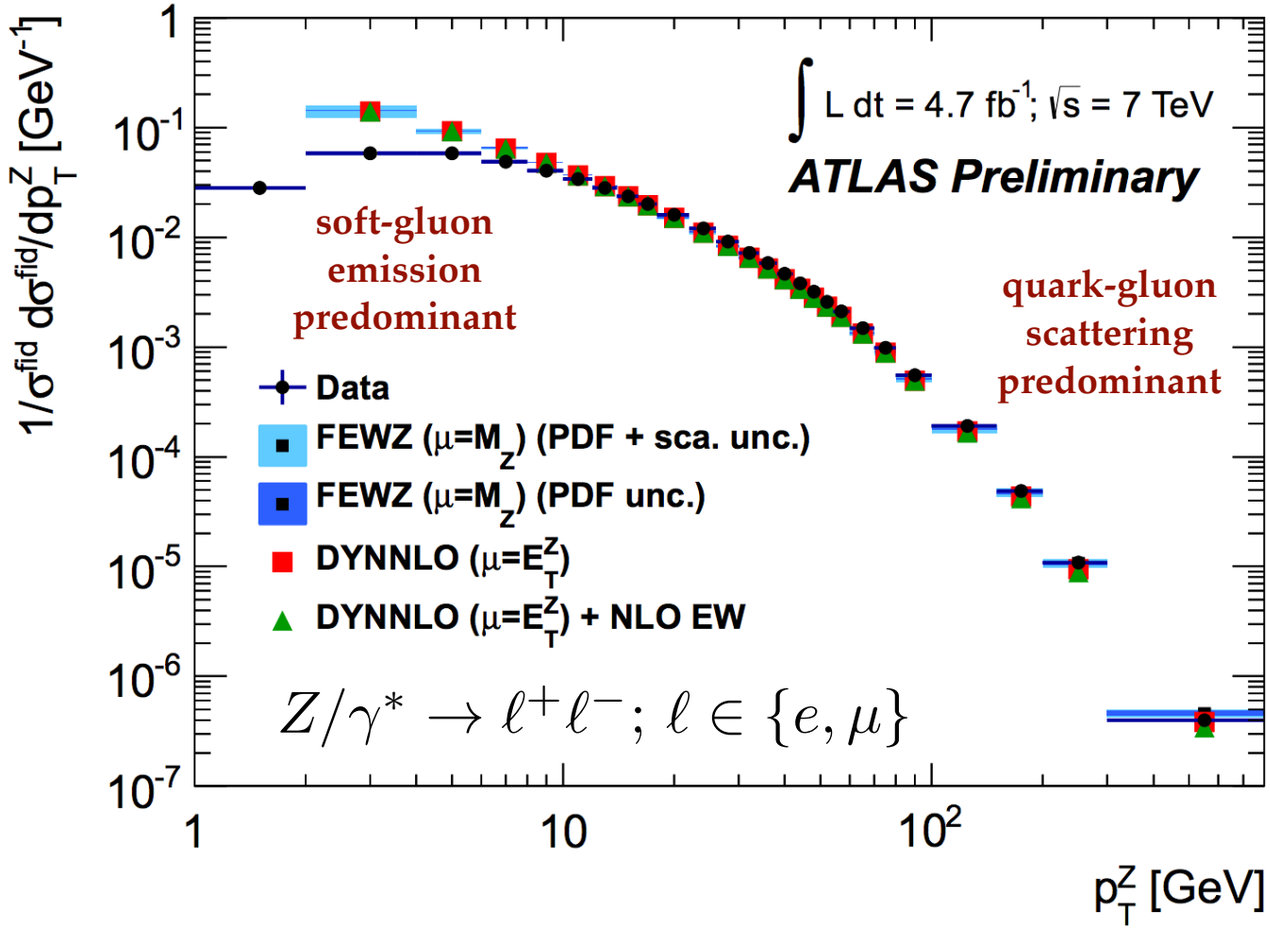
- **Standard candle** to test pQCD and background to Higgs analyses, e.g. VH(H→bb), and BSM searches.
  - N_{jet}, p_T^{jet}, $p_T^{W/Z}$ are basic discriminants in many studies

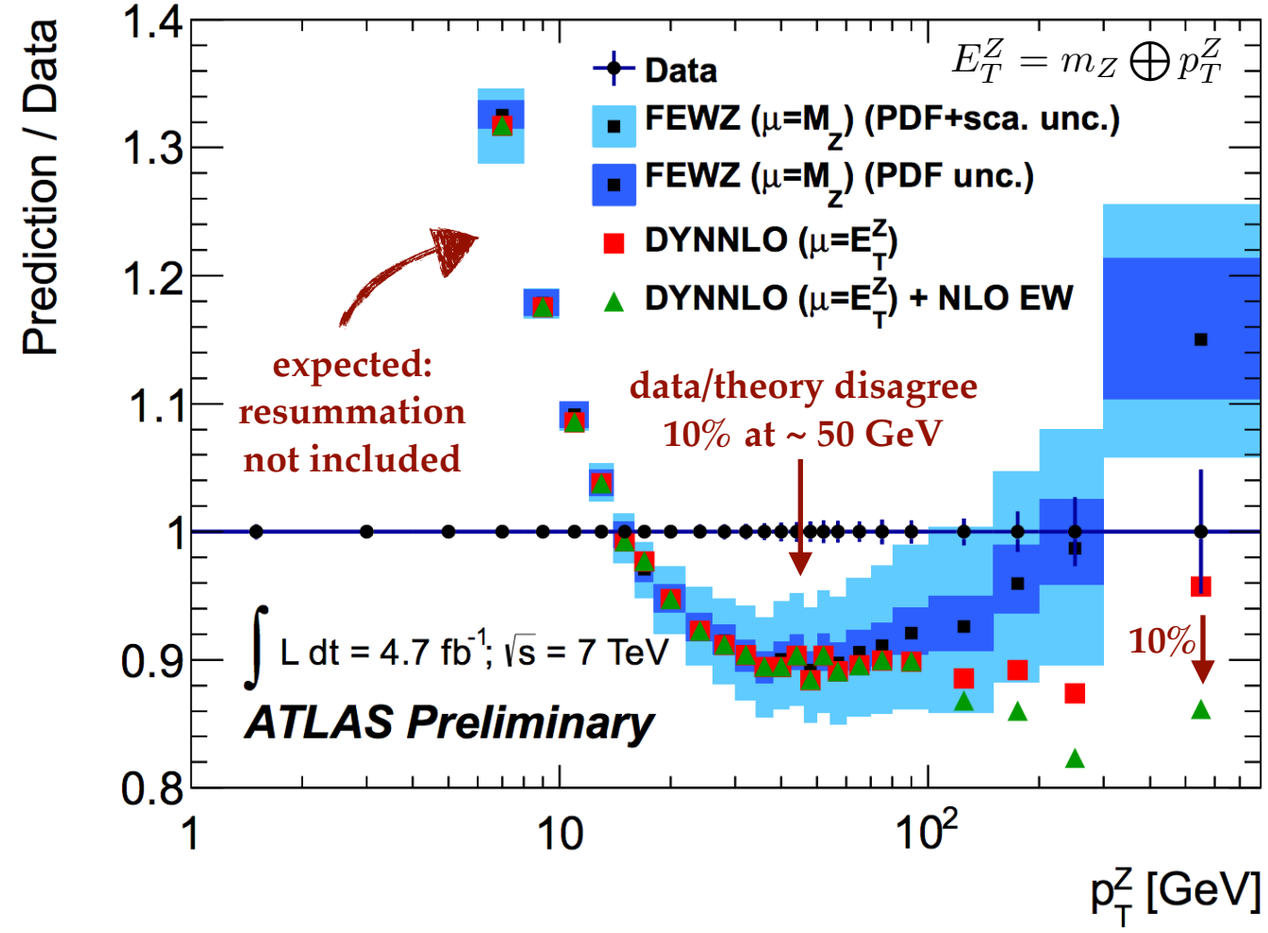


W/Z + jets production

- Correct modelling of **vector boson p_T** important in many analyses
  - e.g. VH(H→bb) analysis binned in p_T^V

- **pQCD at NNLO** (FEWZ, DYNNLO) not incl. resummation (latter in backup)
  - FEWZ/DYNNLO agree with each other with **$\mu_R = \mu_F = m_Z$** & **LO EW** corrections
  - DYNNLO with **$\mu = E_T^Z$ better shape** at p_T>30GeV; + with **LO EW 10%** drop





W/Z + *b*-jets

Overview

- Important to **constrain pQCD** with heavy flavour quarks.
- **Irreducible background** in e.g. VH(H→bb), single top

Strategy

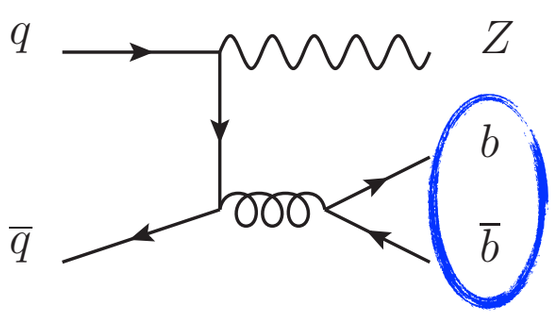
- **Template fit of b-tag weight** of jets (*successive BG fits*)
- Unfolding to particle level

5-flavour number scheme (5FNS)

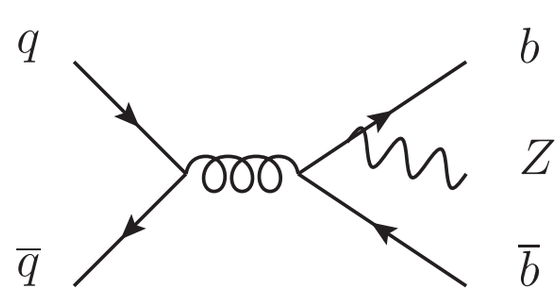
4-flavour number scheme (4FNS)

Double Parton Interactions

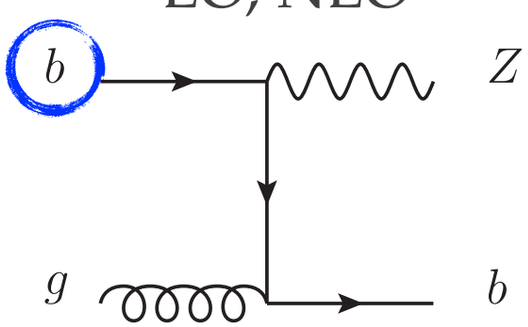
ME (LO, NLO) + PS



Gluon splitting (PS)

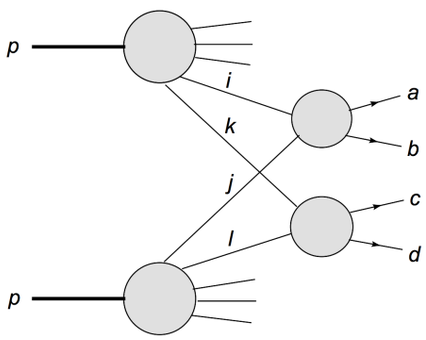


LO, NLO

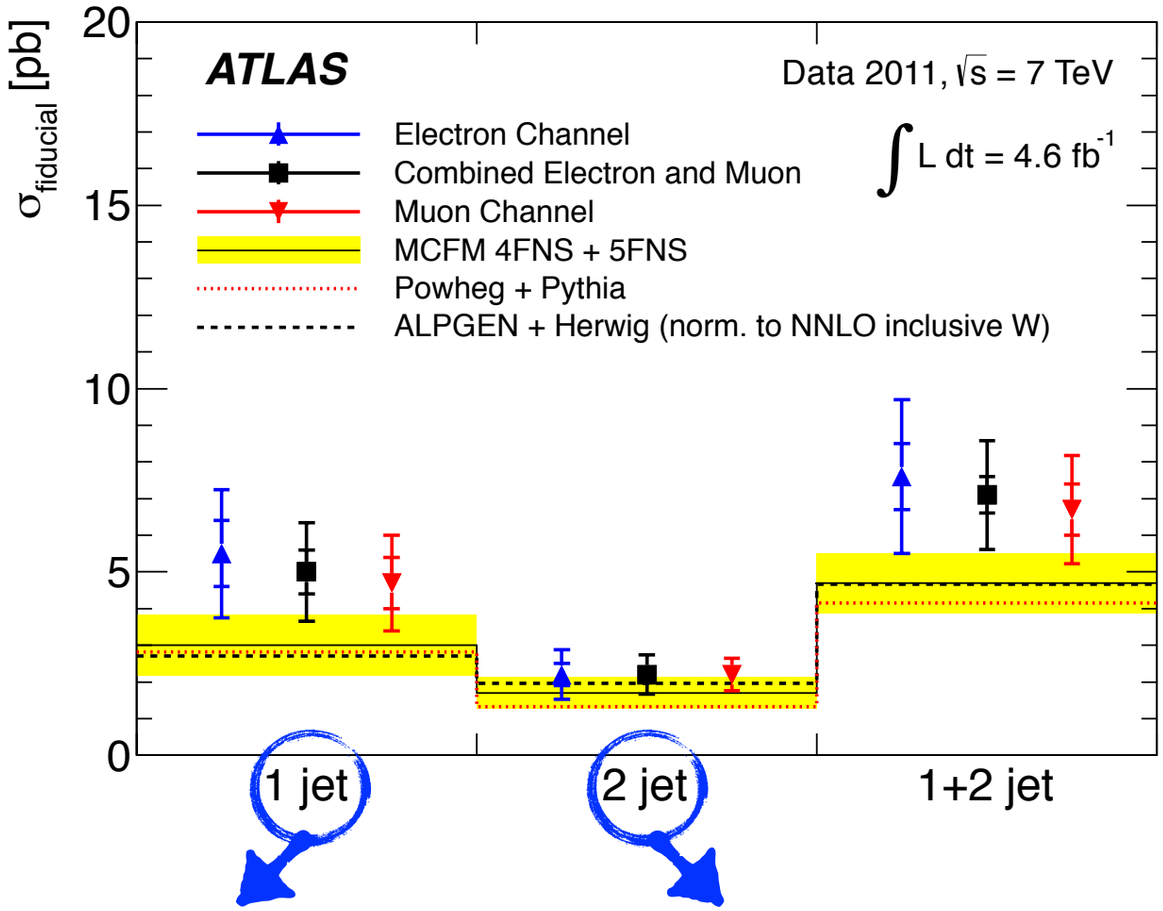


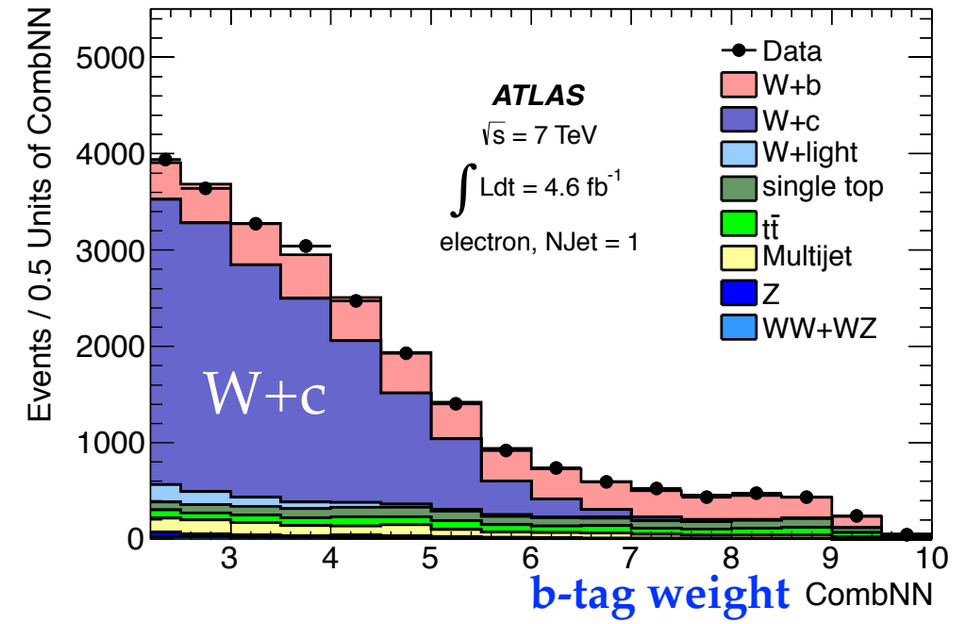
b-quark initial state

Alpgen, Sherpa, …



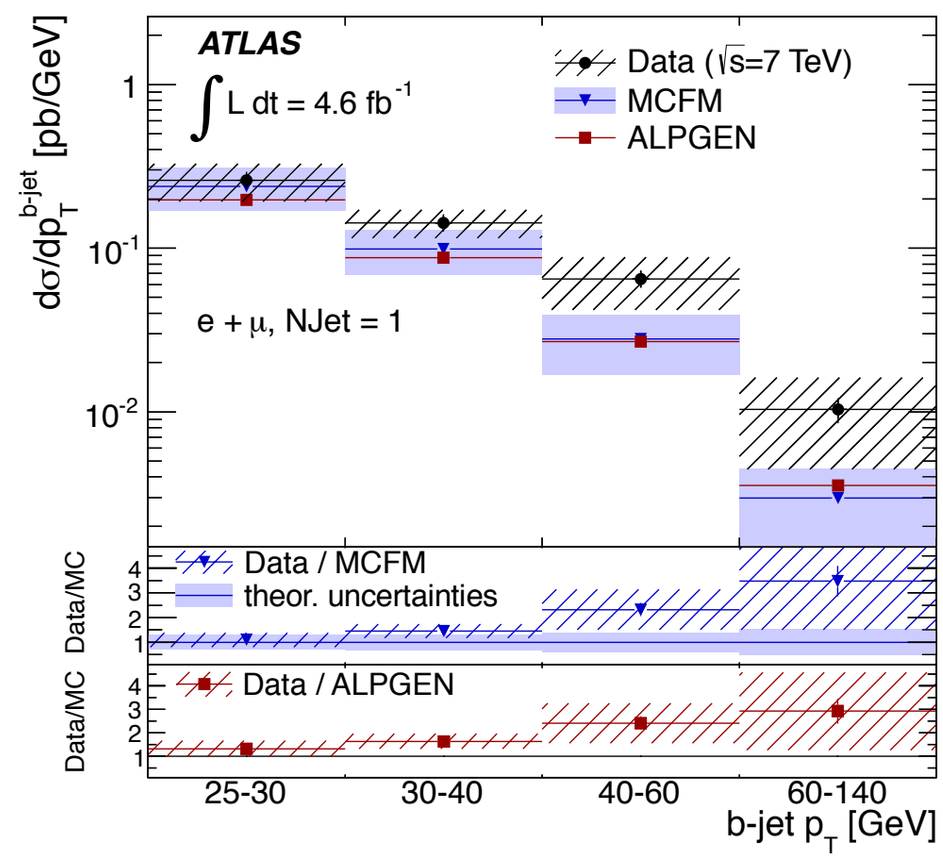
W + *b*-jets





Within 1.5σ consistent

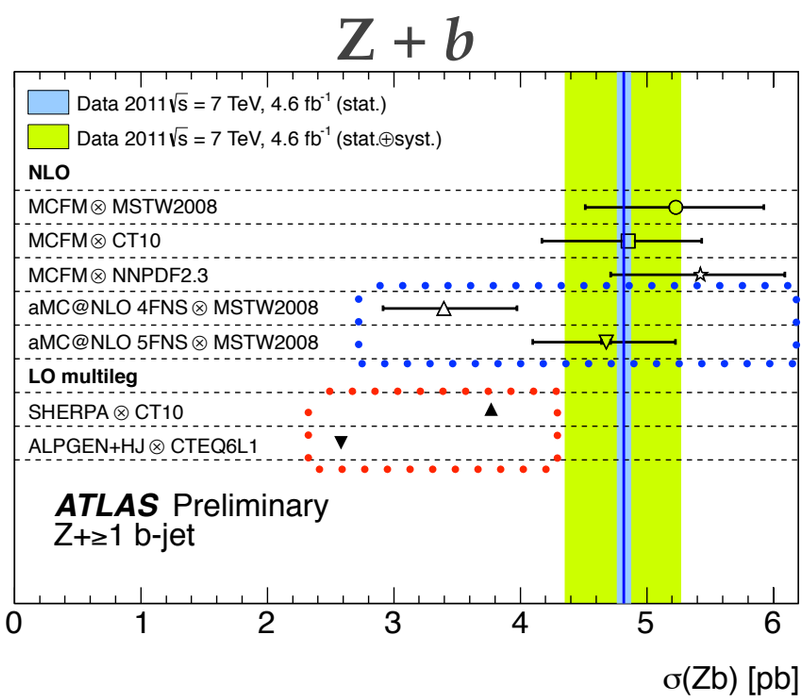
Good agreement of ALPGEN +Herwig & MCFM with data

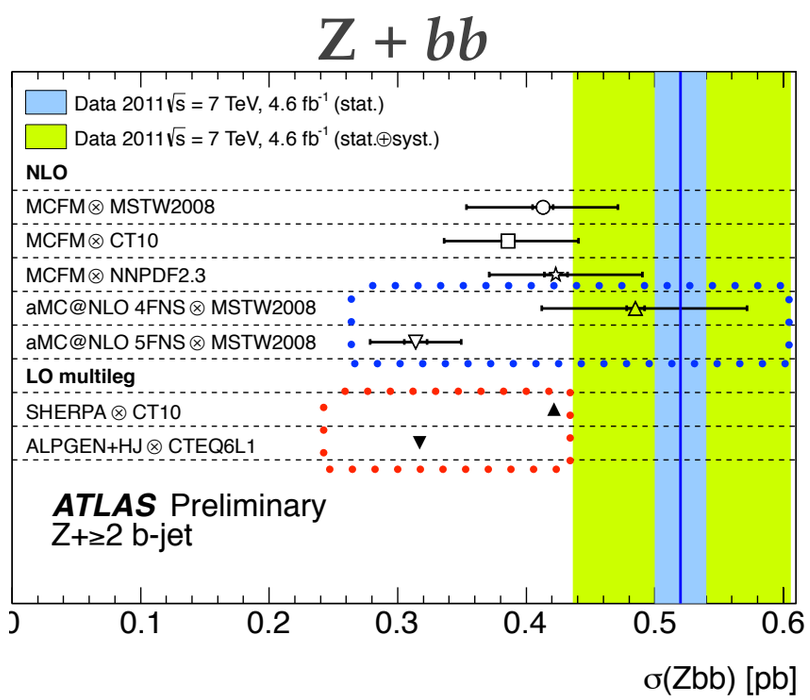


- Data **underestimated at large b-jet p_T**
  - Tension to be confirmed with <u>higher statistics</u> and <u>improved systematics</u>

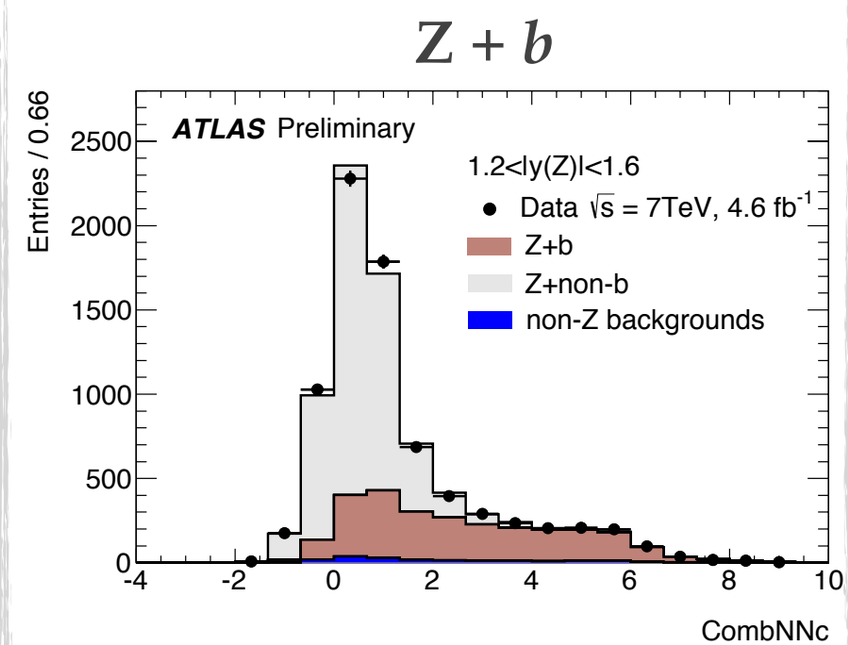
Z + $b(b)$ production

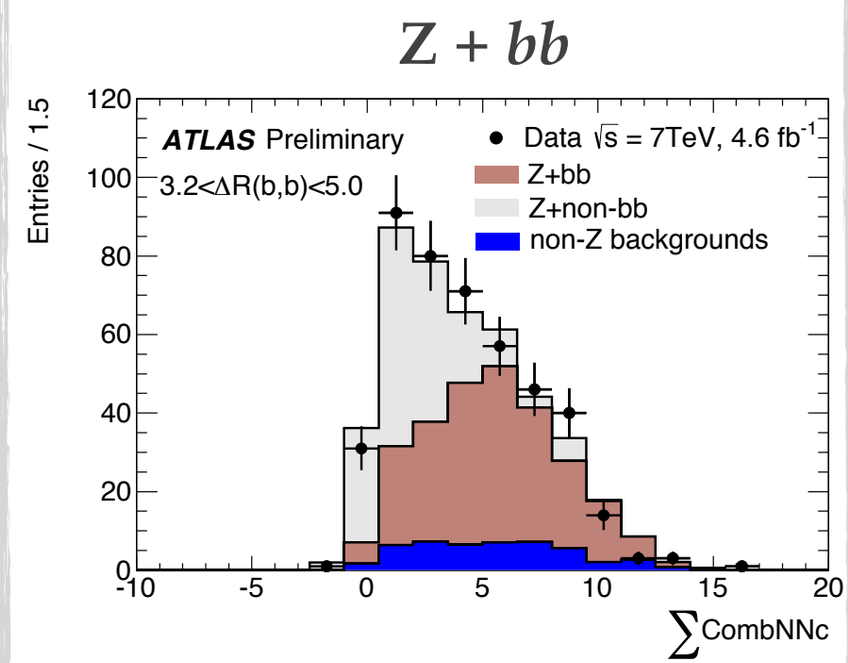
- **MCFM** (5FNS, NLO) **data-compatible**
- aMC@NLO:
  - Z+b favours 5FNS
  - Z+bb favours 4FNS
- LO+PS: σ underestimated (Sherpa better)



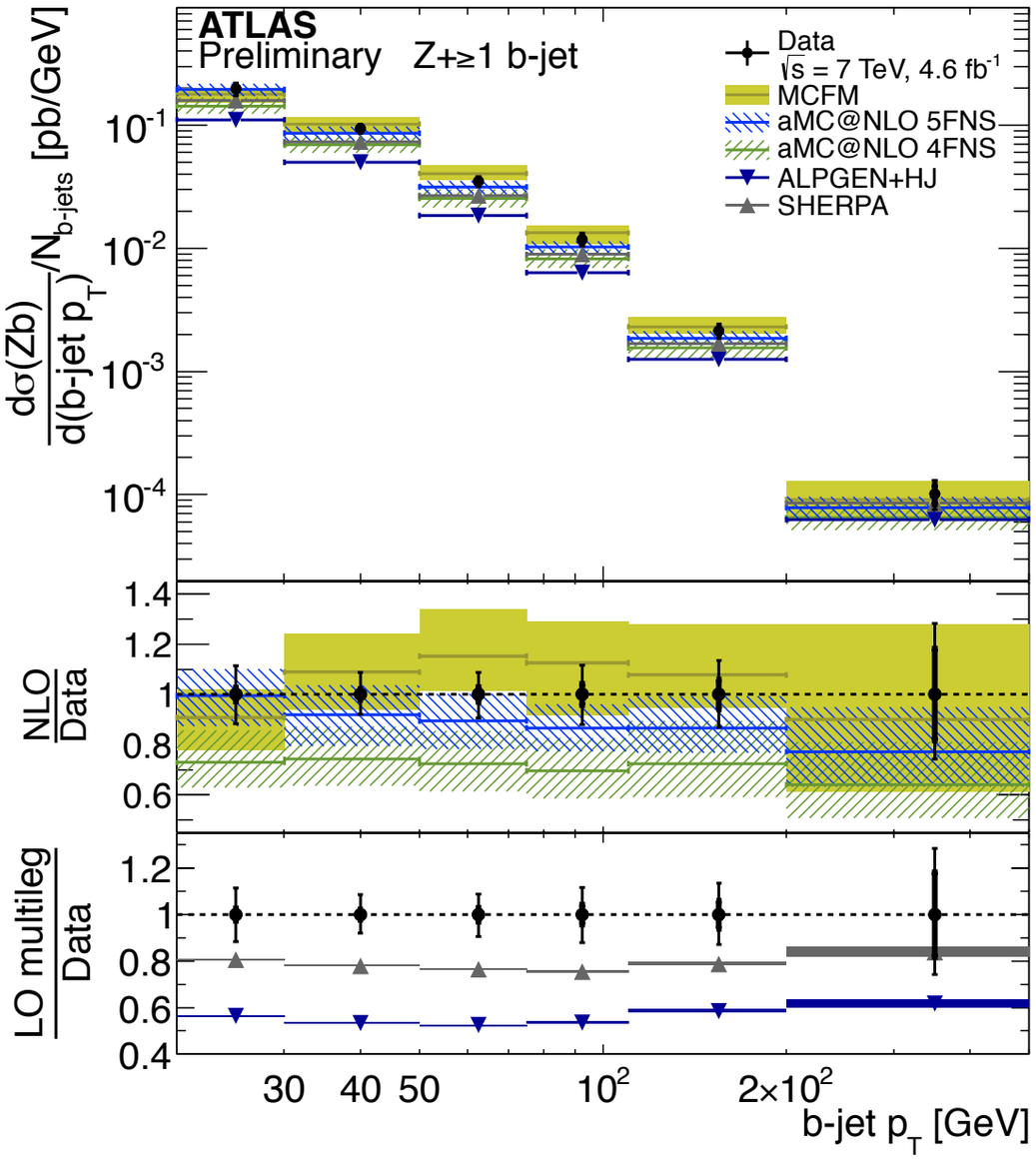


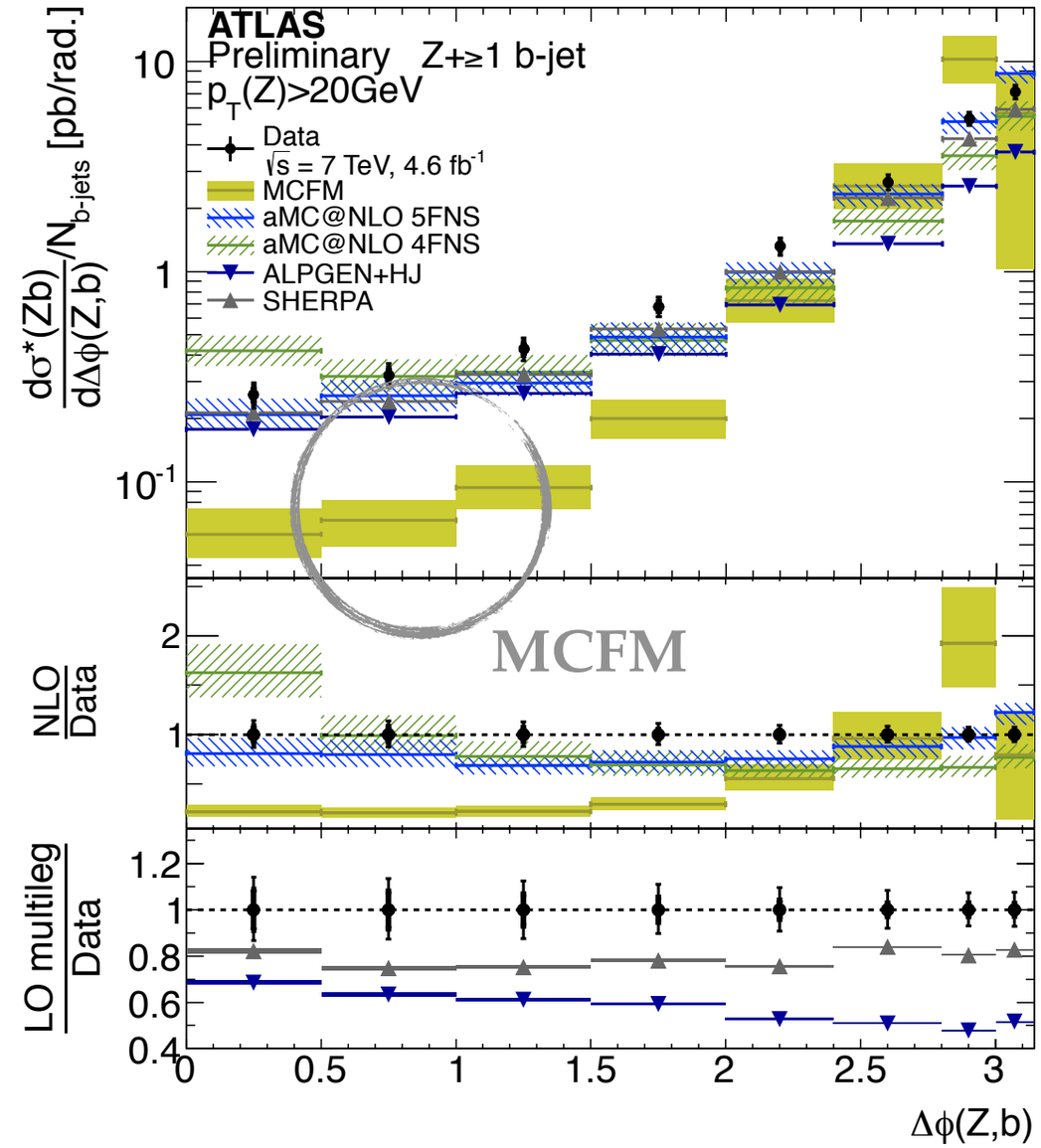
b-tag weights





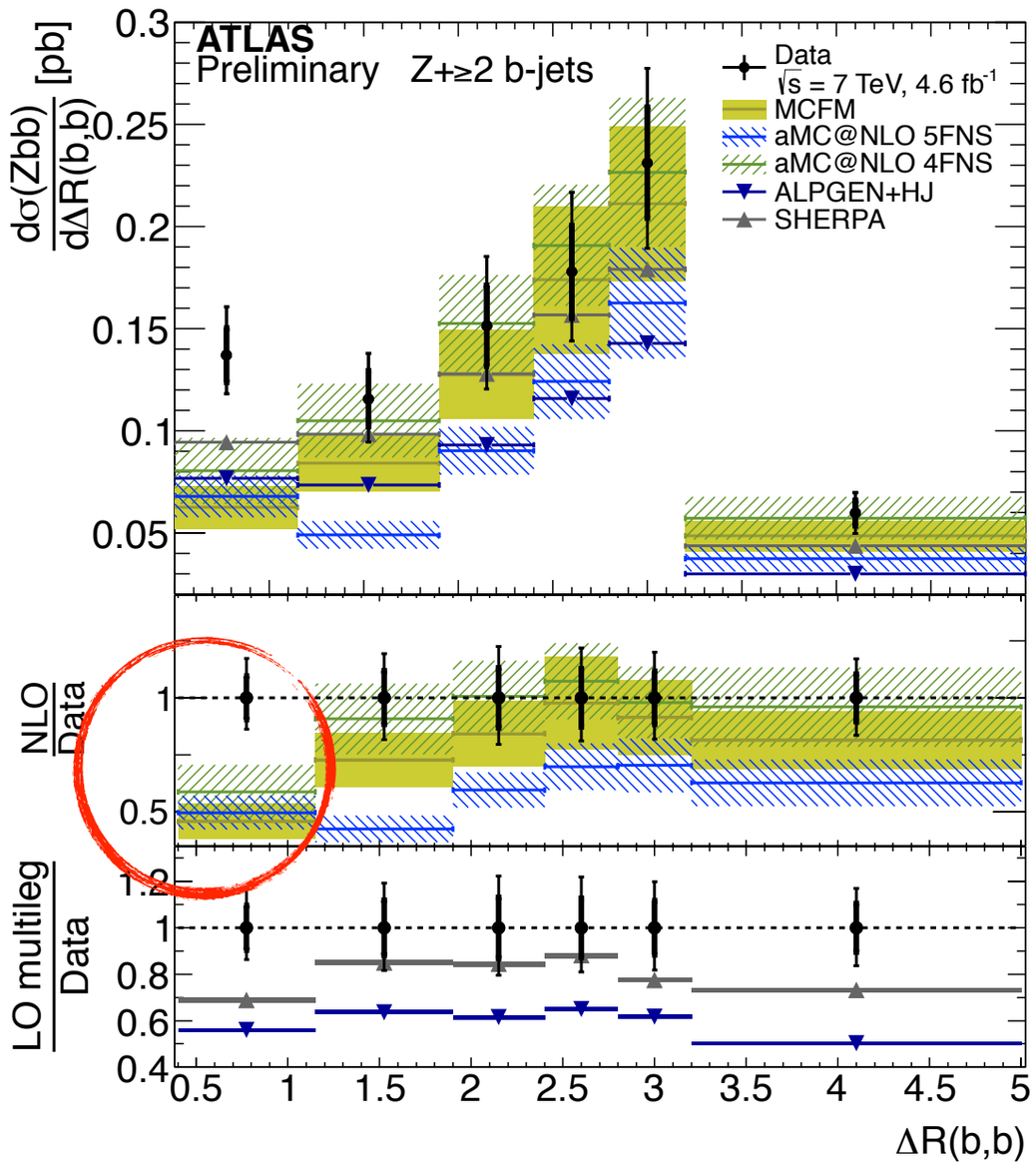
Z + *b*(*b*) production

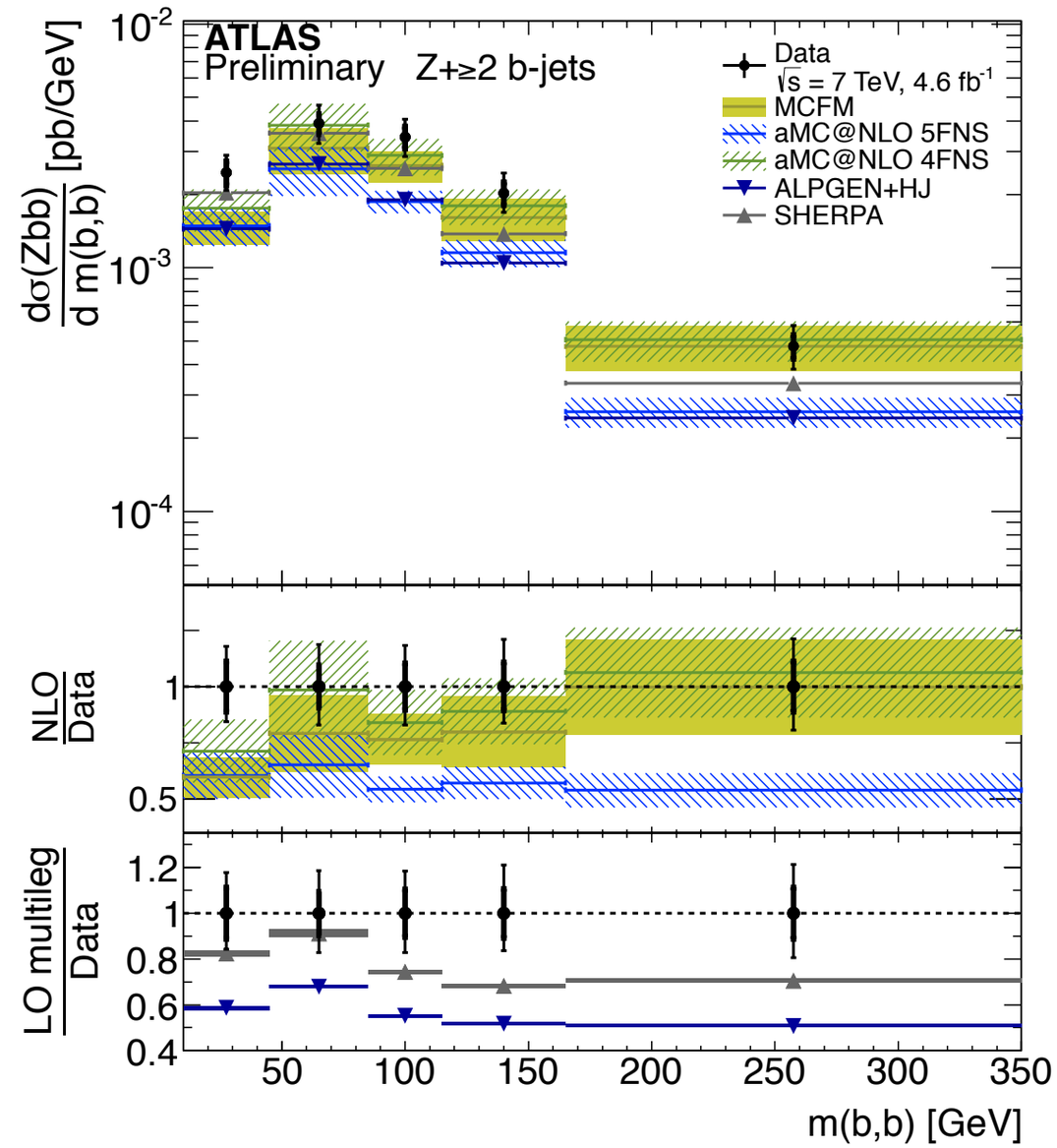




- **All** generators **describe the *b*-jet p_T**
- $\Delta\Phi(Z,b)$ not described by MCFM (exp. from fixed-order); LO+PS better

Z + $b(b)$ production



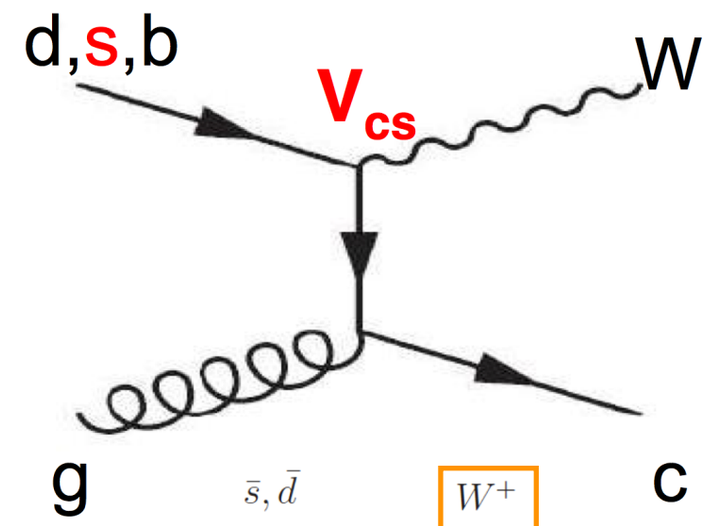


- At **low ΔR(b,b)** predictions from **theory** are **too low**:
  - Maybe from *gluon splitting at low angle*?

W + *c* production

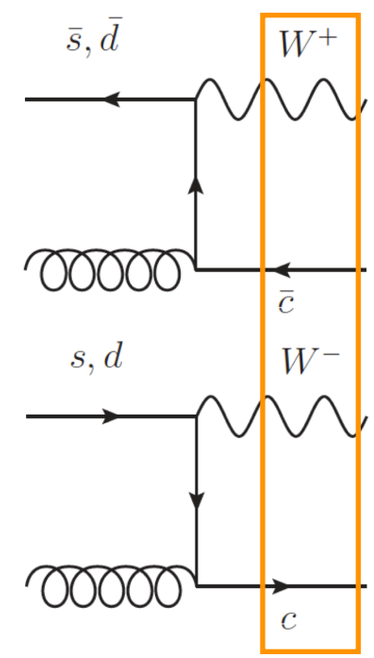
- **W + charm** dominated by LO production;

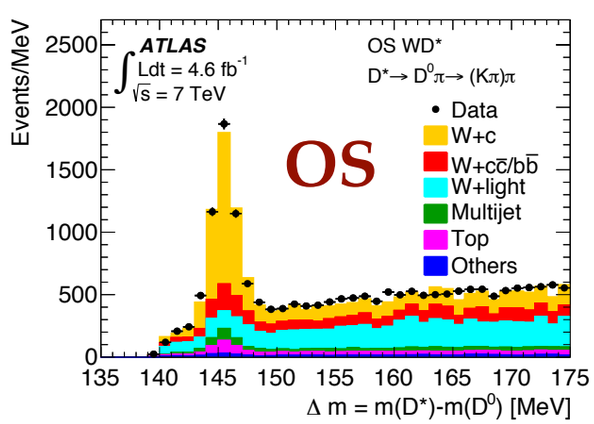
  → directly **sensitive to s-quark PDF** (x ~ 0.01)



Strategy

- Use of the **c-quark / W charge** correlation
  - A. Tag soft muon decay in c-jet
  - B. Reconstruct charged $D^{(*)}$ mesons
- 6 measurements: **$W^{\pm}$+c-jet, $W^{\pm}$+D, $W^{\pm}$+D***
- OS-SS subtraction for <u>pure signal selection</u>





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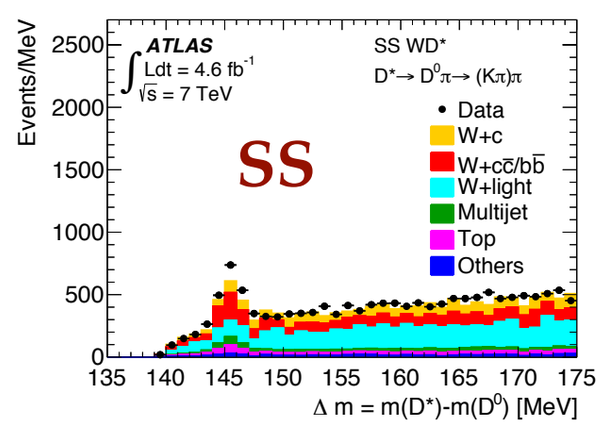

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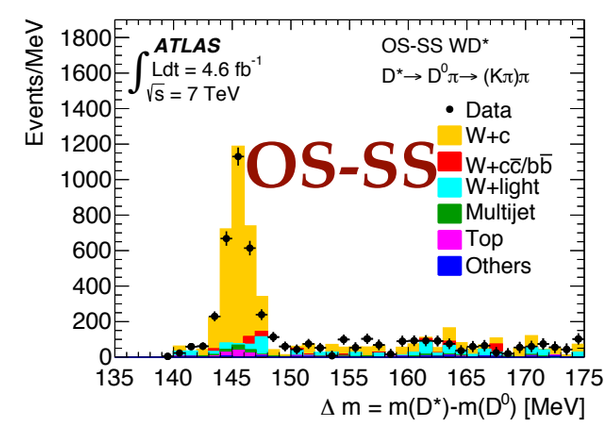
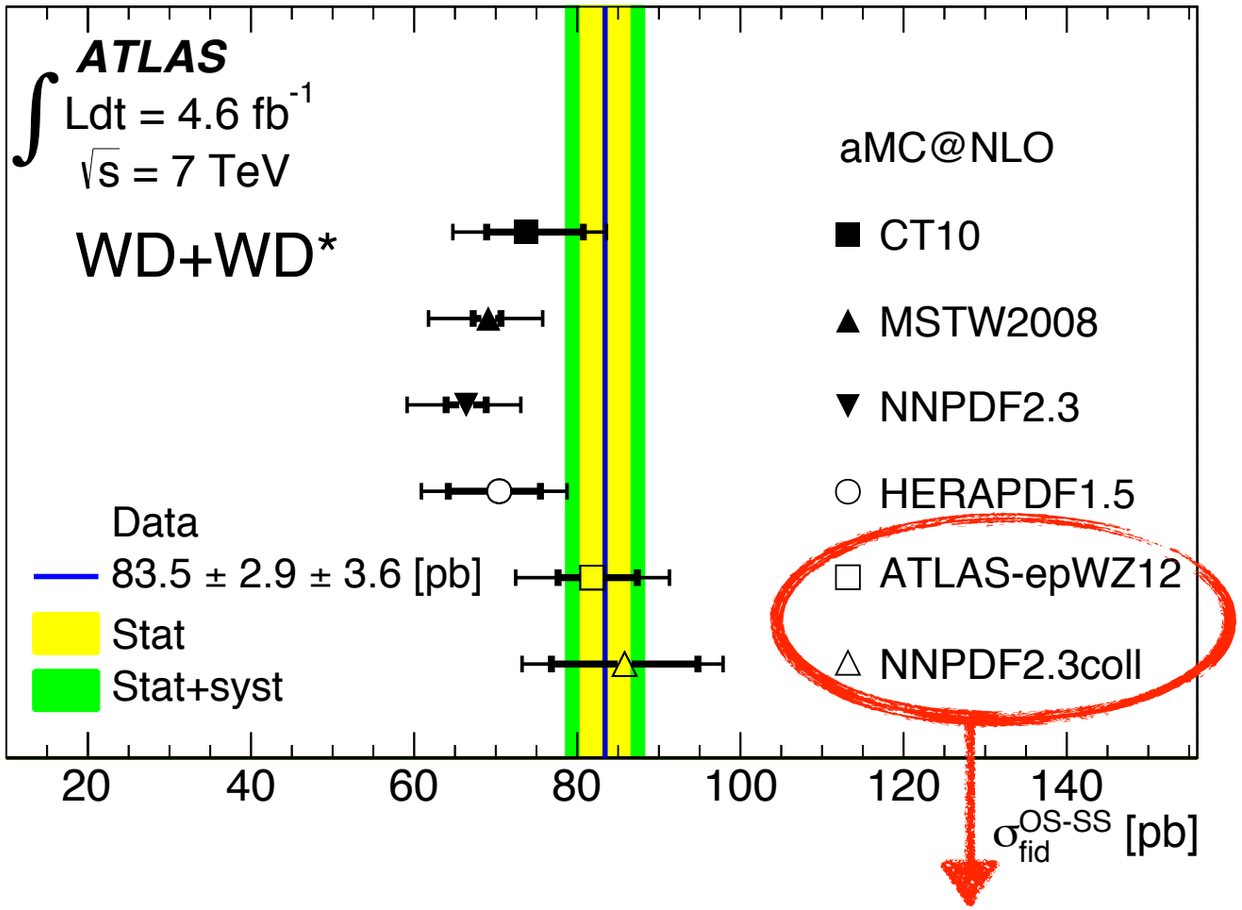
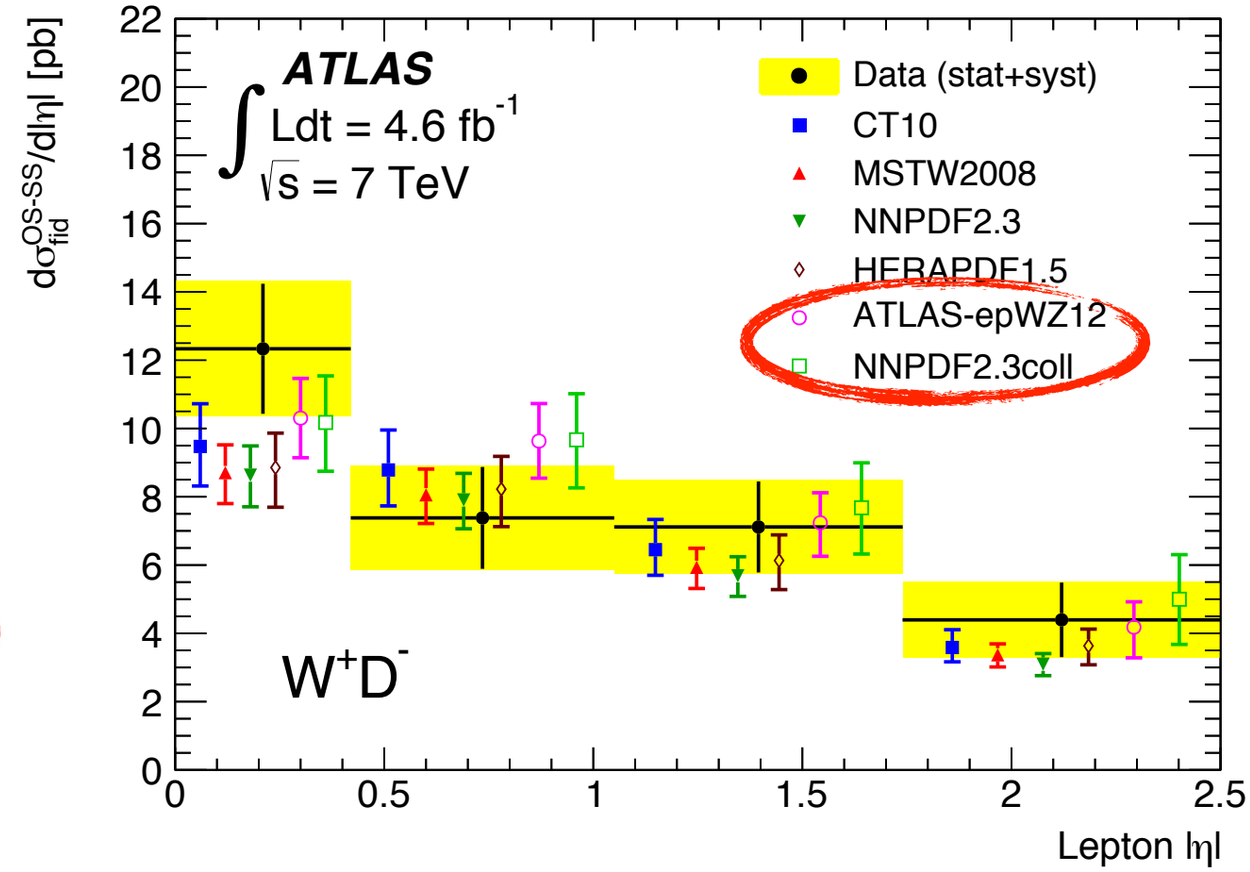


W + *c* production



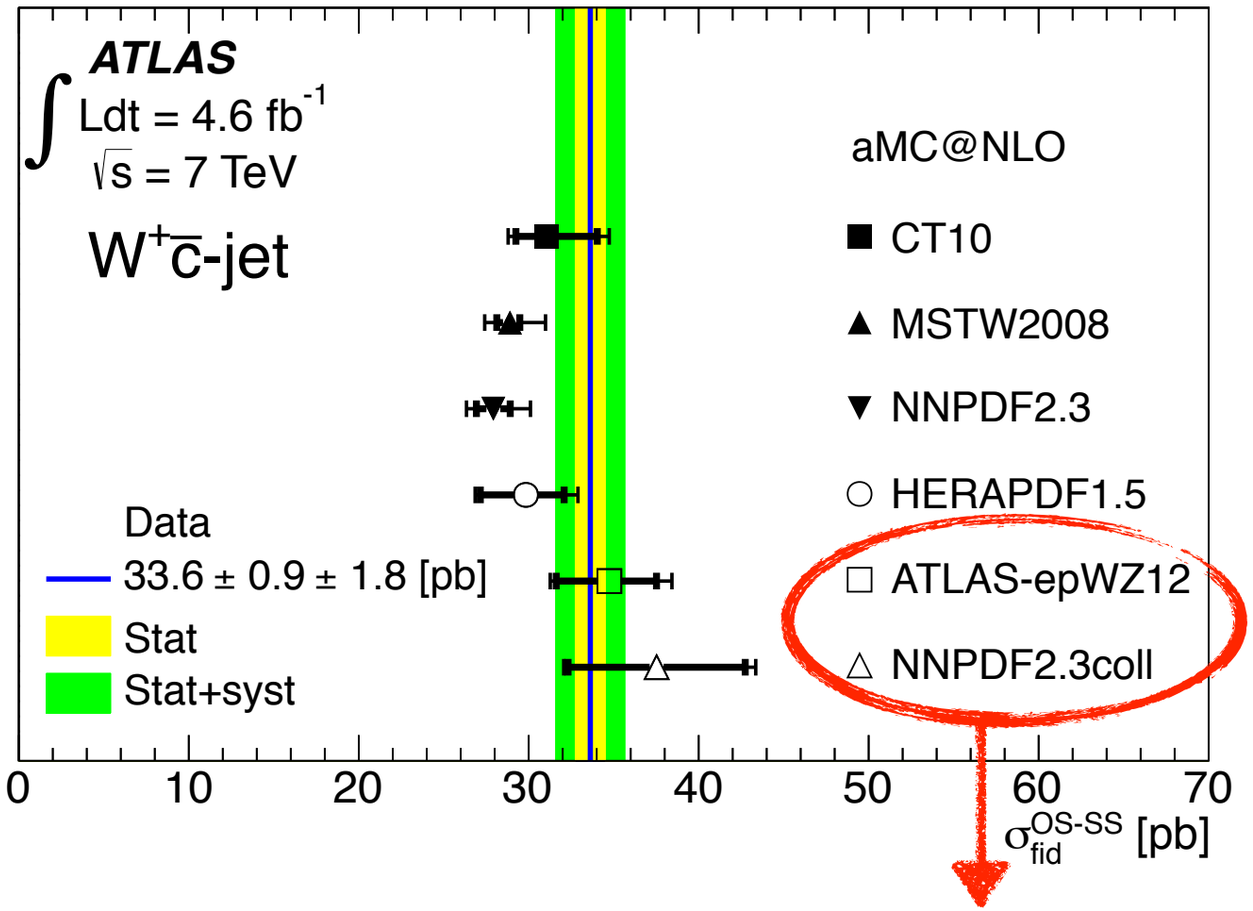


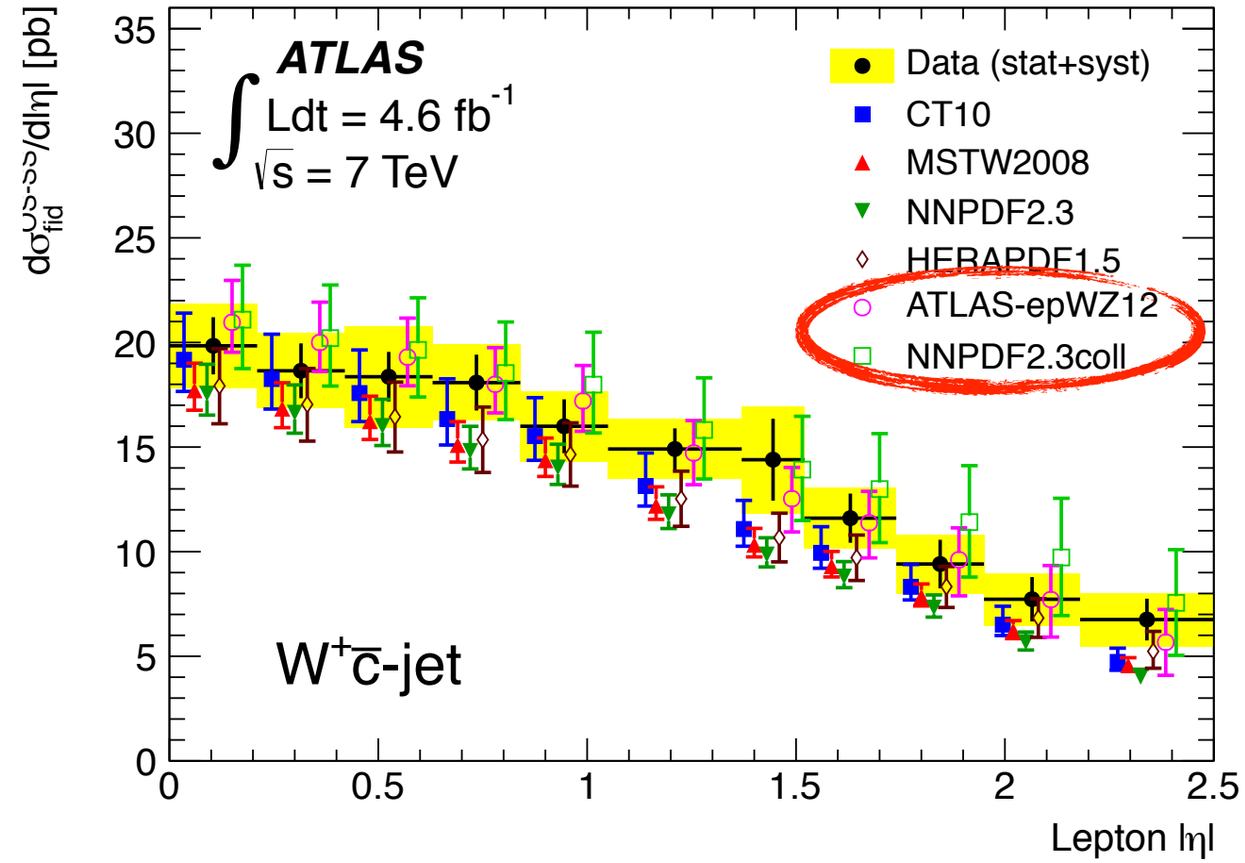
PDFs: symmetric light quark sea

- From PDF comparisons to cross section measurements, it seems

  ⇒ **data favours PDFs with symmetric light quark sea**

W + *c* production

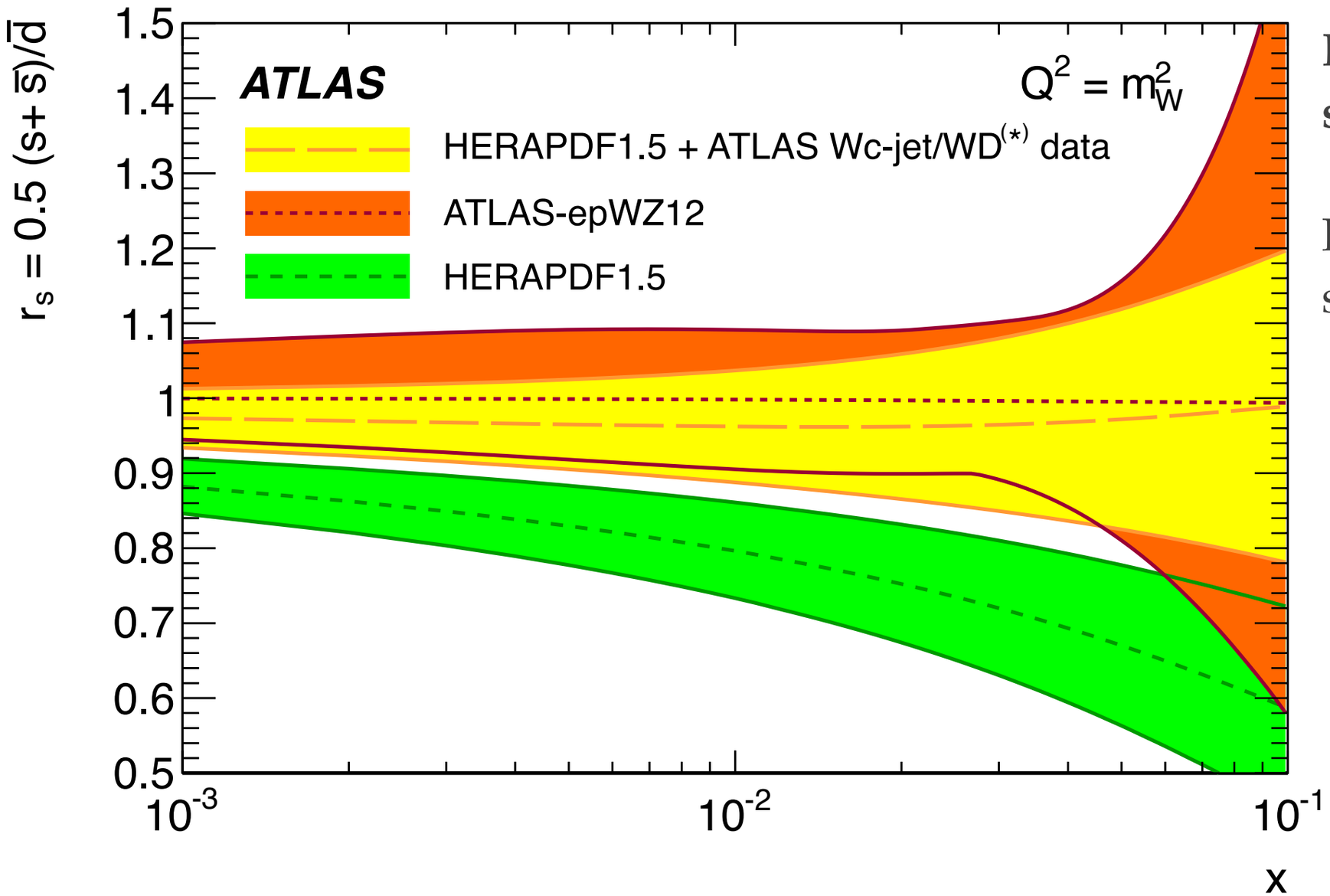




PDFs: symmetric light quark sea

- Measurements **limited by statistical uncertainties**
- **Scale uncertainty (4-9%)** ← theory accuracy (improvement needed)

W + *c* production



Ratio of strange-to-down sea-quark distributions

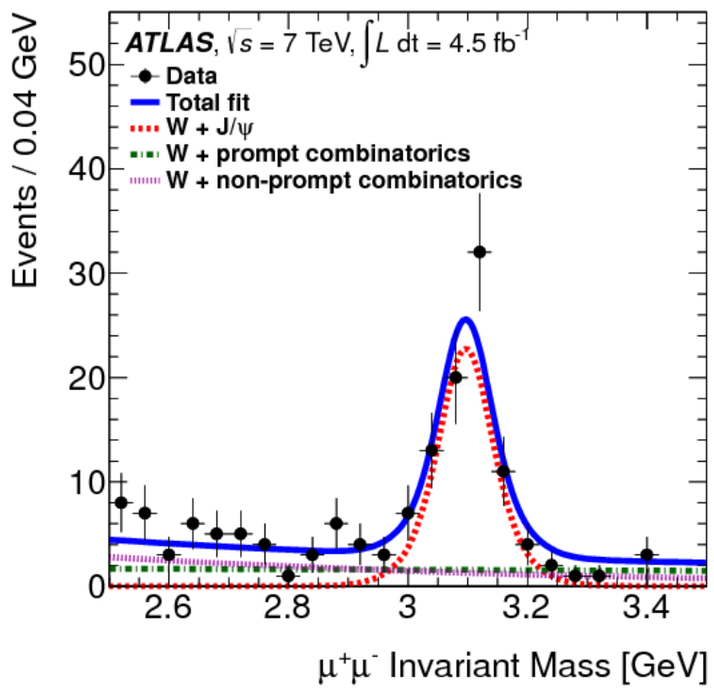
HERA PDF implements s-density as single param.

$$r_s \equiv 0.5(s+\bar{s})\bar{d}$$
$$= f_s/(1-f_s)$$
$$= 0.96^{+0.16(exp.+th.)+0.21(scale)}_{+0.18(exp.+th.)+0.24(scale)}$$
$$(\text{at } Q^2 = 1.9GeV^2)$$

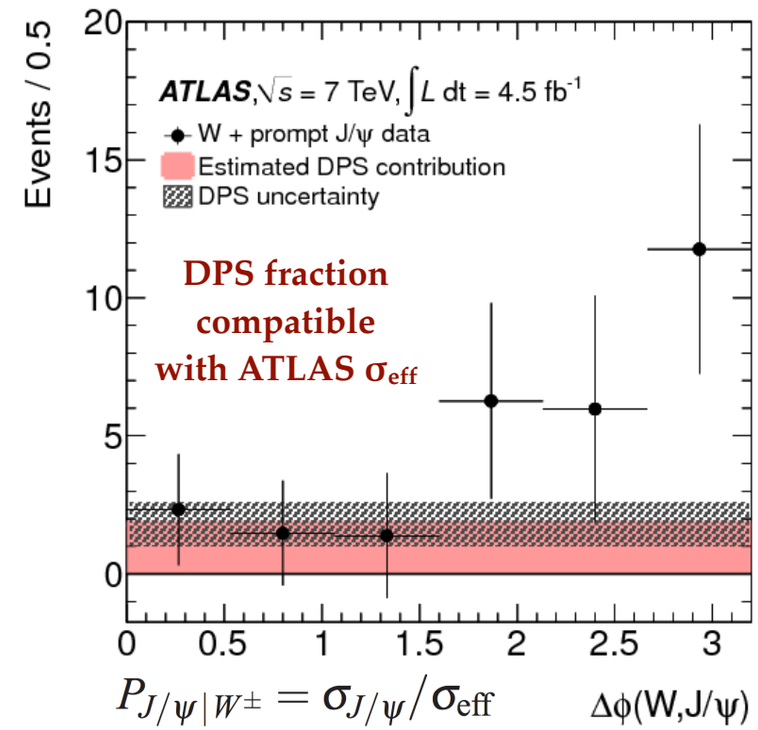
- **ATLAS-epWZ12** PDF **incl. ATLAS W/Z data**: ***results compatible***
- Strong indications: **symmetric light quark sea**

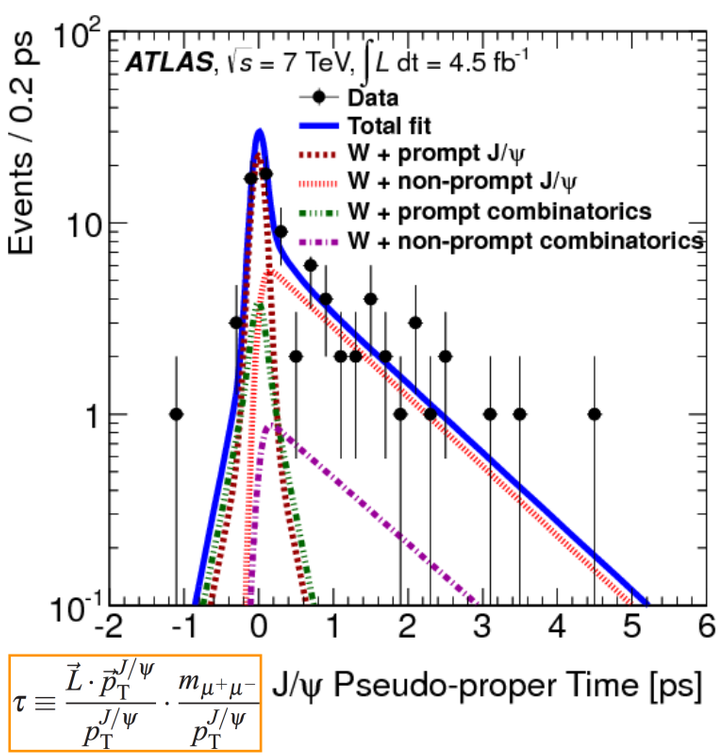
  ⇒ SU(3) flavour symmetry in the proton

Prompt W + J/Ψ production



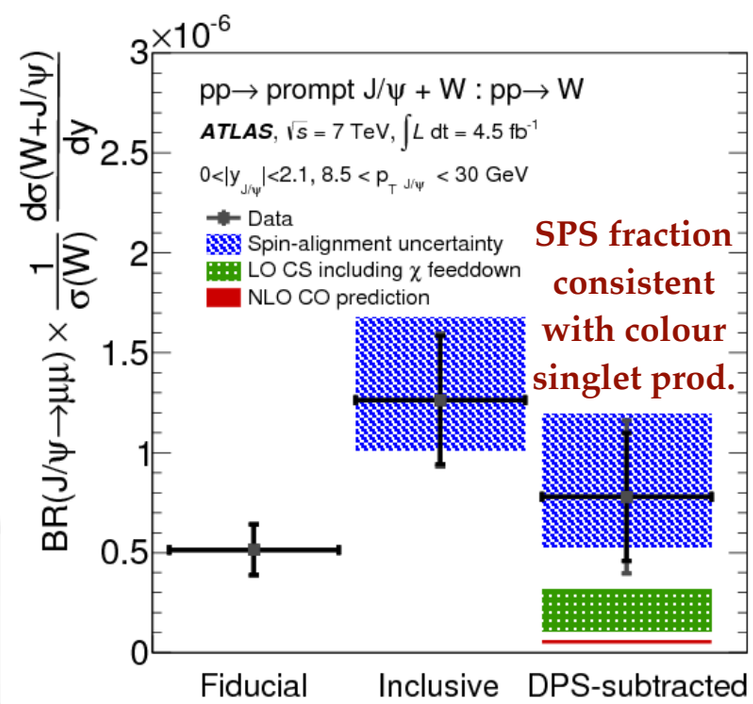
- **Test QCD** at perturbative / non-perturbative boundary
- Sensitive to **Double Parton Scattering**
- Benchmark for **H→cc, BSM**





- W→μν + J/Ψ→μμ candidates
- LLH fit: life time and $m_{\mu\mu}$

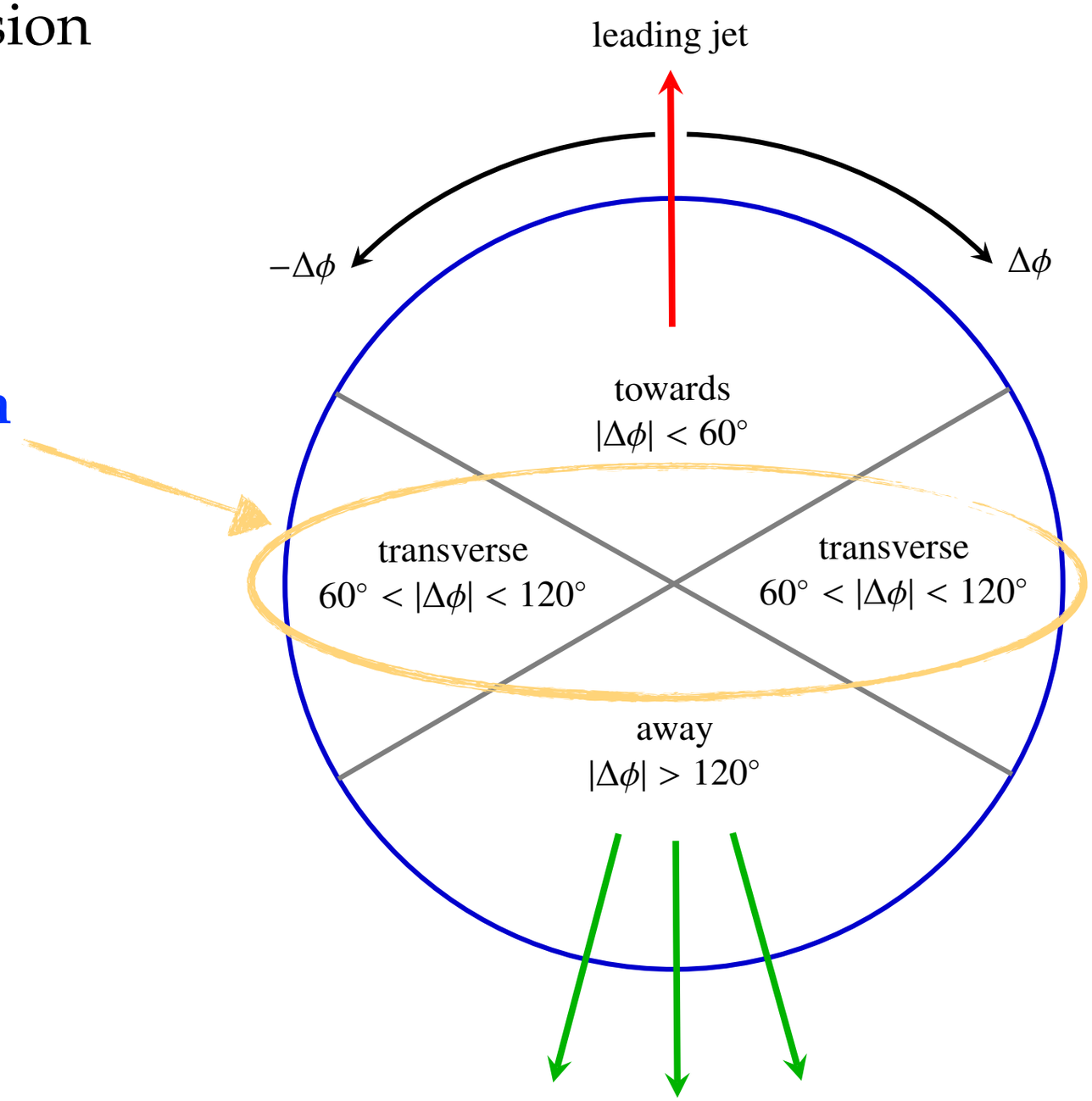
First observation:
Yield of $27.4^{+7.5}_{-6.5}$ observed (5.1σ)



Soft QCD

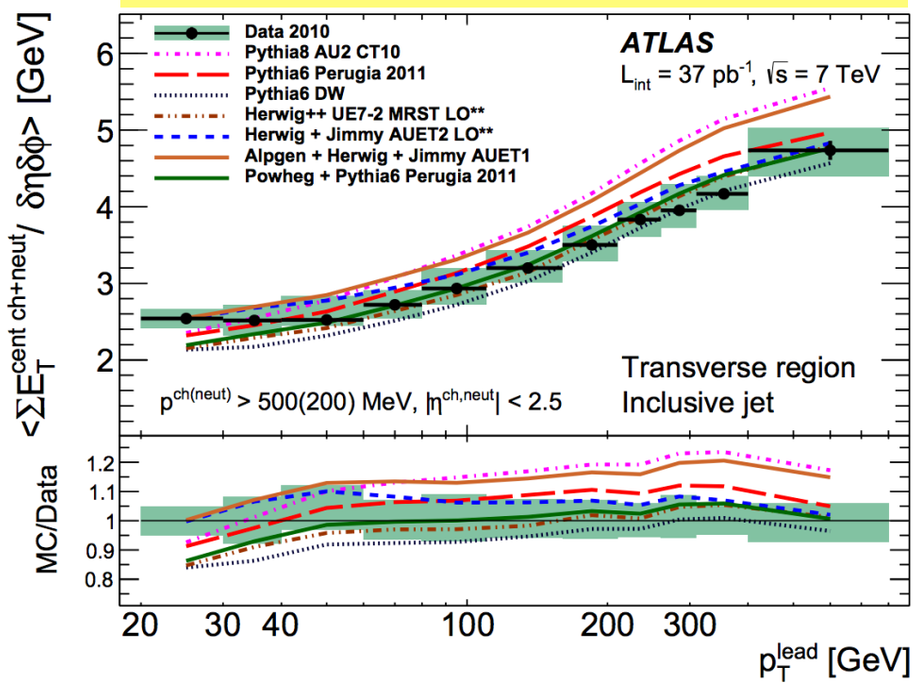
Underlying Event

- **Irreducible background** for precision measurements and BSM searches
- Probe activity in **transverse region** of leading jet
  - most sensitive region to UE
- **Test & Tune MC** predictions
  - Observables considered incl. $N_{ch}/\delta\eta\delta\Phi$, $\Sigma p_T/\delta\eta\delta\Phi$, *mean* p_T, $\Sigma E_T/\delta\eta\delta\Phi$



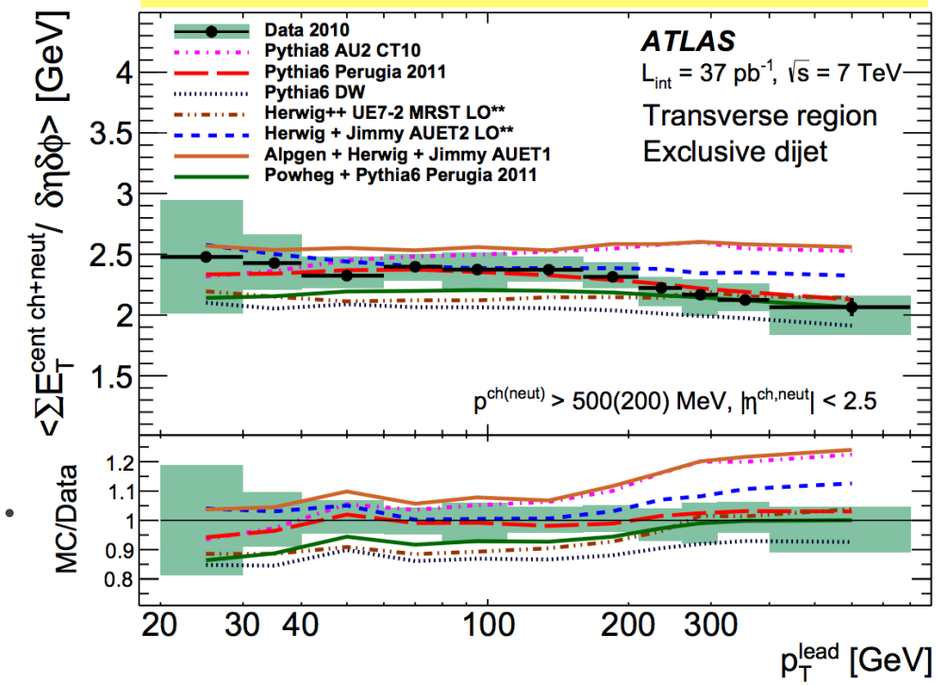
Underlying Event

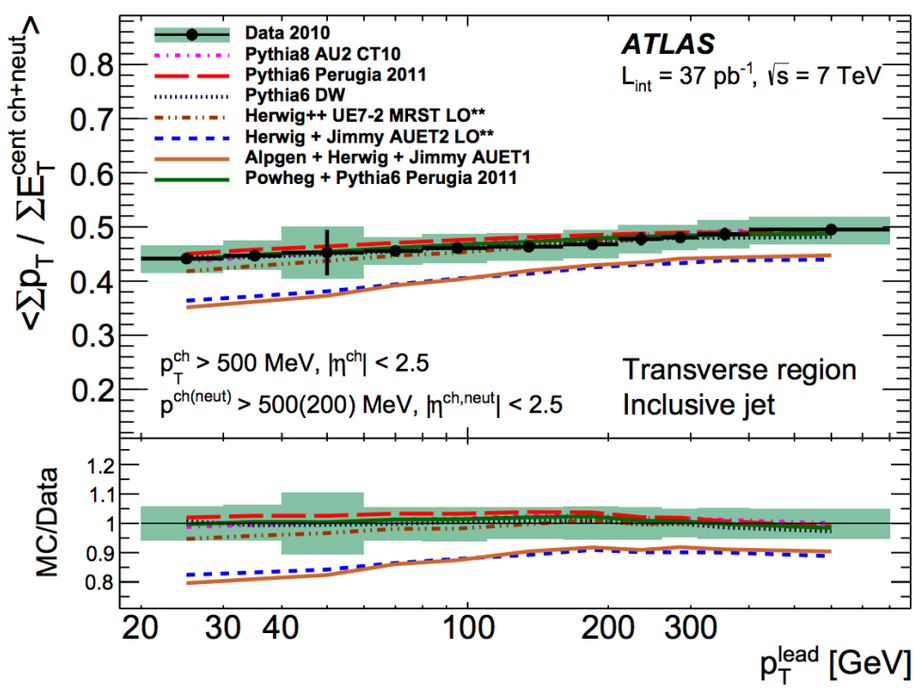
Inclusive Jet



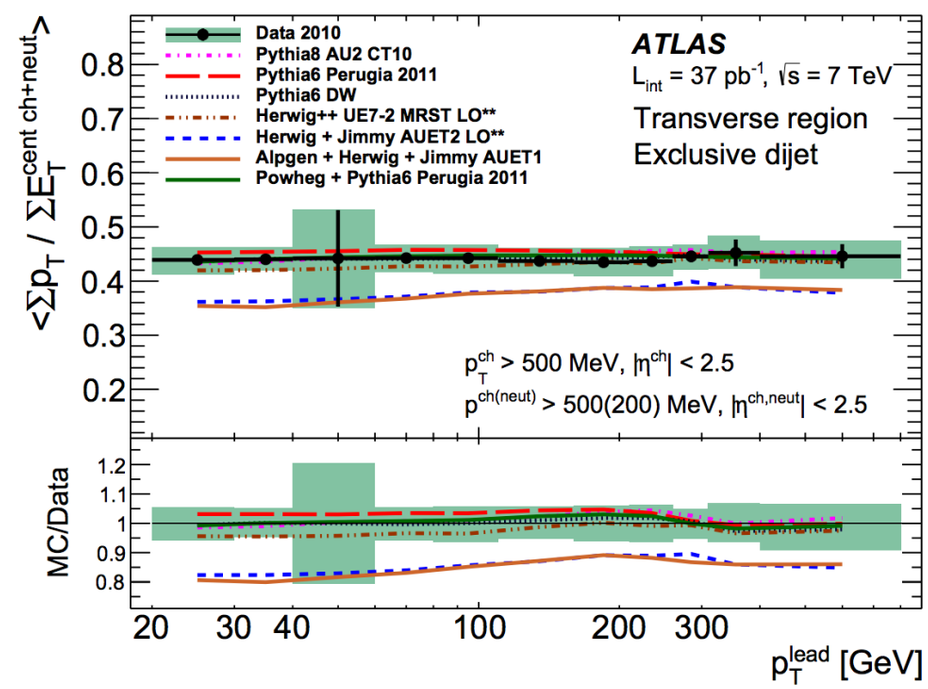
- **Rising activity** in <u>inclusive jet</u> topo.
- **Flat activity** in <u>exclusive dijet</u> topo.

Exclusive Dijet



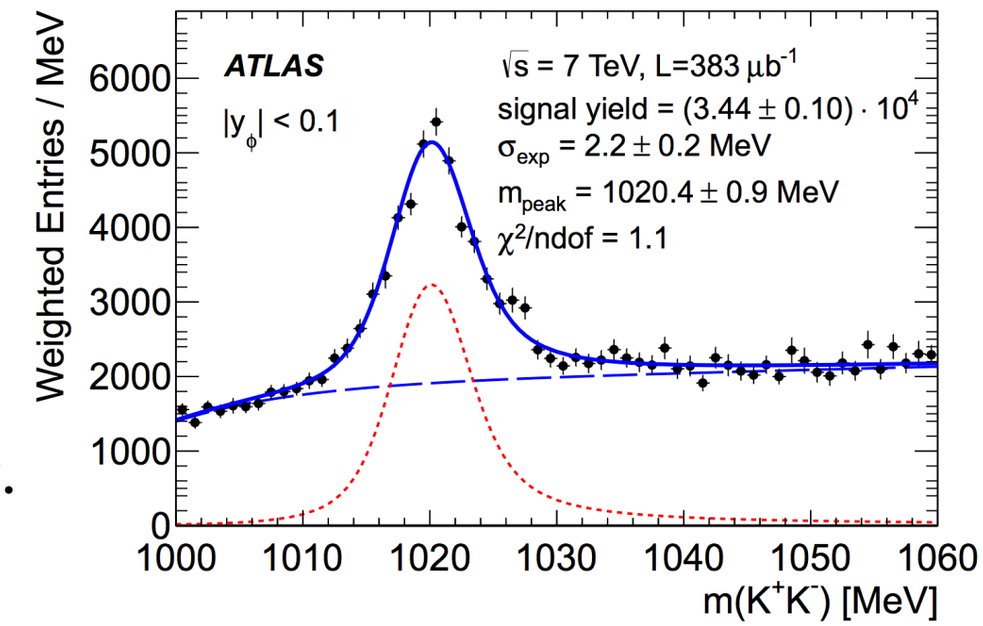


- Soft **UE pedestral** under hard jets <u>correctly predicted</u>
- **MPI activity** <u>independent of hard process scale</u>

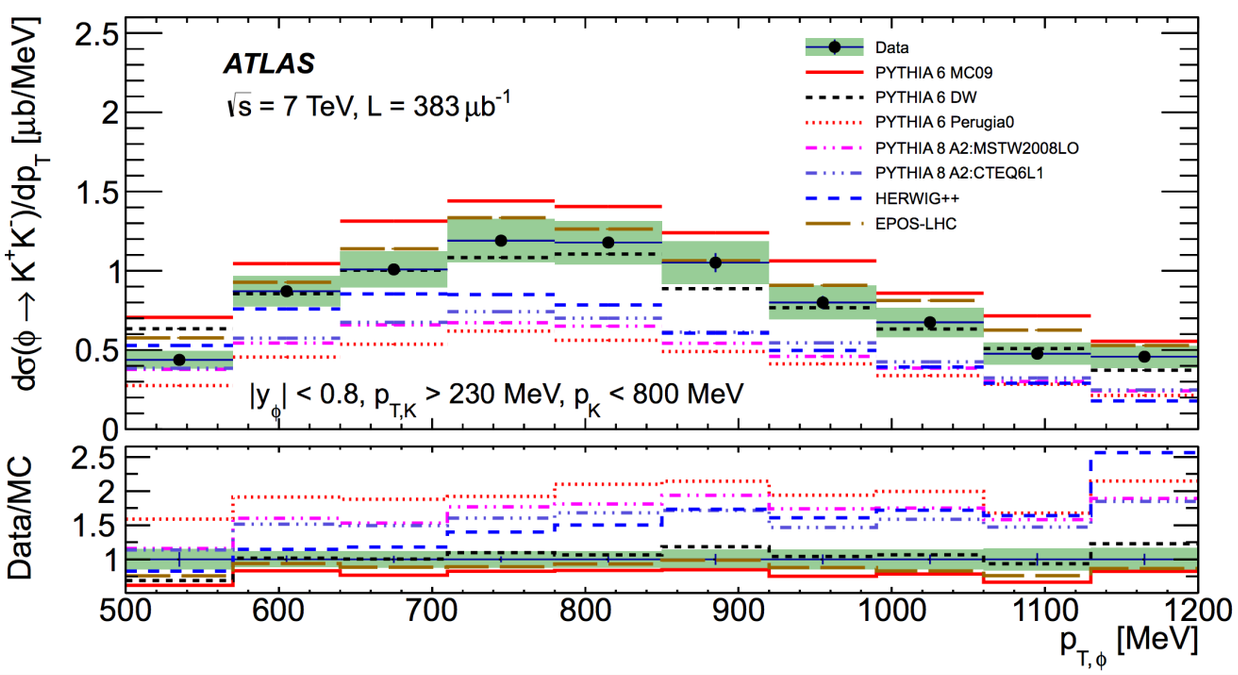


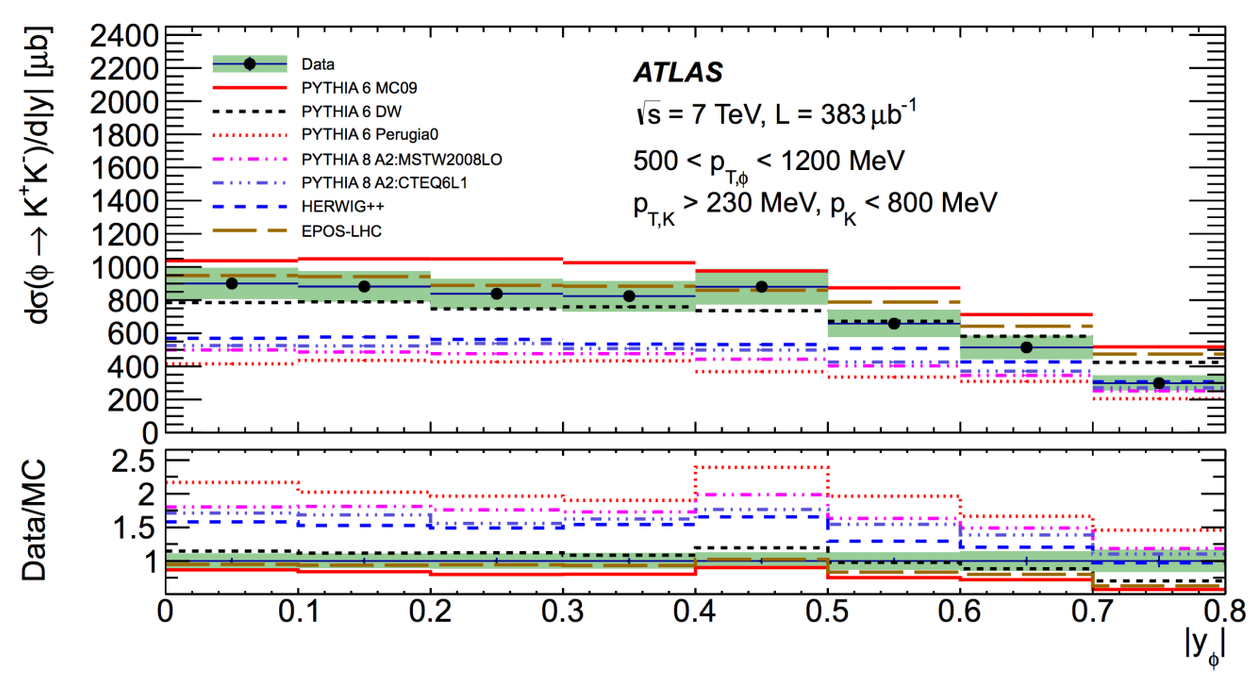
Φ(1020) meson production

- Measurement of Φ(1020)-meson in **$\Phi \rightarrow K^+K^-$** min.bias events
  - **Probe strangeness** production at **Q~1GeV** *(sensitive to s-quark & low-x gluon densities)*
  - Can constrain **soft hadroproduction models**
  - Kaons reconstructed using dE/dx in pixel det.



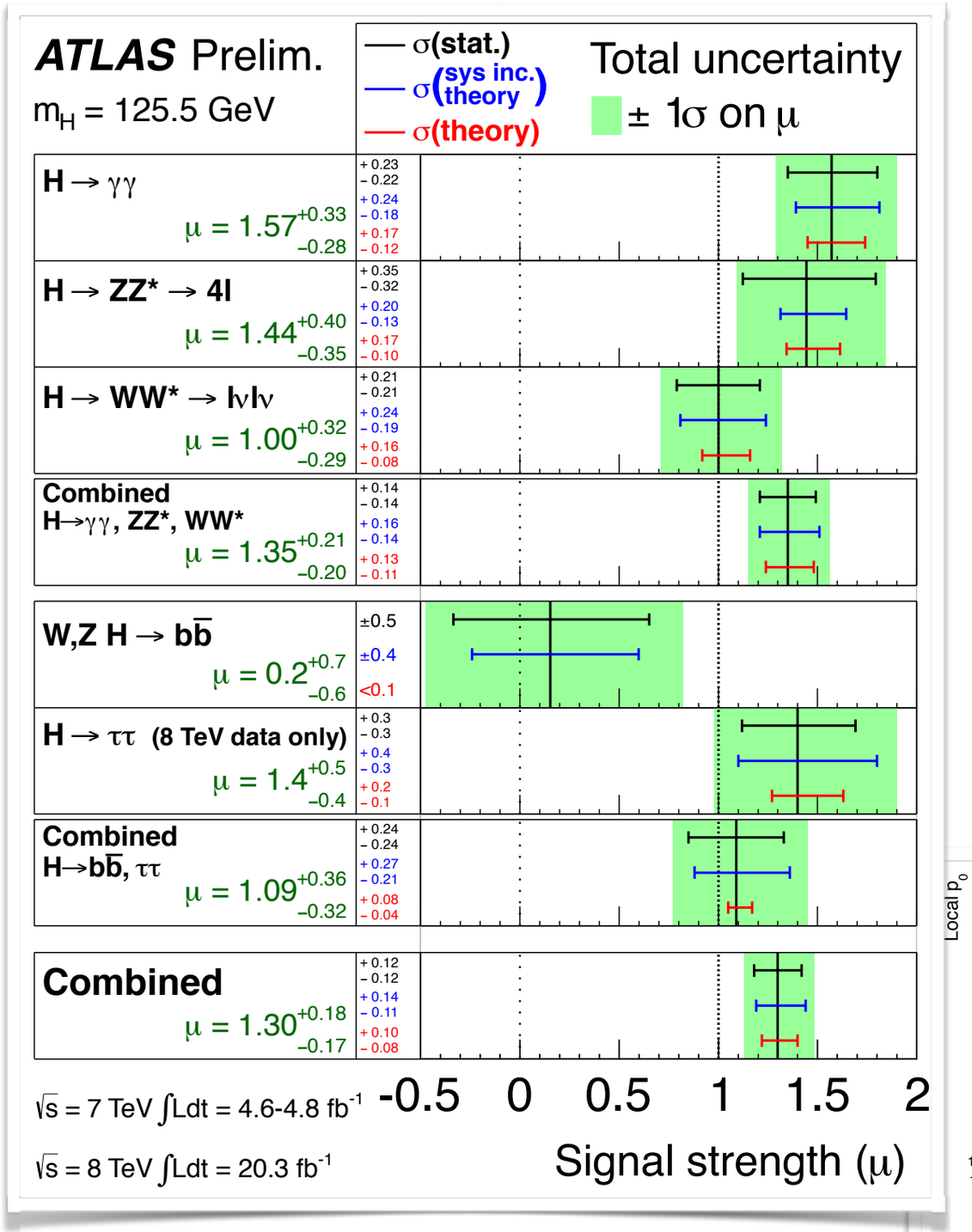
- ***EPOS-LHC*** and ***PYTHIA6 DW*** tunes <u>model data well</u>; others overpredict.





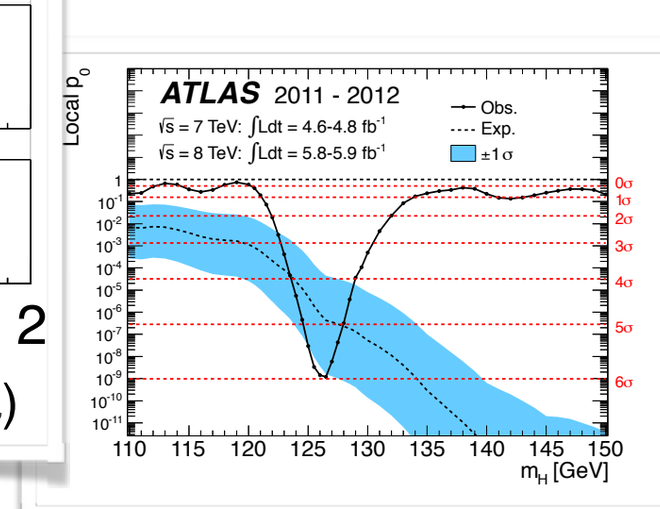
Outlook

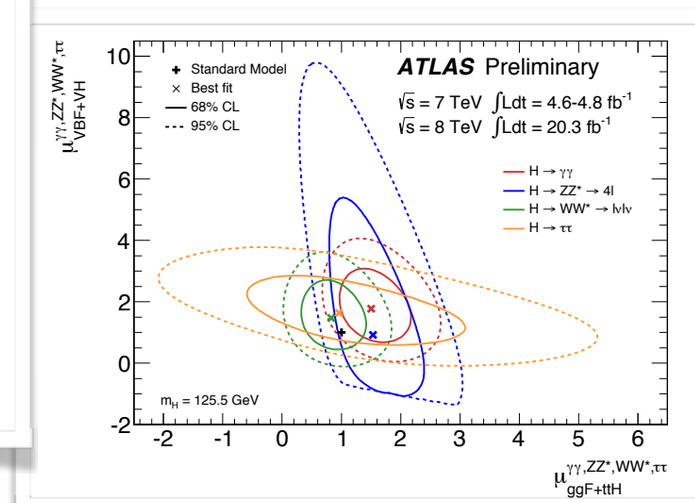
Precision Higgs Studies



Very Successful Run-1 at LHC!

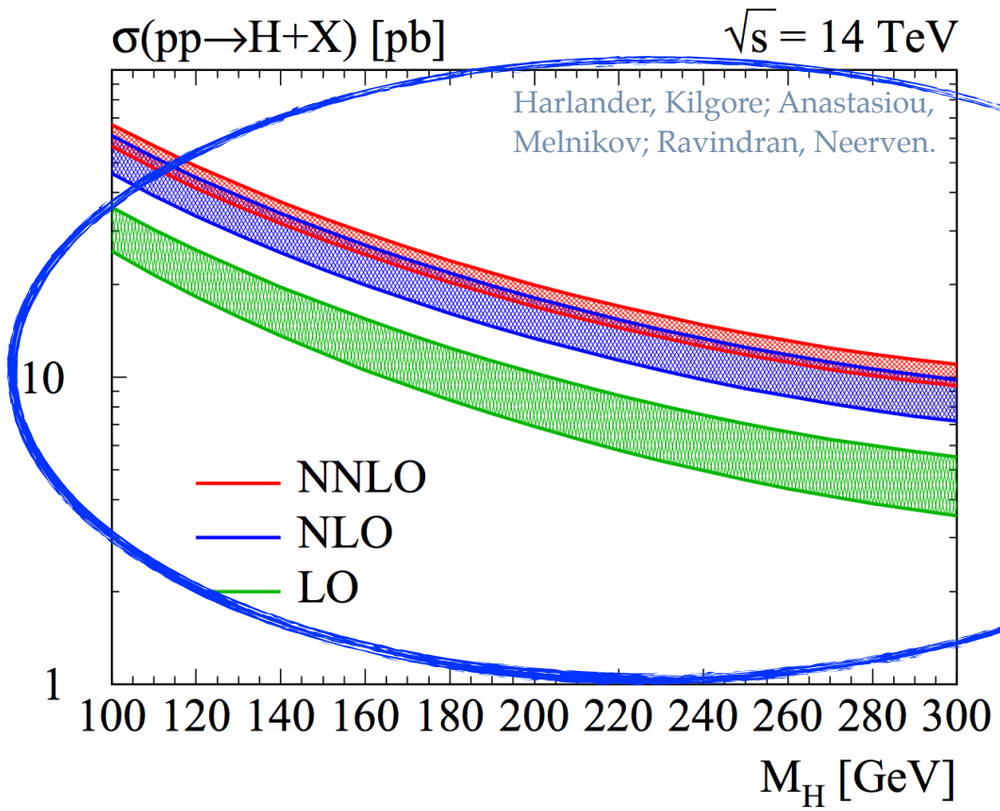
- Opened the door to a rich Precision Higgs Physics program.
- Understanding & Modelling of SM background processes are paramount, especially for **Run-2**.





Precision Higgs Studies: A Note.

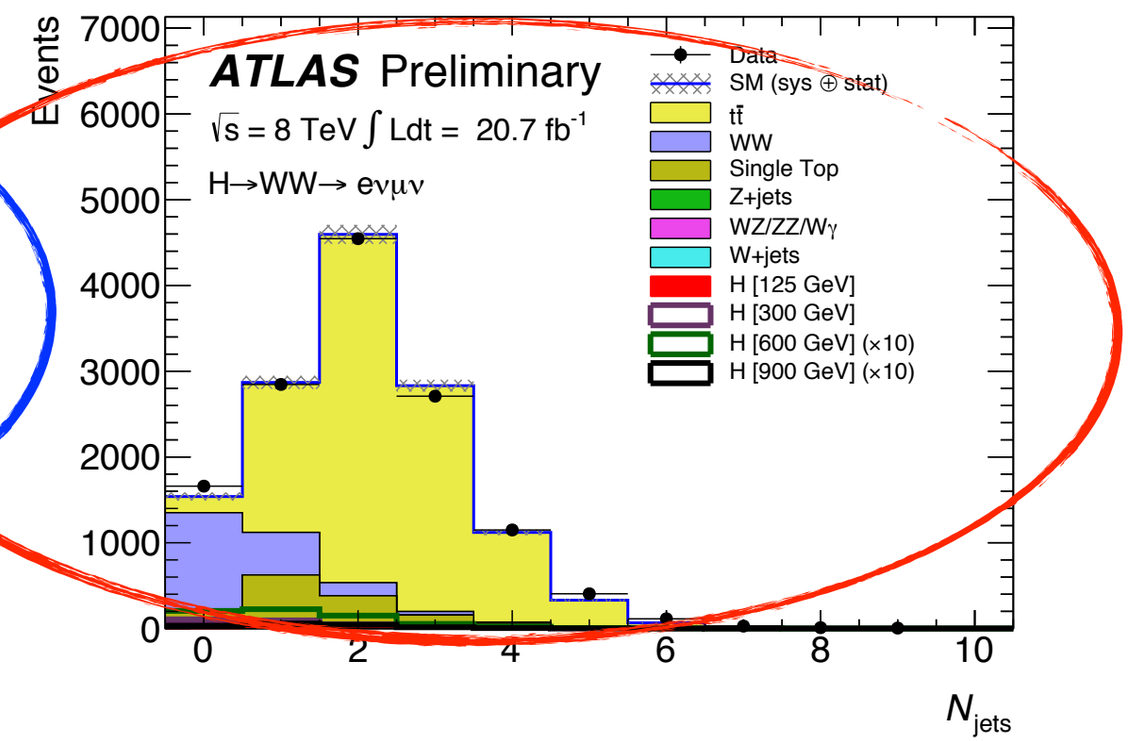
- Example: **Higgs ggF** demonstrates need for high precision theory pred.
- **2 reasons for Theory Uncertainty dominance:**



Large fixed-order QCD corrections

?

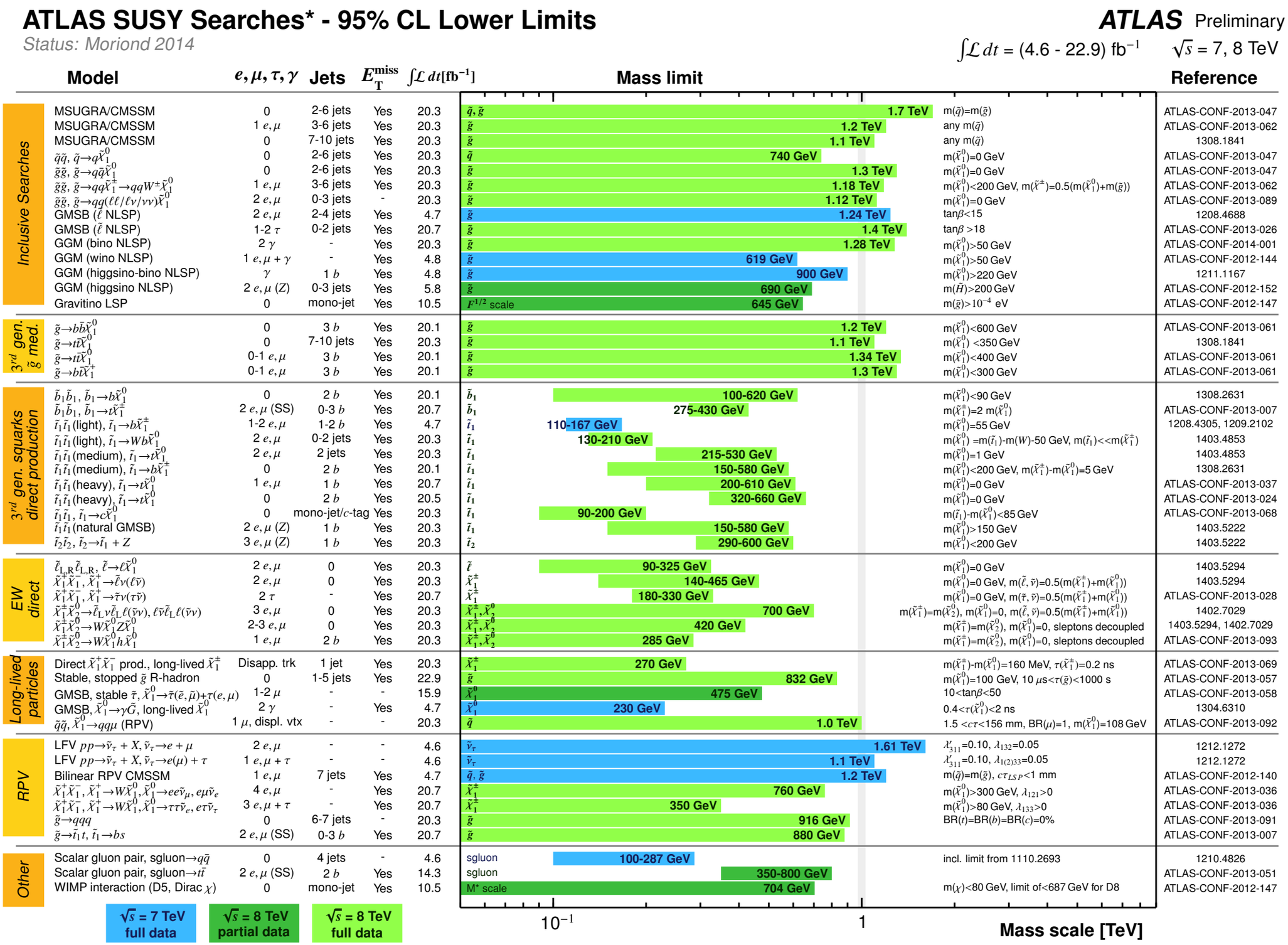
ATLAS-CONF-2013-067



Analysis in jet bins → Large Log ReΣ

- **Towards LHC Run-2:** Improve Higgs signal modelling, control over PDFs and parametric uncertainties → theory & data analysis progress needed.

New Physics Searches: SUSY



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

New Physics Searches: Exotics

ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell/\gamma\gamma$	2γ or $2e, \mu$	–	–	4.7	M_S 4.18 TeV	$n = 3$ HLZ NLO	1211.1150
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	ATLAS-CONF-2014-016
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.47 TeV	$k/\overline{M}_{Pl} = 0.1$	ATLAS-CONF-2013-017
	RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$	2 or 4 e, μ	2 j or –	–	1.0	G_{KK} mass 845 GeV	$k/\overline{M}_{Pl} = 0.1$	1203.0718
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 0.5-2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass 2.86 TeV		ATLAS-CONF-2013-017
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		ATLAS-CONF-2014-015
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	5.0	Λ 13.9 TeV	$\eta_{LL} = -1$	1211.1150
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C\rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator	–	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator	–	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $BB \to Zb + X$	$2\ e, \mu$	≥ 2 b	–	14.3	B mass 725 GeV	B in (B,Y) doublet	ATLAS-CONF-2013-056
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	13.0	q^* mass 3.84 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2012-148
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^\pm$ mass 245 GeV	$\lvert V_e\rvert$=0.055, $\lvert V_\mu\rvert$=0.063, $\lvert V_\tau\rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q\rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g\rvert = 1g_D$	1207.6411

$\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 8 TeV

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

Summary

Summary

- Overall **QCD** calculations have shown a **good description** of the LHC Run-1 data.

- Recent **Precision QCD measurements**:
  - Photon / Photon + Jet / Di-Photon
  - Jet / Dijet cross section & Jet Shapes
  - W/Z + Jets
  - Prompt W + J/Ψ
  - Underlying Event
  - Φ(1020) Meson Production

Test QCD predictions

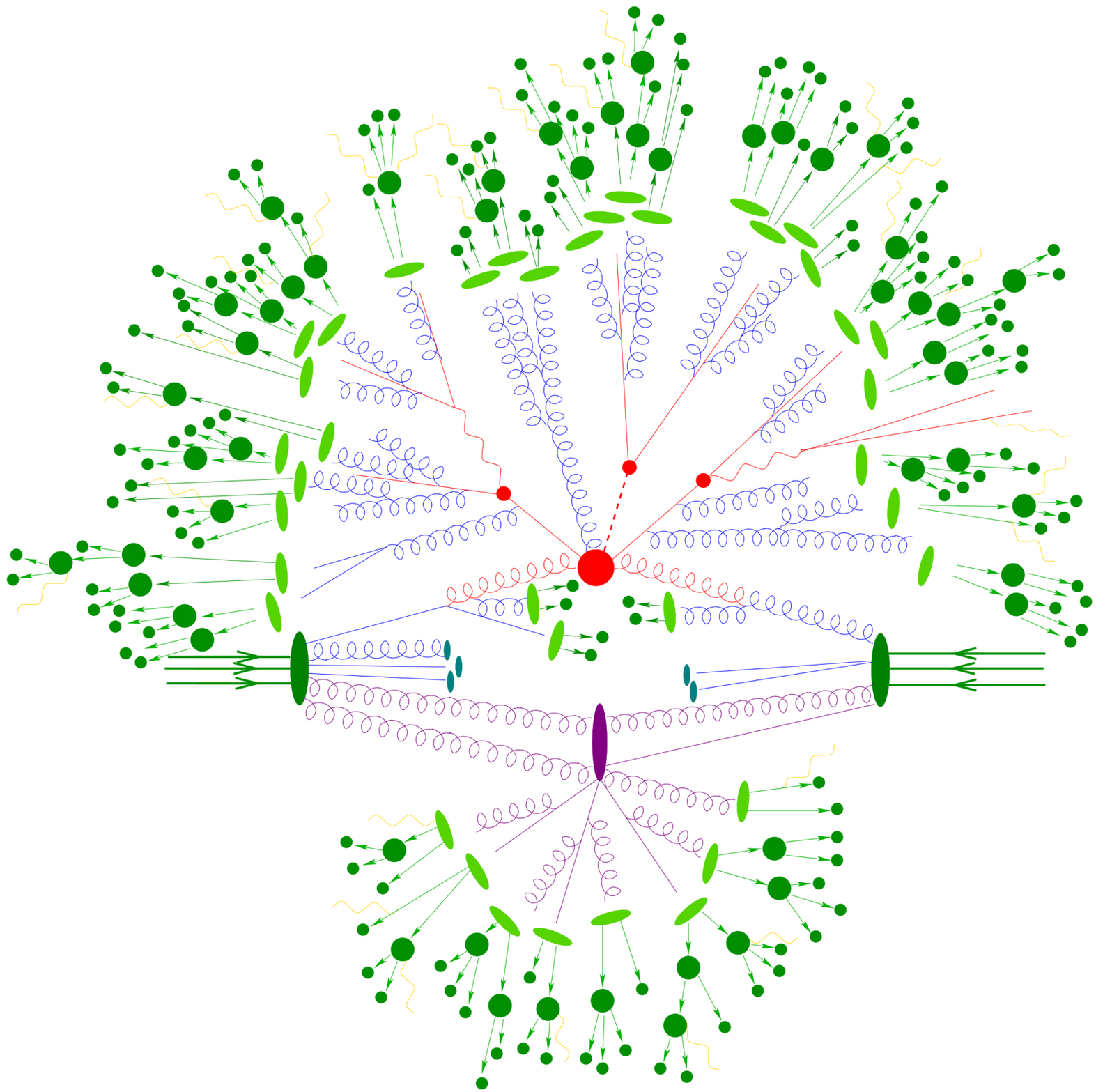
&

Constrain PDFs

- Extensive program for **LHC Run-2** (SM, Higgs, BSM,…).

Backup

Bonus



- Hard scatter
- Parton shower
- Hadronization
- Underlying Event
- Multi-parton interactions

Higgs Production & Modelling

Tools for Higgs Physics

Cross Section

ggF
HIGLU (NNLO QCD+NLO EW)
iHixs (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
SusHi (NNLO QCD)
RGHiggs (NNLO+NNNLL QCD)
ggHiggs (approx. NNNLO QCD)

VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO QCD)

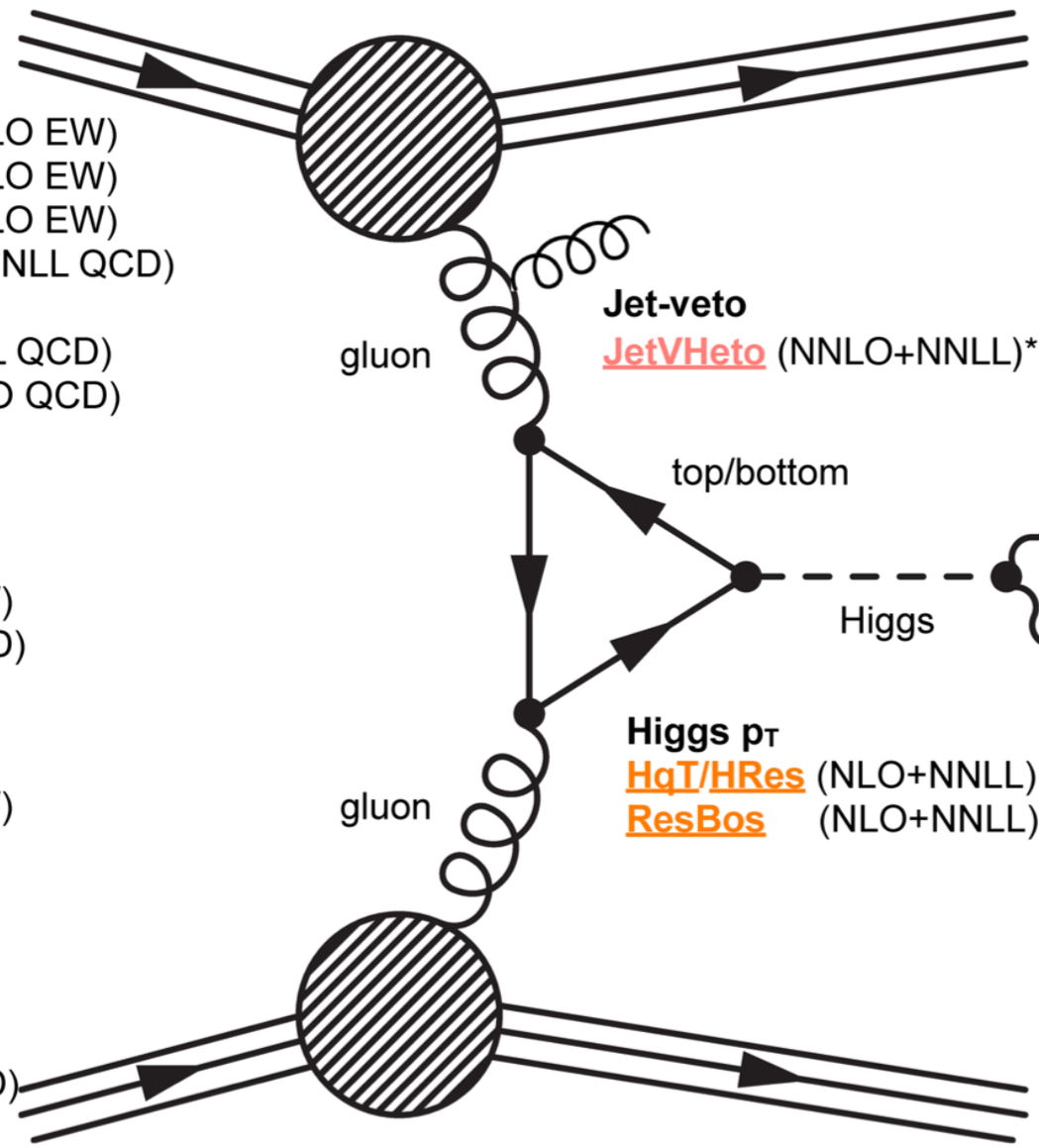
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)

bbH
bbh@NNLO (NNLO QCD)

HH
HPAIR (NLO QCD)

+ private codes.



Jet-veto
JetVHeto (NNLO+NNLL)*

Higgs p_T
HqT/HRes (NLO+NNLL)
ResBos (NLO+NNLL)

PDF: MSTW, CTEQ, NNPDF, etc.
LHAPDF, HOPPET, APFEL

NLO MC
POWHEG MiNLO
MadGrapn5_aMC@NLO
SHERPA MEPS@NLO

LO MC
gg2VV

NLO ME
MCFM, MG5_aMC@NLO

Higgs Decay
HDECAY (NLO++)
Prophecy4f (NLO)

Higgs Properties
MELA/JHU, MEKD
MG5_aMC@NLO (HC)

MSSM/2HDM
FeynHiggs, CPSuperH
SusHi+2HDMC
HIGLU+HDECAY

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

Note on Theory Uncertainties

ATLAS-CONF-2013-030

Source	Signal processes (%) $N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Theoretical uncertainties			
QCD scale for ggF signal for $N_{jet} \geq 0$	13	-	-
QCD scale for ggF signal for $N_{jet} \geq 1$	10	27	-
QCD scale for ggF signal for $N_{jet} \geq 2$	-	15	4
QCD scale for ggF signal for $N_{jet} \geq 3$	-	-	4
Parton shower and UE model (signal only)	3	10	5
PDF model	8	7	3
$H \to WW$ branching ratio	4	4	4
QCD scale (acceptance)	4	4	3
WW normalisation	-	-	-
Experimental uncertainties			
Jet energy scale and resolution	5	2	6
b-tagging efficiency	-	-	-
f_{recoil} efficiency	1	1	-

Stewart-Tackmann prescription (2011) used (fixed-order).

- **Example Higgs(WW):** Jet vetos introduce large uncertainties from $\ln(m_H / p_{veto})$ terms in perturbative expansion → need resummation to NNLL (…)

Isolated Photon Cross Section

- The differential photon cross section as a function of transverse energy and rapidity can be written as

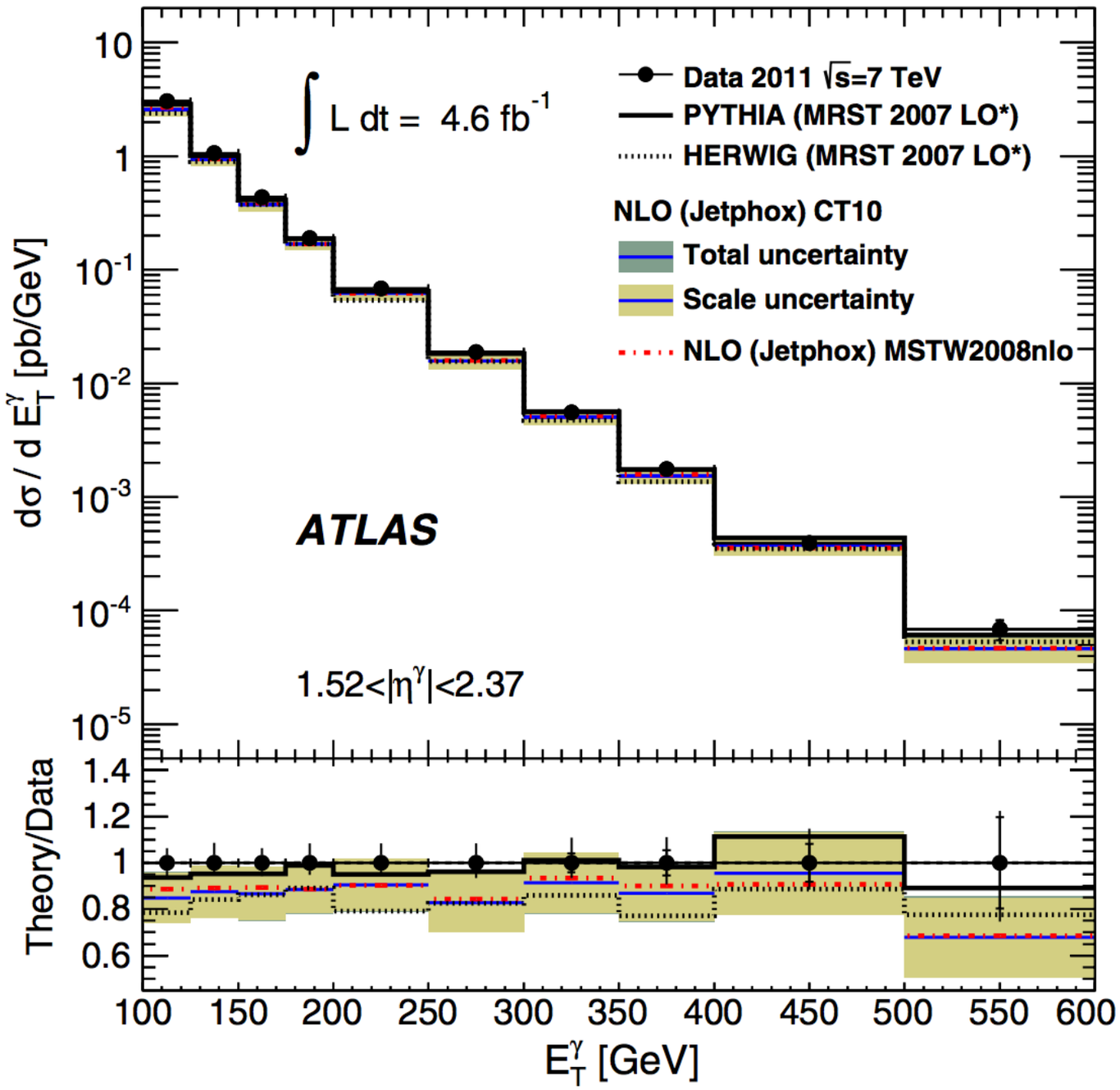
$$d\sigma \equiv d\sigma_{\rm dir} + d\sigma_{\rm frag} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b \; f_a(x_a;\mu_{\rm F}^2) f_b(x_b;\mu_F^2) \times$$
$$\left[d\hat{\sigma}^{\gamma}_{ab}(p_\gamma, x_a, x_b; \mu_{\rm R}, \mu_{\rm F}, \mu_{\rm ff}) + \sum_{c=q,\bar{q},g} \int_{z_{min}}^{1} \frac{dz}{z^2} d\hat{\sigma}^{c}_{ab}(p_\gamma, x_a, x_b, z; \mu_{\rm R}, \mu_{\rm F}, \mu_{\rm ff}) D_c^{\gamma}(z;\mu_{\rm ff}^2) \right]$$

where f_a is the PDF for parton *a* inside the incoming protons at momentum fraction x_a; $d\sigma_{ab}$ are the parton-parton subprocess differential cross section; and $D_{\gamma/k}$ is the fragmentation function of parton k to a photon carrying a fraction z of the parent parton energy, integrated from $z_{min} = x_T \cosh y_\gamma$ to 1.

Phys. Rev. D 89, 052004 (2014)

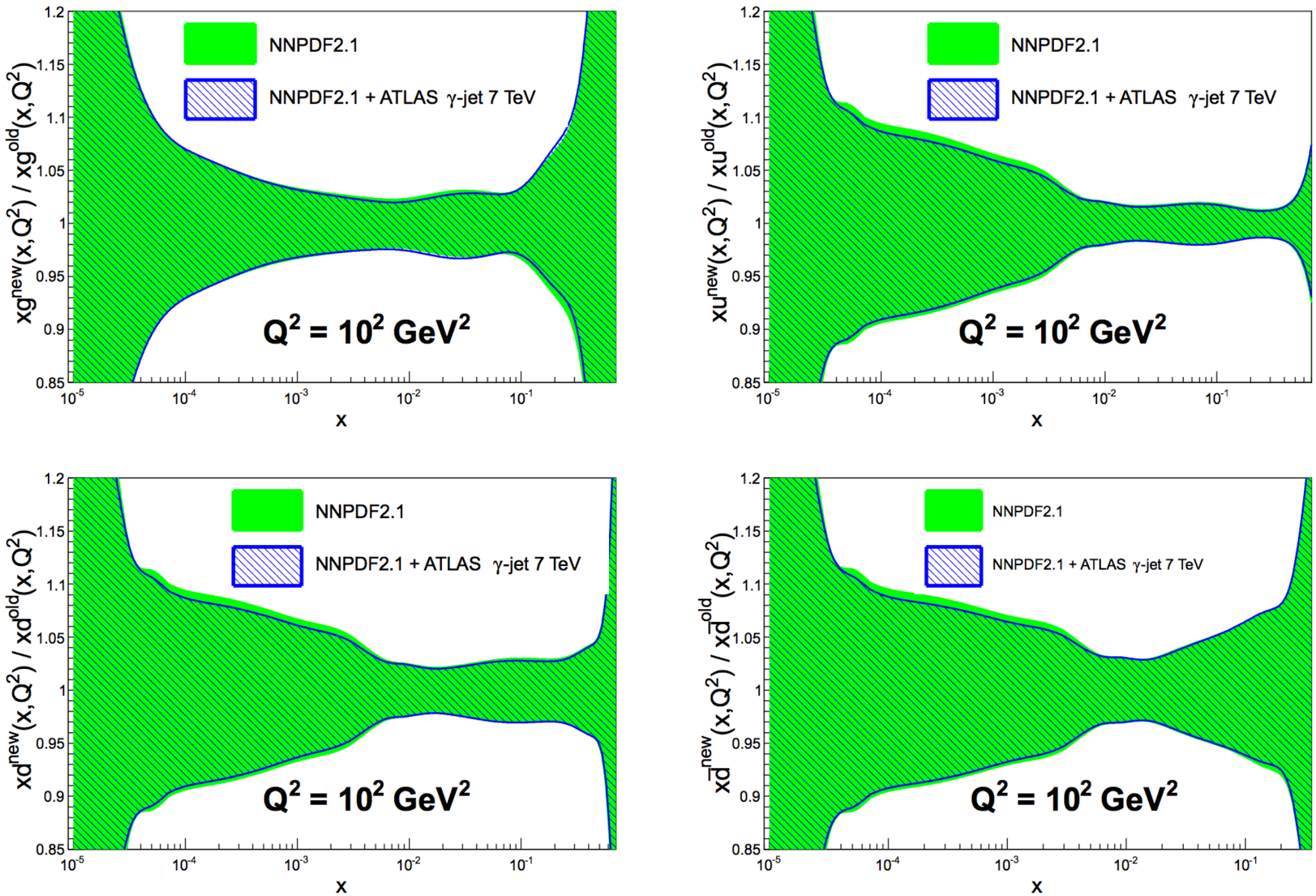
Isolated Photon Cross Section

- The differential photon cross section in the forward region:

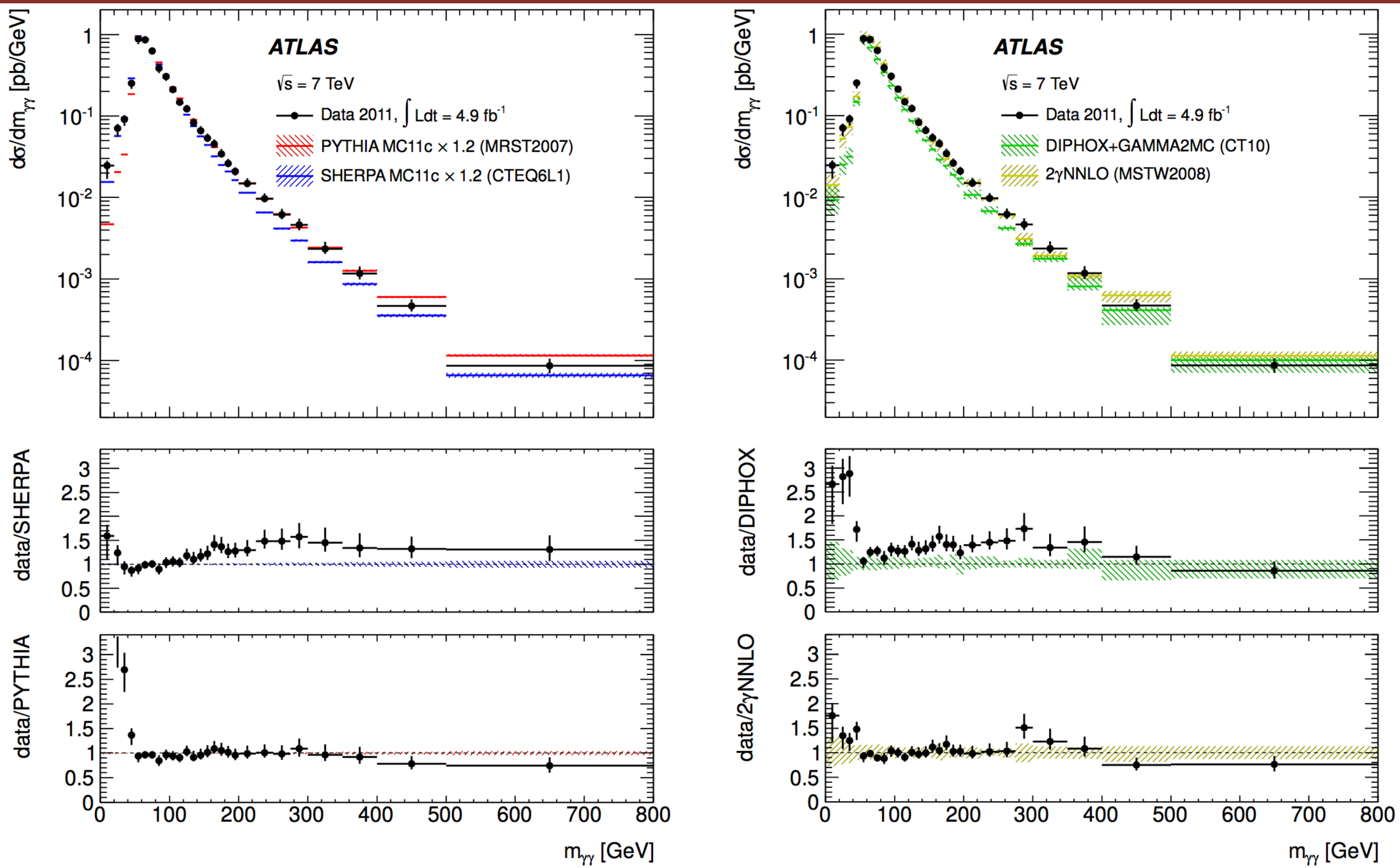


Isolated Photon+Jet production

- NNPDF2.1 with and without ATLAS photon-jet 7 TeV data:

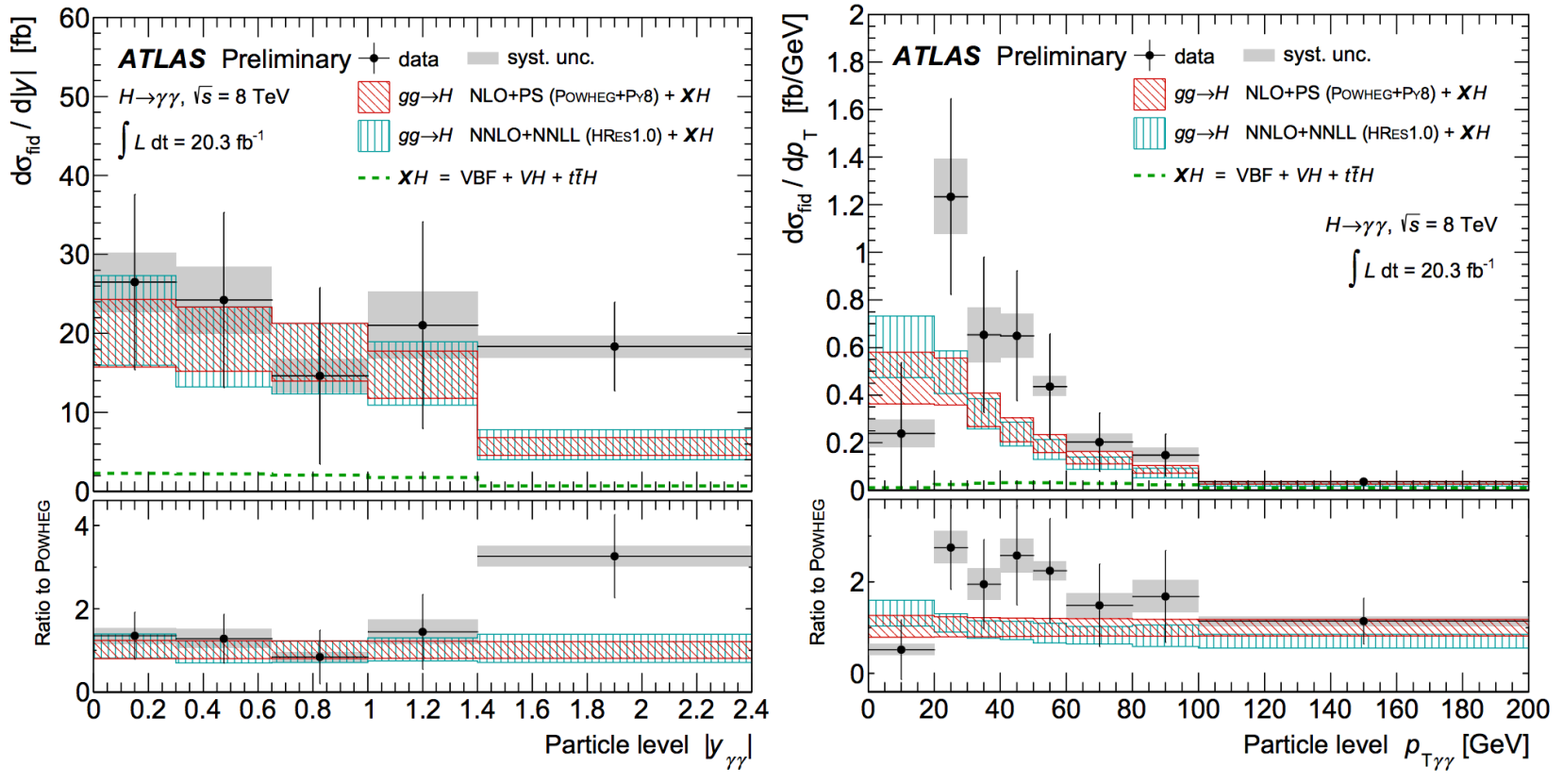


Di-Photon production



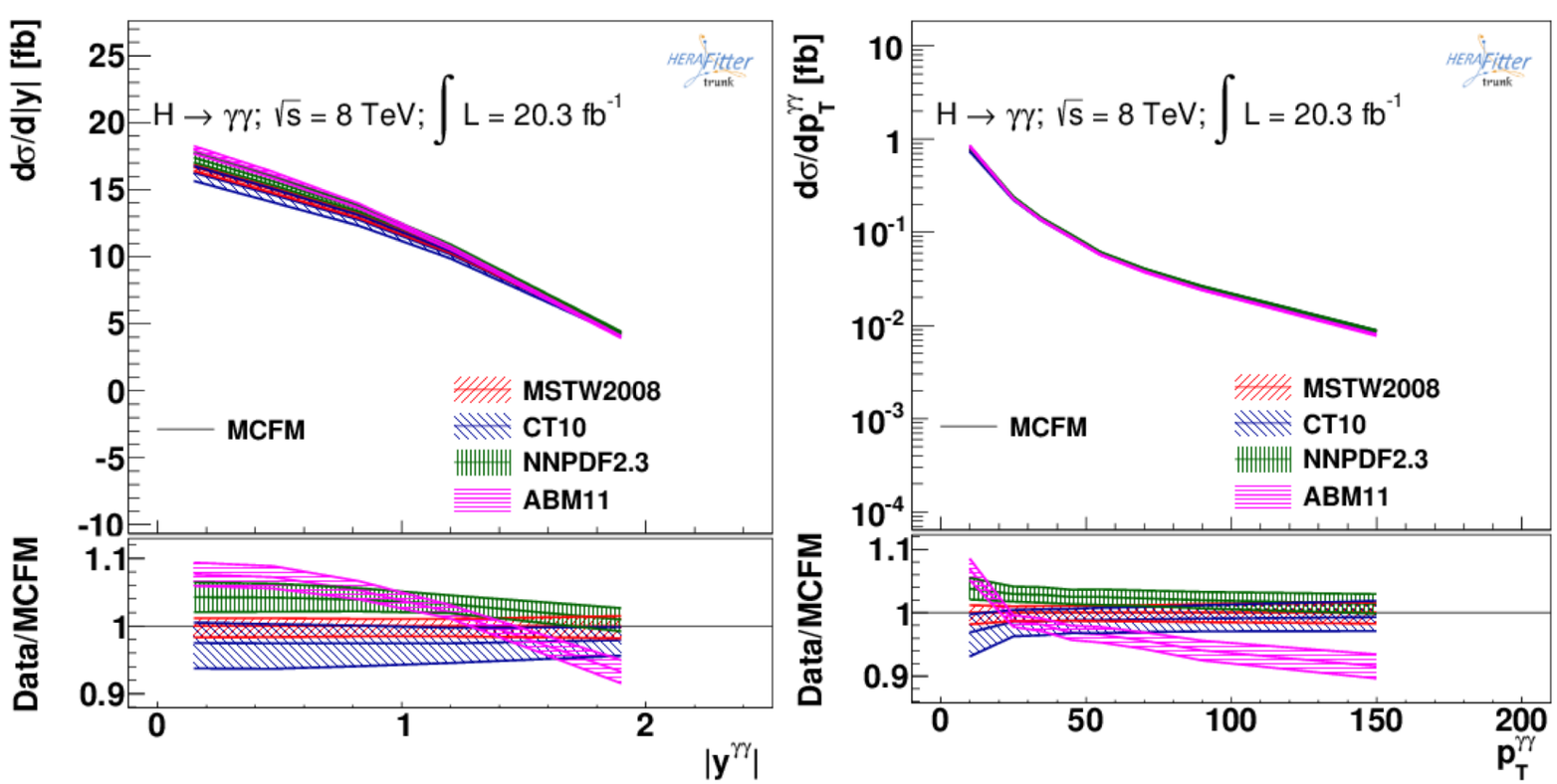
Di-Photon production: H → γ γ

Experiment



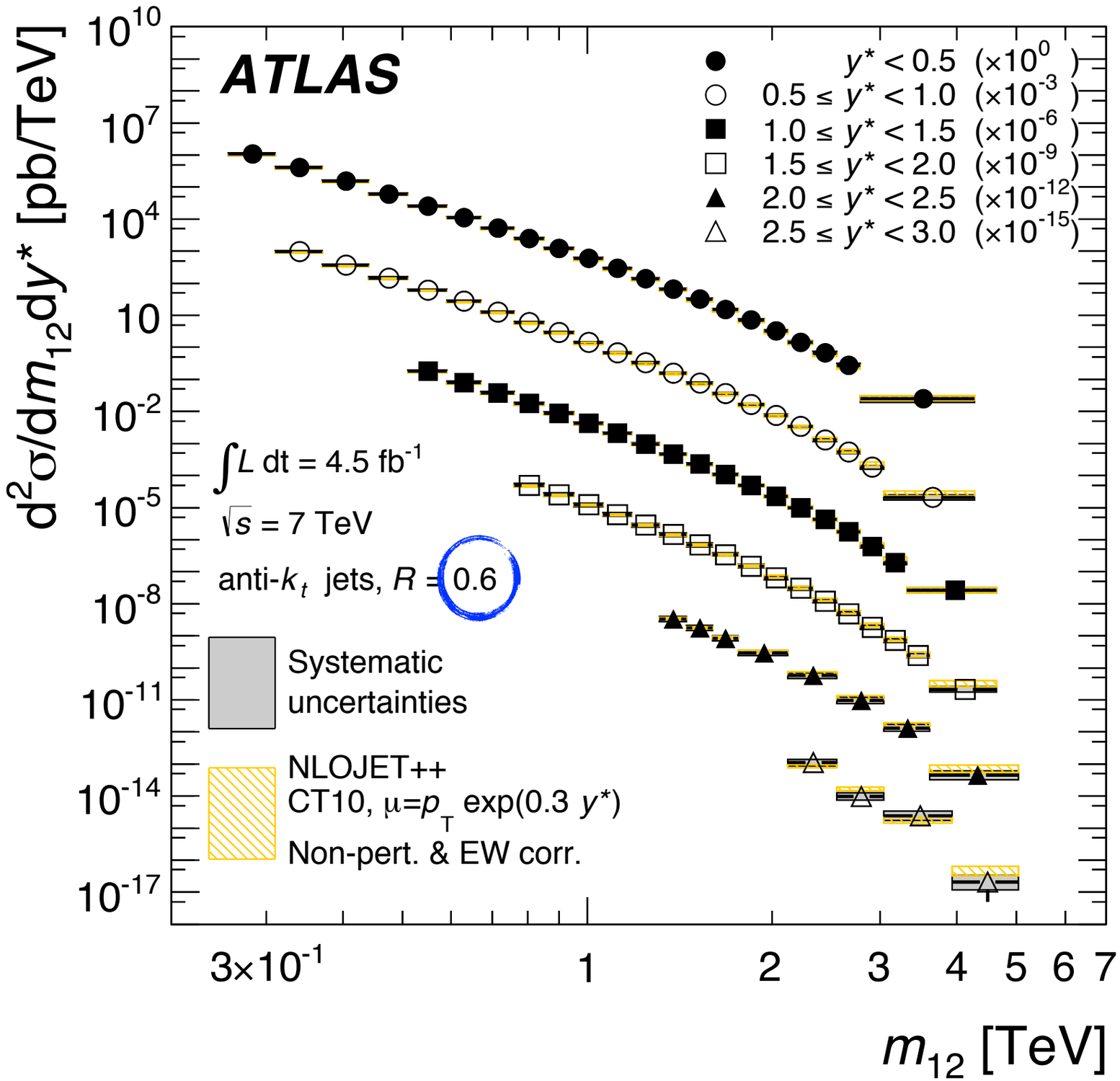
- **8 TeV** differential cross section measurement
- **Very large uncertainties** (first p_T bin: 125%)

Theory



- **Shape difference** between different PDF sets
- **1-2σ tension** between PDFs
- Envelope uncertainty much larger than uncertainty on one PDF

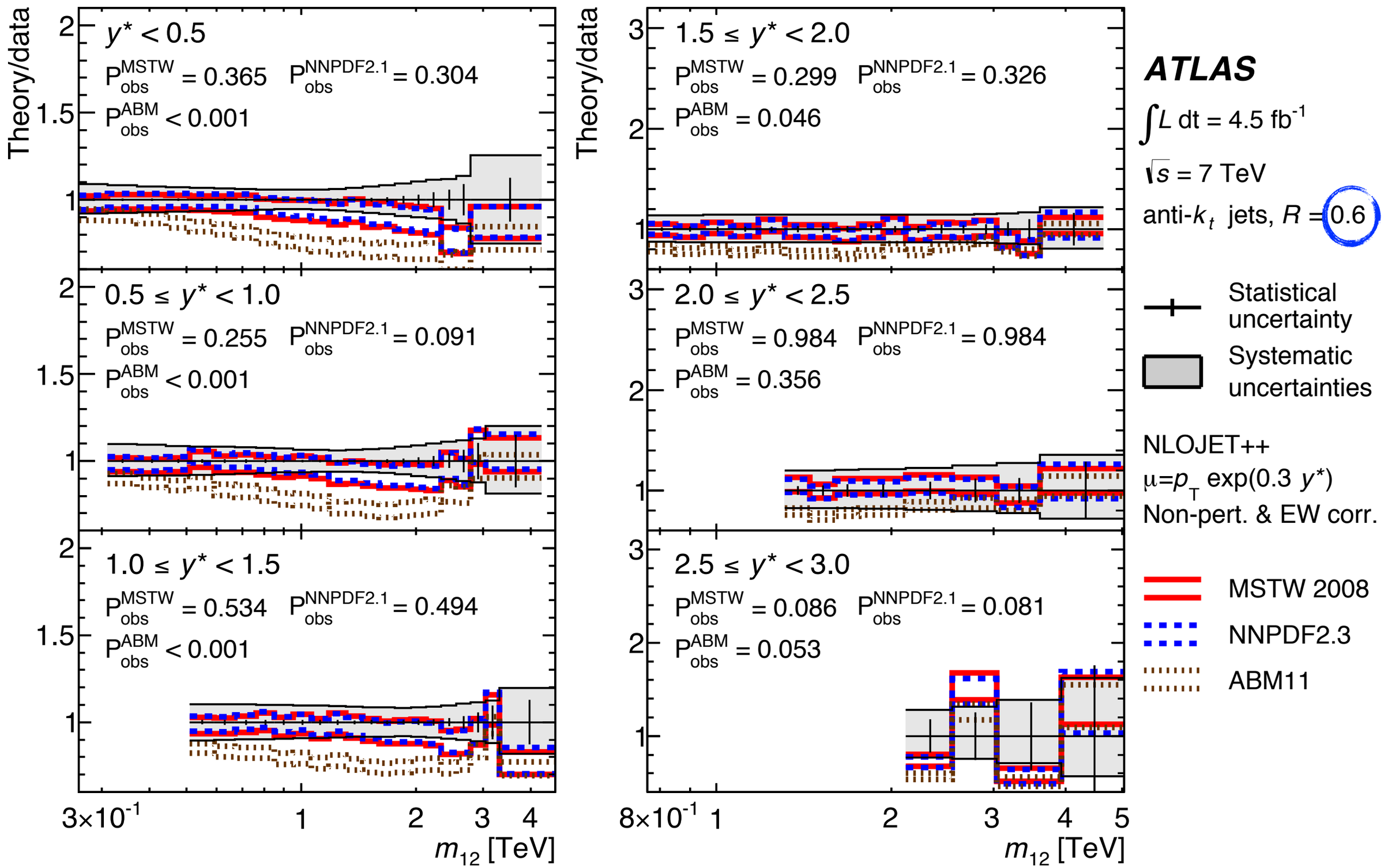
Dijet cross sections



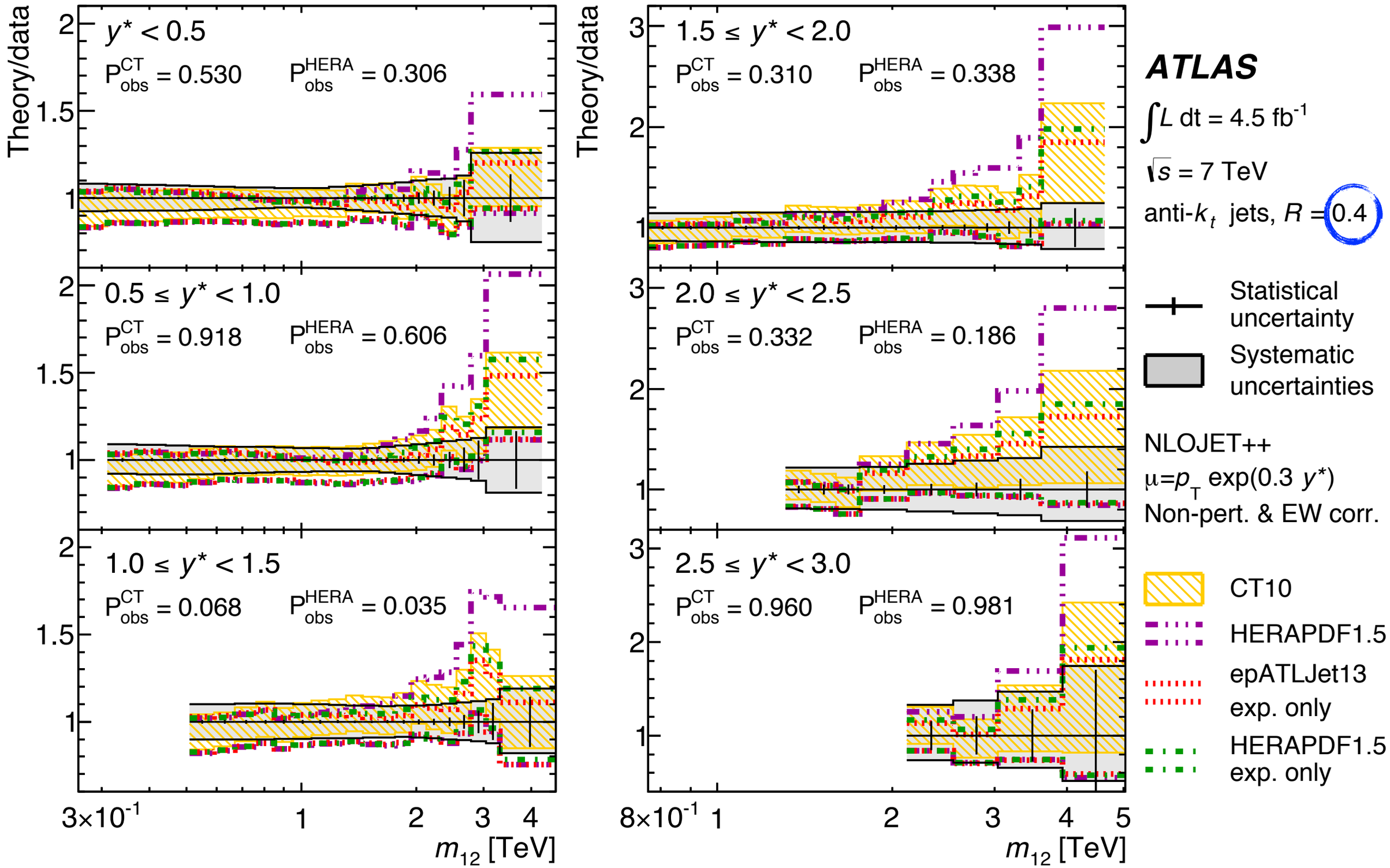
- Ratio of NLOJet++ QCD predictions to dijet double-differential cross section measurements as a function of dijet mass.

JHEP 05 (2014) 059

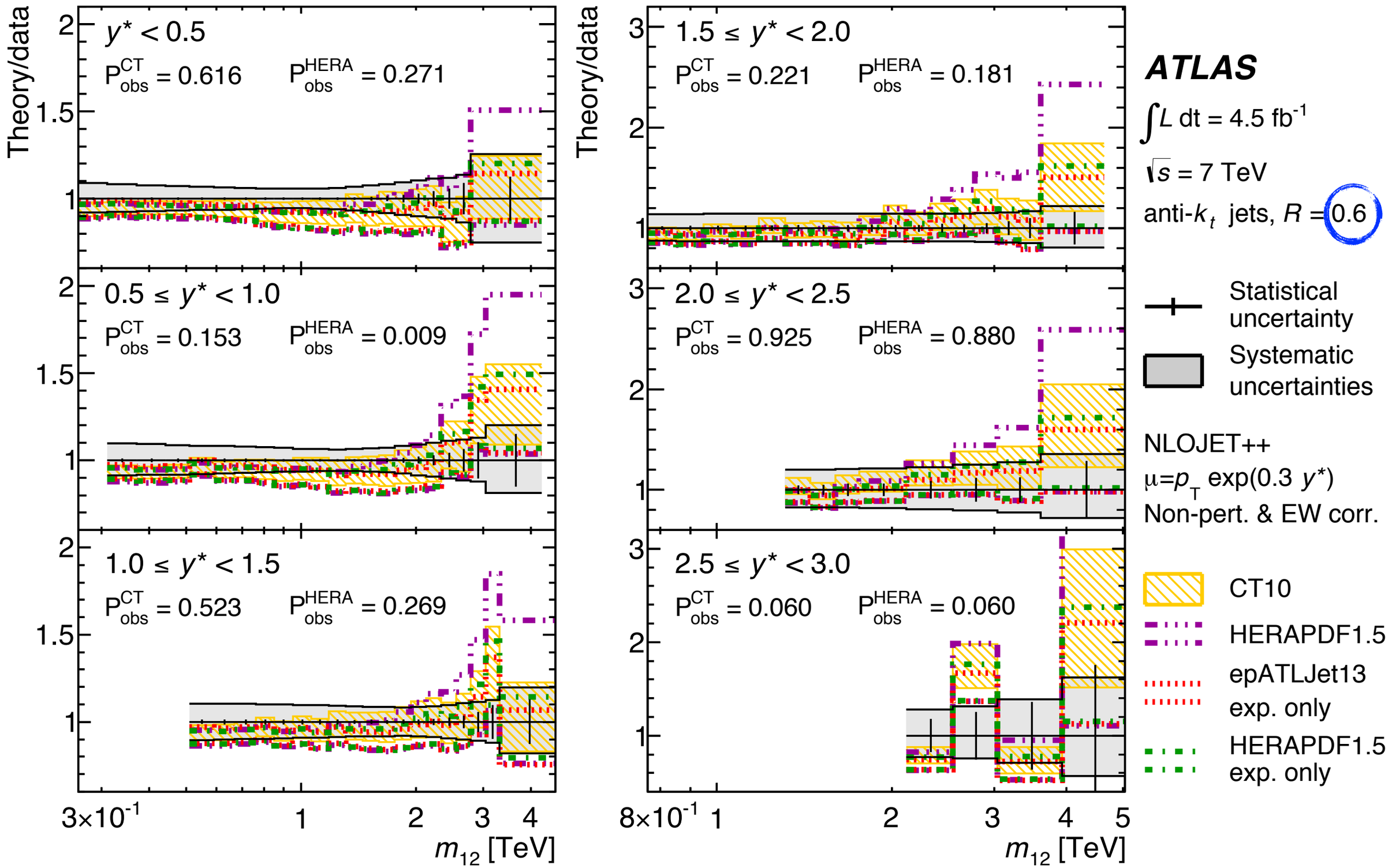
Dijet cross sections



Dijet cross sections

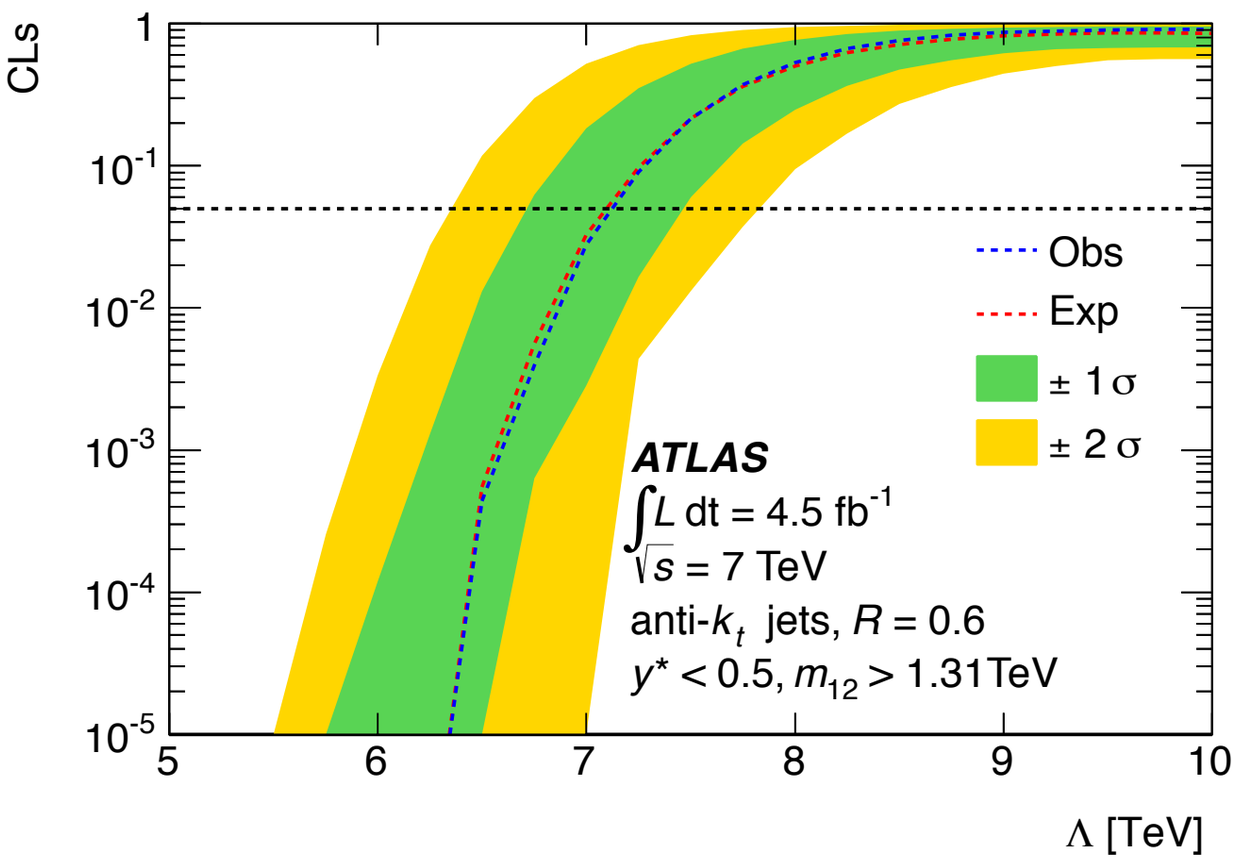


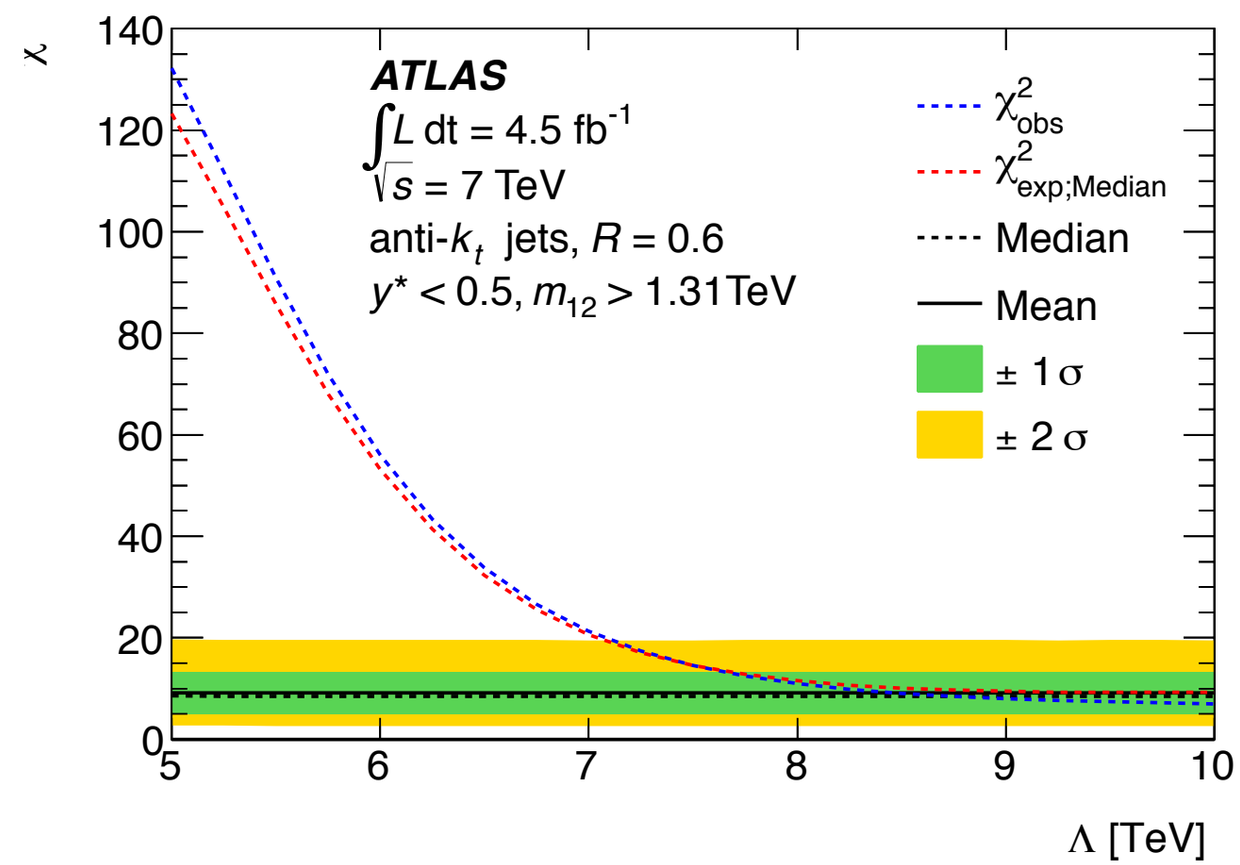
Dijet cross sections



Dijet cross sections: BSM

- Considered model of **QCD plus contact interactions** (CIs) with left–left coupling and destructive interference between CIs and QCD as implemented by the CIJET program.
- **Limits for NLO QCD plus CIs as a function of Λ** using the CT10 PDF set.
- Useful to **confront new physics models**!





Z boson p_T modelling