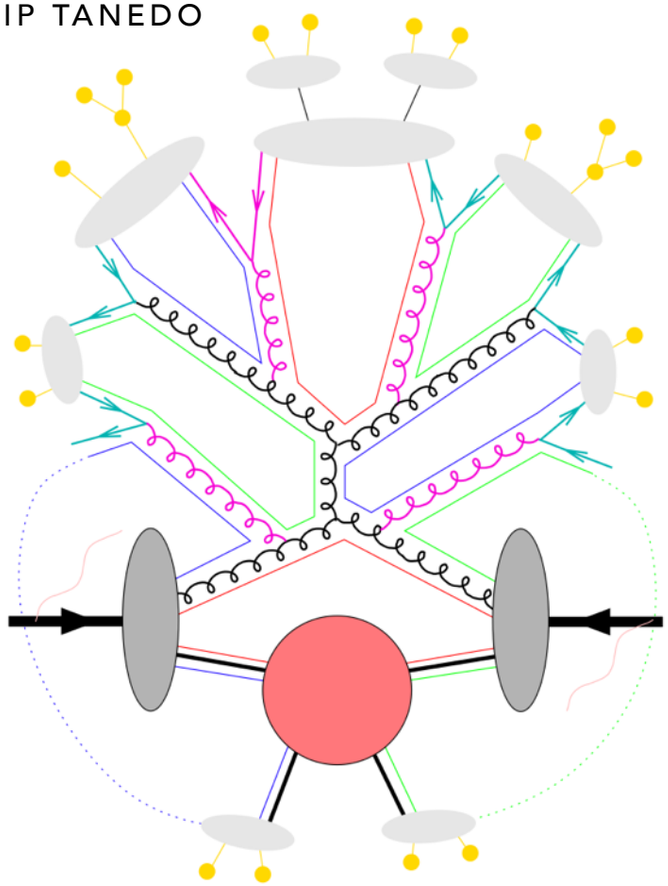
ATLAS QCD AND ELECTROWEAK RESULTS

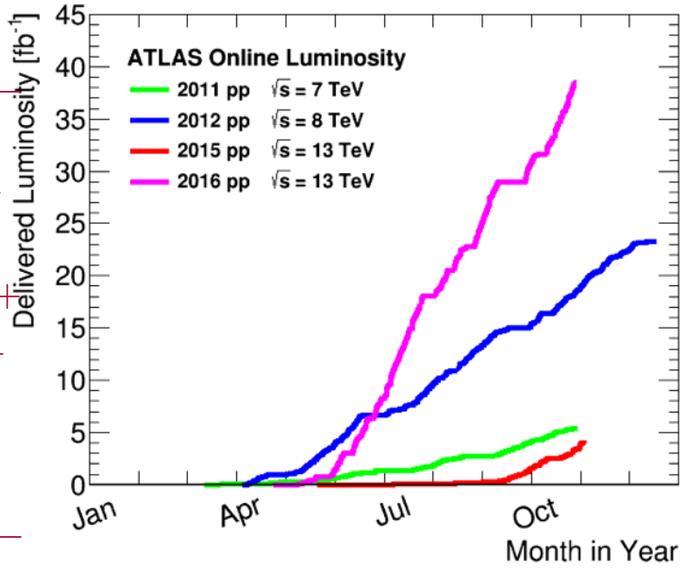
LAUREN TOMPKINS ON BEHALF
OF THE ATLAS COLLABORATION

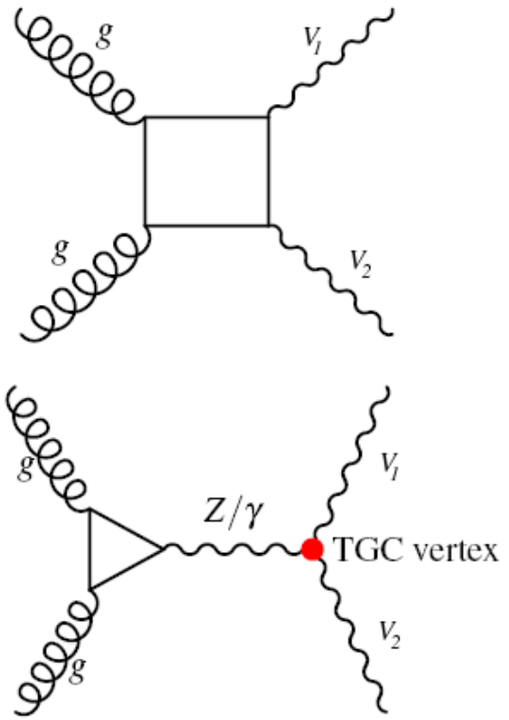
Stanford
University

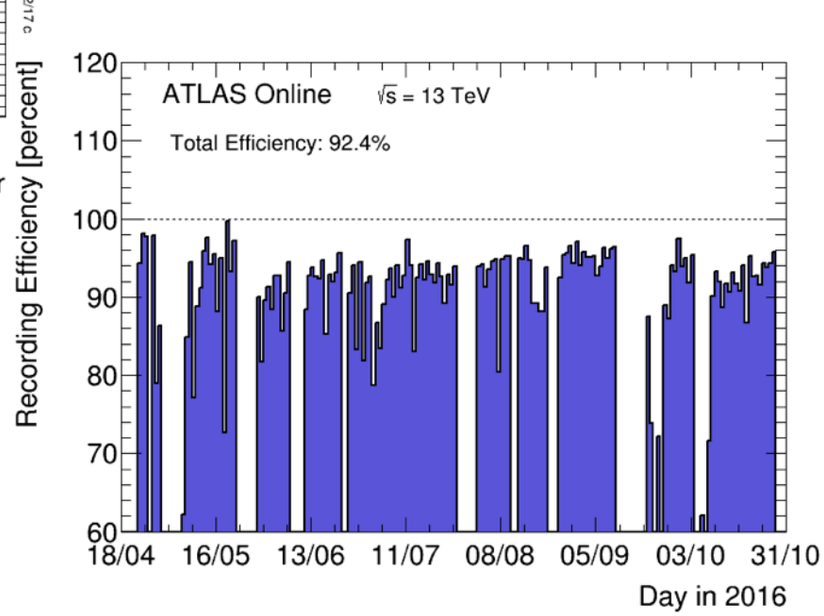
$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig\frac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu (\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w} Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

FLIP TANEDO









TOPICS TO BE COVERED

- **QCD probes:**
  - Inclusive jets @ 8TeV [STDM-2015-01]
  - Inclusive photons @ 13 TeV [arXiv:1701.06882] & di-photons @ 8TeV [STDM-2015-15]
  - Kt splitting scales in Z events [STDM-2015-14]
- **W & Z physics**
  - **W,Z precision cross sections @ 7 TeV [arXiv:1612.03016]**
  - **W mass measurement [arXiv:1701.07240]**
- **Electroweak production:**
  - Vector Boson Fusion W production @ 8TeV [arXiv:1703.04362]
  - Electroweak production of Zγ @ 8 TeV [STDM-2015-21]

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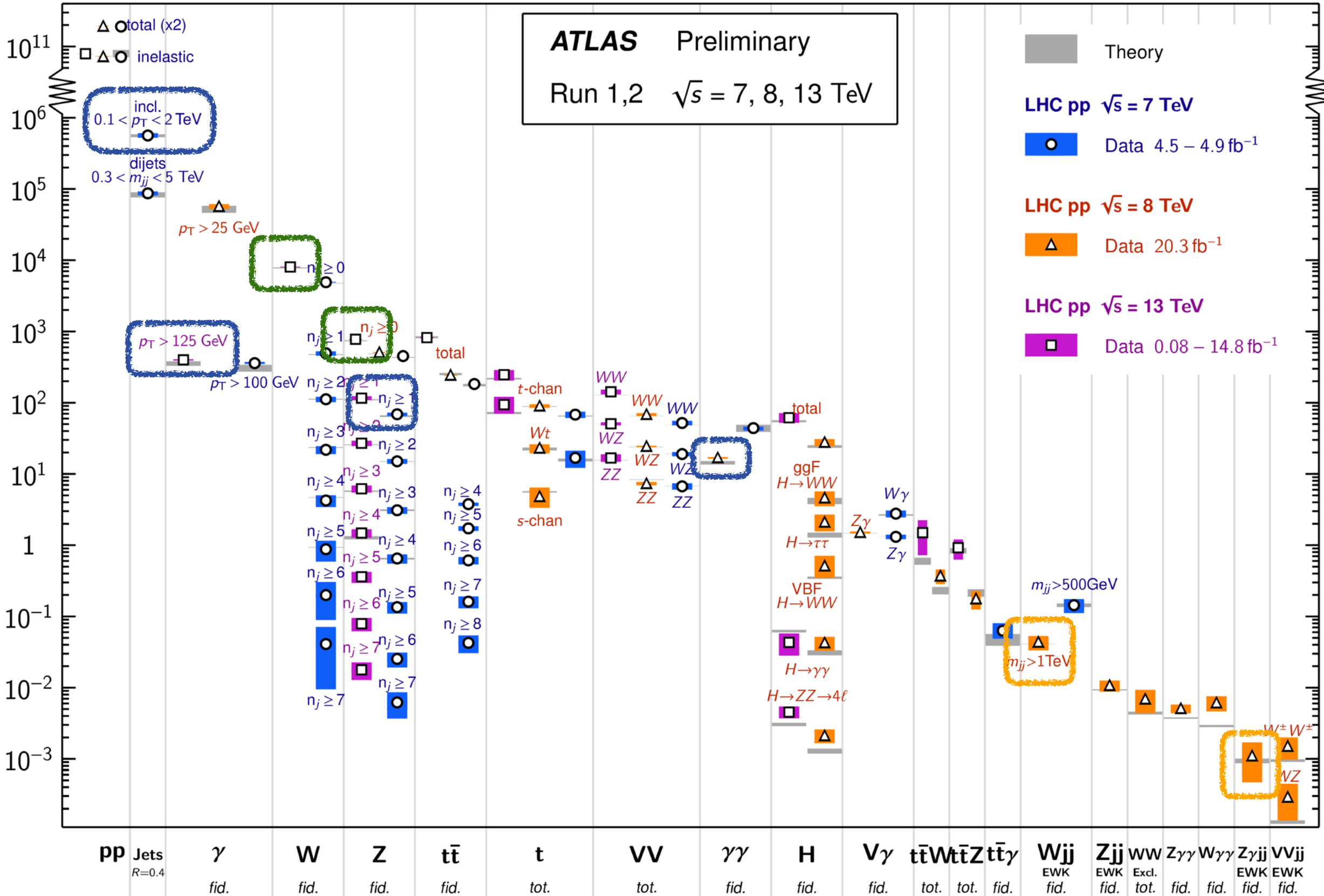
MANY MORE PUBLIC RESULTS AVAILABLE!

Standard Model Production Cross Section Measurements

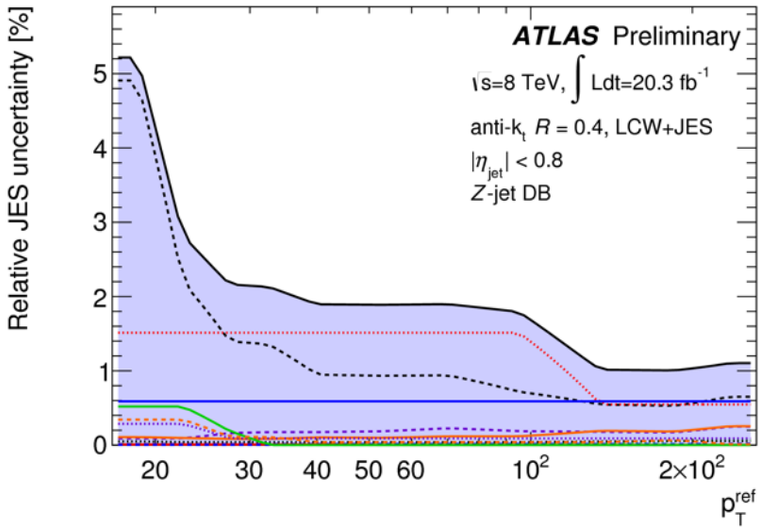
Status: March 2017



THE STANDARD MODEL TOOL BOX

Jets

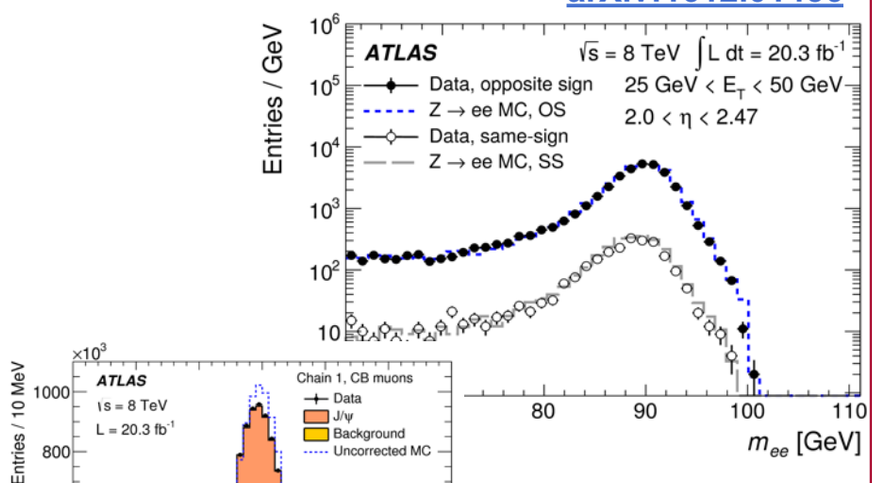
ATLAS-CONF-2015-057

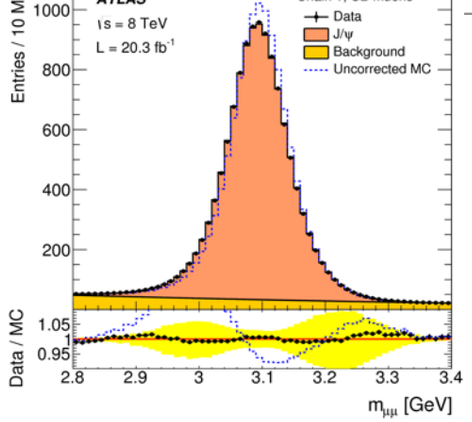


- Use calorimeter & track information for robust reconstruction
- Primary uncertainties on scale & resolution derived from MC & in-situ measurements

Photons, Leptons

arXiv:1612.01456



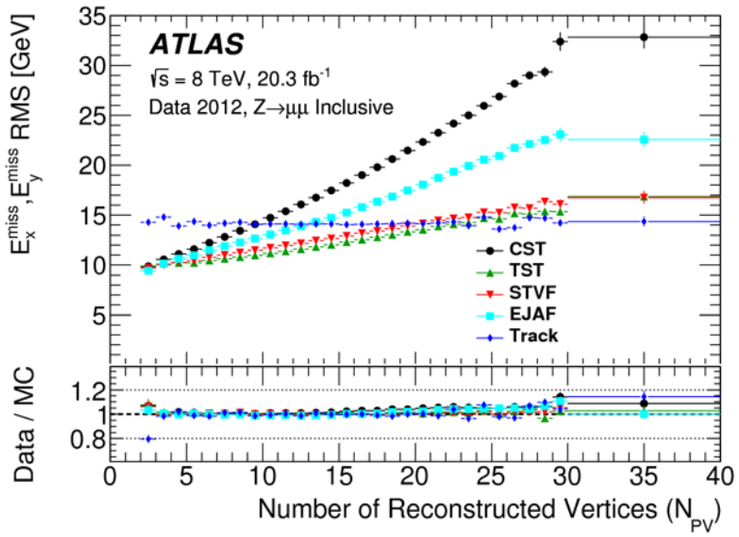


arXiv:1407.3935

- Precise measurements of particle parameters
- Uncertainties on efficiency, scale & resolution derived from comparisons with data (Z, J/Ψ)

MET

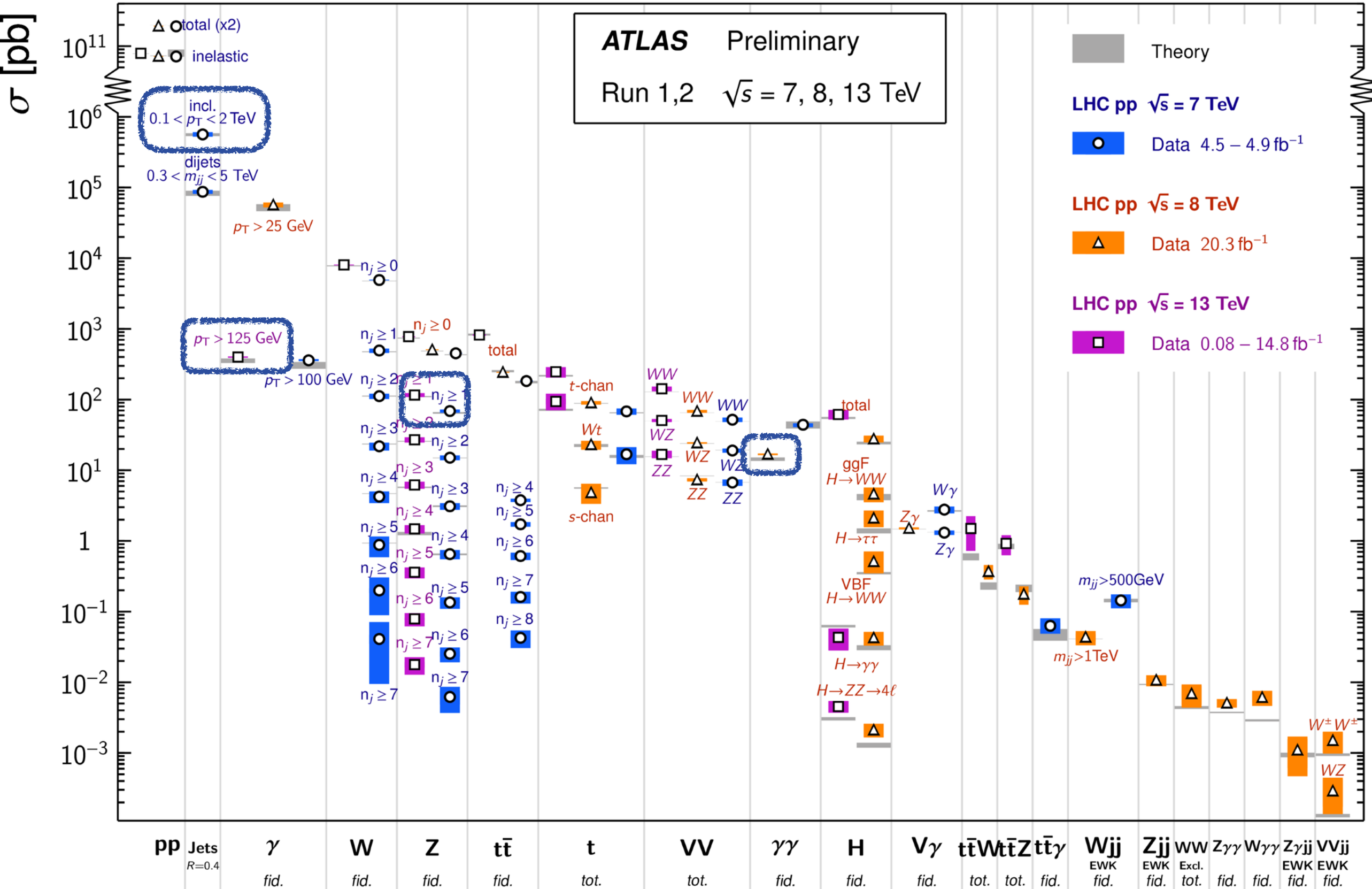
arXiv:1609.09324



- Calorimeter-based + info from tracking for pile-up control
- Multiple algorithms supported for wide variety of analyses

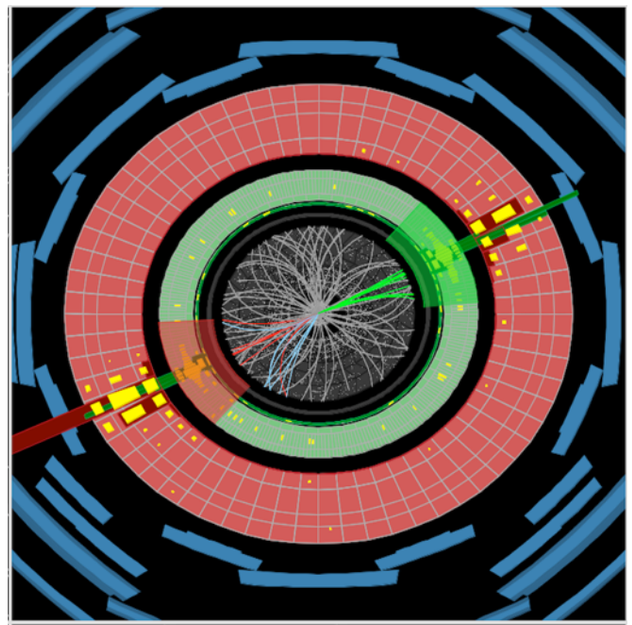
Standard Model Production Cross Section Measurements

Status: March 2017



INCLUSIVE JET PRODUCTION @ 8 TEV

- Why?
  - Probes short distance QCD
  - Sensitive to α_s, PDFs
- How?
  - Measure anti-k_T jets @ R = 0.4, 0.6
  - Correct for detector and non-perturbative effects and compare to NLO predictions
- What?
  - $d^2\sigma/dp_T dy$ for all measured jets with 70 GeV < p_T < 2.5 TeV; $|y| < 3.0$
- Dataset: 20.3 fb^{-1} @ 8 TeV



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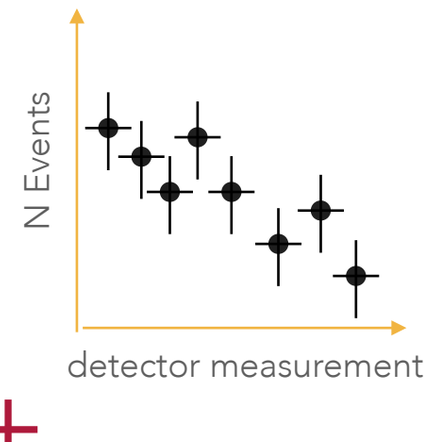
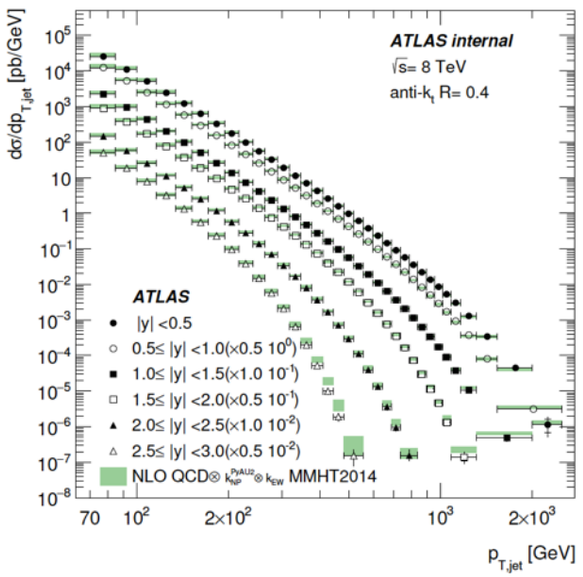
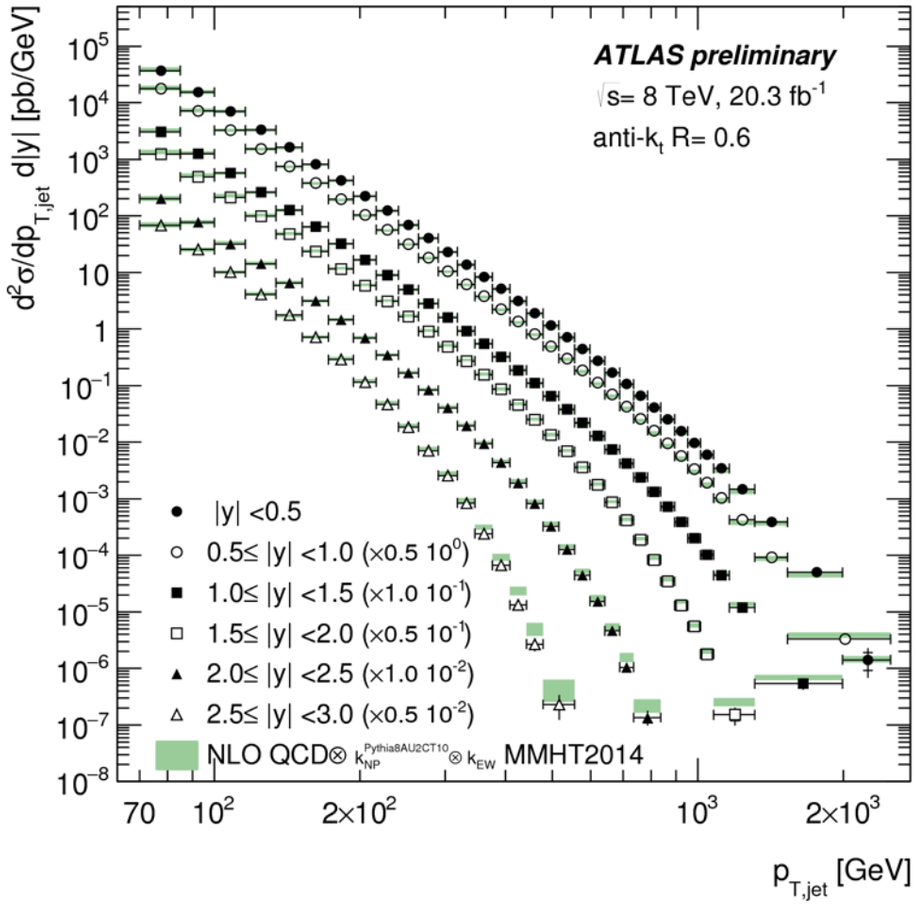


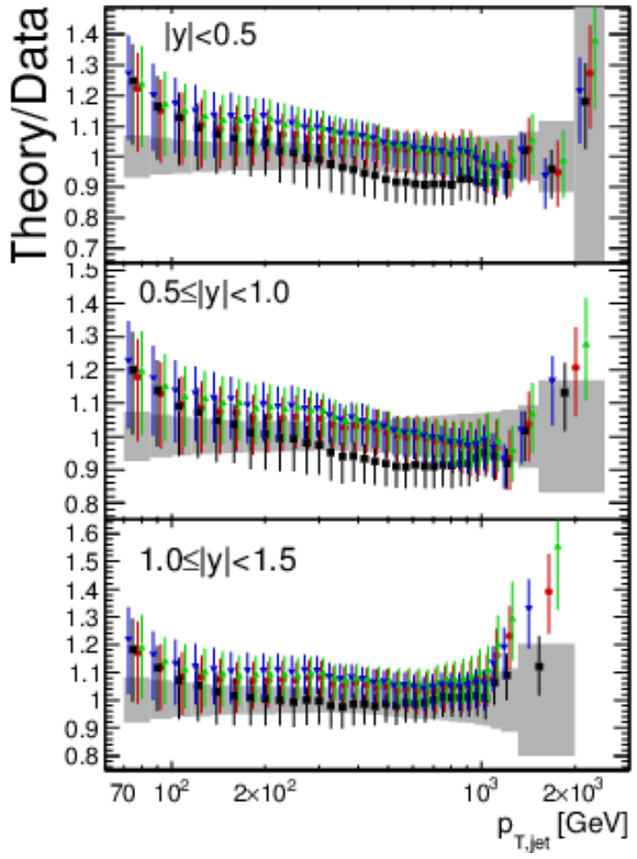
+

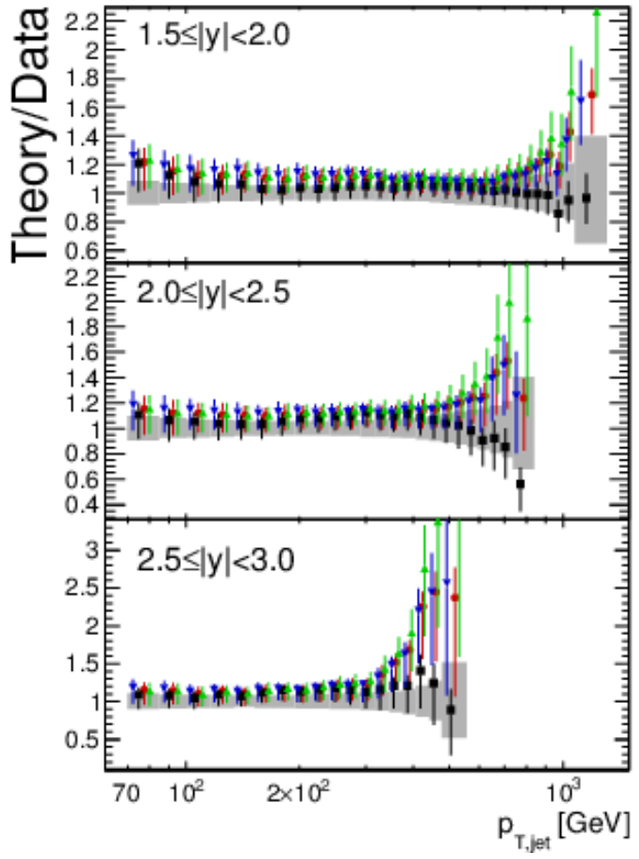
$$\mathcal{N}_i^{\text{part}} = \sum_j \mathcal{N}_j^{\text{reco}} \cdot \mathcal{P}_j \cdot \mathcal{A}_{ij} \,/\, \mathcal{E}_i,$$

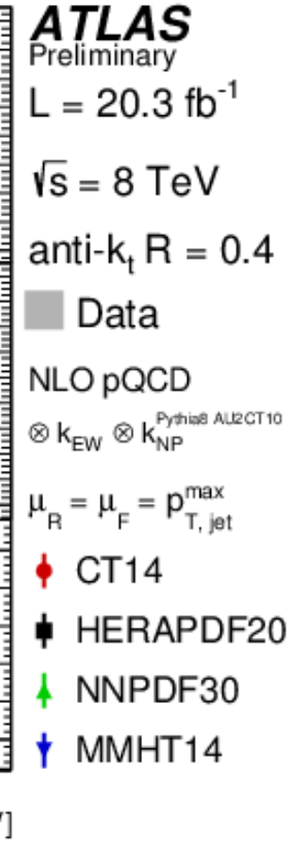


RESULTS





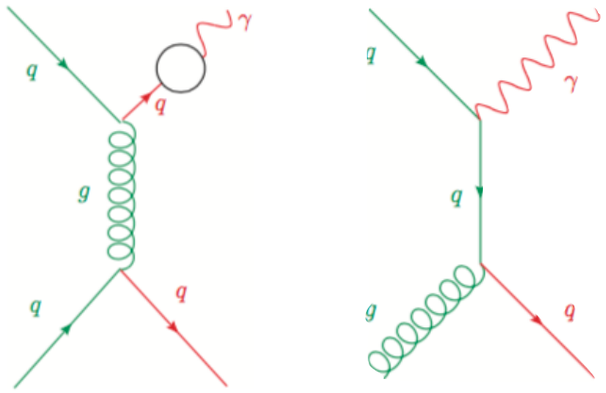




- PDF variations most impactful at low p_T in central η and high p_T at high η
  - Scale variations also worsen agreement
- When correlations in systematic uncertainties are included, strong tensions exist
  - Can be reduced when changing correlation model (e.g. decorrelating the JES & theory uncertainties)*
  - Unclear if remaining disagreements are poor correlation models or missing higher order corrections!

*https://cds.cern.ch/record/2044941

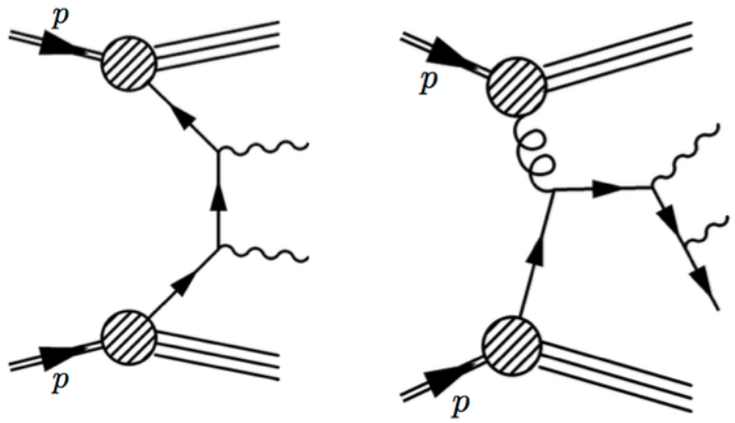
PHOTON MEASUREMENTS



$E_T^\gamma > 125$ GeV

$|\eta^\gamma| < 2.4$

13 TeV!

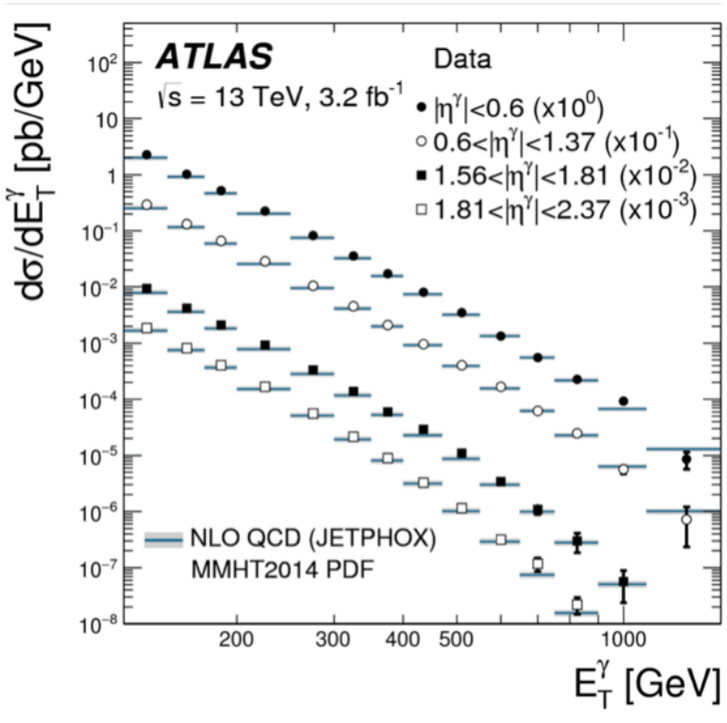


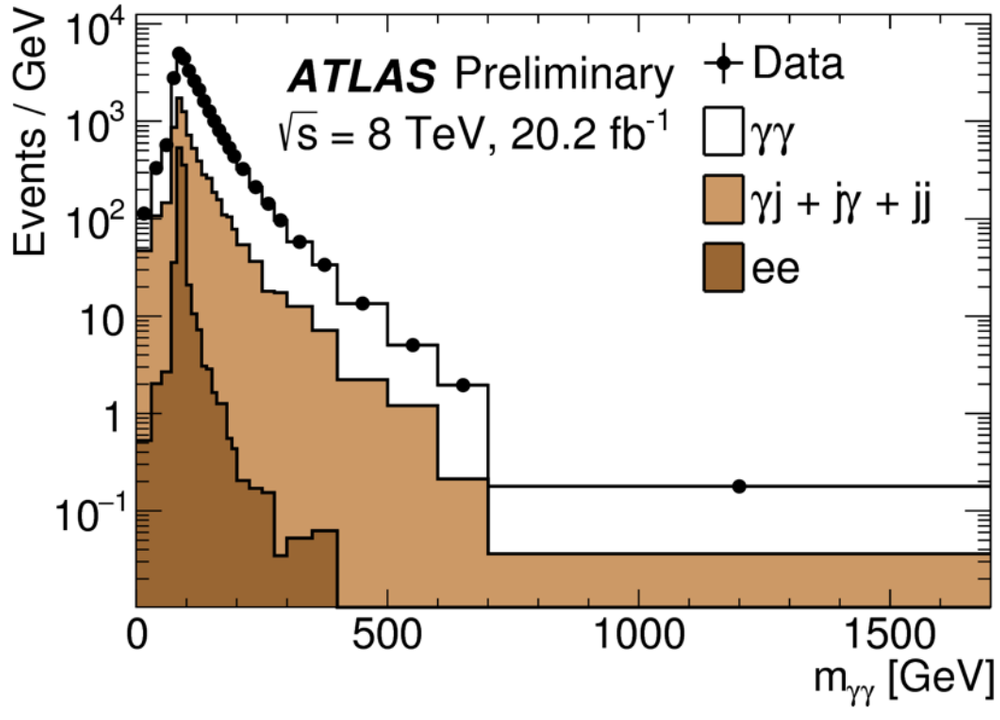
$E_{T,1}^\gamma > 40$ GeV

$E_{T,2}^\gamma > 30$ GeV

$|\eta^\gamma| < 2.4$

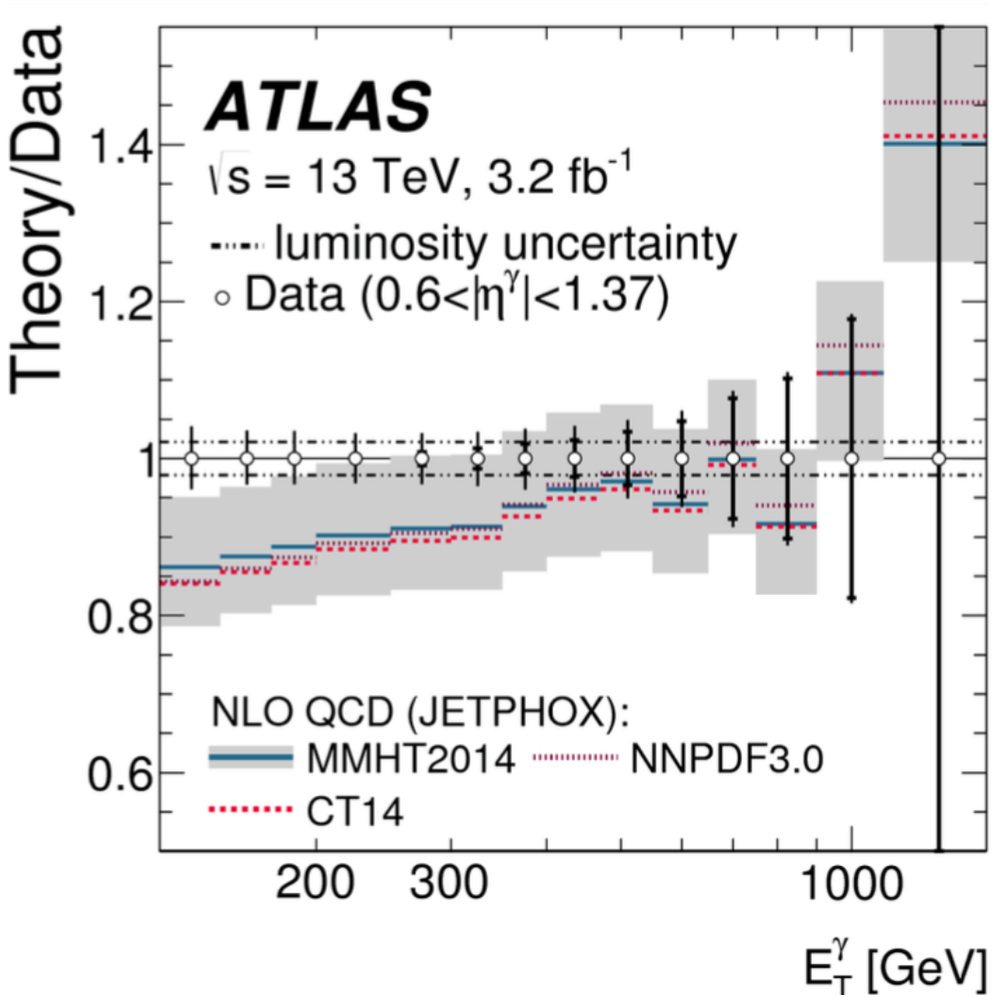
8 TeV

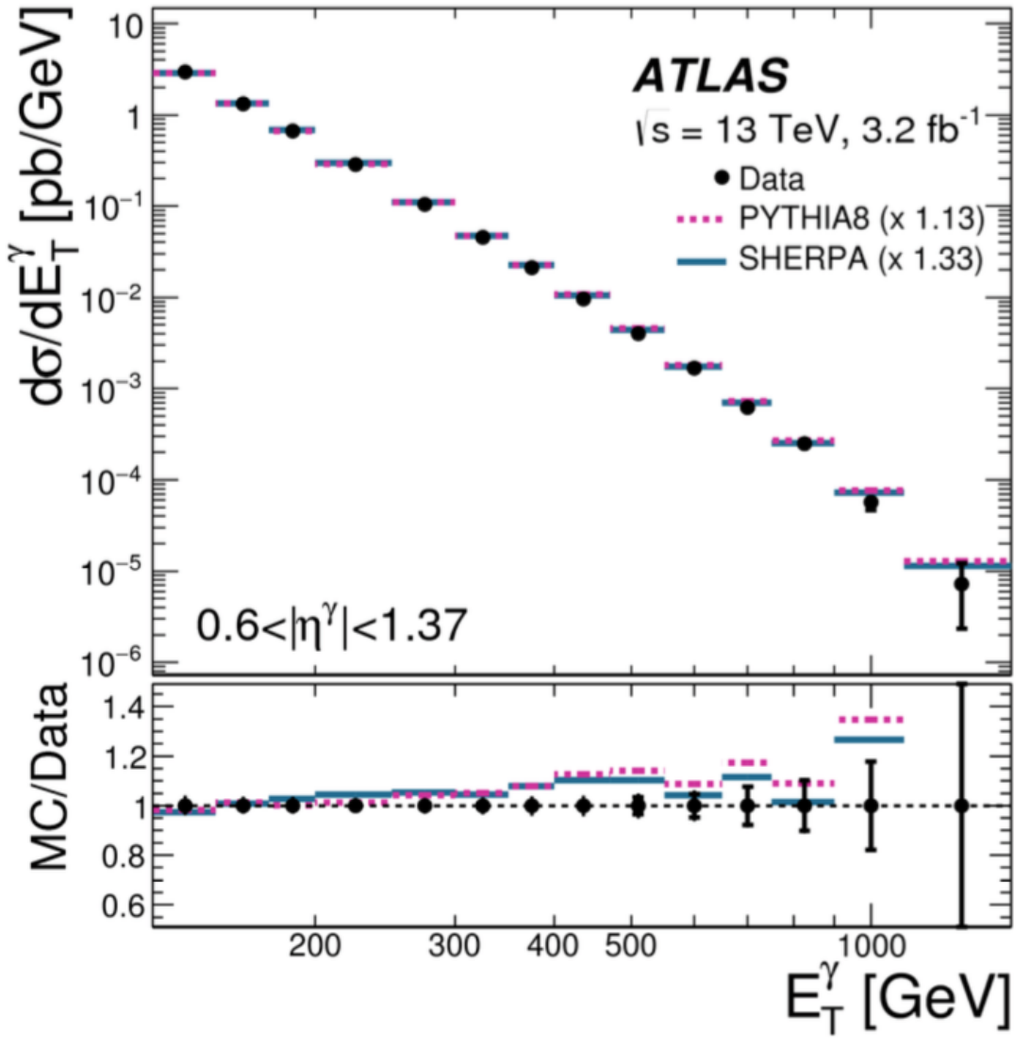




- Why?
  - colorless probe of short distance dynamics (parton radiation, resummation of QCD & EWK corrections) and gluon density in proton
  - Di-photon measurement important for modeling Higgs background

SINGLE PHOTON



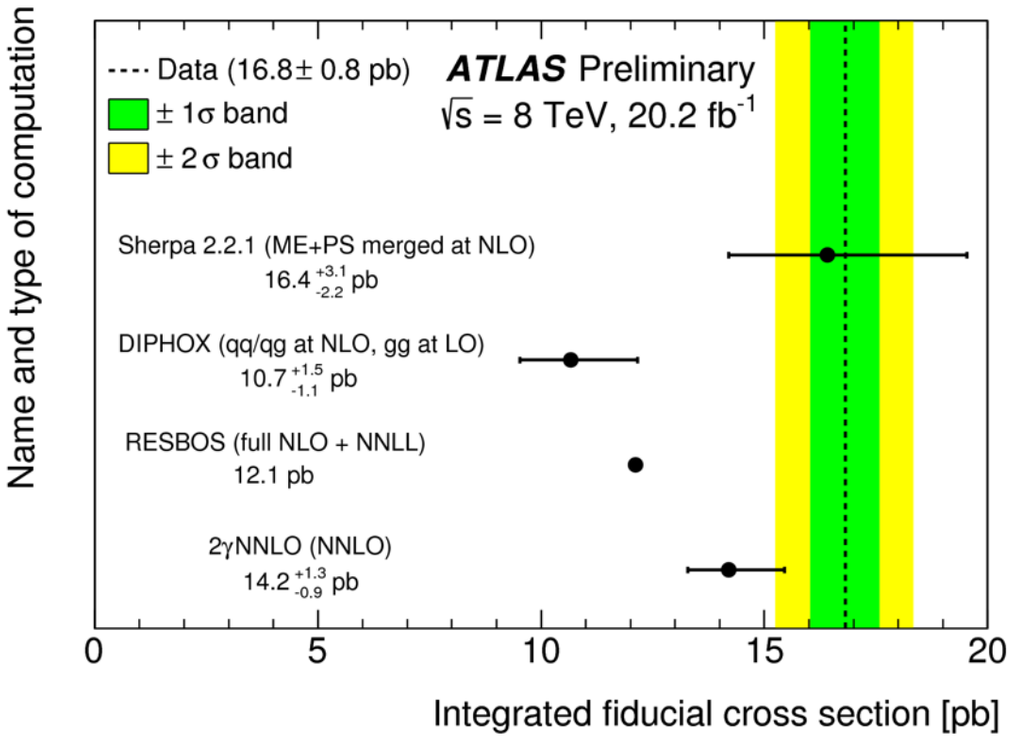


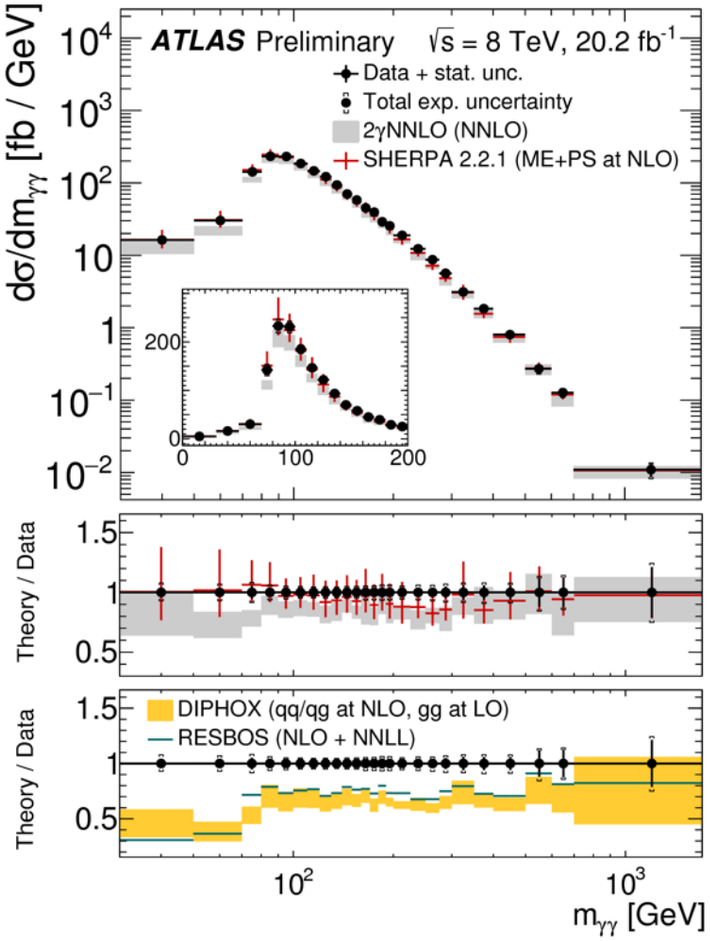
- NLO slightly under predicts at low E_T^γ

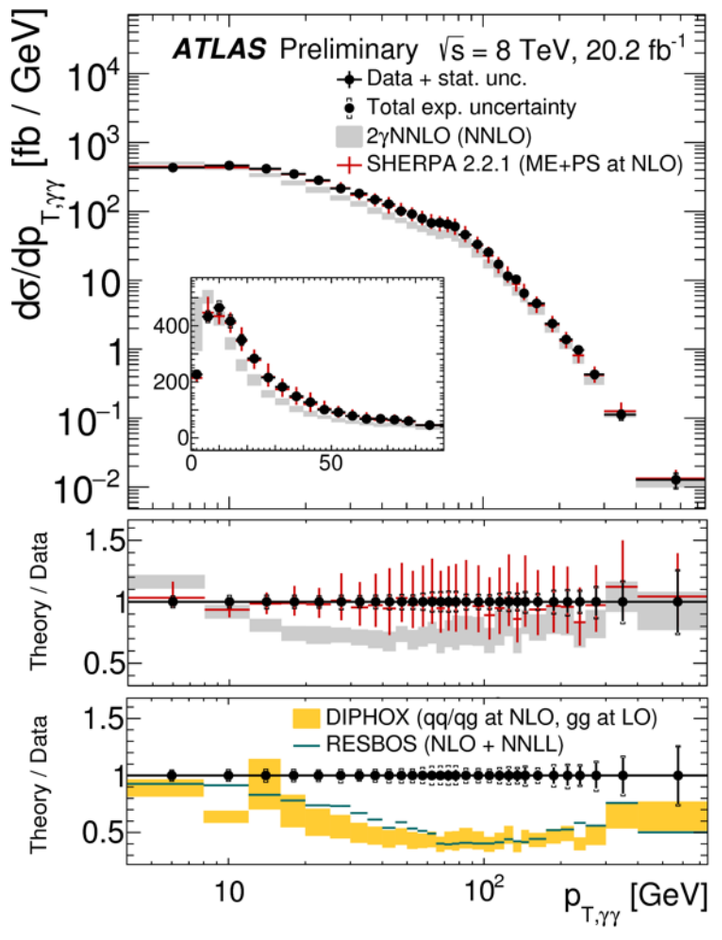
$$\sigma_{\text{meas}} = 399 \pm 13\ (\text{exp.}) \pm 8\ (\text{lumi.})\ \text{pb}$$

- MC generators have harder E_T^γ spectrum than data

INCLUSIVE DIPHOTONS



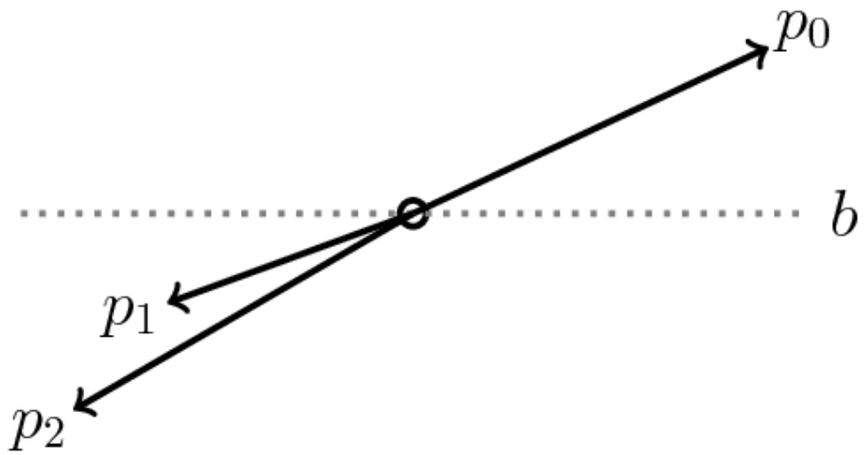




- Best overall agreement with Sherpa (NLO + parton shower)
- Fixed order calculations show significant disagreements with data:
  - However, Resbos accurate in phase-space dominated by infrared emissions
  - Many more distributions in forthcoming paper

SPLITTING SCALES IN Z EVENTS

- Why?
  - Study jet production at different resolution scales
  - Can be used to tune MC predictions, understand jet production
- What?
  - Select events with Z bosons, reconstruct tracks with pT > 400 MeV
  - Measure production cross-section as a function of k_t algorithm step for R =0.4 and R = 1.0
- Dataset: 20 fb^{-1} @ 8 TeV



$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2},$$
$$d_{ib} = p_{\mathrm{T},i}^2,$$
$$d_k = \min_{i,j}(d_{ij}, d_{ib}).$$

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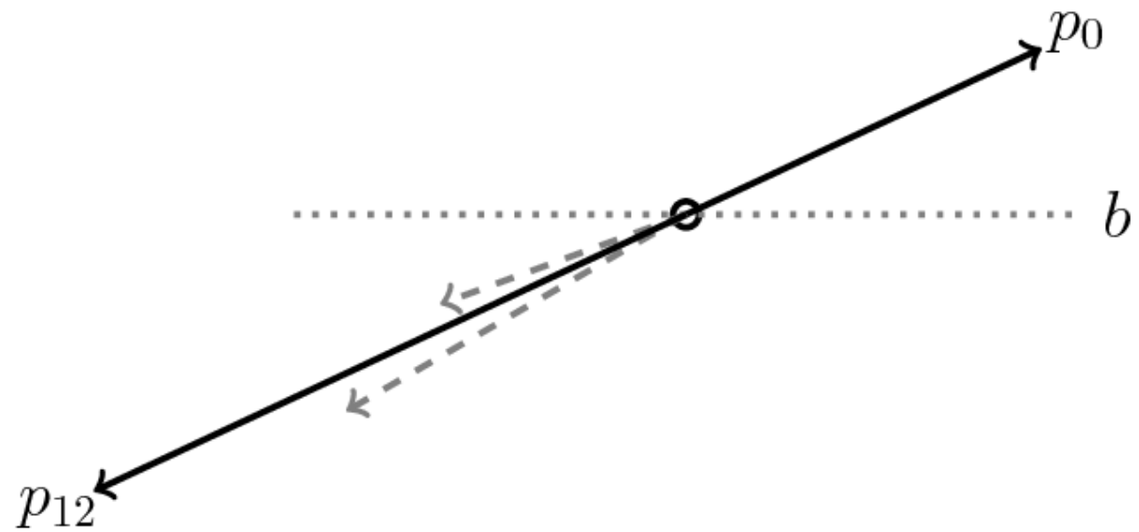

$$
\begin{aligned}
d_{ij} &= \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}, \\
d_{ib} &= p_{\mathrm{T},i}^2, \\
d_k &= \min_{i,j}(d_{ij}, d_{ib}).
\end{aligned}
$$

SPLITTING SCALES IN Z EVENTS

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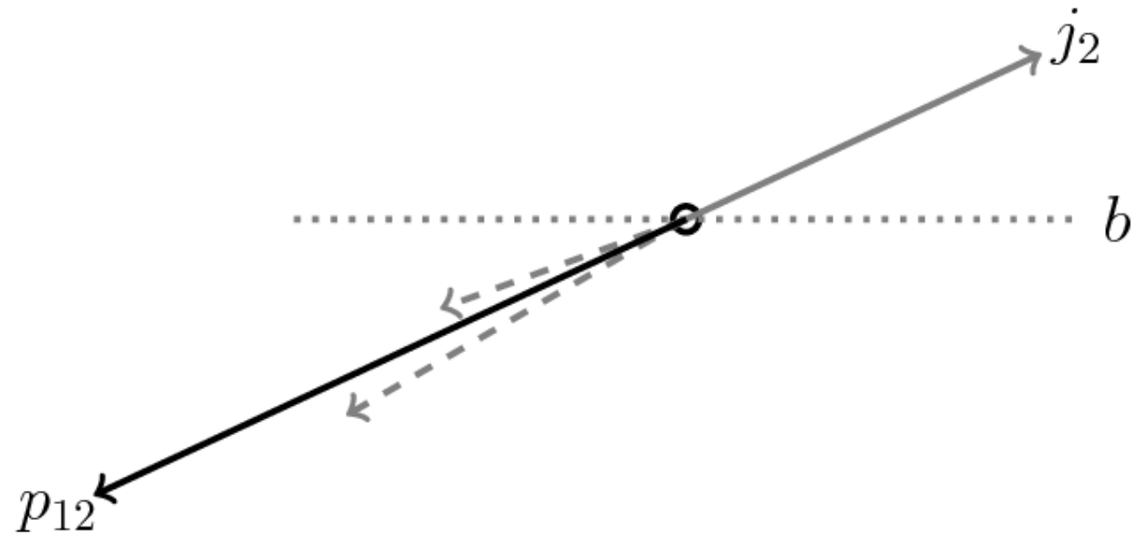

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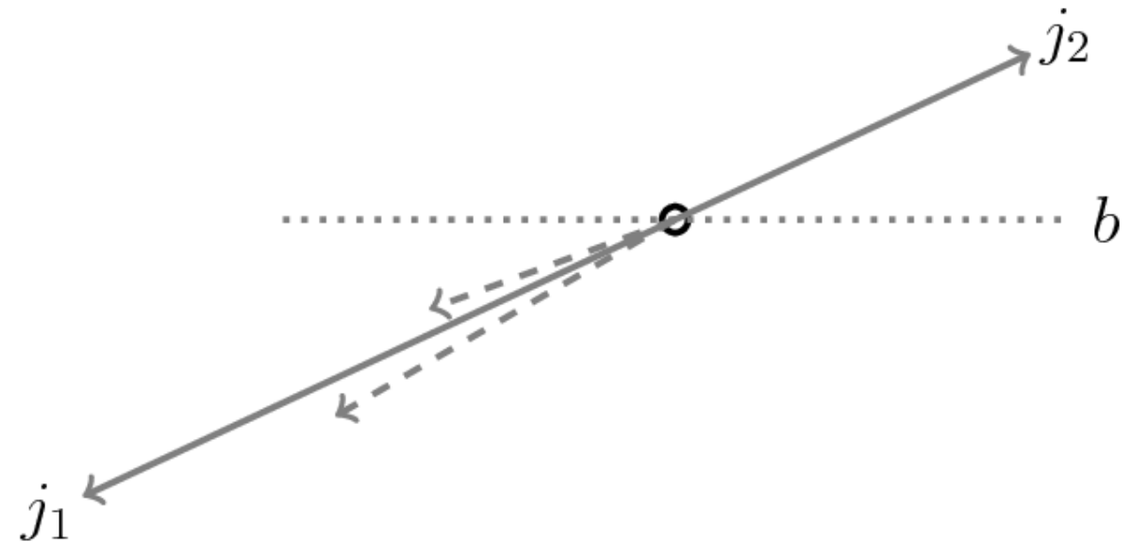

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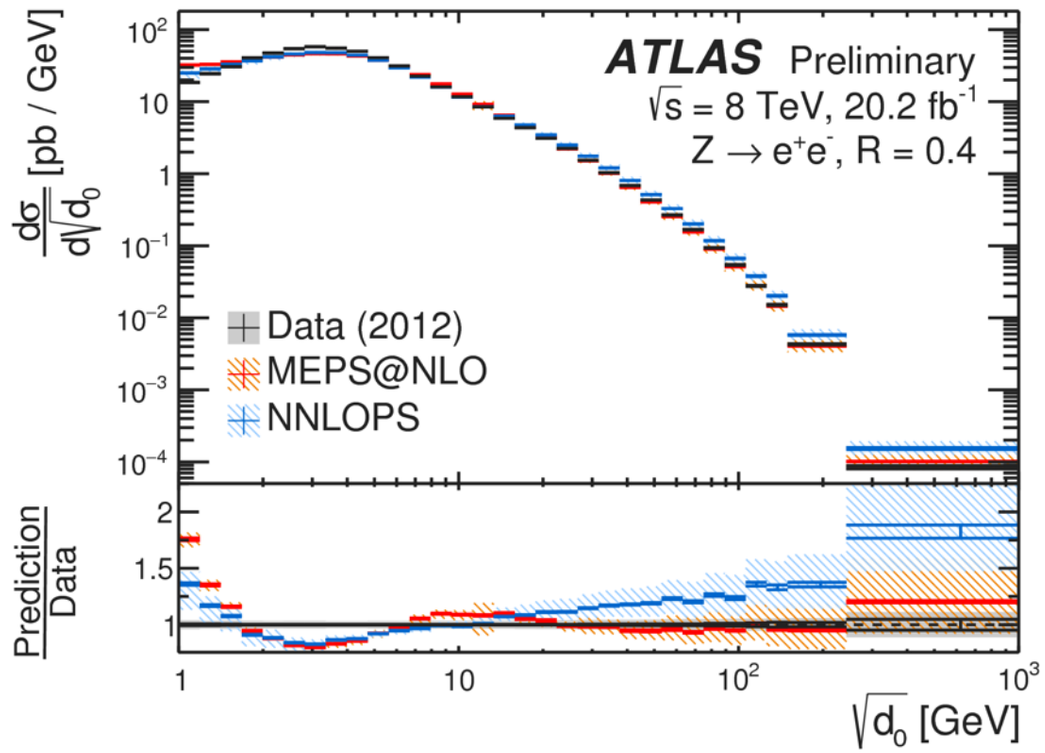
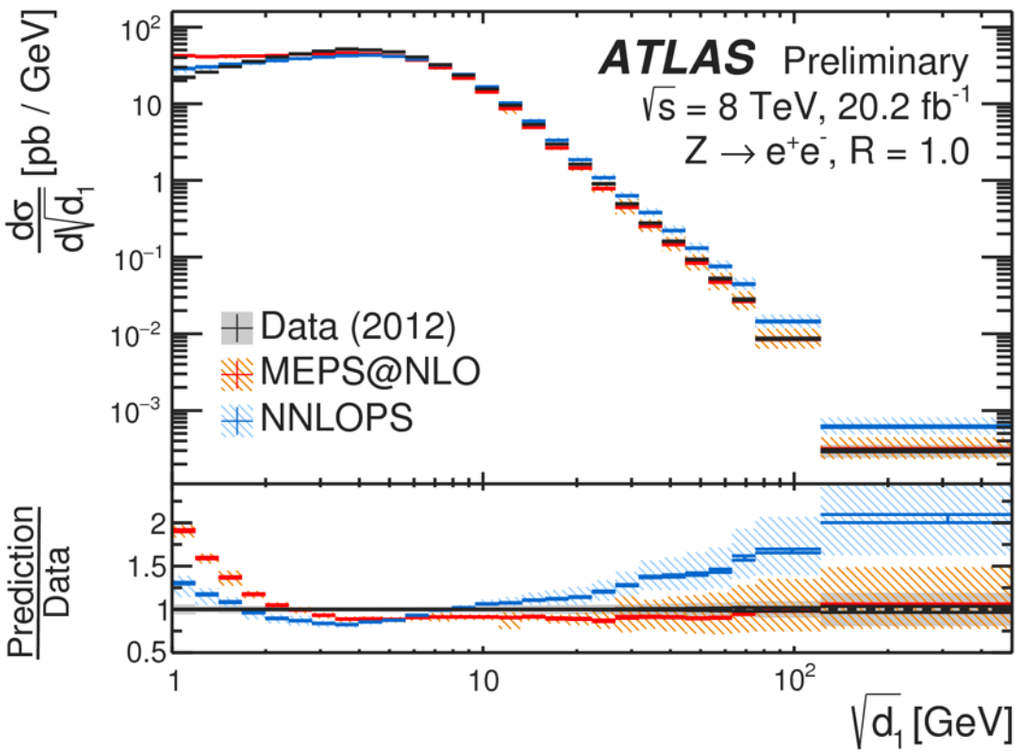
d_k &= \min_{i,j}(d_{ij}, d_{ib}).
\end{aligned}
$$

SPLITTING SCALES IN Z EVENTS

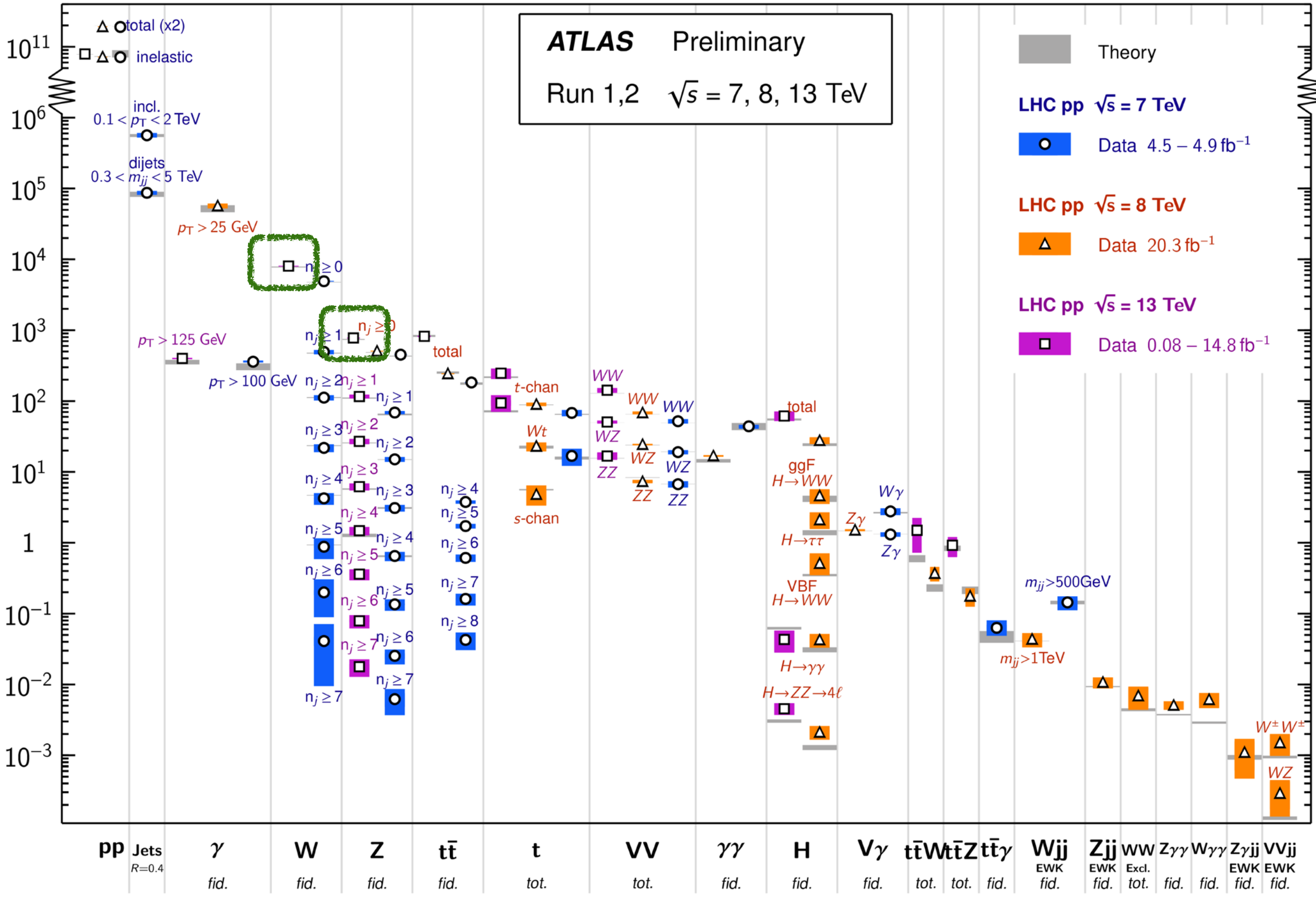
- Compare to Sherpa (MEPS@NLO) & Powheg (NNLOPS):
  - Underestimate cross-section in peak region, overestimate at low scales
  - Sherpa matches at high scales.
  - NNLOPS matches better at higher splitting steps





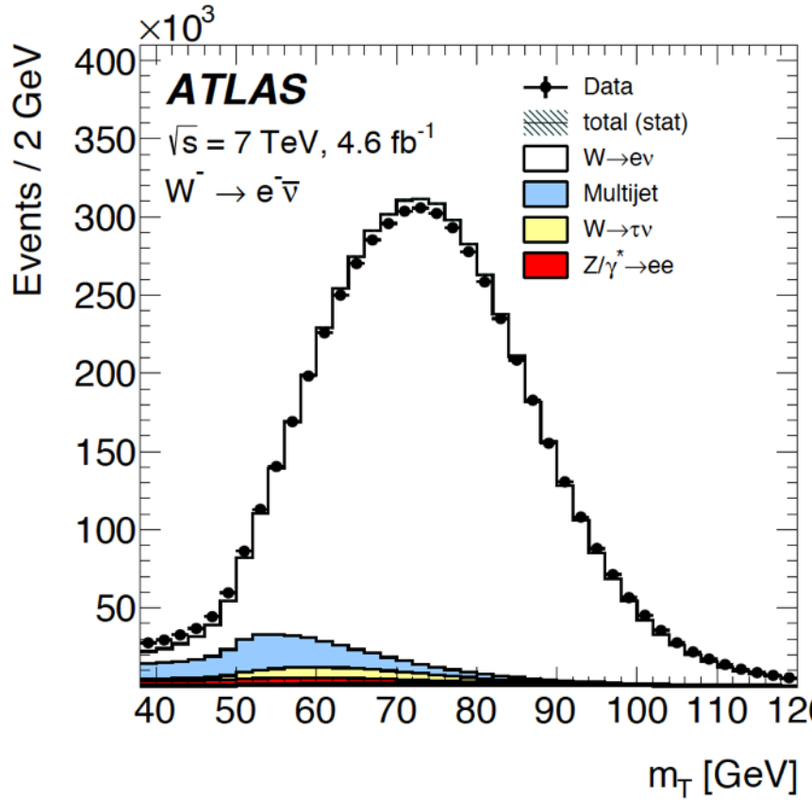
Standard Model Production Cross Section Measurements

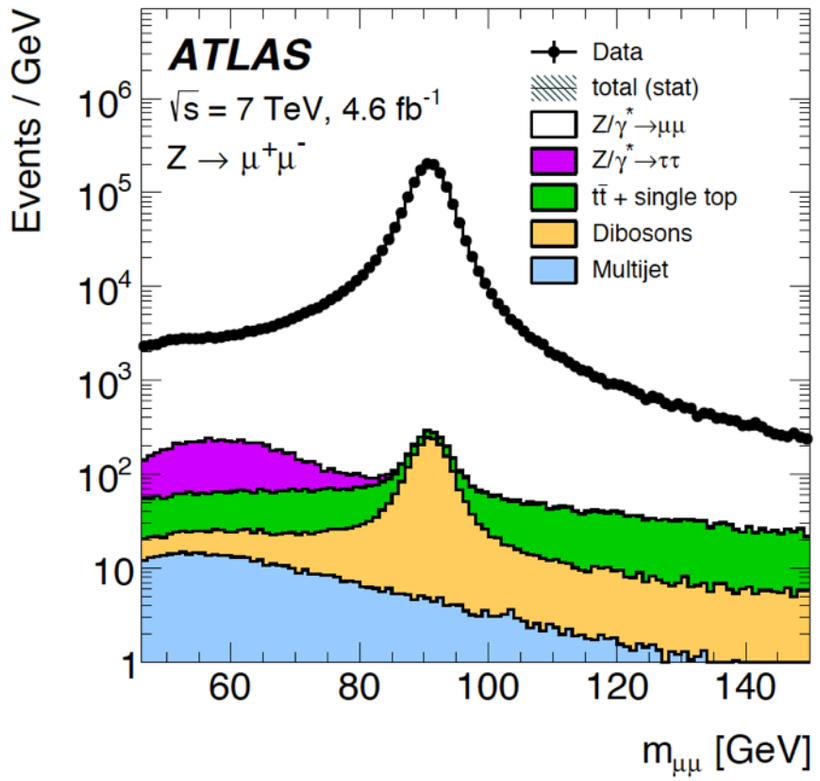
Status: March 2017



W/Z PRECISION MEASUREMENT

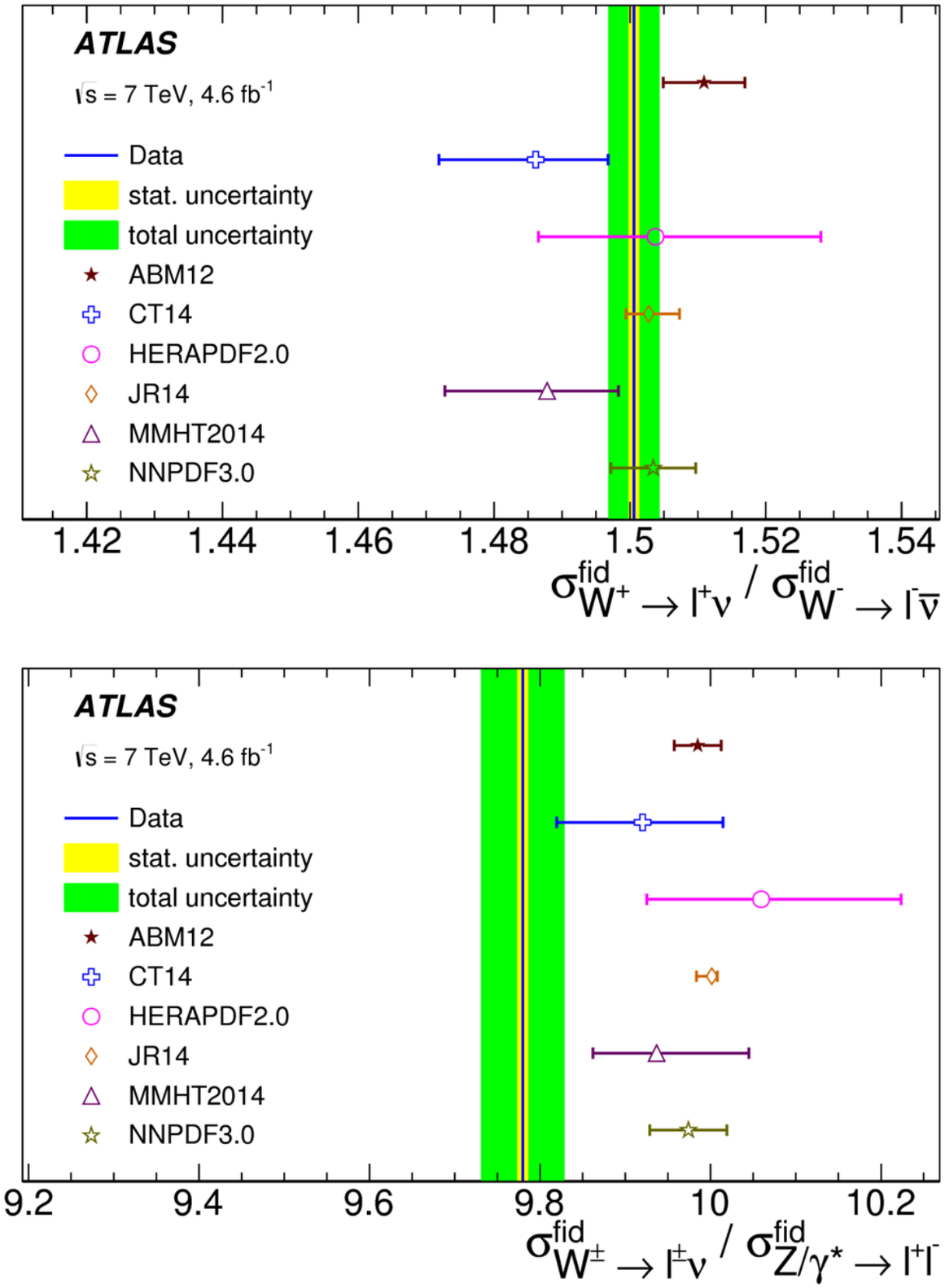
- Why? Leptonic decays of EWK bosons provide a well-defined probe:
  - proton structure (PDFs)
  - EWK lepton-universality
  - NNLO QCD & NLO EWK calculations
- What?
  - Measure W&Z cross-section to e & μ inclusively and differentially in charge, η , *y*
  - Do PDF fits including these data & HERA data (s - to -light PDF ratios!) and measure $|V_{cs}|$
- Dataset: 4.6 fb^{-1} @ 7 TeV



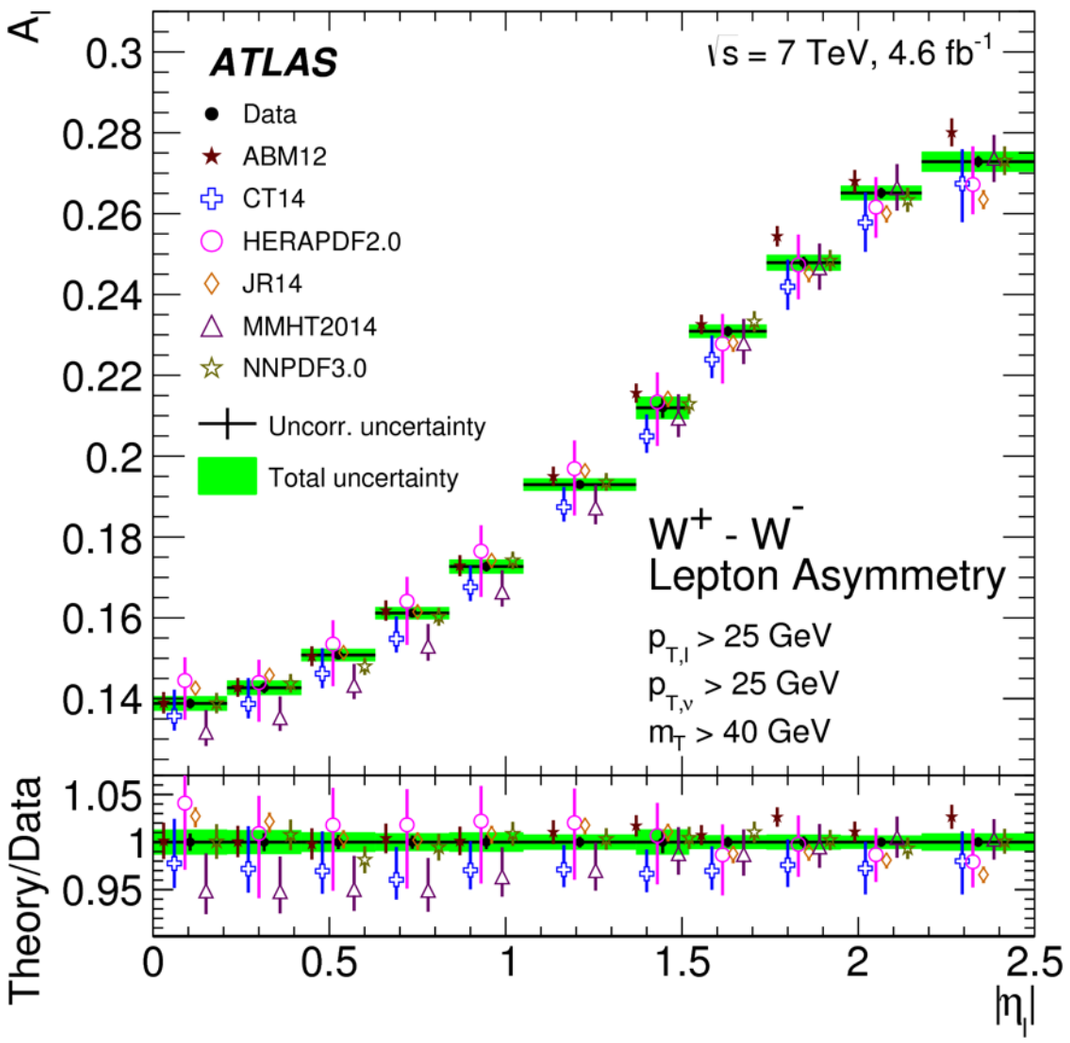


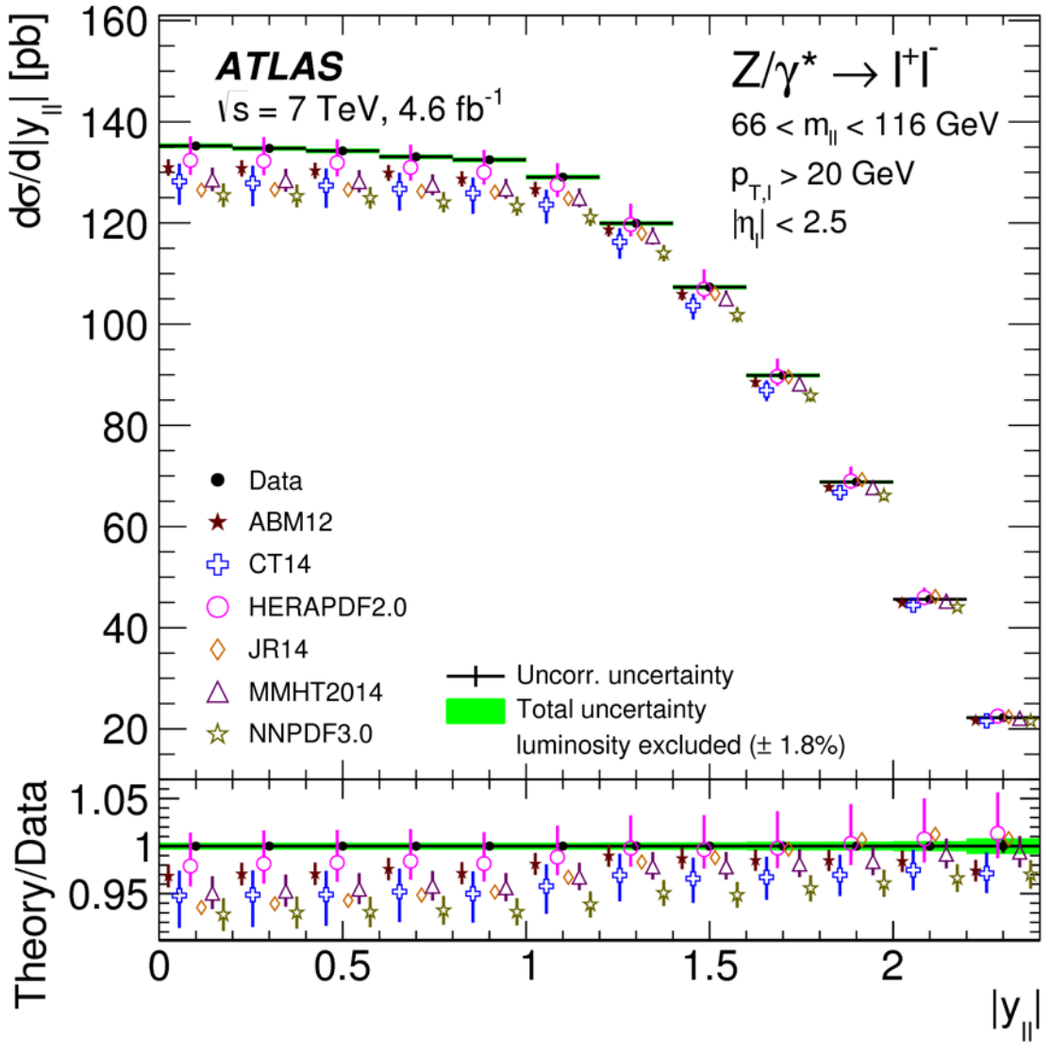
CROSS-SECTION RATIOS

- W^+/W^- cross-section ratios well-reproduced by DYNNLO + various PDF models.
- Z cross-section slightly higher than most models, W/Z ratio systematically lower than predictions



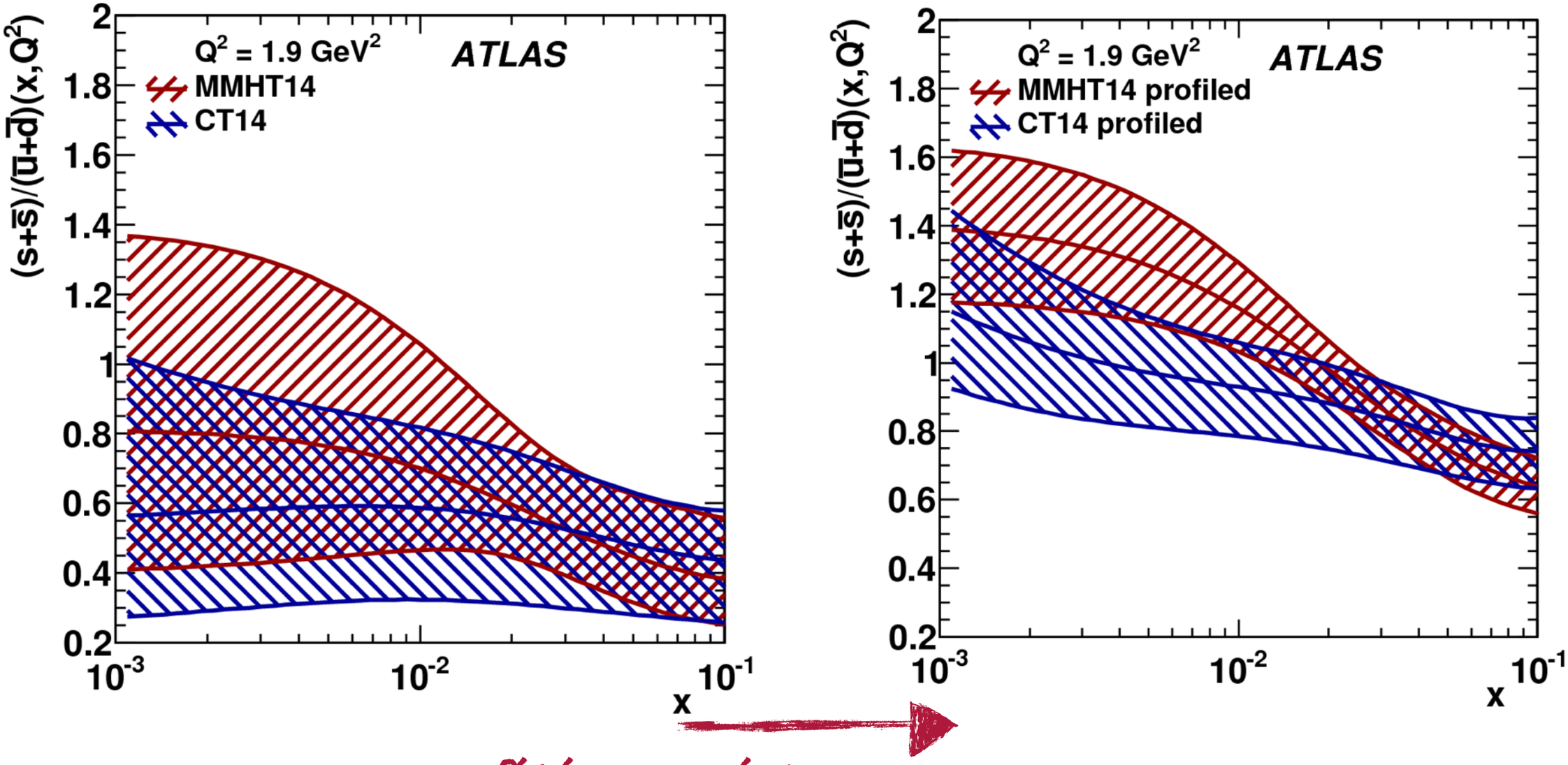
RAPIDITY DEPENDENCE





- W+ - W- lepton asymmetry well-reproduced
- Z production is under predicted at central rapidity

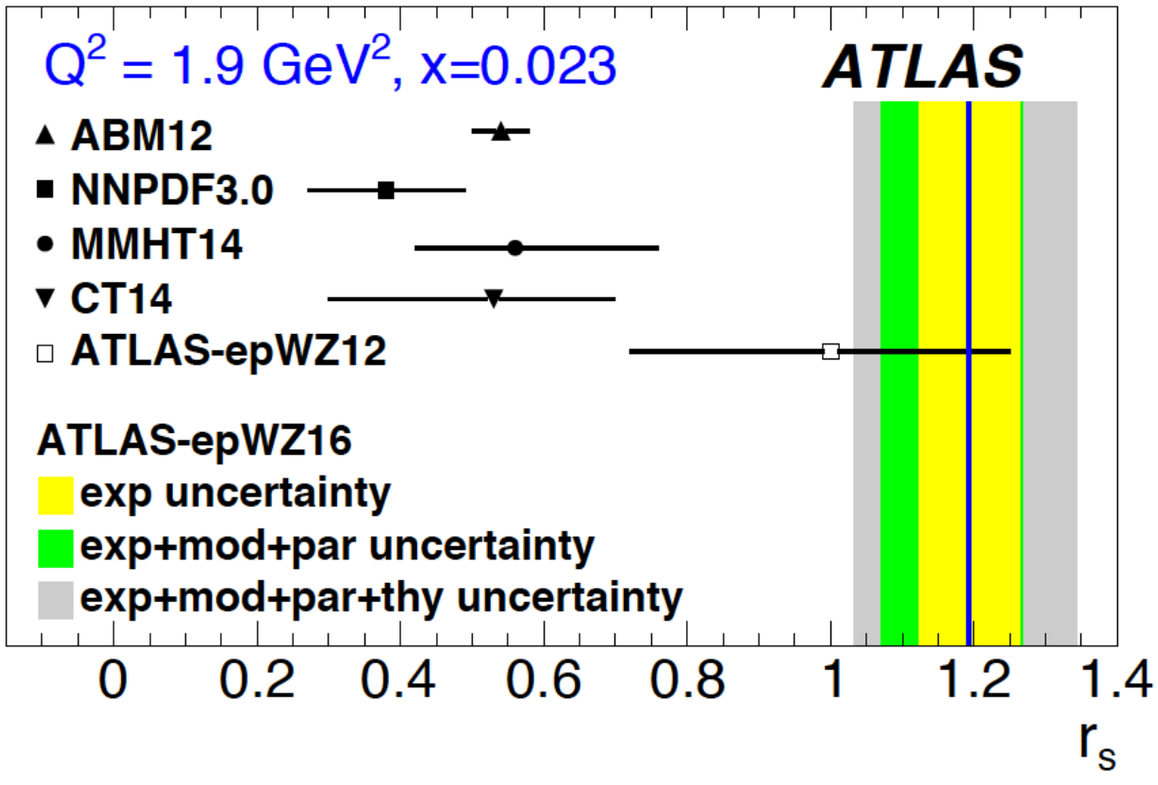
PDF CONSTRAINTS

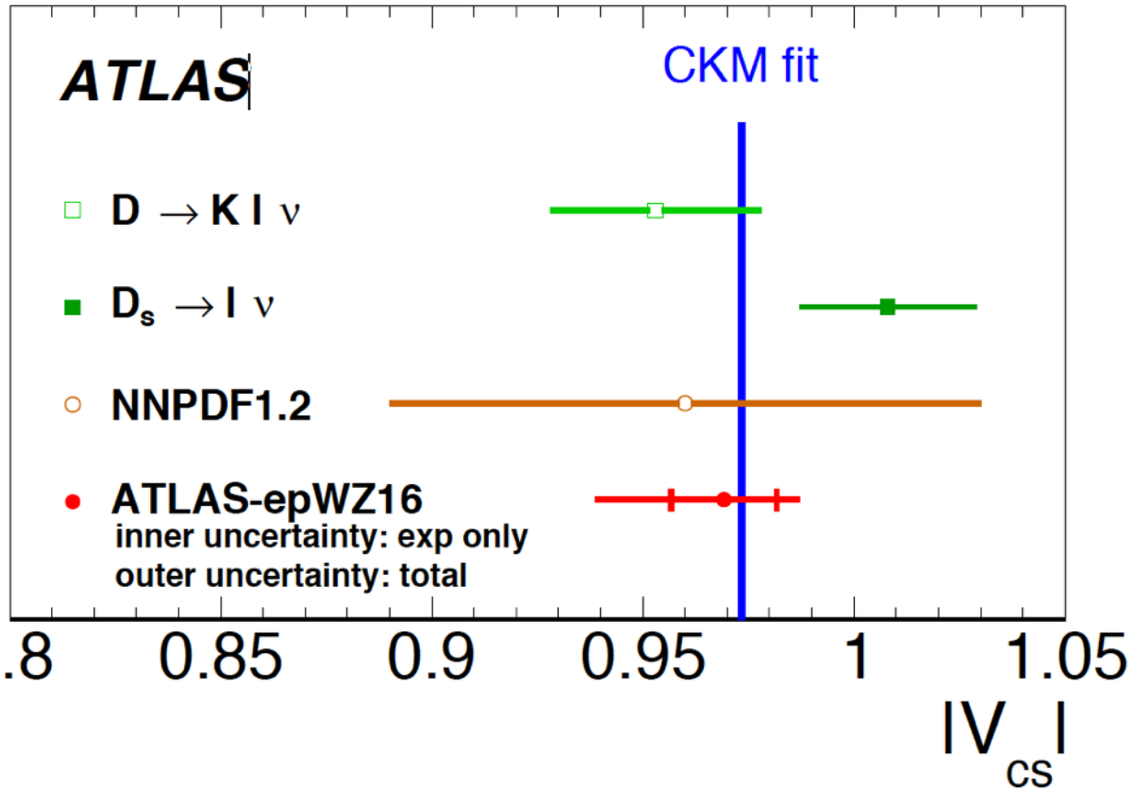


Profiling with ATLAS Data

- Can use ATLAS data to profile PDF uncertainties:
  - Strange to light sea-quark ratio uncertainty reduced, Overall s-quark uncertainties reduced

S-QUARK FRACTION & V_{cs}





- Previous ATLAS measurements indicated *s*-quark unsuppressed at low *x*
- HERA + ATLAS PDF fit —> extract s-quark fraction; confirm previous ATLAS measurements
- Inclusive W xsec & lepton *y* distribution sensitive to $|V_{cs}|$: do PDF fit allowing $|V_{cs}|$ to float

$$|V_{cs}| = 0.969 \pm 0.013\,(\text{exp})\,^{+0.006}_{-0.003}\,(\text{mod})\,^{+0.003}_{-0.027}\,(\text{par})\,^{+0.011}_{-0.005}\,(\text{thy})$$

W MASS: WHY?

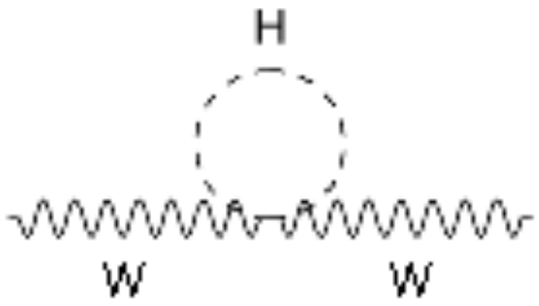
- W mass intimately connected to EWSB mechanism:

what we do

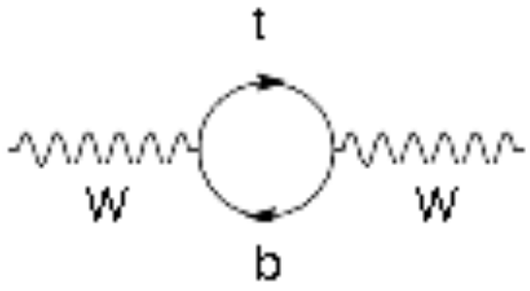
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r),$$

Fun is here:
m_H, m_t, NP

Well known from LEP



$\sim \ln(m^2_H)$

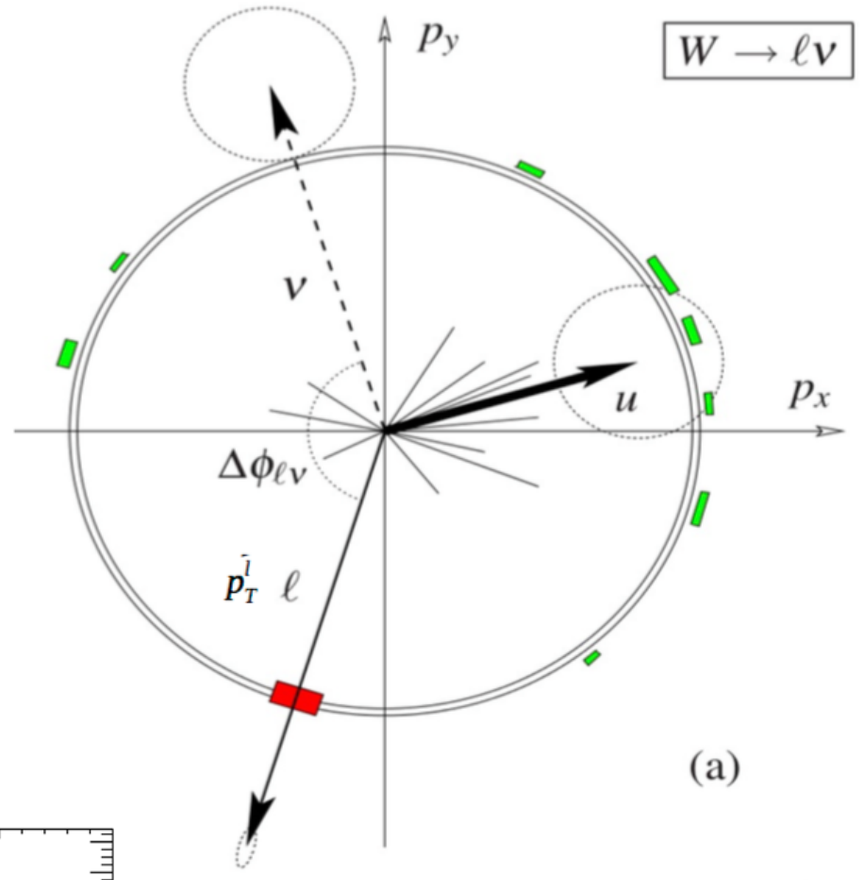


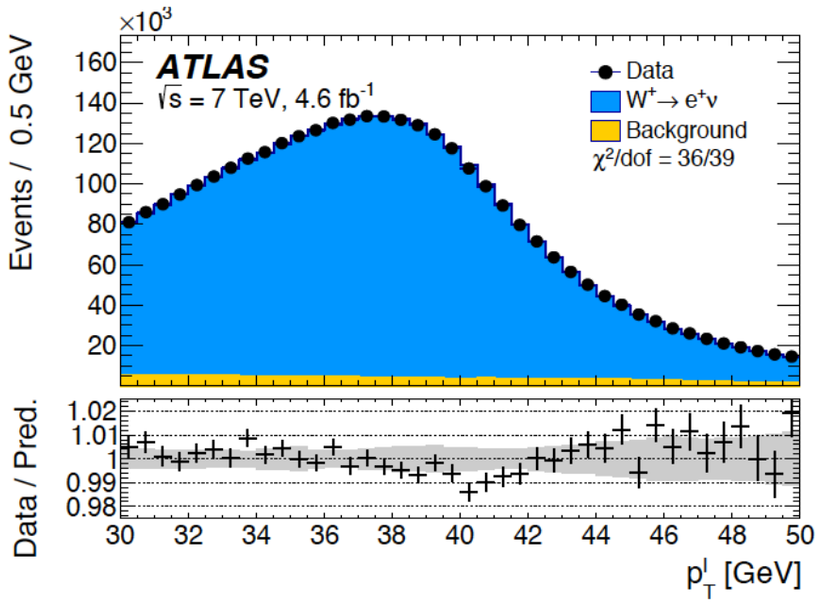
$\sim m^2_{top}$

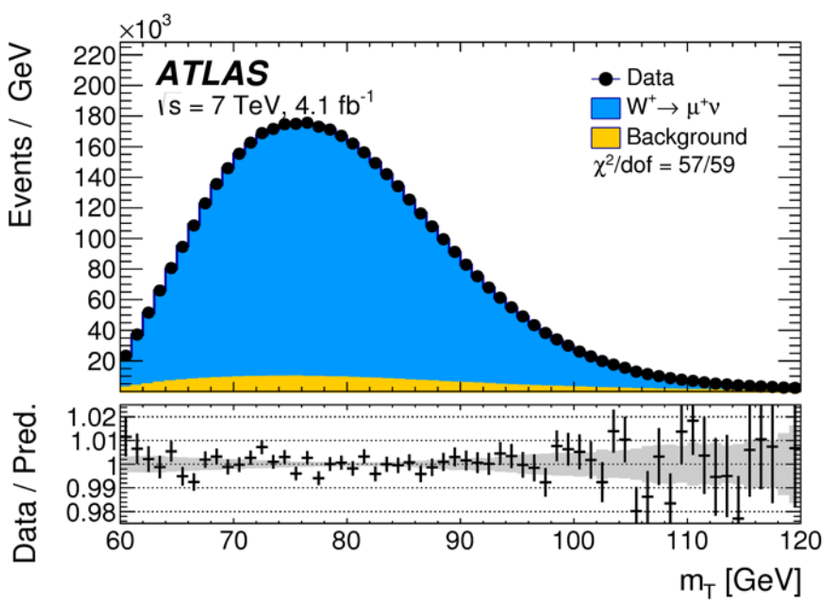
W MASS: HOW WE DO IT

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right), \quad m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

- ***Carefully*** measure p_T^l, m_T
  - Requires O(%) knowledge of resolutions
  - Need very accurate modeling of hadronic recoil
- Simultaneously fit e and μ p_T^l and m_T distributions to signal templates to extract m_W

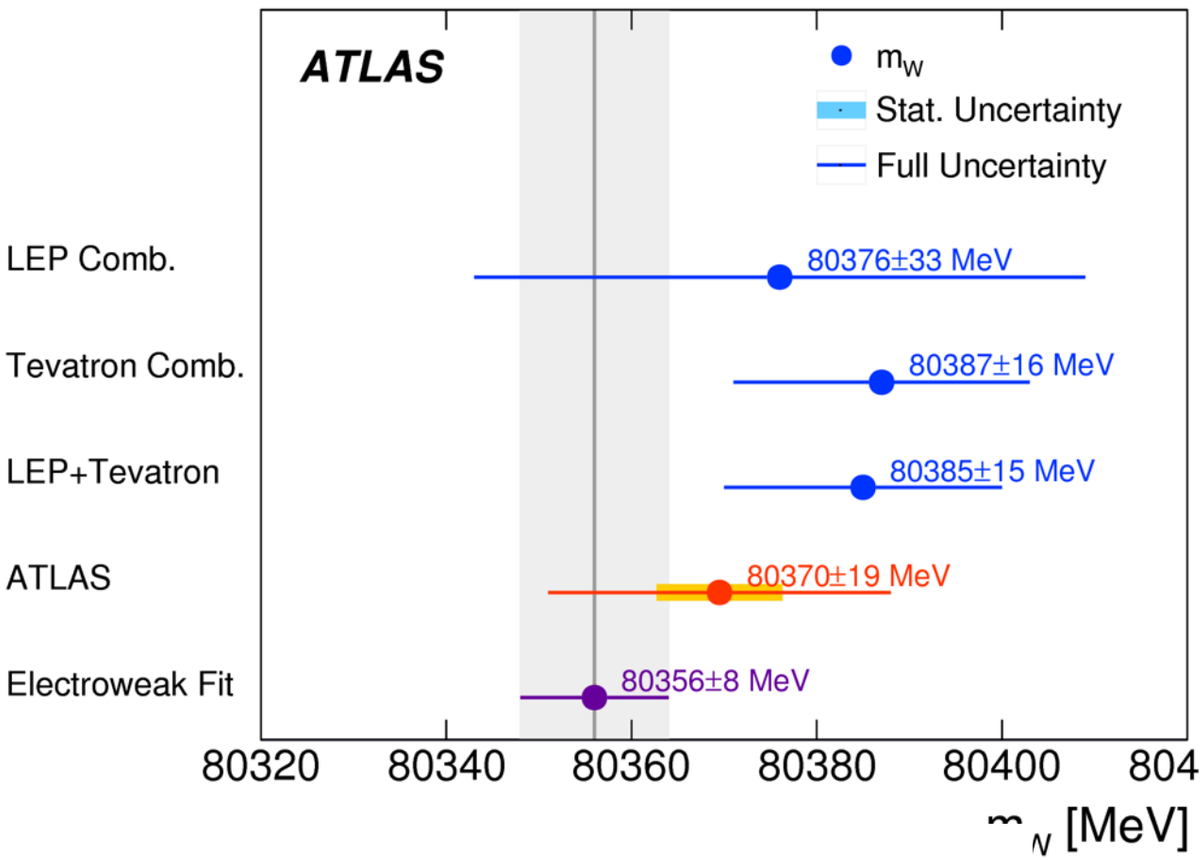




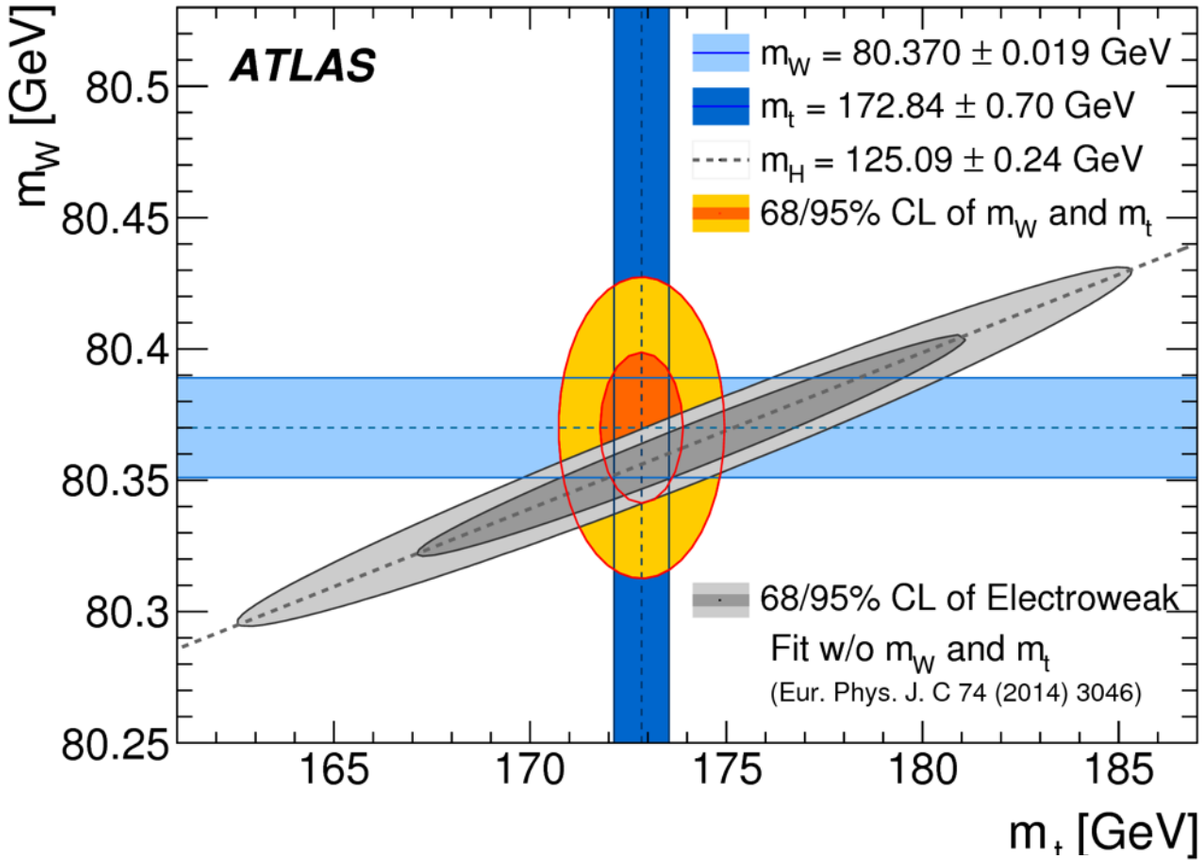


RECOIL MODELING, DETECTOR RESPONSE MEASURED IN Z→ll

PUTTING IT ALL TOGETHER!



SM prediction for m_W, assuming
m_H = 125.09 ± 0.24 GeV
m_t = 172.84 ± 0.70 GeV

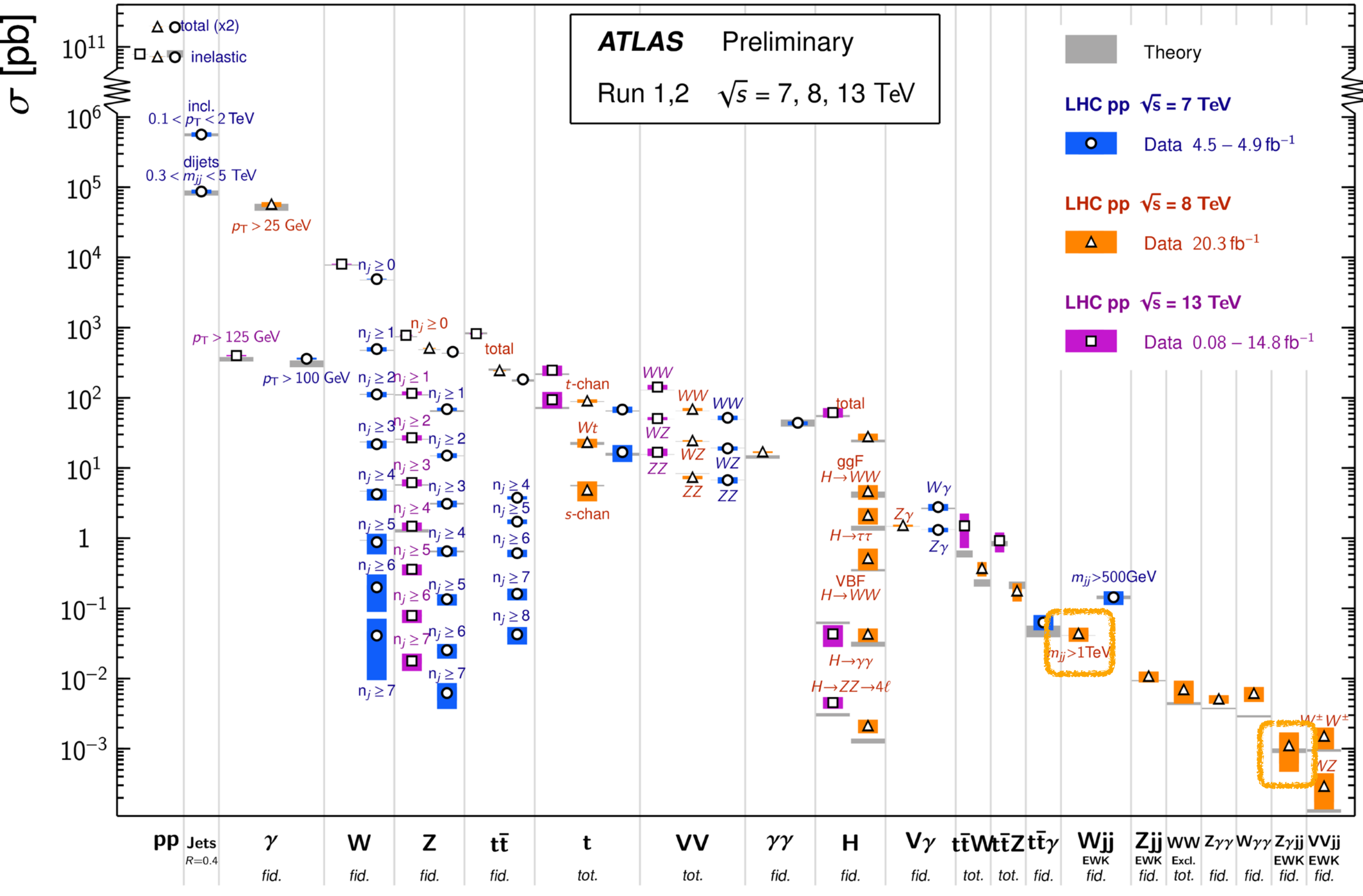


SM prediction for m_W vs m_t,
assuming m_H = 125.09 ± 0.24 GeV

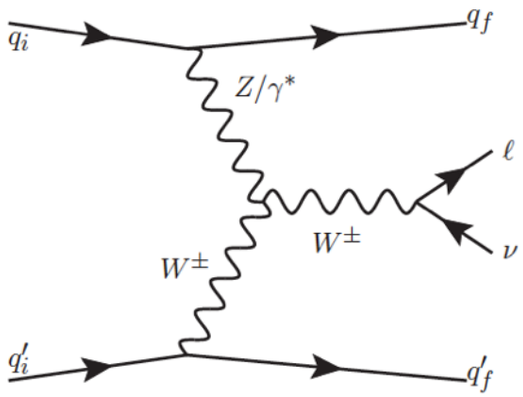
- Need more precise PDFs, improved predictions for Drell-Yann production to reduce uncertainties further
- Large Z&W samples from 8 & 13 TeV available!

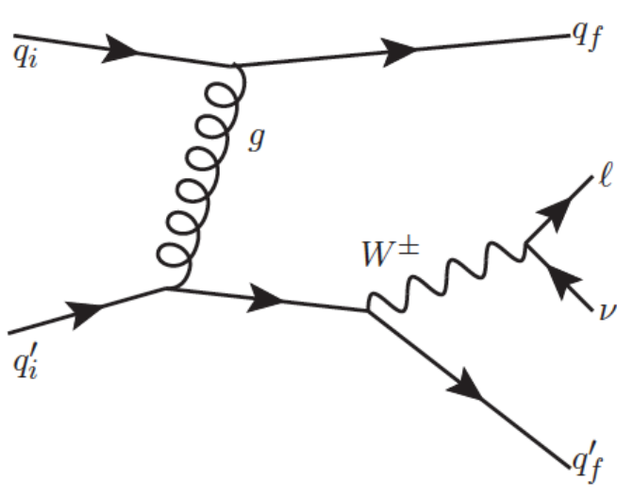
Standard Model Production Cross Section Measurements

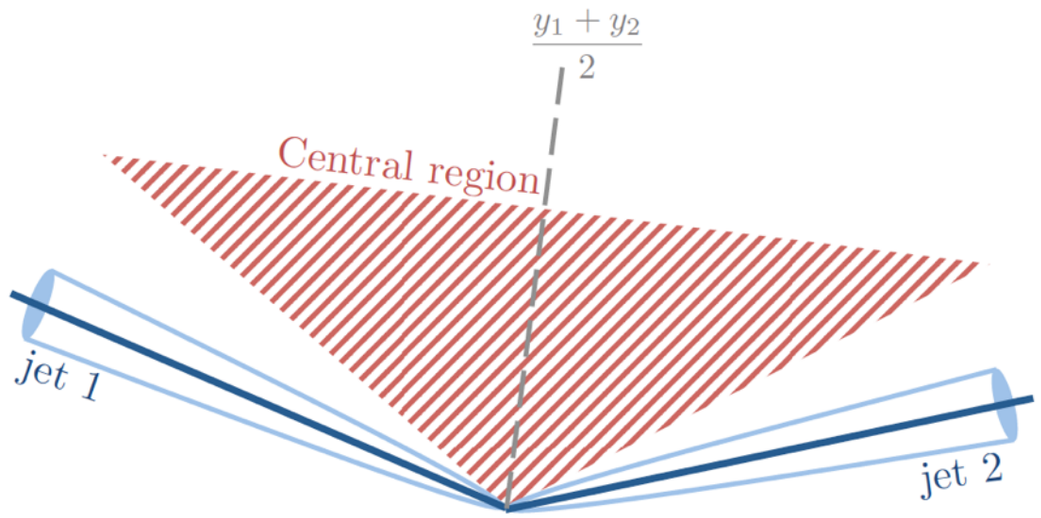
Status: March 2017



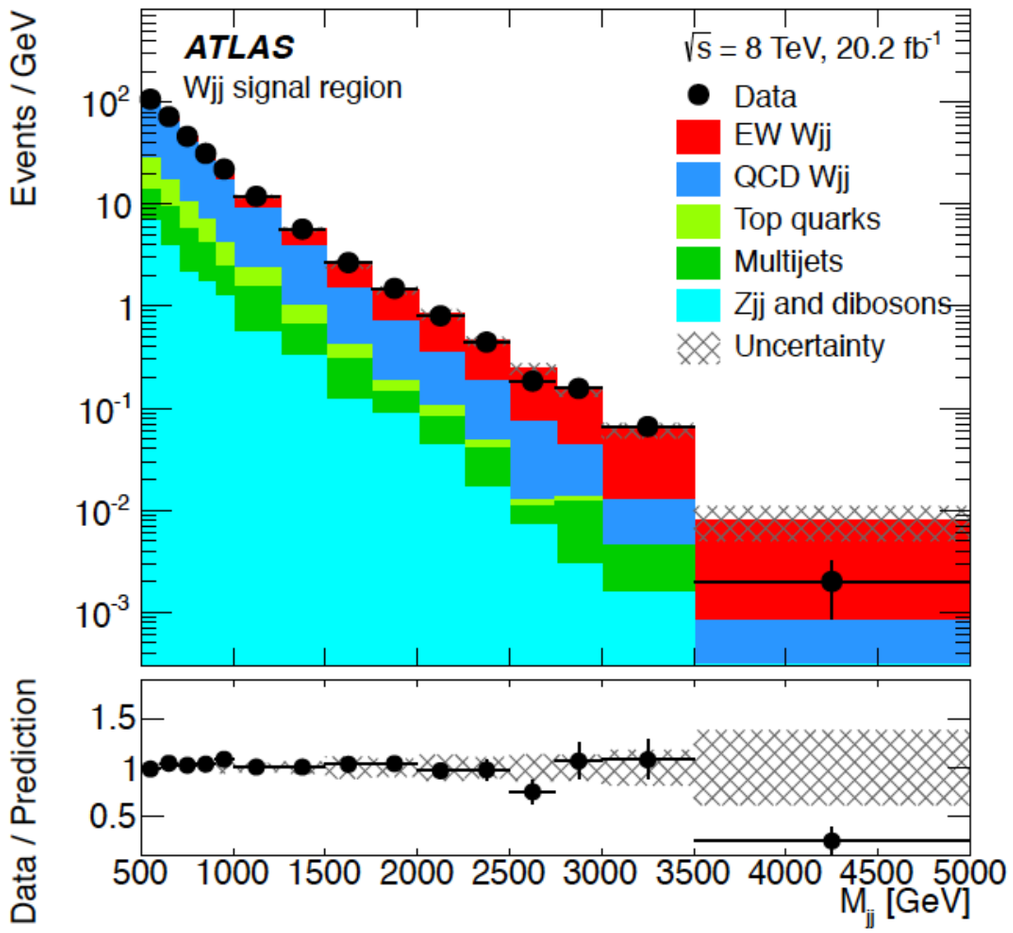
ELECTROWEAK W PRODUCTION



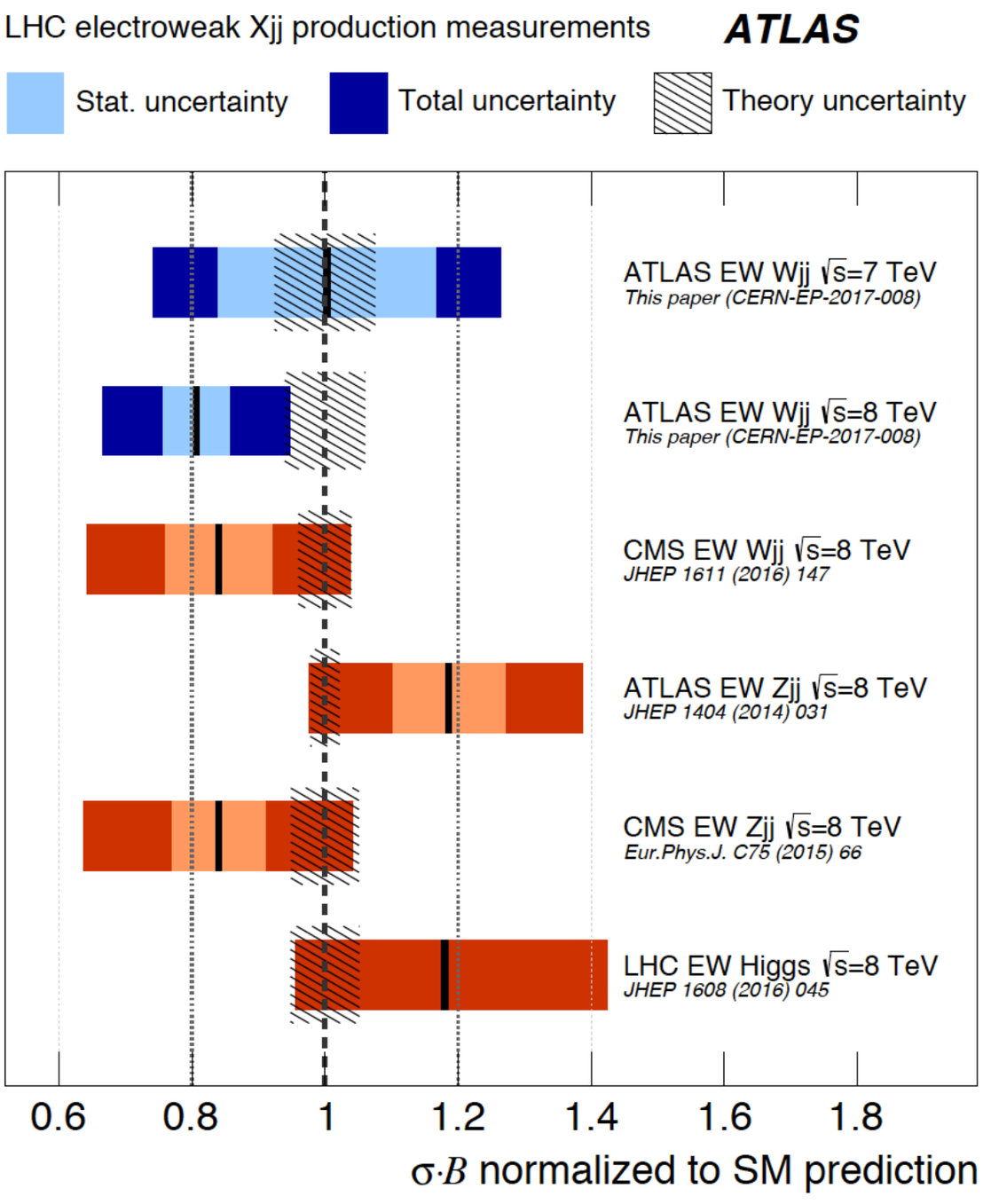


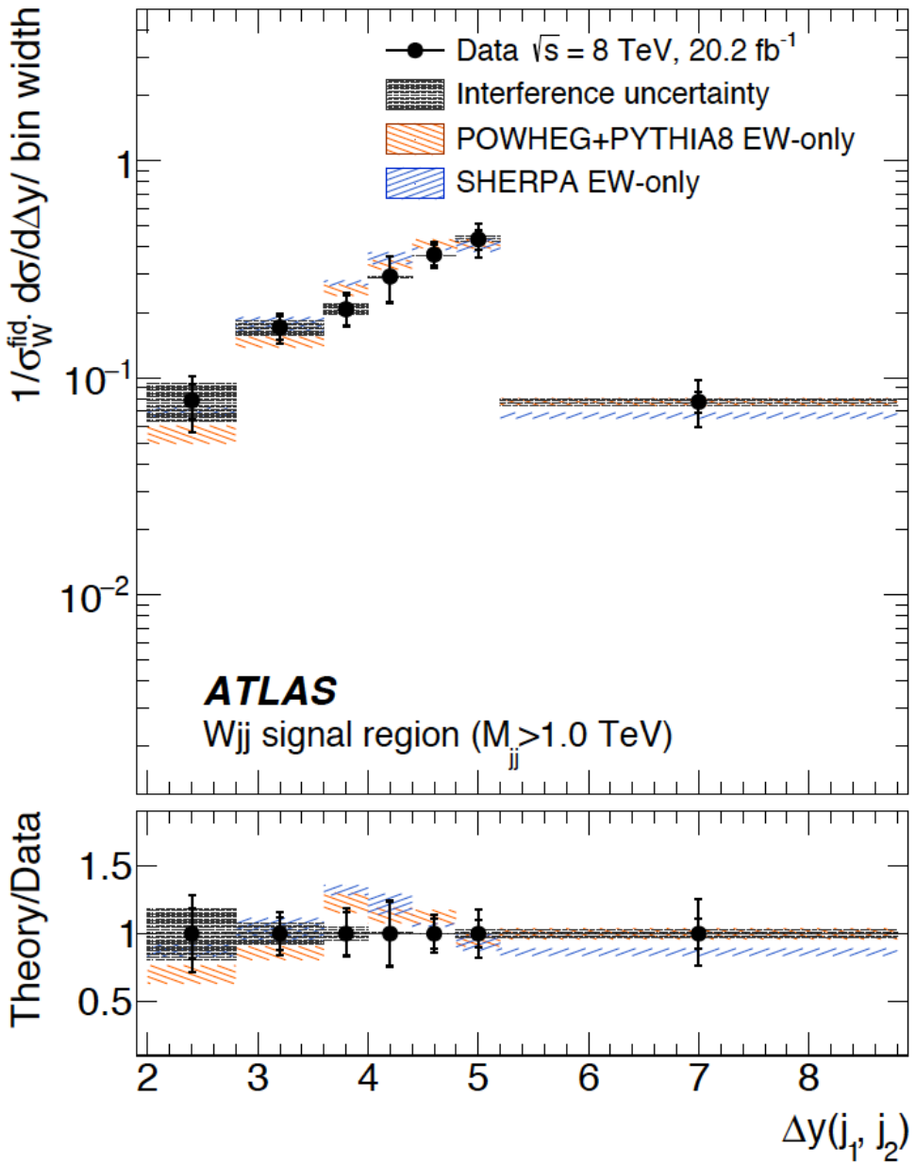


- Why?: Important probe of EWK physics but experimentally very difficult to access
  - Higgs couplings, new phenomena, triple gauge coupling (TGC)
- How?: Exploit rapidity gap structure of events in order to enhance signal, constrain modeling from data



INCLUSIVE & DIFFERENTIAL MEASUREMENTS





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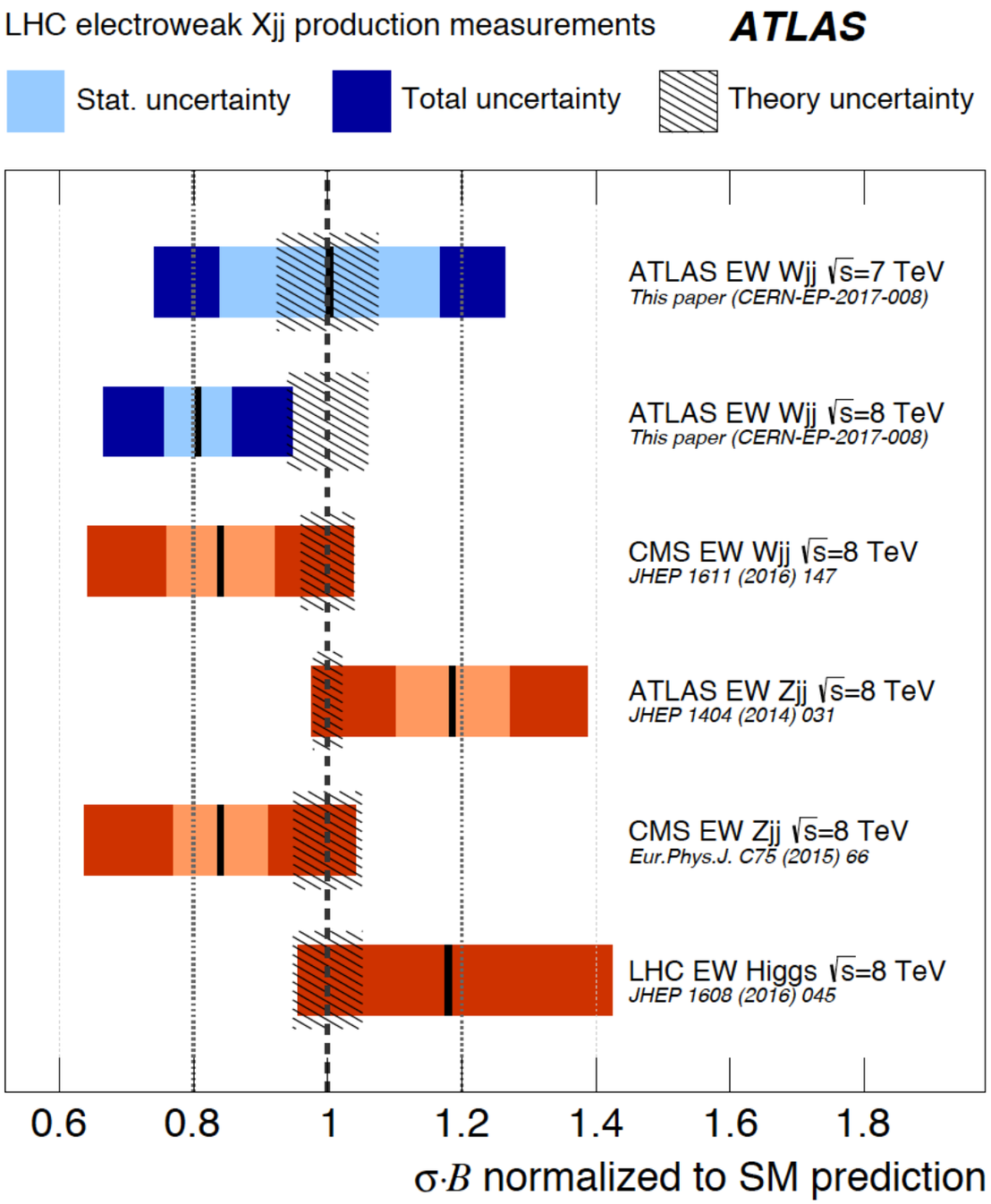
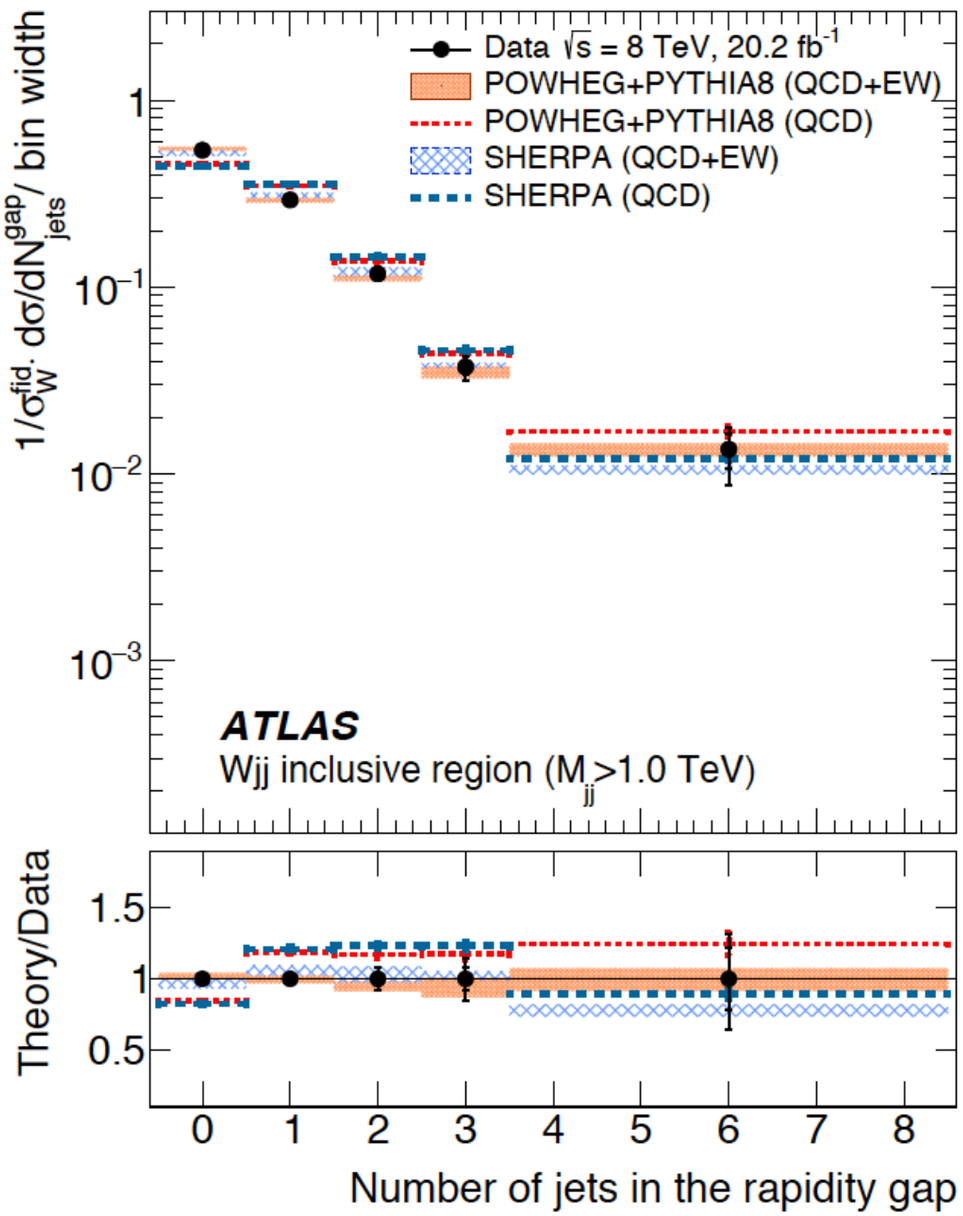
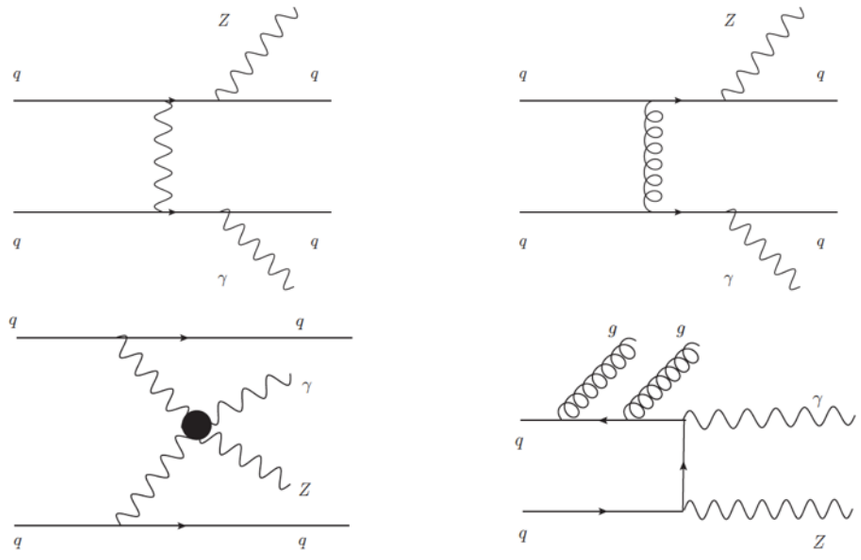




ELECTROWEAK Zγ PRODUCTION

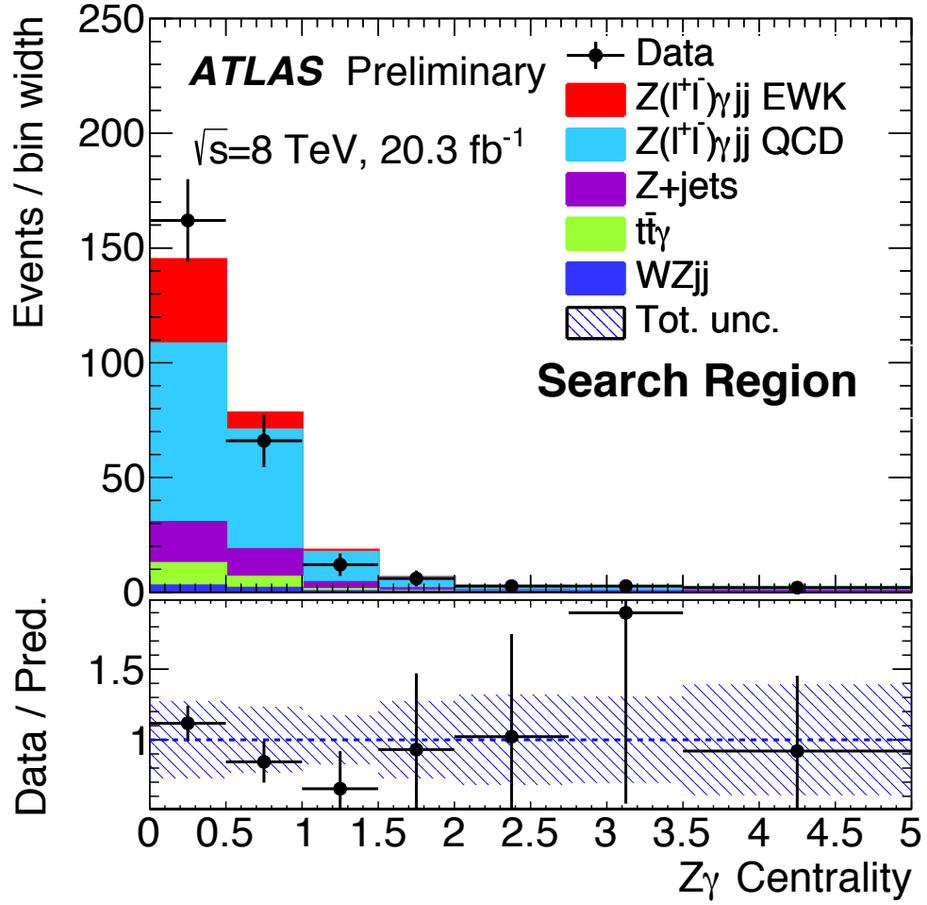
- Why: Zγ production is sensitive to EWK boson self-couplings: tests quartic gauge couplings through vector boson scattering



- What: 15 GeV γ, lepton pair (e,μ,ν-QGC only), two jets with large invariant mass & rapidity separation

- Dataset: 20 fb^{-1} @ 8 TeV

$$\zeta \equiv \left| \frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right|$$



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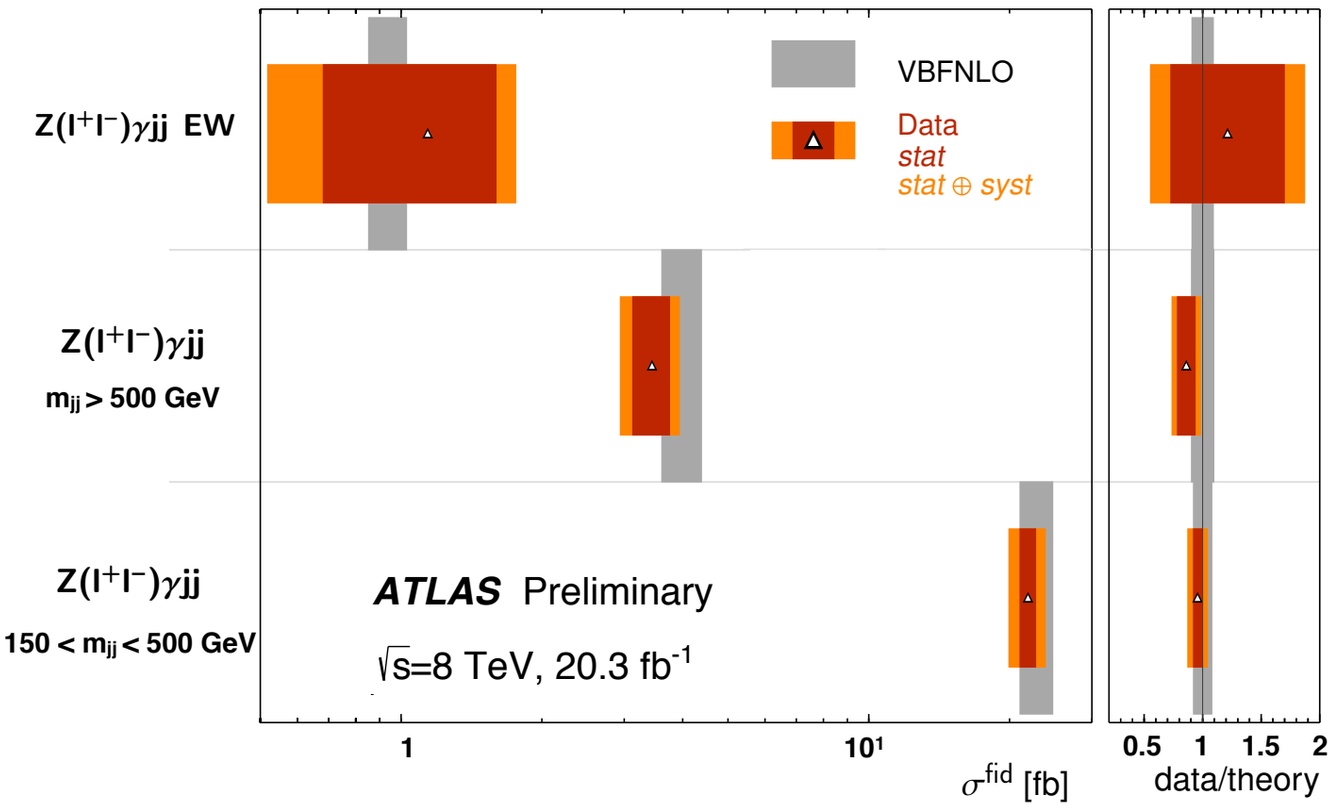


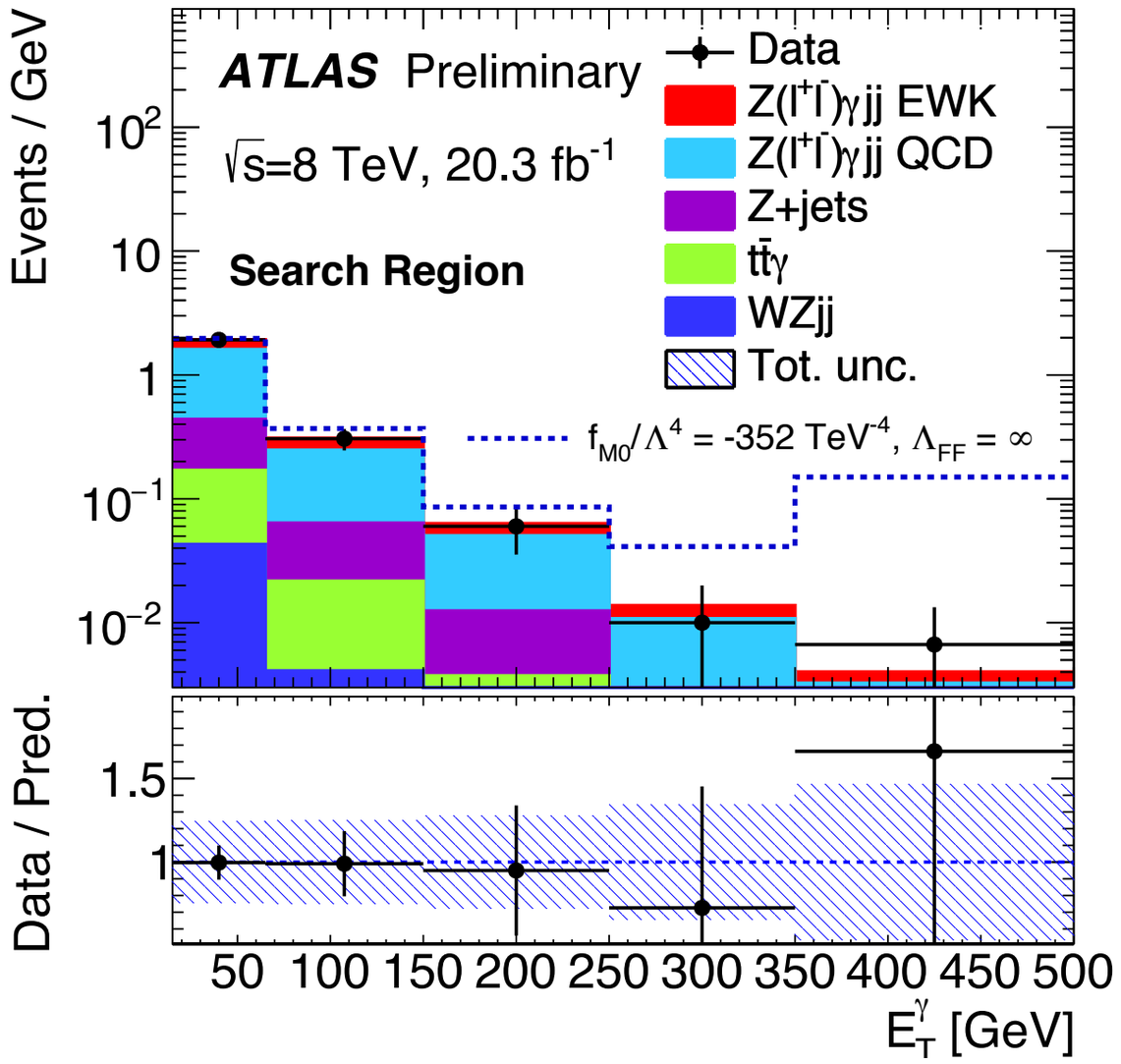
$$\sigma^{EWK}_{Z\gamma jj} = 1.1 \pm 0.5\,(\text{stat}) \pm 0.4\,(\text{syst})\ \text{fb} = 1.1 \pm 0.6\ \text{fb}.$$

ELECTROWEAK Zγ PRODUCTION

- Use high E_T^{γ} to search for aQGG
  - > 250 GeV (ll); 150 GeV (νν)
- Probe dim 8 operators of EFT Lagrangian:

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{f_j}{\Lambda^4} O_j$$

- Set limits on form factors (forthcoming publication)



CONCLUSIONS

- Rich set of QCD & EWK measurements ongoing with 7, 8 and 13 TeV data

  - Improvements in PDFs; constraints on SM parameters, comparisons to state-of-the-art calculations, first measurements of EWK processes!

- Based on precise understanding of detector, large and clean W&Z datasets and solid theory for comparison.

- Expect many more measurements to come!

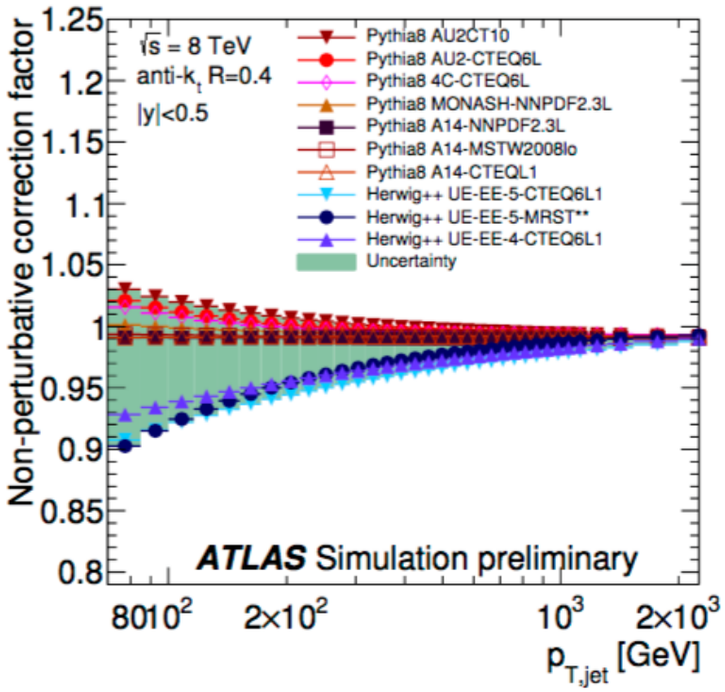
BACK-UP

Stanford University

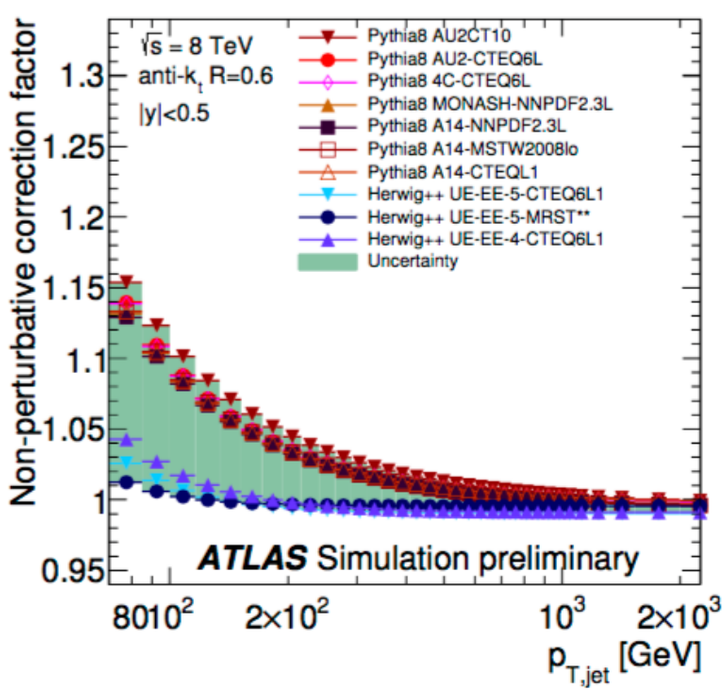
INCLUSIVE JET UNCERTAINTIES

- Detector related uncertainties are 5-45%
- Related primarily to jet energy scale (JES) and resolution (JER)
  - Determined from MC simulations and in-situ measurements of jets + Z/photons
- QCD uncertainties are comparable to detector uncertainties
- EWK corrections small except at high p_T, small y

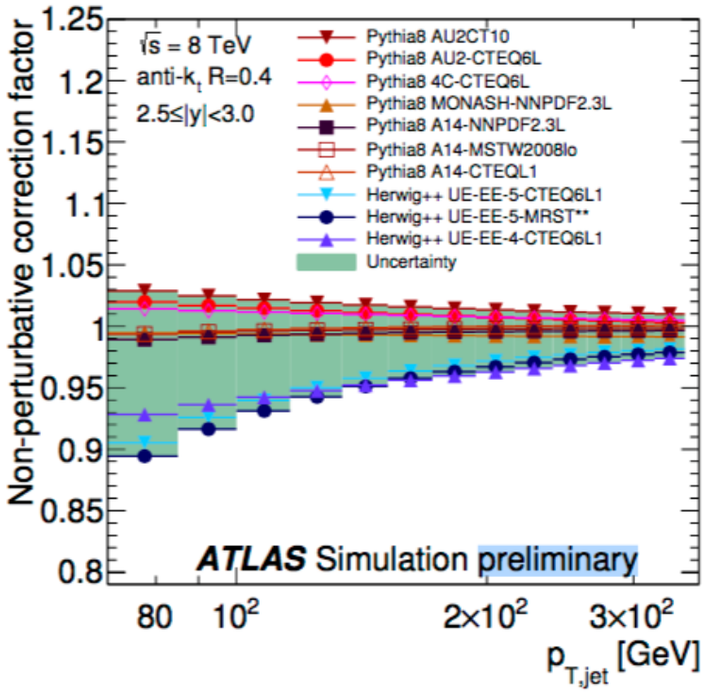
INCLUSIVE JET CORRECTIONS



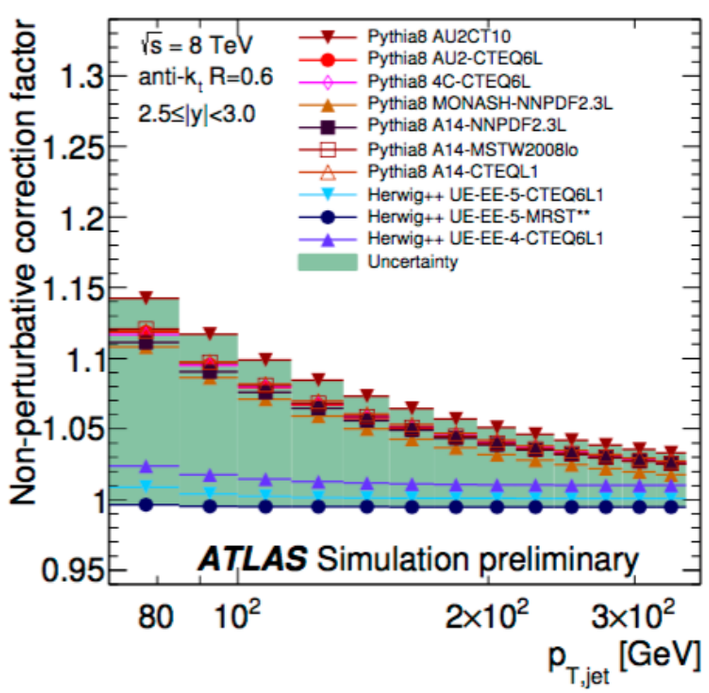
(a) $R = 0.4$, $|y| < 0.5$



(b) $R = 0.6$, $|y| < 0.5$

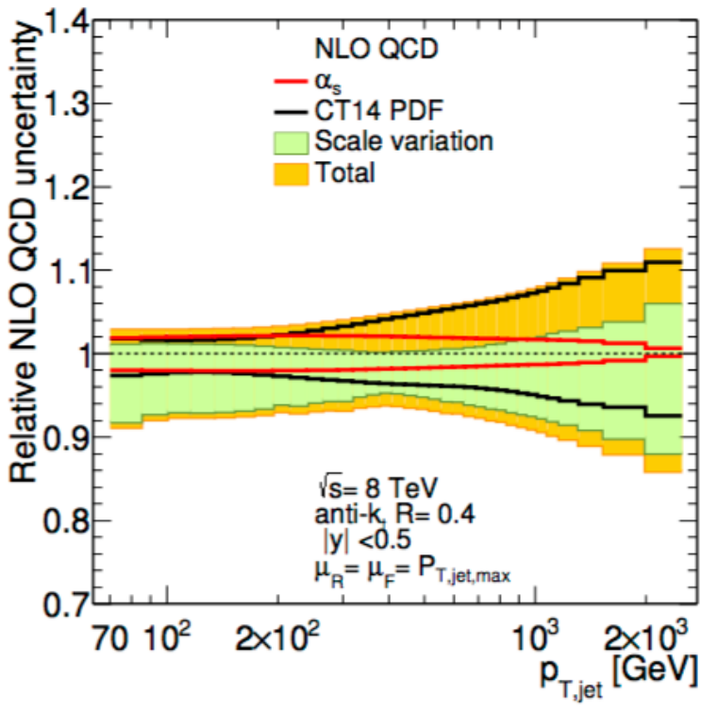


(c) $R = 0.4$, $2.5 \leq |y| < 3.0$



(d) $R = 0.6$, $2.5 \leq |y| < 3.0$

INCLUSIVE JET UNCERTAINTIES



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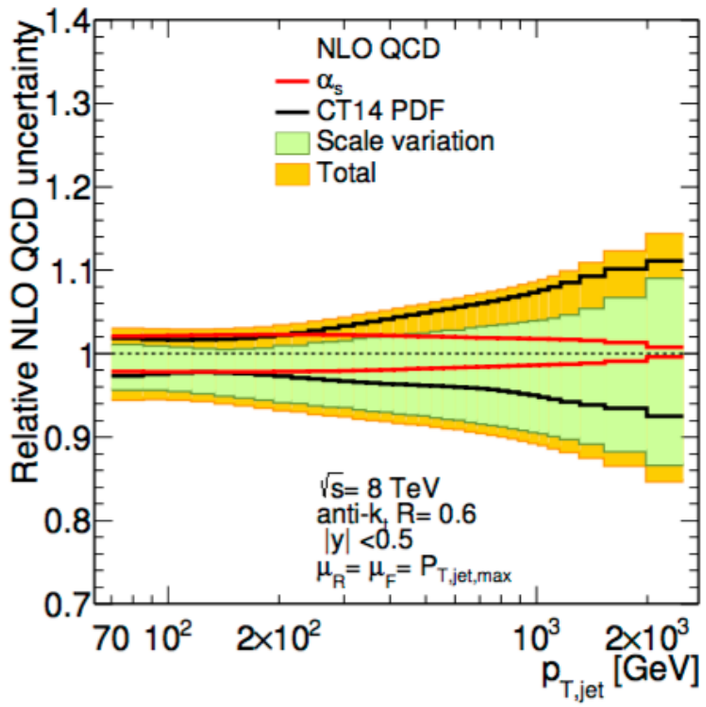

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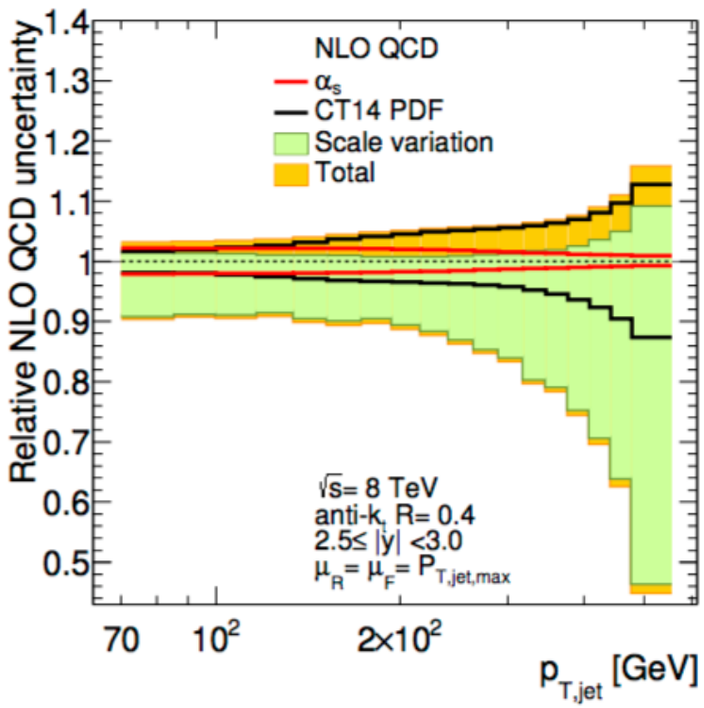
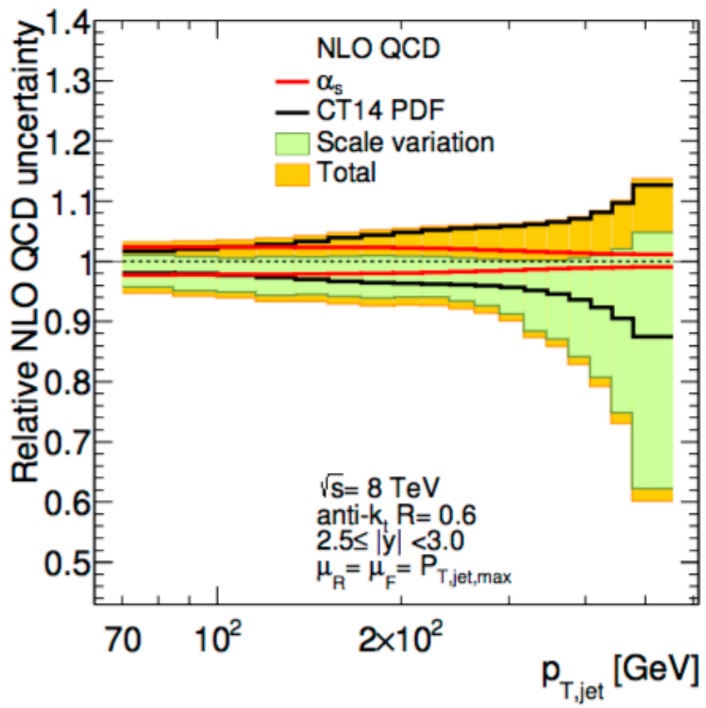
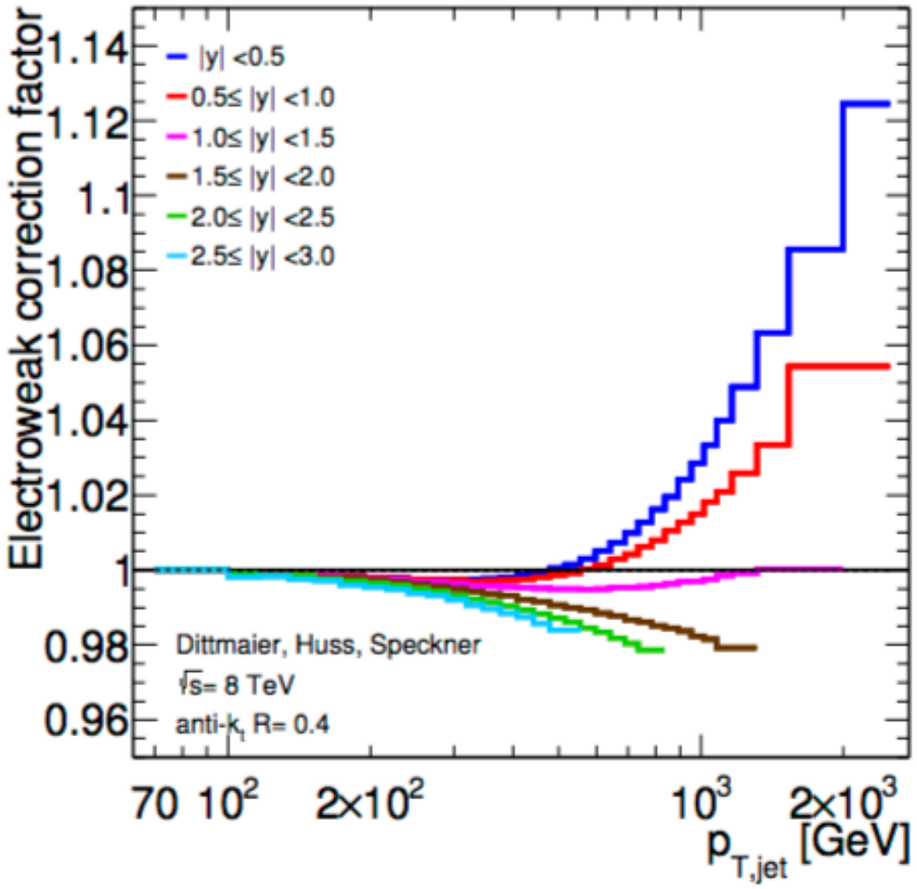


(c) $R = 0.4$, $2.5 \leq |y| < 3.0$

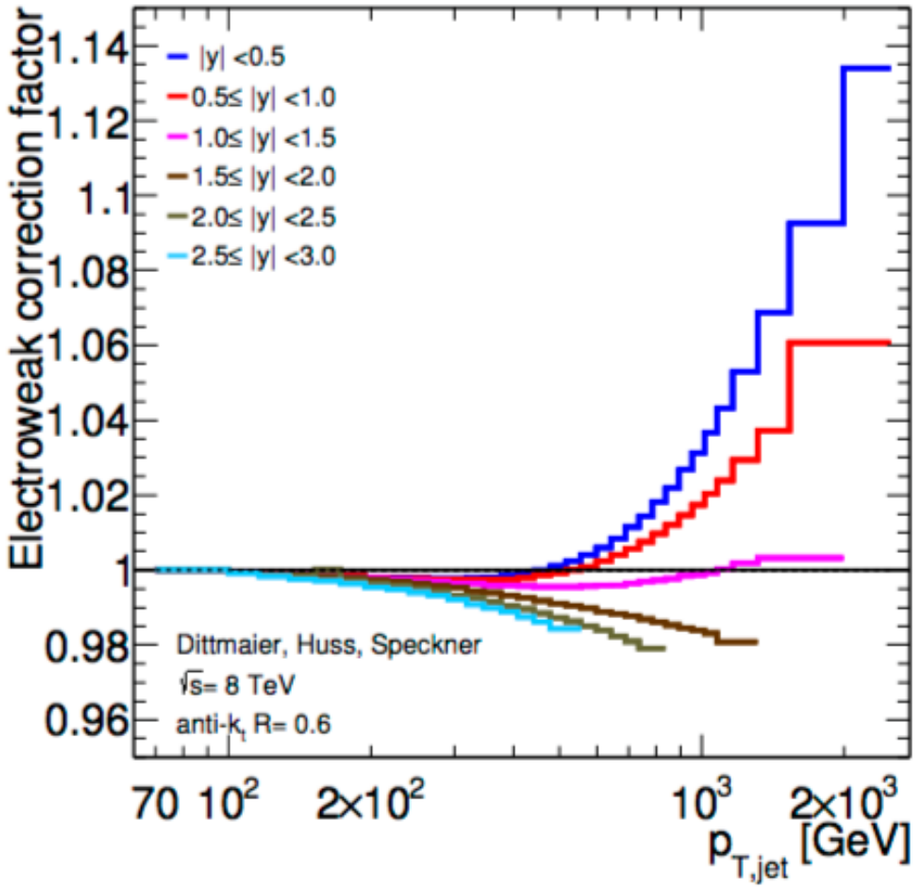


(d) $R = 0.6$, $2.5 \leq |y| < 3.0$

INCLUSIVE JET UNCERTAINTIES



(a) $R = 0.4$



(b) $R = 0.6$

INCLUSIVE PHOTON DETAILS

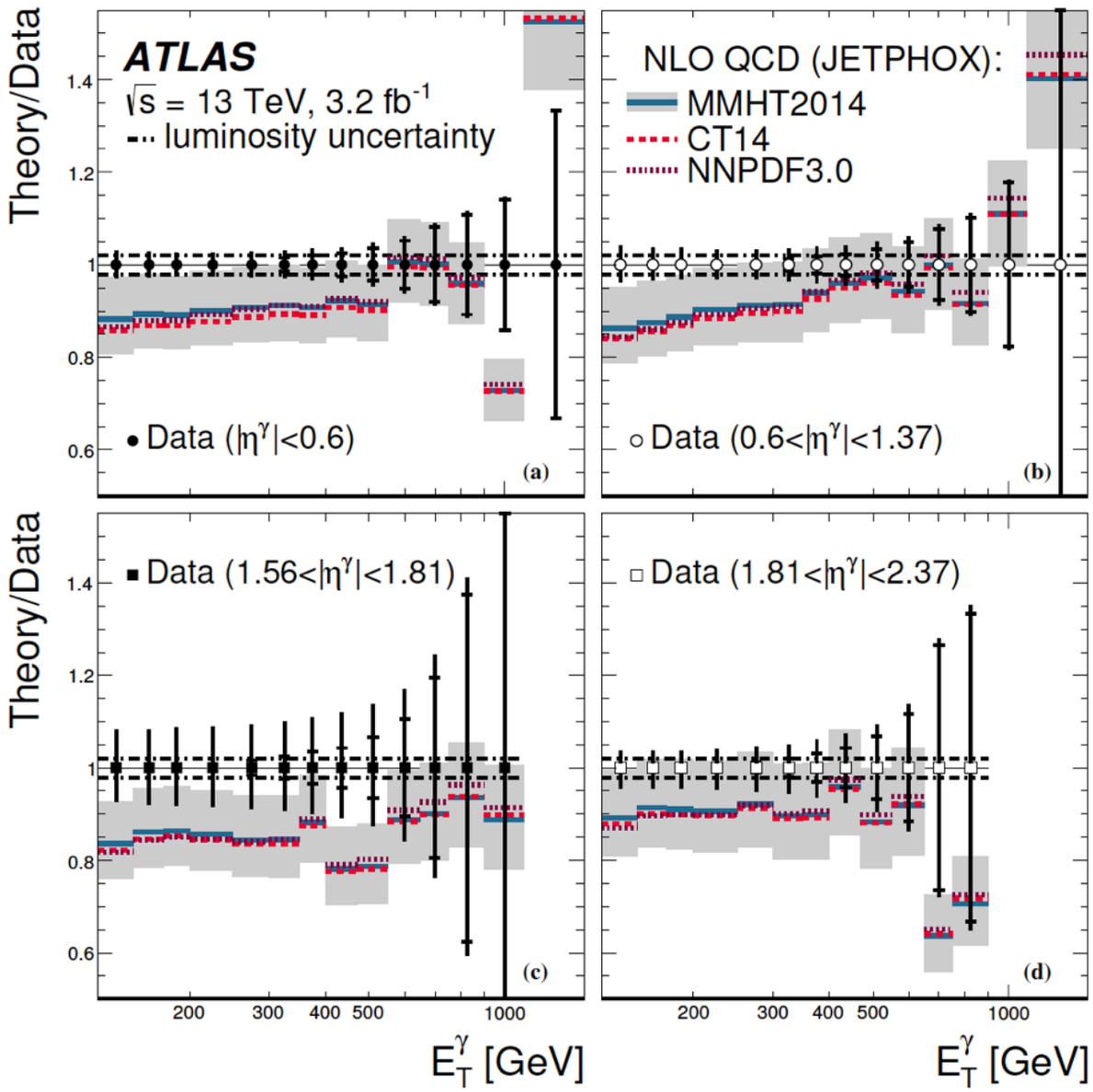
	Phase-space region			
Requirement on E_{T}^{γ}	$E_{\mathrm{T}}^{\gamma} > 125$ GeV			
Isolation requirement	$E_{\mathrm{T}}^{\mathrm{iso}} < 4.8 + 4.2 \cdot 10^{-3} \cdot E_{\mathrm{T}}^{\gamma}$ [GeV]			
Requirement on $\lvert\eta^{\gamma}\rvert$	$\lvert\eta^{\gamma}\rvert < 0.6$	$0.6 < \lvert\eta^{\gamma}\rvert < 1.37$	$1.56 < \lvert\eta^{\gamma}\rvert < 1.81$	$1.81 < \lvert\eta^{\gamma}\rvert < 2.37$
Number of events	356 604	480 466	140 955	275 483

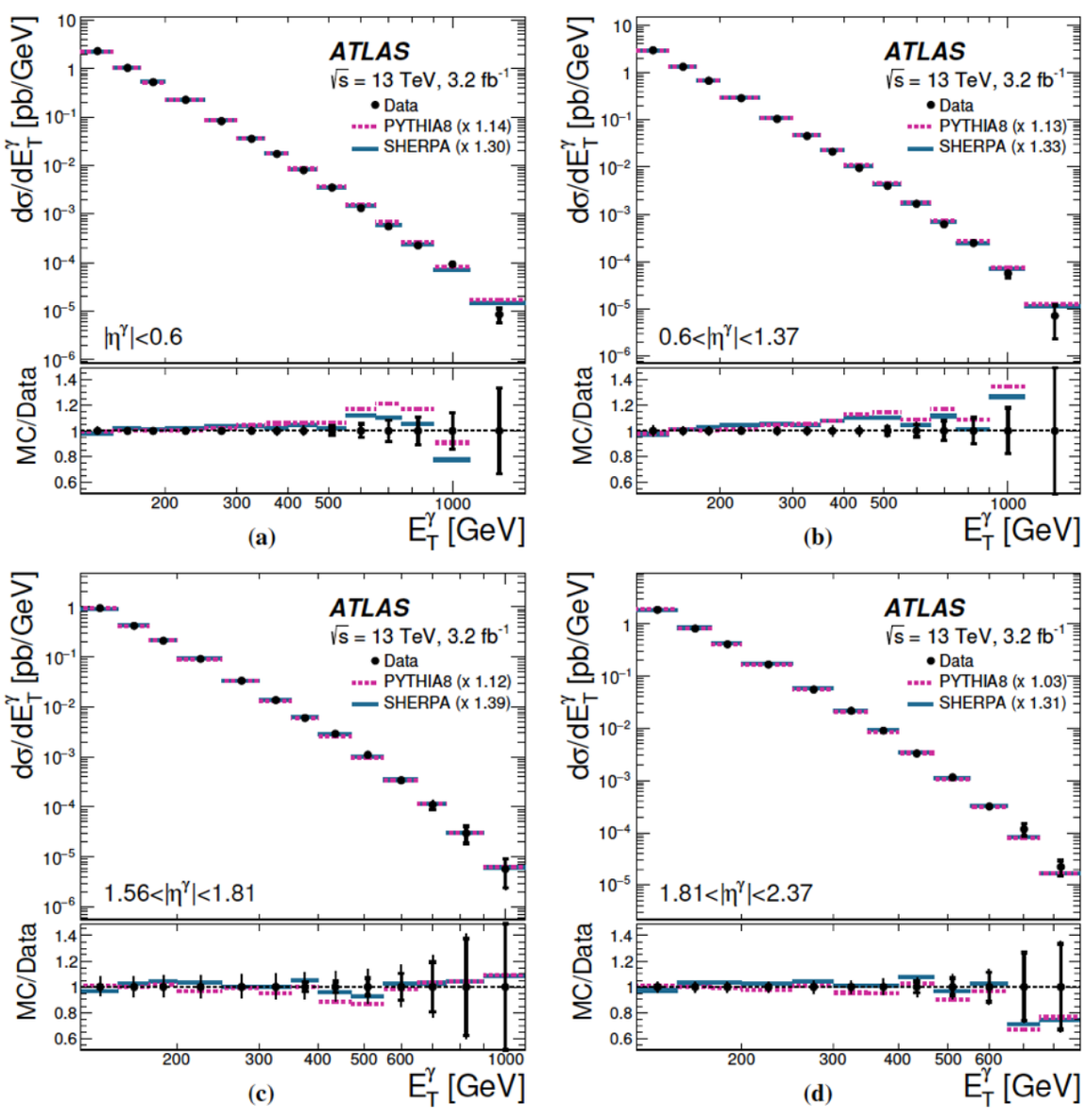
- The calculations are performed using the MMHT2014 parameterisations of the proton PDFs and the BFG set II of parton-to-photon fragmentation functions at NLO.

- Parton level isolation in cone of 0.4 around photon applied to prediction

Uncertainties [pb]					
γ ID	$(-5.2, +5.4)$	γ ES+ER	$(-7.9, +8.4)$	$E_{\mathrm{T}}^{\mathrm{iso}}$ Gap	± 0.3
$E_{\mathrm{T}}^{\mathrm{iso}}$ upp. lim.	$+0.6$	γ invert. var.	$(-4.1, +3.5)$	R^{bg}	$(-6.2, +6.1)$
Leak. SHERPA	± 4.1	Unf. SHERPA	± 2.9	$E_{\mathrm{T}}^{\mathrm{iso}}$ MC	-2.8
Hard and brem	$(-1.0, +1.9)$	Pile-up	$(-1.1, +1.3)$	MC stat.	± 0.4
Trigger	± 1.1	Data stat.	± 0.4	Luminosity	± 8.4

INCLUSIVE PHOTONS





DIPHOTON MODELS

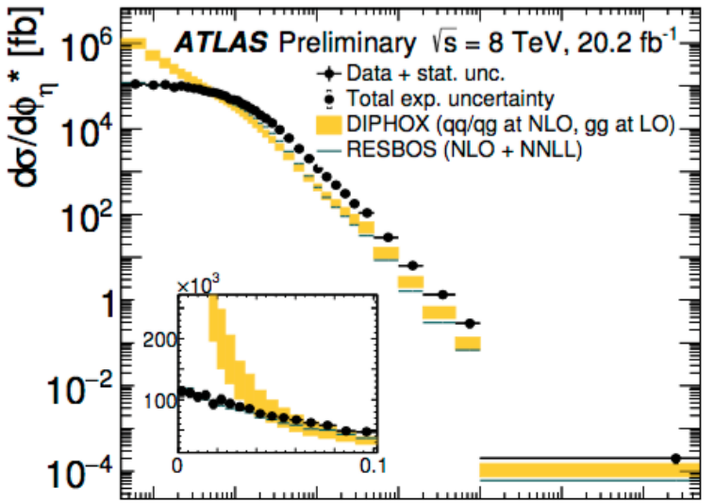
- DIPHOX: NLO with direct & fragmentation production as well as quark loop contributions

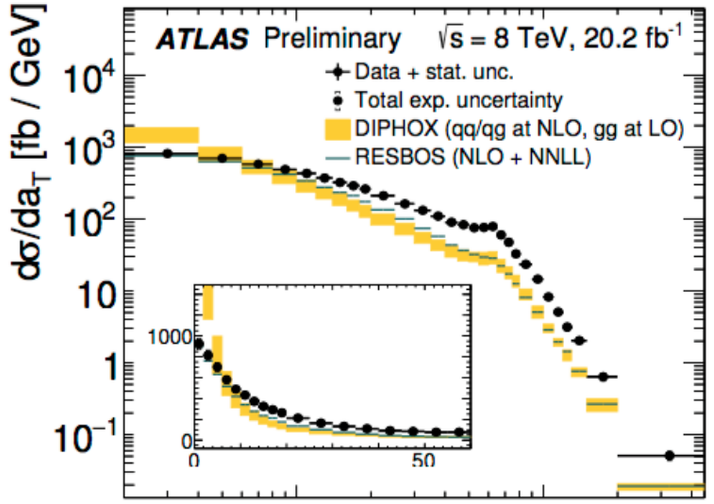
- Resbos: NLO where fragmentation contributions based on a combination of a sharp cutoff on the transverse isolation energy of the final-state quark or gluon and a smooth cone isolation while the first corrections to the gg-initiated process and resummation of initial-state gluon radiation to NNLL accuracy are included.

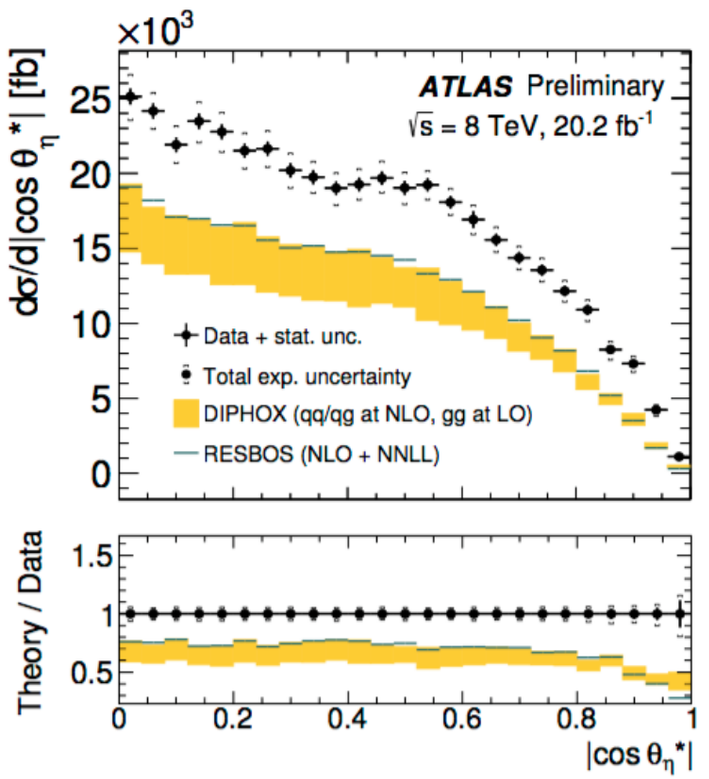
- 2γNNLO: direct diphoton production at parton level w/NNLO pQCD, but no fragmentation

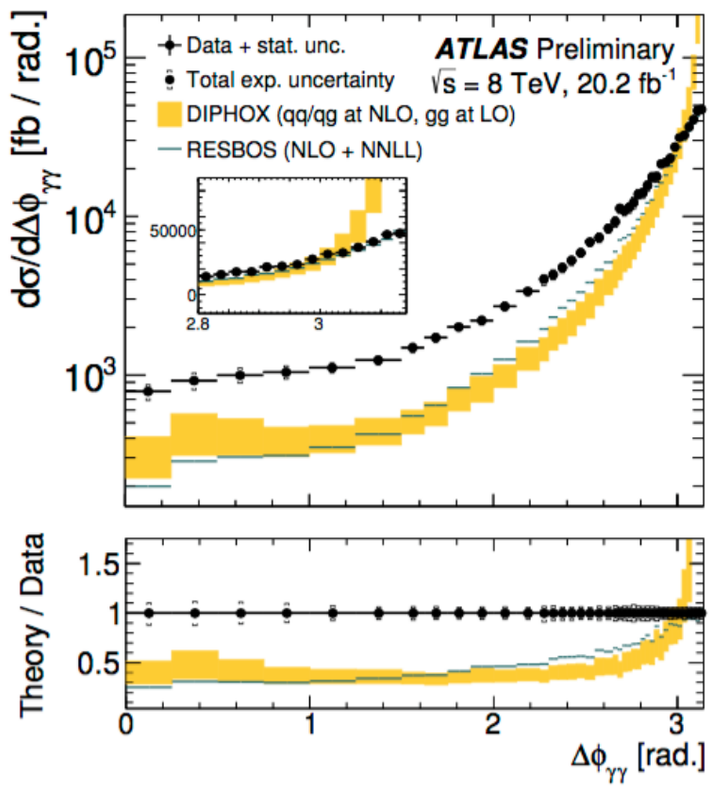
- Uncertainties from renormalization & factorization scales, set to $m_{\gamma\gamma}$

DIPHOTON DISTRIBUTIONS

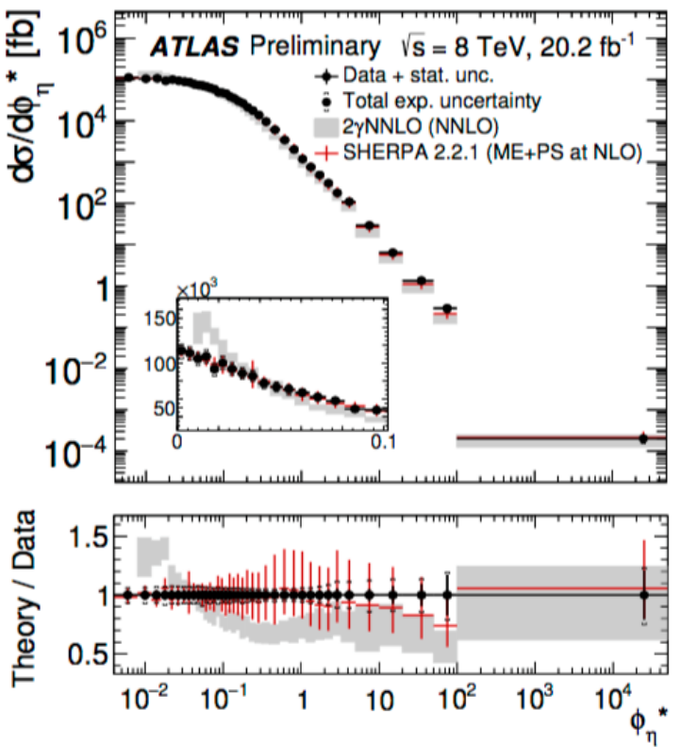


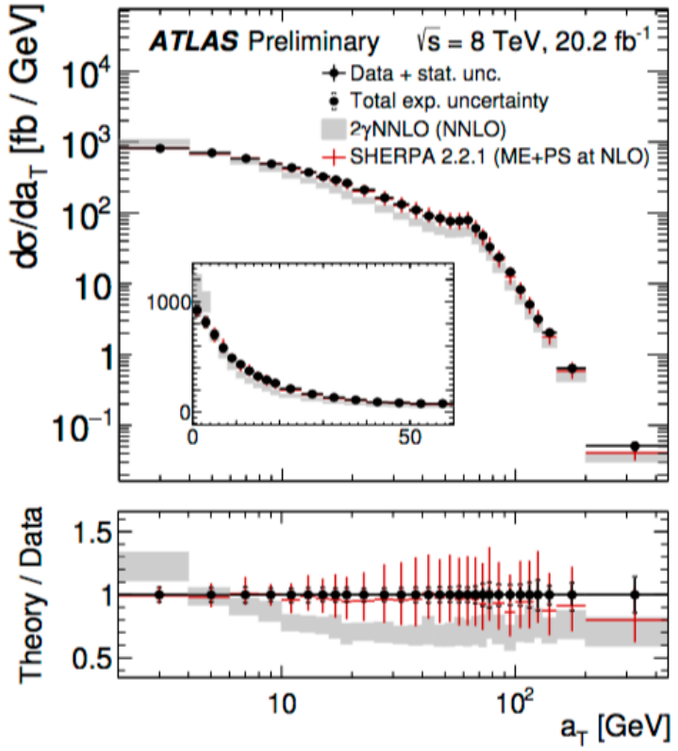


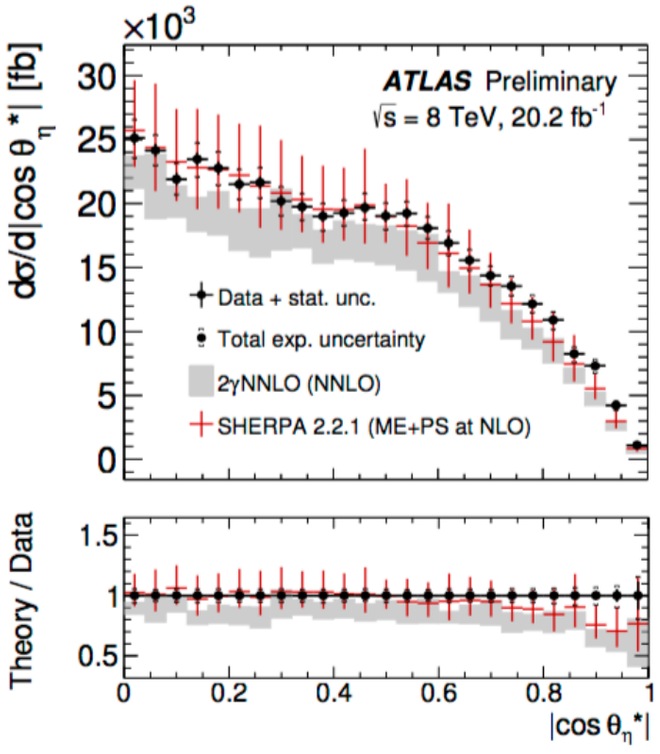


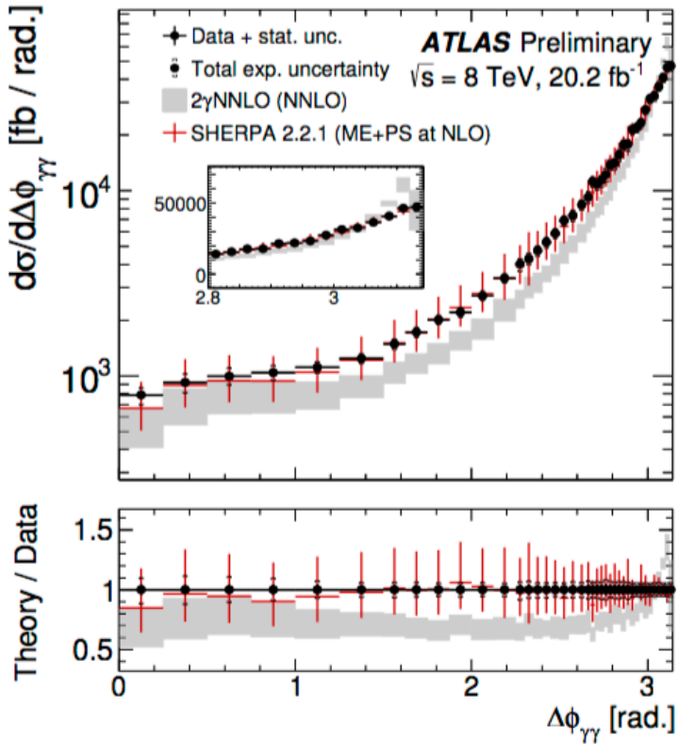


DIPHOTON DISTRIBUTIONS

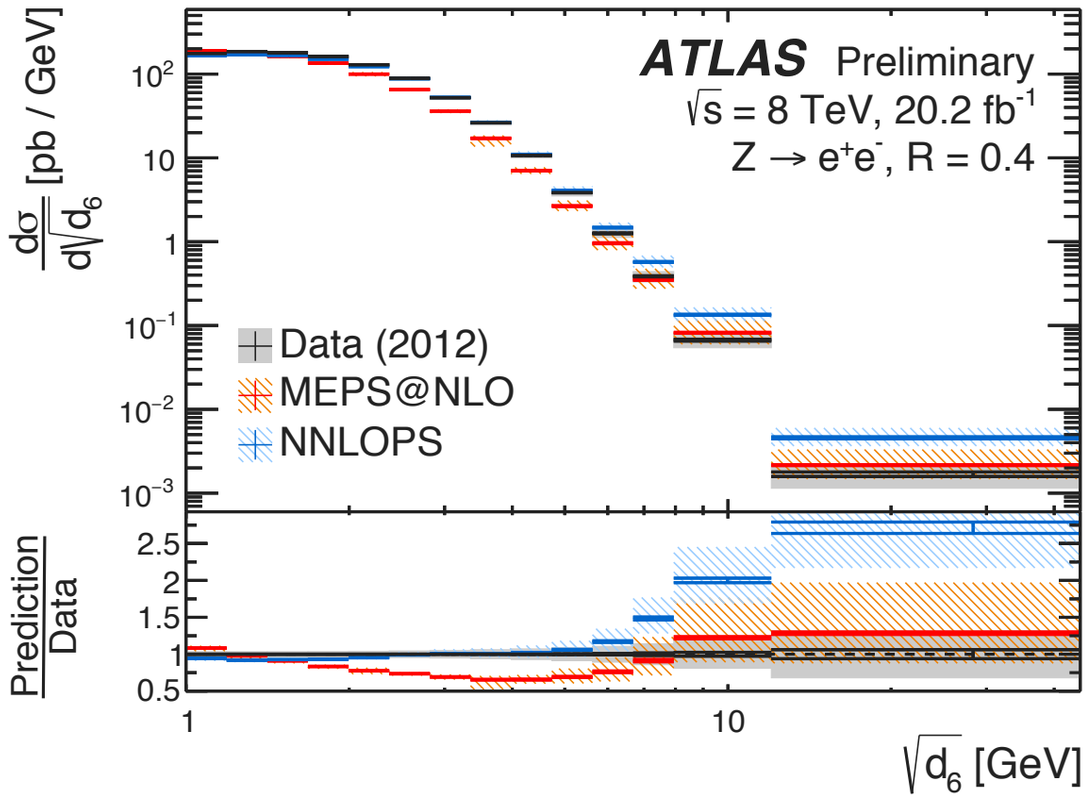


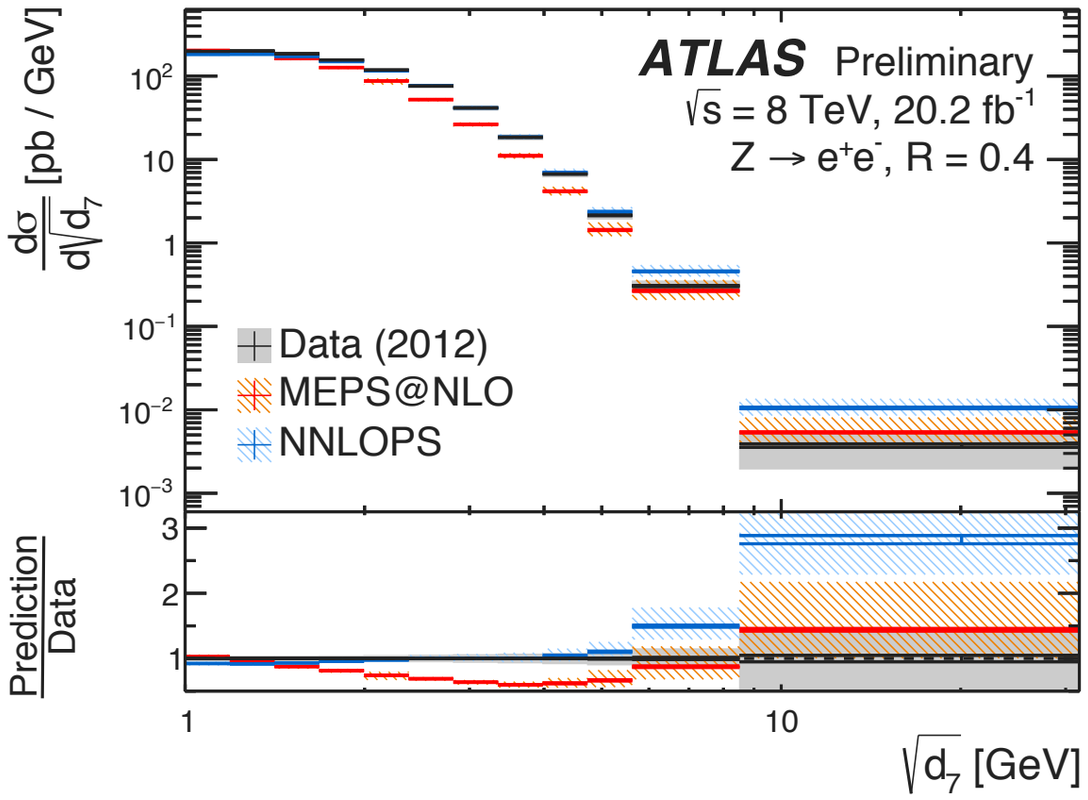


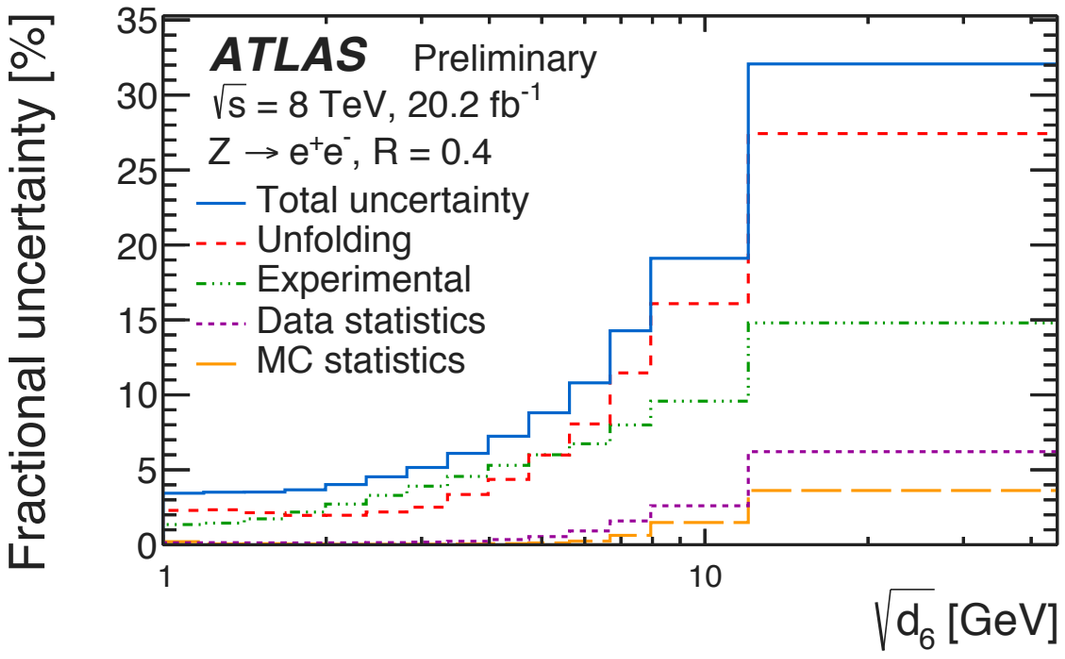


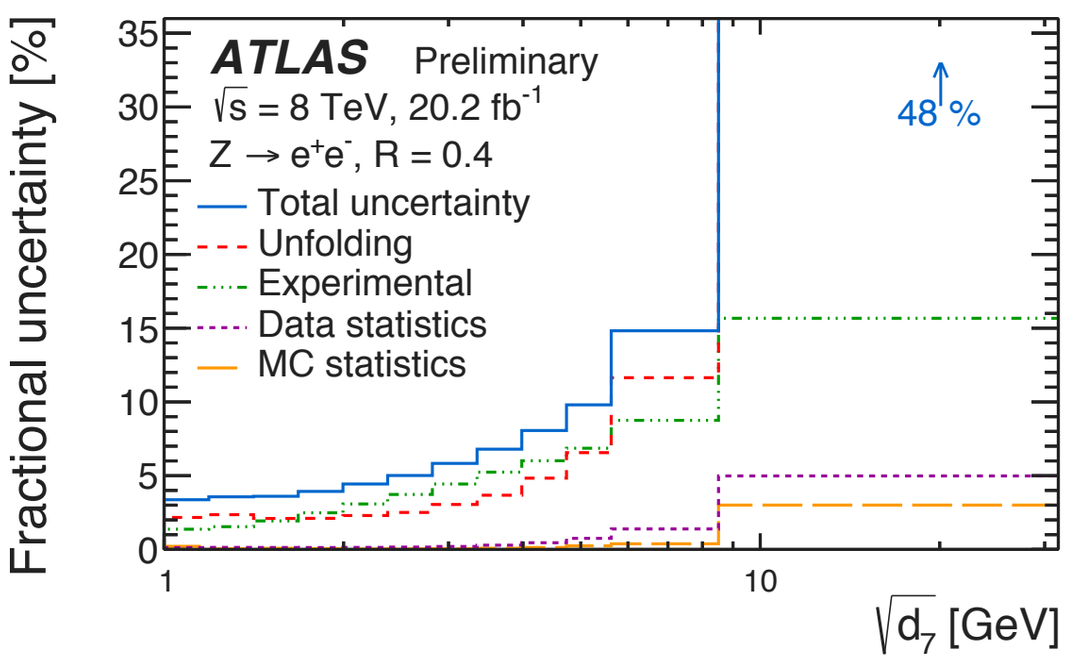


KT SPLITTING HIGHER STEPS









W & Z CROSS-SECTION UNCERTAINTIES

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]
Trigger efficiency	0.08	0.07	0.05
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_{T} resolution	0.01	0.01	<0.01
Muon p_{T} scale	0.18	0.17	0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.19	0.19	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.10	0.09	–
Jet energy scale	0.09	0.12	–
Jet energy resolution	0.11	0.16	–
Signal modelling (matrix-element generator)	0.12	0.06	0.04
Signal modelling (parton shower and hadronization)	0.14	0.17	0.22
PDF	0.09	0.12	0.07
Boson p_{T}	0.18	0.14	0.04
Multijet background	0.33	0.27	0.07
Electroweak+top background	0.19	0.24	0.02
Background statistical uncertainty	0.03	0.04	0.01
Unfolding statistical uncertainty	0.03	0.03	0.02
Data statistical uncertainty	0.04	0.04	0.08
Total experimental uncertainty	0.61	0.59	0.43
Luminosity		1.8	

PROFILING DETAILS

- Impact of new data on PDF estimate by profiling with:

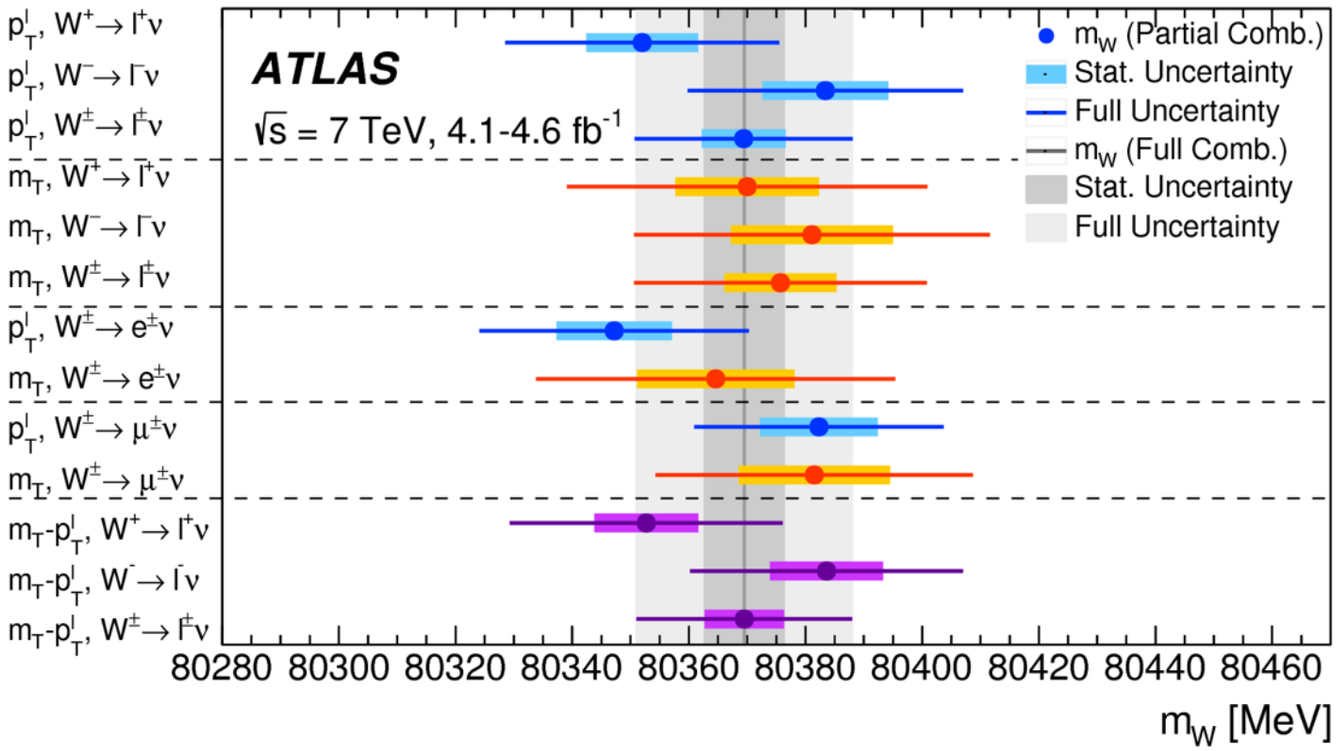
$$\chi^2(\vec{b}_{\rm exp}, \vec{b}_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left[\sigma_i^{\rm exp} - \sigma_i^{\rm th}(1 - \sum_j \gamma_{ij}^{\rm exp} b_{j,\rm exp} - \sum_k \gamma_{ik}^{\rm th} b_{k,\rm th})\right]^2}{\Delta_i^2}$$

$$+ \sum_{j=1}^{N_{\rm exp.sys}} b_{j,\rm exp}^2 + \sum_{k=1}^{N_{\rm th.sys}} b_{k,\rm th}^2 \,.$$

$$\Delta_i^2 = \delta_{i,\rm sta}^2 \sigma_i^{\rm exp} \sigma_i^{\rm th} + \left(\delta_{i,\rm unc} \sigma_i^{\rm th}\right)^2$$

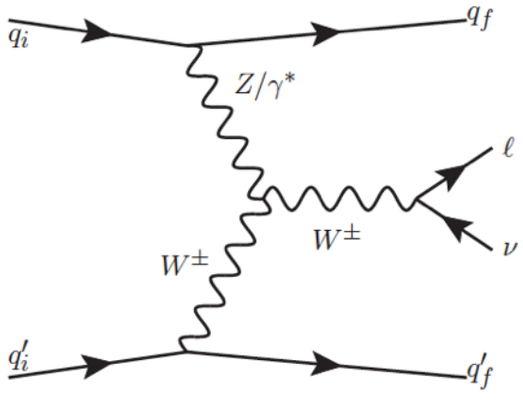
W MASS: RESULTS

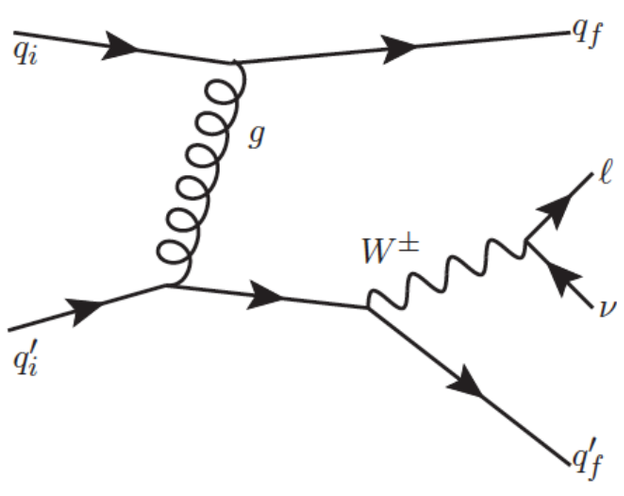
$$
\begin{aligned}
m_W &= 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV} \\
&= 80370 \pm 19\ \text{MeV},
\end{aligned}
$$

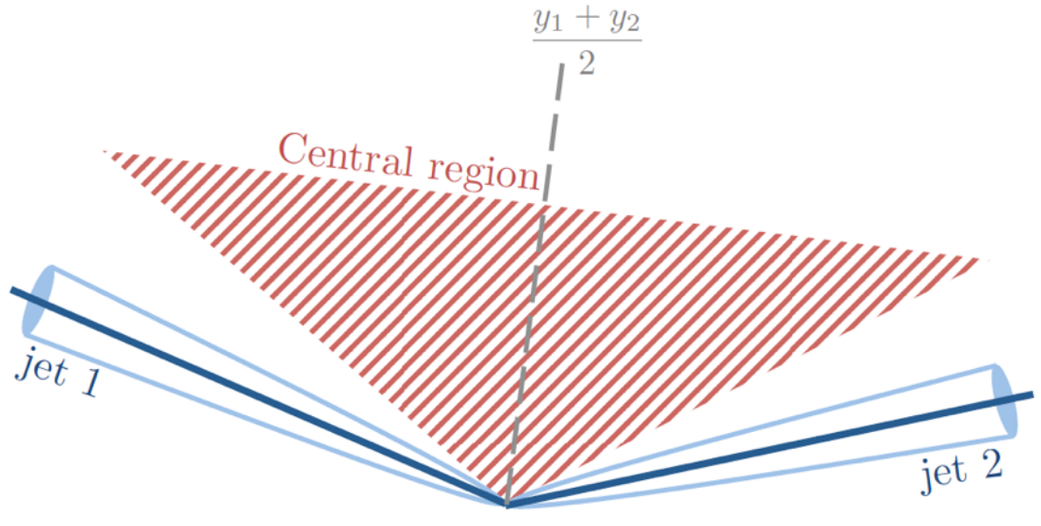


Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_{T}-$p_{\mathrm{T}}^{\bar{\ell}}$, $W^{\pm}$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
m_{T}-p_{T}^{ℓ}, $W^{\pm}$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_{T}-p_{T}^{ℓ}, $W^{\pm}$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

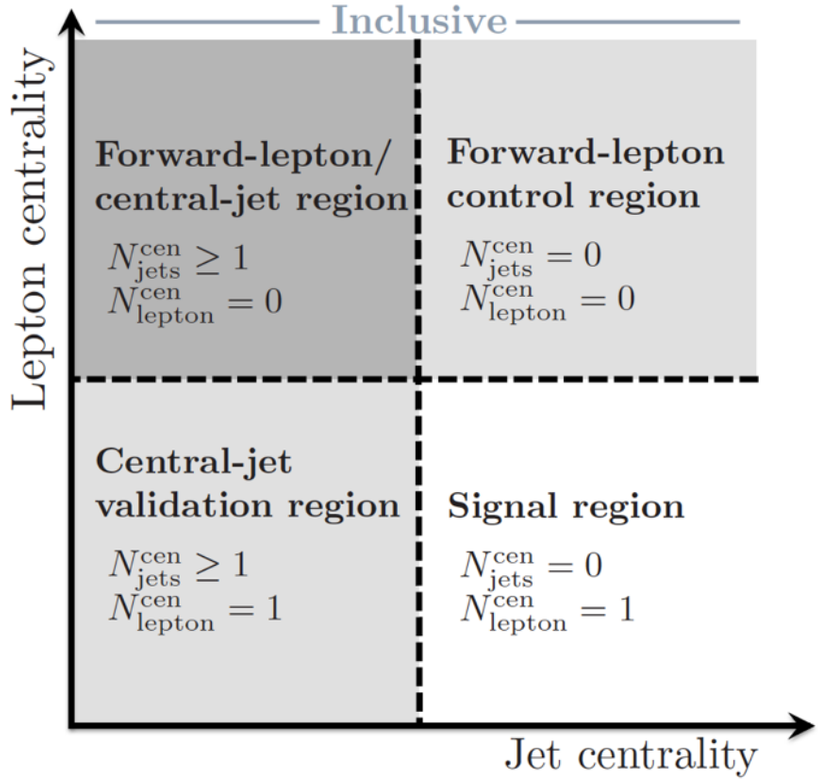
EWK W PRODUCTION



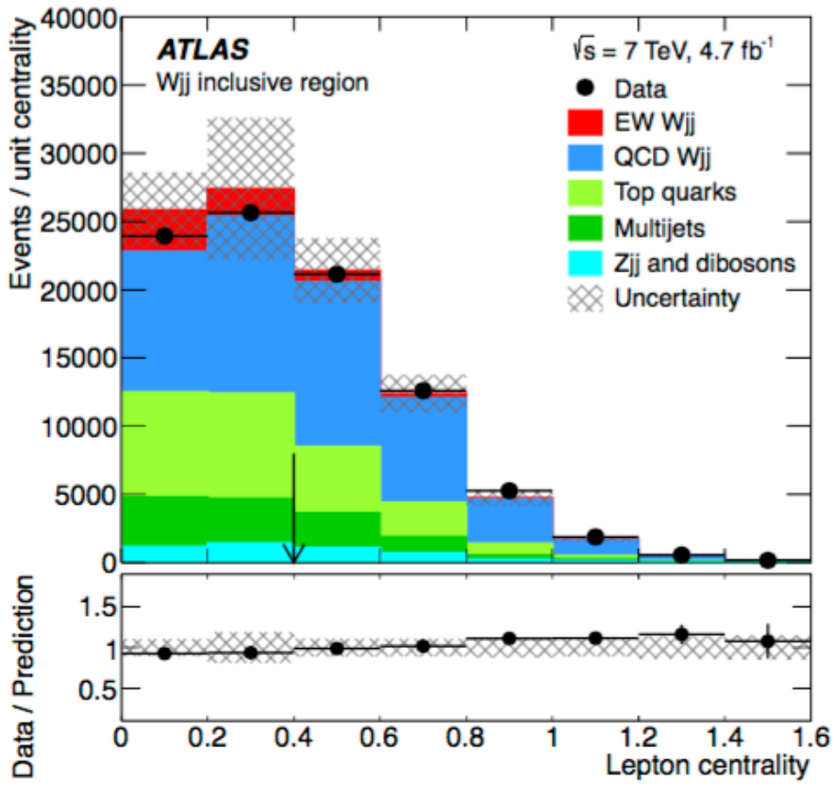


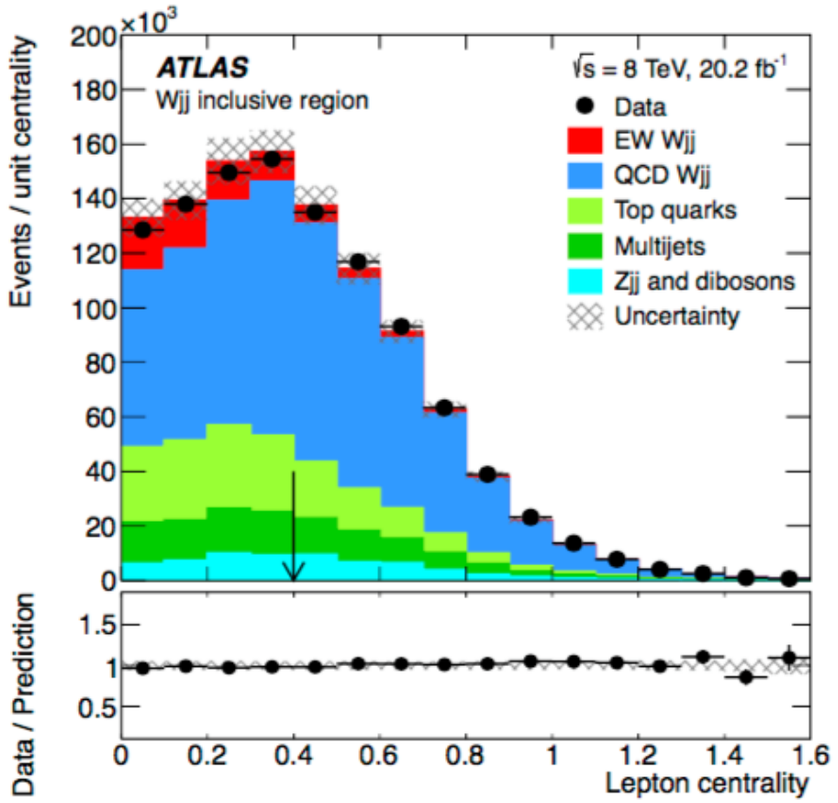


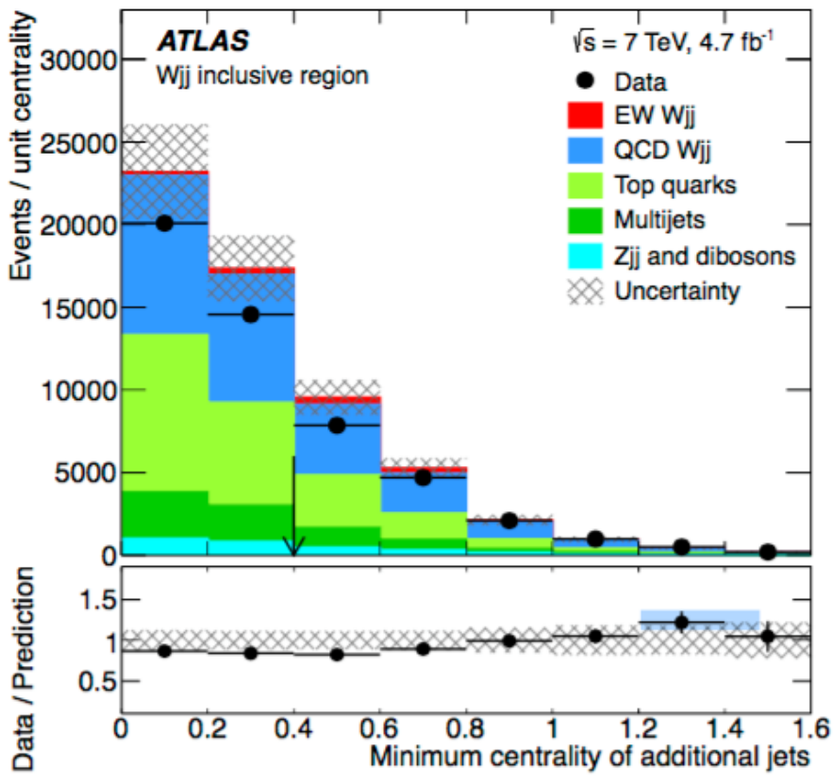
- Vector boson fusion production important probe of EWK physics but experimentally very difficult to access
  - Higgs couplings, new phenomena, TGC
- Exploit rapidity gap structure of events in order to enhance signal, constrain modeling from data

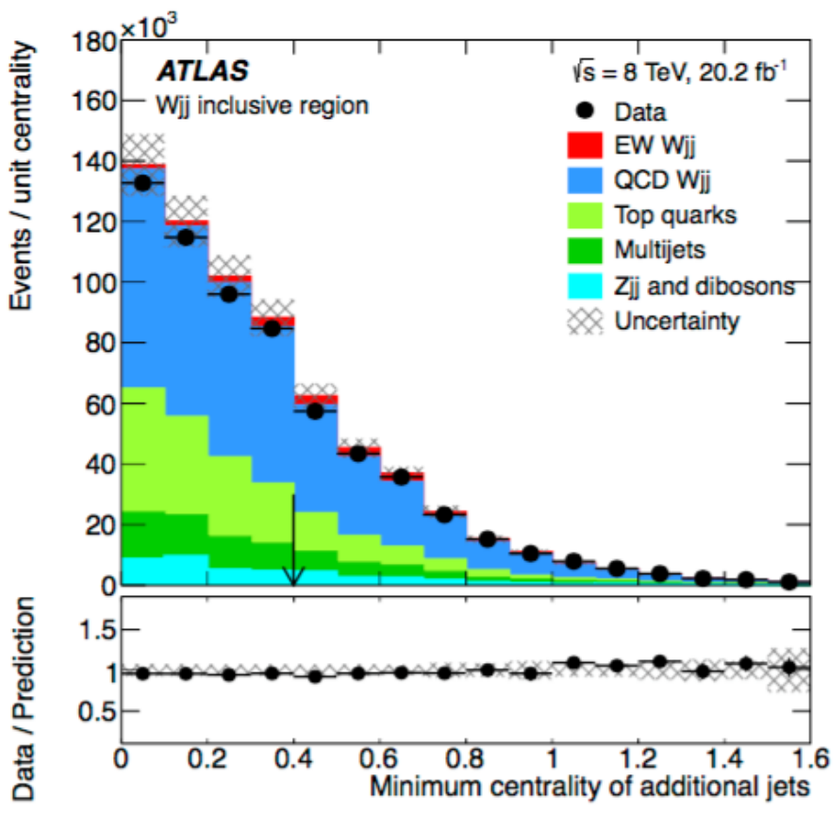


EWK W SELECTION

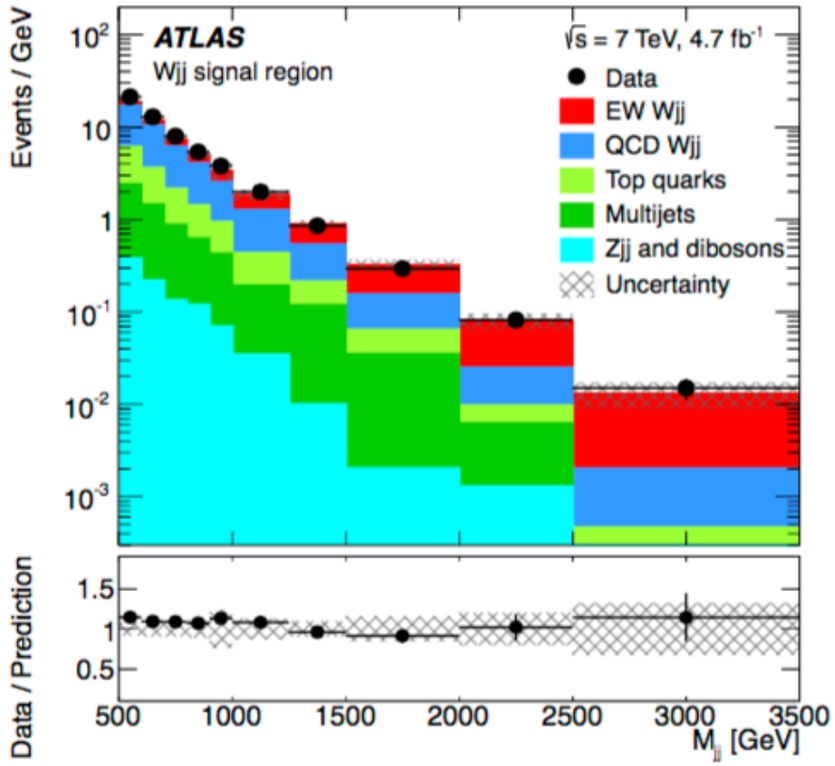


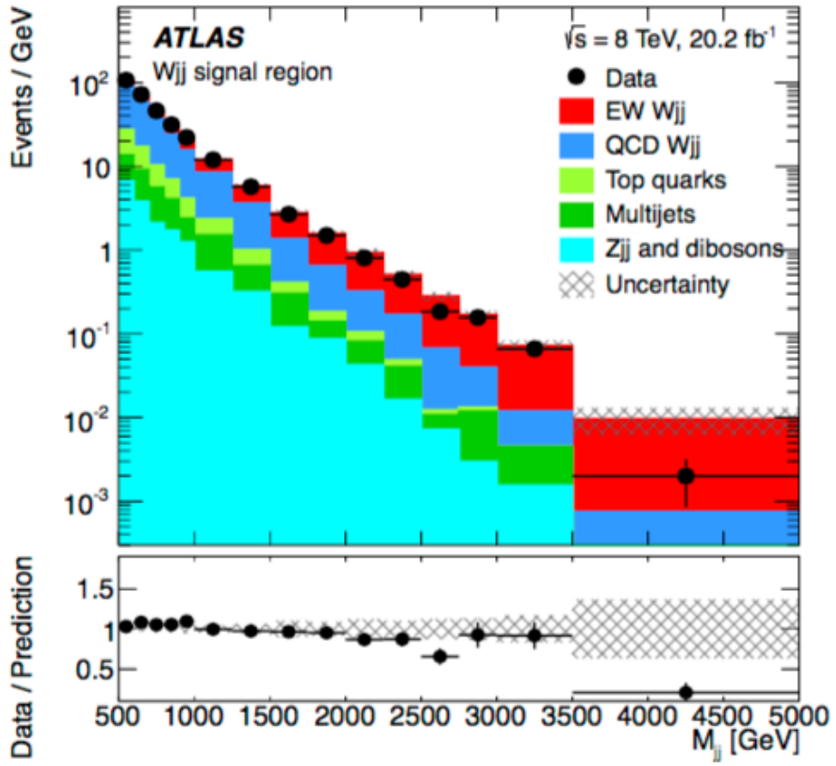


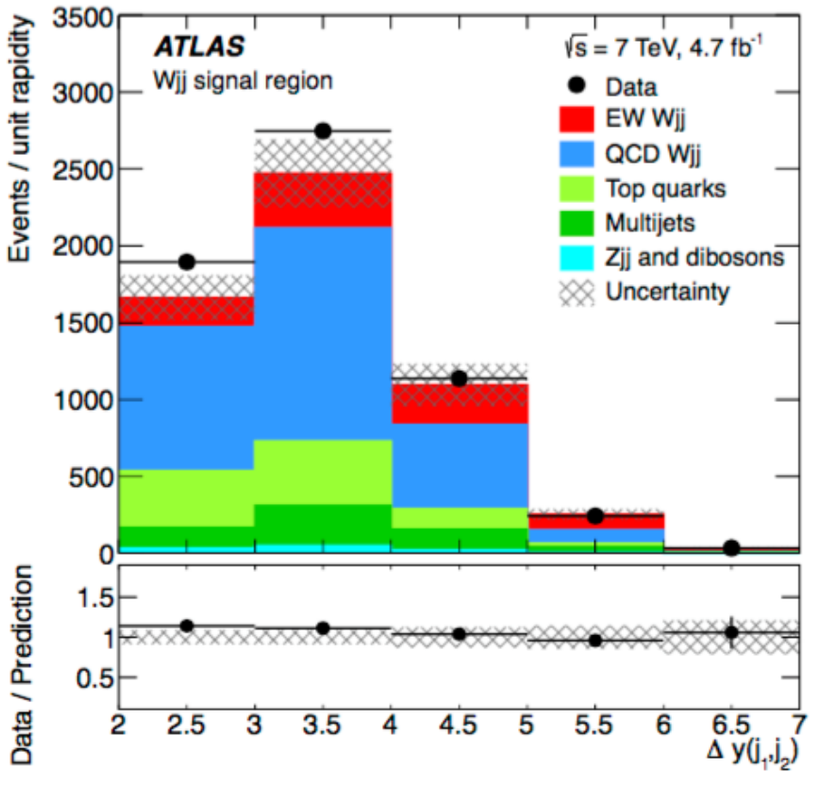


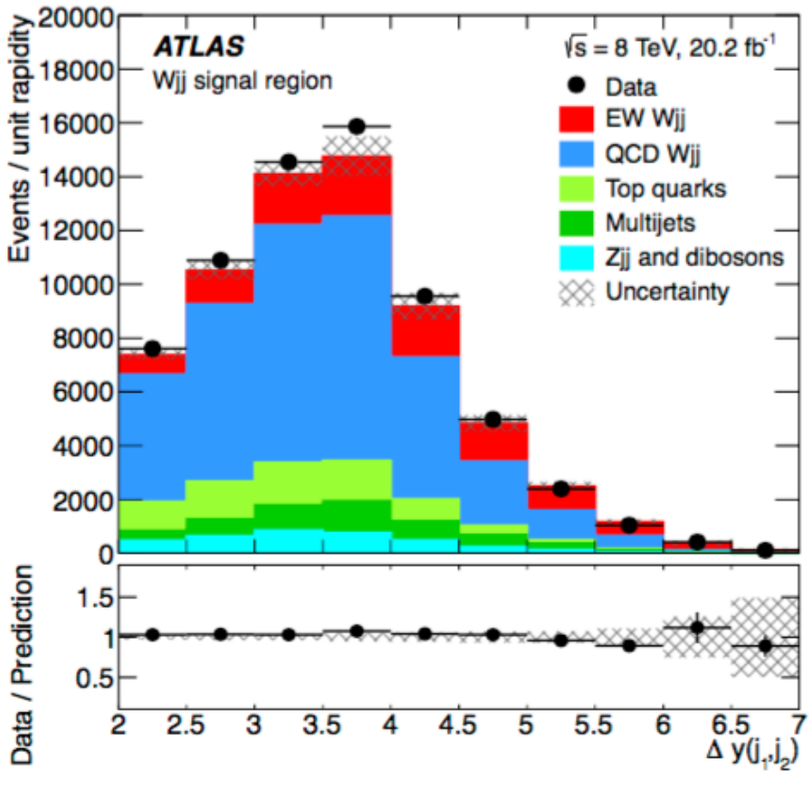


EWK W SIGNAL REGION

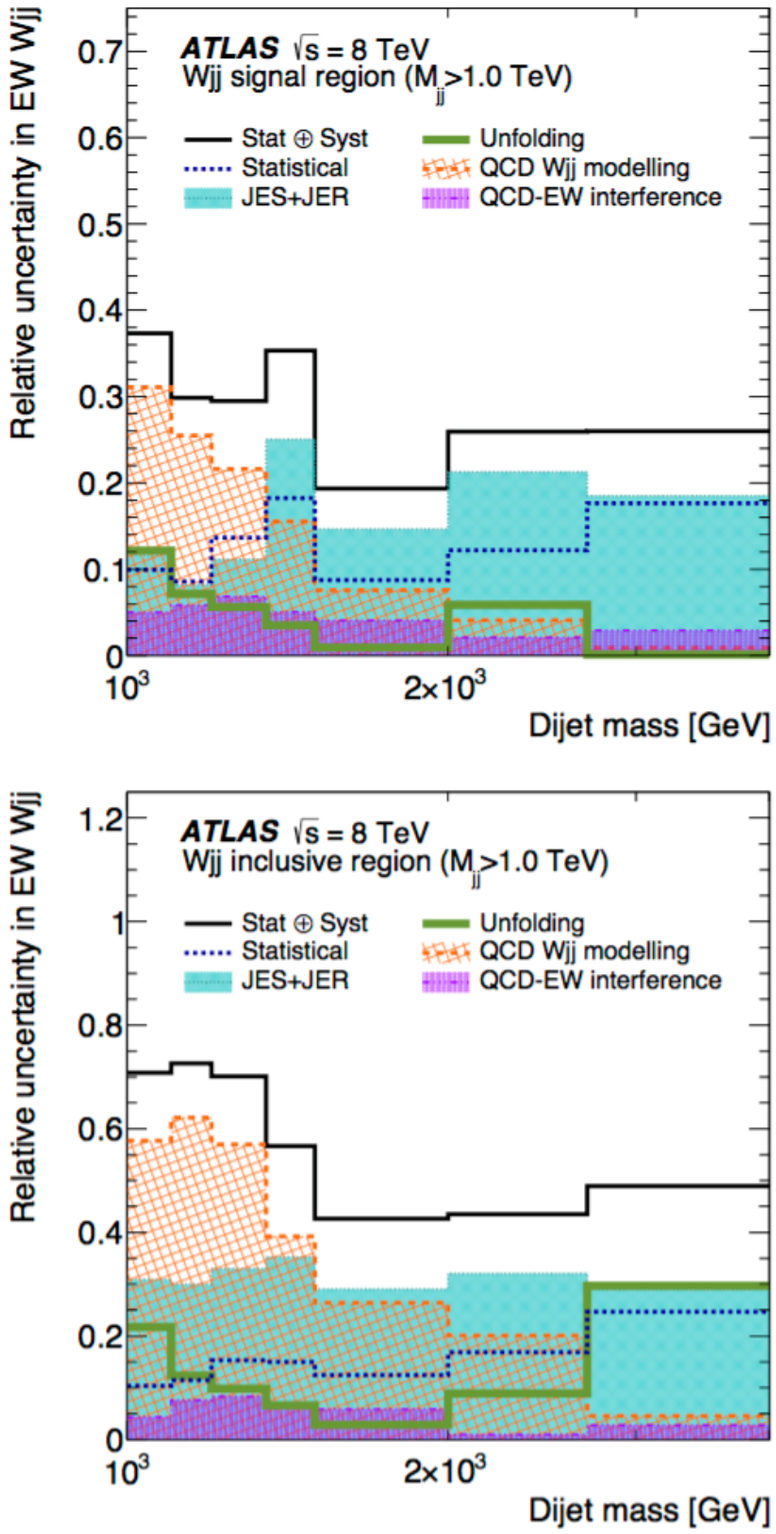


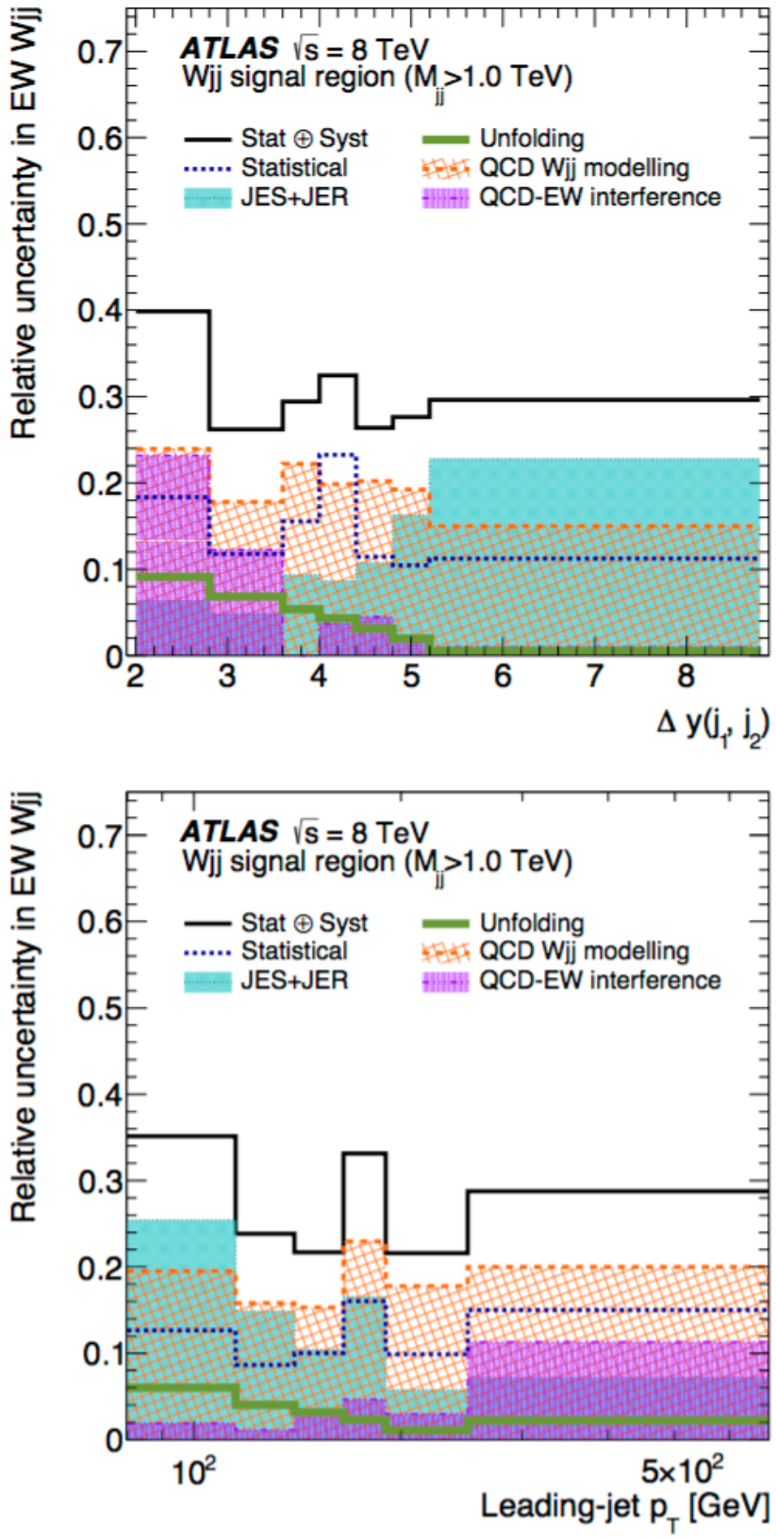




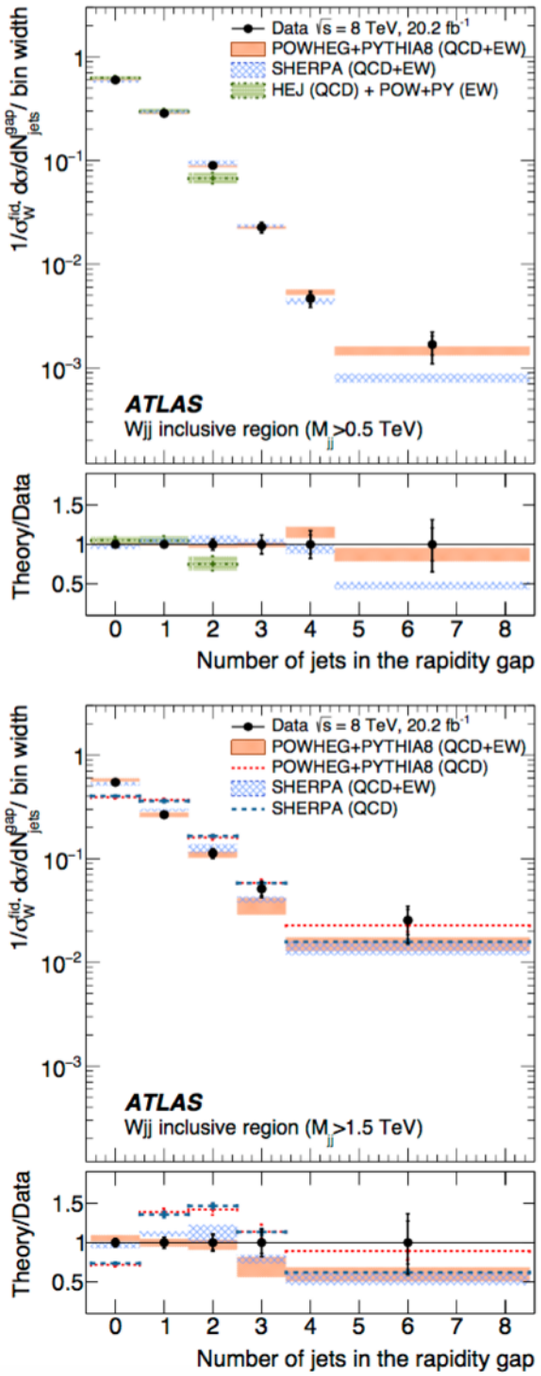


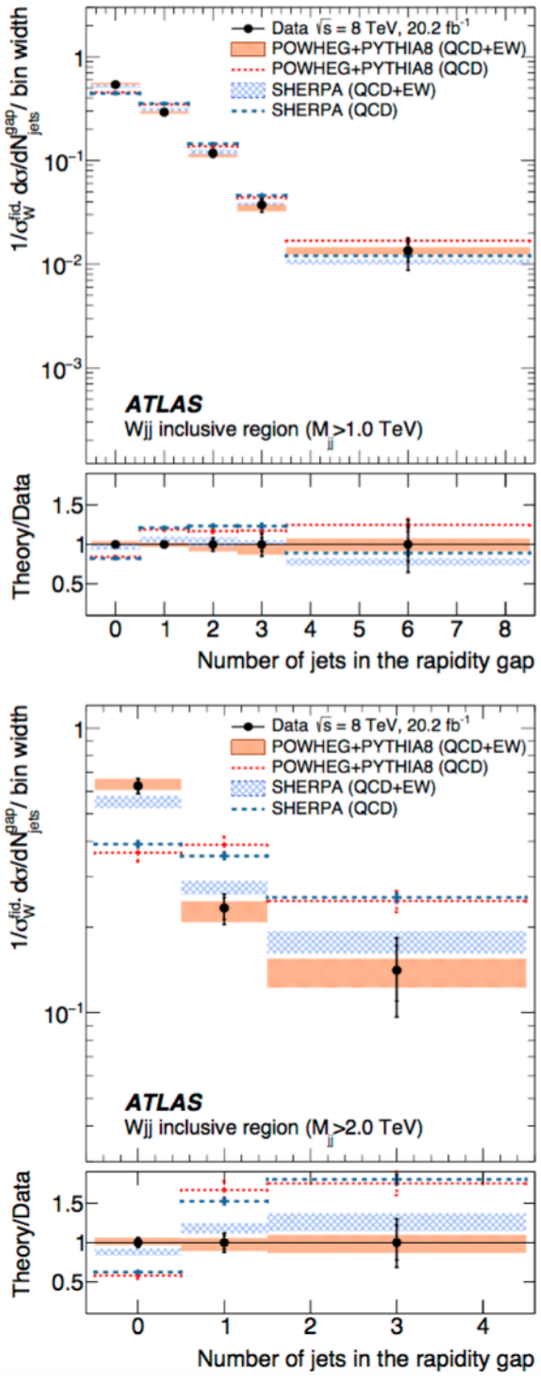
EWK SR W ERRORS

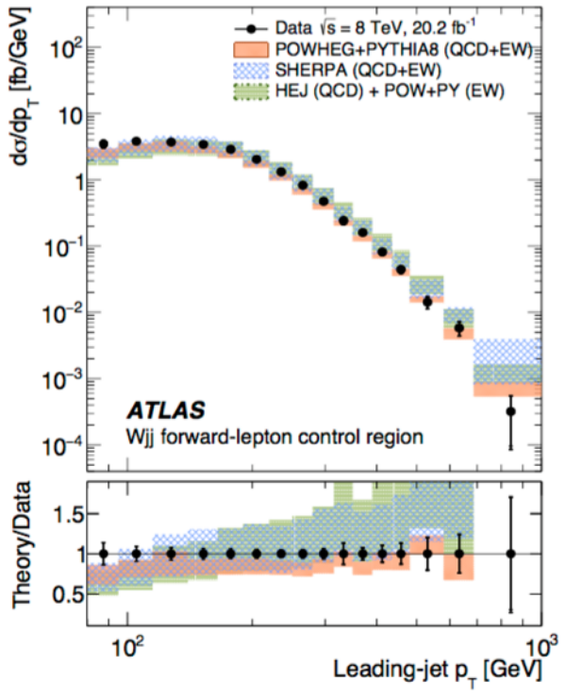


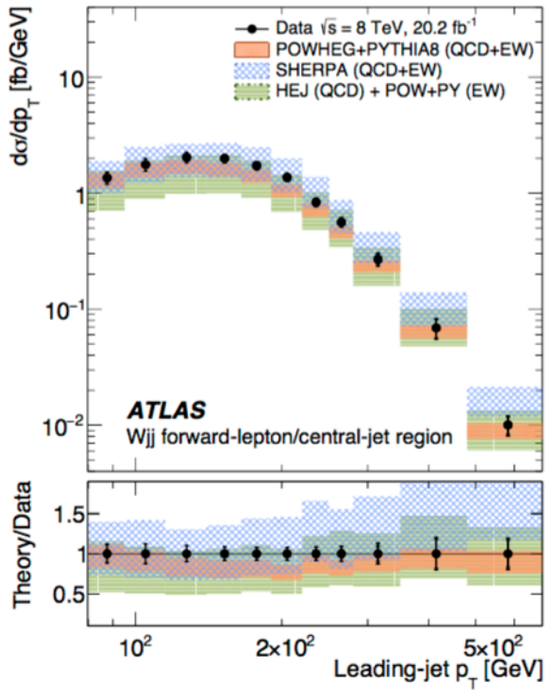


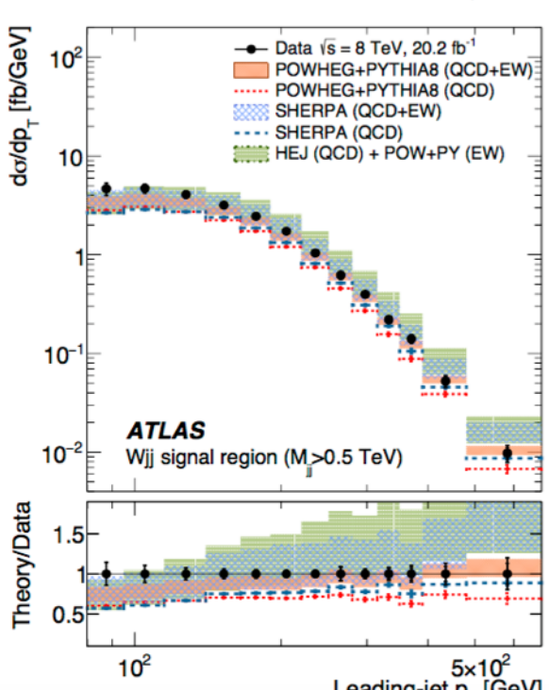
EWK W INCLUSIVE

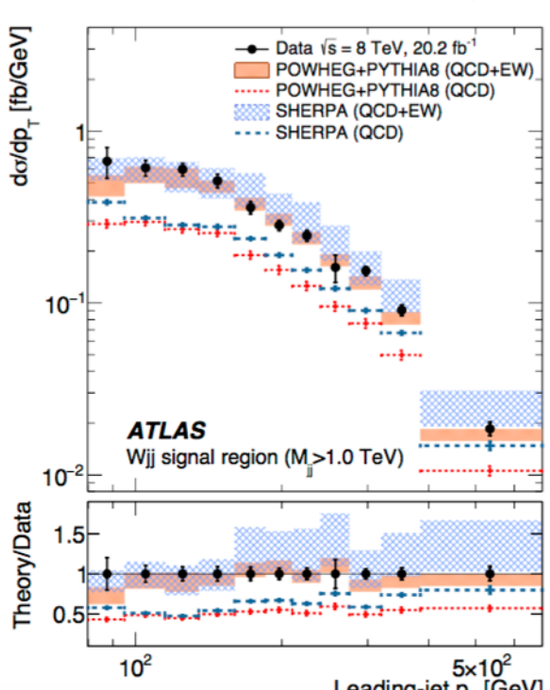












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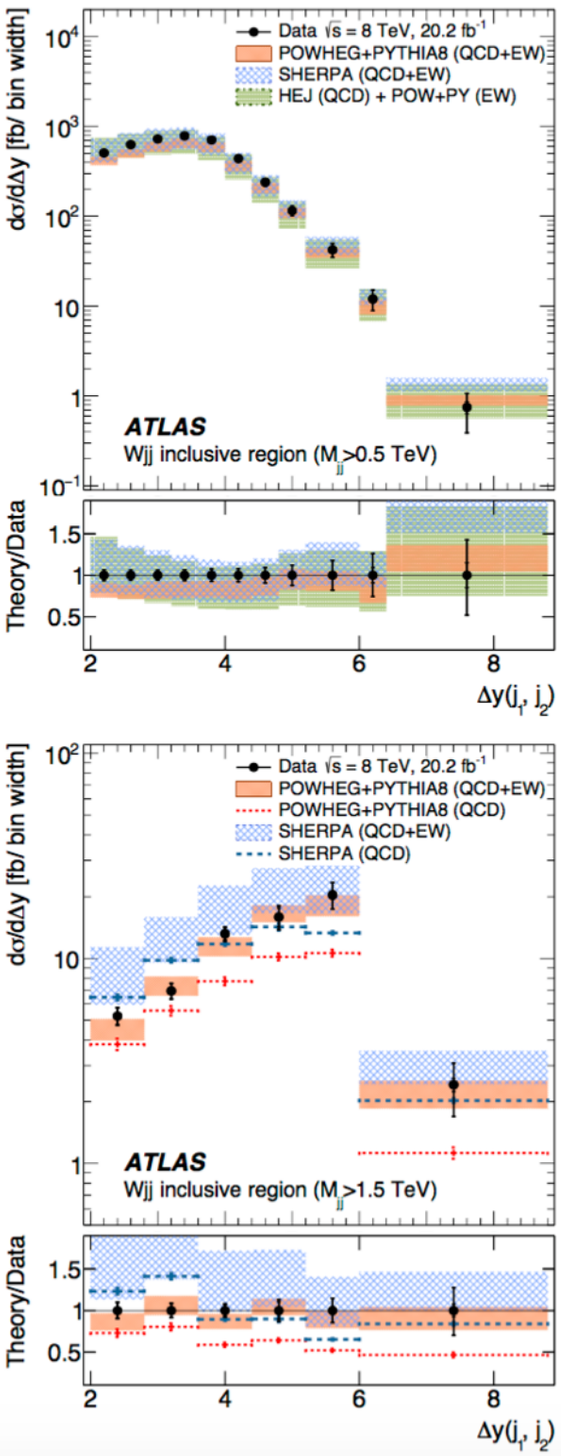
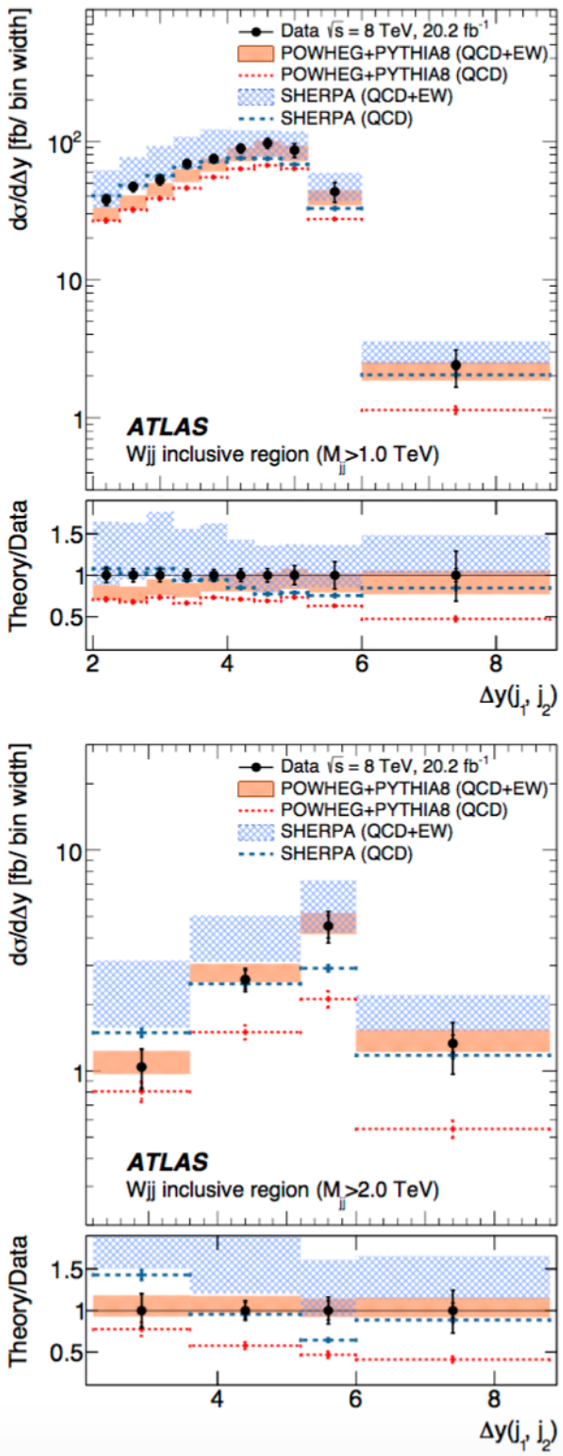
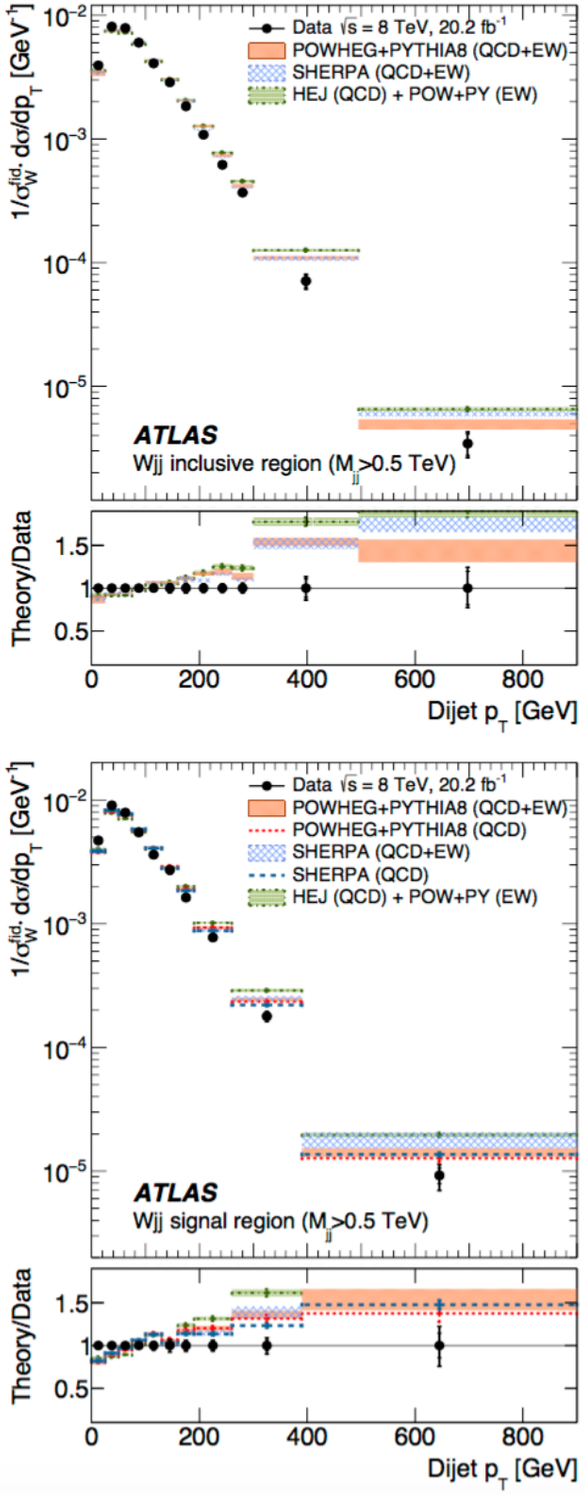
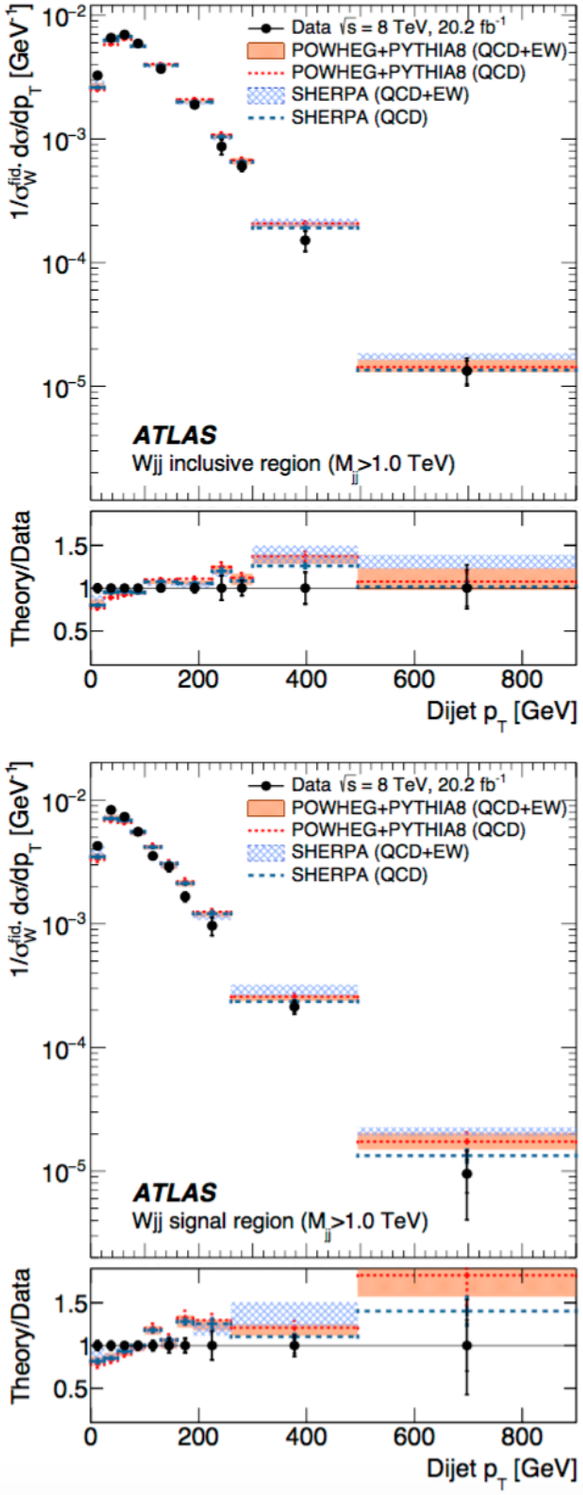
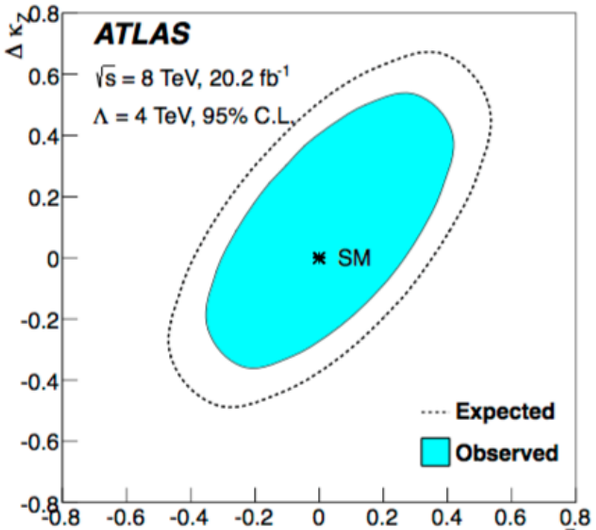


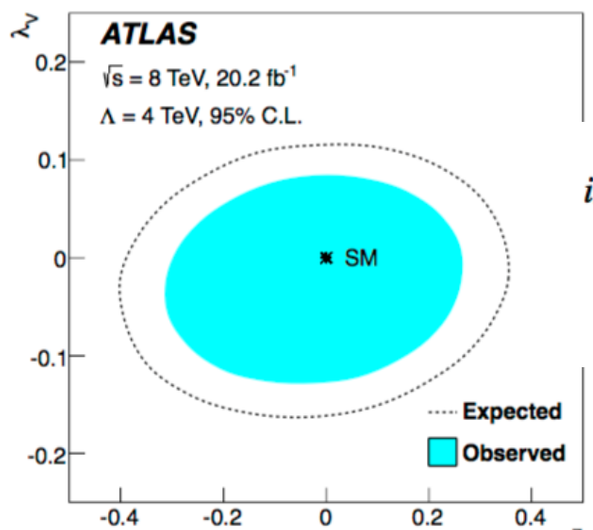




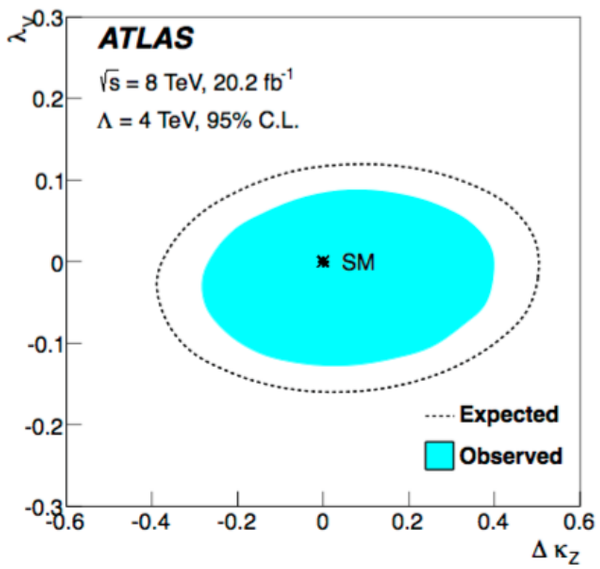


EWK W TGC





$$i\mathcal{L}_{\text{eff}}^{WWV} = g_{WWV}\left\{\left[g_1^V V^\mu (W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}\right]\right.$$
$$\left. - \left[\frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} + \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\right]\right\},$$



$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma, \quad \lambda_\gamma = \lambda_Z \equiv \lambda_V,$$

$$g_1^\gamma = 1, \quad \tilde{\kappa}_\gamma = -\cot^2\theta_W \tilde{\kappa}_Z, \quad \text{and} \quad \tilde{\lambda}_\gamma = \tilde{\lambda}_Z \equiv \tilde{\lambda}_V.$$

$$\frac{c_W}{\Lambda^2} = \frac{2}{m_Z^2}(g_1^Z - 1),$$
$$\frac{c_B}{\Lambda^2} = \frac{2}{\tan^2\theta_W m_Z^2}(g_1^Z - 1) - \frac{2}{\sin^2\theta_W m_Z^2}(\kappa_Z - 1),$$
$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda_V,$$
$$\frac{c_{\tilde{W}}}{\Lambda^2} = -\frac{2}{\tan^2\theta_W m_W^2}\tilde{\kappa}_Z,$$
$$\frac{c_{\tilde{W}WW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\tilde{\lambda}_V,$$

VBS Z GAMMA SELECTION

Objects	Particle- (Parton-) Level Selection
Leptons	$p_{\mathrm{T}}^{\ell} > 25$ GeV and $\lvert\eta^{\ell}\rvert < 2.5$ Dressed leptons, OS charge
Photon Kinematic	$p_{\mathrm{T}}^{\gamma} > 15$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$ $\Delta R(\ell, \gamma) > 0.4$
Photon Isolation	$E_{\mathrm{T}}^{\mathrm{iso}} < 0.5 \cdot E_{\mathrm{T}}^{\gamma}$ (no isolation)
FSR cut	$m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $m_{\ell\ell} > 40$ GeV
Particle Jets (Outgoing Partons) (j = jets) (p = outgoing quarks or gluons)	At least two jets (outgoing partons) $E_{\mathrm{T}}^{\mathrm{j(p)}} > 30$ GeV, $\lvert\eta^{\mathrm{j(p)}}\rvert < 4.5$ $\Delta R(\ell, j(p)) > 0.3$ $\Delta R(\gamma, j(p)) > 0.4$
Control Region (CR)	$150 < m_{\mathrm{jj(pp)}} < 500$ GeV
Search Region (SR)	$m_{\mathrm{jj(pp)}} > 500$ GeV
aQGC Region	$m_{\mathrm{jj(pp)}} > 500$ GeV $E_{\mathrm{T}}^{\gamma} > 250$ GeV