Review of electroweak physics at hadron colliders

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DPF 2011

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NORTHWESTERN UNIVERSITY

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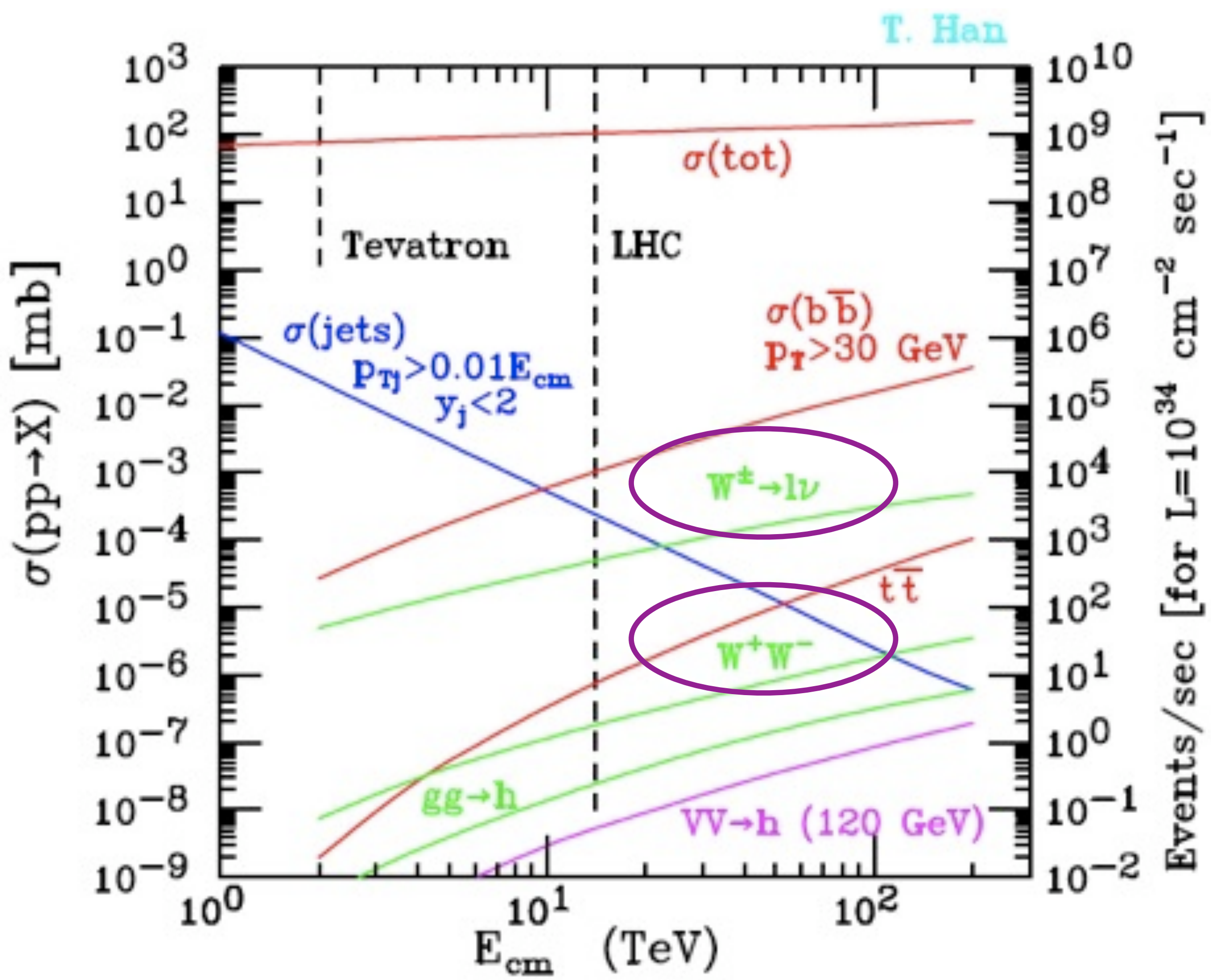
Outline

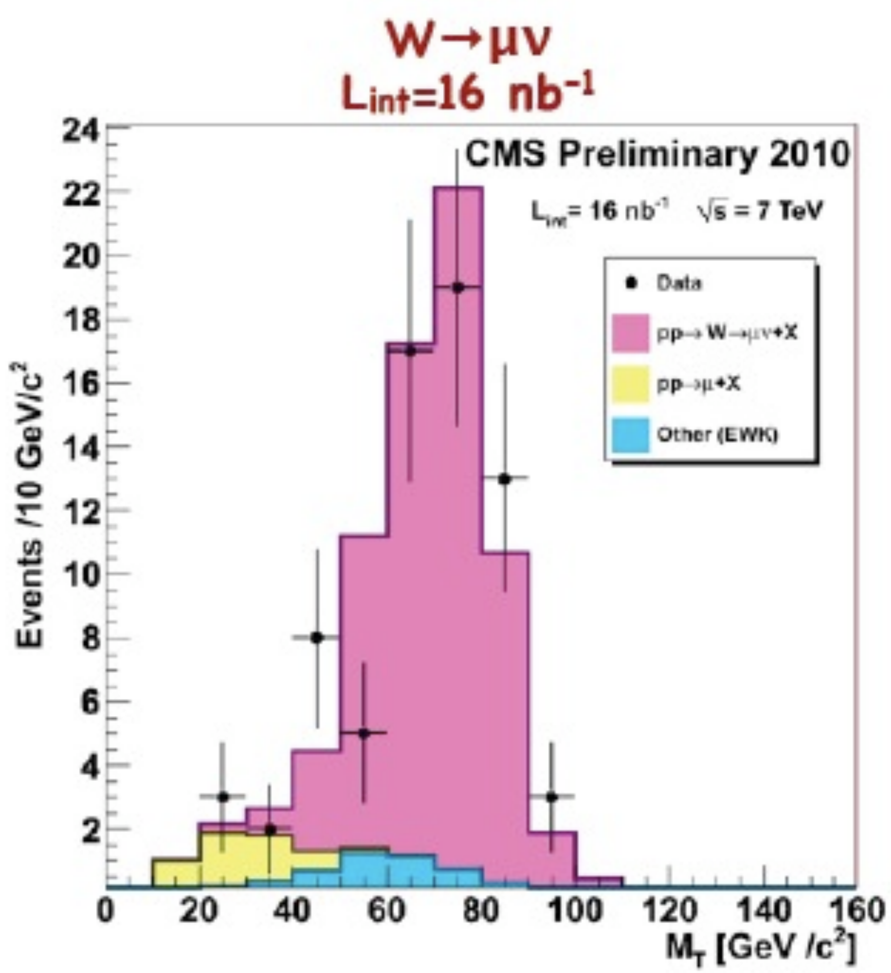


- Will begin with a review of the variety of important measurements with W/Z(γ) final states
- Will focus on recent LHC and Tevatron results, and theoretical issues associated with them
- Emphasis on impact of QCD on analyses, the status of theoretical knowledge and tools, and some examples of the tricky interplay between QCD and experimental cuts

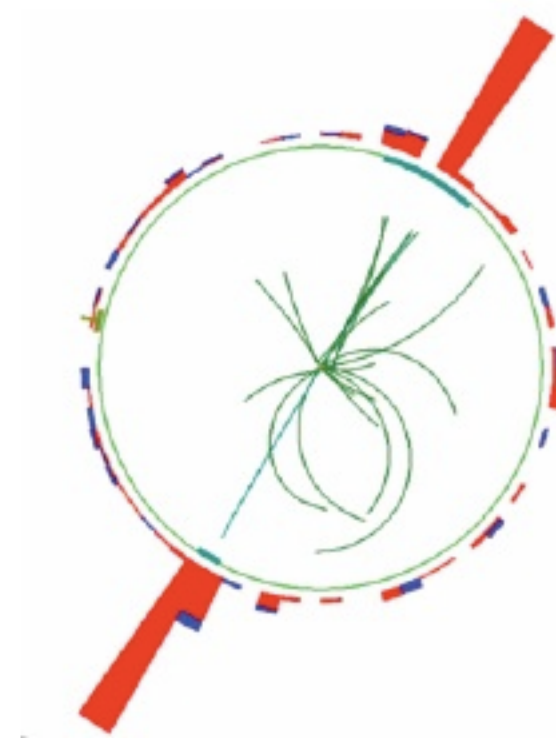
W, Z at the LHC circa 2010

Z boson events have been observed in both channels

Observed	3 events
Expected	4.8 events



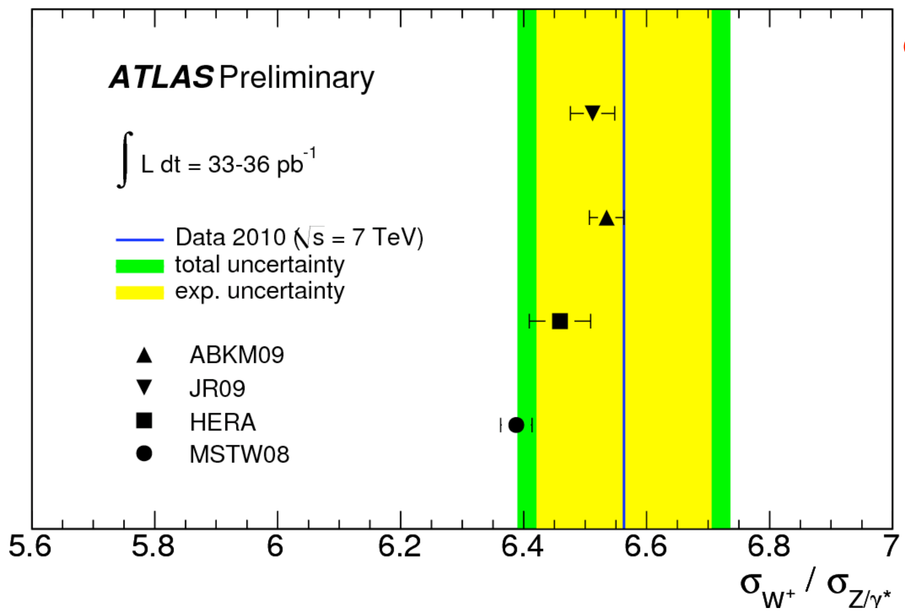
- W, Z candidate events feature prominently in talks
- A few sparsely populated $p_{T,W}$ and M_T distributions

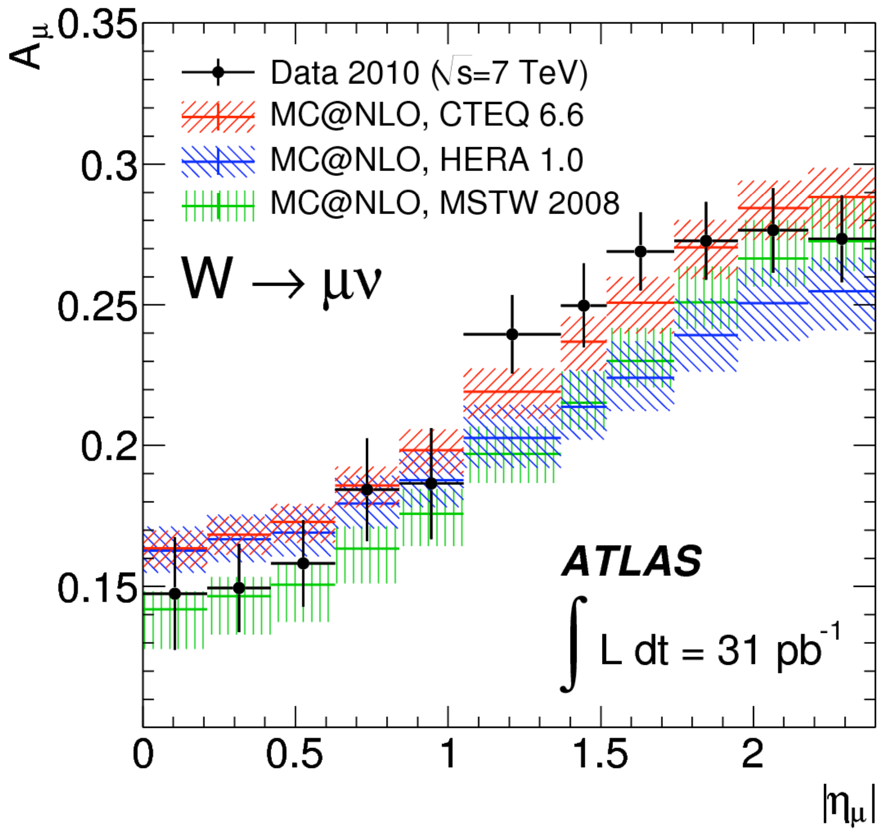


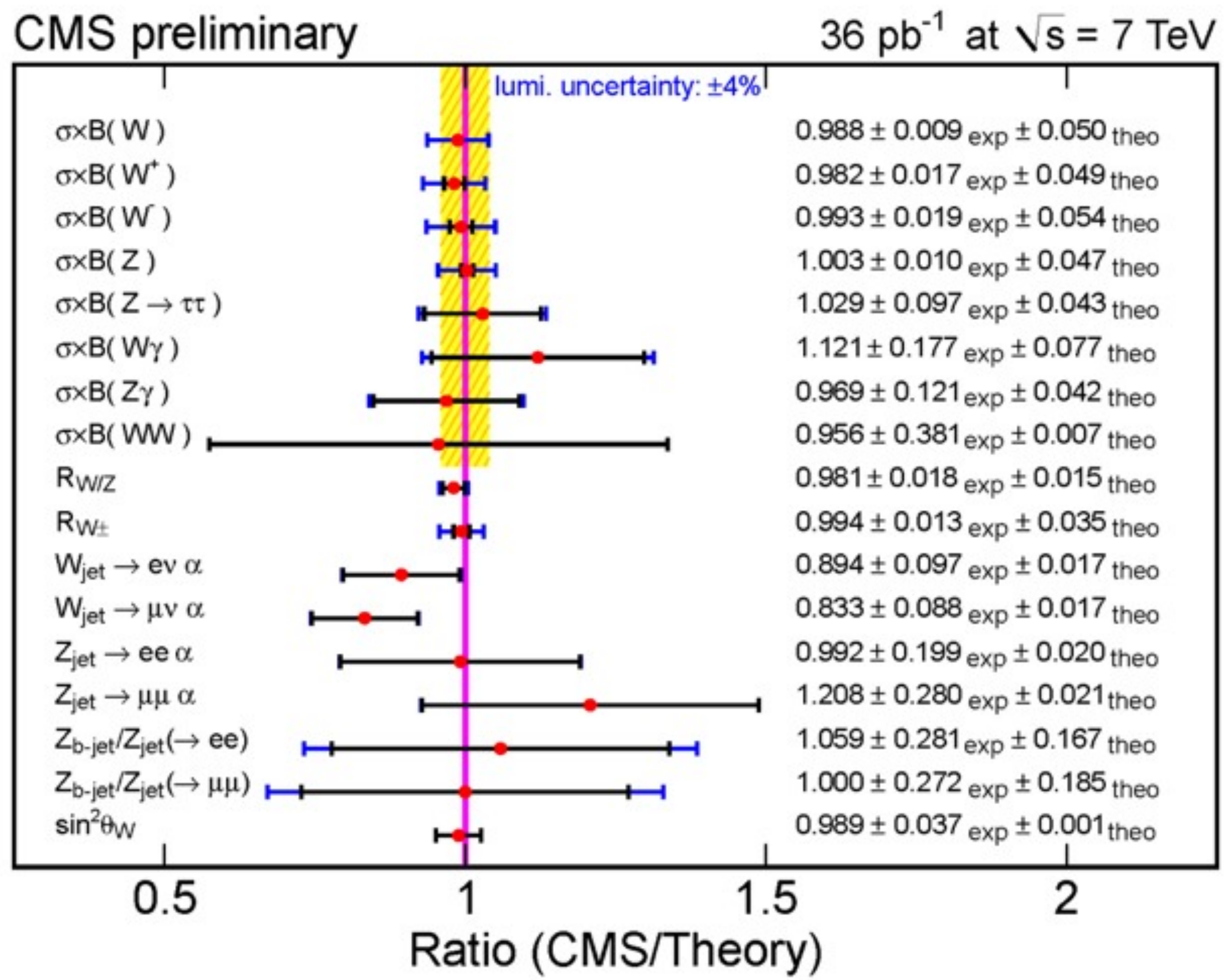
CMS $Z \rightarrow e^+e^-$

W, Z at the LHC now

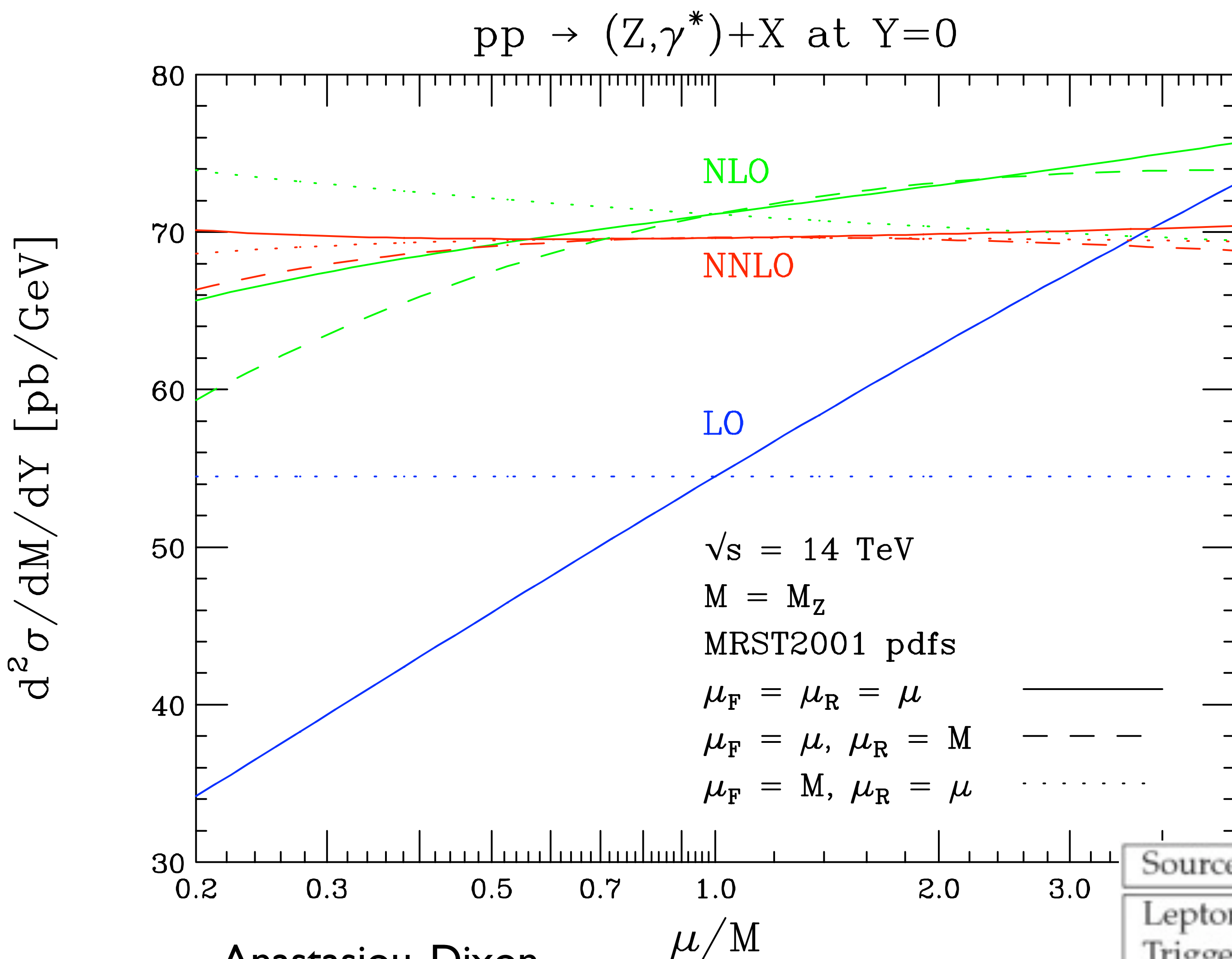
- Detailed measurements of W, Z properties
- Already improving PDFs, a first $\sin^2\theta_W$ determination







Why are we interested?



Anastasiou, Dixon, Melnikov, FP 2003

- Residual theory error from uncalculated terms at the percent level
- Experimental systematics at the percent level, high statistics
- Permits precision measurements in a hadronic environment

Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	1.4	0.9	1.8	n/a
Trigger prefiring	n/a	0.5	n/a	0.5
Energy/momentum scale & resolution	0.5	0.22	0.12	0.35
$\not{E}_T$ scale & resolution	0.3	0.2	n/a	n/a
Background subtraction / modeling	0.35	0.4	0.14	0.28
Trigger changes throughout 2010	n/a	n/a	n/a	0.1
Total experimental	1.6	1.1	1.8	0.7
PDF uncertainty for acceptance	0.6	0.8	0.9	1.1
Other theoretical uncertainties	0.7	0.8	1.4	1.6
Total theoretical	0.9	1.1	1.6	1.9
Total (excluding luminosity)	1.8	1.6	2.4	2.0

CMS, EPS 2011

Luminosity and PDFs

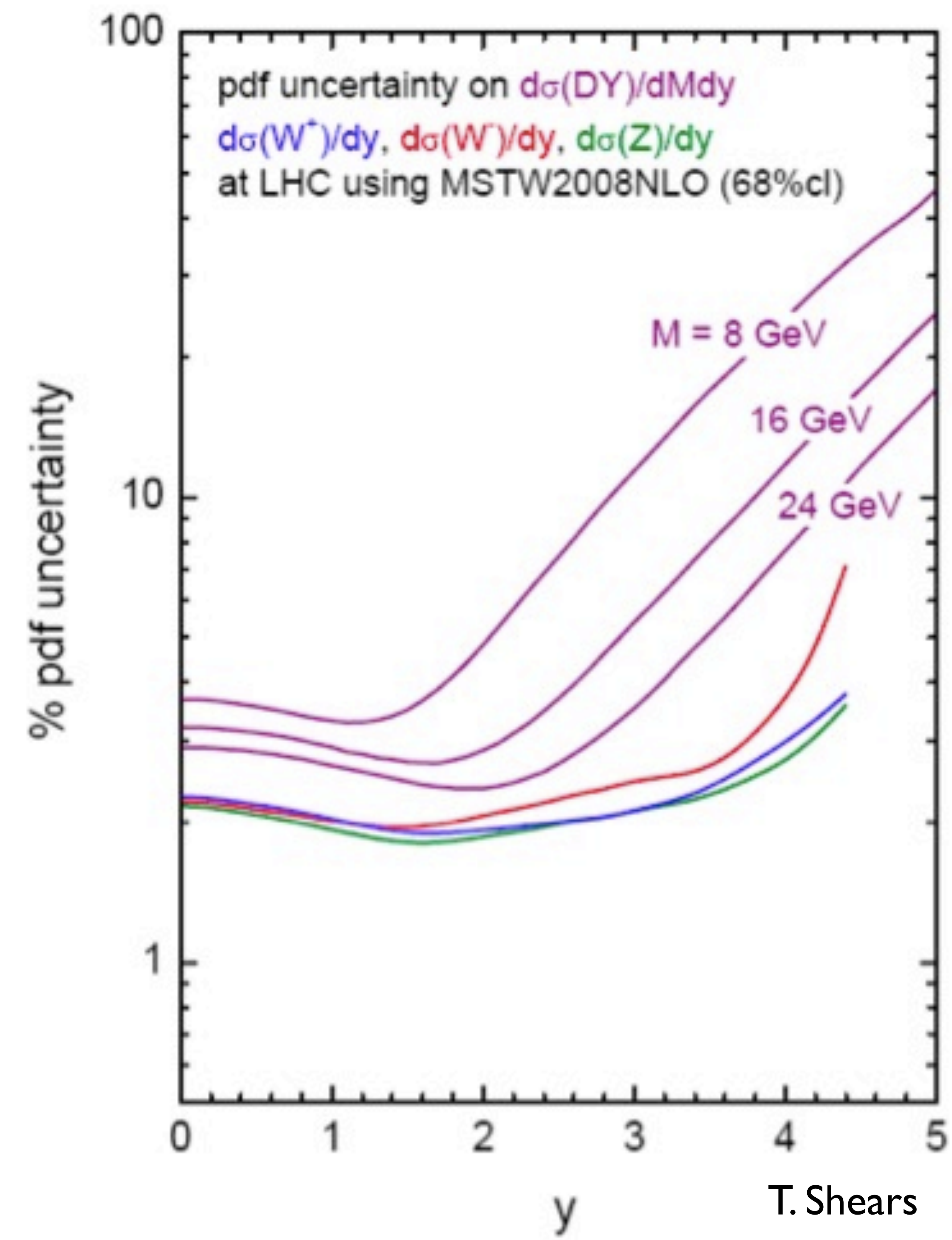
compute theoretically

$$N_{pp\to WW} = N_{pp\to Z} \cdot \frac{\sigma_{q,\bar{q}\to WW}}{\sigma_{q,\bar{q}\to Z}} \cdot \frac{PDF(x_1',x_2',Q'^2)}{PDF(x_1,x_2,Q^2)}$$

$\Delta L_{pp} = 0!$

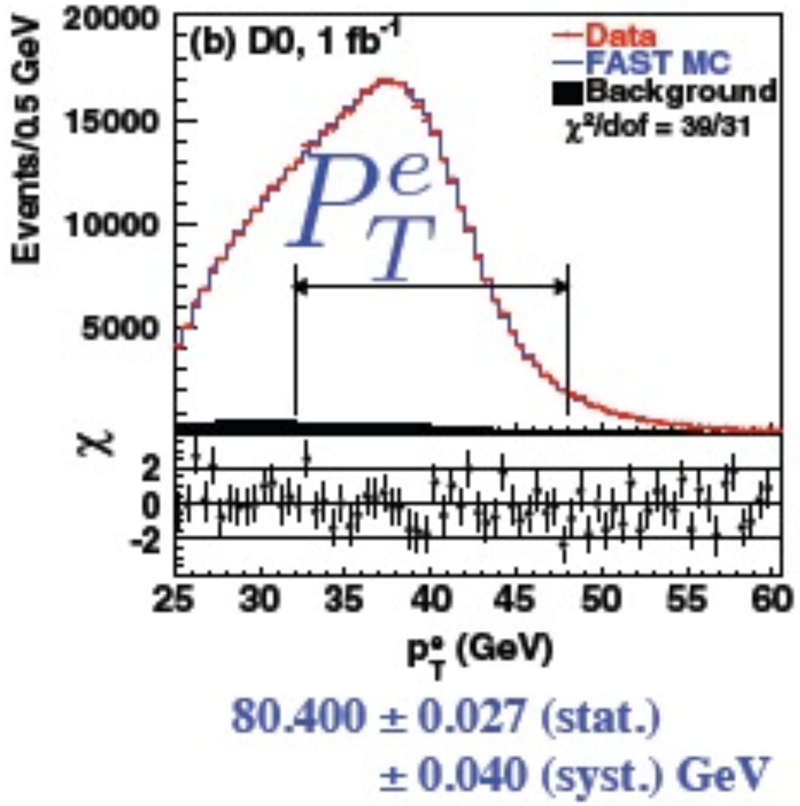
Normalization process

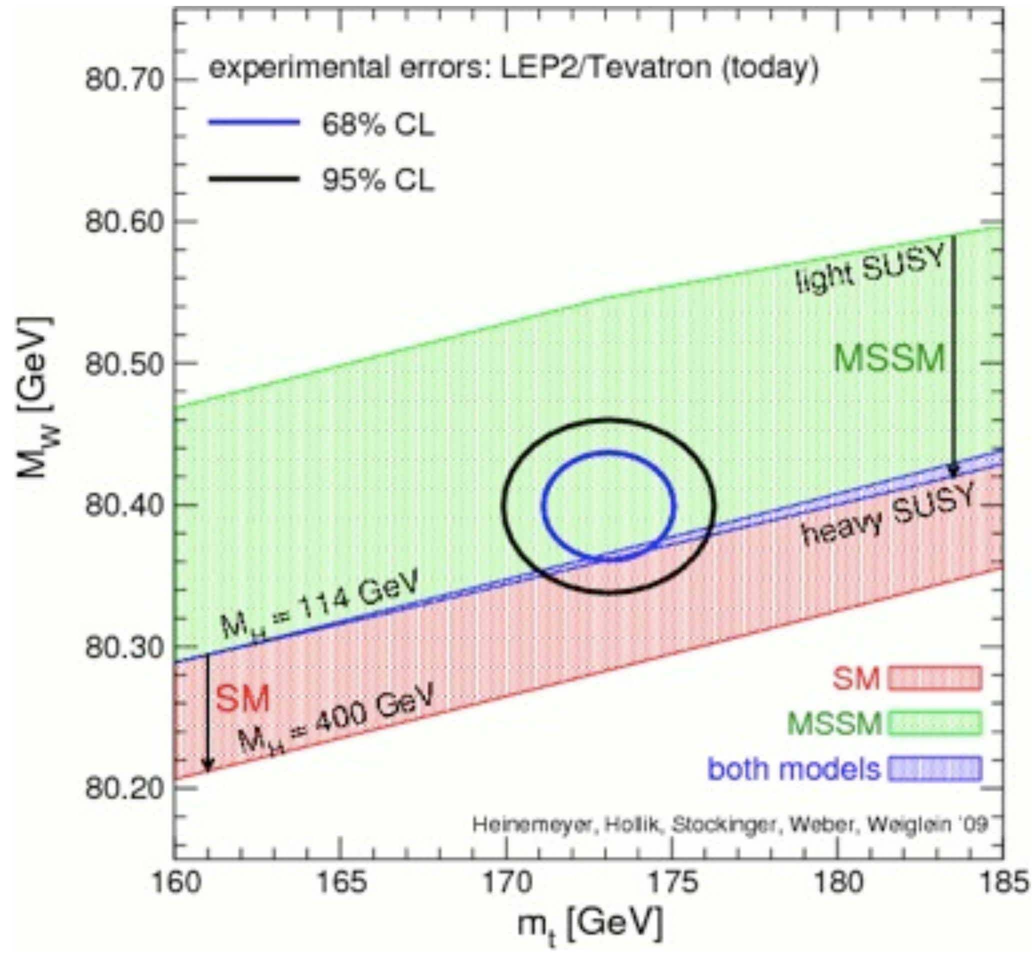
- Use to remove luminosity error from processes with similar initial states
- Use in PDF extractions; control over differential distributions crucial

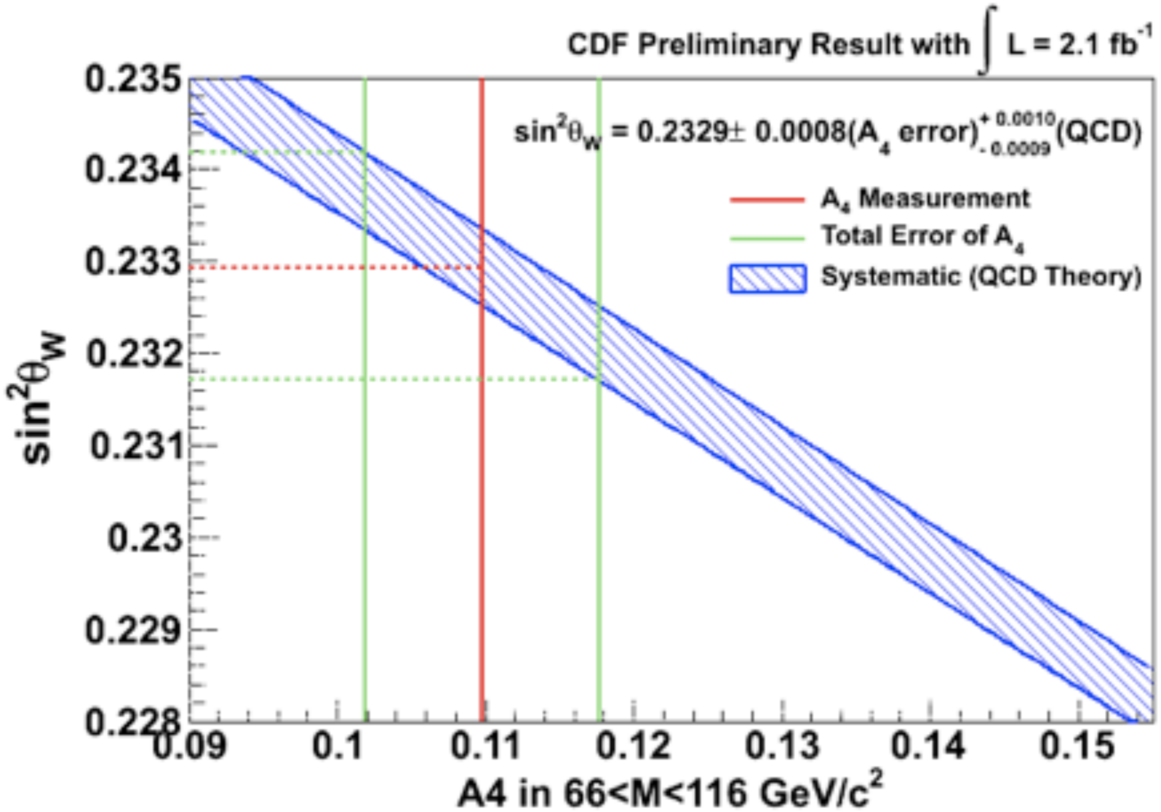


T. Shears

Fundamental parameters

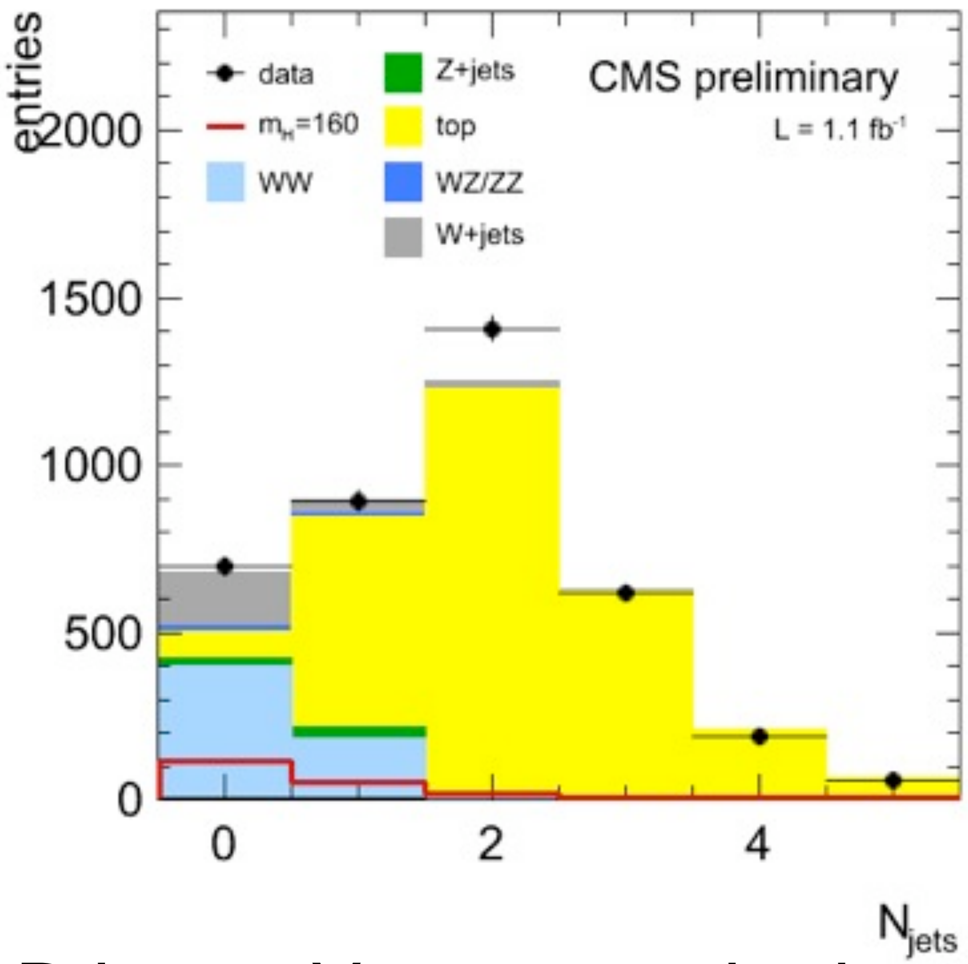


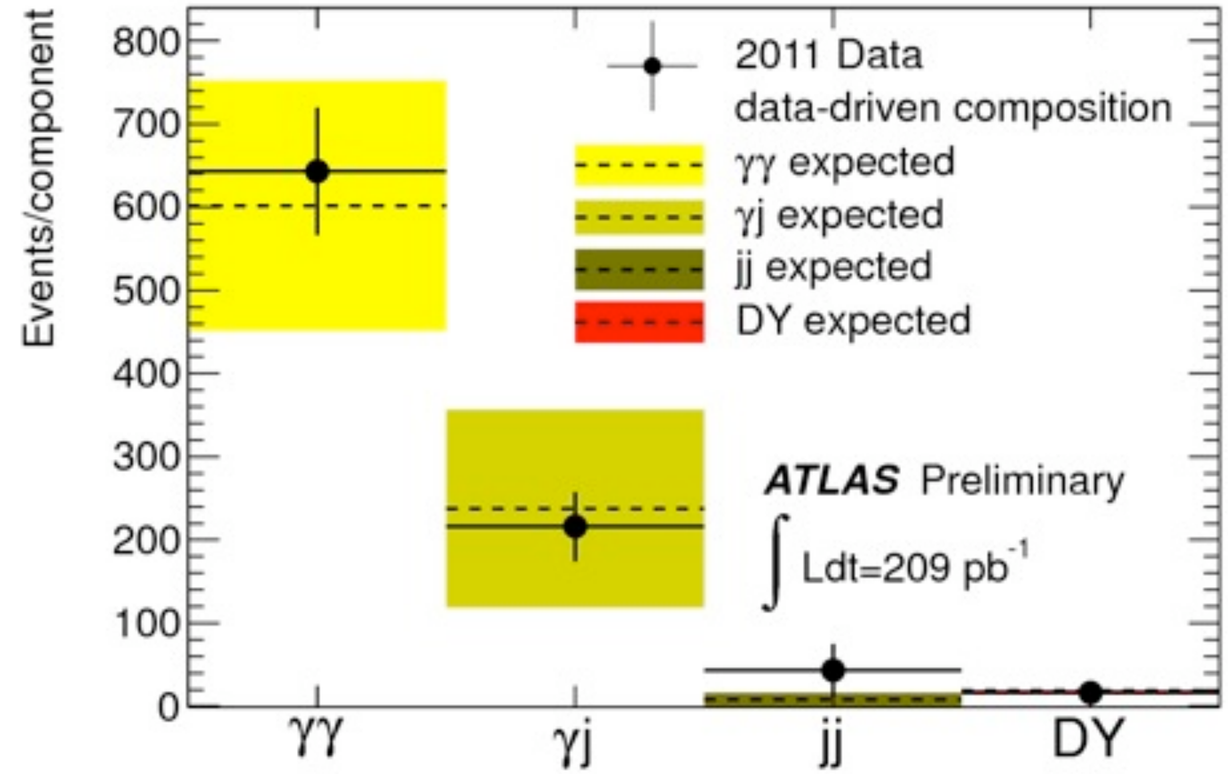




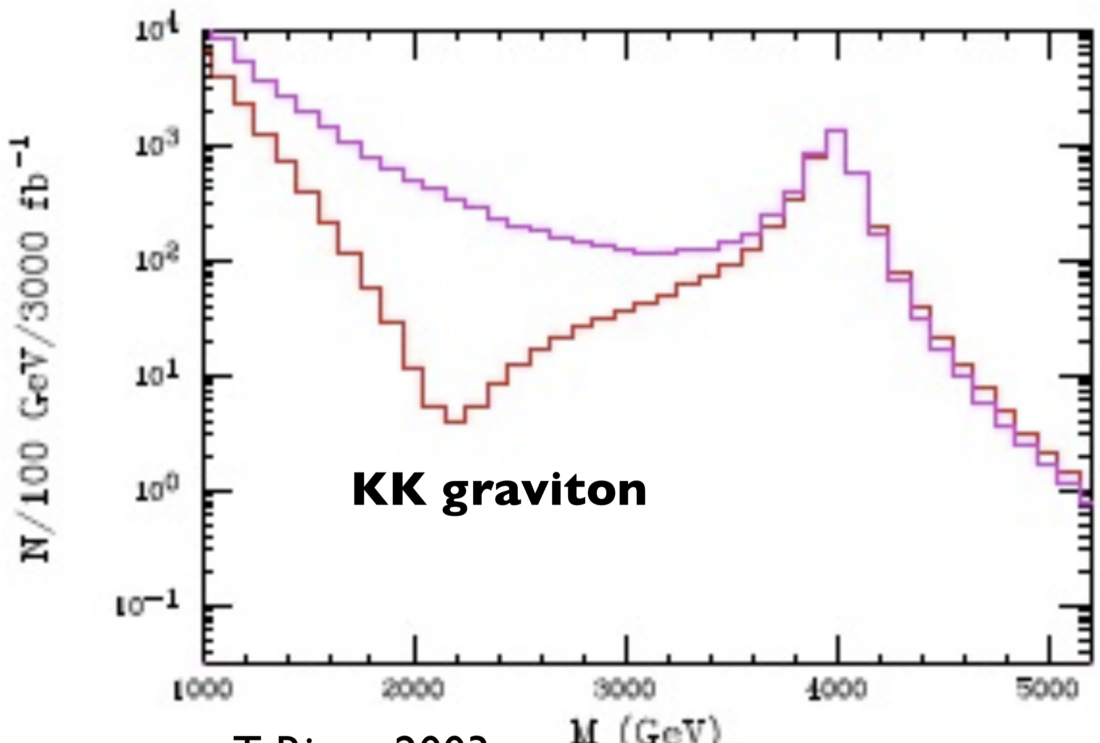
- Most precise determination of M_W from Tevatron
- Check on LEP $\sin^2\theta_W$ measurement; also complete determination of angular properties of Z decay (Collins-Soper moments), other QCD properties

Background to new physics





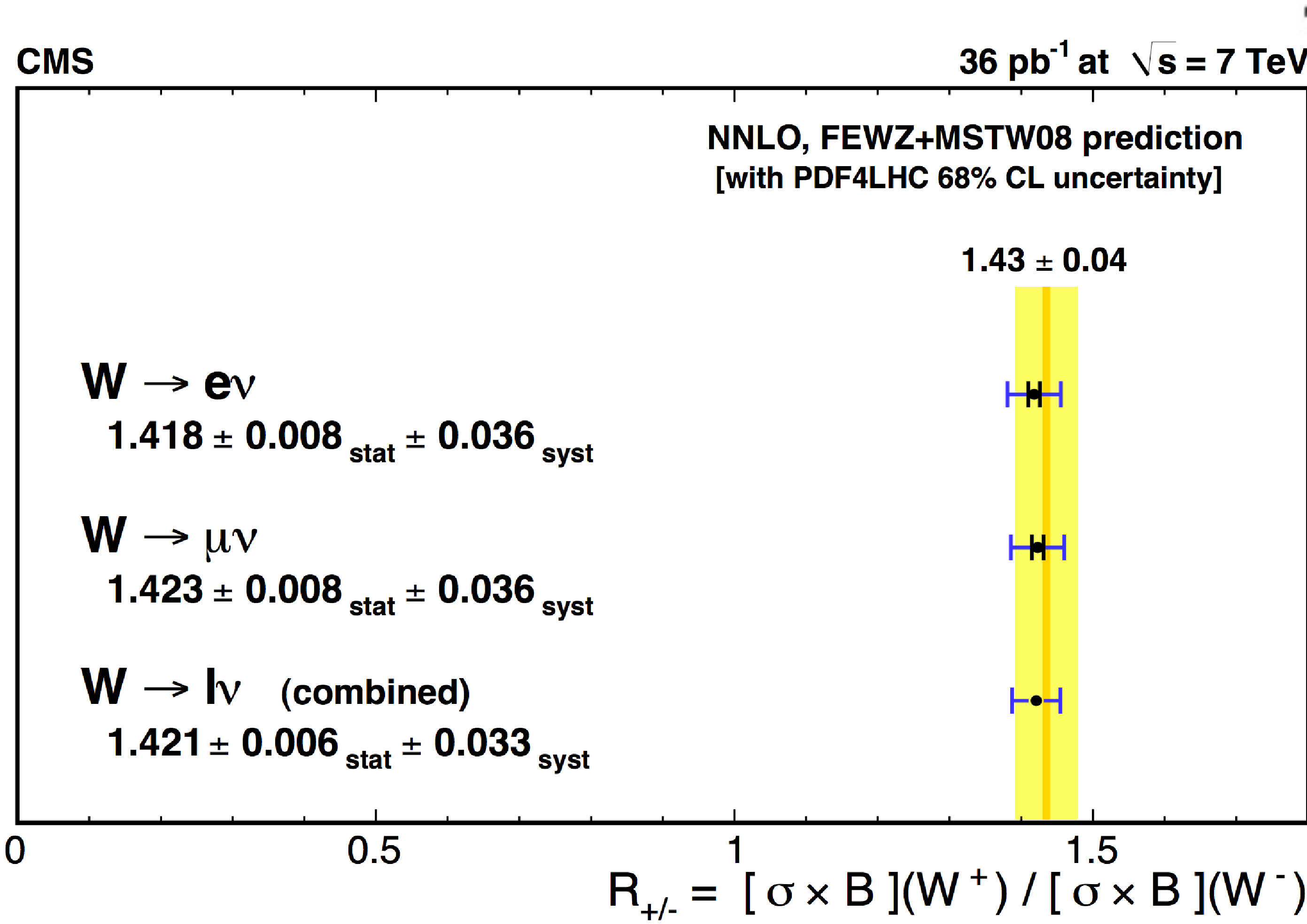
- Diboson, V+jet major backgrounds to both high and low mass Higgs
- High mass tail needed for heavy resonance searches; interference with SM possibly a useful diagnostic tool

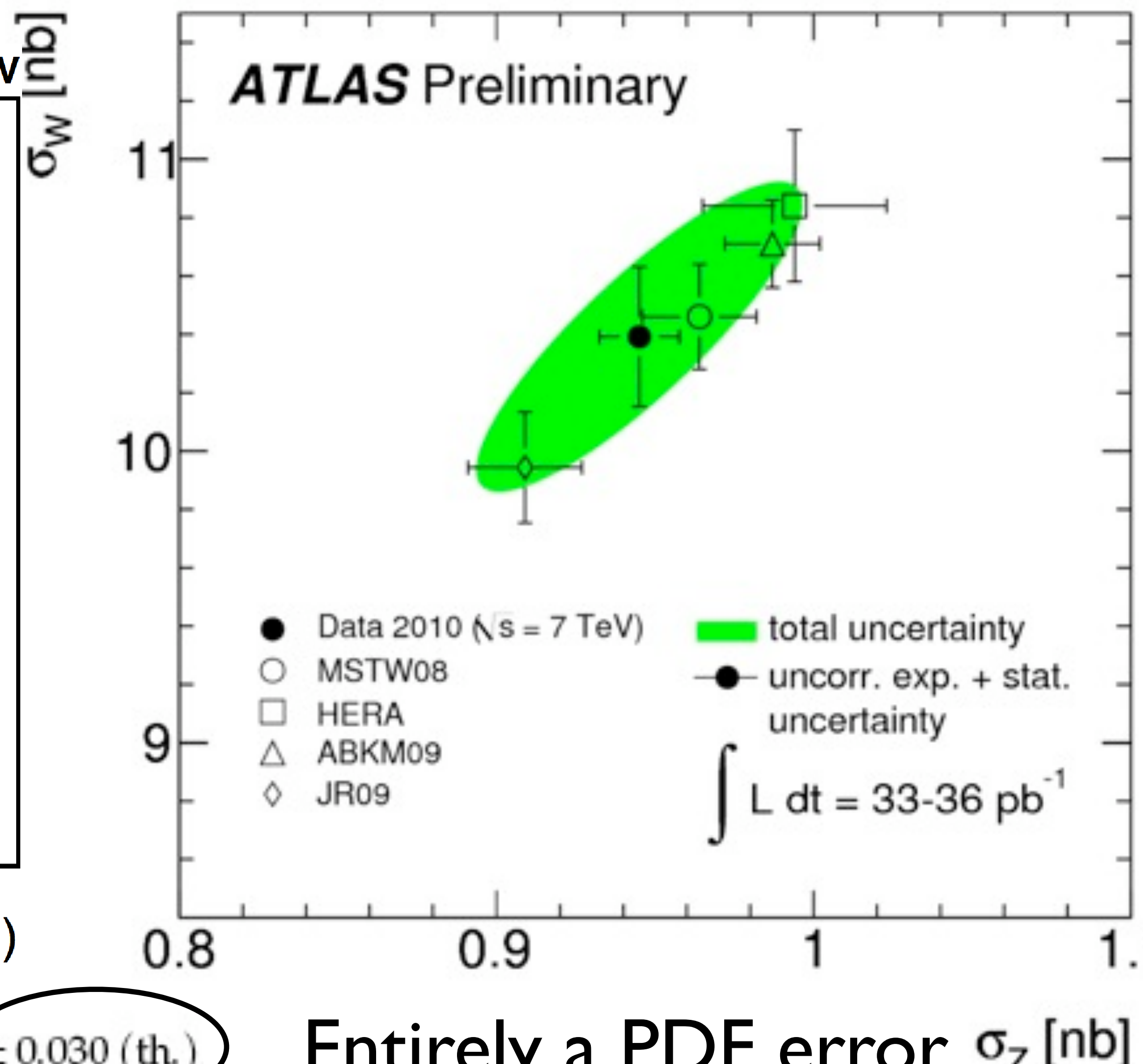


T. Rizzo 2003

Inclusive cross sections

- Known through NNLO in QCD van Neerven et al. 1991; Harlander, Kilgore 2001
- NLO EW corrections known Baur, Brein, Hollik, Keller Wackeroth; Dittmaier, Kramer; Carloni Calame et al., 1998-2006





$$\frac{\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to \ell^+\nu)}{\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to \ell^-\bar{\nu})} = 1.421 \pm 0.006\,(\mathrm{stat.}) \pm 0.014\,(\mathrm{syst.}) \pm 0.030\,(\mathrm{th.})$$

Entirely a PDF error

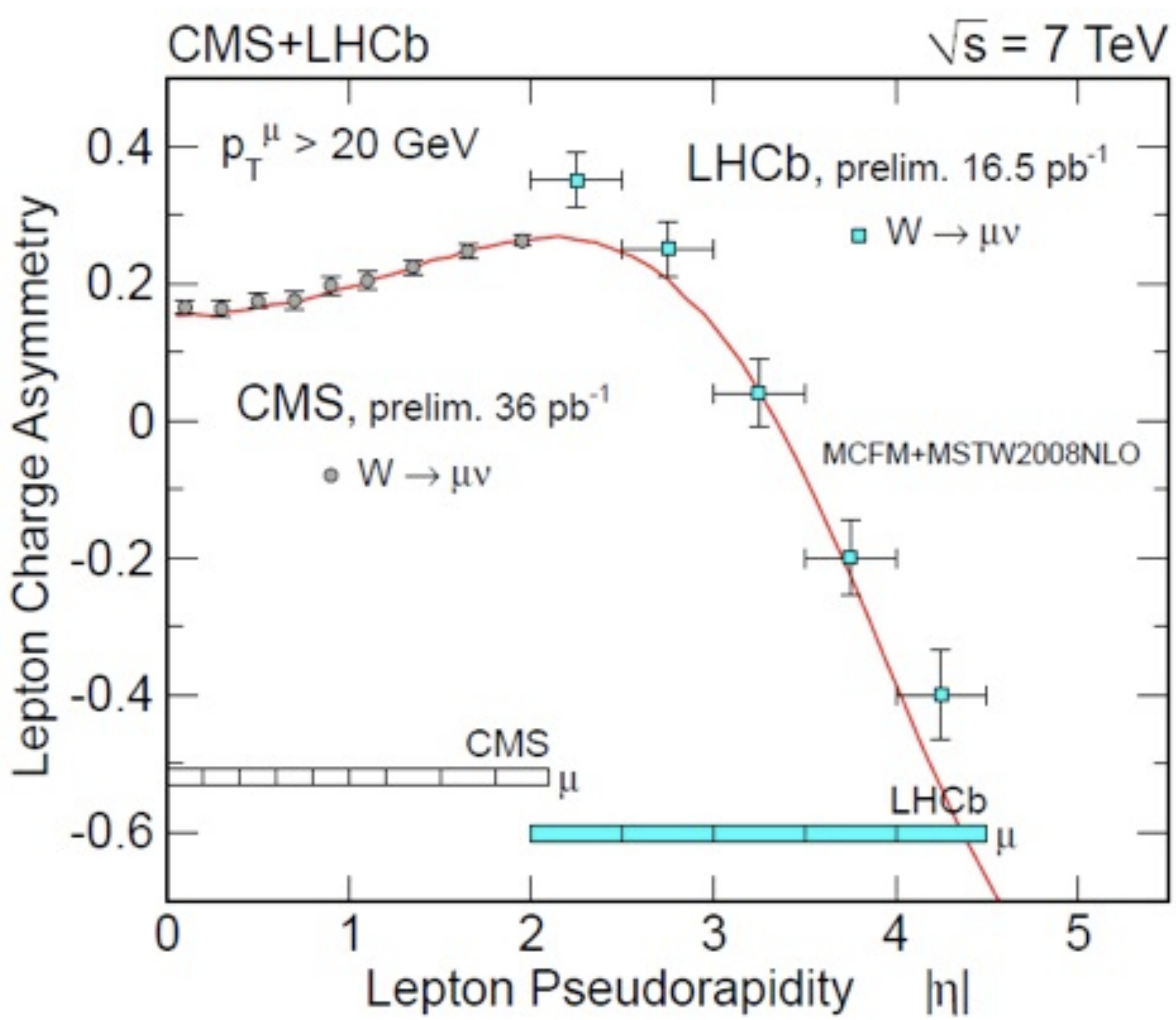
$$\sigma\,(pp \to ZX) \times \mathrm{BF}\,(Z \to \ell^+\ell^-) = 0.975 \pm 0.007\,(\mathrm{stat.}) \pm 0.007\,(\mathrm{syst.}) \pm 0.018\,(\mathrm{th.}) \pm 0.039\,(\mathrm{lumi.})\,\mathrm{nb.}$$

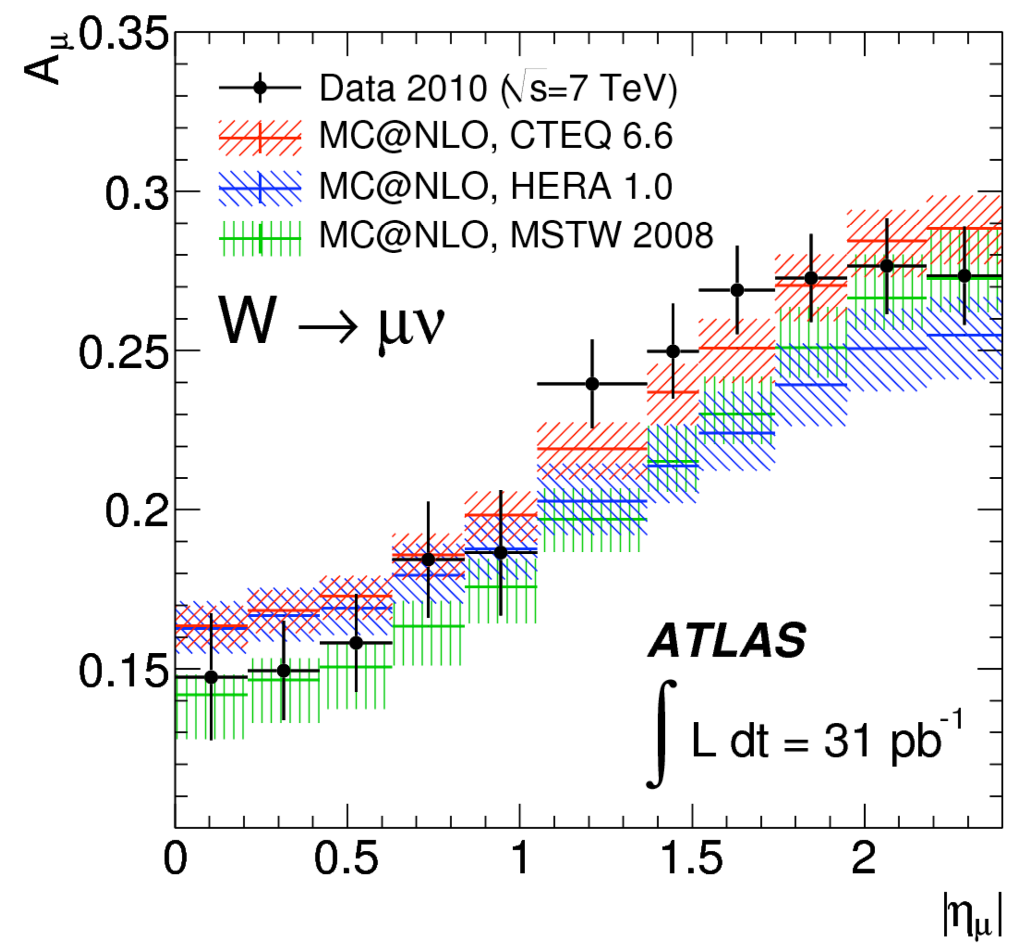
$$\sigma\,(pp \to W^+X) \times \mathrm{BF}\,(W^+ \to \ell^+\nu) = 6.04 \pm 0.02\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}) \pm 0.08\,(\mathrm{th.}) \pm 0.24\,(\mathrm{lumi.})\,\mathrm{nb;}$$

W charge asymmetry

- Probes both valence and sea distributions

$$A_W(y) = \frac{N_{W+}(y) - N_{W-}(y)}{N_{W+}(y) + N_{W-}(y)} \quad \Rightarrow \quad A_\ell(\eta) = \frac{N_{\ell+}(\eta) - N_{\ell-}(\eta)}{N_{\ell+}(\eta) + N_{\ell-}(\eta)}$$





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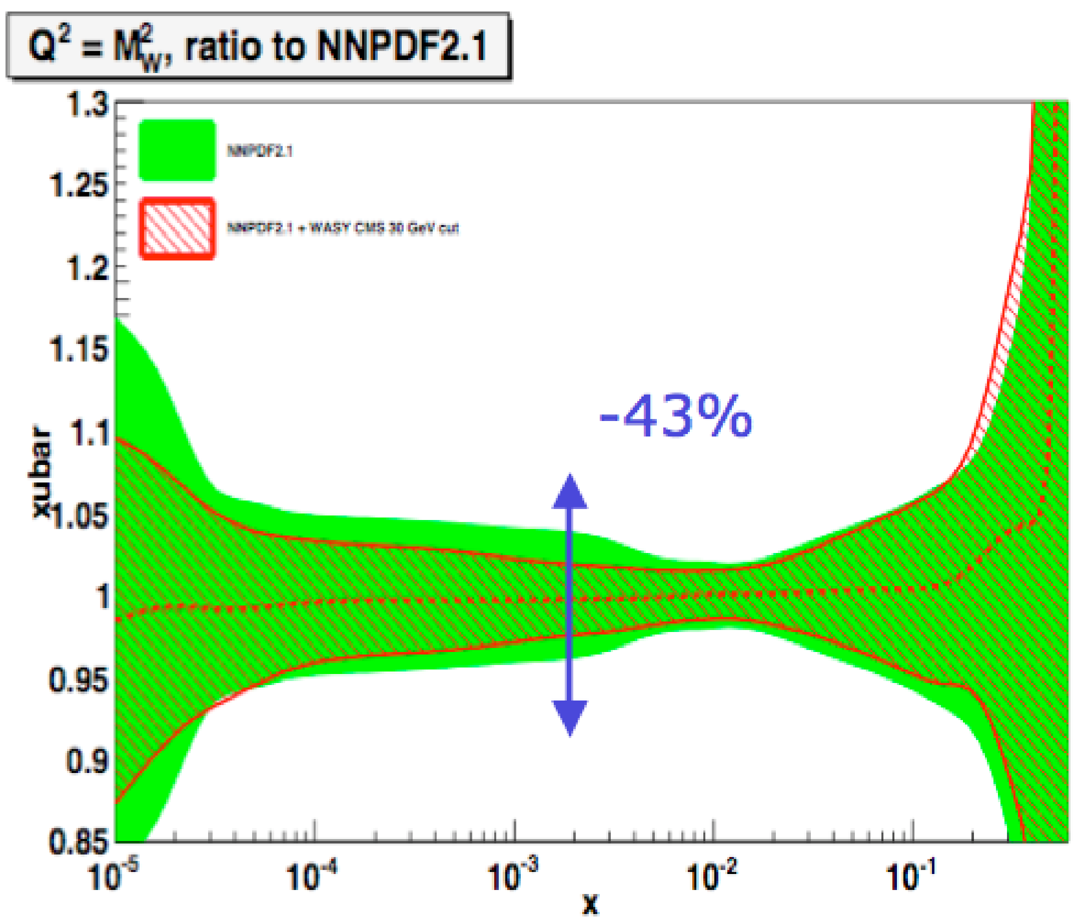

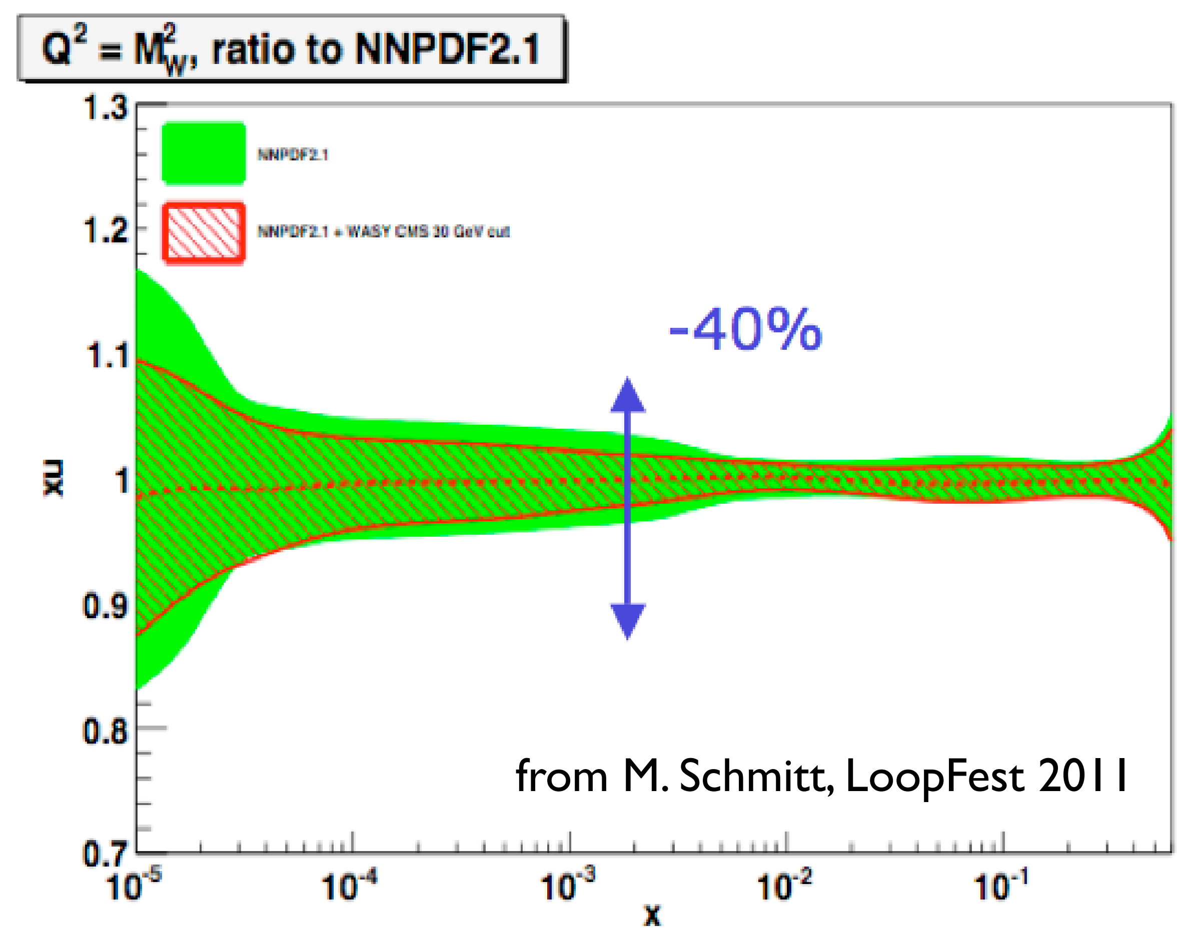

Already entering PDF determinations

Importance of precision tools I

- Probes both valence and sea distributions

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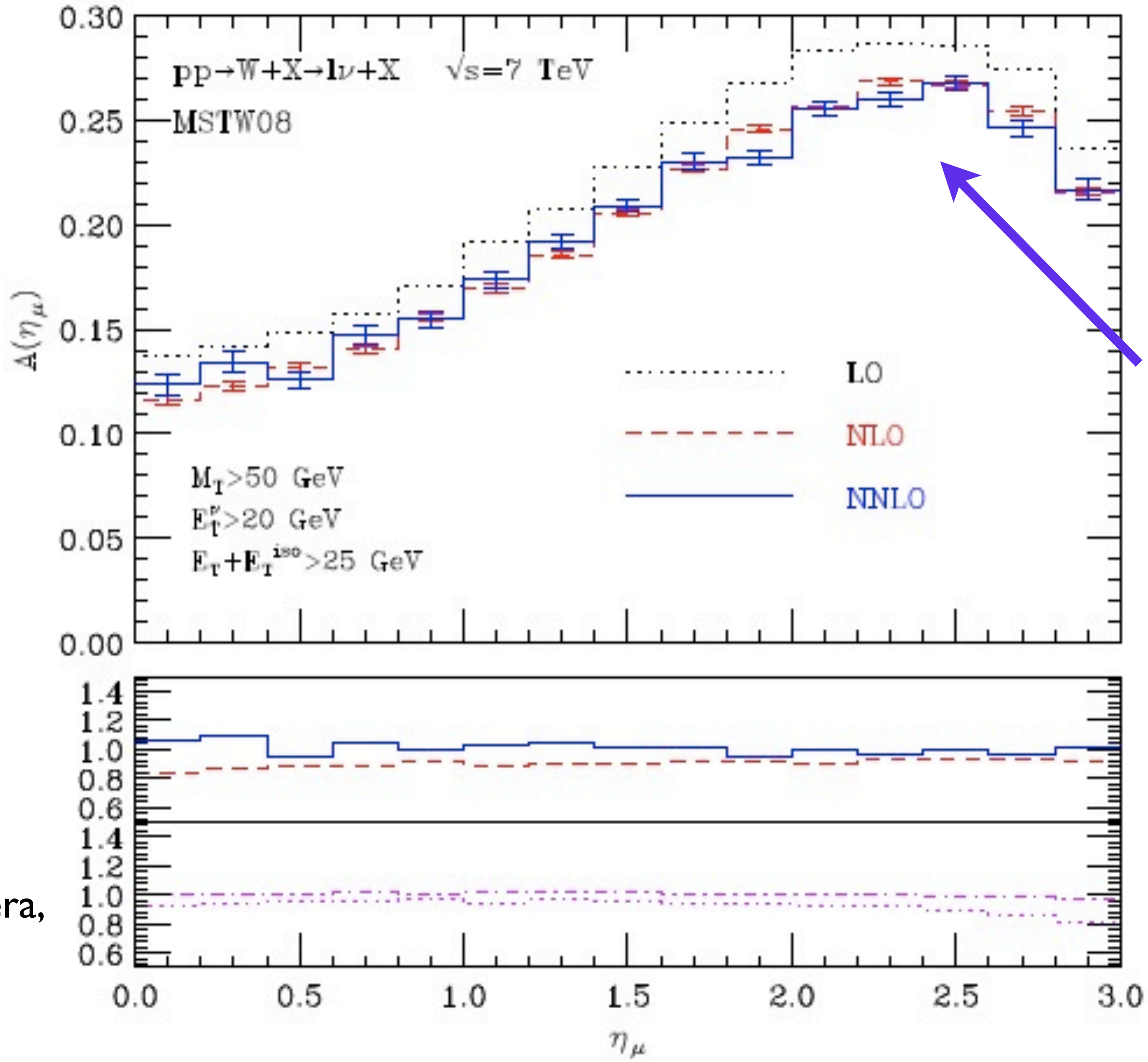


O(10%) shape corrections from QCD; not due to PDFs alone

DYNNLO: Catani, Cieri, Ferrera, de Florian, Grazzini 2009-10

Toward collider-only PDFs

- W charge asymmetry just one of many measurements with PDF impact

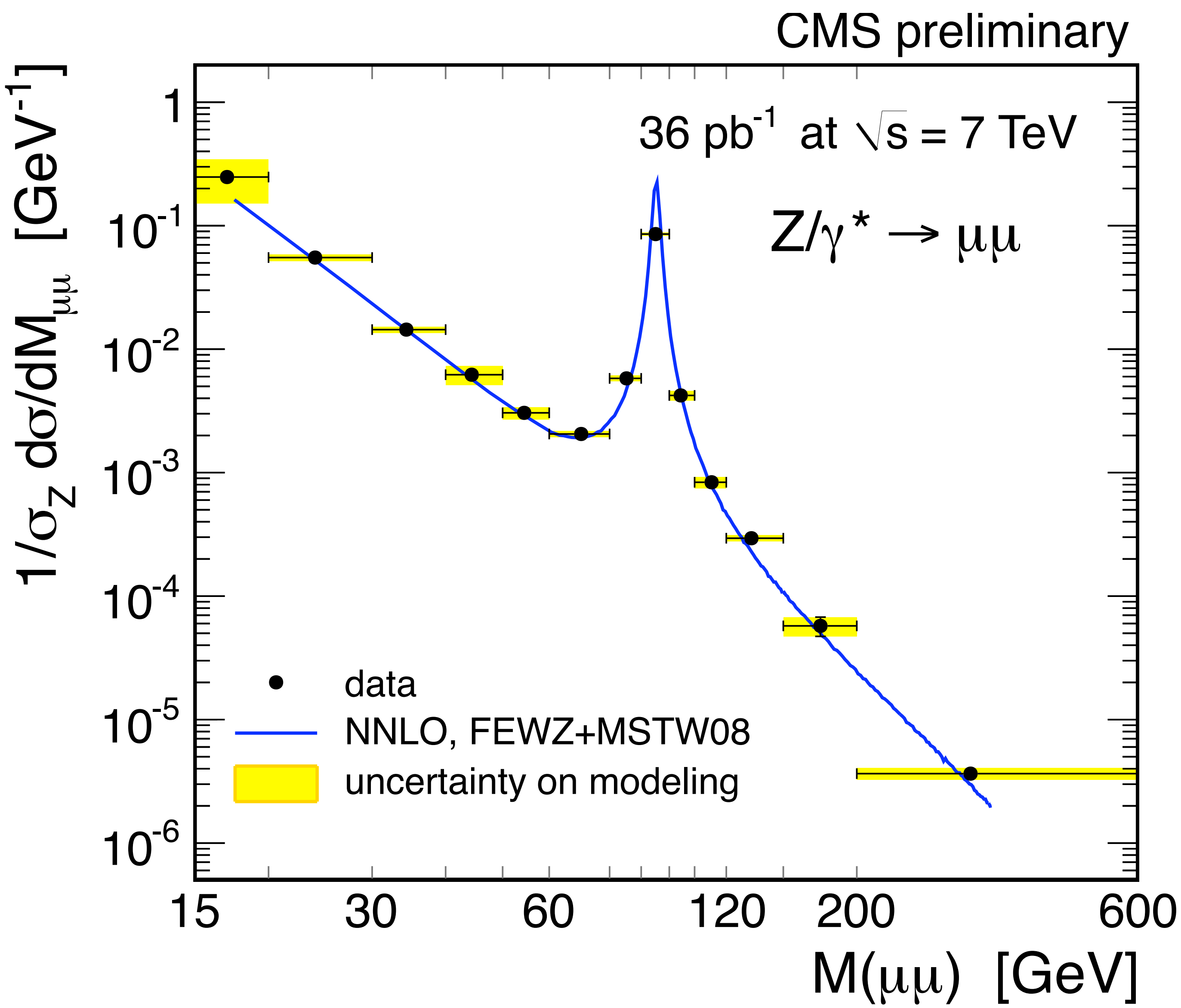
THE FUTURE: COLLIDER-ONLY PDFS

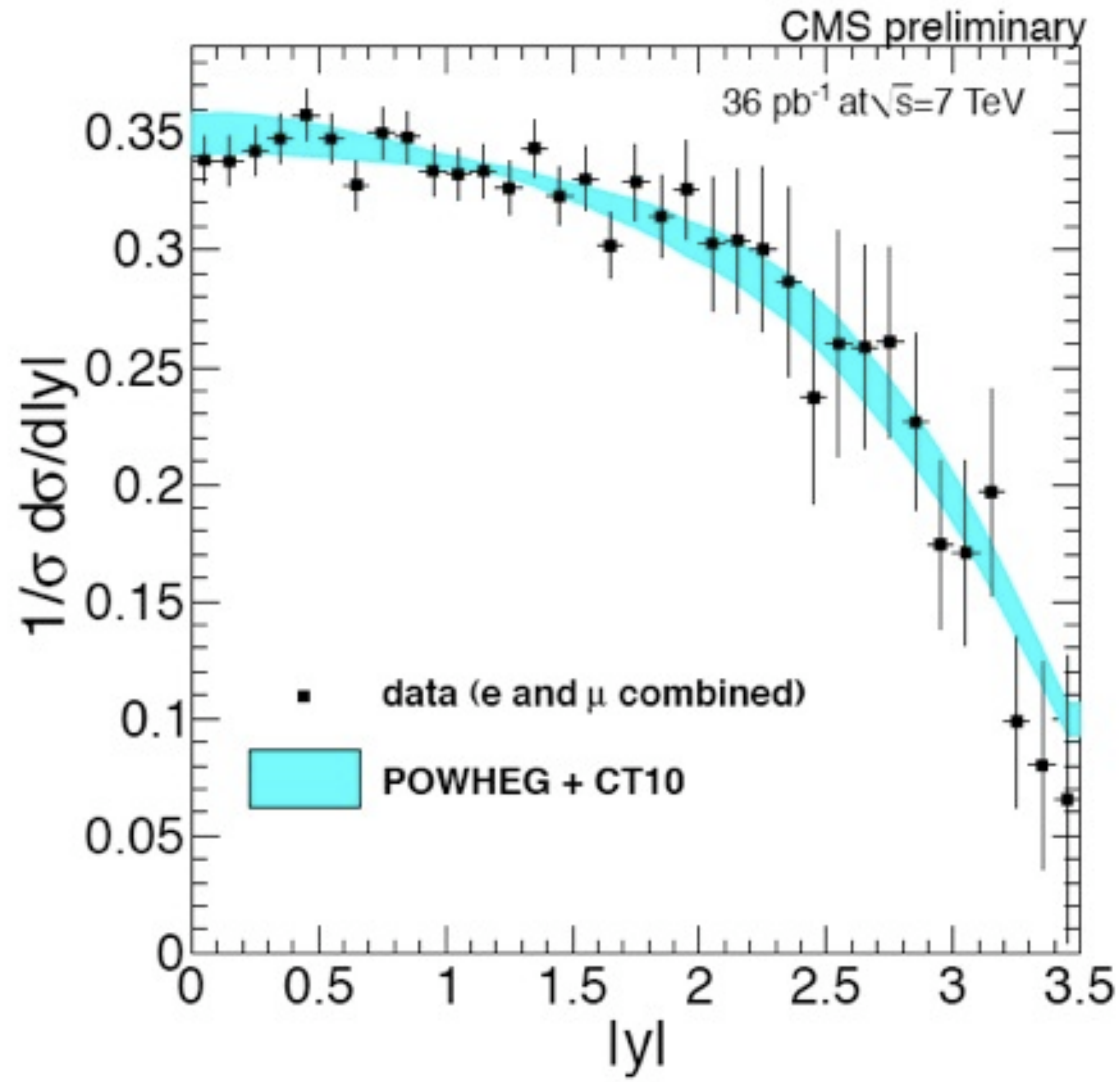
- LHC CAN PROVIDE US PRECISION INFORMATION ON PDFs
- TOWARDS A "COLLIDER ONLY" HERA+LHC PDF FIT (TEVATRON DATA MIGHT BE SUPERFLUOUS)
  - MEDIUM & LARGE x GLUON
    - PROMPT PHOTONS AVAILABLE
    - (PRECISION) JETS IN PROGRESS
  - LIGHT FLAVORS AT MEDIUM @ SMALL x, FLAVOR SEPARATION @ SMALL x
    - LOW–MASS DRELL-YAN PRELIM.
    - Z RAPIDITY DISTRIBUTIONS PRELIM.
    - ✓ W ASYMMETRIES AVAILABLE
  - STRANGENES & HEAVY FLAVORS
    - STRANGENESS $\Rightarrow W + c$ FUTURE?
    - CHARM $\Rightarrow Z + c$, $\gamma + c$ FUTURE?
    - BOTTOM $Z + b$ IN PROGRESS

Let's look briefly at these ☞

S. Forte, BNL 2011

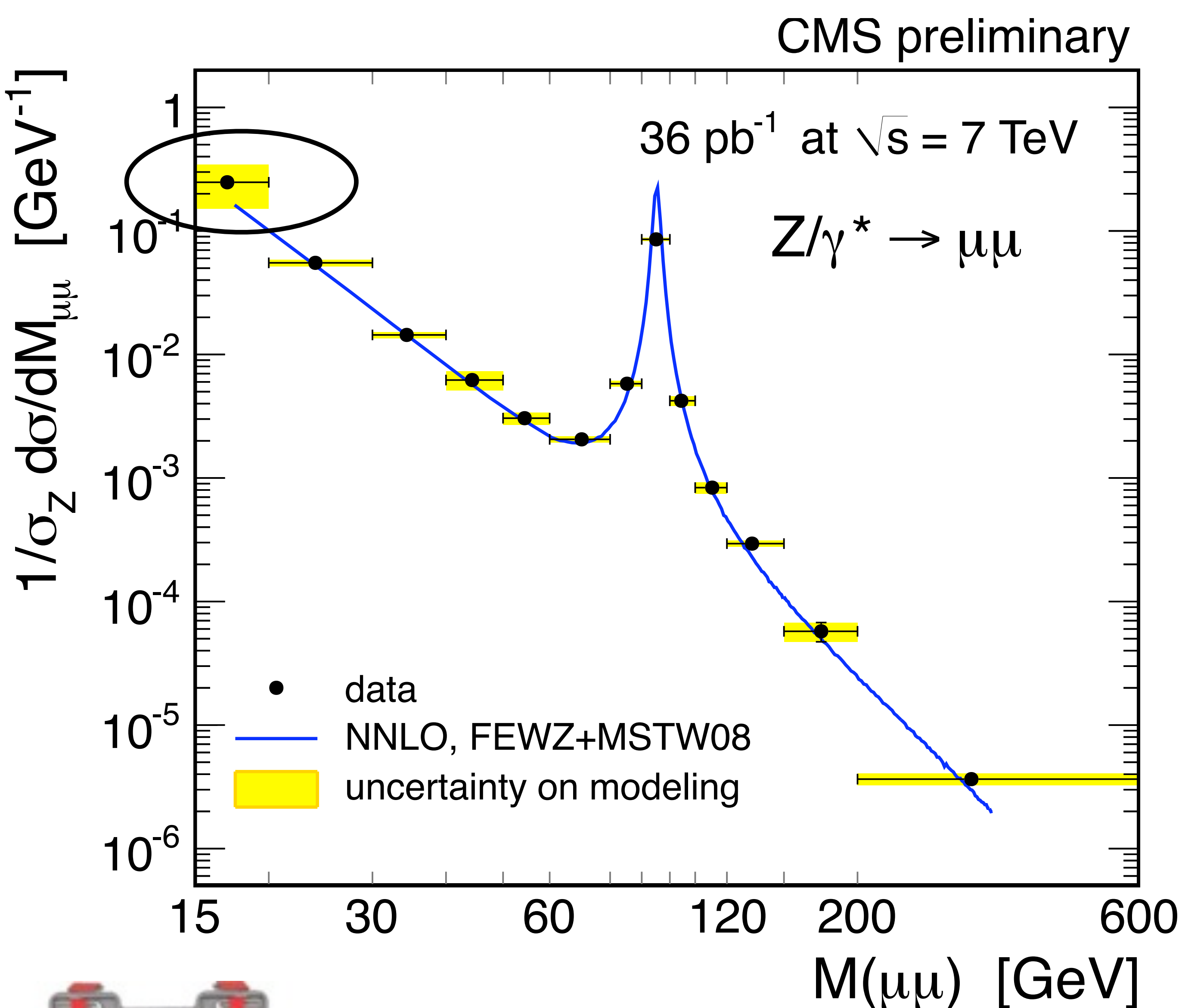
M^2, Y distributions





- Together these probe x from 10^{-4} to 10^{-1} with small theoretical errors

Importance of precision tools II



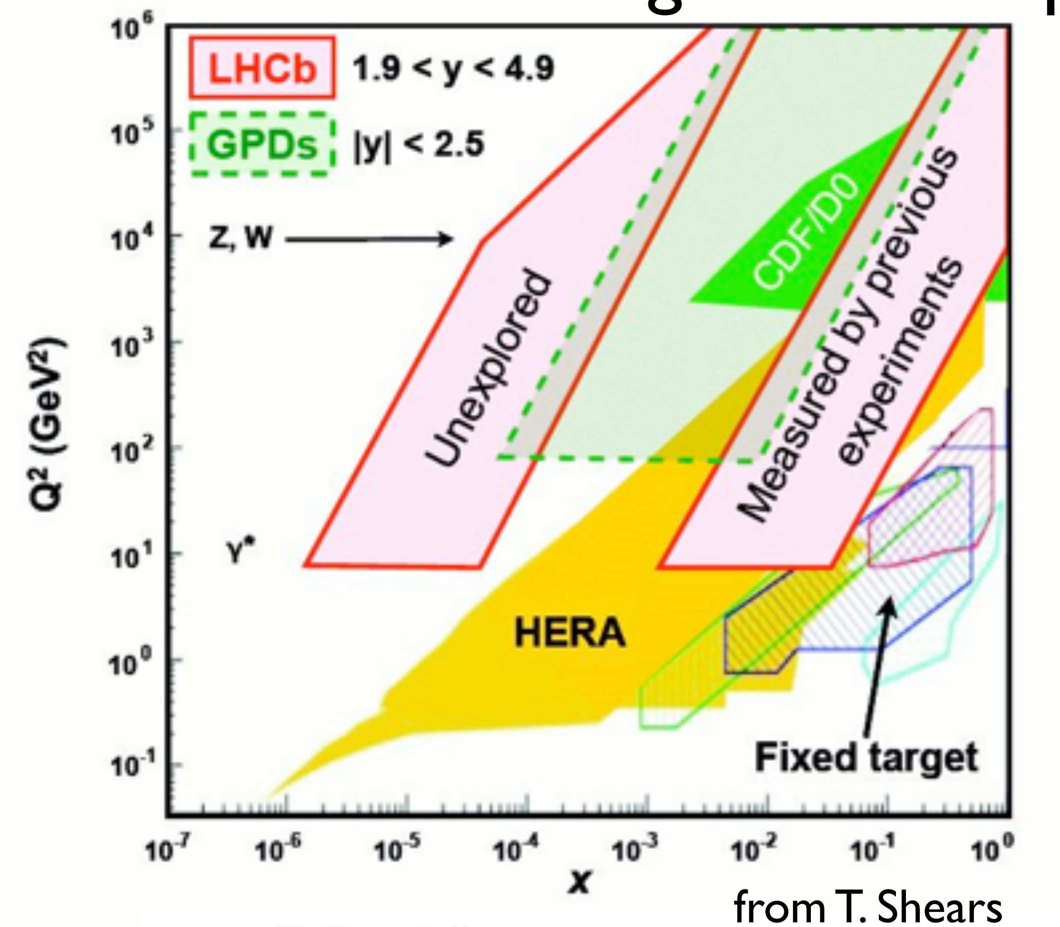
- Double muon trigger: p_{T1}>16 GeV, p_{T2}>7 GeV
- For M=[15,20] GeV: NLO→LO, NNLO→NLO, need a hard jet to generate this configuration
- α_S(15 GeV)≈0.17, K-factor≈1.9 when going from 'N'LO→'N'NLO
- Corrections to POWHEG acceptance of ≈1.5-2

FEWZ: Melnikov, FP; Gavin, Li, Quackenbush, FP, 2006-2010

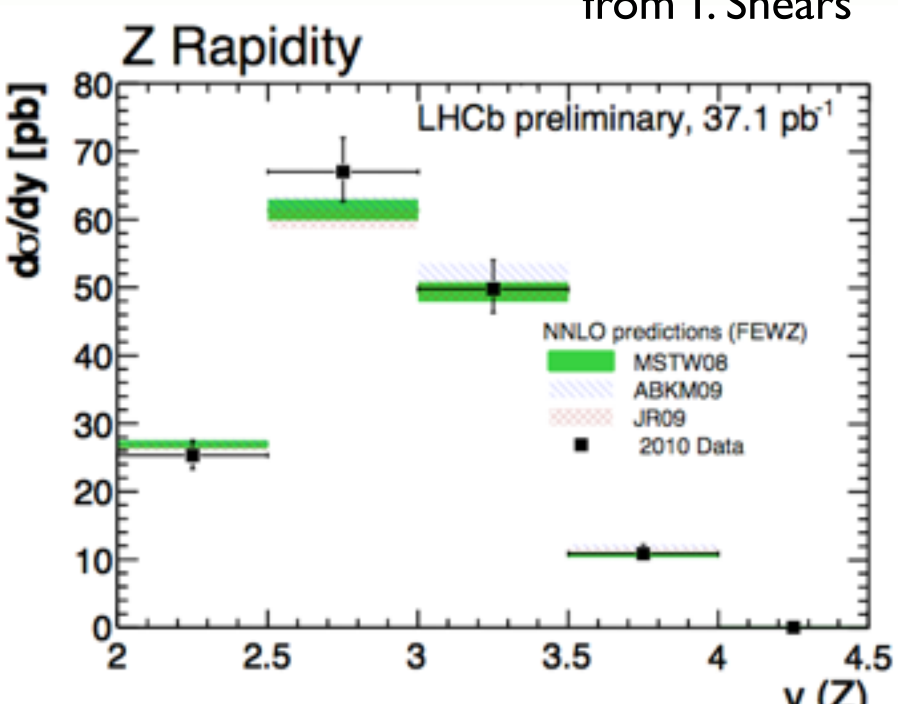
☑ Important to have tools incorporating all our knowledge to catch effects like this

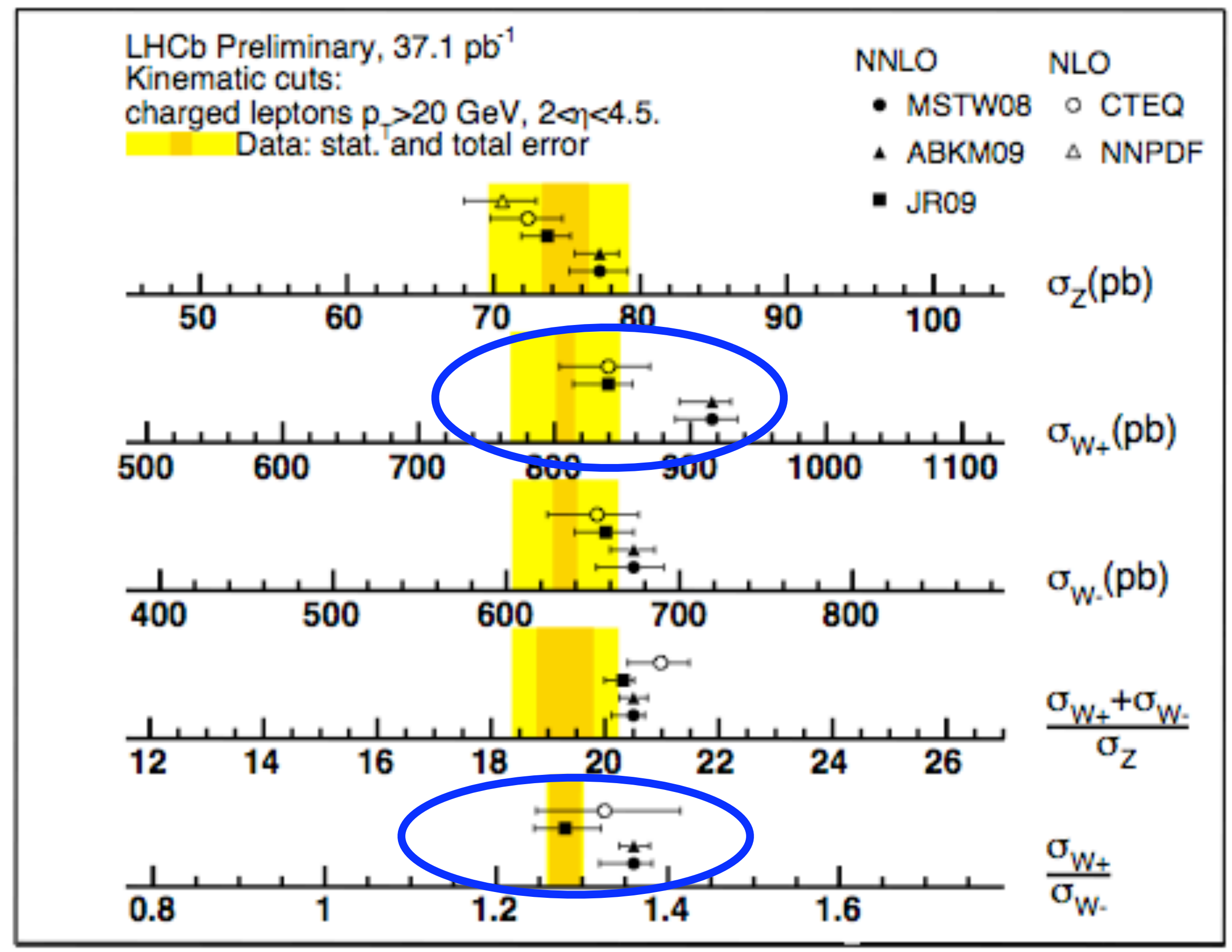
The forward region

- Forward coverage at LHCb probes complimentary x region to ATLAS, CMS



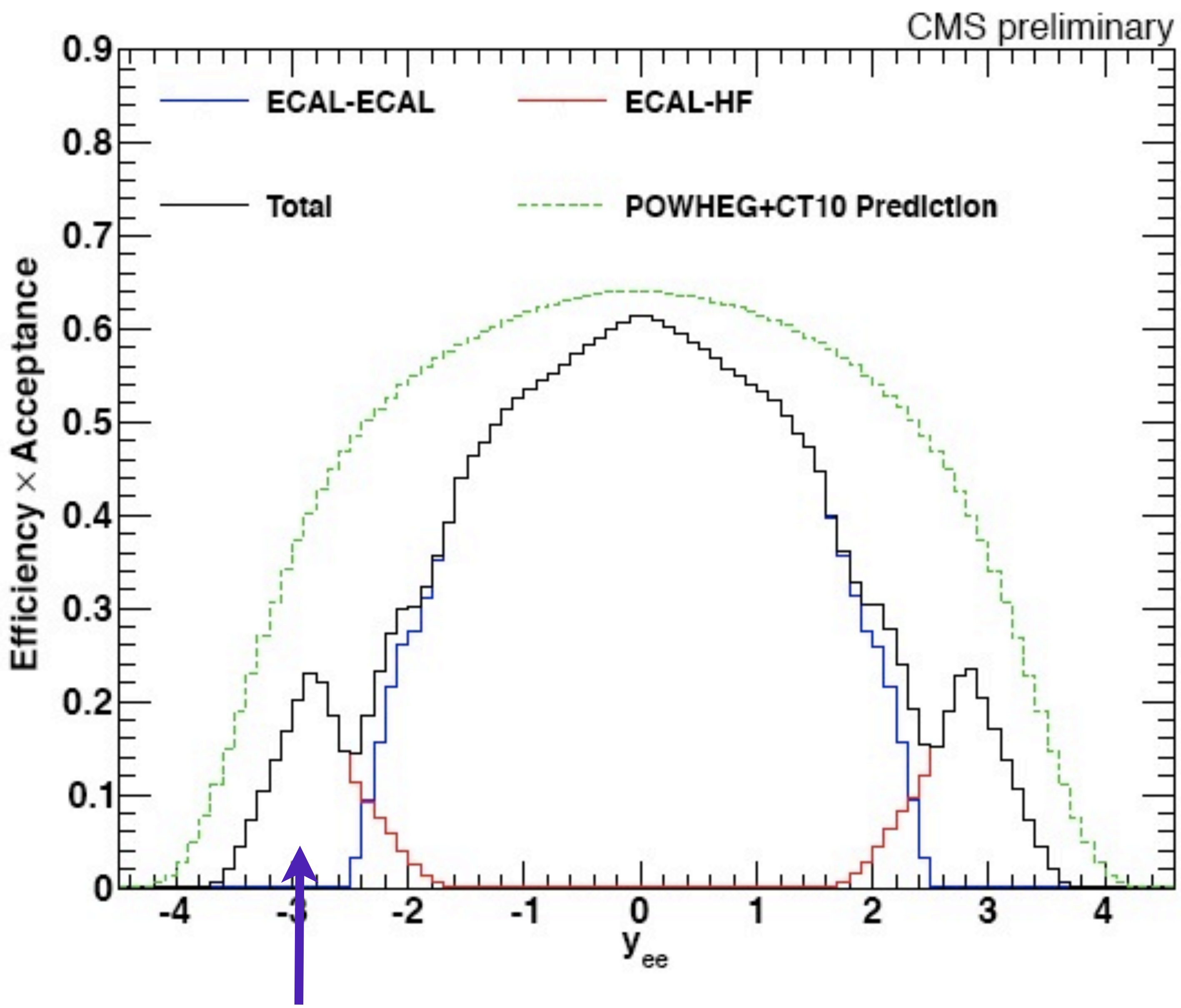
from T. Shears

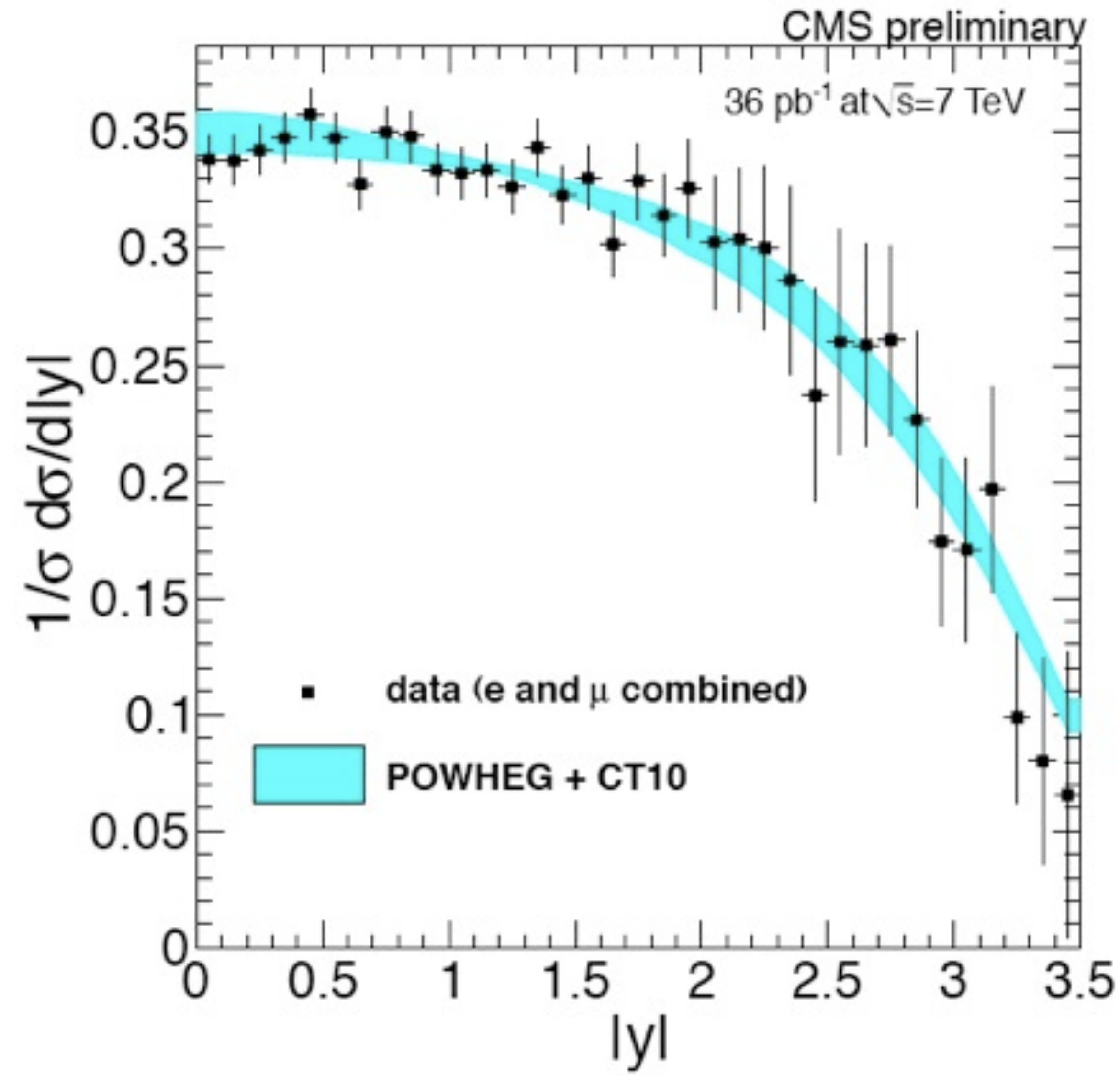




- Clear potential to discriminate between PDF fits

Importance of clever experimenters





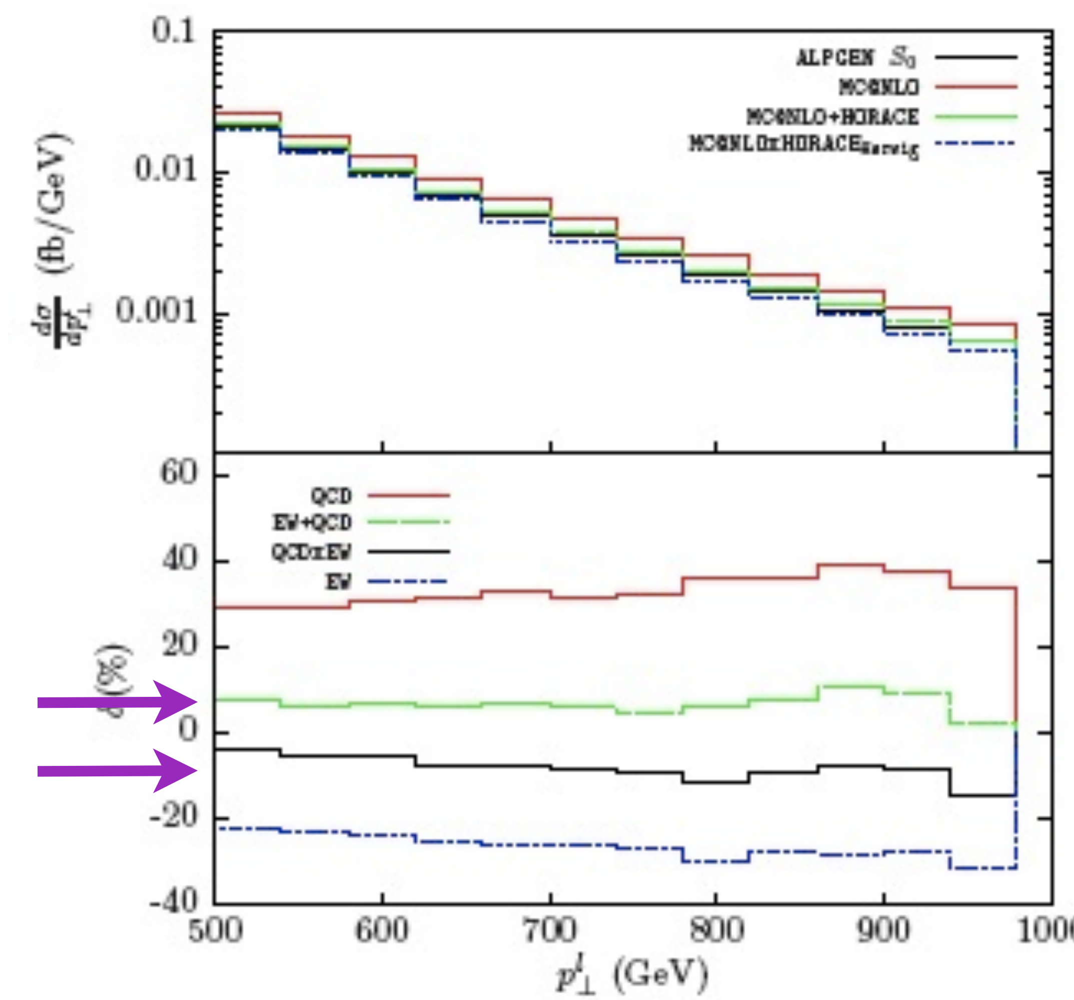
- Can also access forward region in CMS (ATLAS)!
- Reconstruction of electrons in forward HCAL allows extension of Y range
- Should lead to improved PDFs and other EW measurements

Combining QCD and EW

- At percent level, combination of QCD and EW corrections essential: $\alpha_s^2 \sim \alpha_{EW}$

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD\&EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\text{QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{LO}}\right\}_{\text{HERWIG PS}}$$

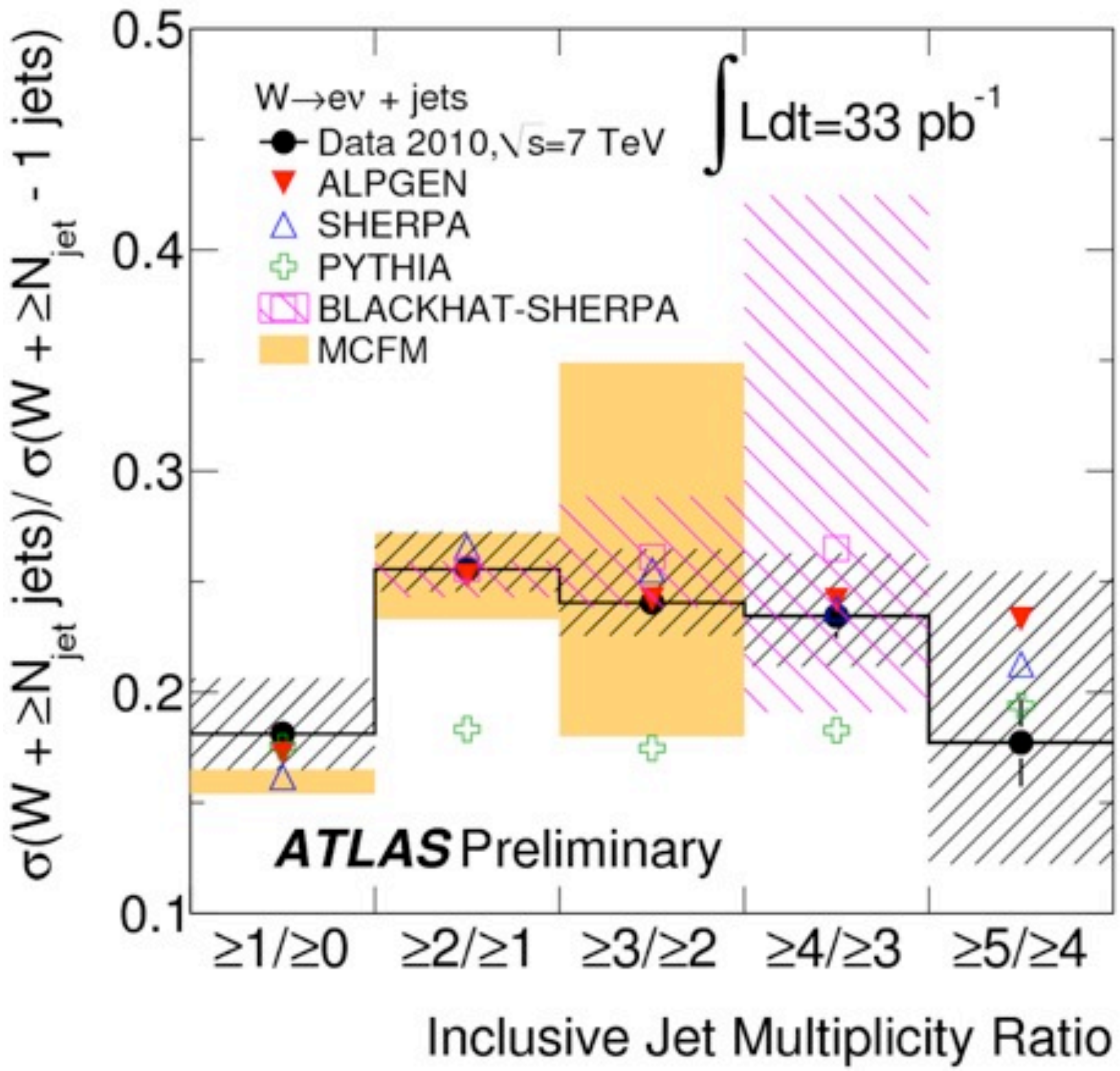
$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1 + \frac{[d\sigma/d\mathcal{O}]_{\text{MC@NLO}} - [d\sigma/d\mathcal{O}]_{\text{HERWIG PS}}}{[d\sigma/d\mathcal{O}]_{\text{LO/NLO}}}\right) \times \left\{\frac{d\sigma}{d\mathcal{O}_{\text{EW}}}\right\}_{\text{HERWIG PS}},$$

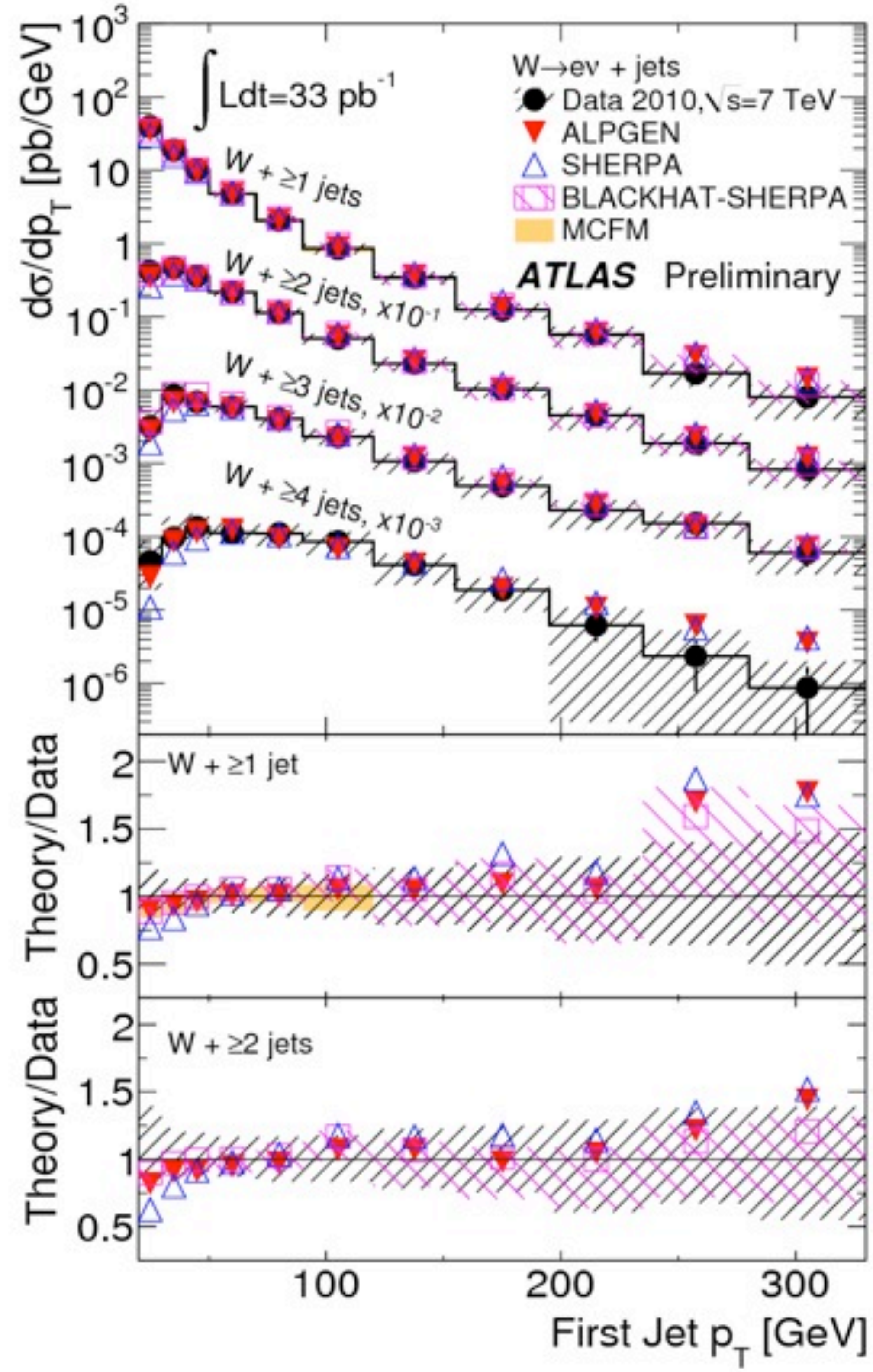


- Differences in prescription can reach few % in certain phase-space regions
- First step toward exact $O(\alpha_s\alpha_{EW})$ to resolve taken Kilgore, Sturm 2011

Balossini, Carloni Calame, Montagna, Moretti, Nicrosini, Piccinini, Treccani, Vicini, 2009

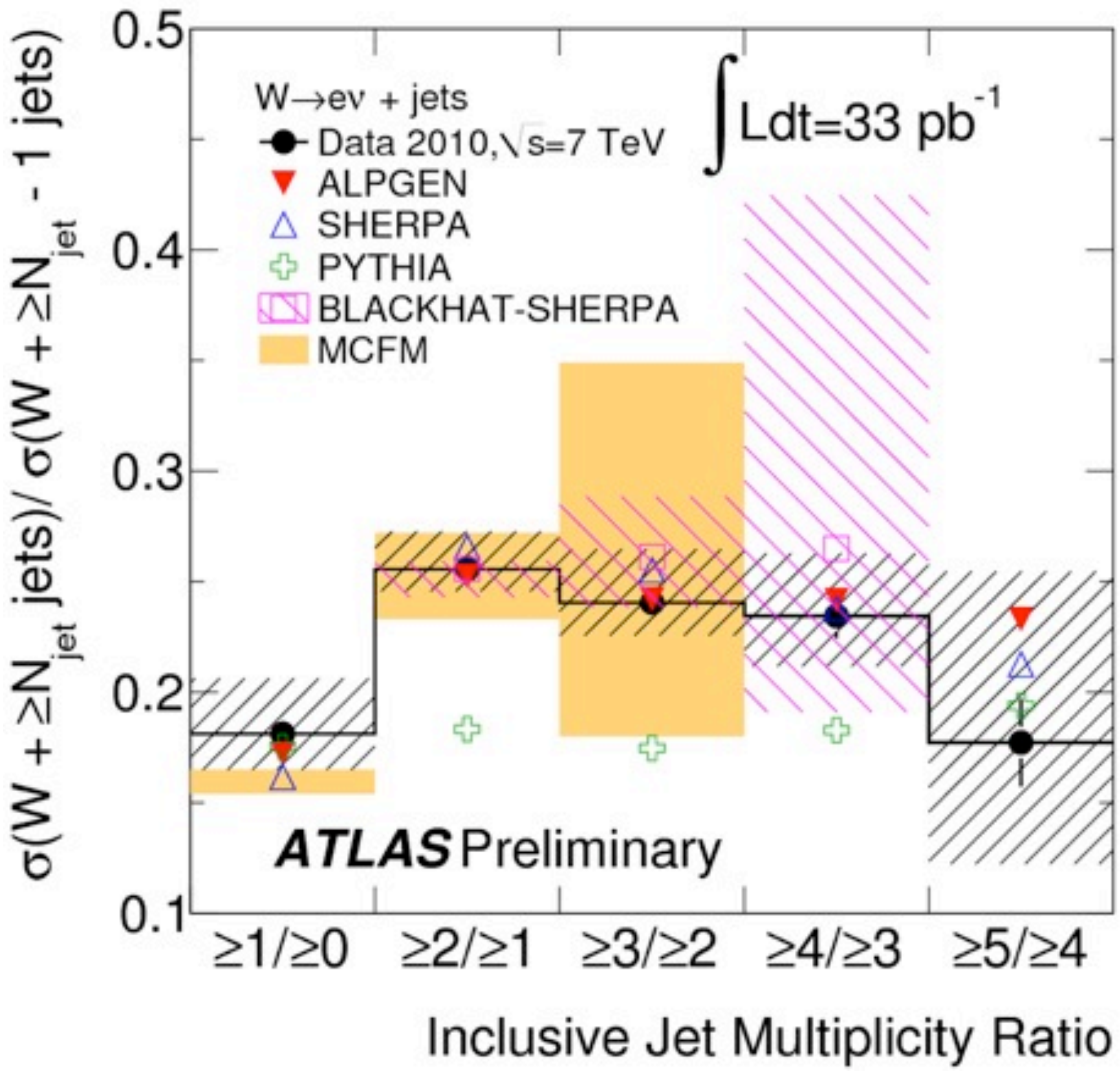
W, Z+jets

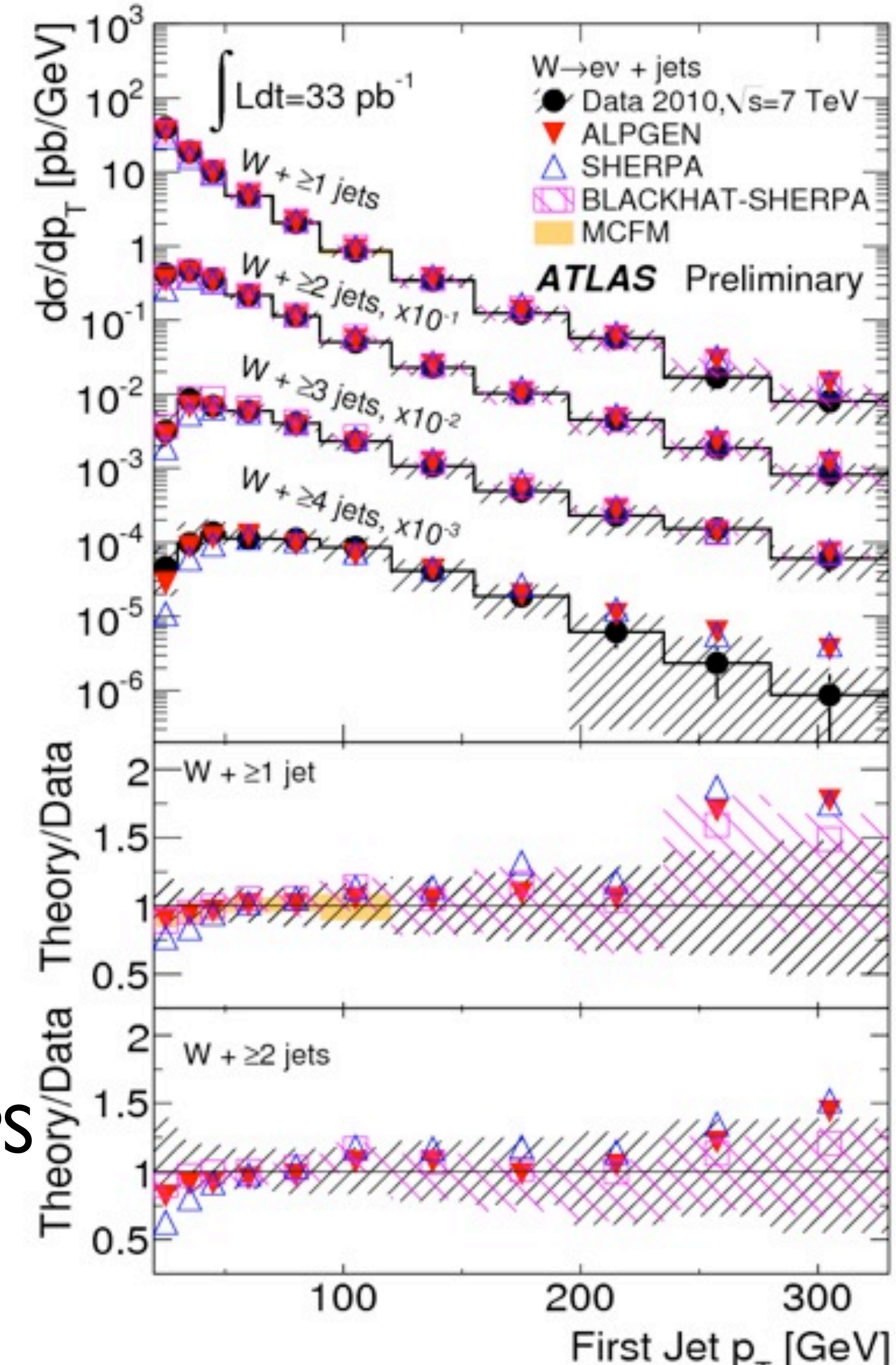




- Agreement across all jet bins, large kinematics region between data and multiple tools

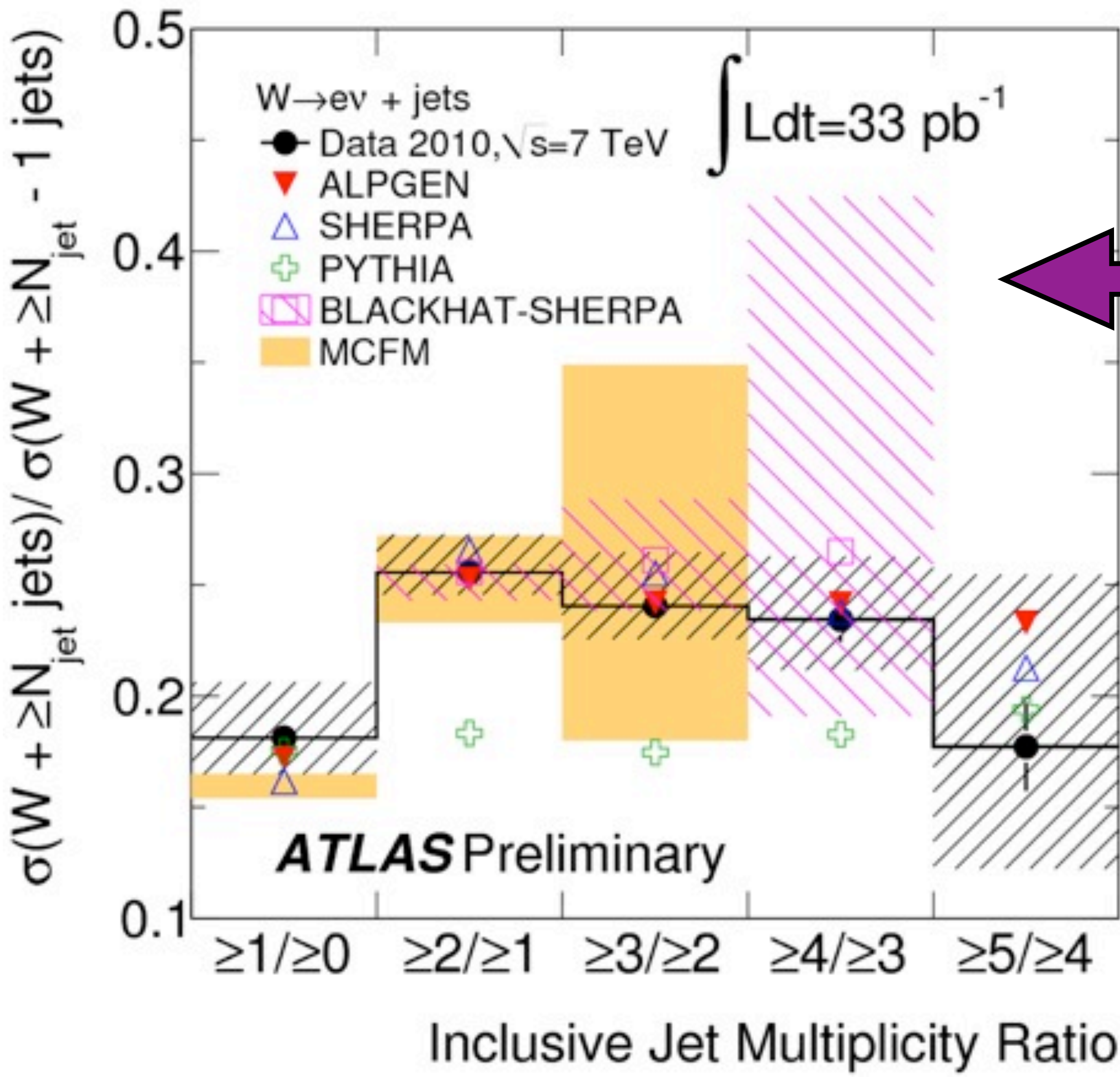
W, Z+jets



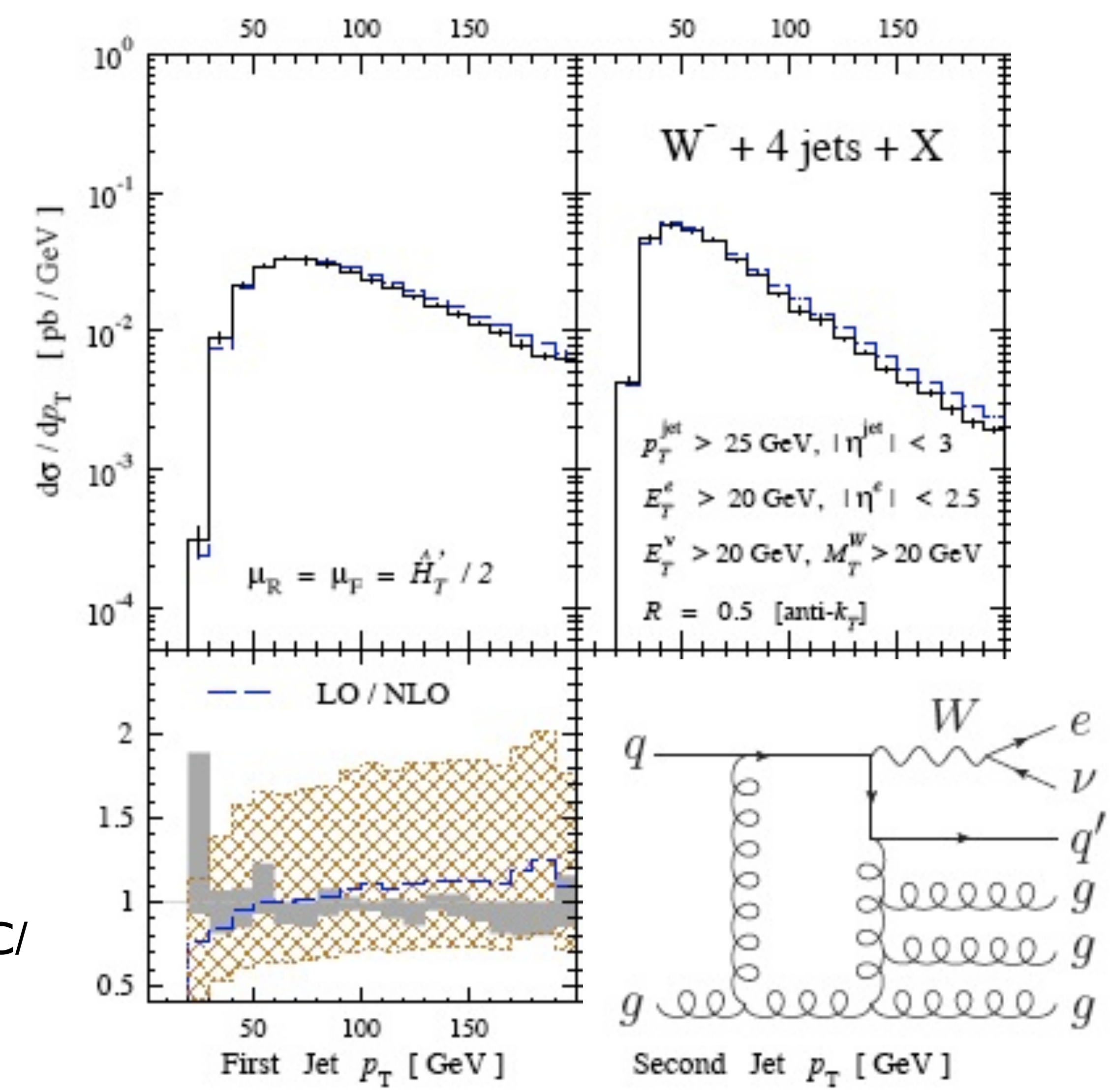


- Once anchored at low bins, tools with ME+PS merging describes kinematics for most processes to ~20%.

W, Z+jets



here, LO for W+4 jets; there is an NLO result now! BLACKHAT+SHERPA: Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre 2010



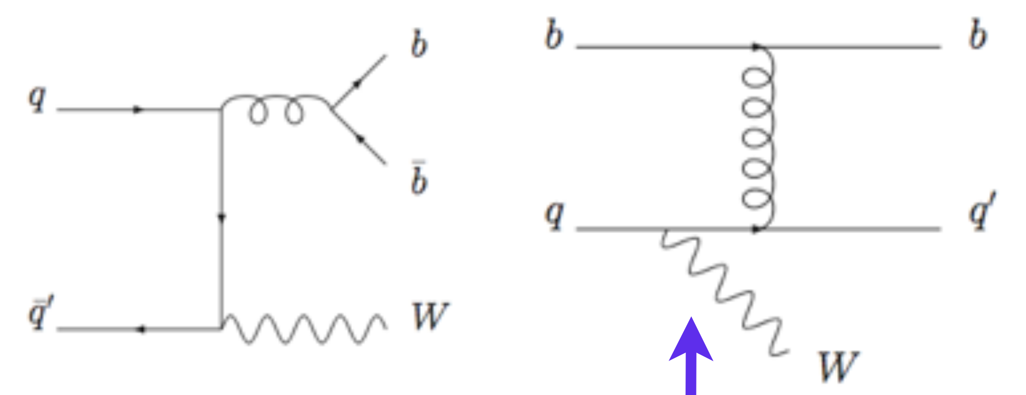
Enormous progress and too many new NLO tools to properly reference here... GOLEM, BLACKHAT, HELAC/ CUTTOOLS,ROCKET, SAMURAI, MCFM, NLOJET++,MADLOOP,VBFNLO,Bredenstein/Denner/Dittmaier/ Pozzorini; MADDIPOLE,AUTODIPOLE,MADFKS+others

W+b jet

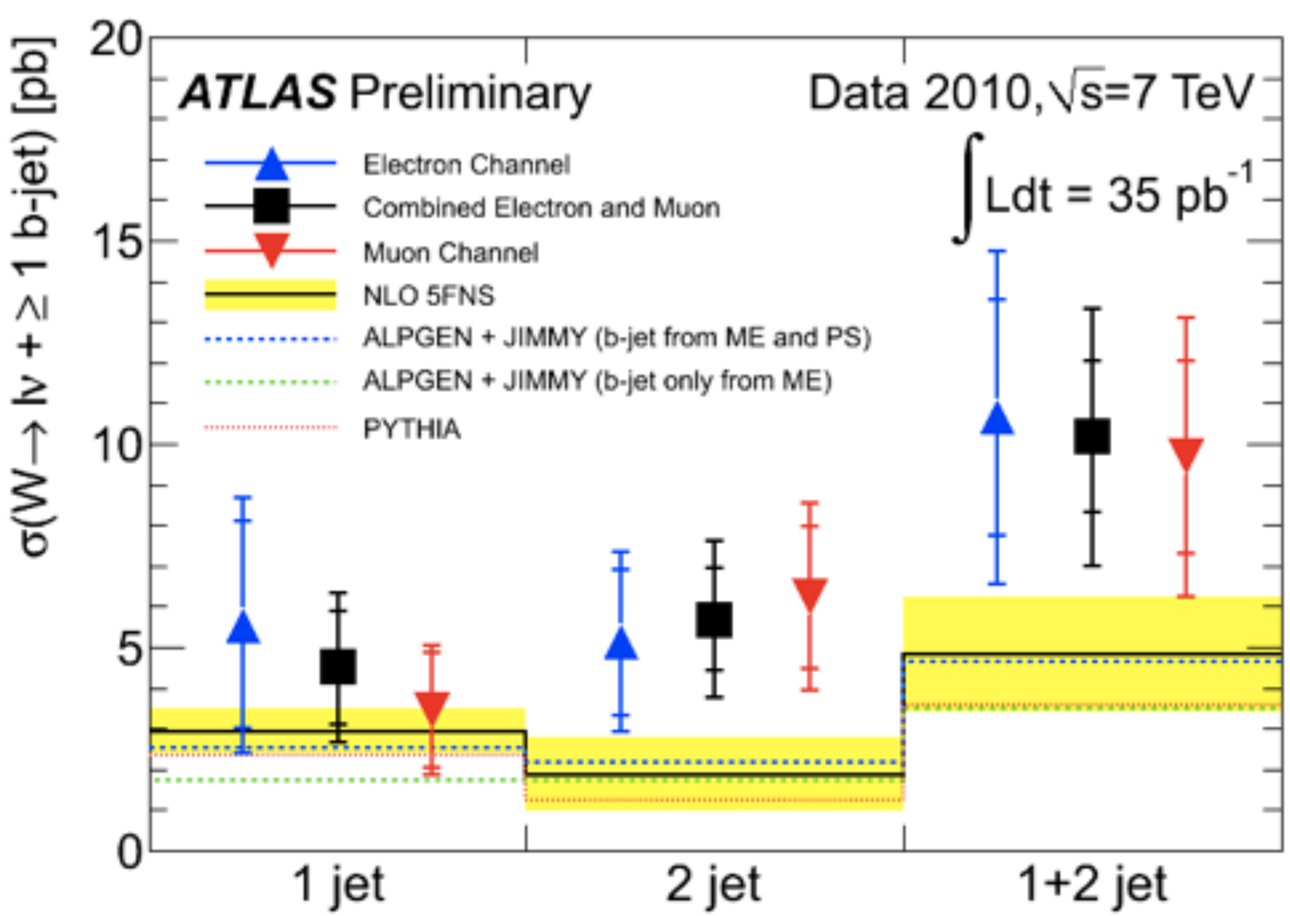
- Discrepancy for W+1 b-jet observed at CDF; difficult to resolve theoretically

CDF	**2.74** pb ±0.27 (stat) ±0.42 (syst)
ALPGEN	**0.78** pb
PYTHIA	**1.10** pb
NLO	**1.22** pb ±0.14(scale)

Campbell et al. 2008



occurs in the 5FNS, with b quark PDF



- Preliminary results agree with NLO to 1.5σ

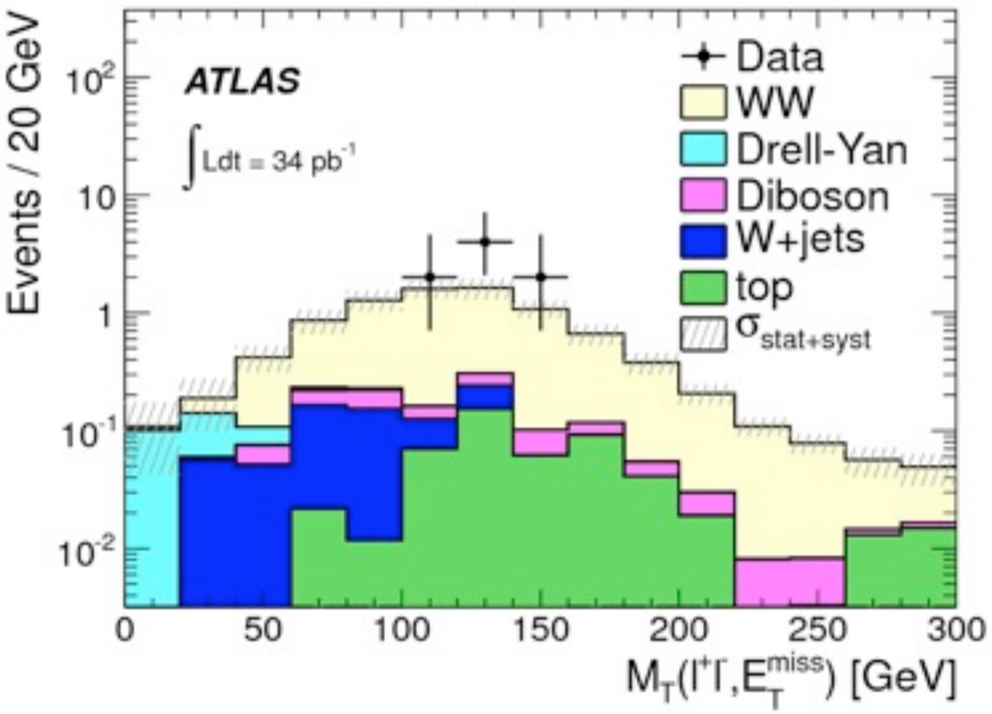
	W^+b incl.	
	Full	4FNS
$\mu = \mu_0/4$	66.3	67.3
$\mu = \mu_0/2$	60.4	52.5
$\mu = \mu_0$	56.7	42.6
$\mu = 2\mu_0$	53.2	35.5
$\mu = 4\mu_0$	50.0	30.1

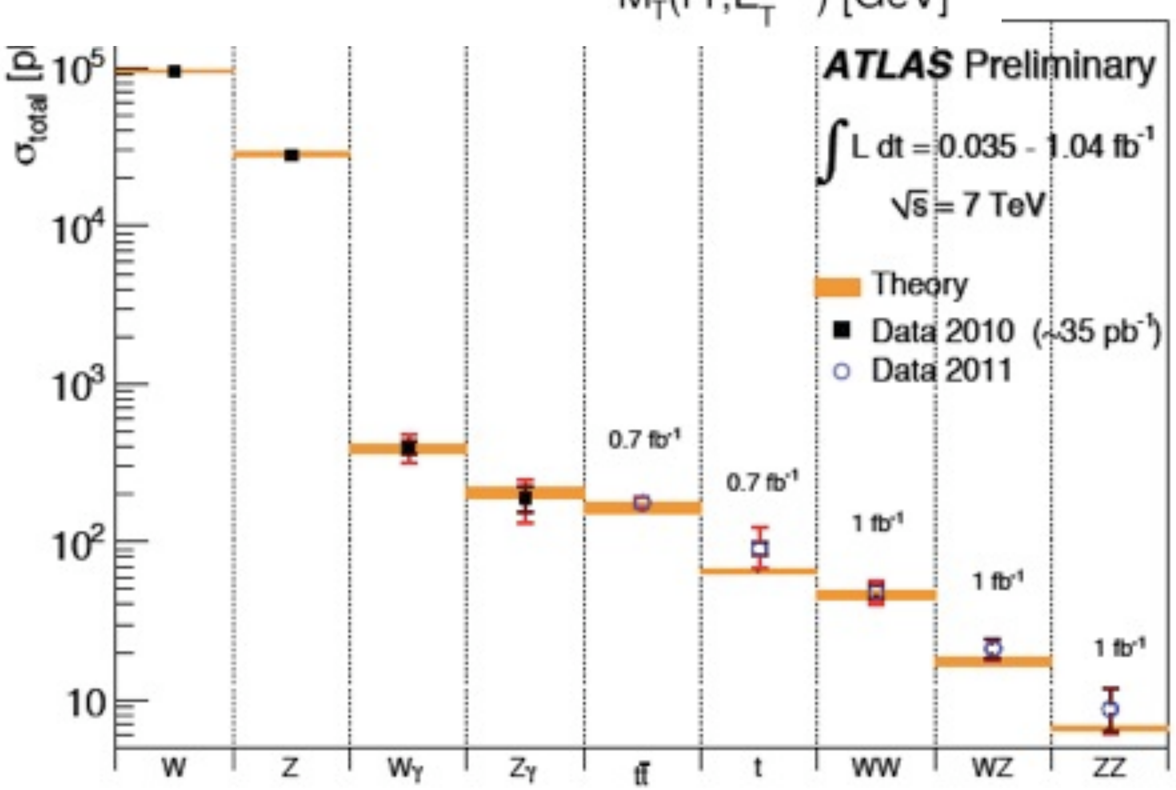
Caola, Campbell, Febres Cordero, Reina, Wackeroth 2011

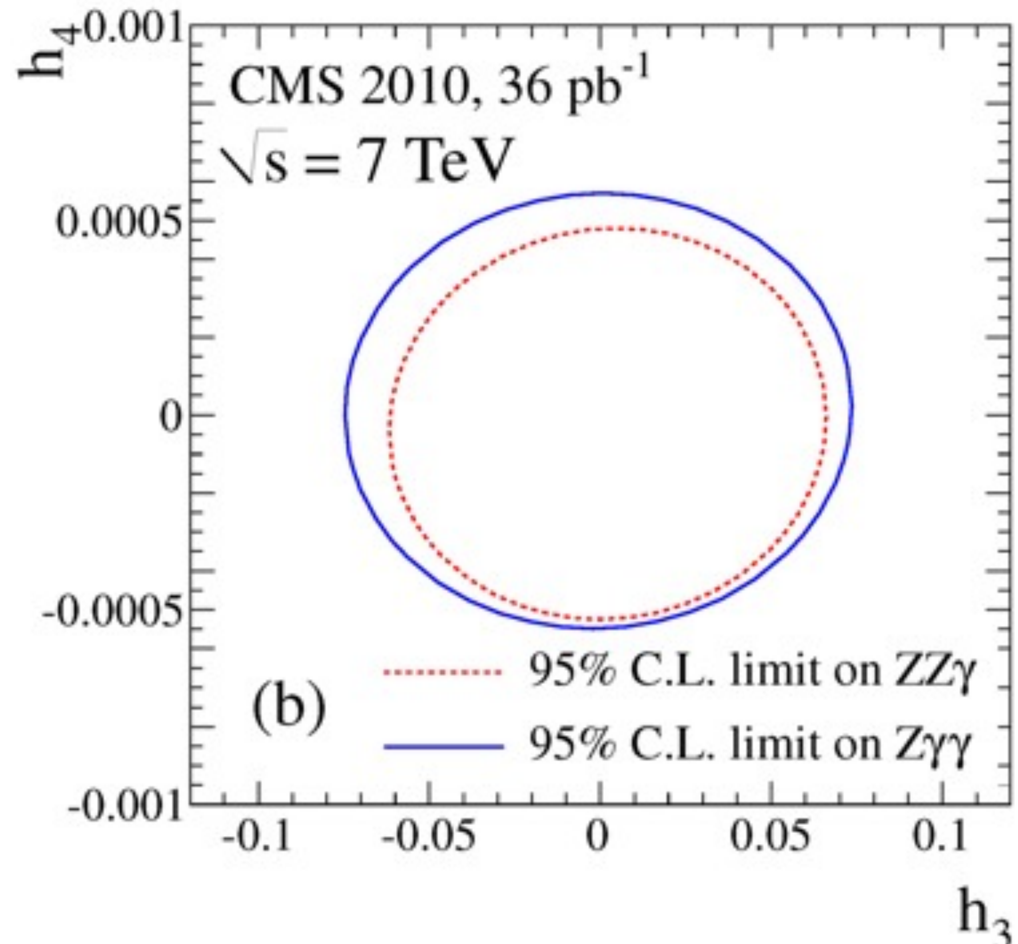
☑ Greatly reduced scale dependence in 5FNS

Di-boson production

- All modes have been observed at the LHC



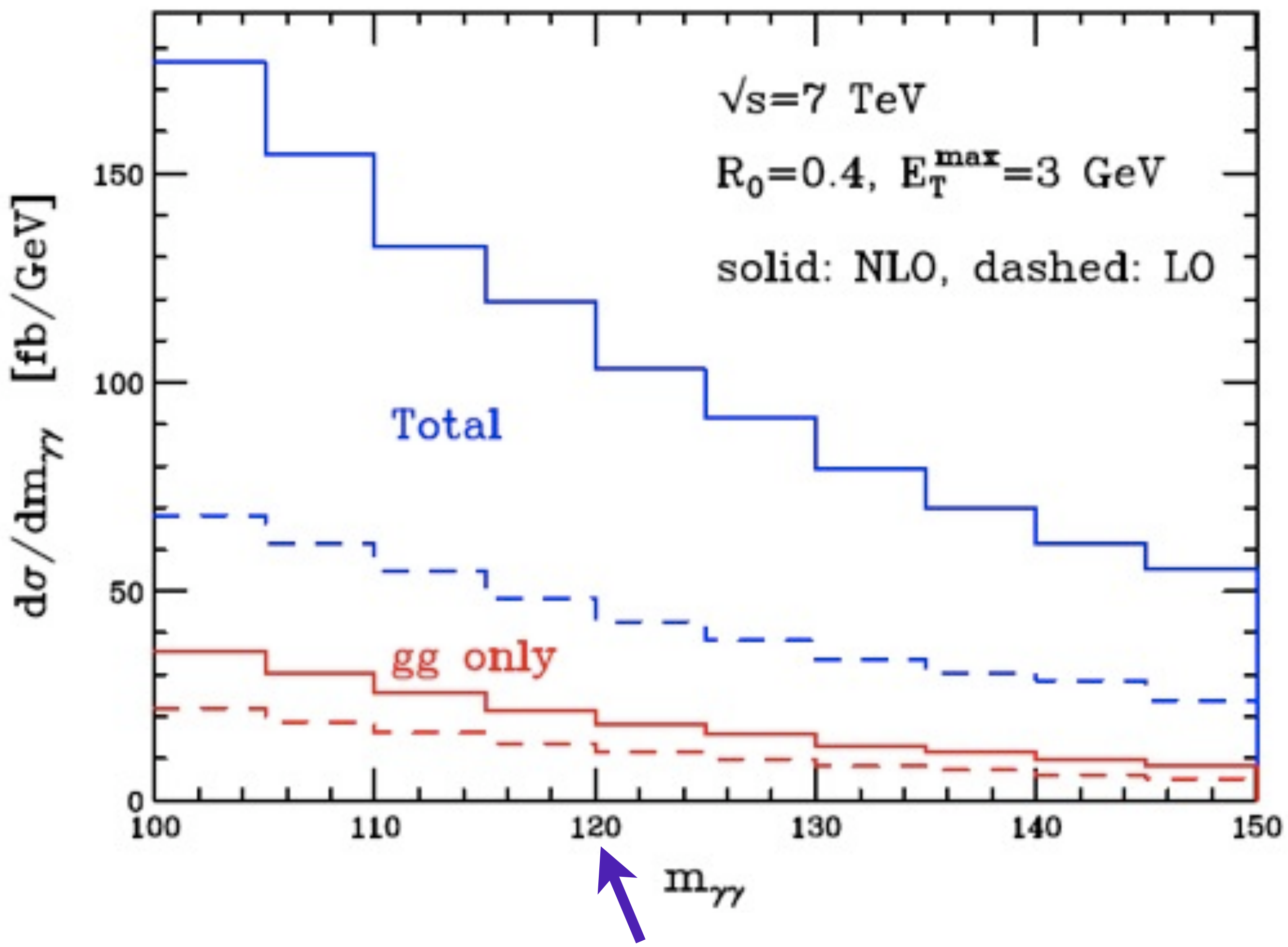




- Already providing impressive constraints on triple gauge couplings

Di-photon Higgs background

- Major interest in di-boson production is as background to Higgs



$p_T^{\gamma 1} > 40$ GeV , $p_T^{\gamma 2} > 25$ GeV , $|\eta_{\gamma_i}| < 2.5$

from MCFM: Campbell, Ellis, Williams 2011

$\sqrt{s}$ [TeV]	$\sigma^{LO}(\gamma\gamma)$ [pb]	$\sigma^{NLO}(\gamma\gamma)$ [pb]
7	35.98(0)	$47.0(1)^{+5\%}_{-6\%}$

$p_T^{\gamma} > 25$ GeV , $|\eta_\gamma| < 5$

- 'Staggered' momentum cuts change K=1.3→3
- At LO, $p_{T1}=p_{T2}$, cut effectively 40 GeV
- Region between 25-40 GeV first opens at NLO, leading to large corrections
- Are the staggered cuts experimentally necessary? They complicate QCD background predictions

Conclusions

- After only one year, W and Z physics at the LHC is approaching percent-level... theory/PDF limited already in some results
- Benefit to extensive interactions between theorists and experimenters working in this area; non-trivial interplay between QCD and experimental cuts
- Great progress in theory; W+3,4 jets now known at NLO (W+4 jets almost unthinkable a few years ago)
- In preparing for this, was struck by the experimental progress from LHC 2010→LHC 2011
- My hope for 2012 talks on EW physics:

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