

DPF 2011 – Brown University

Electroweak Physics

Michael Schmitt

Northwestern University

August 9, 2011

What is Electroweak Physics.

fermions

- masses
- couplings / mixing

$$G_F \sin^2 \theta_W$$

gauge bosons

- masses
- tri-linear couplings

Higgs boson / EWSB

New Measurement of G_F

- new (2011) measurement of muon lifetime

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} (1 + \Delta q)$$

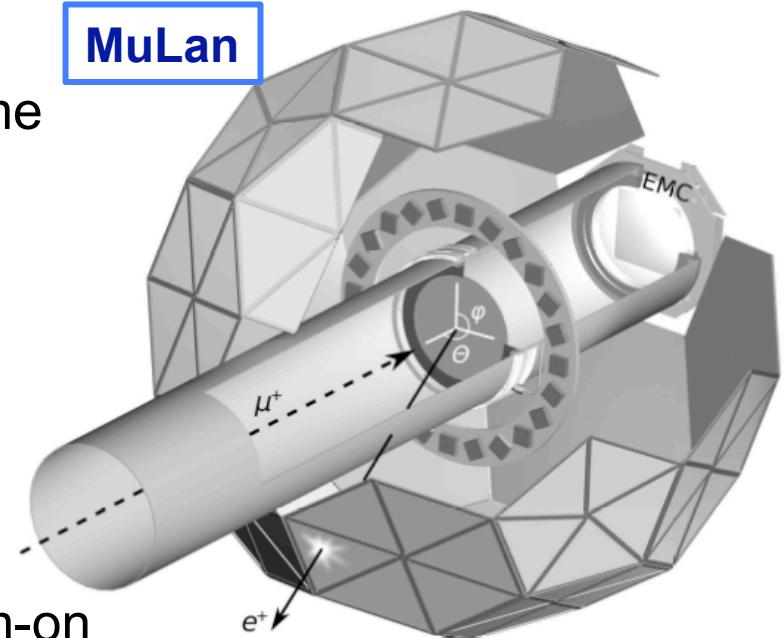
- improvement by factor 15 over all prior measurements
- $2 \times 10^{12} \mu^+$ decays
- accumulate muons in target during beam-on
- record individual e^+ pulses (24 slices)
- icosahedral arrangement reduces systematics

$$G_F = 1.1663788(7) \times 10^{-5} GeV^{-2}$$

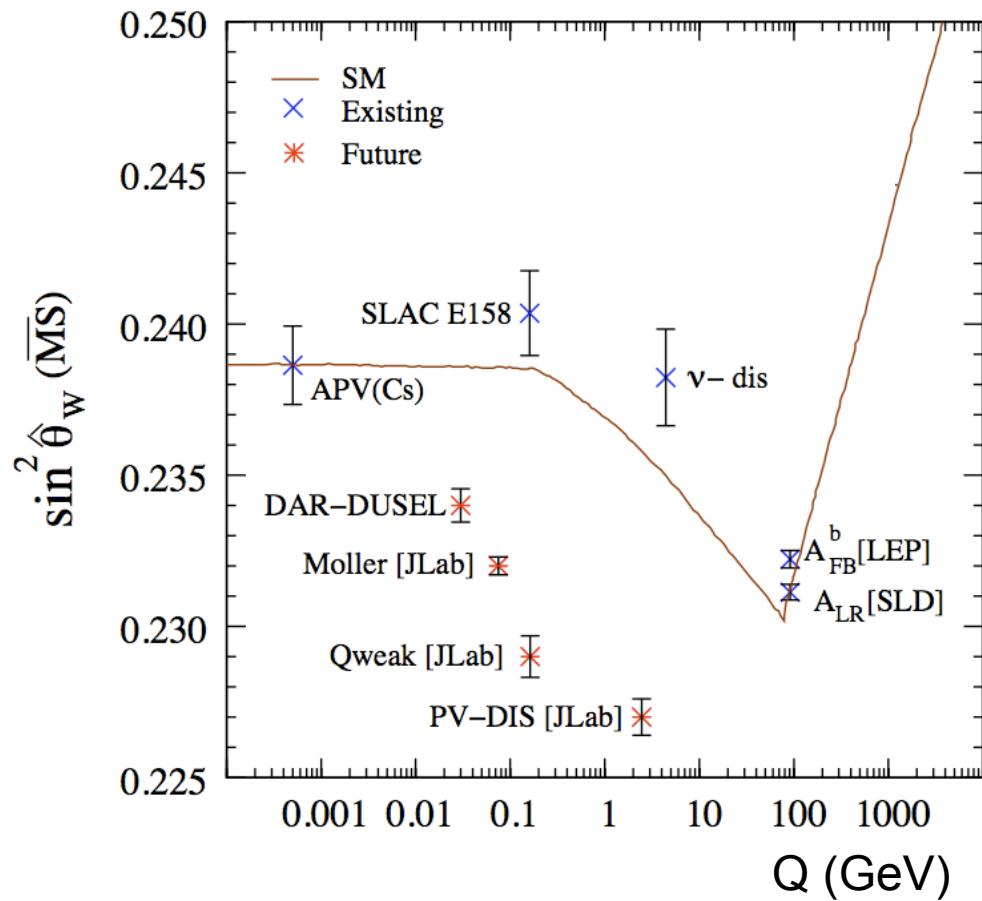
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0.6 ppm

Phys.Rev.Lett. **106** (2011) 041803



$\sin^2\theta_W$ at Low Energy



Argwalla, arXiv:1005.1254

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- NuTeV anomaly has proved to be provocative...
- E158 demonstrated a precise measurement of $\sin^2\theta_W$ and that $\sin^2\theta_W$ runs.
- **Qweak** just completed 1st run
 - longitudinal e⁻ on liquid H₂
 - very low $Q^2 \approx 0.07 \text{ GeV}^2$
 - $A_{PV} \approx 230 \text{ ppb}$, measure to 2.5%, expect $\sin^2\theta_W$ to 0.3%
 - 24% of proposed data recorded
 - “teething pains” overcome
 - look forward to 1st results soon.
- **Møller** approved
 - error 3 times smaller than Qweak
 - $\sin^2\theta_W$ to ± 0.00029 (\approx LEP)

W and Z Production at Hadron Colliders

- production
 - copious, even in a pp machine like the LHC
 - depends on proton structure
 - PDFs and pQCD inseparable from EWK physics at hadron colliders
- decay
 - leptonic decays are the most useful by far
 - tau final states are clear but less precise than decays to e^- and μ^-
 - neutrinos in the final state implies use of “missing energy”

$$Z \rightarrow \ell^\pm \ell^\mp$$

- energetic & isolated e^+e^- or $\mu^+\mu^-$
- resonant peak in $M_{\ell\ell}$

$$W^\pm \rightarrow \ell^\pm \bar{\nu}$$

- energetic & isolated e^- or μ^-
- neutrino: E_t^{miss}
- Jacobian peak in M_T

see talks by F. Petriello, J. Anderson

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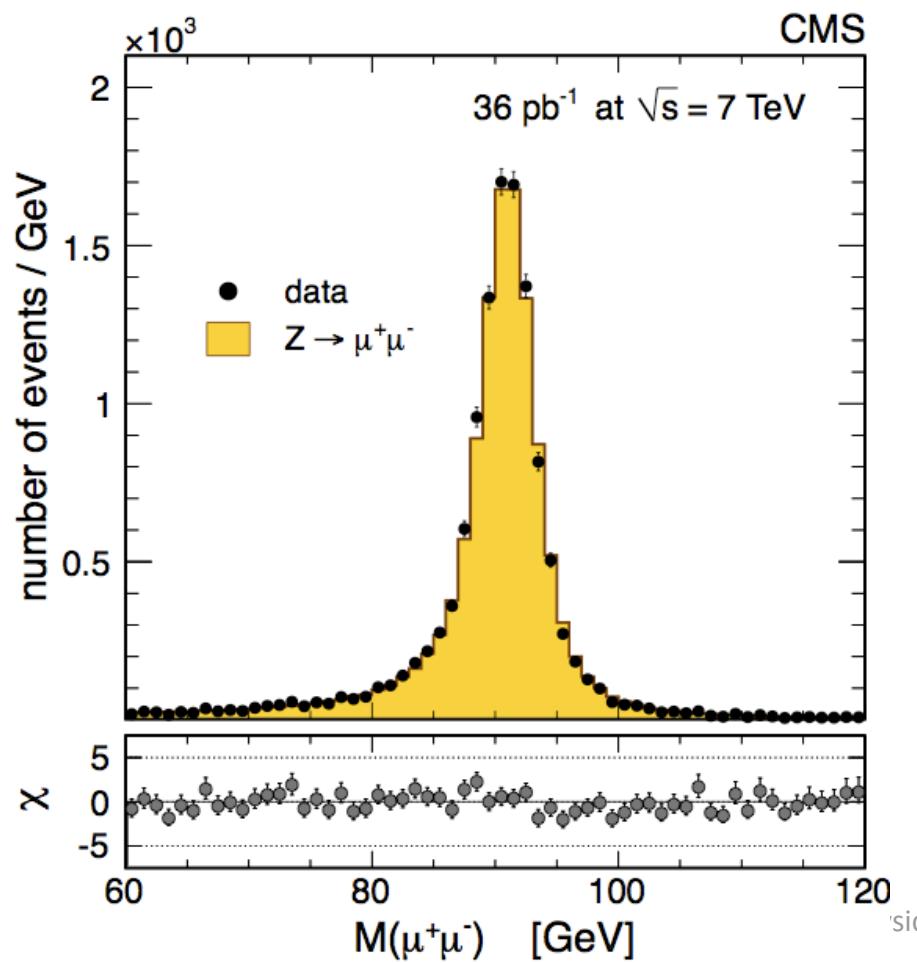
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These results are based on 36 pb^{-1} collected in 2010. Today: *nearly* 2 fb^{-1} .

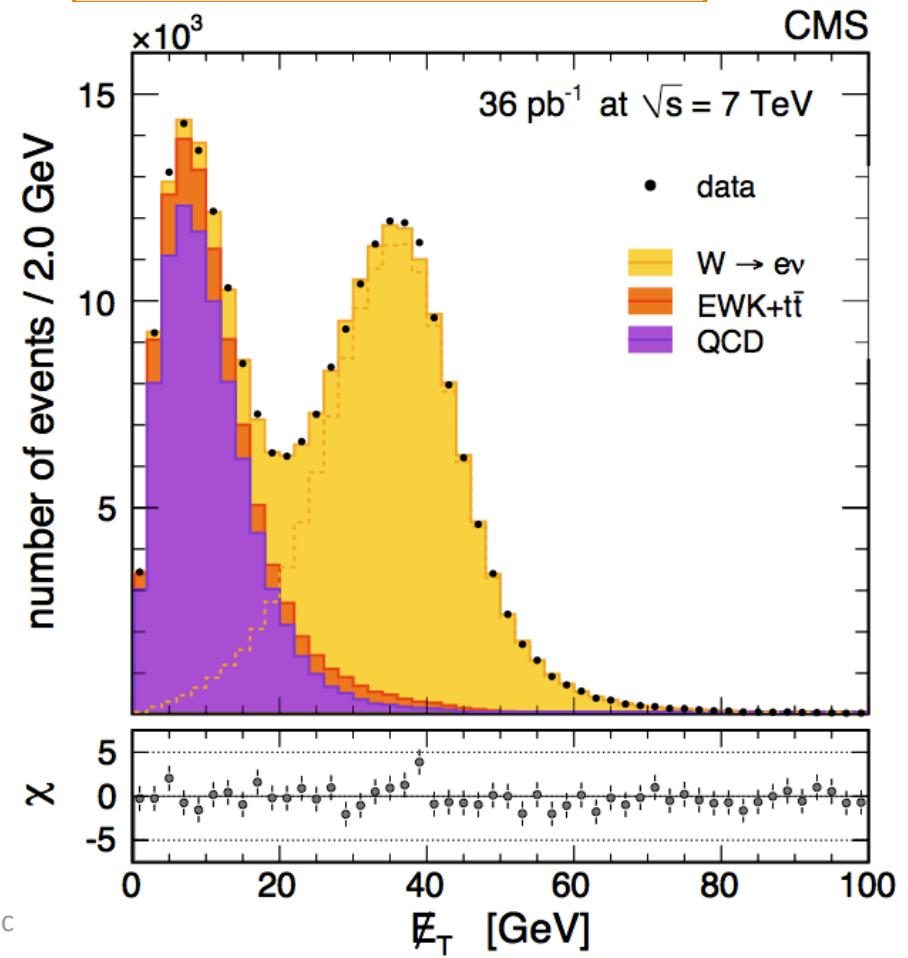
$$Z \rightarrow \ell^\pm \ell^\mp$$

- energetic & isolated e^+e^- or $\mu^+\mu^-$
- resonant peak in $M_{\ell\ell}$

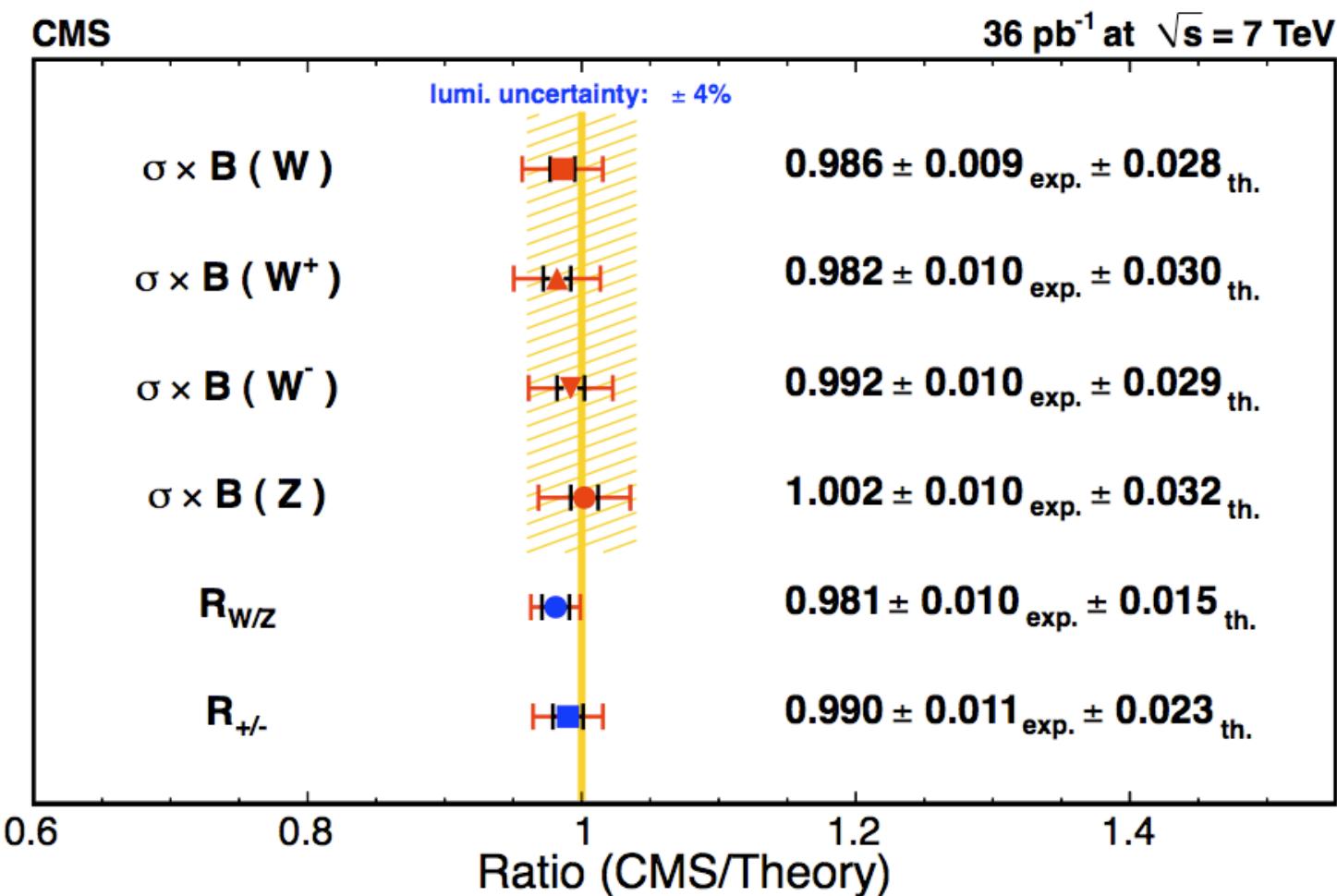


$$W^\pm \rightarrow \ell^\pm \bar{\nu}$$

- energetic & isolated e or μ
- neutrino: E_t^{miss}
- Jacobian peak in M_T

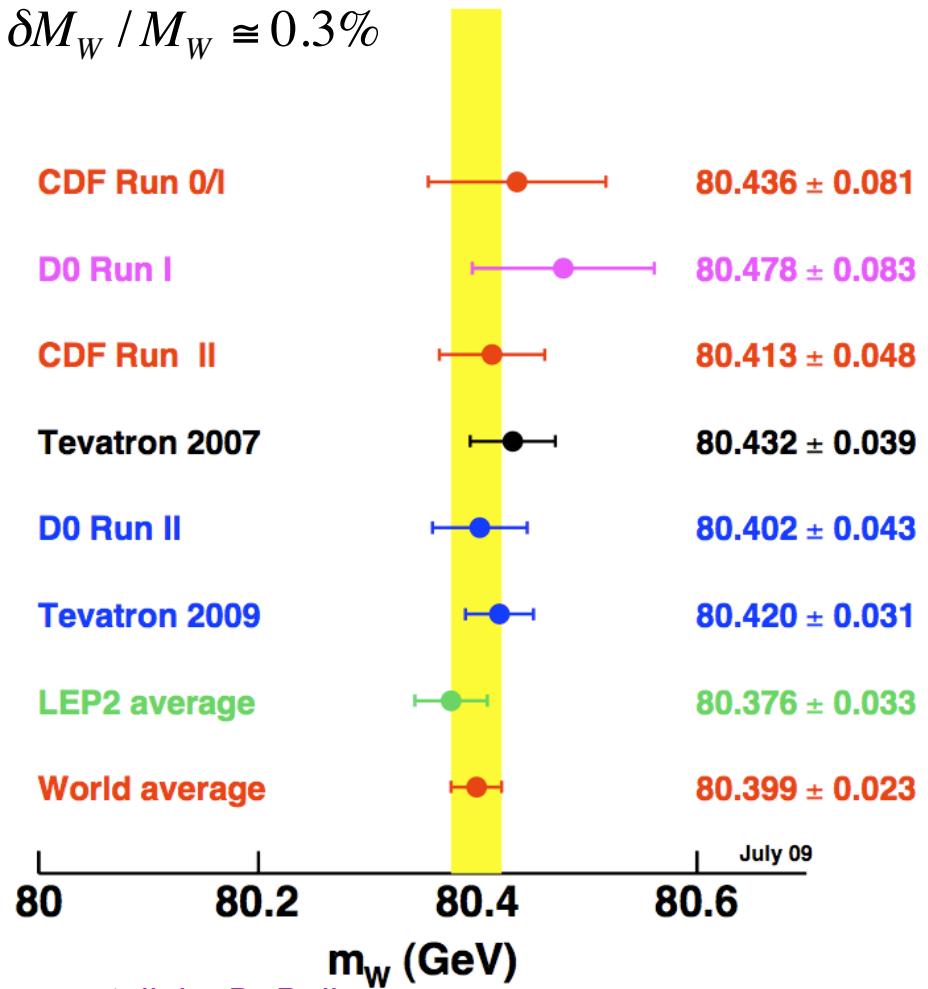


- experimental accuracy about 1% (aside from 4% luminosity uncertainty)
- theoretical uncertainty – mainly from PDFs – about 3%
- most stringent test of theory comes from ratios of cross sections
- no signs of any discrepancy



W Mass

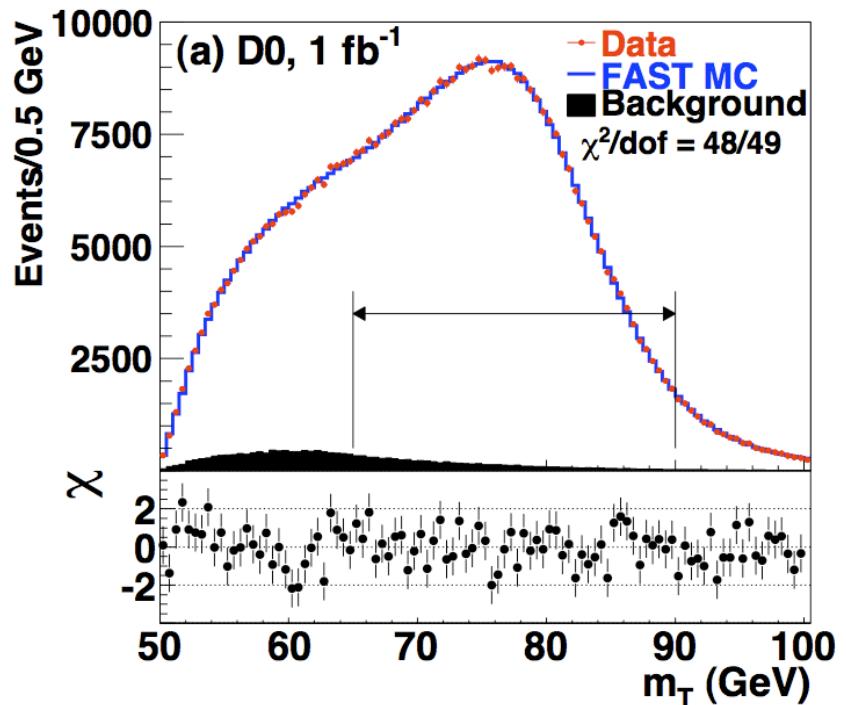
$$\delta M_W / M_W \cong 0.3\%$$



see talk by D. Boline

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- beautiful measurements from D0 & CDF
- Tevatron & LEP numbers compatible
- LHC will need more time to do this kind of very challenging measurement.

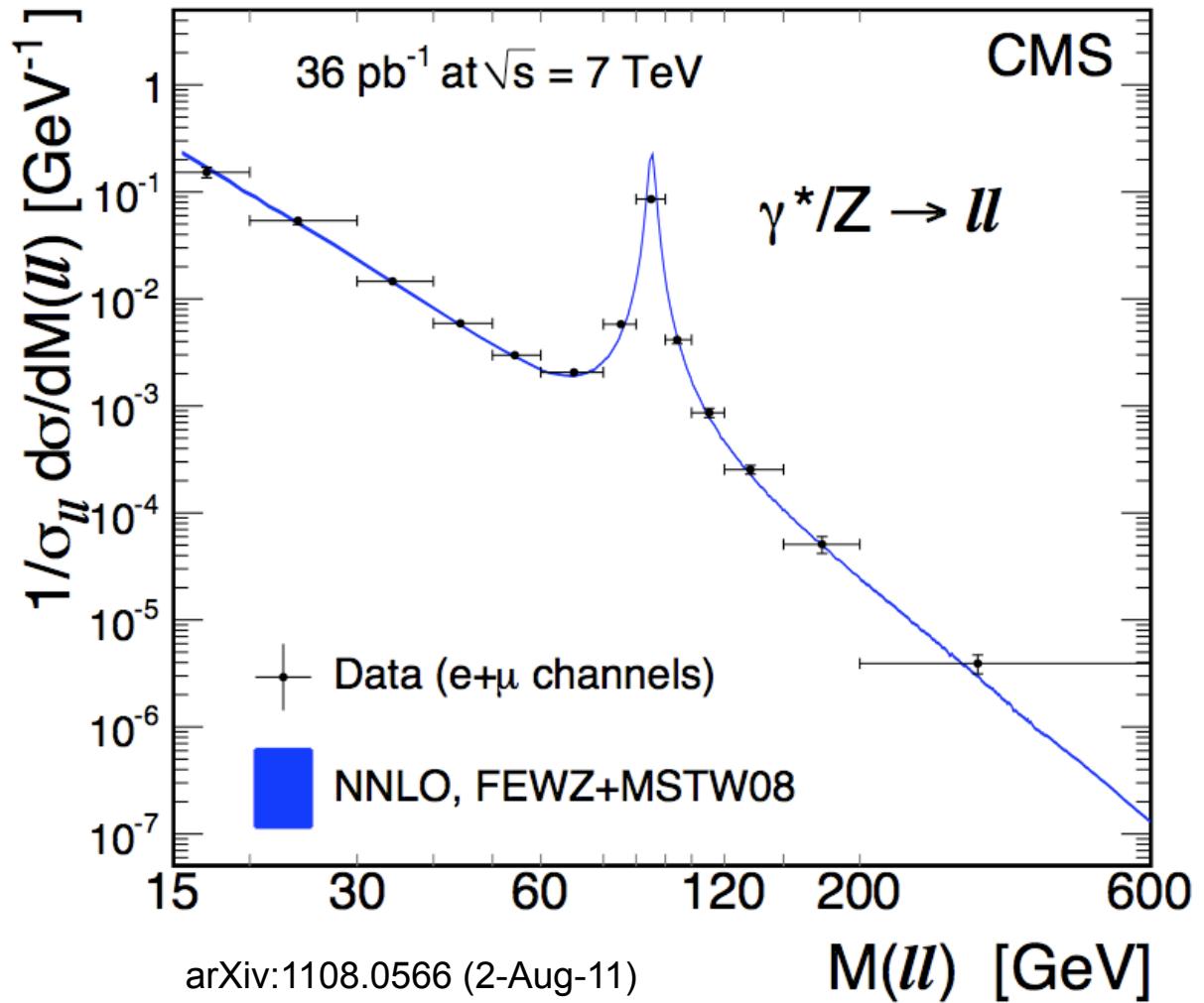


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$d\sigma/dM$

- The Z peak sits on top of the Drell-Yan continuum.
- A correct theoretical description requires both Z and γ^* exchange.
- An extra gauge boson could become visible in this spectrum.
- Accurate PDFs are also essential.



see talk by S. Stoynev

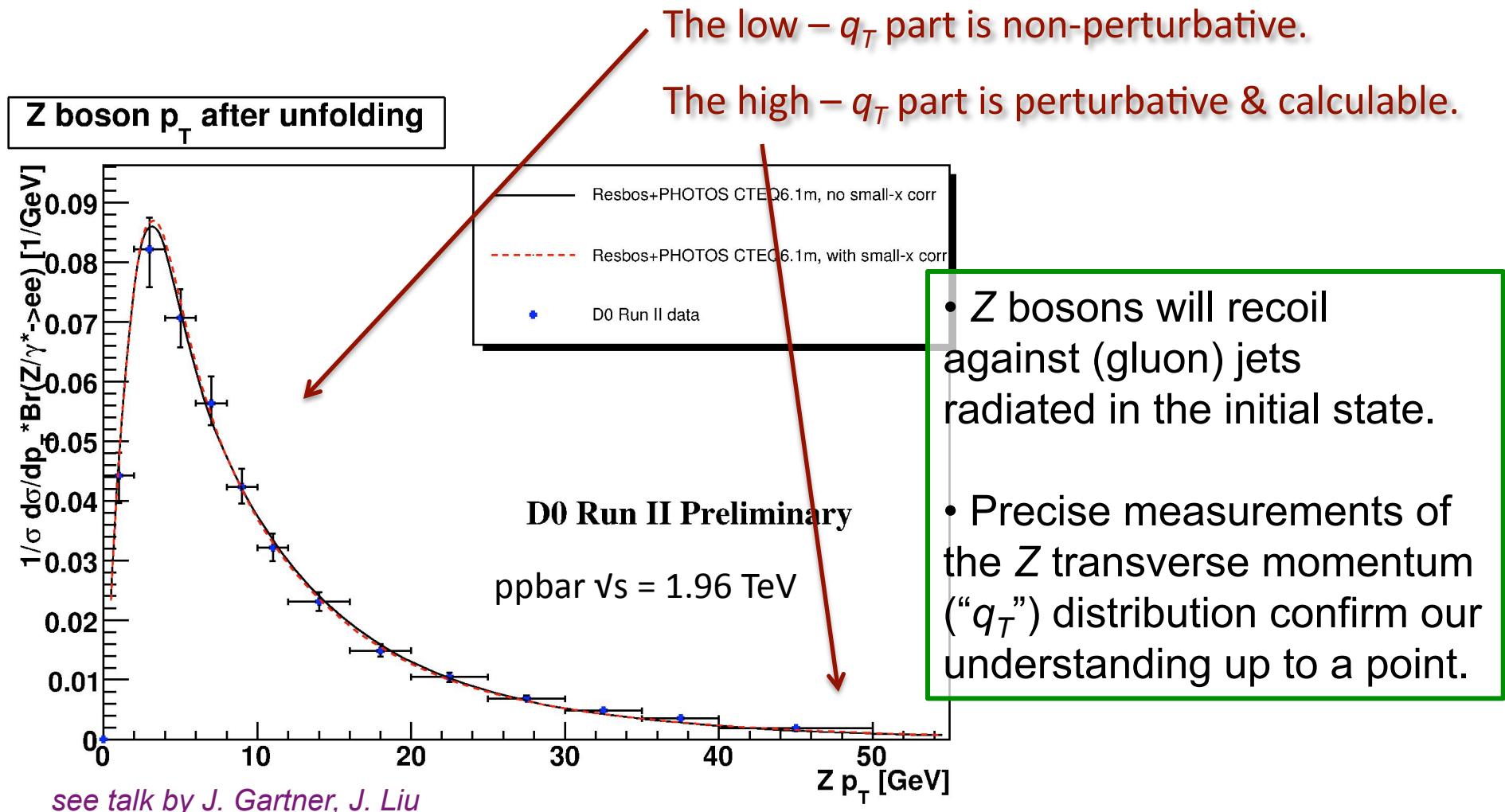
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arXiv:1108.0566 (2-Aug-11)

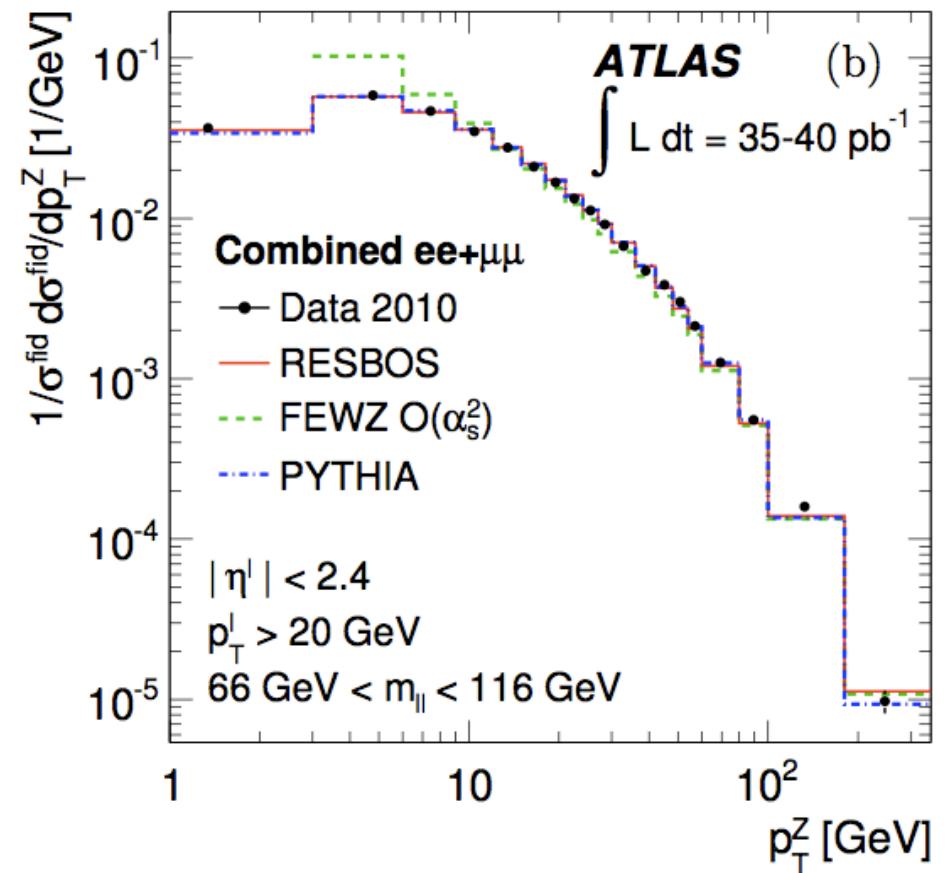
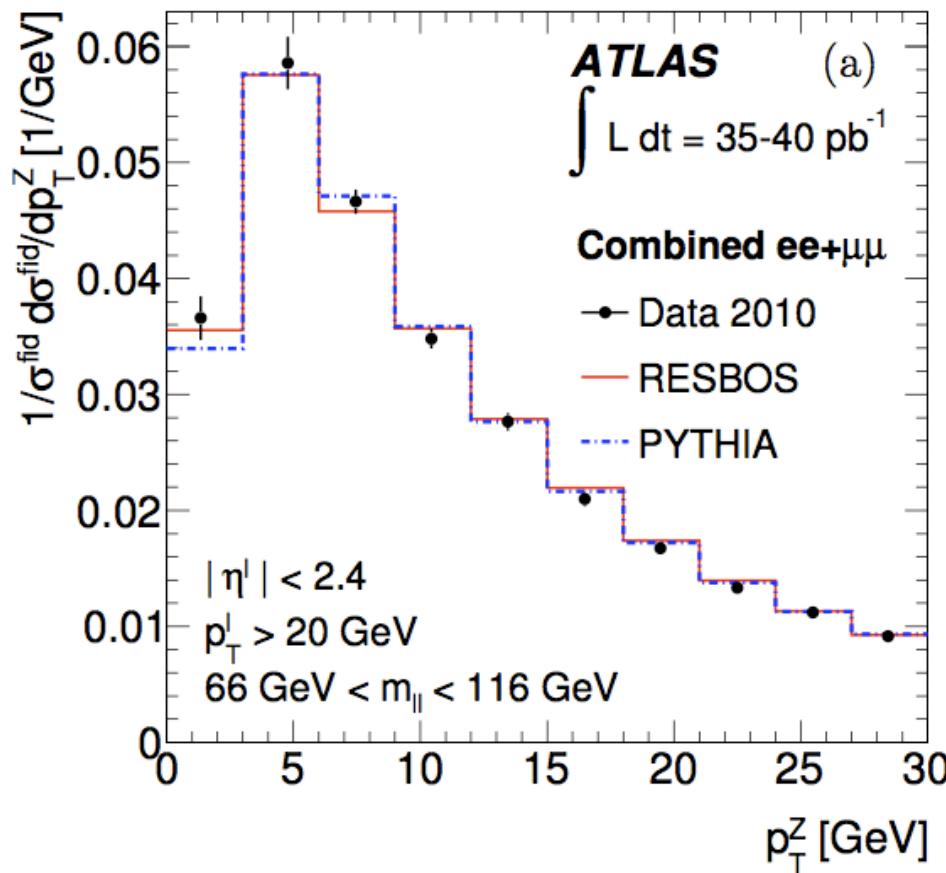
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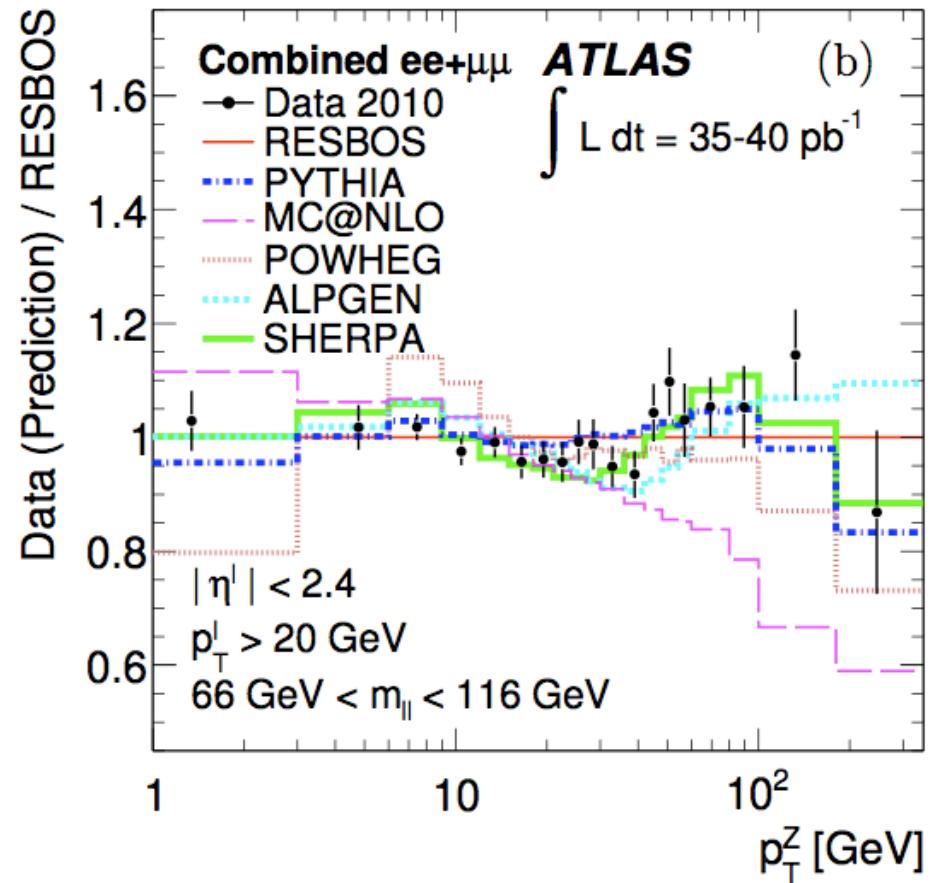
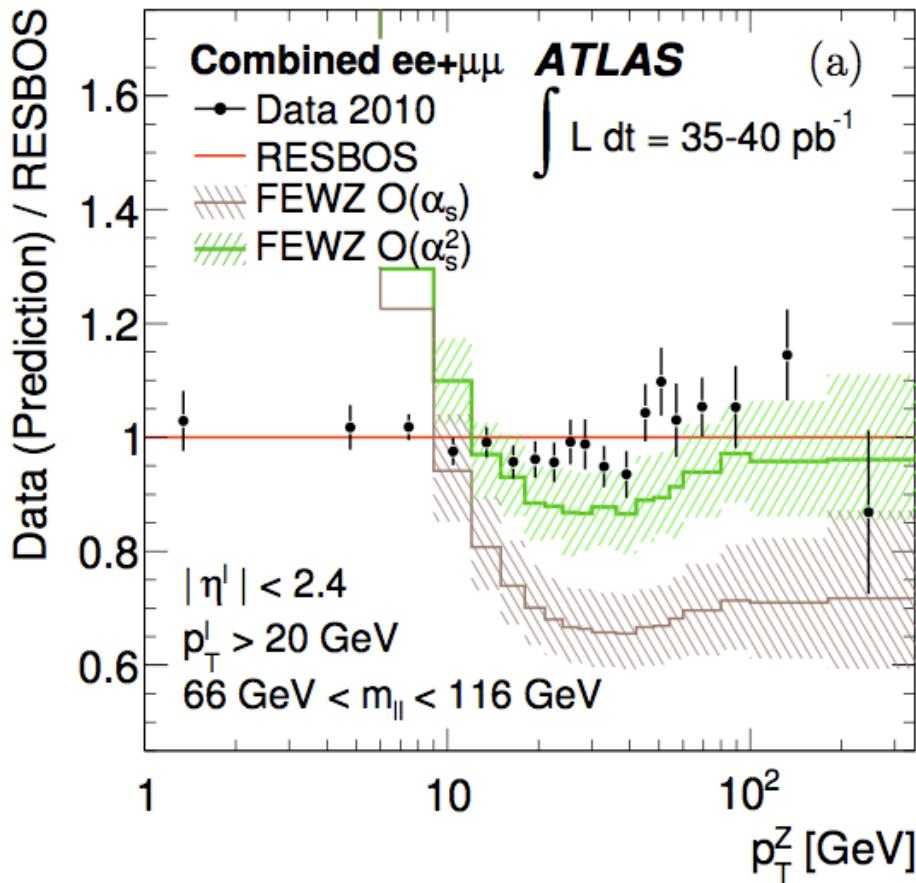
$d\sigma / dq_T$



- ATLAS measurements show good agreement for q_T out to 100 GeV.
- The low- q_T region has to be “tuned”.
- The high- q_T region is sensitive to higher-order terms.



- Use the RESBOS Monte Carlo as the base line.
- NNLO calculations are fairly accurate at high- q_T
- Matched parton shower & higher-order matrix element calculations like SHERPA and ALPGEN do the best.



Let's return to the Electroweak Sector of the Standard Model:

The W and Z are electroweak bosons.

Key signature: parity violation

for W:

“V-A” coupling

strongly favors f_L, \overline{f}_R over f_R, \overline{f}_L

for Z:

more complicated – relative couplings for
 f_L, \overline{f}_R vs. f_R, \overline{f}_L depends on
the fermion and a universal parameter

$$\sin^2 \vartheta_W = 1 - \frac{M_W^2}{M_Z^2}$$

W Charge Asymmetry

parity violation (PV) occurs

at the production $u\bar{d} \rightarrow W^+$

and at the decay $W^+ \rightarrow \ell^+ \bar{\nu}$

$$A_W(y) = \frac{N_{W_+}(y) - N_{W_-}(y)}{N_{W_+}(y) + N_{W_-}(y)}$$

interesting twist:

(forward) W production is polarized due to PV at production,
so there is a strong asymmetry in the lepton decay distribution
(in the W rest frame)

→ the lepton charge asymmetry is useful

$$A_\ell(\eta) = \frac{N_{\ell_+}(\eta) - N_{\ell_-}(\eta)}{N_{\ell_+}(\eta) + N_{\ell_-}(\eta)}$$

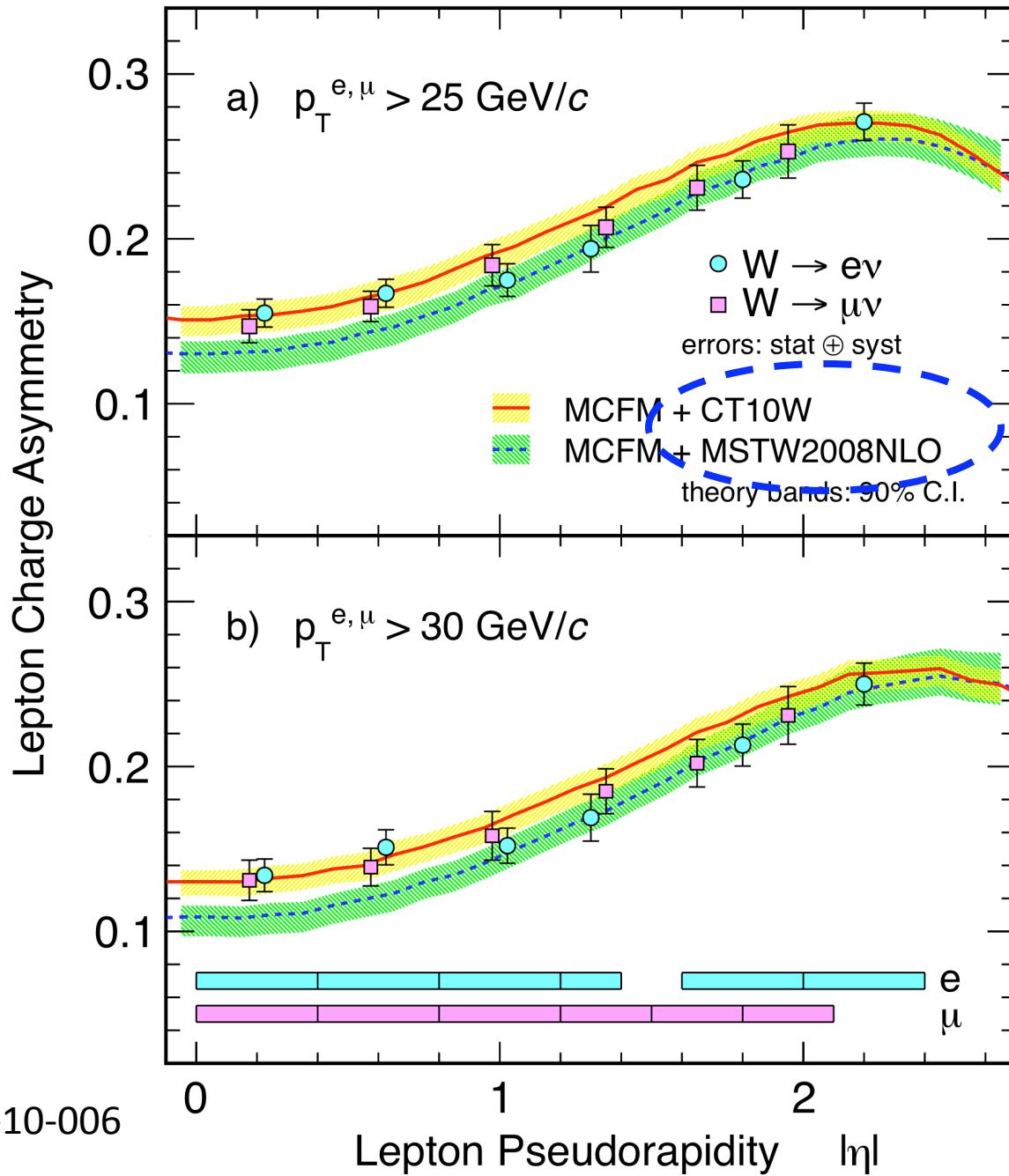
see talk by J.Y. Han

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CMS

36 pb⁻¹ at $\sqrt{s} = 7 \text{ TeV}$ 

two up-to-date
PDF sets

W Polarization at high- q_T

This is a bona fide PV effect.

It is something new – it has not been seen at the Tevatron.

$$qg \rightarrow q'W$$

i.e., W + 1-jet

i.e., high- p_T W

The W will tend to be left-polarized.

***W* polarization**

The W will tend to be left-polarized.

We observe this through a kinematic variable:

$$W^\pm \rightarrow \ell^\pm \nu$$

$$L_P = \frac{\vec{p}_{T,\ell} \bullet \vec{p}_{T,W}}{|\vec{p}_{T,W}|^2} \rightarrow \frac{1}{2}(1 + \cos\theta^*)$$

at very high $p_T(W)$

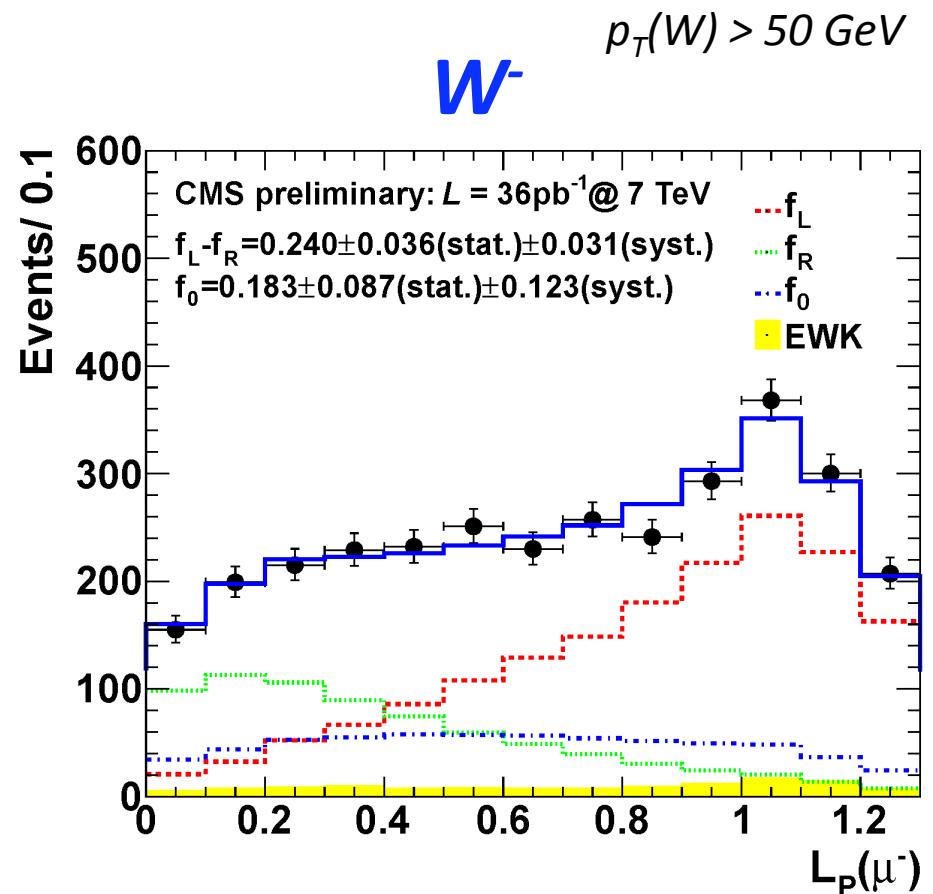
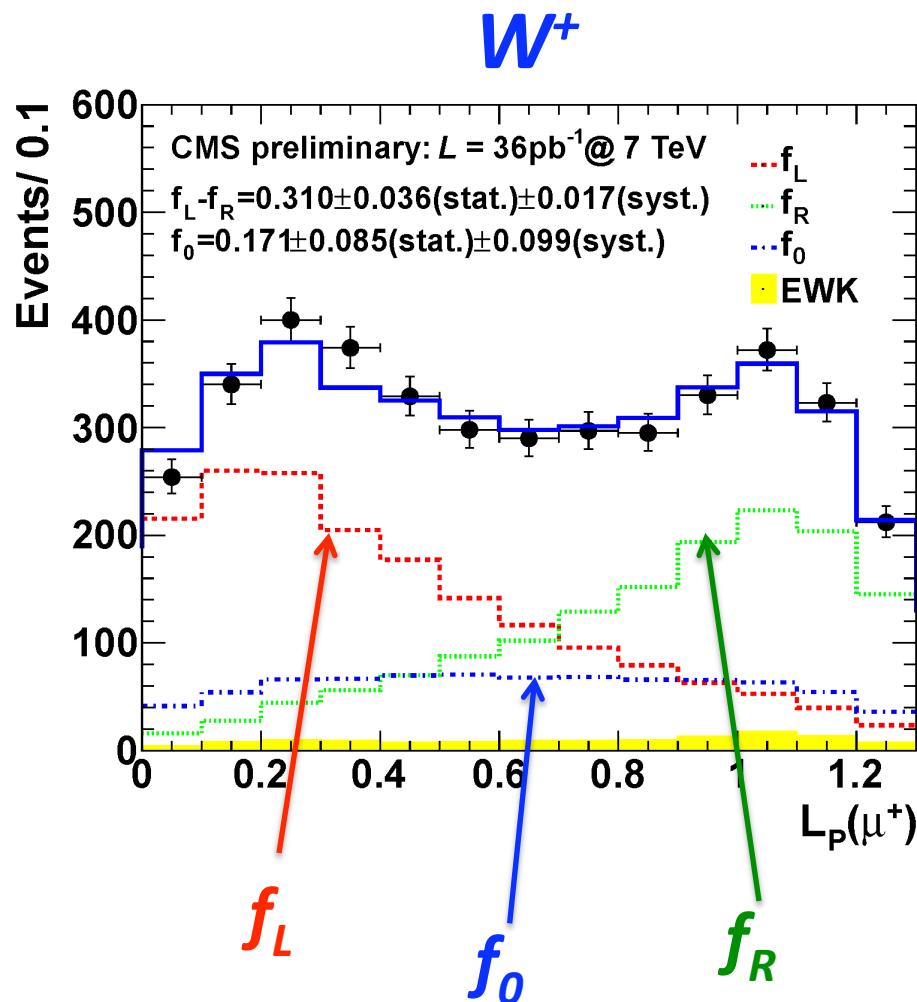
$\ell_L, \bar{\ell}_R$ will peak toward one - fraction f_L

$\ell_R, \bar{\ell}_L$ will peak toward zero - fraction f_R

there is also a longitudinal piece, fraction f_0

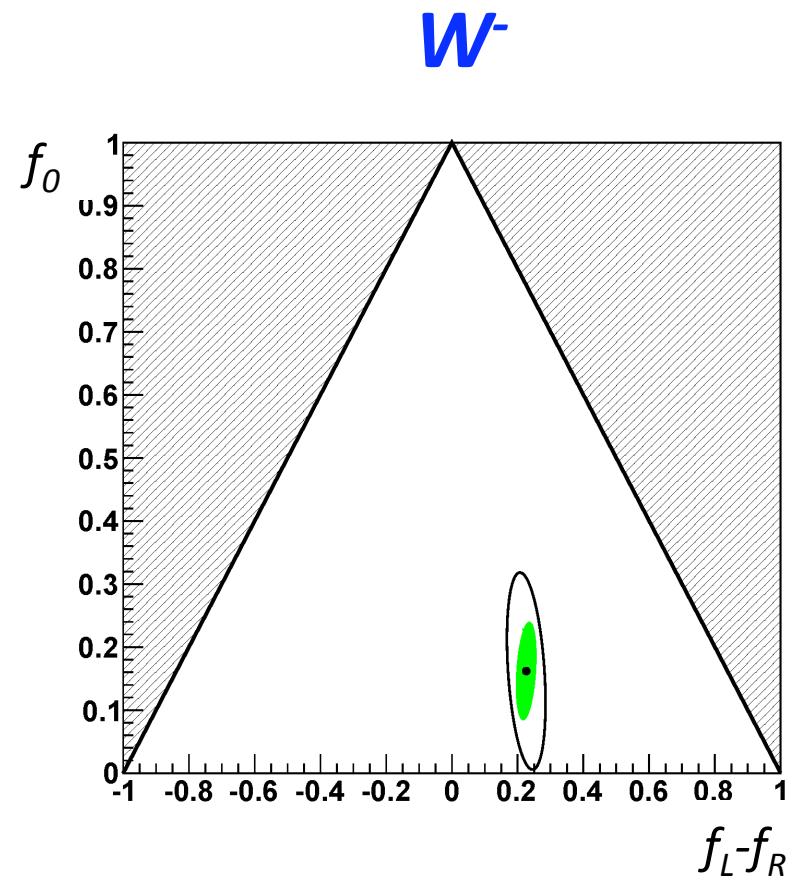
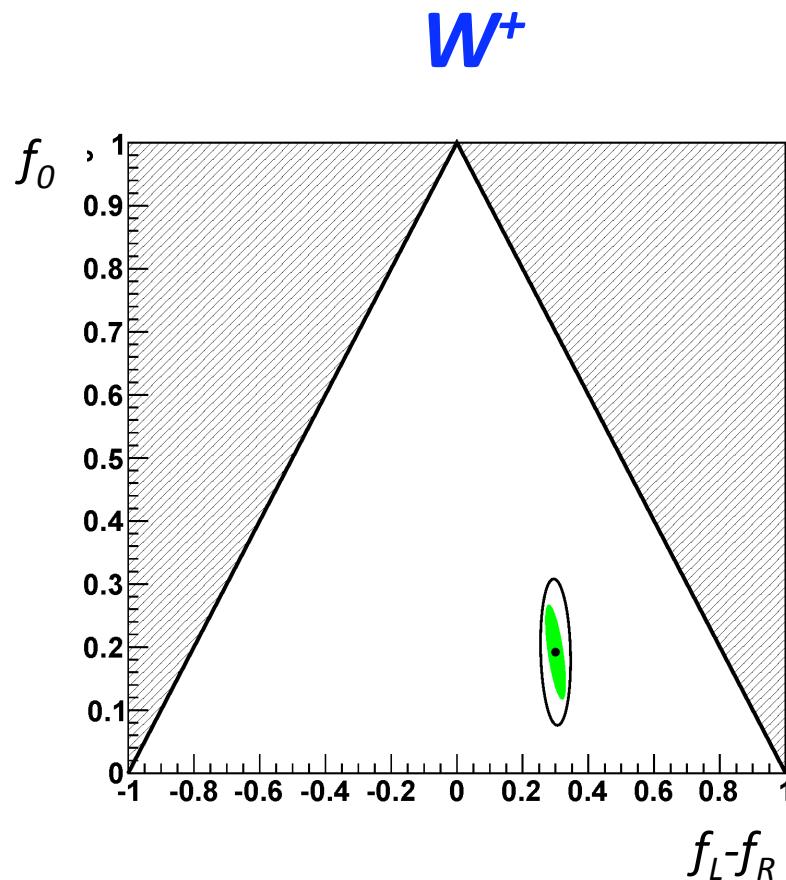
W polarization

In practice, we form templates for f_L , f_R and f_0 and fit them to the observed distributions:



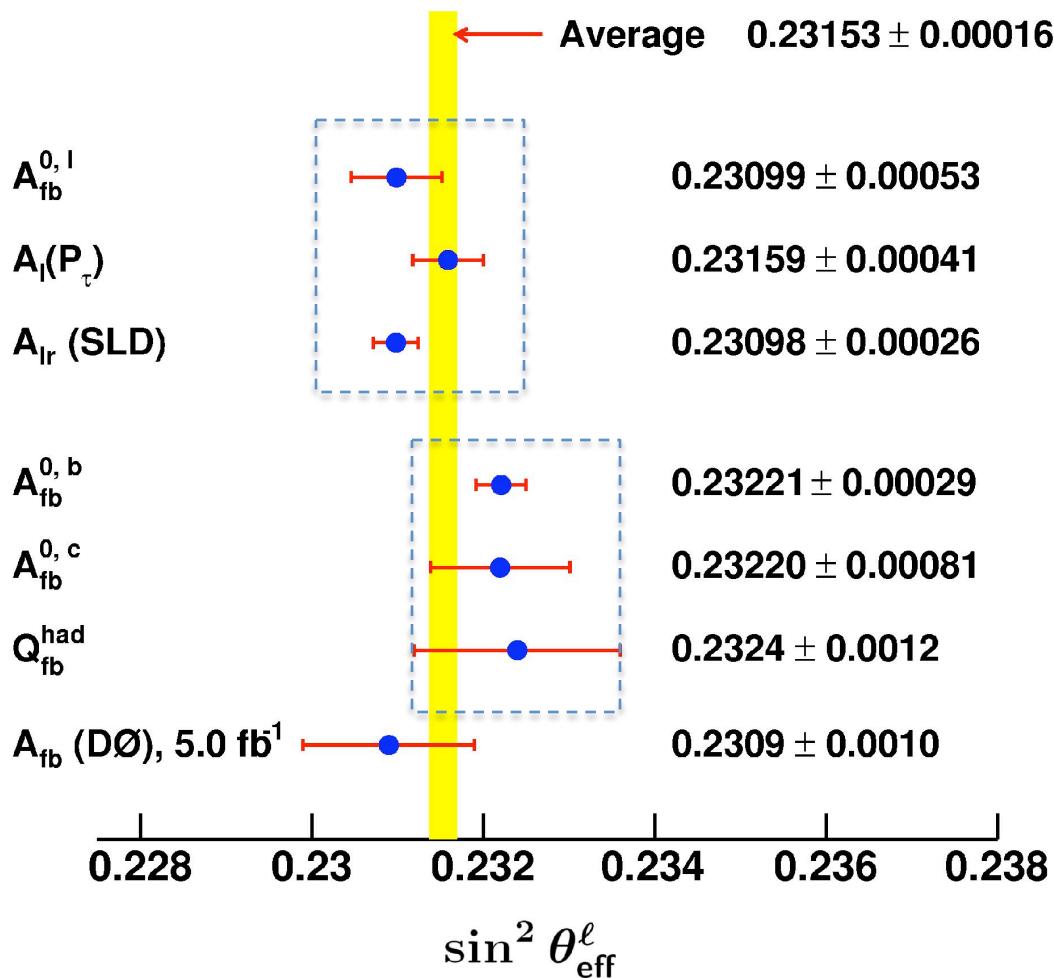
W polarization

These are the fit results for $(f_L - f_R)$ and f_0 :



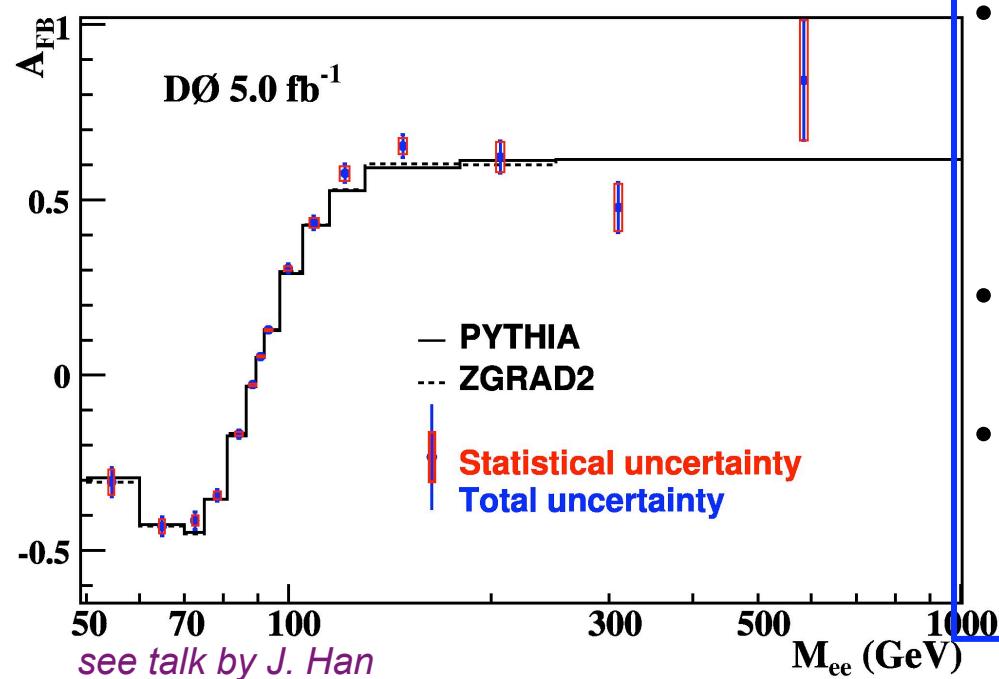
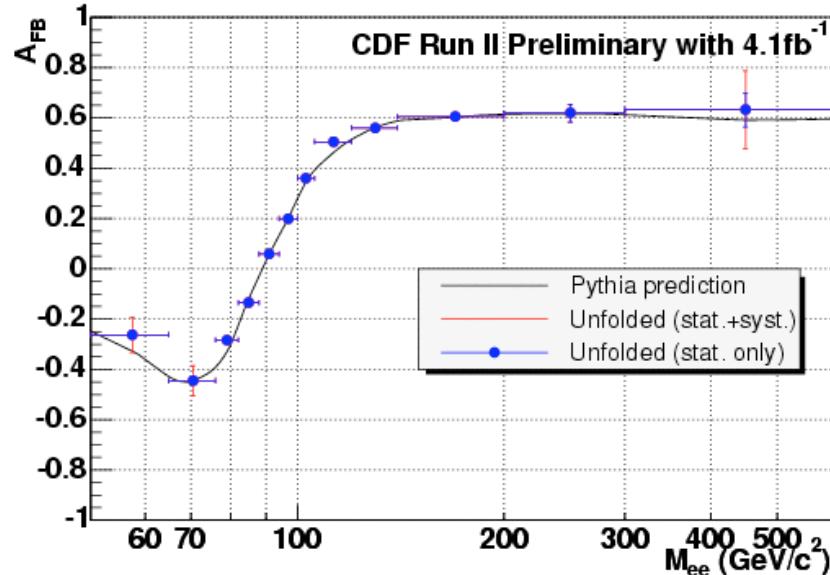
A clear demonstration that Ws are polarized.

A_{FB} and $\sin^2\theta_W$ at High Energy



- Well-known tension among e^+e^- Z-pole measurements
- “leptonic” values are 3σ lower than “hadronic” ones
- major issue for indirect bounds on the Higgs mass
- $\sin^2\theta_W$ can be measured in hadron colliders, too.
- It is very challenging.

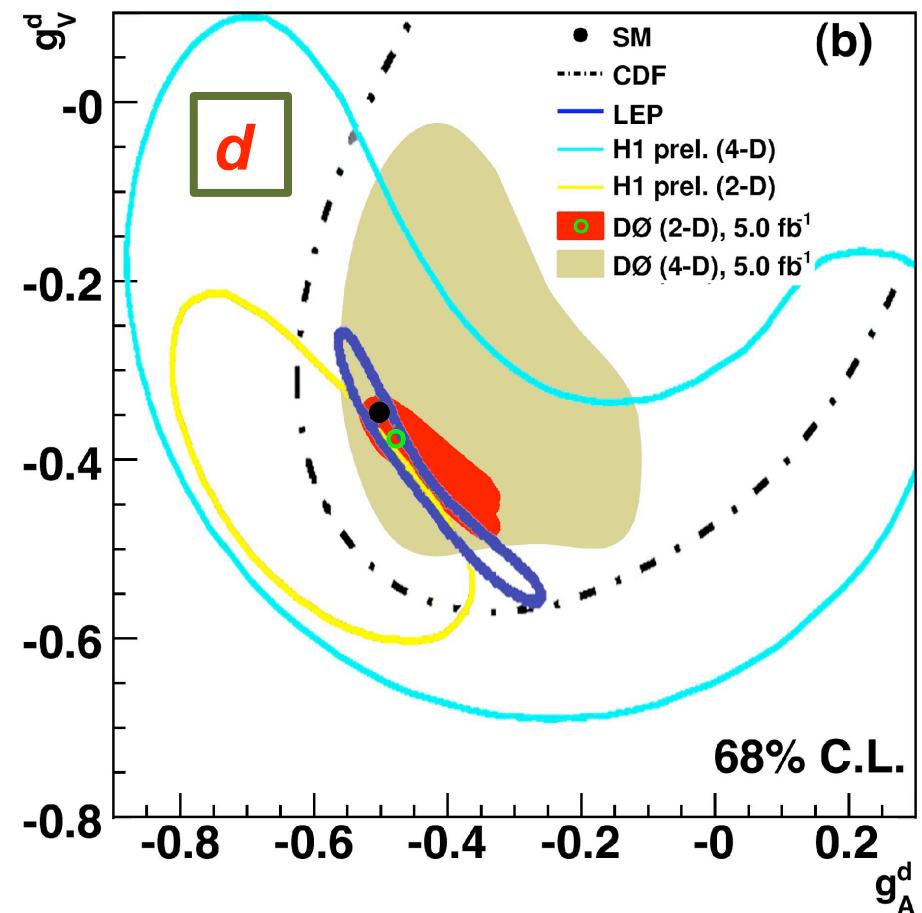
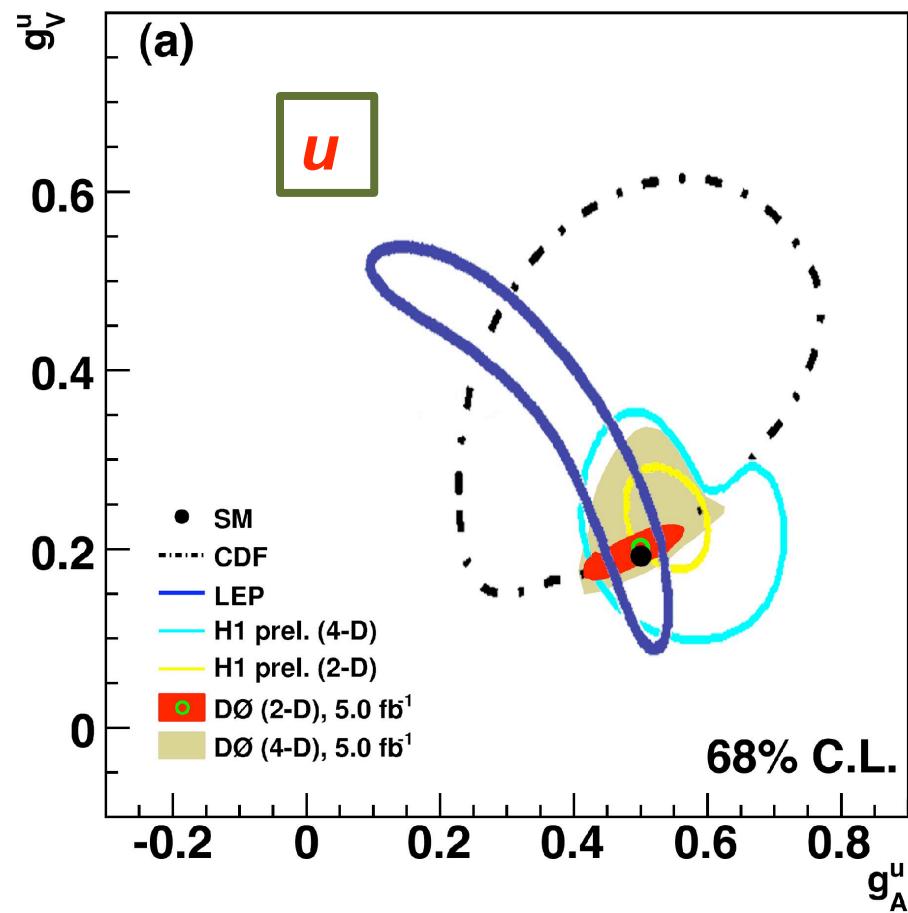
Forward-Backward Asymmetry, A_{FB}



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- Beautiful measurements completed by CDF & D0.
- Variation of A_{FB} with \sqrt{s} shows quantum-mechanical interference of the photon and the Z boson.
- Unfolded and corrected measurements agree very well with the SM.
- (No new physics in sight.)
- Use this to extract values for $\sin^2\theta_W$ and light-quark couplings at the Z-pole

- D0 derived constraints on the u and d -quark couplings.
- The exact shape depends on how many parameters are fitted.
- Nice complementarity with LEP; stronger than H1.



CDF have done a nice analysis measuring the angular distributions as a function of $Z q_T$.

This analysis confirms the mechanisms for production of Z bosons at high q_T and the fact that the gluon has spin 1.

CMS have begun an analysis to extract $\sin^2 \theta_W$ or better, the light quark couplings.

Perform a likelihood fit to a multi-dimension probability density function; detector effects are parameterized with analytical functions.

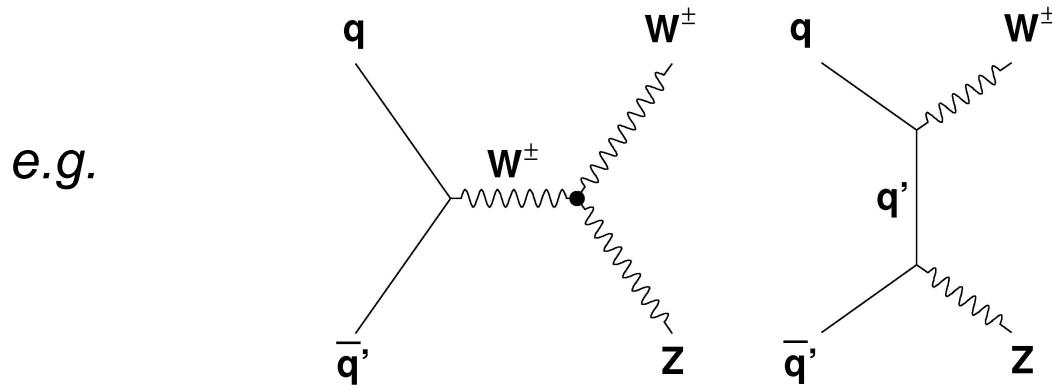
$$\mathcal{P}_{\text{sig}}(Y, s, \cos \theta_{CS}^*; \sin^2 \theta_W) = \mathcal{G}(Y, s, \cos \theta_{CS}^*) \times \int_{-\infty}^{+\infty} dx \mathcal{R}(x) \mathcal{P}_{\text{ideal}}(Y, s - x, \cos \theta_{CS}^*; \sin^2 \theta_W)$$

Given only 36 pb⁻¹, $\sin^2 \theta_W = 0.2287 \pm 0.0077 \pm 0.0036$.

CMS PAS EWK-10-011

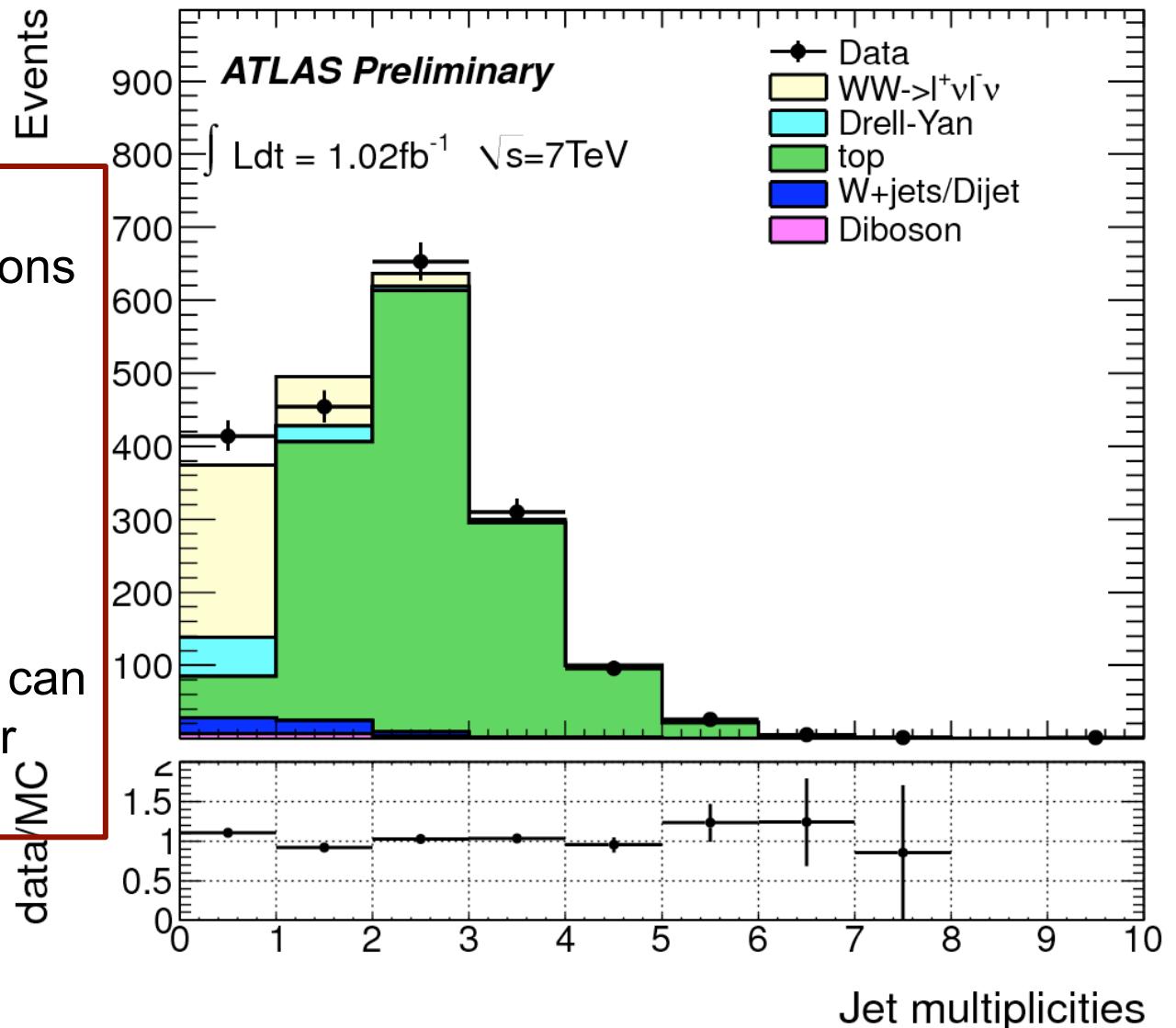
tri-Linear Gauge Couplings

- an **indirect probe of New Physics**
- model-independent as a matter of principle
- very general framework with many free parameters
 - introduction of *ad hoc* form factors is a nuisance
 - makes comparing LEP, Tevatron and LHC results difficult
 - since the goal is to find deviations from SM predictions, one should not be overly concerned about unitarity
- presently trying to measure total cross sections for di-boson production
- sensitive *s*-channel production is “diluted” by *t*-channel production



- long-term future: differential distributions and polarization

- WW events have two energetic & isolated leptons and missing energy.
- Most WW events have no jets, in contrast to the main background: tt.
- The number of tt events can be checked by looking for b-tagged jets.



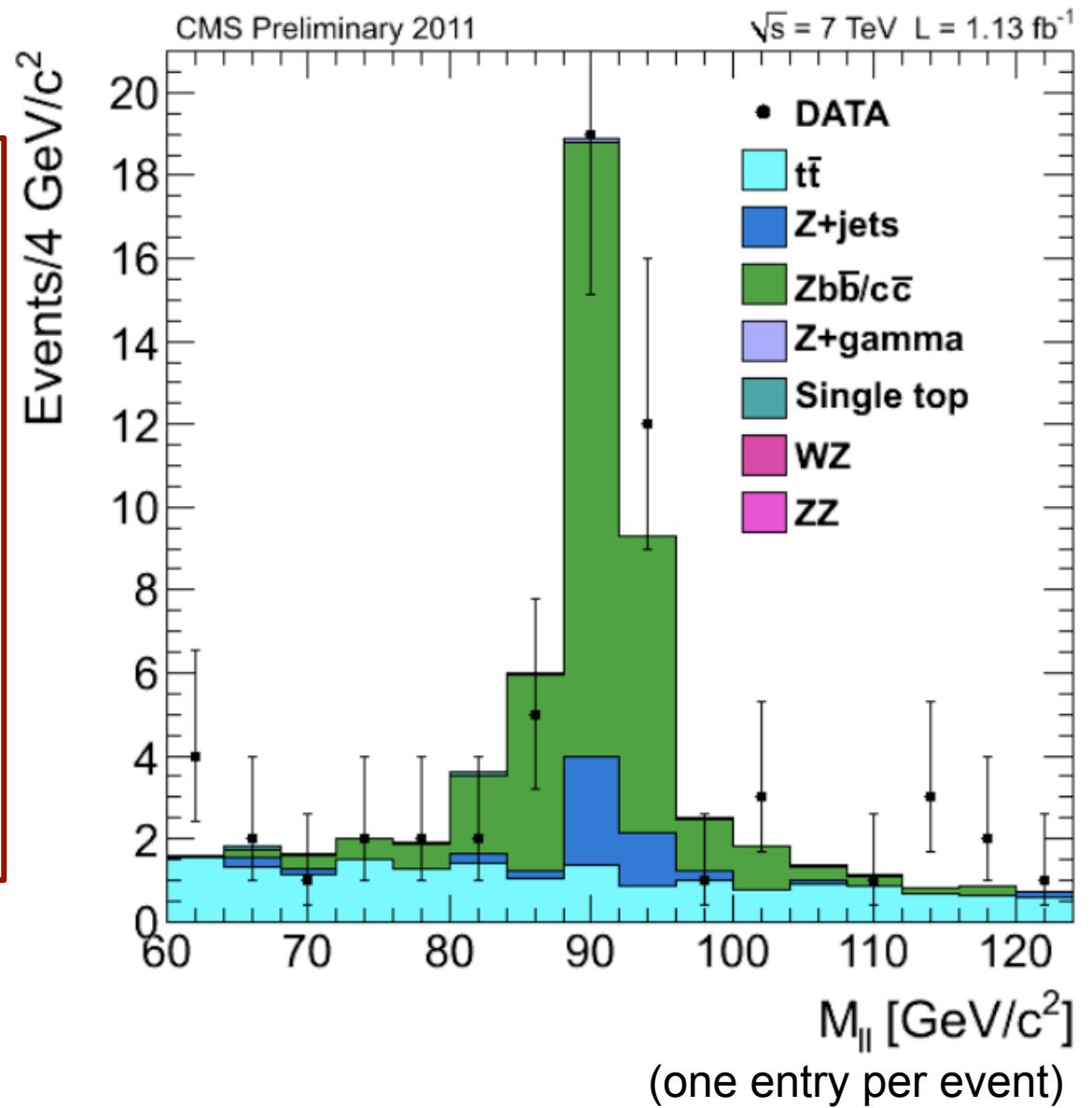
see talk by H. Yang

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- These ZZ events have four energetic leptons.
- Two pairs make two Z bosons
- Backgrounds are very small.
- Signal is very clean and statistically significant with about 1 fb^{-1} .



see talk by S. Hsu

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see talk by K. Mishra

Preliminary cross section measurements based on 1 fb⁻¹

channel	ATLAS	CMS	theory
WW	414 events 59% purity $48.2 \pm 4.0 \pm 6.4 \pm 1.8$	626 events 68% purity $55.3 \pm 3.3 \pm 6.9 \pm 3.3$ (6% prec)	46 ± 3 pb
WZ	71 events 85% purity $21.1 \pm 3.0 \pm 1.2 \pm 0.9$	75 events 89% purity $17.0 \pm 2.4 \pm 1.1 \pm 1.0$	17 ± 1 pb
ZZ	12 events purity 97% $8.4 \pm 2.5 \pm 0.6 \pm 0.3$	9 events 93% purity $3.8 \pm 1.4 \pm 0.2 \pm 0.2$	6.5 ± 0.3 pb

↑
stat syst lumi

Measurements are in broad agreement with theory.

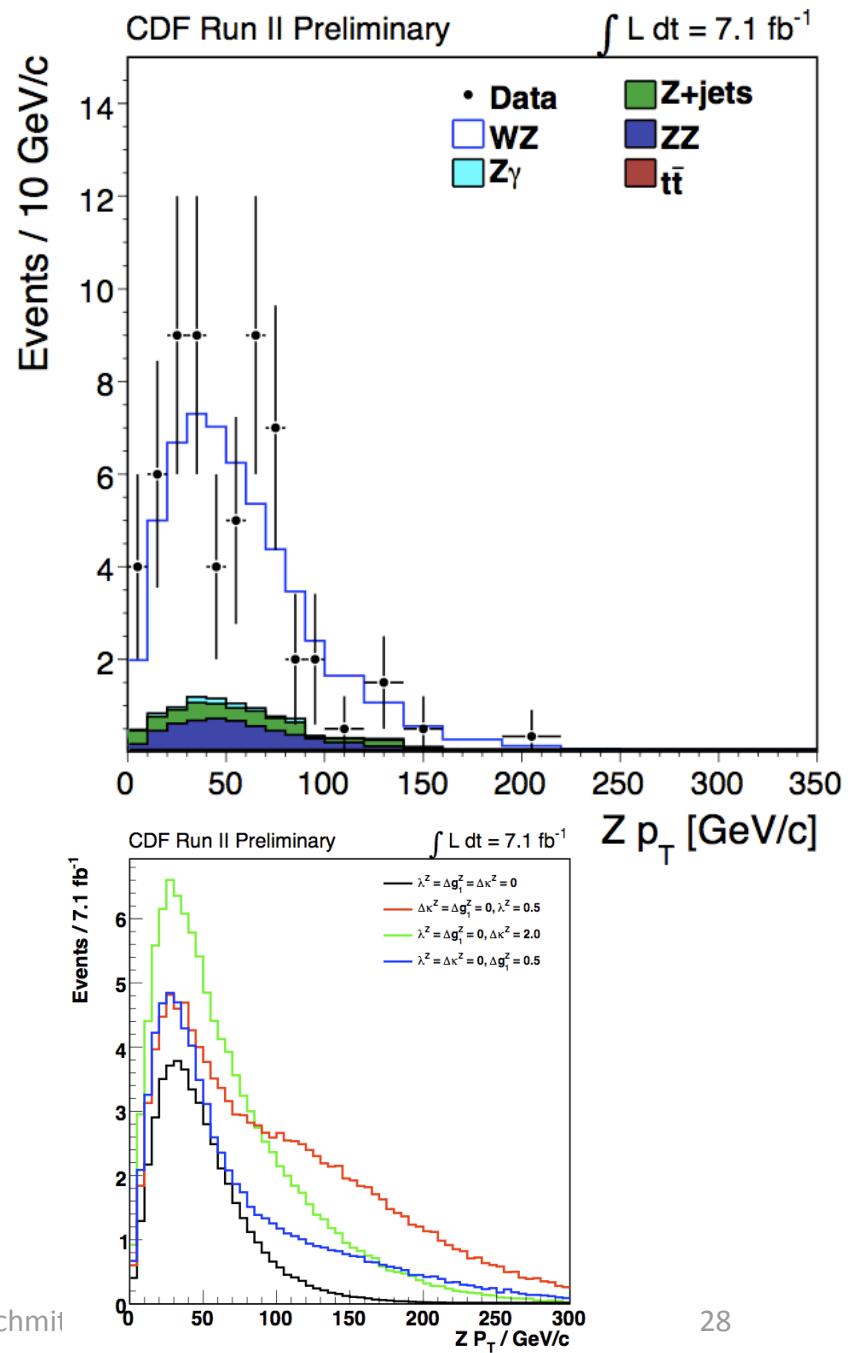
ATLAS limits on aTGC similar to Tevatron limits (beware of FF however!).

CDF uses $Z q_T$ spectrum

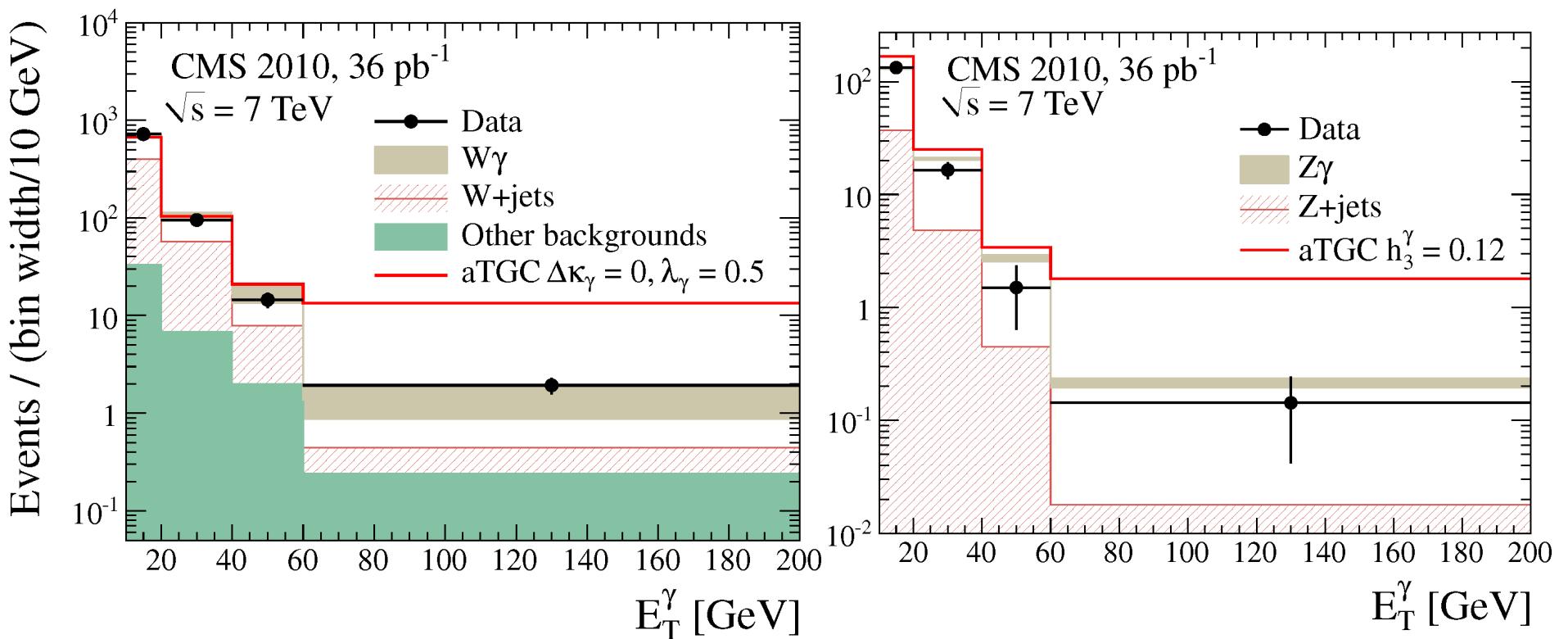
- $WZ \rightarrow 3 \text{ leptons} + \text{neutrino}$
- 7.1 fb^{-1} gives 62 events
- shape and size of q_T spectrum varies strongly with the anomalous couplings λ^Z , Δg_1^Z and $\Delta \kappa^Z$
- fit the observed q_T spectrum directly and place bounds on each anomalous coupling directly.
- results are consistent with no anomalous couplings
- D0 also incorporated this information in an earlier publication. *see talk by M.Cooke*

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- $W+\gamma$ and $Z+\gamma$ also probe anomalous couplings. *see talk by A. Goshaw*
- Large deviations in the tri-linear couplings would lead to an excess of high-energy photons.
- Agreement with the SM is good.

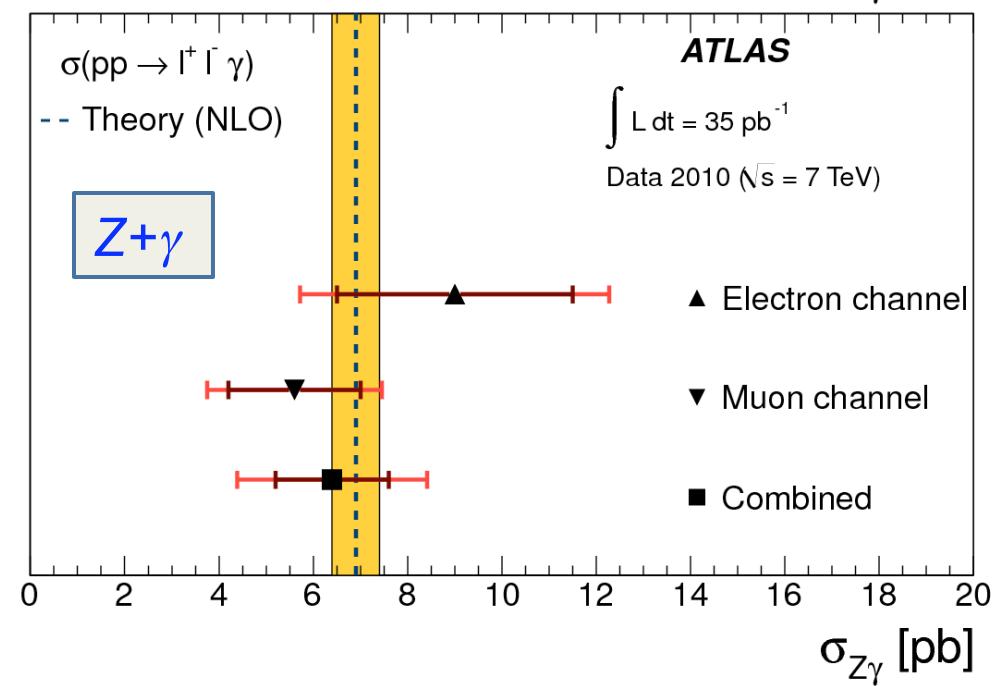
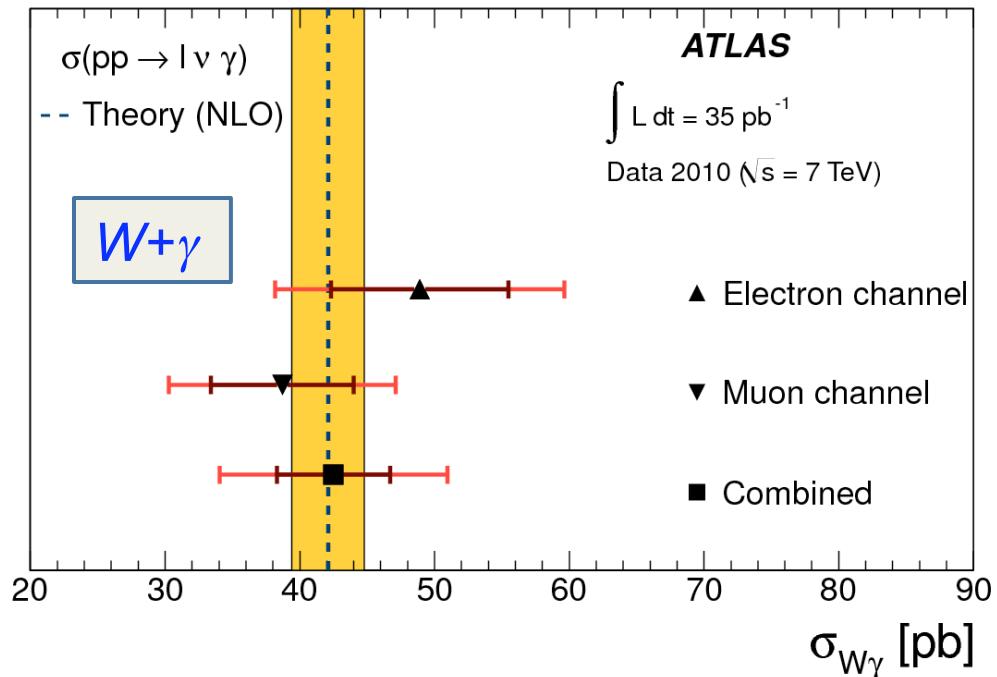


CMS PAS EWK-10-009

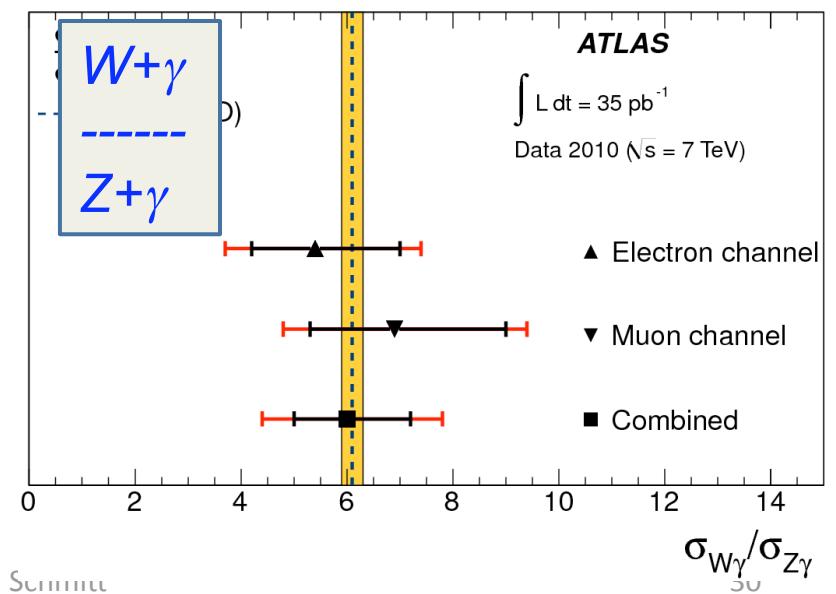
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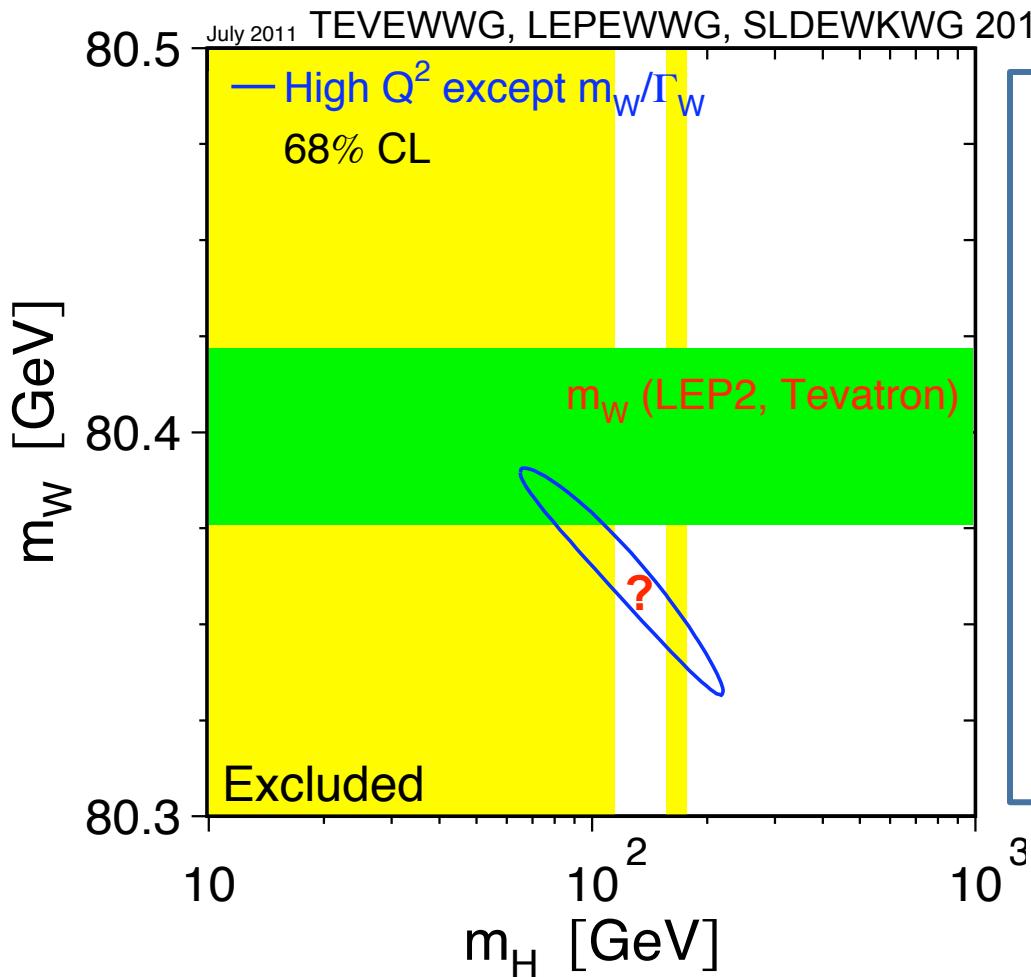
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- ATLAS measurements also agree with the SM
- 192 $W+\gamma$ candidates, purity = 71%
- 48 $Z+\gamma$ candidates, purity = 85%
- ratio $W+\gamma/Z+\gamma$



Higgs Bosons / EWSB



- Perhaps the real electroweak physics news will be the first positive indications for M_H .
- W -boson and t -quark are already very well known.
- Once M_H is known, precision measurements of electroweak observables may well point to inconsistencies.

see plenary talk by A. Juste

Summary

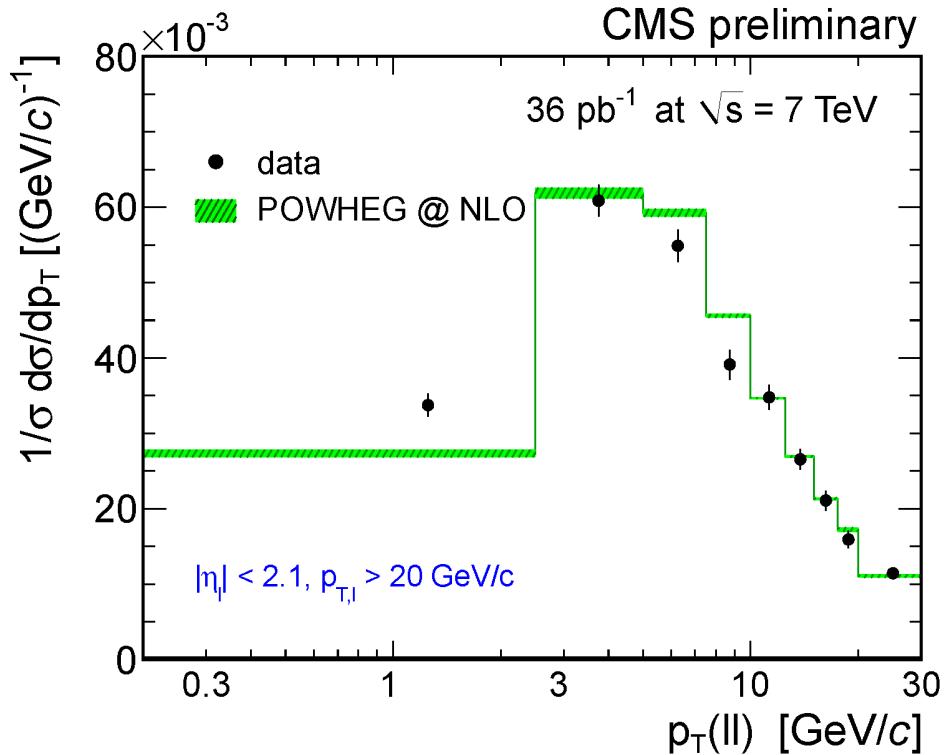
- Significant advances have been and will be made at the “precision frontier” – including low-energy.
- D0 & CDF have shown that high-precision measurements which constrain deviations from the SM can be done at hadron colliders.
- CMS & ATLAS already accumulate large samples of W and Z bosons which allow measurements that rival those of the Tevatron – di-bosons will soon come very interesting.
- If the Higgs boson is discovered, the whole “game” of precision electroweak measurements will be transformed.

BACKUP

CMS has presented the first measurements of $d\sigma/dq_T$ vs = 7 TeV

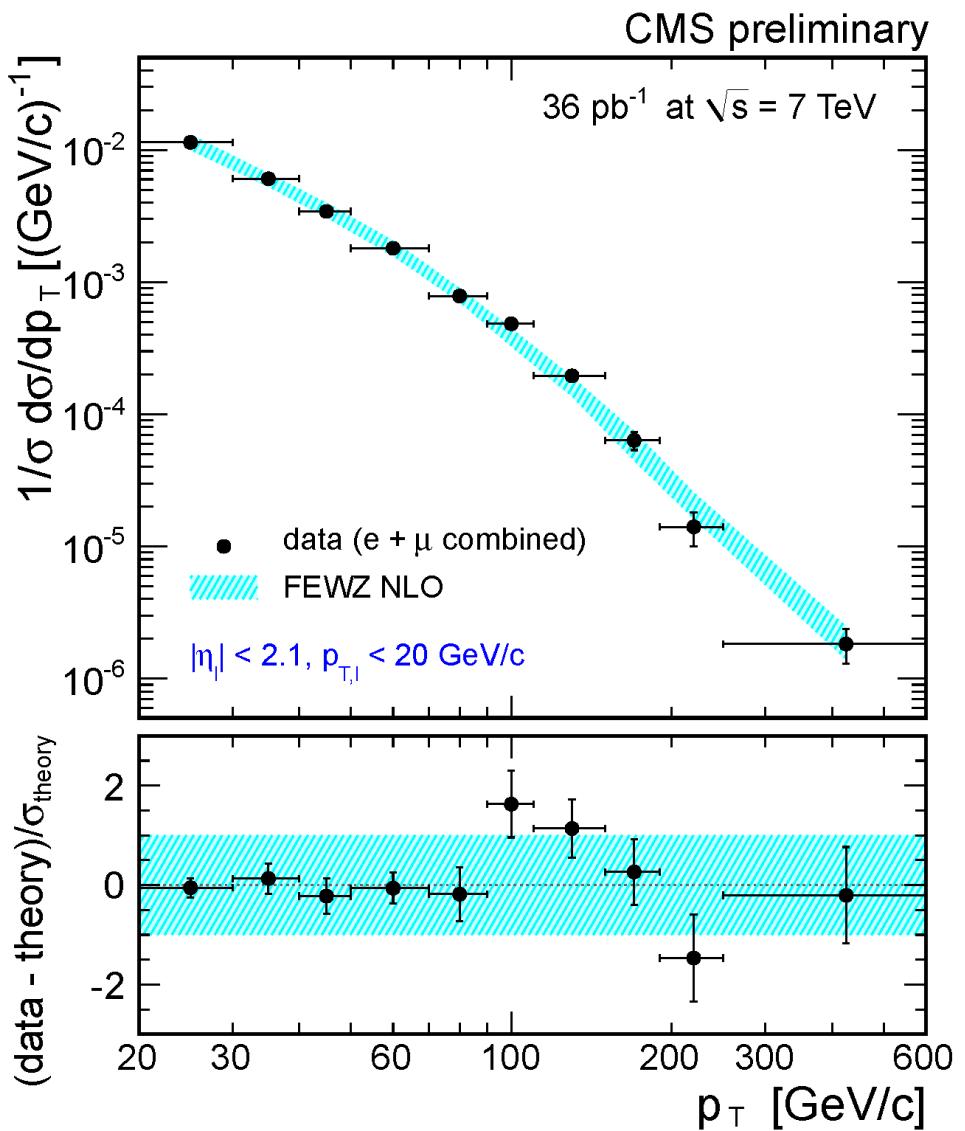
high – p_T prediction is OK.

low – p_T model needs tuning



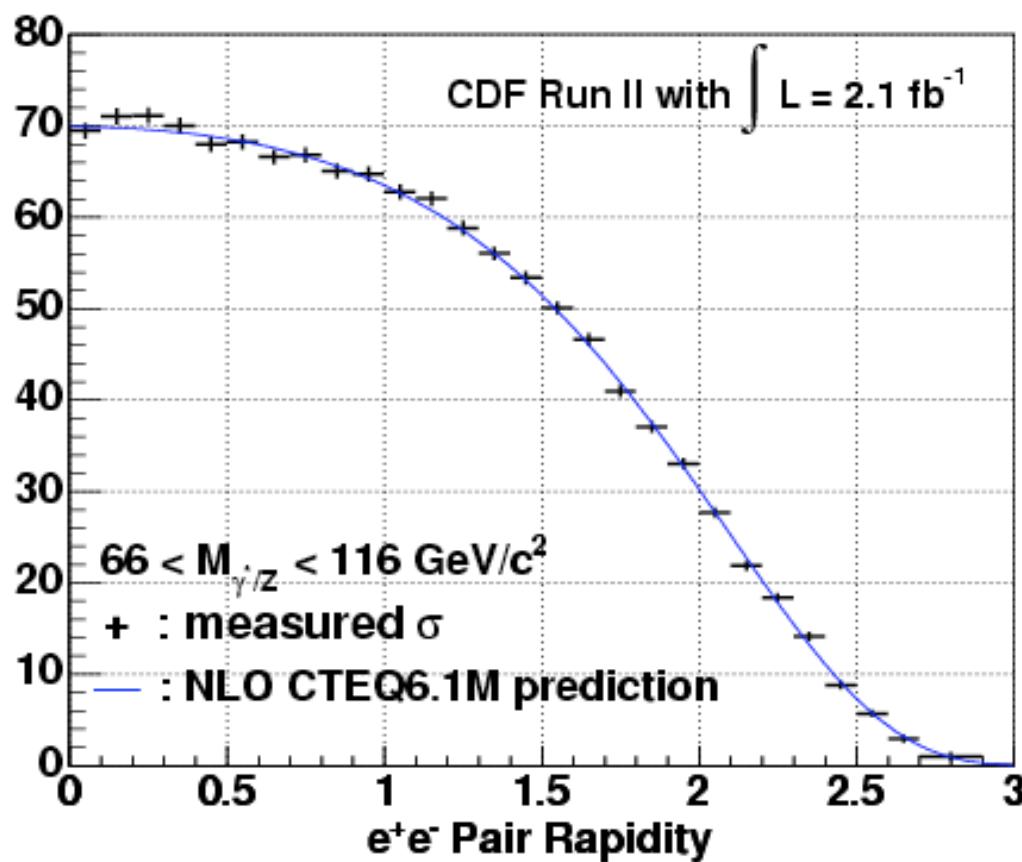
CMS PAS EWK-10-010

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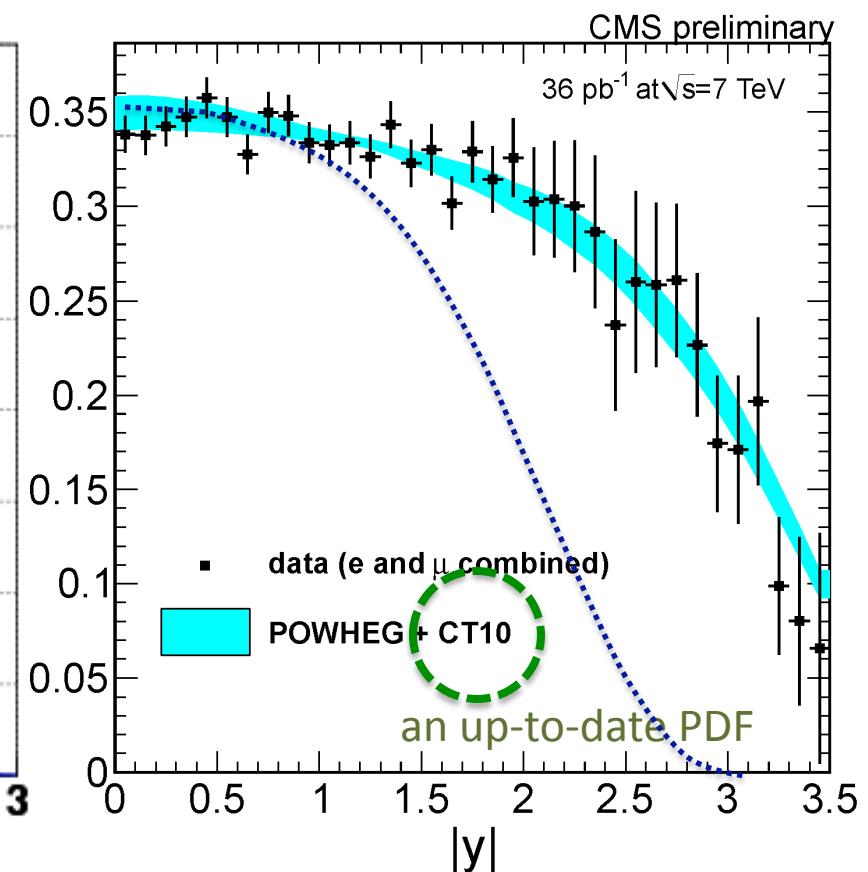


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CDF $\sqrt{s} = 1.96$ TeV

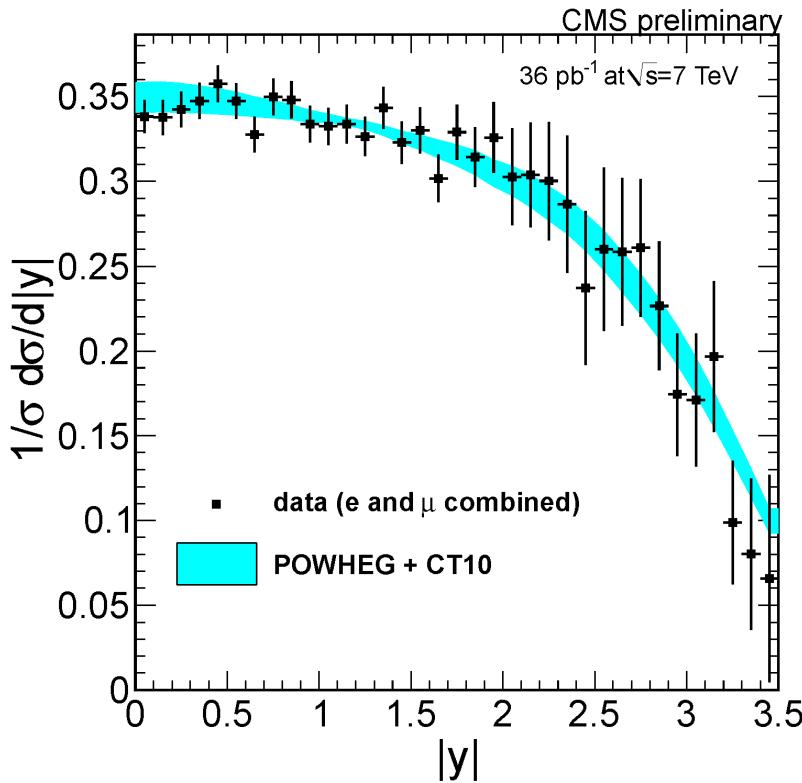


CMS $\sqrt{s} = 7$ TeV



Notice that the CMS range in $|Y|$ is significantly larger.
The CMS error bars will diminish rapidly this year.
Soon they will be good enough to constrain the PDFs...

How exactly does the γ distribution relate to the pdfs?



$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

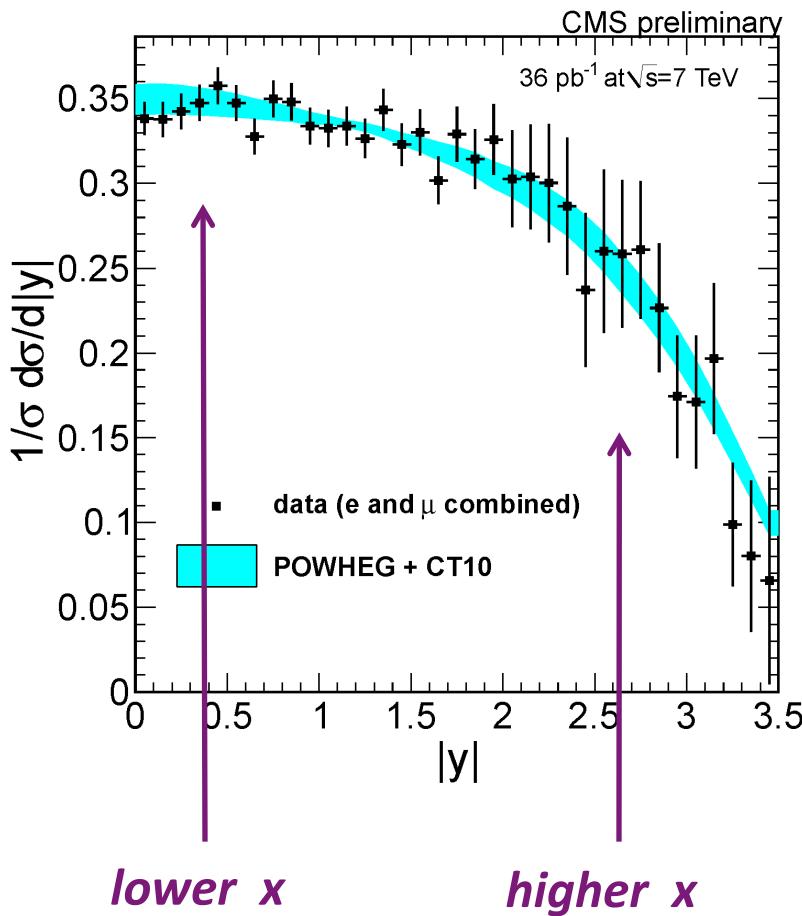
γ gives a constraint on the ratio x_1/x_2

$$y = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right)$$

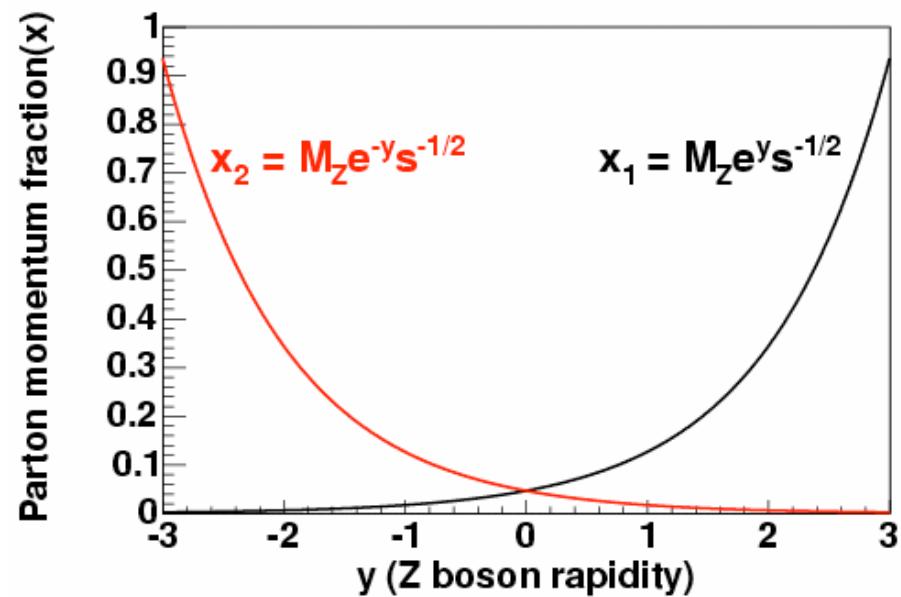
Or, for fixed M ,

$$y = \ln(x_1) - \ln(\sqrt{s}/M)$$

How exactly does the γ distribution relate to the pdfs?

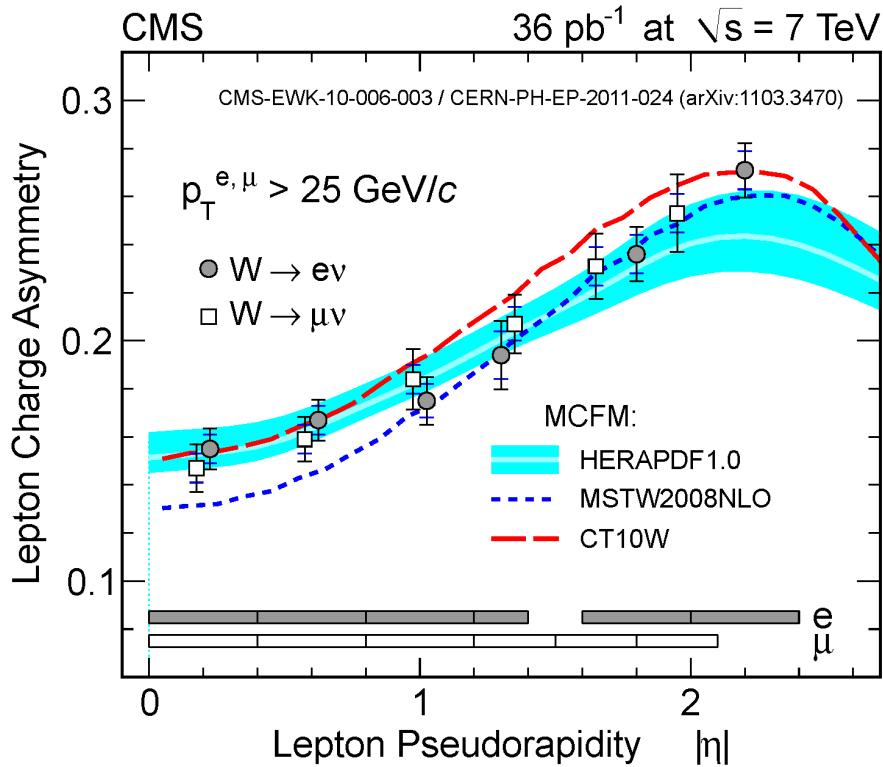


$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

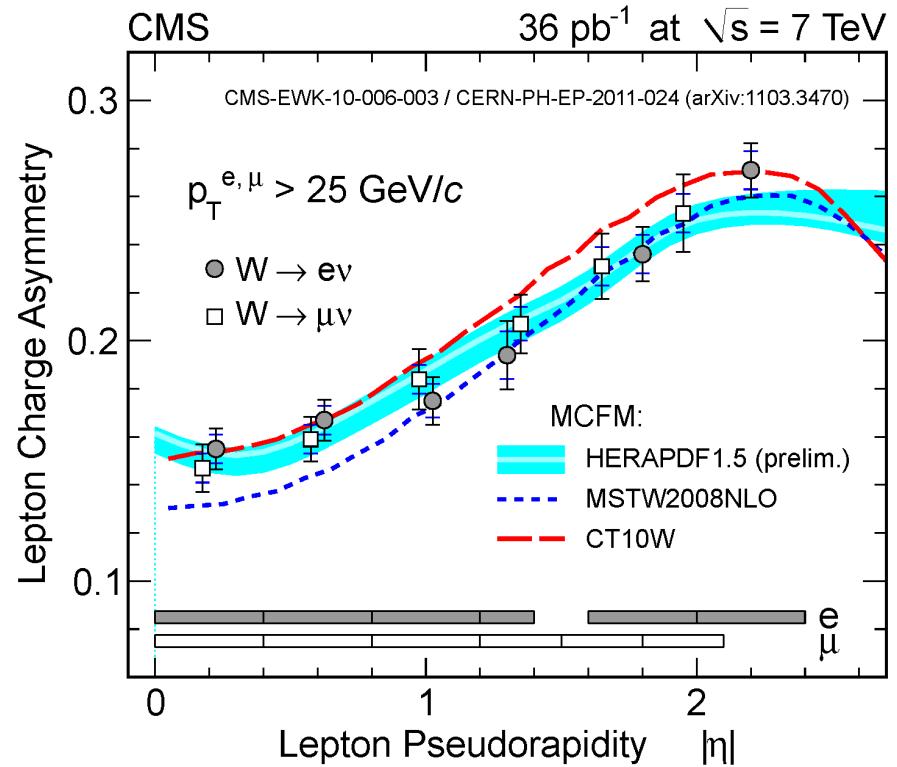


$$y = \ln(x_1) - \ln(\sqrt{s} / M)$$

Katerina Lipka (HERAPDF) already incorporated the CMS measurement:



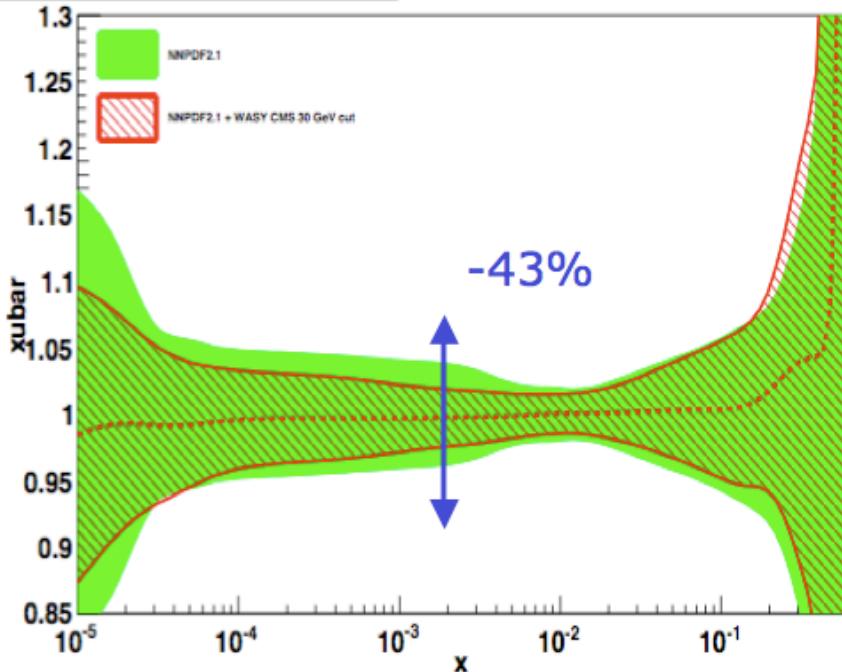
before



after

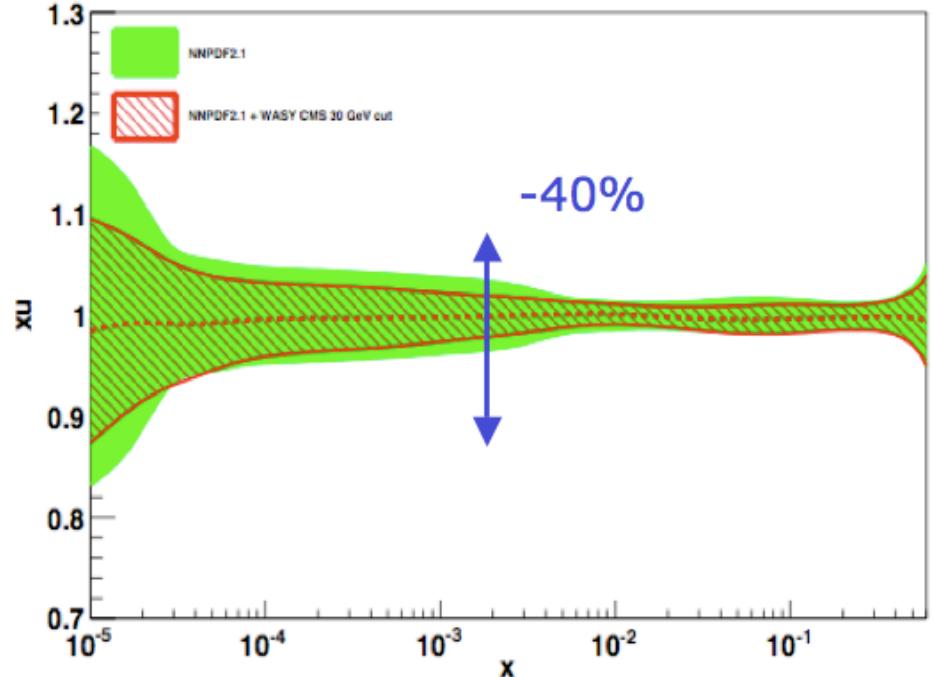
Maria Ubiali (NNPDF) shows that the W asymmetry measurement leads to *significant* reduction in PDF uncertainties:

$Q^2 = M_W^2$, ratio to NNPDF2.1



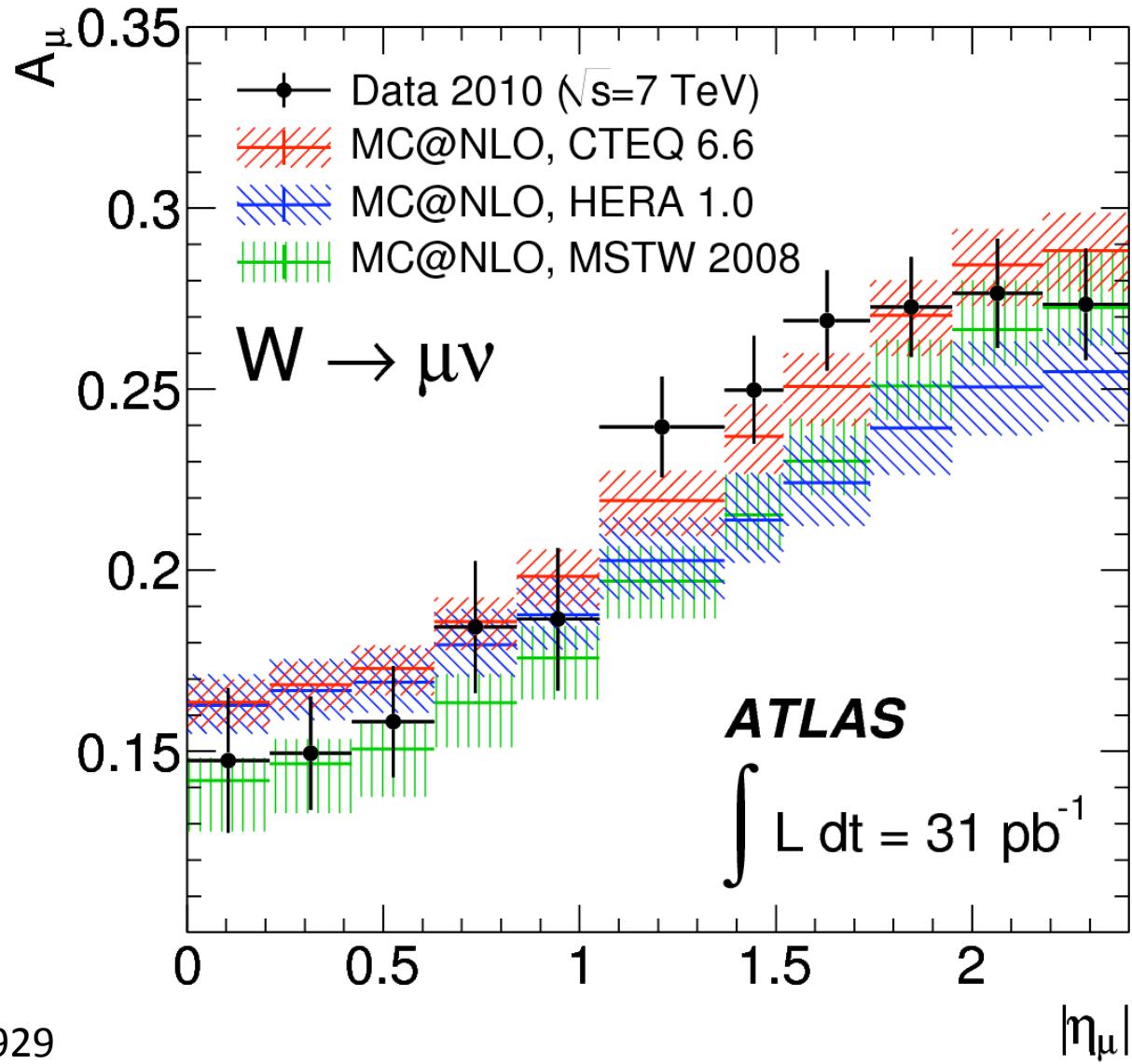
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$Q^2 = M_W^2$, ratio to NNPDF2.1



u

ATLAS measured the W asymmetry with muons:



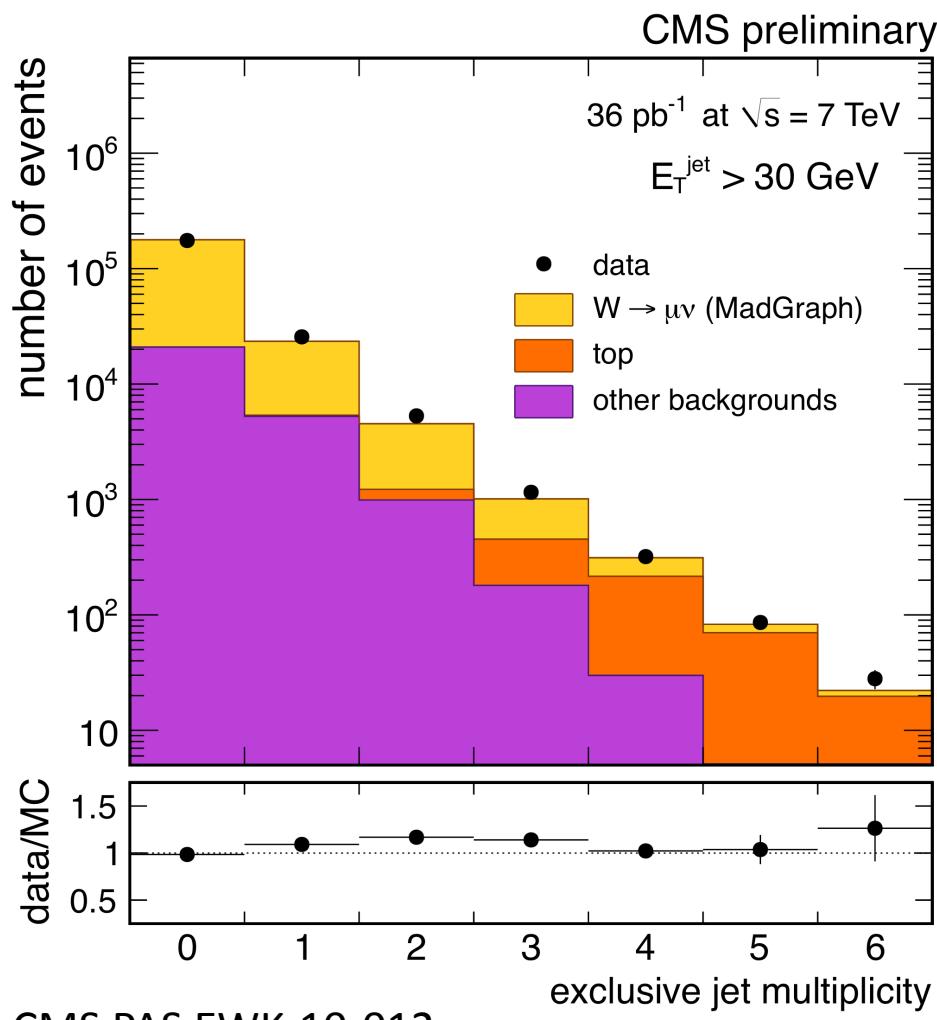
arXiv:1103.2929

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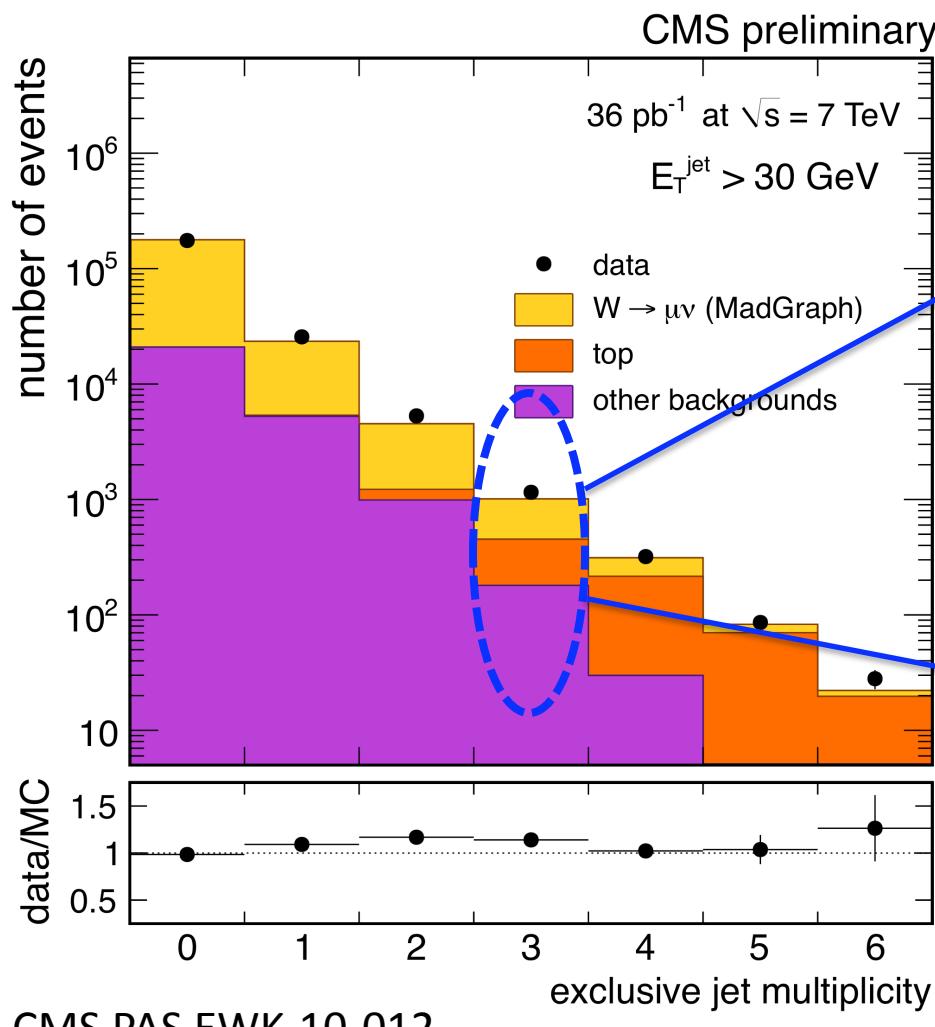
W,Z + Jets



Number of jets produced
in association with a W boson

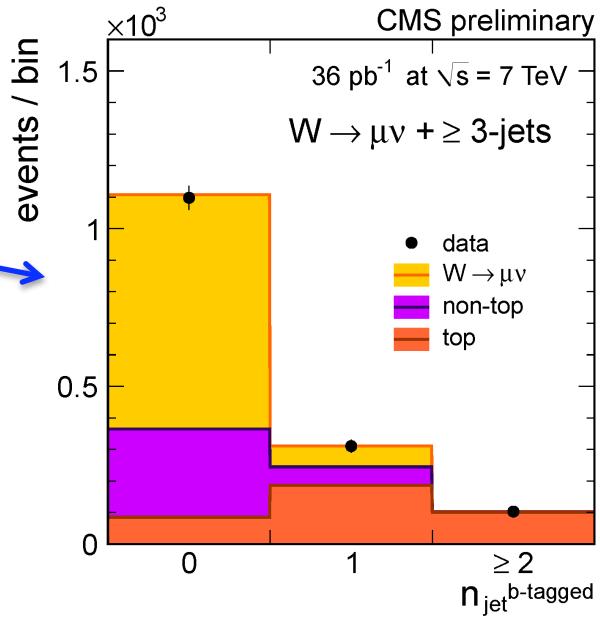
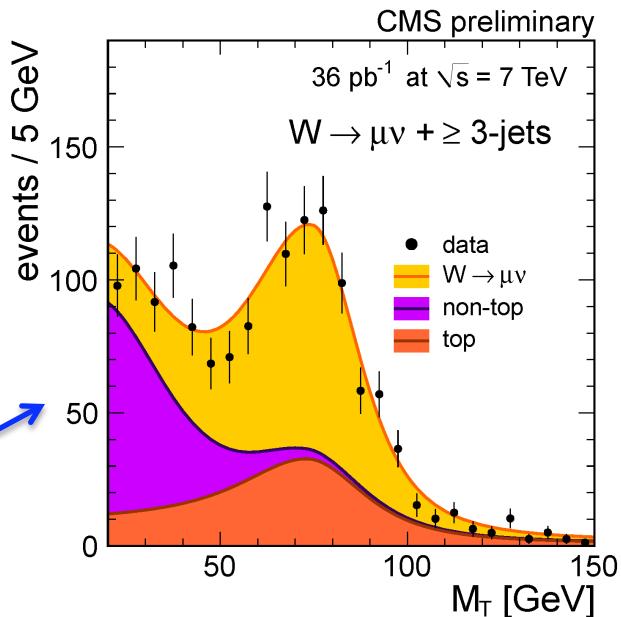
W,Z + Jets

Fit for the
top-quark fraction



CMS PAS EWK-10-012

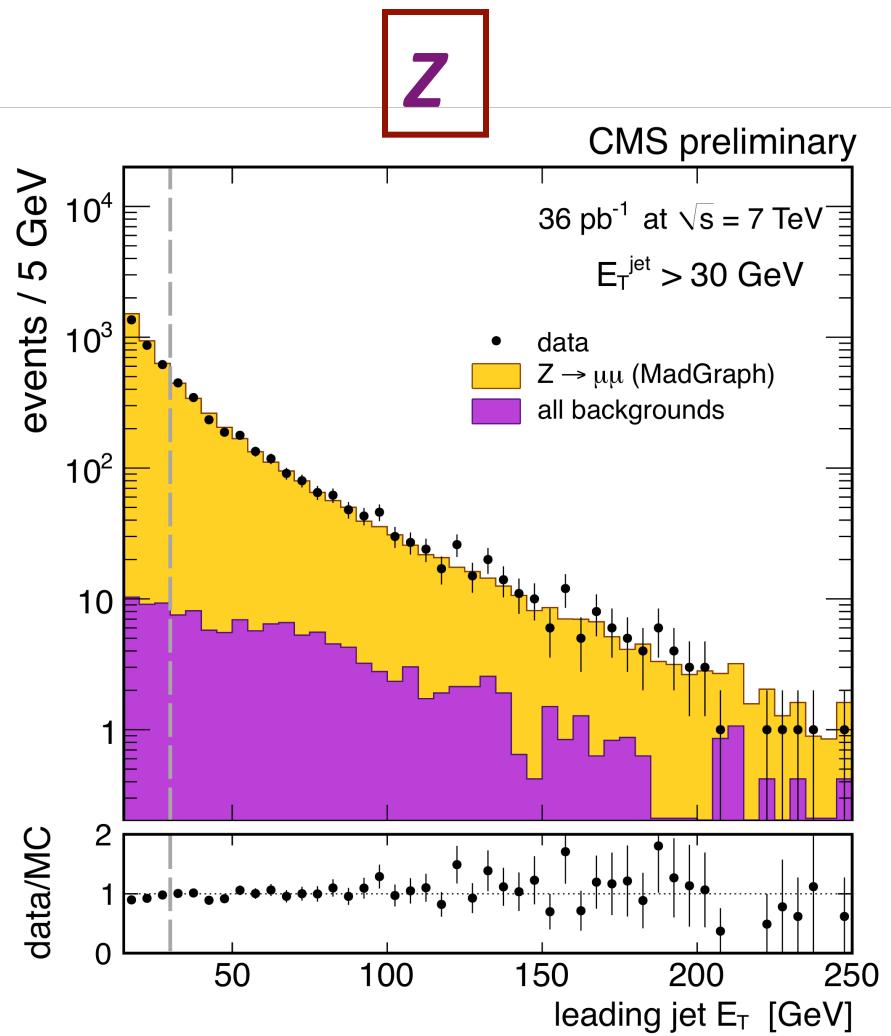
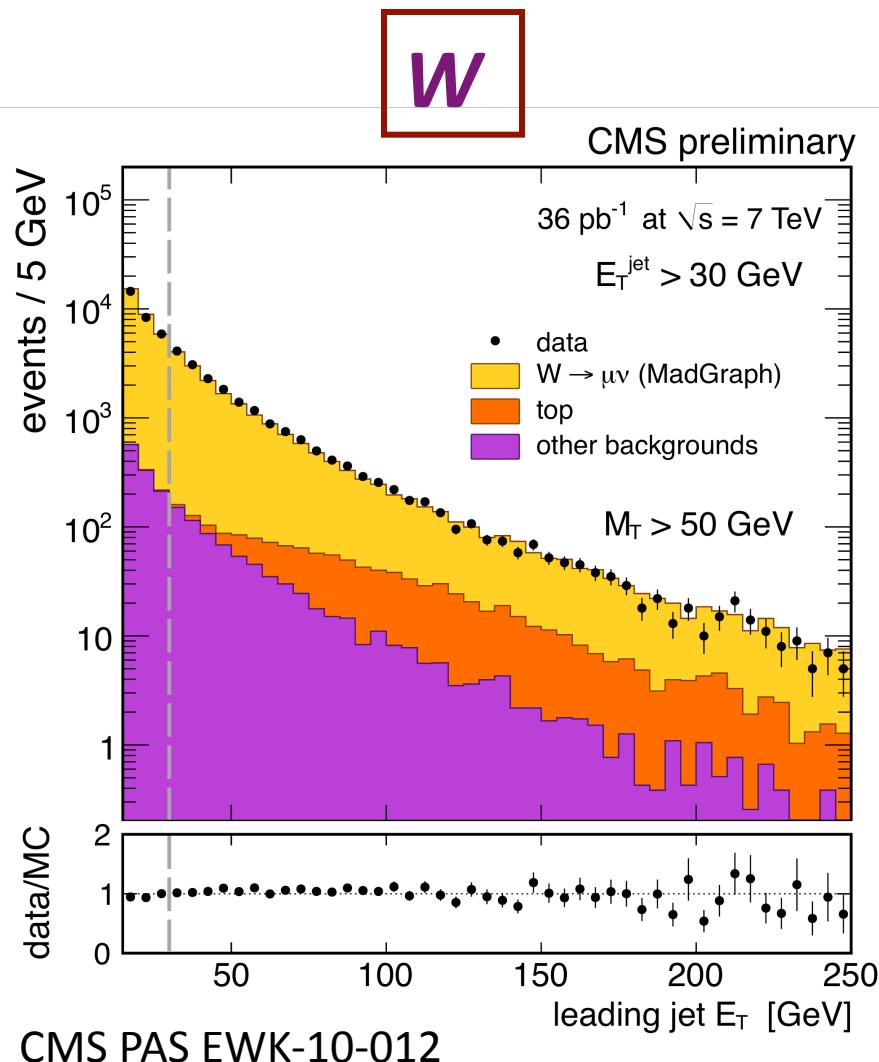
28-April-2011

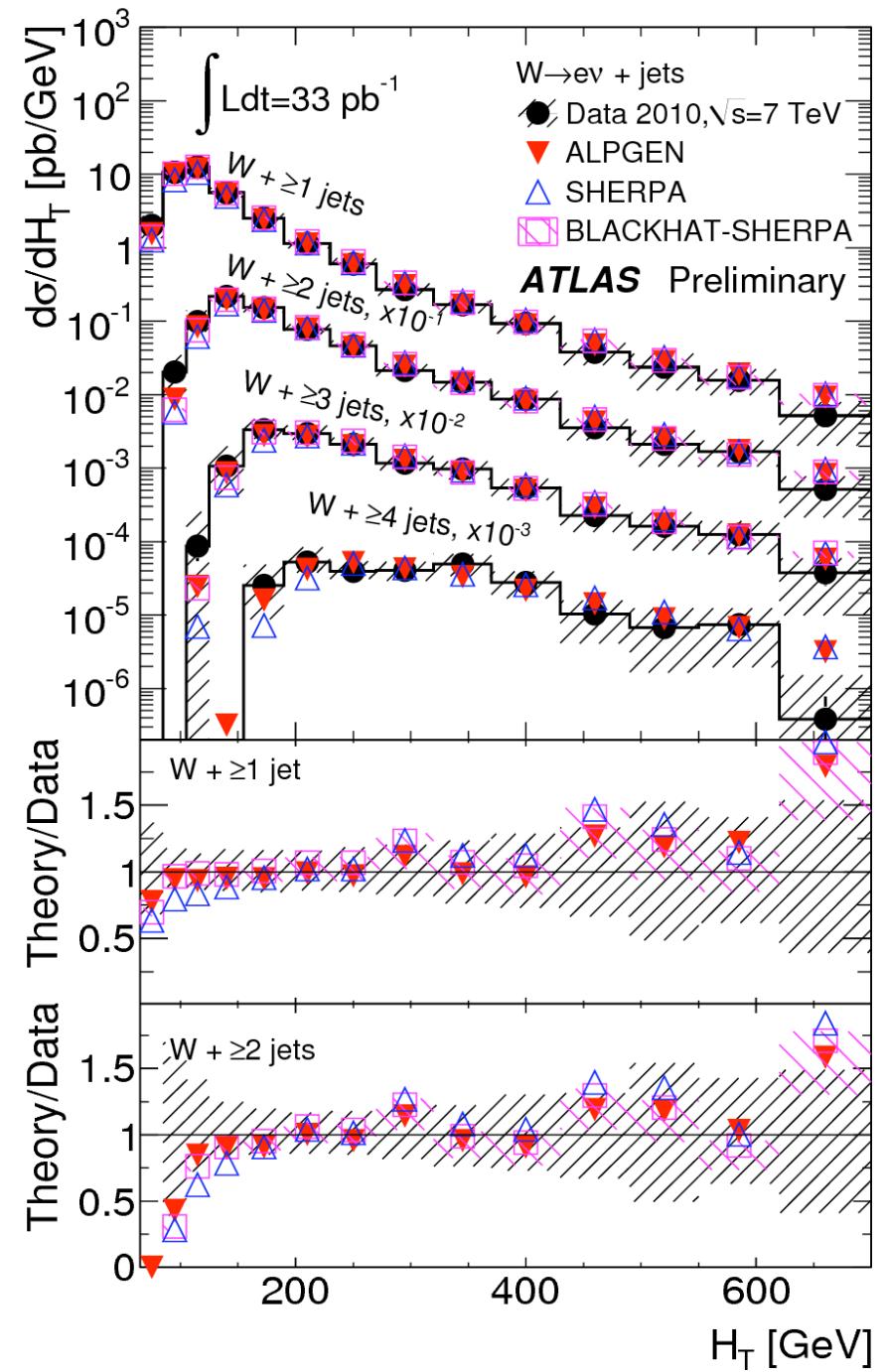
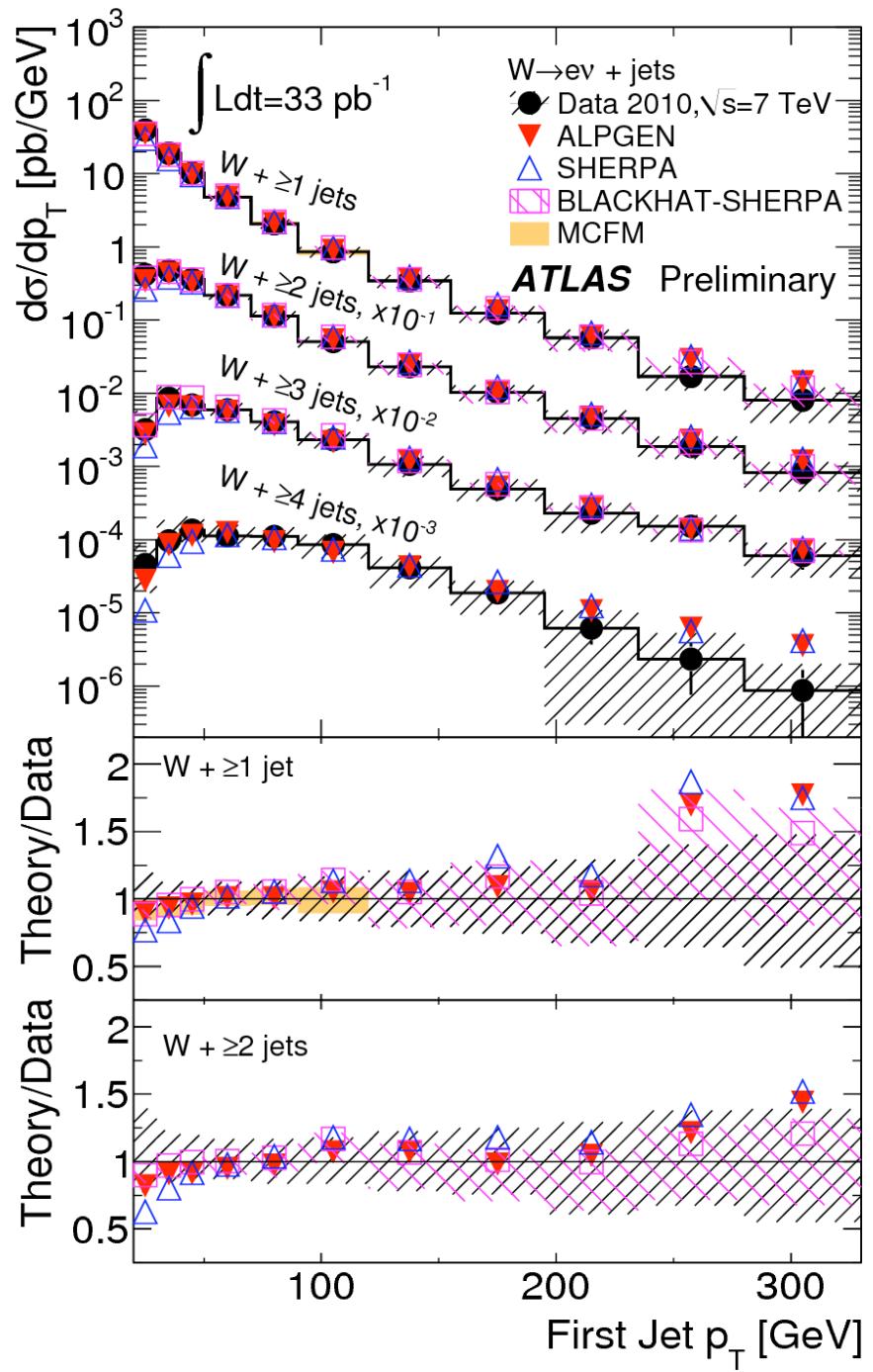


LHC Electroweak Physics - Michael Schmitz

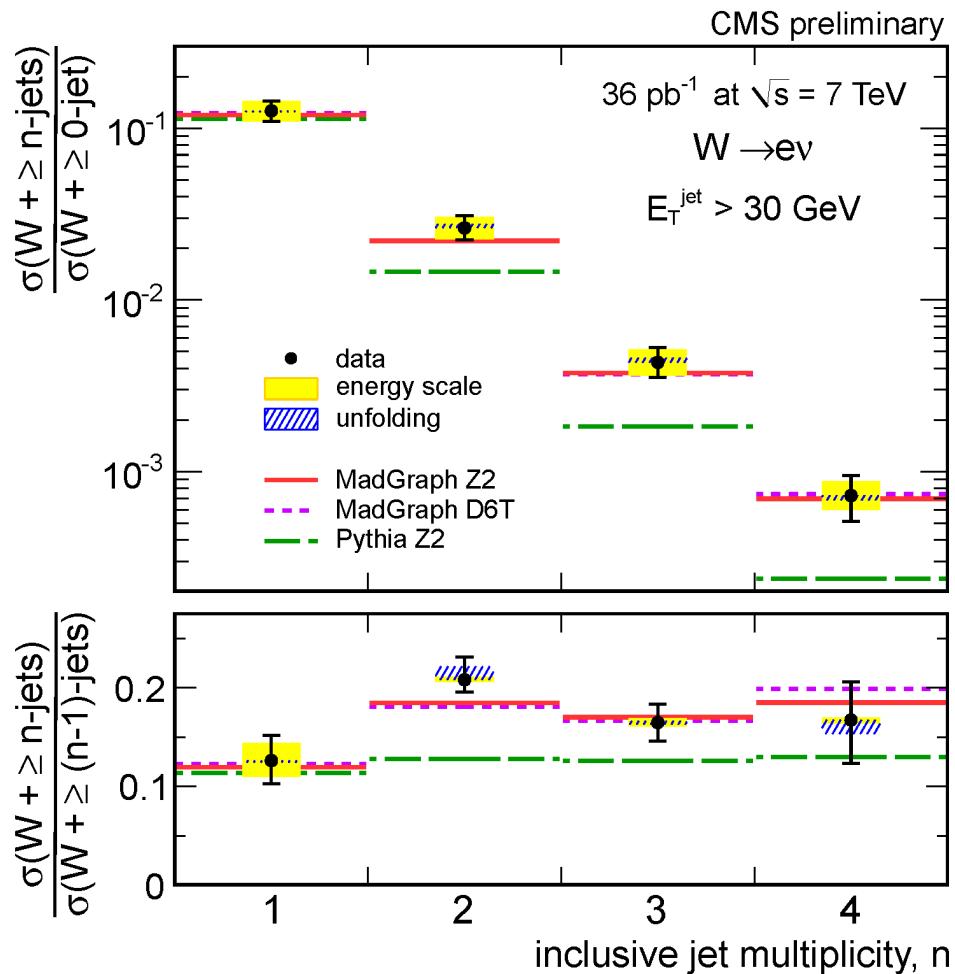
W,Z + Jets

Notice there is no top-quark contribution in the Z sample.





W,Z + Jets



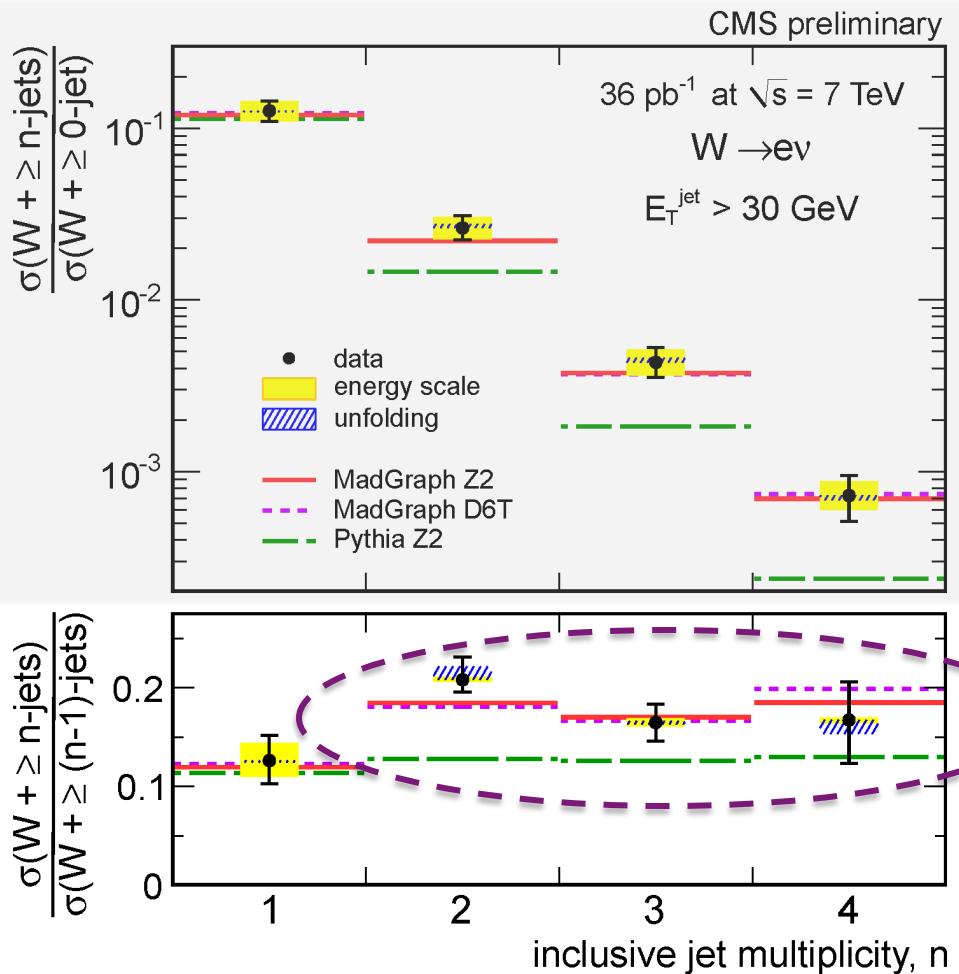
Take ratios to reduce systematic uncertainties:

$$\frac{\sigma(W + \geq n \text{ jets})}{\sigma(W \text{ inclusive})}$$

$$\frac{\sigma(W + \geq n \text{ jets})}{\sigma(W + \geq (n - 1) \text{ jets})}$$

Good agreement is reached for matrix-element calculations, not for parton-shower calculations.

W,Z + Jets

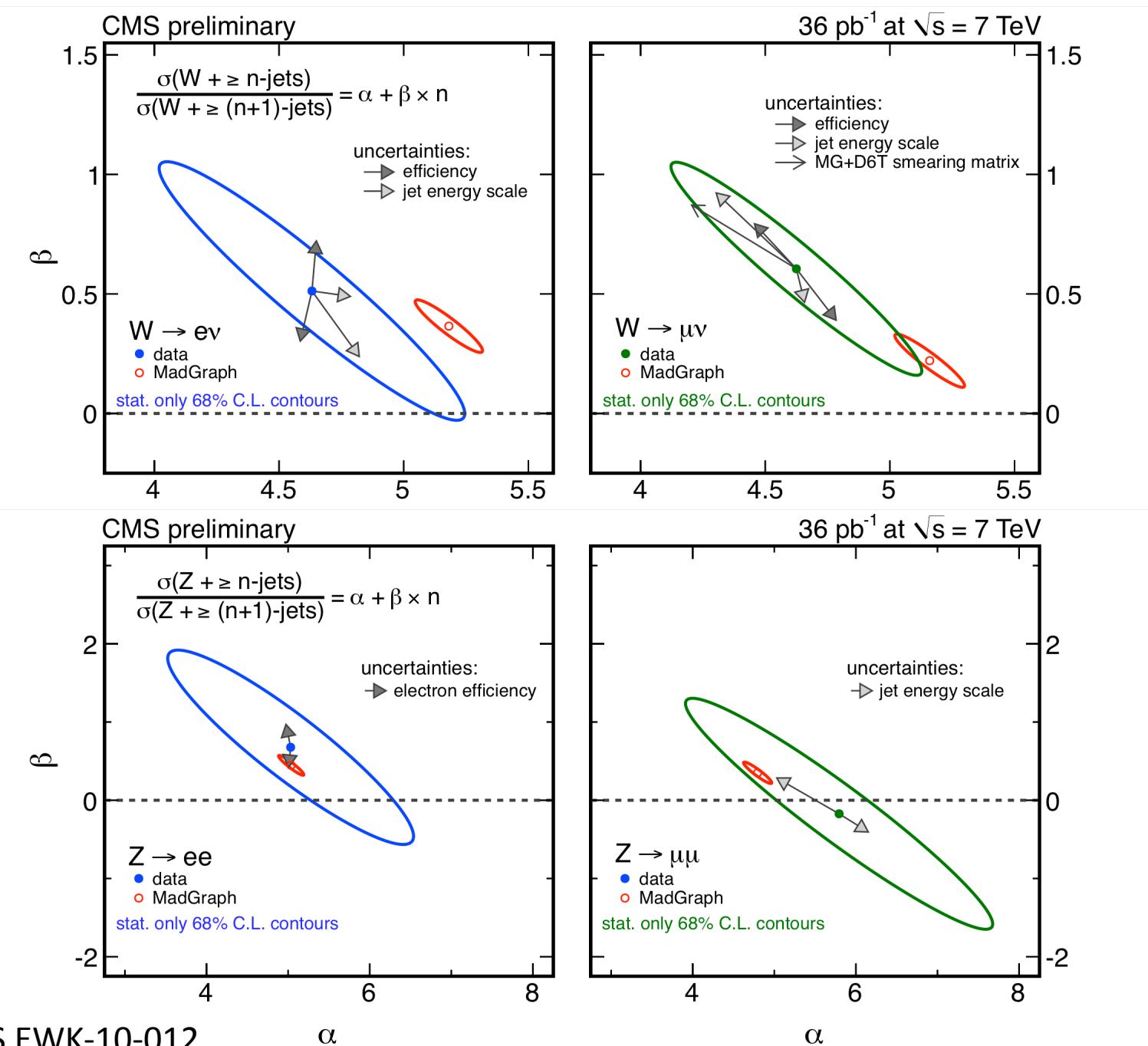


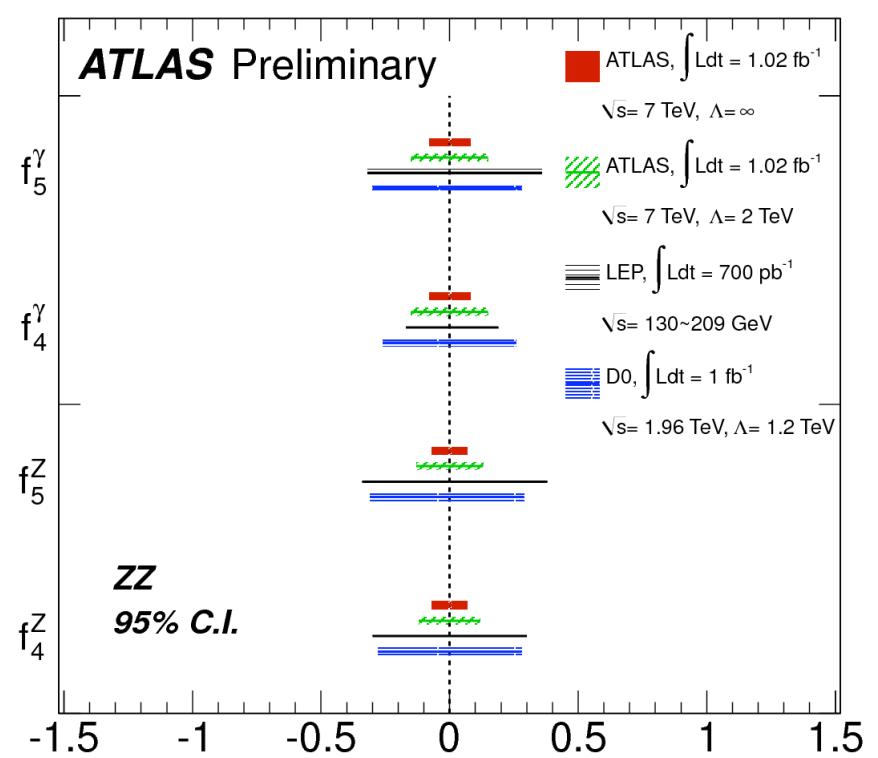
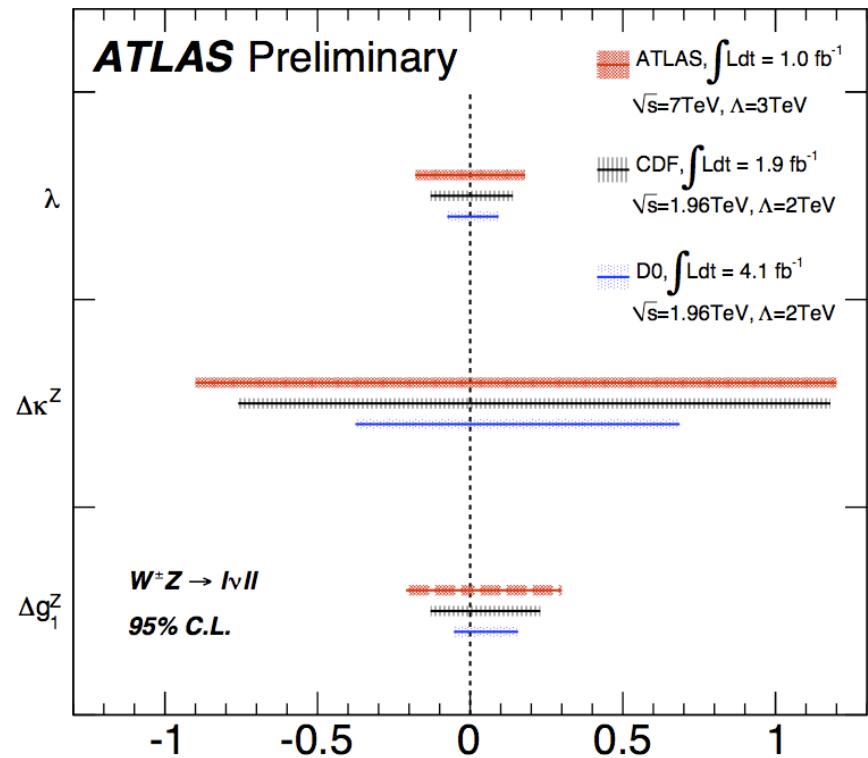
$$\frac{\sigma(W + \geq n \text{ jets})}{\sigma(W + \geq (n - 1) \text{ jets})}$$

The results and phenomenology suggest some sort of scaling law.

Following Berends-Giele, we tried

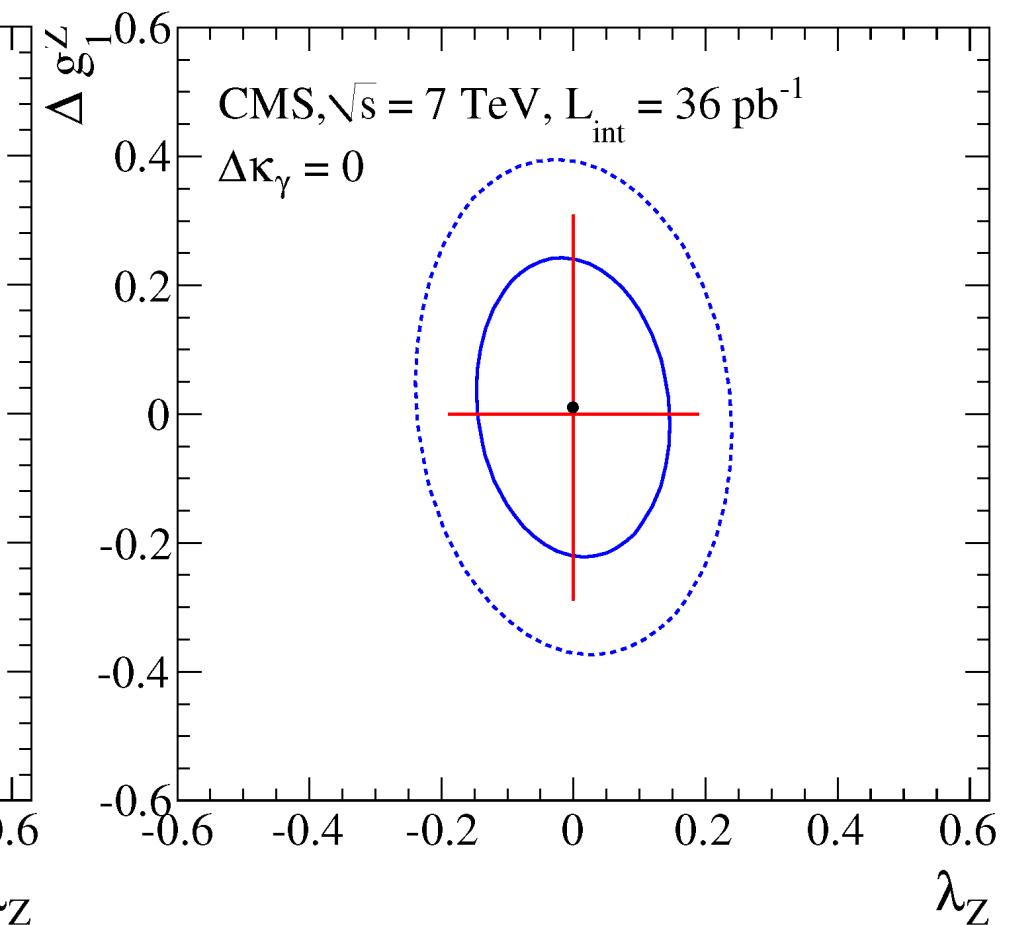
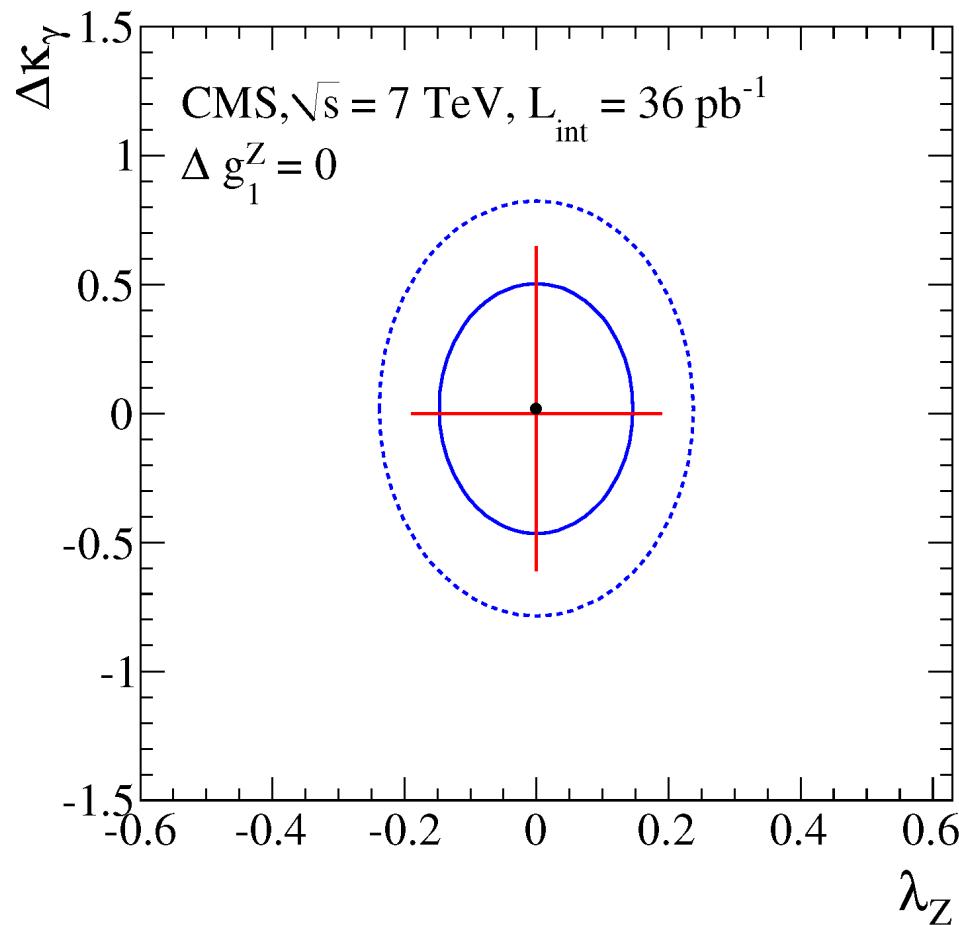
$$\alpha + \beta \times n$$





The cross section $\sigma(WW)$ is sensitive to anomalous tri-linear couplings

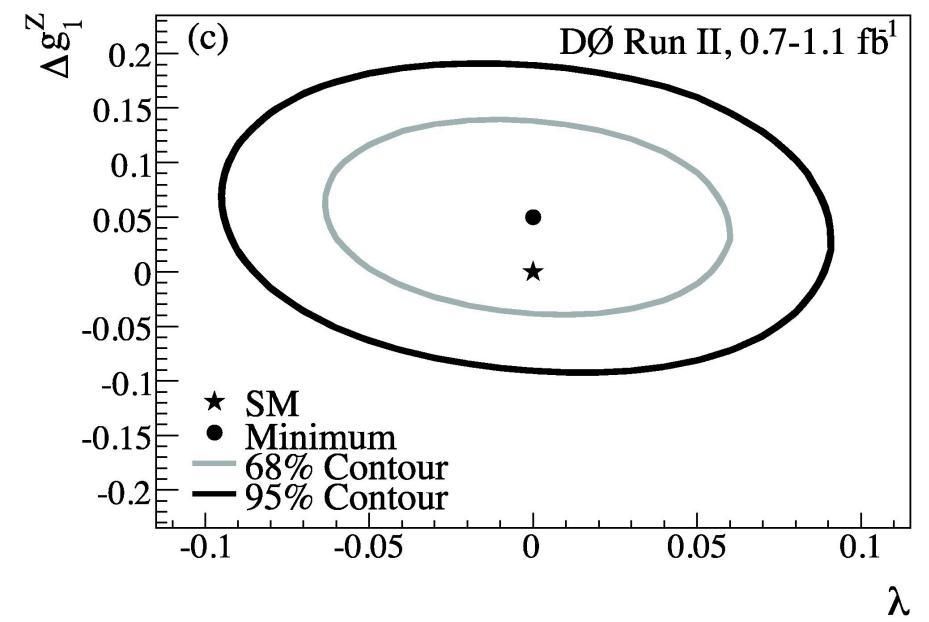
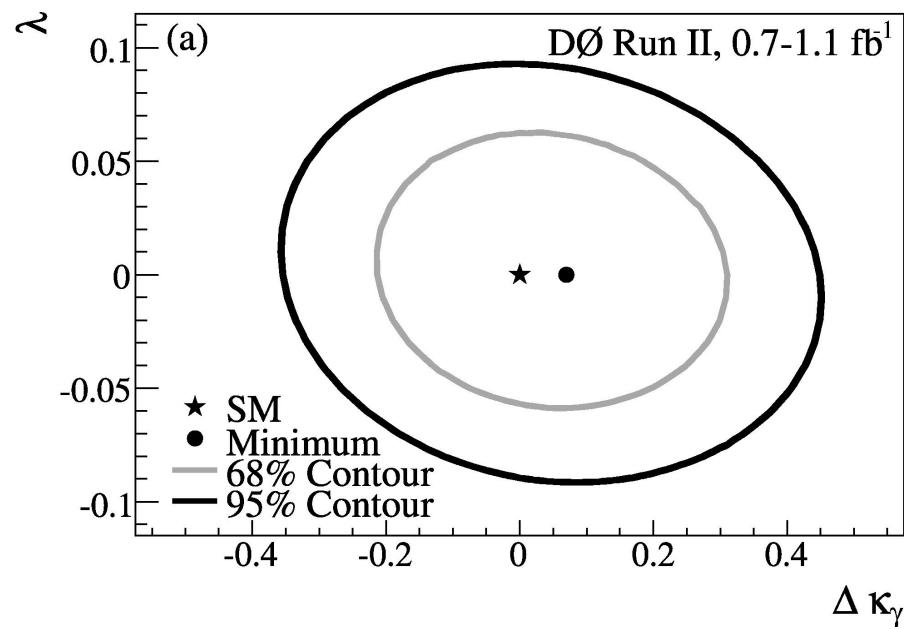
(i.e., deviations from the expected WWZ & $WW\gamma$ coupling constants)



These bounds are not yet very constraining – more data is needed.

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D0 combined results: much tighter bounds than CMS



NB: form factors with $\Lambda = 2$ TeV.

arXiv:0907.4952