November 20th, 2014

ICTP-NCP School on LHC Physics

LHC results: Standard Model (W, Z, γ, jets)

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At this point we have to discuss a bit more the

PARTON DISTRIBUTION FUNCTIONS (PDF)

LHC: the initial state

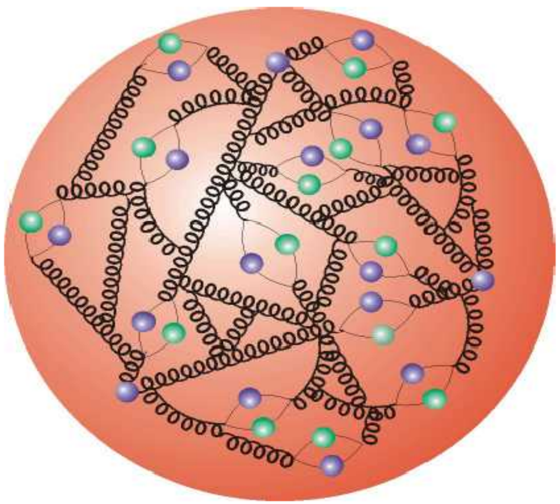
Parton Distribution Functions (PDFs)

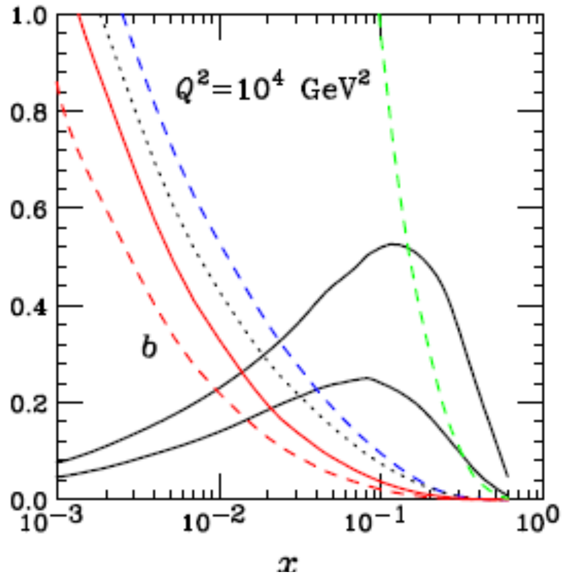
a complex target: uud valence+sea

Proton content:

u,d,s,c,b,gluons

Current picture of the proton





LHC parton kinematics
- definitions -

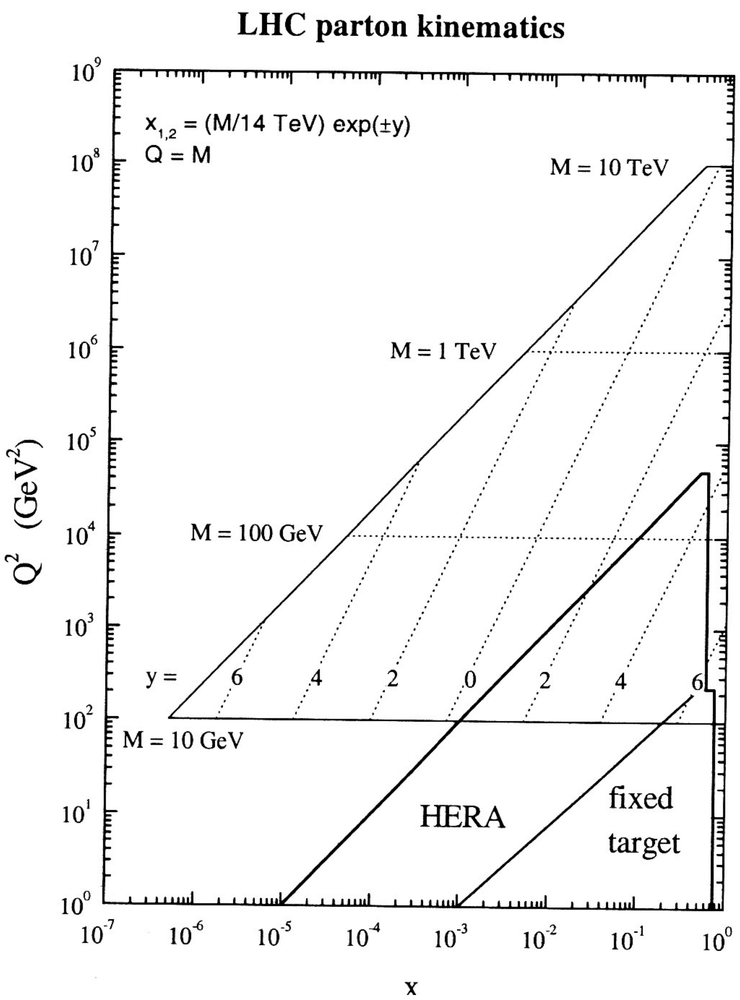
A particle of mass M and rapidity y produced by a pair of partons (1,2) carrying a fraction

$$x_{1,2} = \frac{P^L{}_{1,2}}{P_{\mathrm{BEAM}}(= 7\ \mathrm{TeV})} = \frac{P^L{}_{1,2}}{\sqrt{s}/2}$$

of the proton momentum.

Can show that

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



Demonstration (left as exercize)

$$y = \frac{1}{2}\ln\left(\frac{E + P_L}{E - P_L}\right) \;;\; M = \sqrt{x_1 x_2 s} = \sqrt{\tau s}$$

$$e^y = \sqrt{\frac{E + P_L}{E - P_L}} = \sqrt{\frac{(E + P_L)^2}{E^2 - P_L{}^2}} = \frac{E + P_L}{\sqrt{\tau s}}$$

$$P_L = P_{1L} - P_{2L} \;;\; E \approx P_{1L} + P_{2L} \;;\; (\text{if } E >> M)$$

$$\sqrt{\tau} e^y = \frac{E + P_L}{\sqrt{s}} \approx x_1 \;;\; \sqrt{\tau} e^{-y} = \frac{E - P_L}{\sqrt{s}} \approx x_2$$

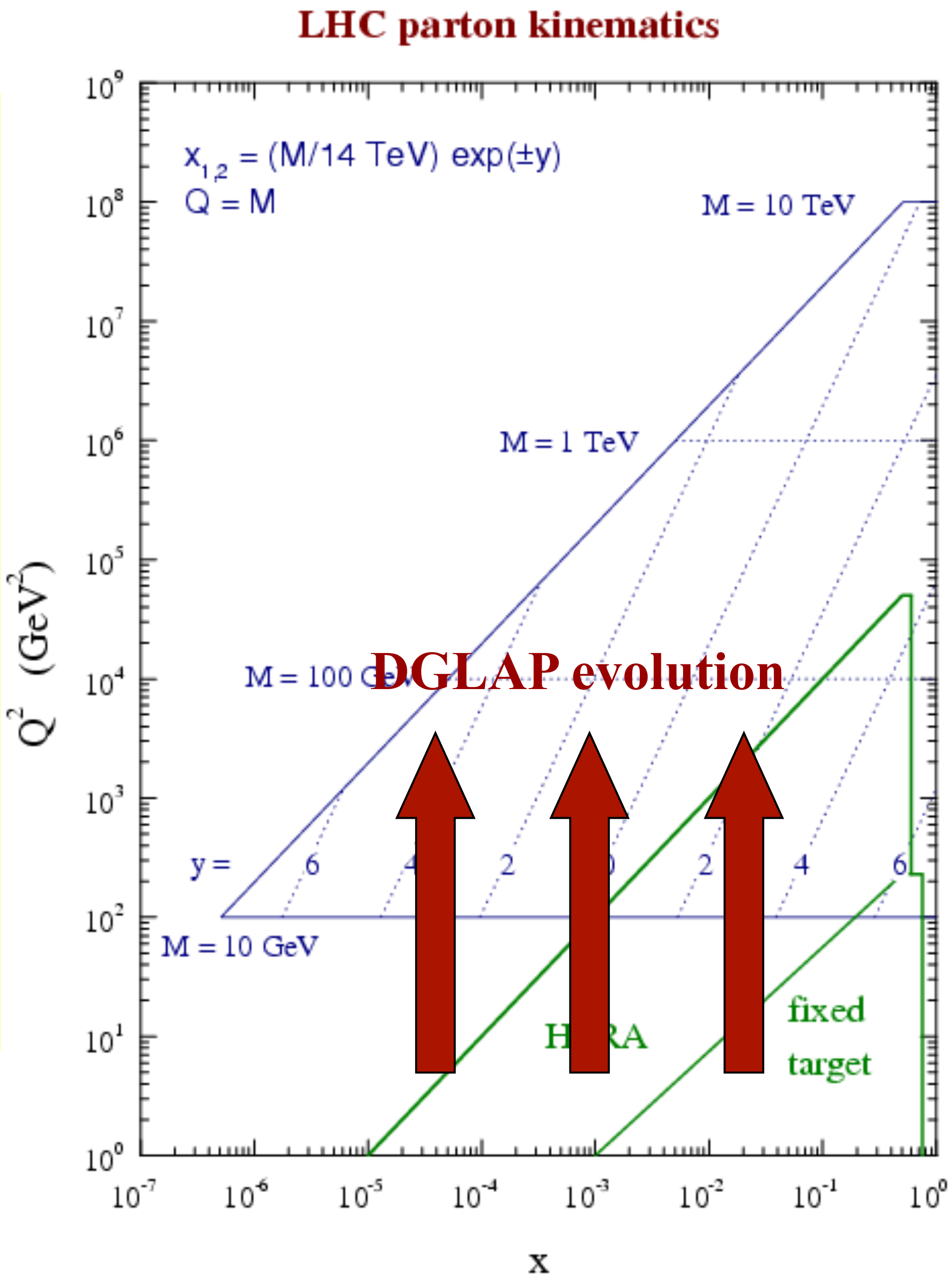
$$x_{1,2} \approx \frac{M e^{\pm y}}{\sqrt{s}}$$

QCD Evolution of PDFs

At the LHC: momentum fractions x_1 and x_2 determined by mass and rapidity of X

HERA measurements do not cover the LHC region, eg. for central Higgs production
⇒PDFs evolved via DGLAP equations from (x,Q^2_0) to (x,Q^2)

Note: W,Z, Higgs production needs PDFs from the x range 10^{-4} – 10^{-1}



Computing the cross sections

$$\sigma(p_1,p_2;Q,\{...\}) = \sum_{a,b}\int dx_1 dx_2 f_{a/h_1}(x_1,Q^2) f_{b/h_2}(x_2,Q^2)\hat{\sigma}_{a,b}(x_1 p_1, x_2 p_2, Q, \{...\};\alpha_s(Q))$$

Need a specific PDF set, example from MRST(2000)

$$\sqrt{s} = 14\ \text{TeV}$$

$$\sigma_{\text{tot}} = 99.\ \text{mb}$$

$$\sigma_{\text{b}} = 63.\ \mu\text{b}$$

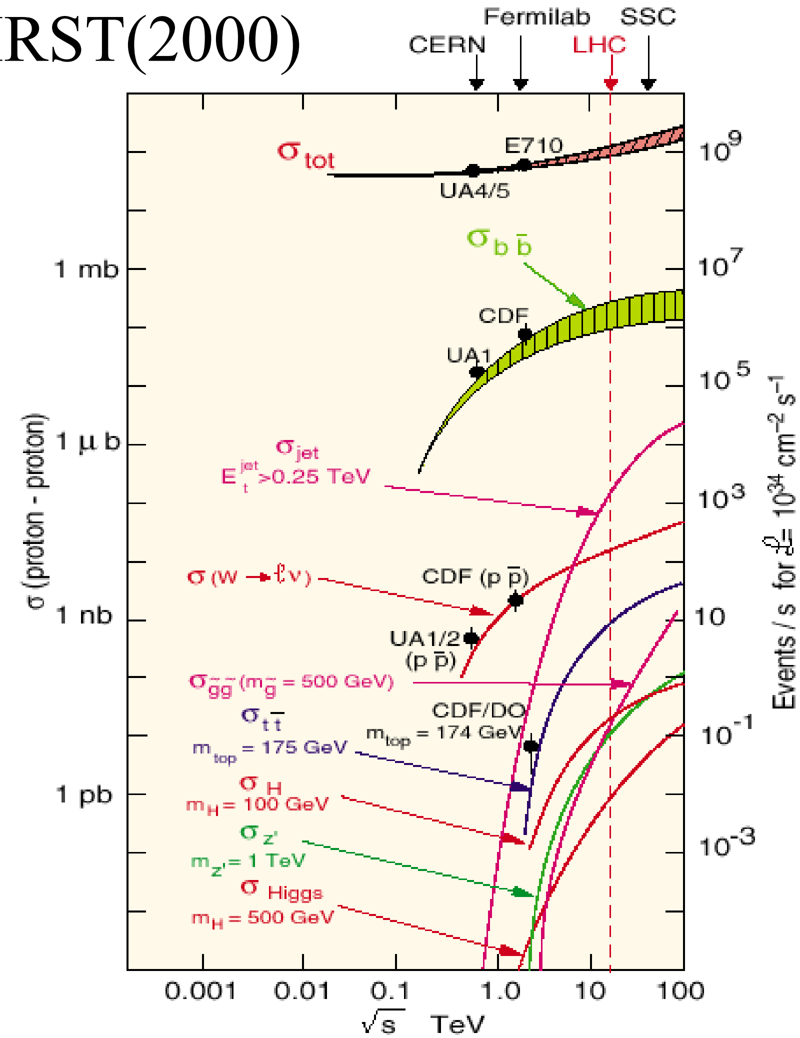
$$\sigma_{\text{t}} = 890\ \text{pb}$$

$$\sigma_{\text{W}} = 190\ \text{nb}$$

$$\sigma_{\text{Z}} = 56\ \text{nb}$$

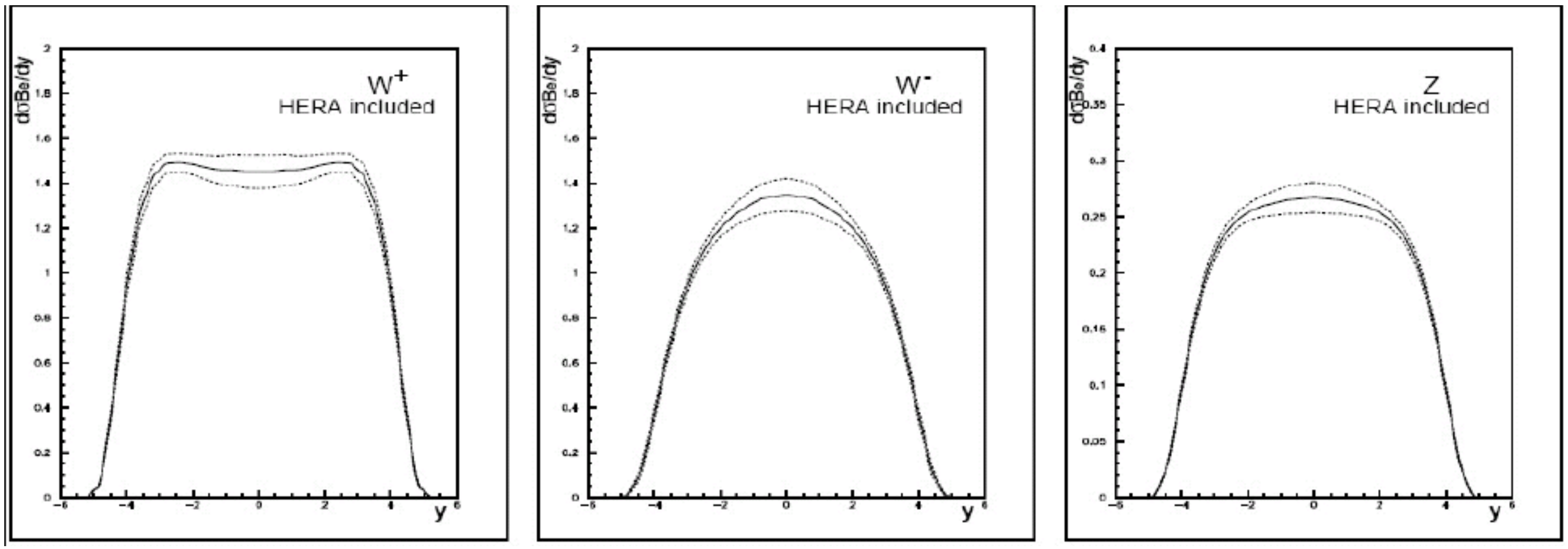
$$\sigma_{\text{Higgs},(m_{\text{Higgs}}=150\ \text{GeV})} = 24\ \text{pb}$$

$$\sigma_{\text{Higgs},(m_{\text{Higgs}}=500\ \text{GeV})} = 3.8\ \text{pb}$$



Measure PDF with LHC data

- Production cross sections (W, Z, γ, jets)
  - e.g. γ+Jet for gluons (qg→qγ) **QCD Compton**
  - HF tagged qg→qγ, qZ, qW for c,b PDF
- Differential cross sections increase sensitivity
  - W, Z rapidity
  - W charge asymmetry → $\sigma(W^+) \sim 1.35\ \sigma(W^-)$

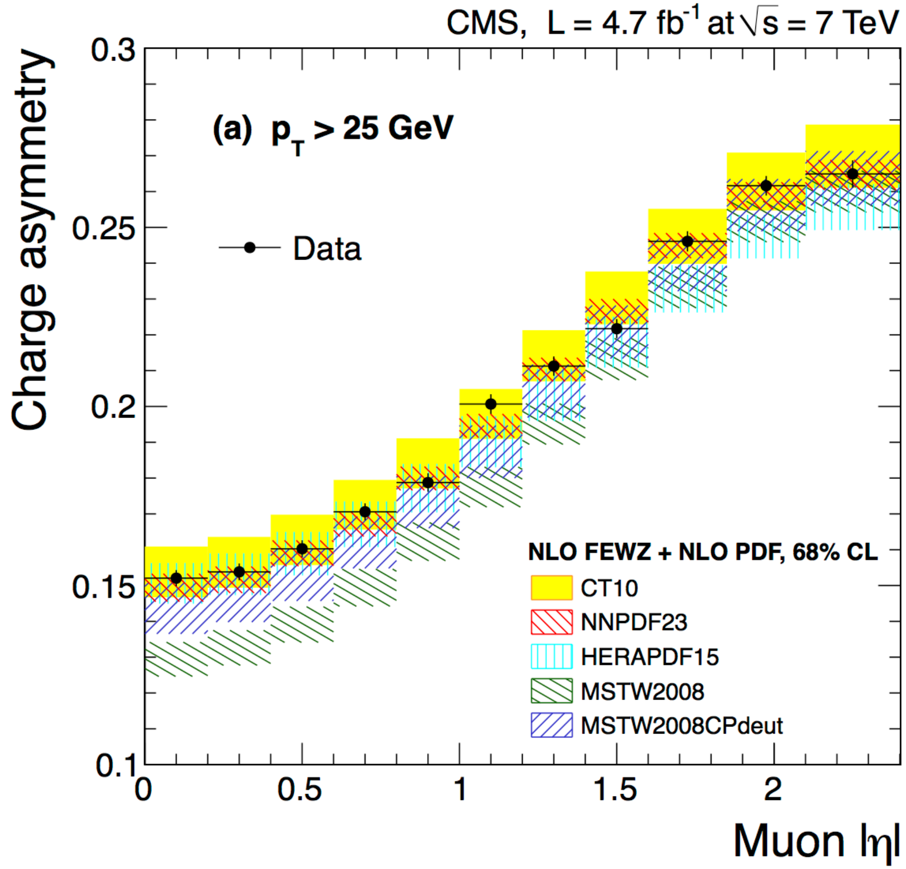


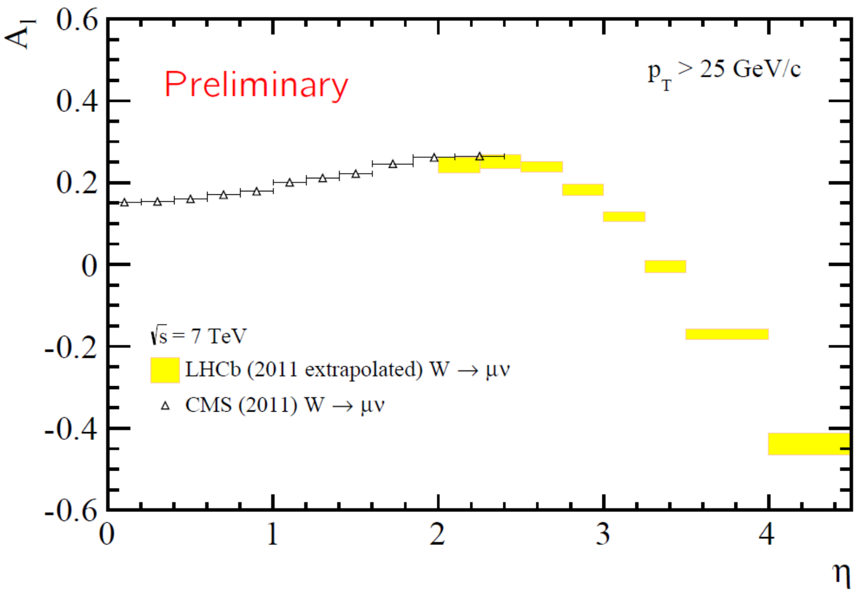
PRD 90 (2014) 032004

W charge asymmetry

- The differential charge asymmetry: sensitive to u/d ratio as a function of rapidity
- Asymmetry measured at permil level per bin
- Forward measurement from LHCb, sensitivity to low x !

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$



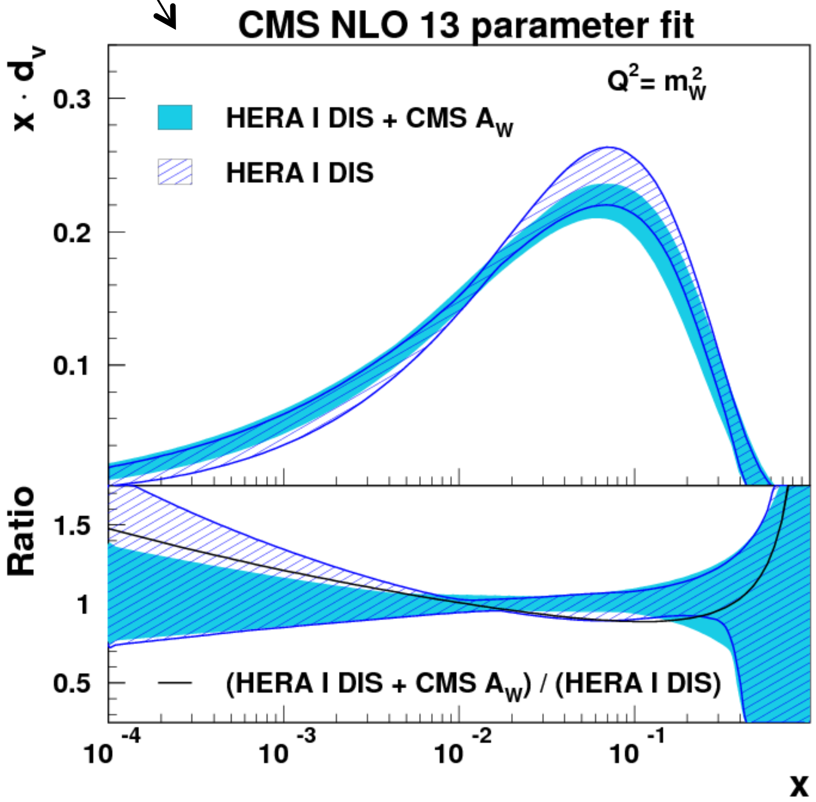


The dependence from $|\eta|$ follows from $x_{1,2} \approx \frac{Me^{\pm y}}{\sqrt{s}}$

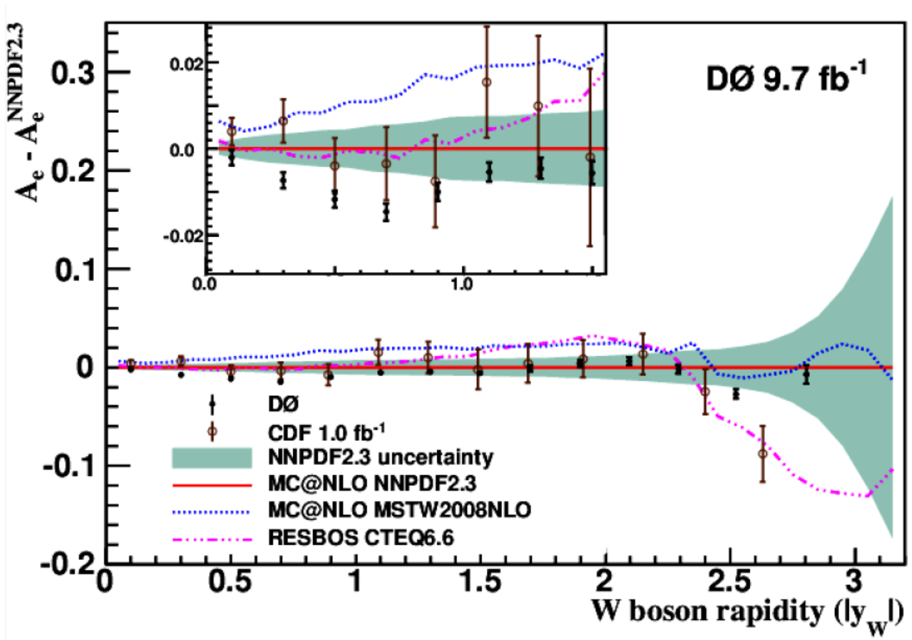
at high rapidity need one parton at very high x

W charge asymmetry and PDF fits

LHC data combined with HERA DIS to improve d-valence PDF

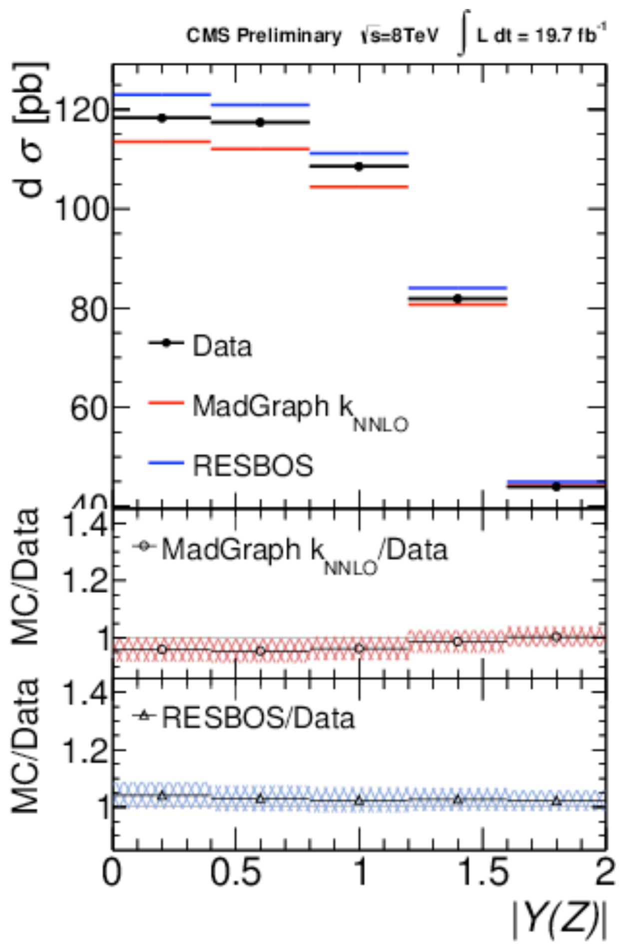


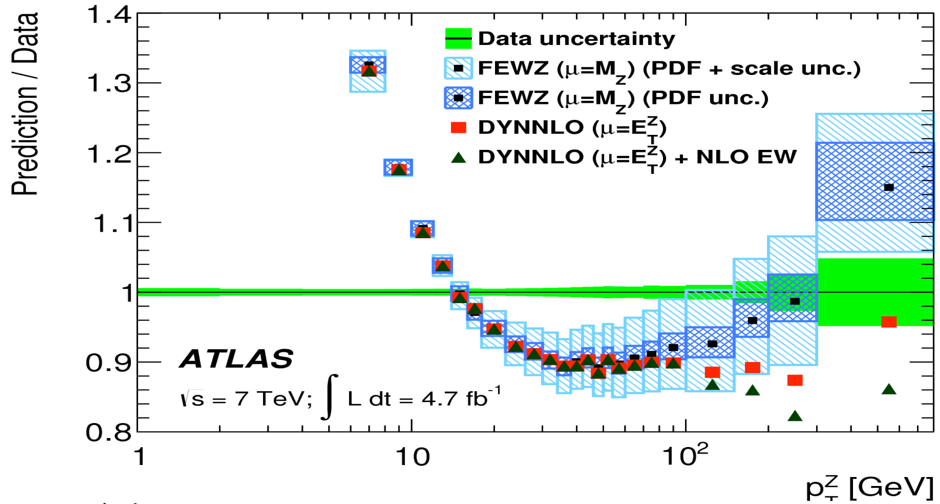
Input from W charge asymmetry at Tevatron

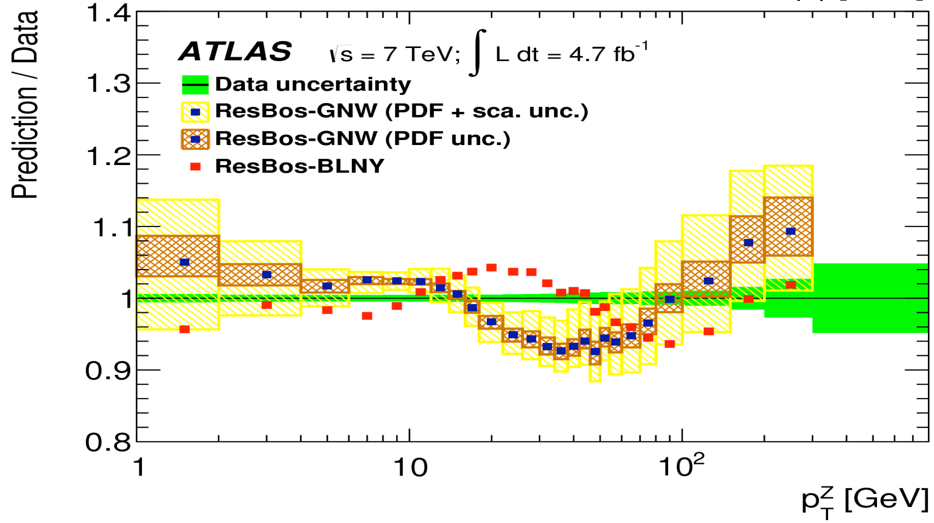


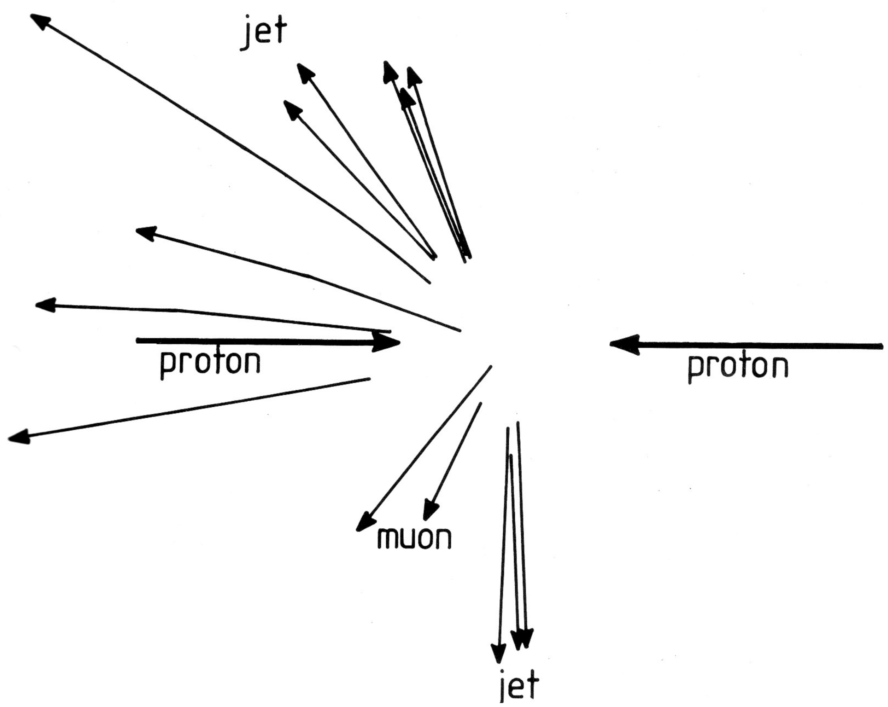
Z rapidity and p_T

Enough statistics to measure double differential cross section
Sensitivity to PDF and higher order QCD calculations (NNLO)









JETS

Alone or with Vector Bosons

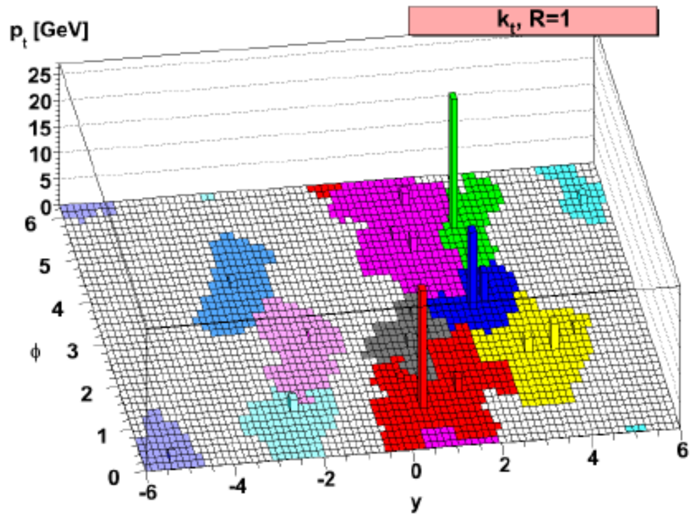
(acknowledgements: Jeff Berryhill and Chiara Roda [ICHEP 2015])

Jets @ hadron machines

- Dualism jet←→parton; (unphysical) attempt to match the two
- Cone algorithms, based on

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

- **non infrared safe**
- problem of black towers

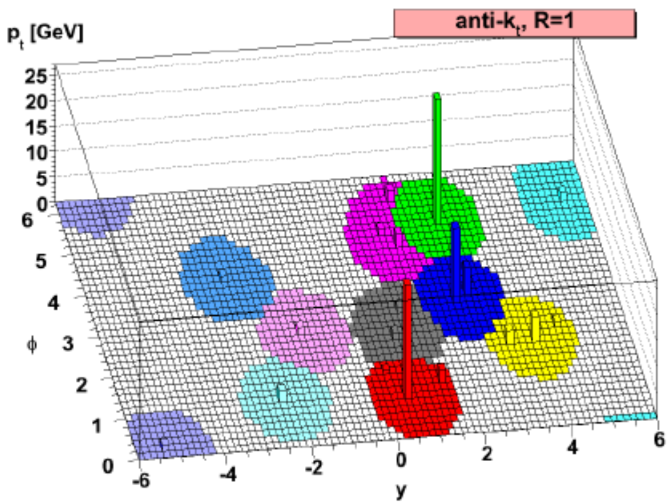


- Recombination algorithms: P=1 k_T algorithm, P=-1 anti-k_T algorithm

$$d_{ij} = \min(k_{Ti}^{2P}, k_{Tj}^{2P})\Delta R^2_{ij}$$

$$d_i = k_{Ti}^{2P}\ \mathrm{R}\ ;\ \text{parameter R} \approx 1$$

$$\text{if}\quad d_{ij} \le d_i\ \text{join}$$

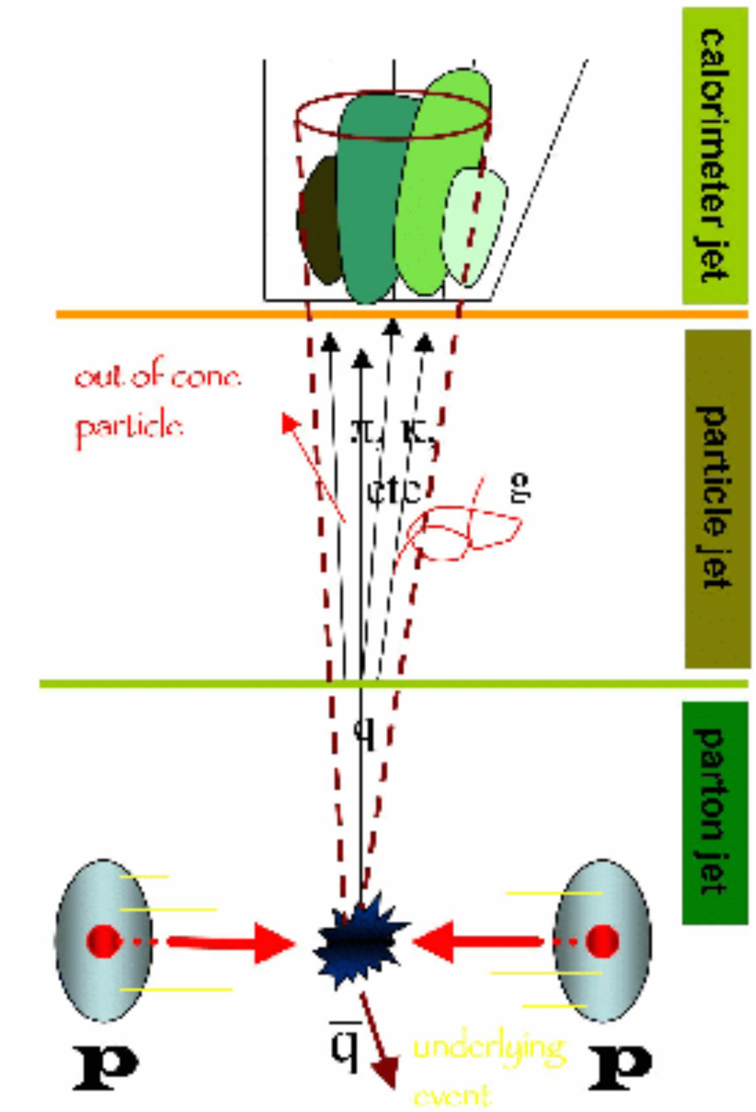


Jet Energy Corrections

Determine true "particle"or "parton" jet E_T from measured jet E_T

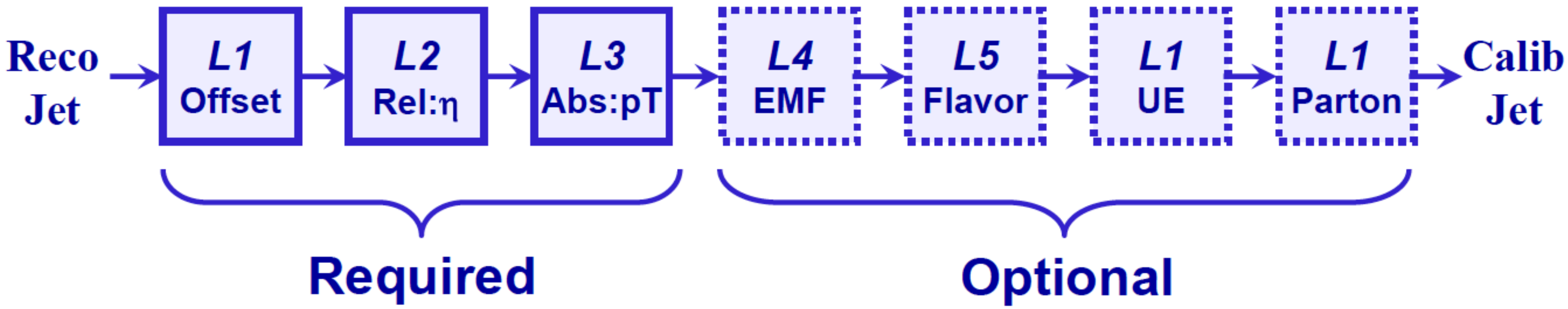
- Non-linear response
- not-instrumented regions
- Response to different particles
- Out of cone E loss
- Spectator interactions
- Underlying event

Note that the "elements" of a jet can be calorimeter towers or "particles" from particle flow reconstruction

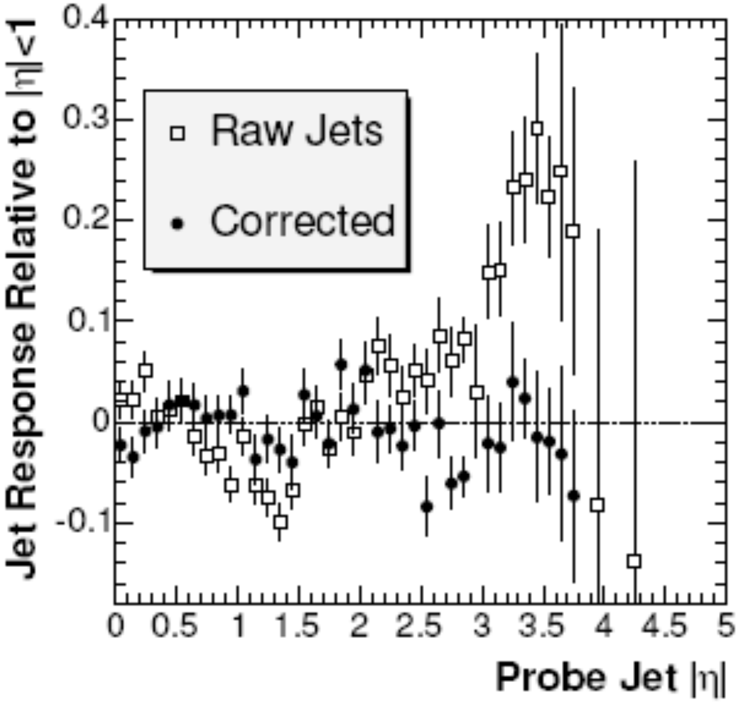


Factorized Jet Corrections

1. Offset: removal of pile-up and residual electronic noise.
2. Relative (η): variations in jet response with η relative to control region.
3. Absolute (p_T): correction to particle level versus jet p_T in control region.
4. EM fraction: correct for energy deposit fraction in em calorimeter
5. Flavor: correction to particle level for different types of jet (b, τ, etc.)
6. Underlying Event: luminosity independent spectator energy in jet
7. Parton: correction to parton level



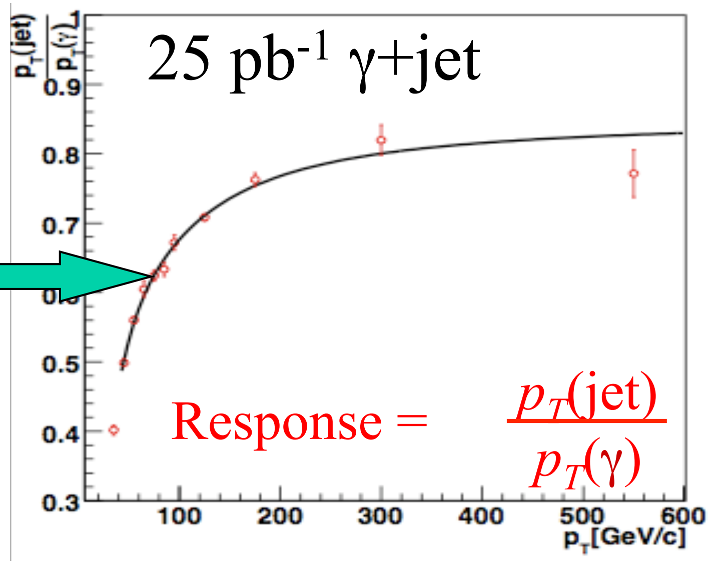
Jet Equalization with dijet balancing



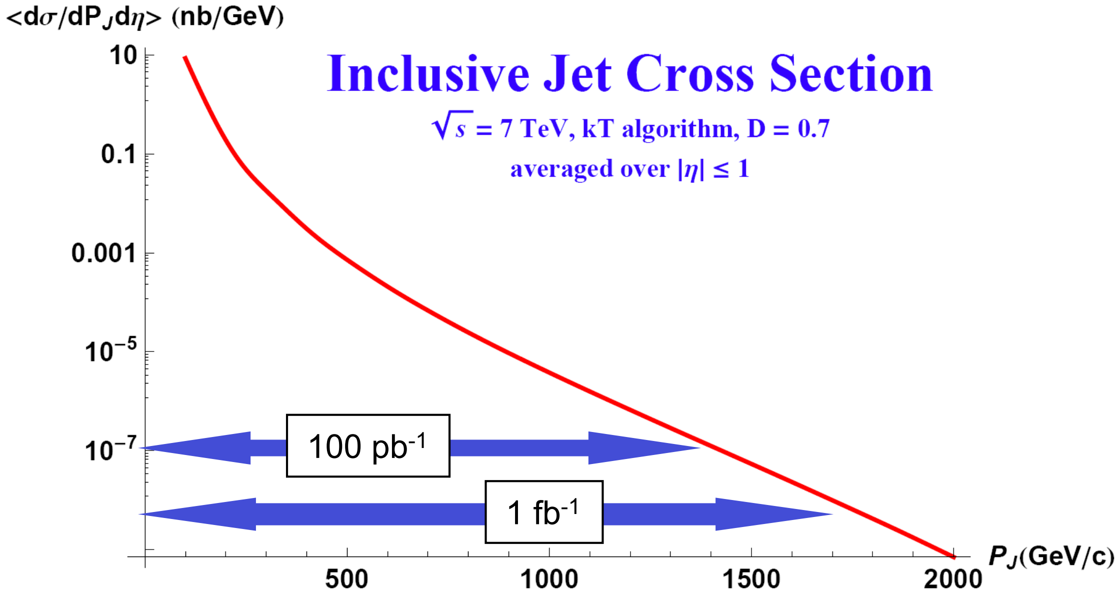
- We can quickly equalize at " low Et" until we run out of statistics
- One must assume equalization holds at higher energy (but MC needed for this)

Absolute energy scale:

- use γ+jet or Z+jet



Inclusive Jet Physics

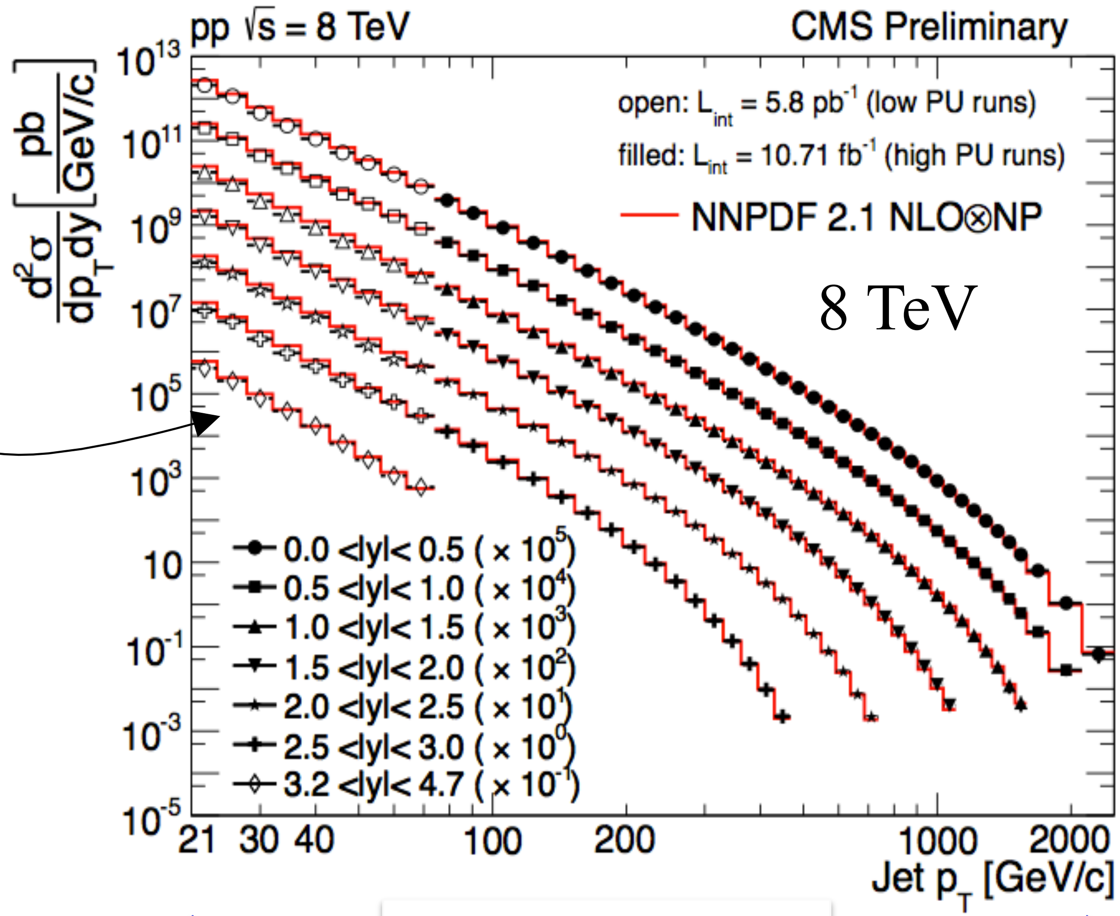


NLO QCD jet spectrum – no detector effects included

- Jets with E_T's of around 1.4 TeV with 100 pb^{-1}
- Jets with E_T's of around 1.7 TeV after the first fb^{-1}
- As a rule of thumb, the sensitivity to a contact interaction Λ is roughly 4x the E_T of the most energetic jet.

STDM-2013-11 CMS-PAS-FSQ-12-031 CMS-PAS-SMP-12-012

Inclusive cross-section @ 8 TeV



Low pile-up data to extend to the low p_T range down to 20 GeV and |y|<4.7

11 orders of magnitude

20 Gev – 2 TeV

LHC data allows pQCD tests in a new kinematic regime – extended in p_T and y
Covers 11 orders of magnitude / two jet sizes
Reference prediction: NLOJET + NNPDF2.1 but other PDF tested

CMS-PAS-SMP-12-028 CMS-PAS-SMP-12-027 arXiv 1406:470

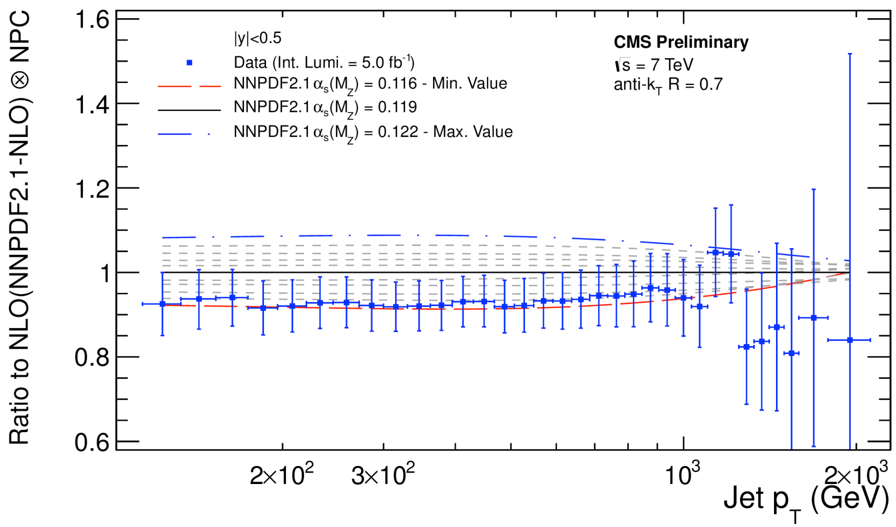
α_s measurement

World average (2014)

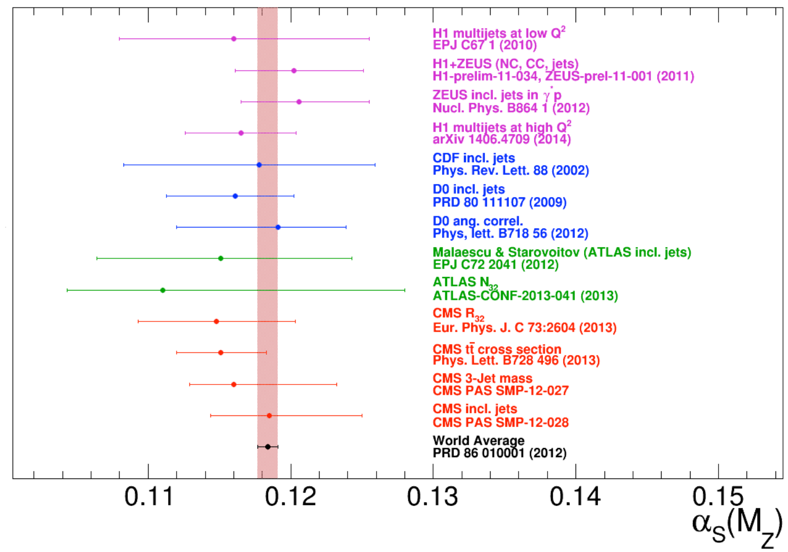
$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (0.5%)

CMS Most recent: inclusive jet (5%)

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019(\exp) \pm 0.0028(PDF)$$
$$\pm 0.0004(NP) \pm^{0.0055}_{0.0022} (scale)$$



Ratio of measured inclusive jet to NNLO prediction, with various α_s inputs

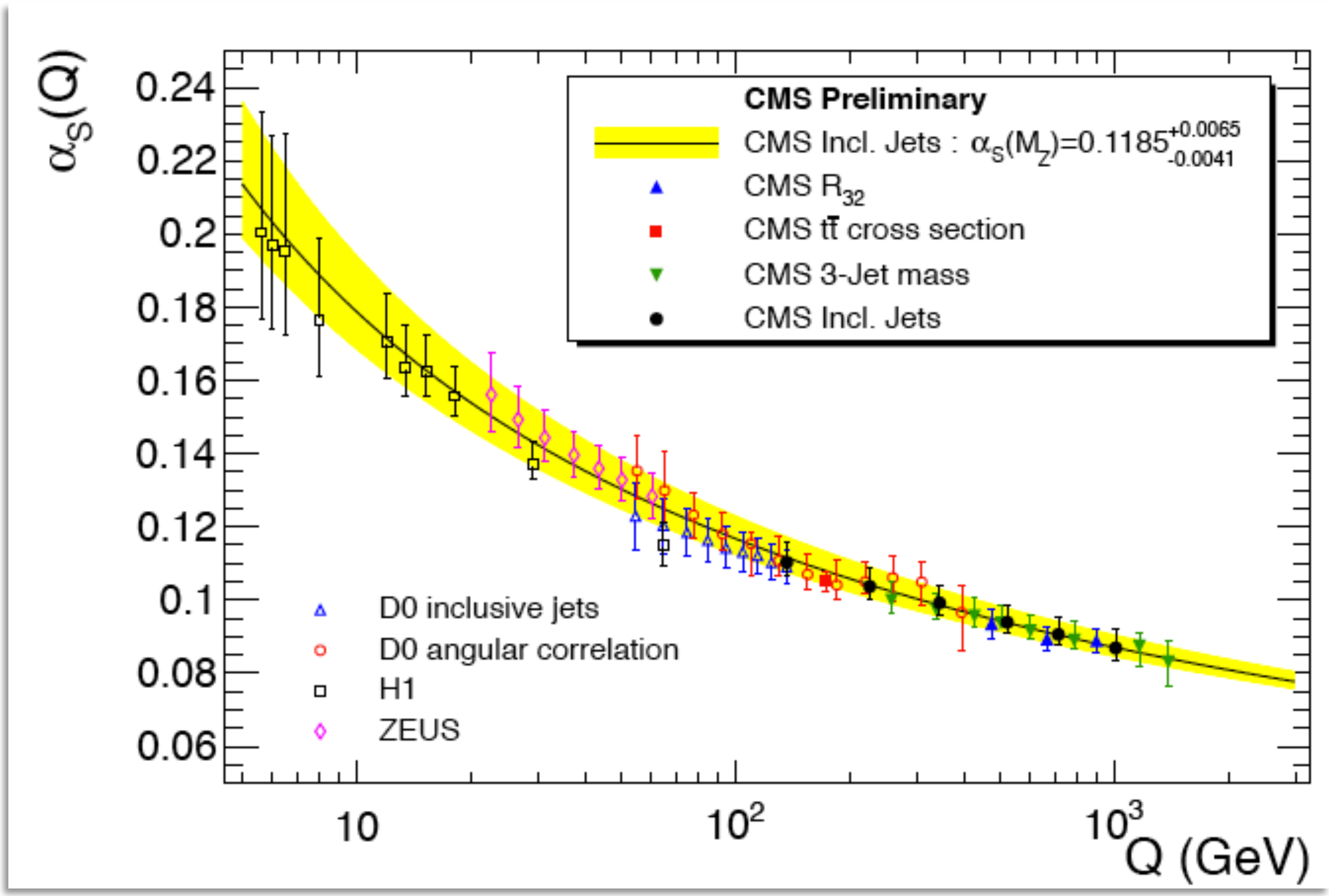


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

All measurements consistent with world average

Impressive proof of $\alpha_s(Q)$ running up to the TeV region

Running of α_s



back to W and Z, but γ before !

VECTOR BOSONS PLUS JETS

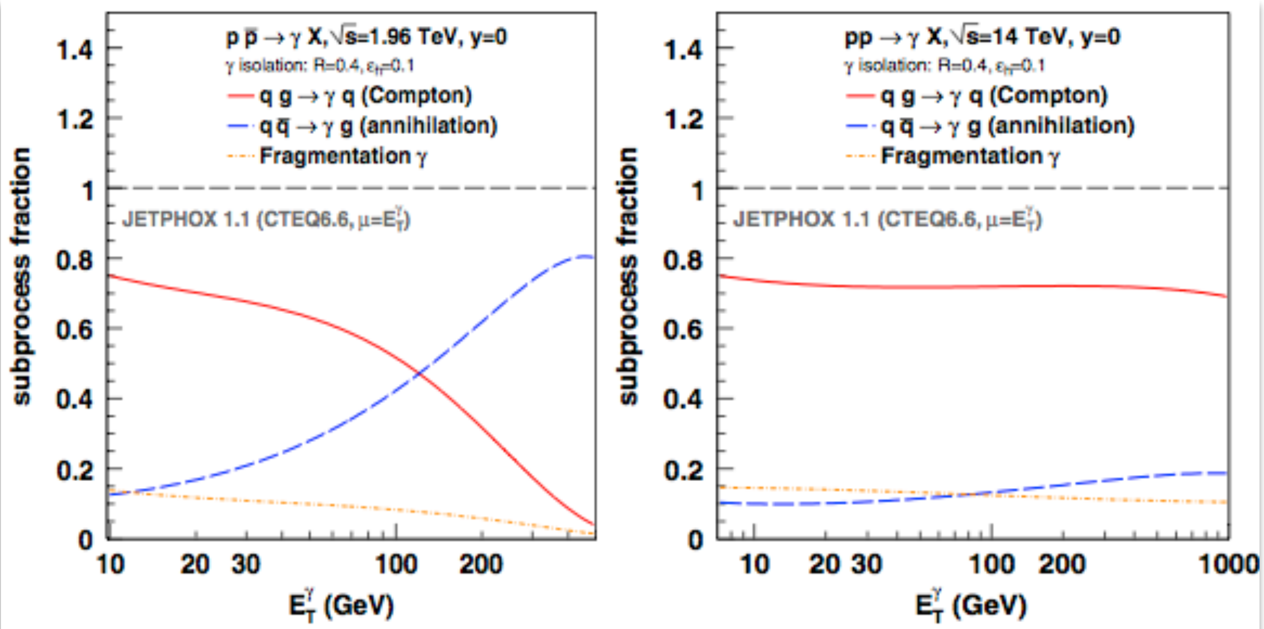
(acknowledgements: Jeff Berryhill and Chiara Roda [ICHEP 2015])

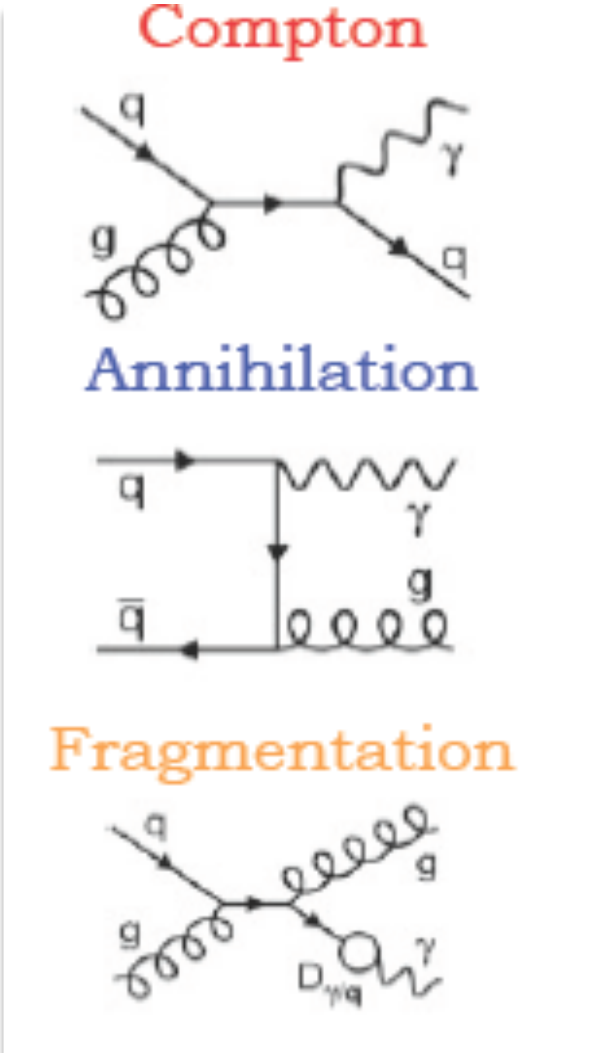
Isolated photon production

- Photon is used as clean/uncolored probe for underlying parton-parton interaction
- Test pQCD but also sensitive to non-prompt photons produced in fragmentation processes
- Provide information on PDFs

Tevatron

LHC – 14 TeV

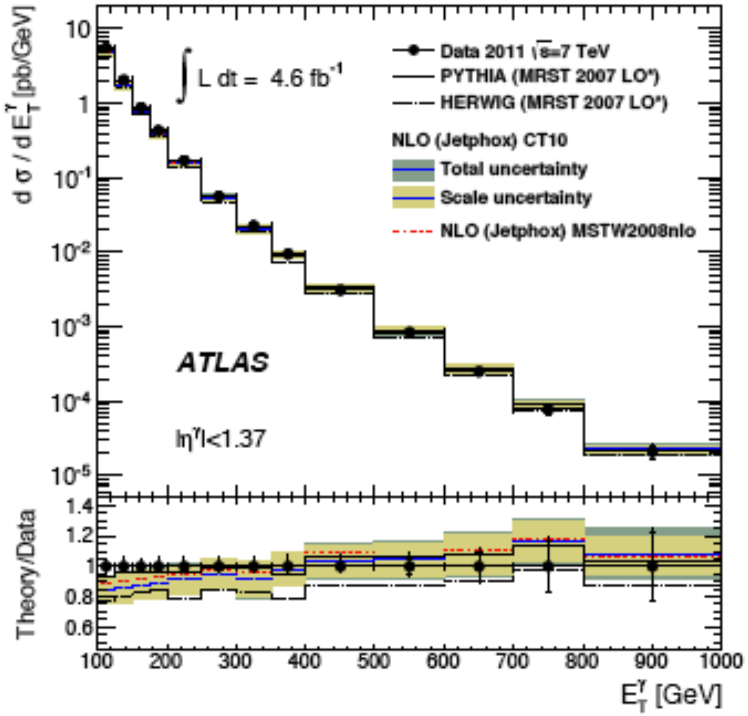




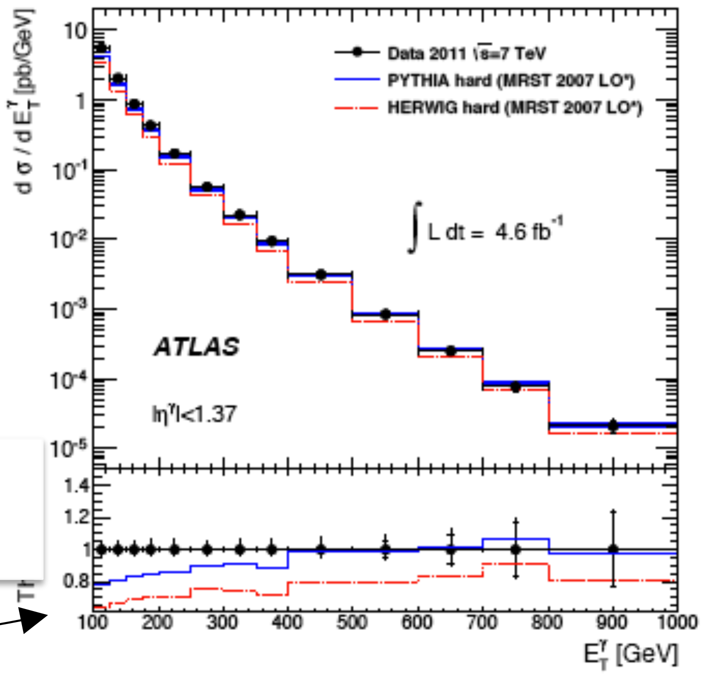
Valencia

Phys.Rev.D 89, 052004 (2014) ATL-PHYS-PUB-2013-018

Isolated photon production



7 TeV



No γ from fragmentation

- New measurement extend the range from 0.1-1TeV E_T and 5 orders of magnitude
- NLO prediction (Jetphox+MSTW or CT10) describe very well the data up to high E_T
- Data demonstrate the need to have fragmentation photon to describe the data

Data is also used to verify the sensitivity to the gluon-PDF and show some tensions with all PDFs expectially with ABM shows a too soft gluon-PDF.
Measurement limited by scale uncertainty, NNLO prediction would help.

W+jet – ATLAS & CMS

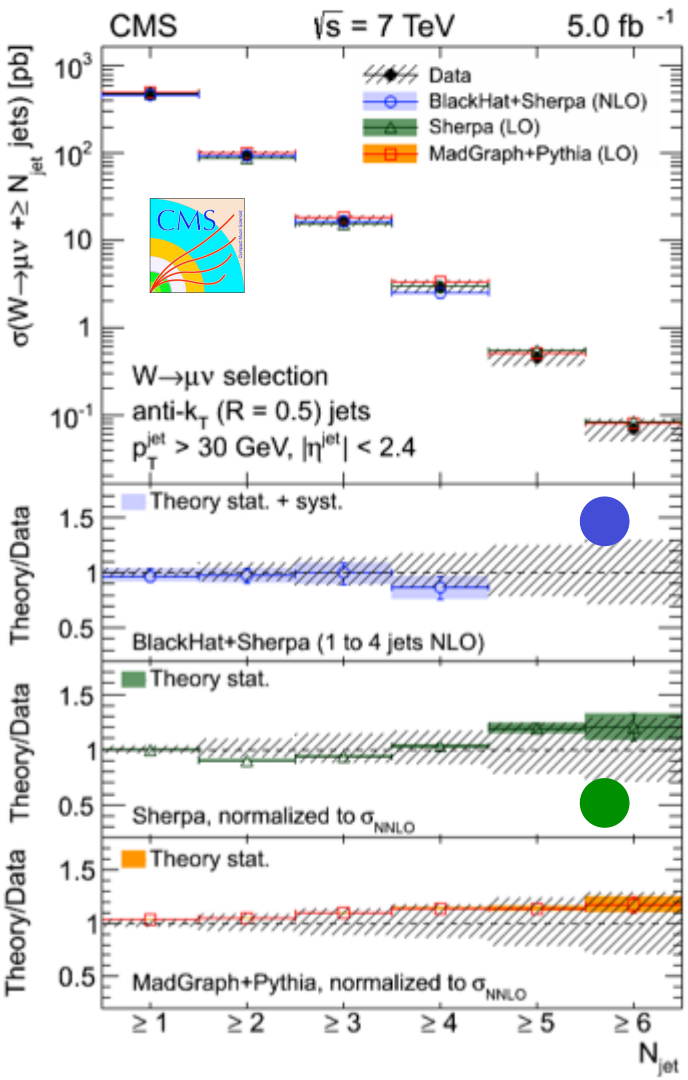
A detailed comparison on a high statistics sample and in a large kinematics range → precious information to validate/tune the predictions.

Tested variables: 1^{st} , 2^{nd}, 3^{rd} 4^{th}-leading jet p_T and η, H_T,S_T (Sum p_T including or not lepton and neutrino), angular separation of jets, invariant mass of lead-subleading jets. Inclusive and exclusive distributions…

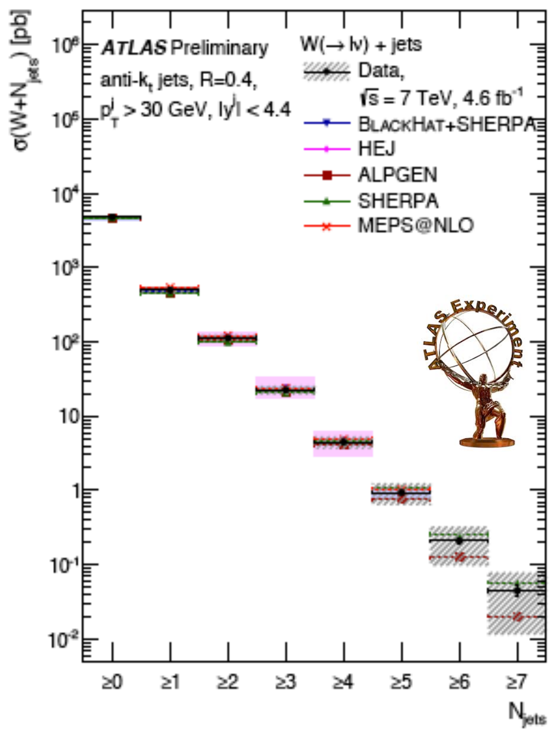
Predictions: NLO calculations, resummation calculations, MC generators NLO,LO + PS

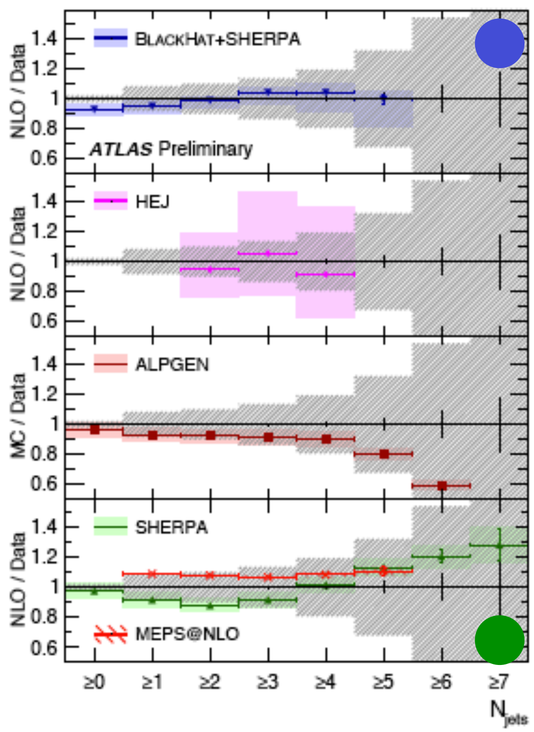
CMS-PAS-SMP-12-023 ATLAS-CONF-2014-035

W+jet – ATLAS & CMS



Jet multiplicity

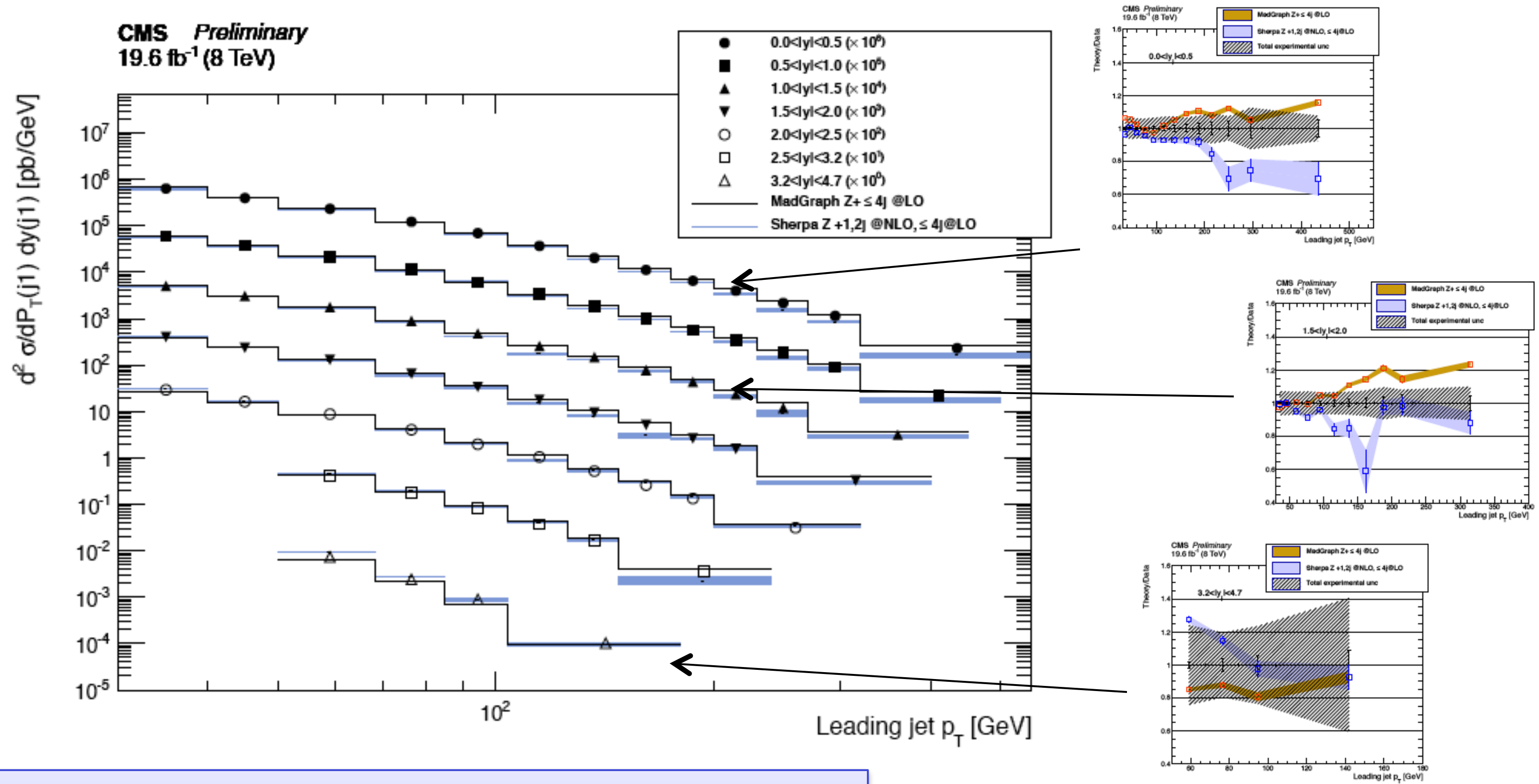




Jet multiplicity well reproduced up to ≥7 jets on 5 order of magnitudes !
Best overall description NLO+PS (BlackHat +Sherpa) with some exception for high H_T, S_T distributions.

CMS-PAS-SMP-14-009

Double differential Z+jet @ 8



First double differential measurement Z+jet
Jet up to $|\eta|<4.7$ – $30 < p_T < 550$ GeV
Largest experimental uncertainty JES
Predictions: MadGraph norm.NNLO / Sherpa2
(NLO 1j,2j /LO<=4j)

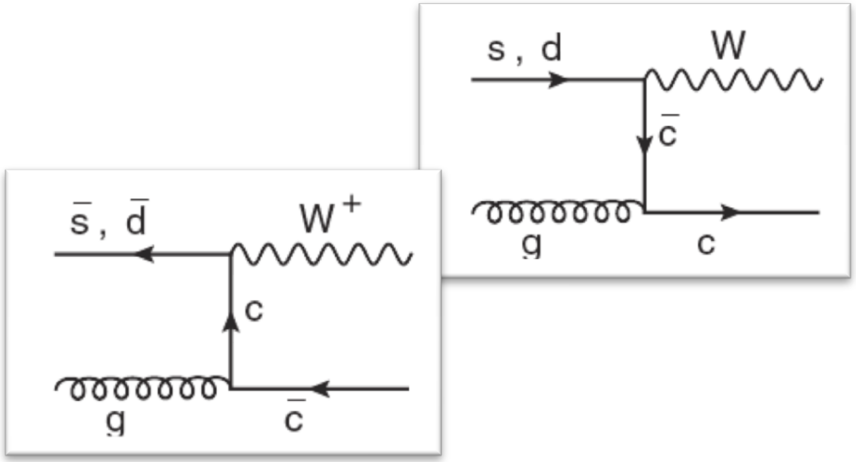
MadGraph overshoot for $p_T$jet > 100 GeV
Reasonable description from Sherpa2,
some regions to investigate

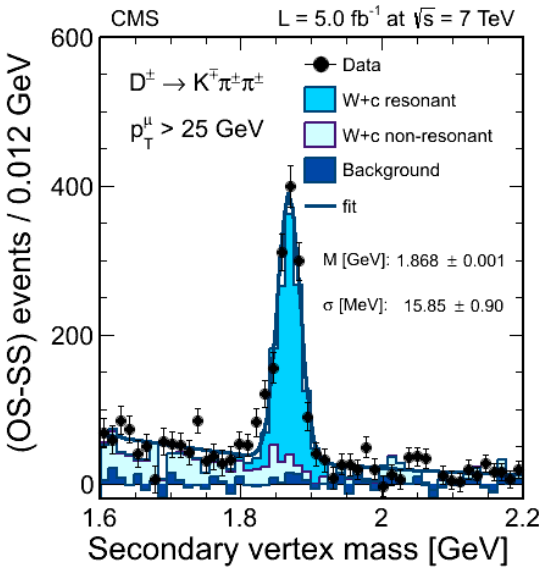
W+charm - LHC

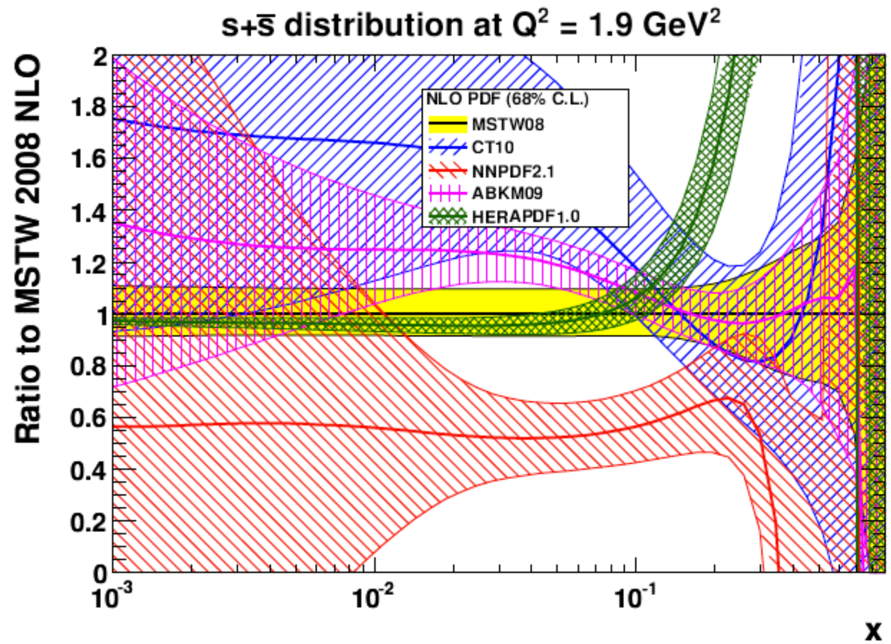
Probes the strange content of the proton

- contribution from d quark about ~10% (Cabibbo suppressed)

- Different PDFs assume different level of suppression of s-quark w.r.t. to d-quark sea.





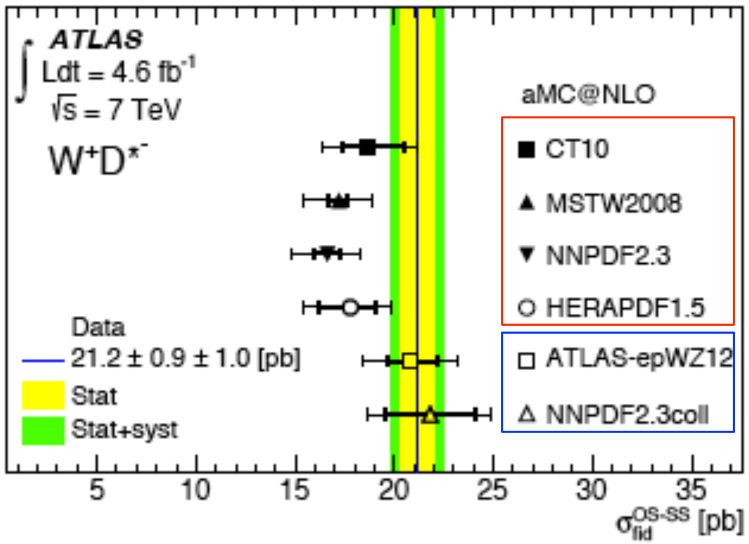


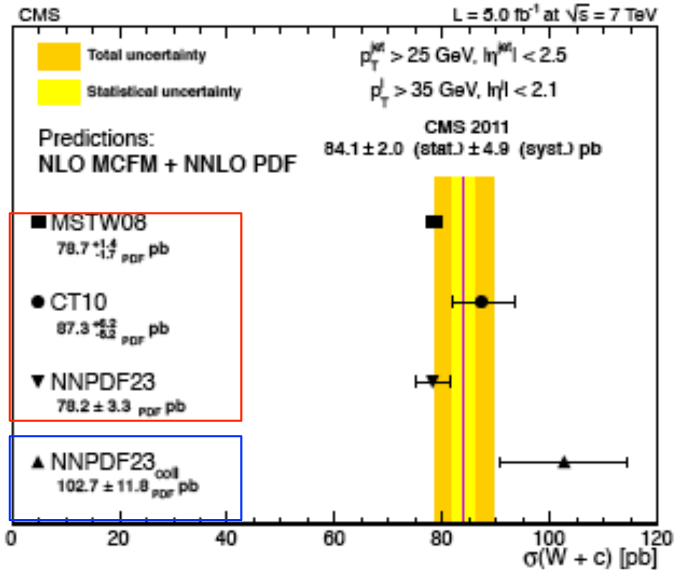
JHEP05(2014)068 arXiv:1402.6263 arXiv:1312.6283

W+c – LHC

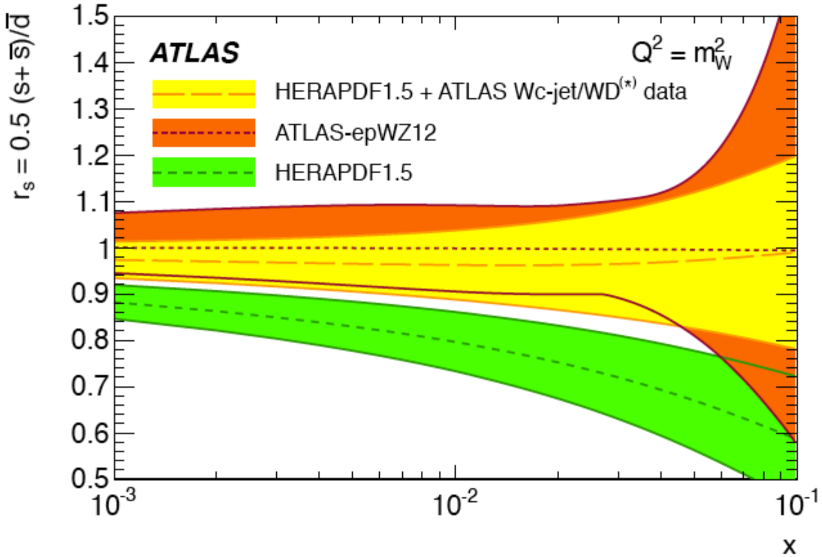
ATLAS → no s-sea suppression w.r. to light flavour sea

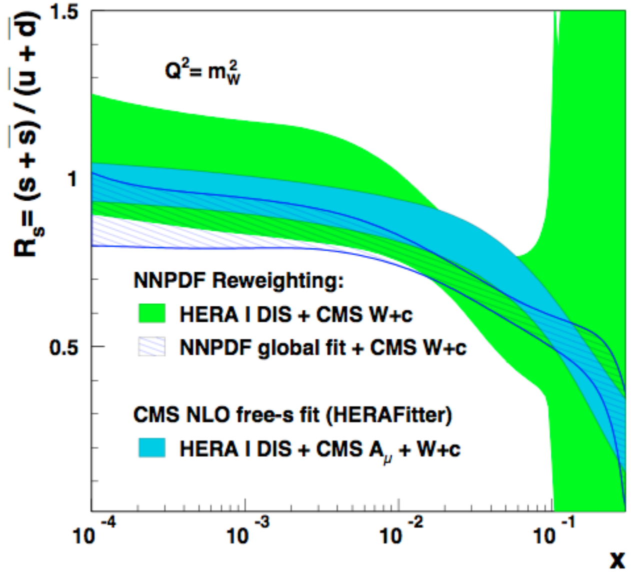
CMS → consistent with s-sea suppression





Fit s-quark PDF: HERAPDF including W +c data



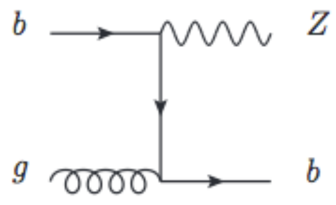


Z+b/bb cross-sections - ATLAS

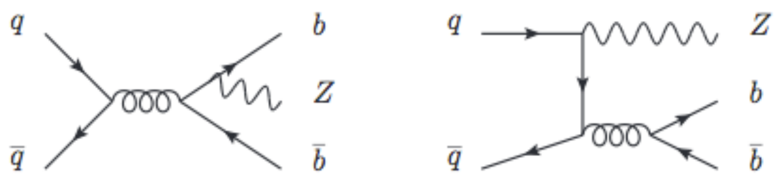
Test of NLO/LO multileg predictions

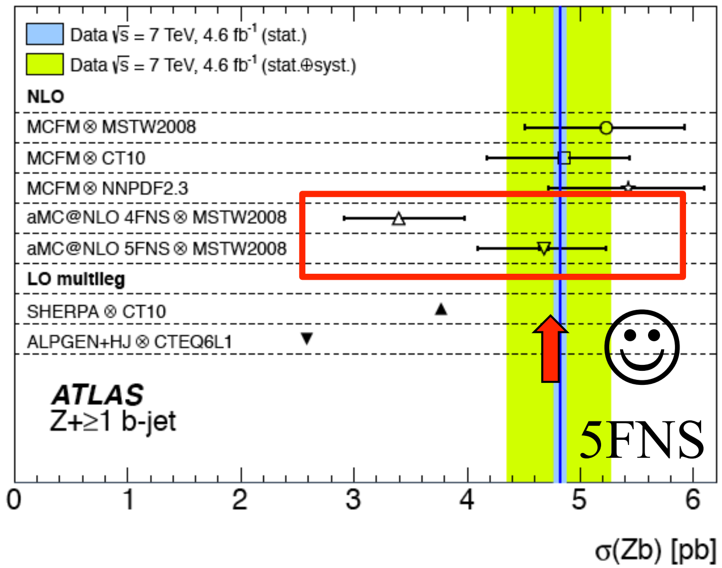
Test of Number Flavour schemes (4NFS / 5NFS)

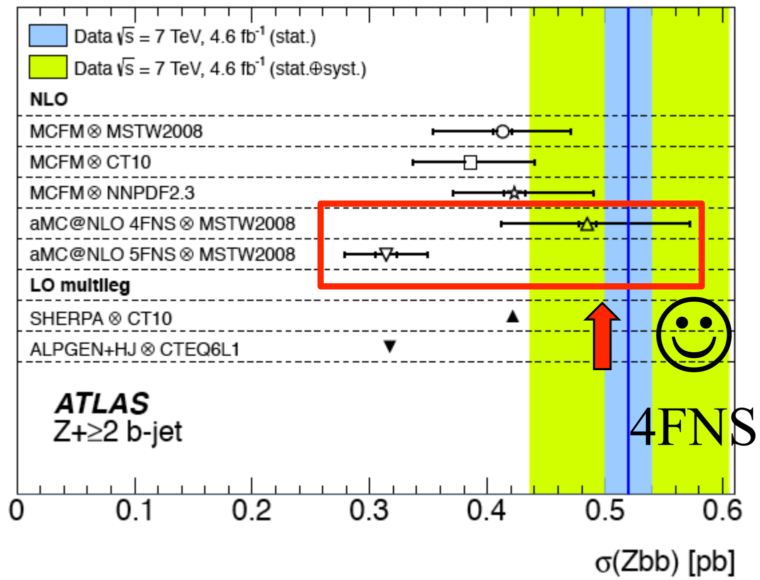
5FNS



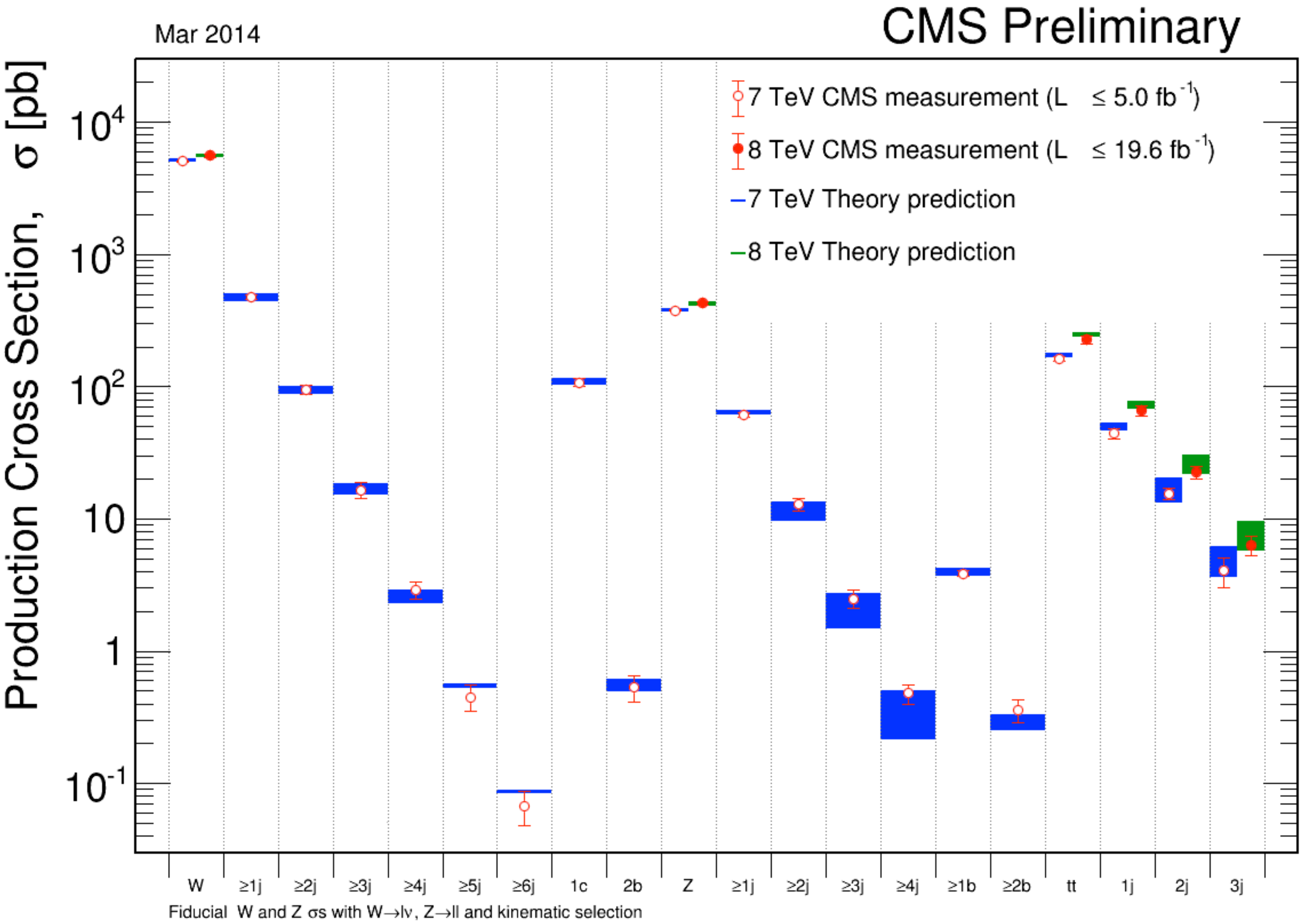
4FNS and 5FNS







MCFM agrees well with data
NLO is still too affected by scale uncertainty to be sensitive to PDFs
Double differential distributions are also compared to different predictions



Mar 2014
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
7 TeV Theory prediction
8 TeV Theory prediction
10⁴
10³
10²
10
1
10⁻¹
W
≥1j
≥2j
≥3j
≥4j
≥5j
≥6j
1c
2b
Z
≥1j
≥2j
≥3j
≥4j
≥1b
≥2b
tt
1j
2j
3j
Fiducial W and Z σs with W→lν, Z→ll and kinematic selection

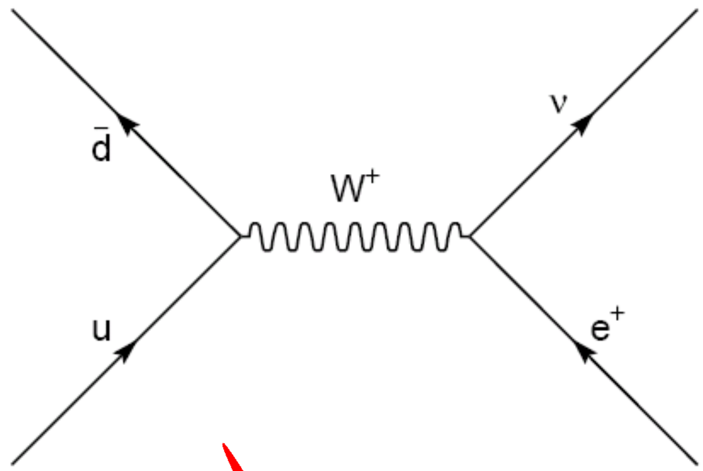
W MASS

can improve at LHC ?

(acknowledgements: Jeff Berryhill
[ICHEP 2015])

W mass measurement at hadron colliders

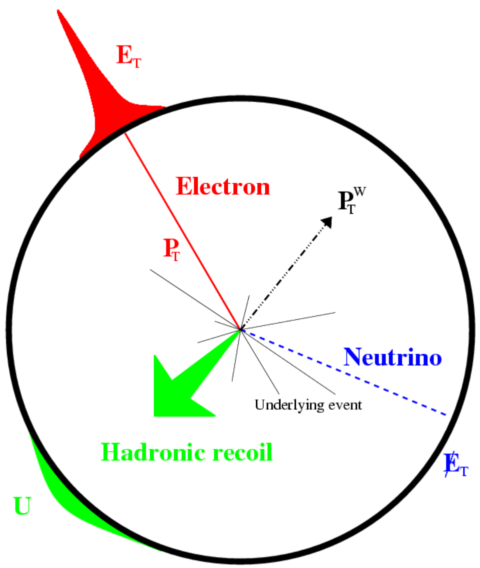
- Production from quark-antiquark annihilation
- Leptonic W decays (e o μ) + neutrino
- Fit to transverse mass distribution M_W^T



$$M_W^T = \sqrt{(E_T^{lepton} + E_T^{\nu})^2 - (\mathbf{p}_T^{lepton} + \mathbf{p}_T^{\nu})^2}$$

$$(E_T^i)^2 = (p_T^i)^2 + m_i^2$$

$$\mathrm{M}_{\mathrm{W}}^{\mathrm{T}} = \sqrt{2 p_T^{lepton} p_T^{v} (1 - \cos\varphi)}$$

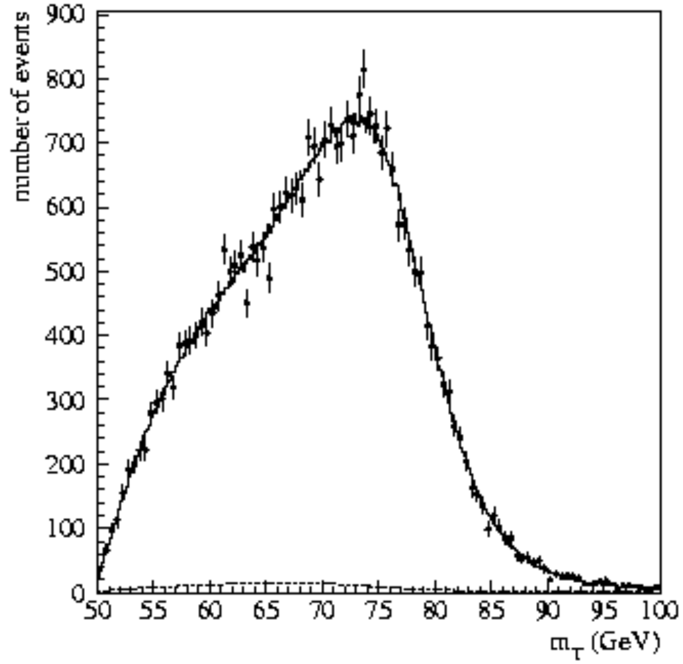


Precision measurement of W mass at hadron colliders

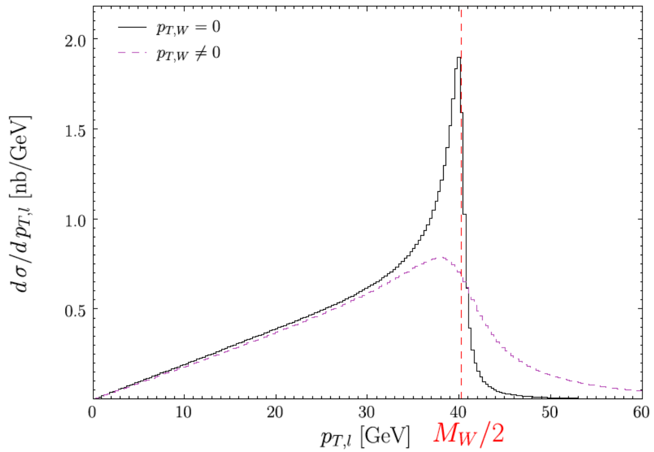
• Fit to transverse mass distribution M_W^T

•Jacobian peak

$$M_W^T = \sqrt{2 p_T^{lepton} p_T^{\upsilon} (1 - \cos\varphi)}$$



Lorenz invariance only for longitudinal translations ! However M^T is less affected than p_T by gluon emission

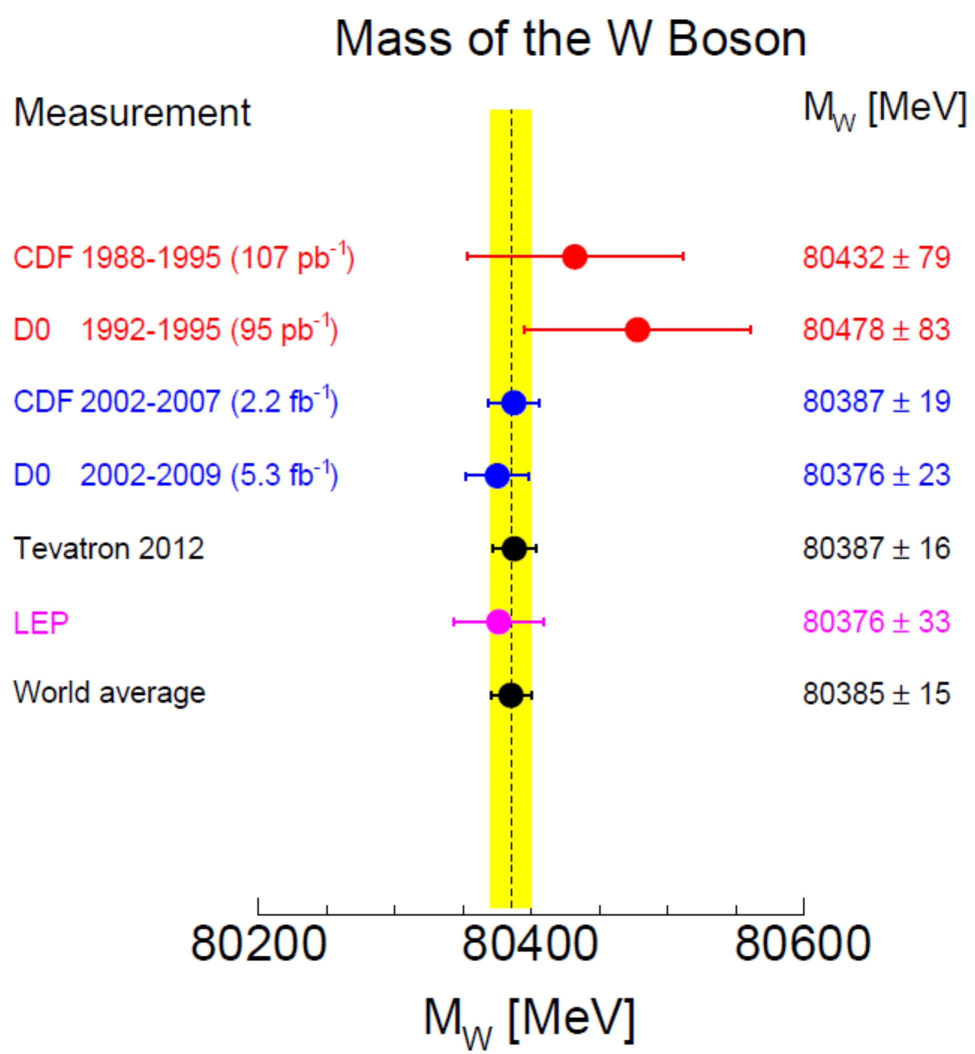


$$\frac{d\sigma}{dM_W^T} = \frac{d\sigma}{dcos\theta}\frac{dcos\theta}{dM_W^T} = \frac{d\sigma}{dcos\theta}\left(\frac{M_W^T}{2m_W}\right)(m_W^2 - (M_W^T)^2)^{-\frac{1}{2}}$$

Status of W mass

PRL 108 (2012) 151803 PRD 89 (2014) 072003

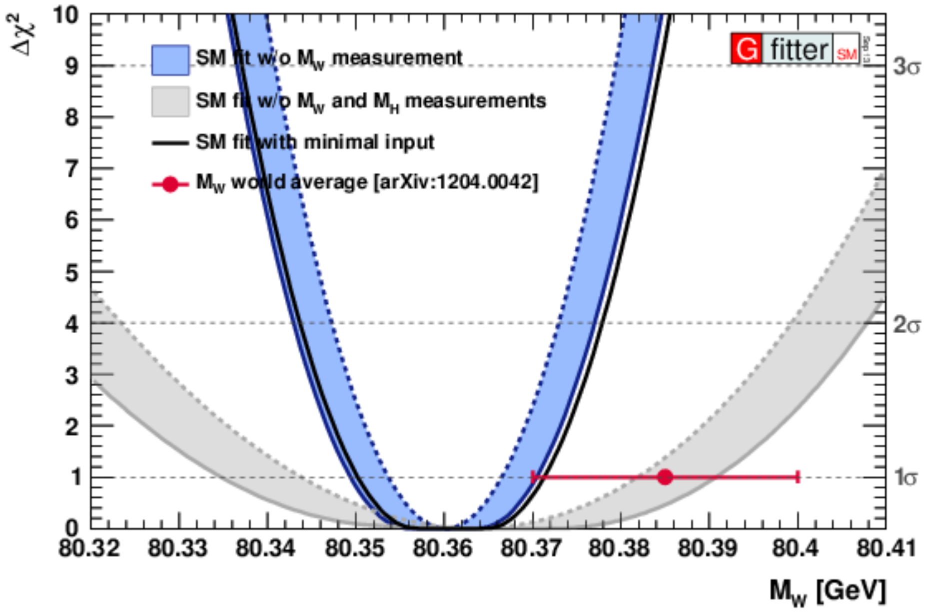
- CDF and DØ currently have world's most precise measurements based on 20% and 50% of their data → 1.1M and 1.7M Ws, resp.
- MT is the most sensitive single variable, lepton PT and MET used also
- Precision lepton response (0.01%) and recoil models (1%) built up from Z dileptons, Z mass reproduced to 6X LEP precision
- **MW precision:**
    - **CDF 19 MeV,**
    - **DØ 23 MeV,**
    - **LEP2 33 MeV**
    - **2012 world average: 15 MeV**



Prospects for Tevatron W mass [arxiv:1310.6708]

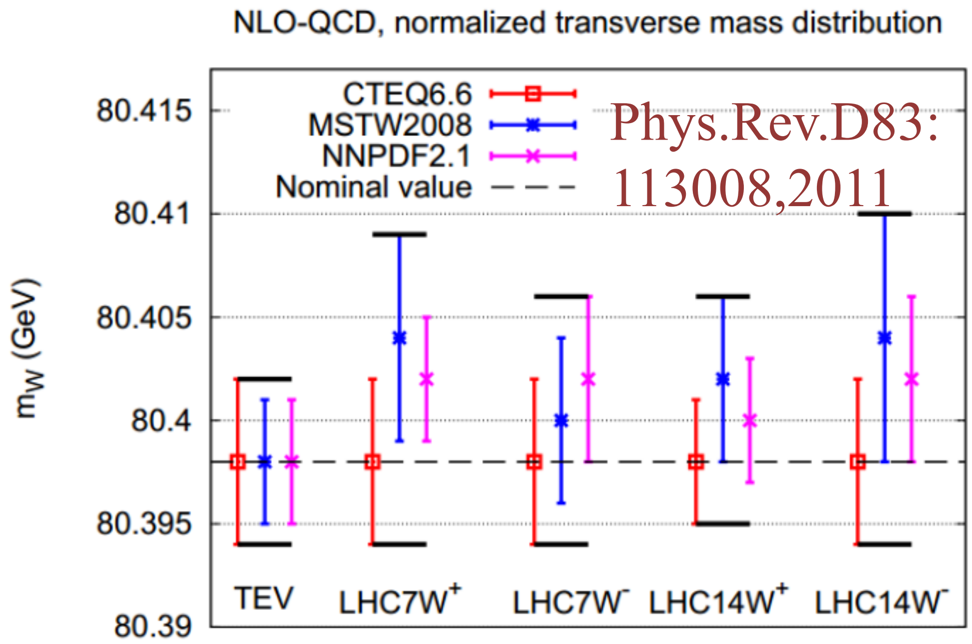
- Largest single uncertainties are **stat. and PDF syst.**
- **2X PDF improvement** and incremental improvement elsewhere results in **9 MeV projected final Tevatron precision**
- <10 MeV precision is well motivated to **further confront indirect precision (11 MeV)**

ΔM_W [MeV]	CDF	D0	combined	projected combined
$\mathcal{L}[\text{fb}^{-1}]$	2.2	4.3 (+1.1)	7.6	20
PDF	10	11	10	5
QED rad.	4	7	4	3
$p_T(W)$ model	5	2	2	2
other systematics	10	18	9	4
W statistics	12	13	9	5
Total	19	26 (23)	16	9



Prospects for LHC W mass

- The LHC has excellent detectors and semi-infinite statistics and thus has a good *a priori* prospect for a <10-MeV measurement
- Biggest three obstacles to surmount:
  - PDFs: sea quarks play a much stronger role than the Tevatron. **Need at least 2X better PDFs.**
  - Momentum scale
  - Recoil model/MET



ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}$[fb^{-1}]	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

arxiv:1310.6708

ASYMMETRIES AND $SIN^2\Theta_W$

can improve at LHC ?

Z couplings and the electroweak mixing angle

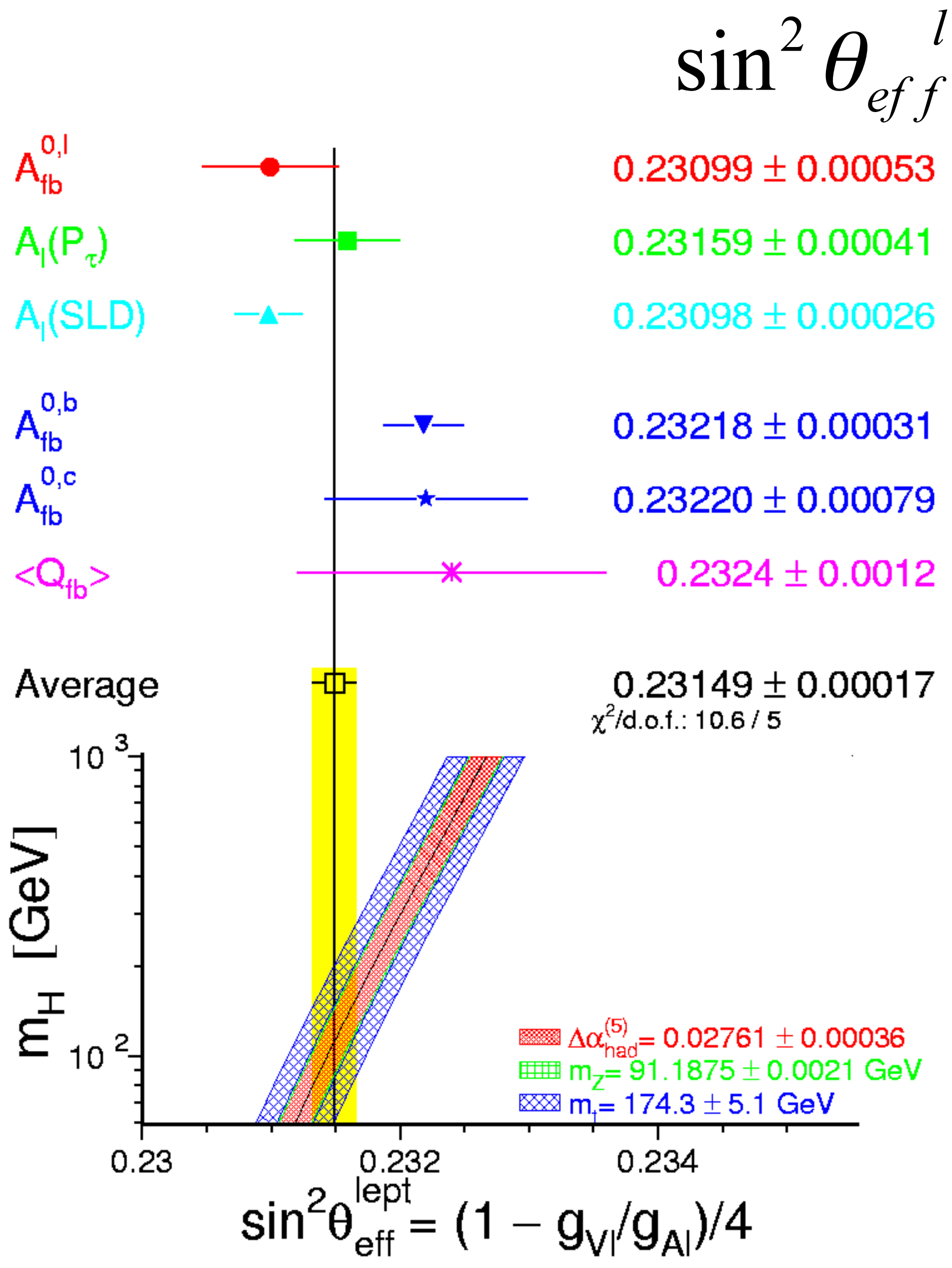
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_f$$

$$A_{LR} = \frac{\sigma_l - \sigma_r}{\sigma_{tot}} = A_e$$

$$A_f = \frac{2 g_{Vf} g_{Af}}{(g_{Vf})^2 + (g_{Af})^2}$$

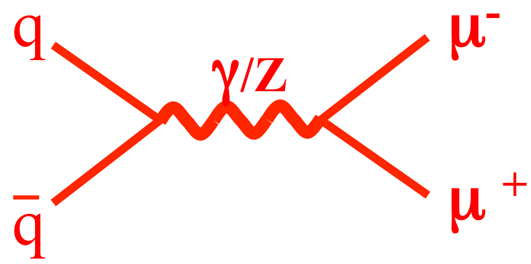
$$\sin^2\theta_{eff}^{\,l} \equiv \frac{1}{4}\left(1 - \frac{g_{Vl}}{g_{Al}}\right)$$

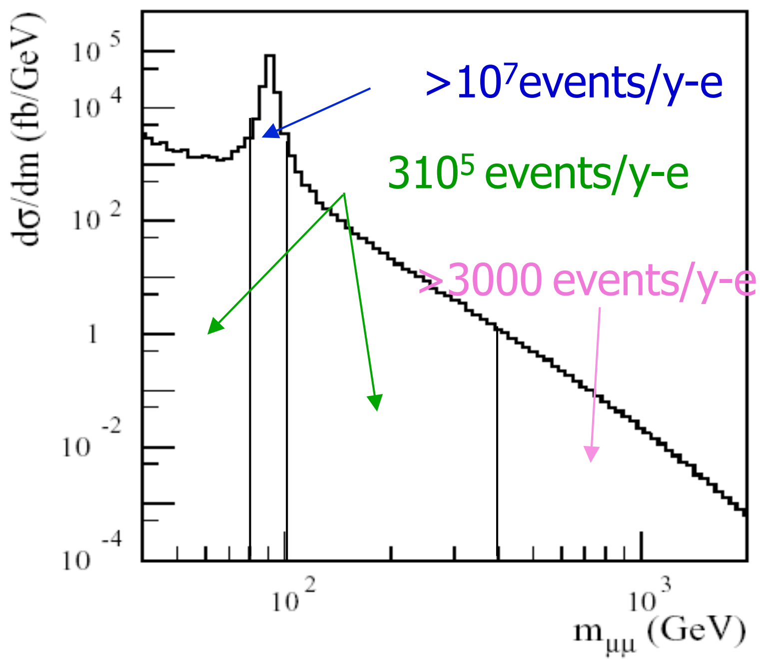
- Obtained 10^{-4} precision, but consistency between A_{LR} (from SLC) and A_{FB}(b) at 3 σ level

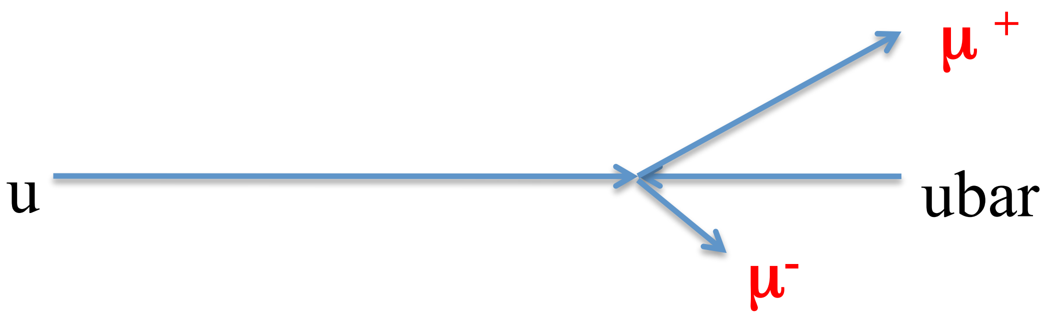


Asymmetry from Drell-Yan events at LHC

- Signature is clear and background is low, however →
- forward-backward asymmetry: need to know quark direction
- at LO easy at Tevatron (p – pbar)
- at LHC study DY cross section as a function of invariant mass and
- assume that at high rapidity direction gives information on direction of valence quark



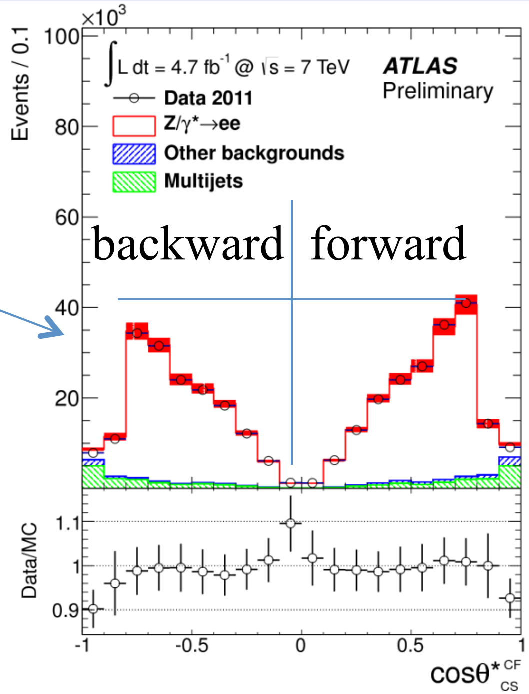


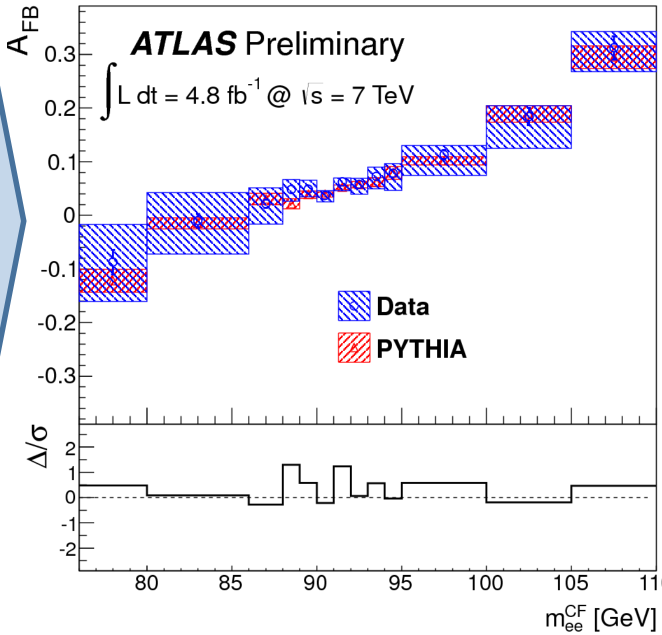


Weak mixing angle at LHC

ATLAS-CONF-2013-043

- Select central dilepton pairs, **and also central-forward electrons** with full 7 TeV dataset
- Raw AFB = Count forward/ backward abundance in CS frame
- AFB in good agreement with PYTHIA * PHOZPR NNLO K-factor (MSTWNNLO2008)
- 1.8σ lower angle than LEP +SLD average



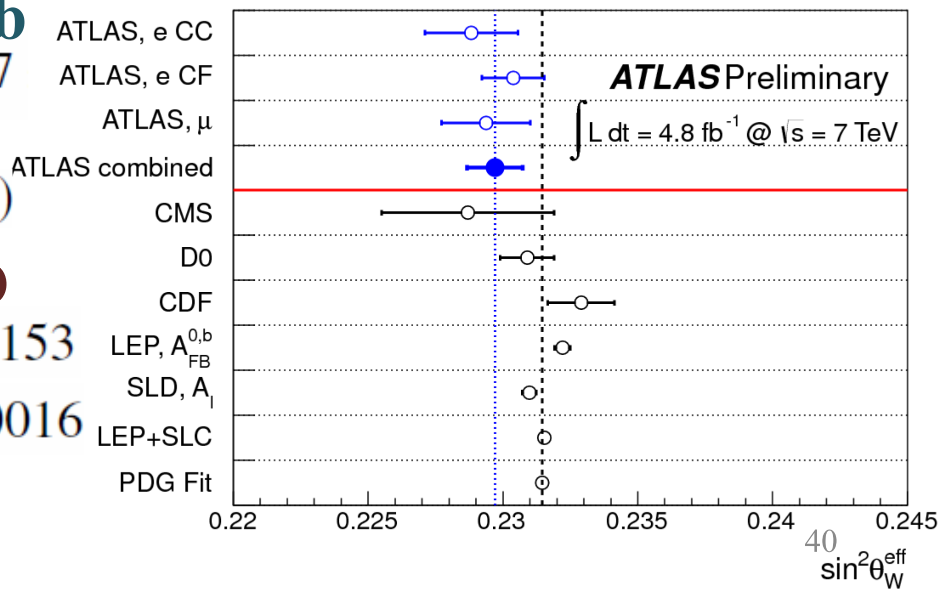


ATLAS 5/fb

$$\sin^2\theta_W^{eff} = 0.2297 \pm 0.0004(\text{stat.}) \pm 0.0009(\text{syst.})$$

LEP + SLD

$$\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$$

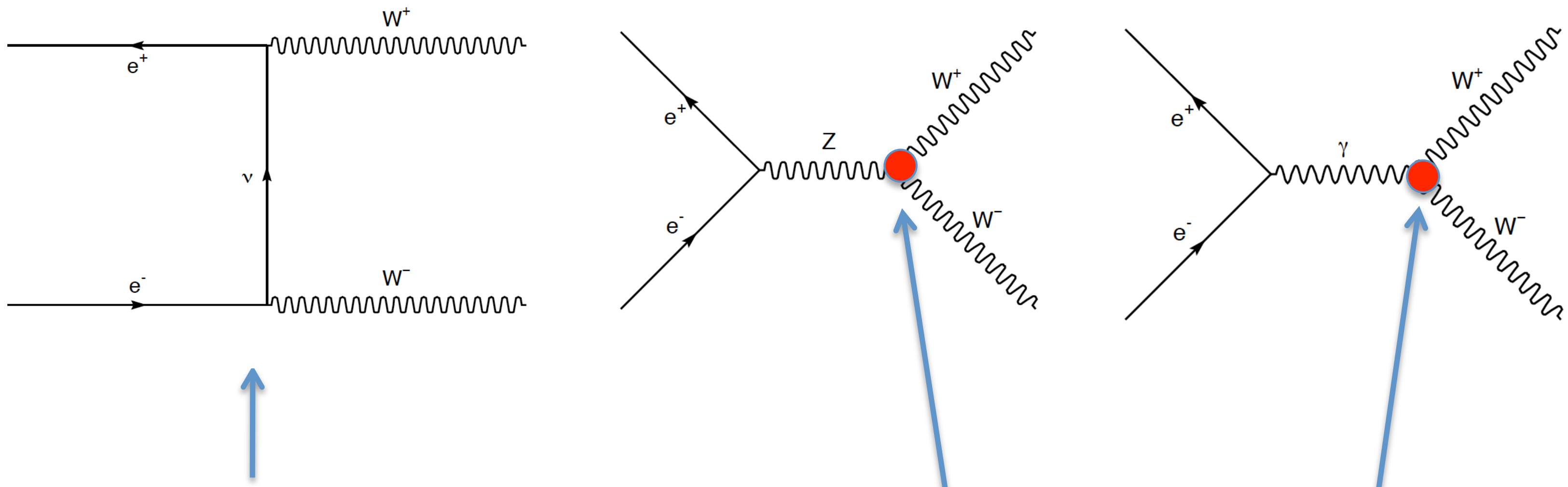


WW, ZZ, WZ, Wy

DIBOSON PRODUCTION AND TRIPLE GAUGE COUPLINGS

WW Production, example from two-fermion annihilation

Three diagrams contribute at Born level (CC03 diagrams) :



Dominant diagram at production threshold in e+e-, alone it gives a cross section which violates unitarity

Triple Gauge Couplings

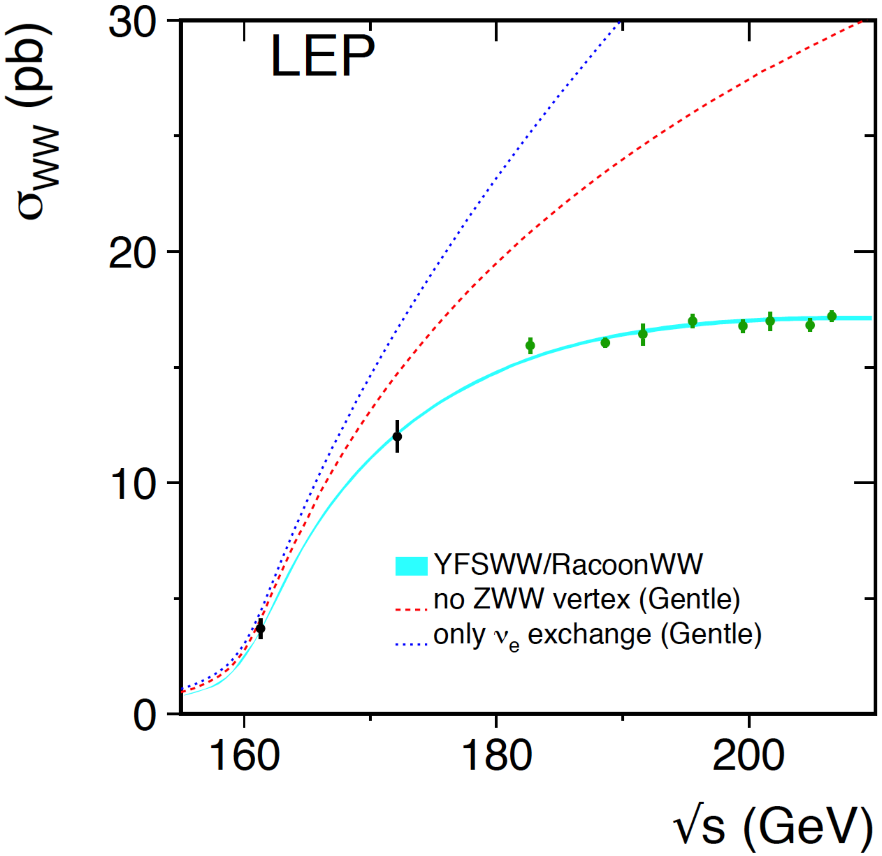
Total WW Cross Section

Strong evidence of Triple Gauge Couplings

- Precision reached by LEP experiments a challenge to theoretical predictions
  - Predictions with non-leading O(α) radiative corrections were needed !

$$R_{\text{with } O(\alpha)} = \frac{\sigma(\text{LEP})}{\sigma(\text{Theory : YFSWW})} = 99.32 \pm 0.89$$

$$R_{\text{without } O(\alpha)} = \frac{\sigma(\text{LEP})}{\sigma(\text{Theory : KORALW})} = 97.42 \pm 0.87$$



Probing Triple Gauge Couplings

- Triple gauge boson vertices ($WW\gamma$, WWZ) : probing the non-Abelian structure of the Standard Model. Search for anomalous couplings.
- The most general Lorentz invariant Lagrangian involves 14 couplings (7 for $WW\gamma$ and 7 for WWZ)
- Assuming electromagnetic gauge invariance, C and P conservation, leaves 5 parameters

$$\left\{ g_1^z, \kappa_Z, \kappa_\gamma, \lambda_Z, \lambda_\gamma \right\}$$

W anomalous magnetic moment $\quad \mu_W = \frac{e}{2m_W}(1 + k_\gamma + \lambda_\lambda)$

W anomalous electric quadrupole moment $\quad Q_w = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$

Triple Gauge Couplings

Precise LEP1 measurements motivated SU(2)xU(1) constraints

TGC contributes via loops

$$\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_Z^1$$

$$\lambda_Z = \lambda_\gamma$$

Δ is deviation from SM

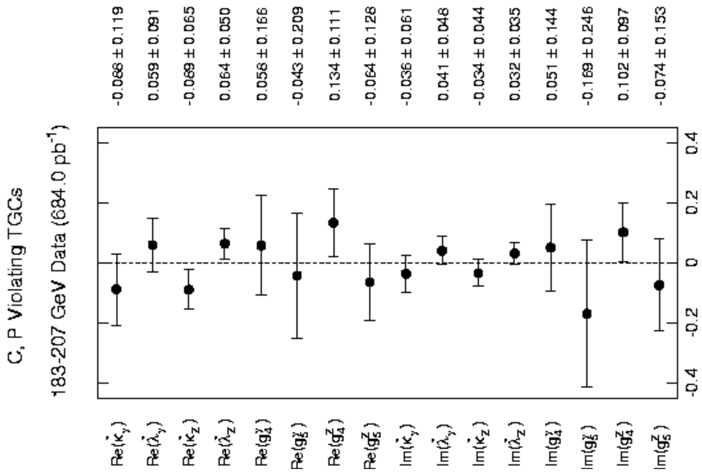
Within Standard Model

$$\left\{\Delta g_Z^1, \Delta\kappa_\gamma, \lambda_\gamma\right\} \equiv \left\{0,0,0\right\}$$

Typical analyses (and LEP combinations) in terms of three couplings.

However more general constraints of C, P and CP violating couplings were published: all 14 couplings were probed at LEP !!

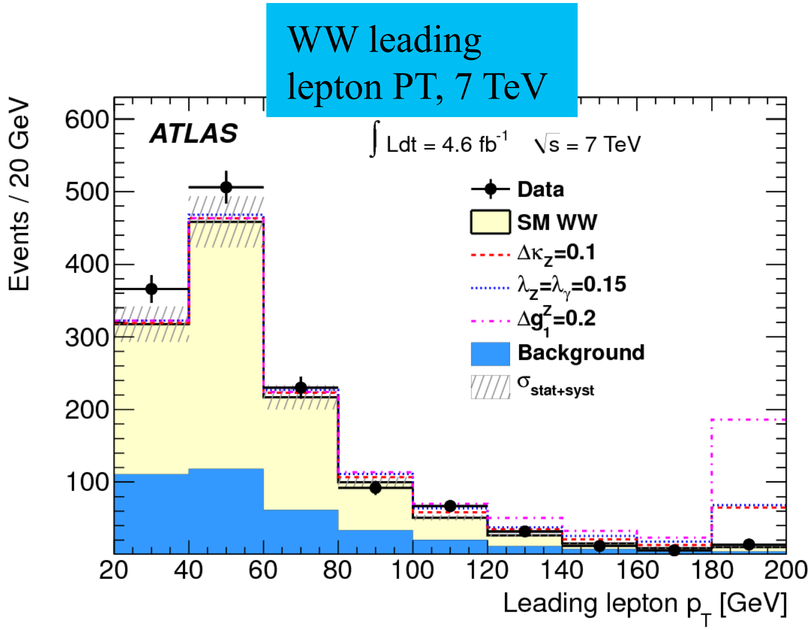
PLB 614 (2005) 7

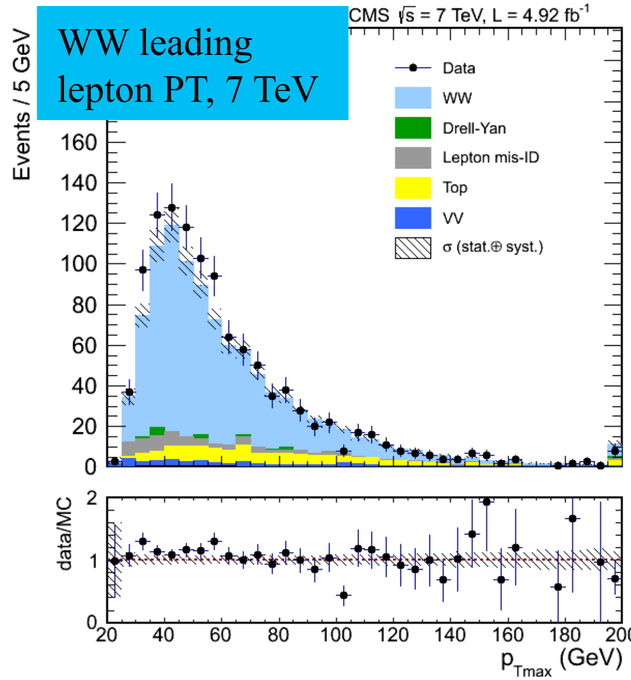


WW Production (7 TeV)

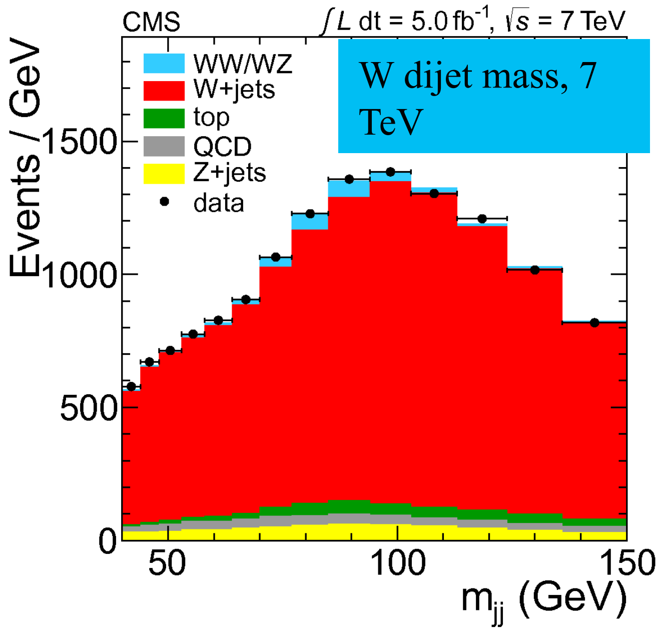
PRD 87 (2013) 112001
EPJC 73 (2013) 2283
EPJC 73 (2013) 2610
ATLAS-CONF-2012-157

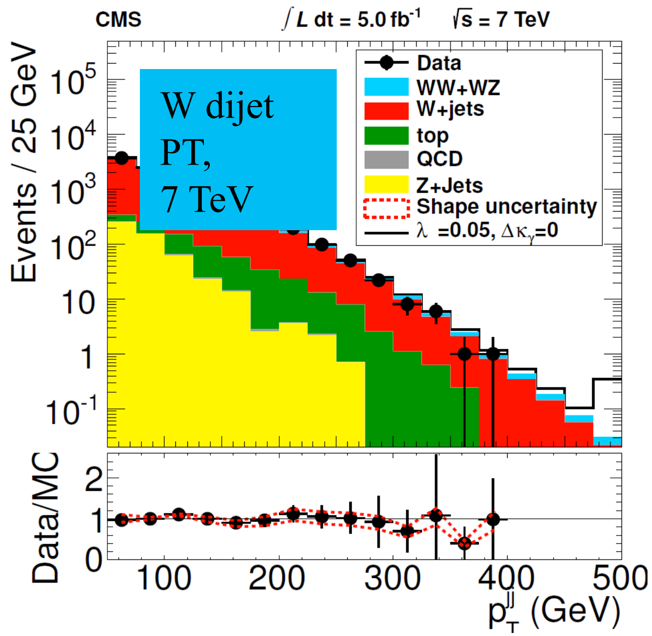
- Thousands of candidates in dilepton channel
- Leading lepton PT shows no anomalous contribution





- Significant diboson signal in semileptonic channel
- Higher BR and low background at high PT gives superior TGC constraint

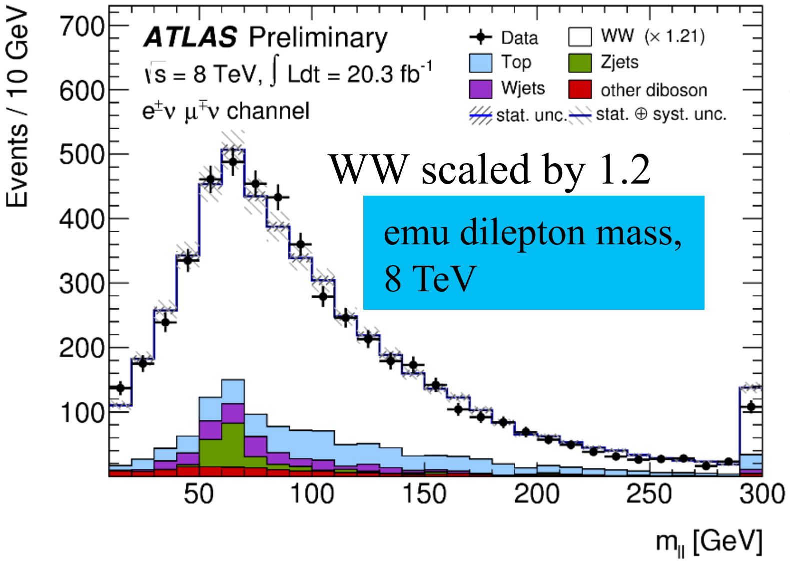


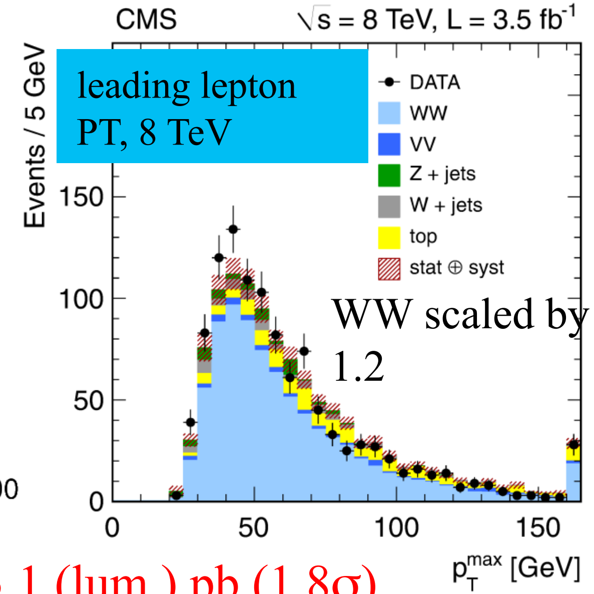


WW Production (8 TeV)

PLB 721 (2013) 190
ATLAS-CONF-2014-033

- **Kinematic shapes agree with prediction, but cross section excess observed at 20% level in CMS and ATLAS**
- ~5000 emu ATLAS candidates with 20/fb!
- Systematics from jet veto acceptance, background methods
- Not yet reporting: CMS lvlv 20/fb, WW→lvjj 20/fb
- Theory calculation being actively studied (jet vetoes, NNLO)





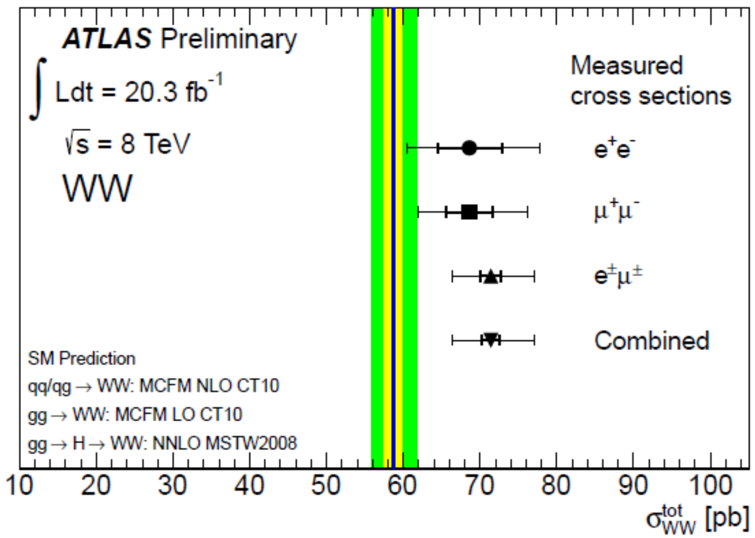
CMS 69.9±2.8 (stat.)±5.6 (syst.)±3.1 (lum.) pb (1.8σ)

ATLAS 71.4±1.2 (stat.)±5.0 (syst.)±2.2 (lum.) pb (2.1σ)

MCFM 58.7±3.0 (syst.) pb

=qq,qg 53.2 MCFM NLO
+gg 1.4 MCFM LO
+HWW 4.1 NNLO+NNLL

Higher order/other≈ +3-4pb?

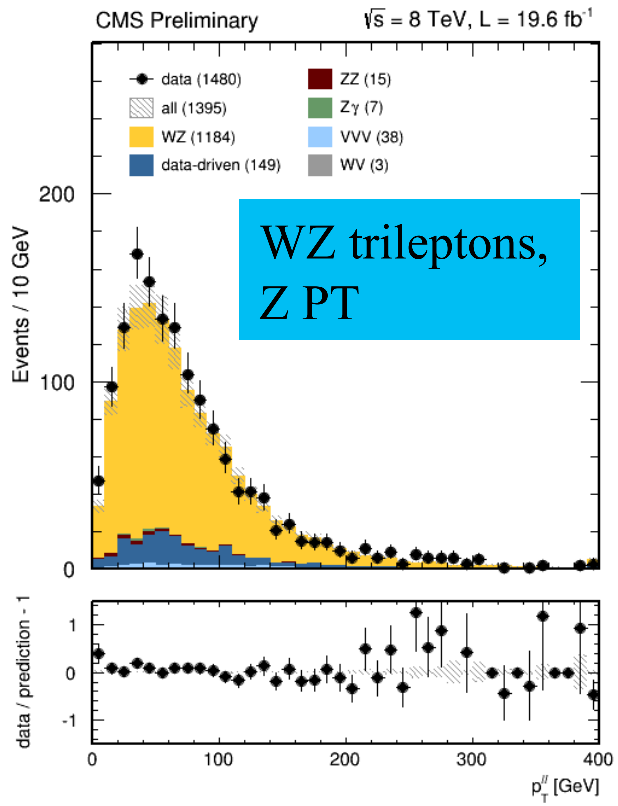


WZ and Wγ Production

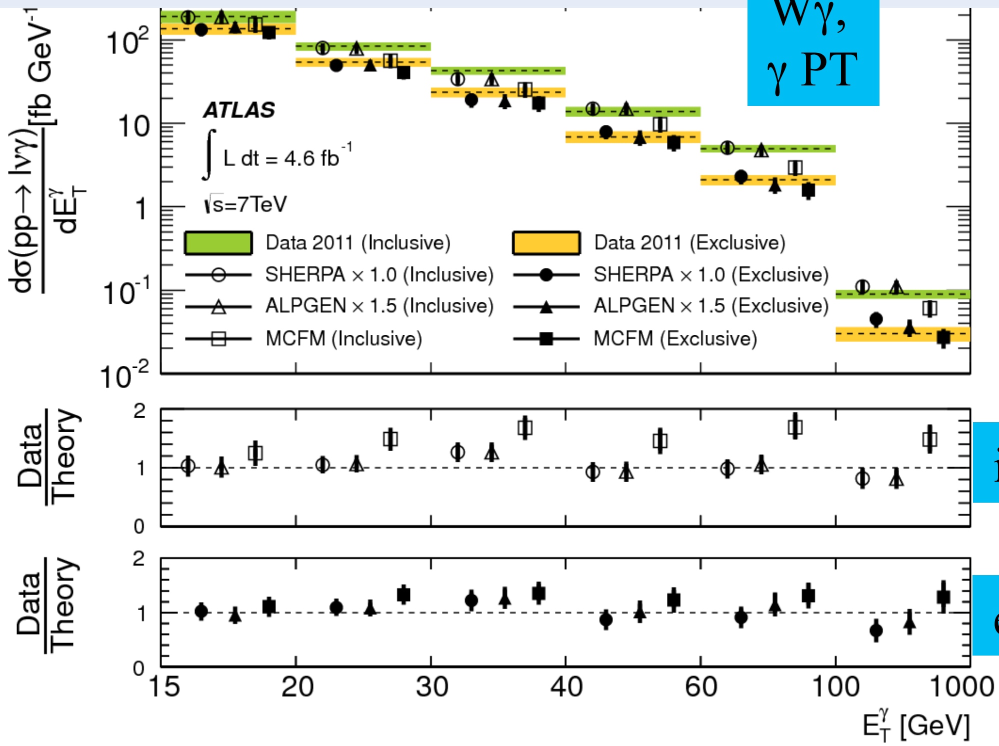
[PRD 87, 112003 (2013)](#)

[CMS-PAS-SMP-12-006](#)

- LHC has thousands of high purity trilepton WZ candidates, tens of thousands of Wγ
- Photon and lepton fakes are the predominant background
- No evidence of new physics in high PT tails



WZ trileptons, Z PT



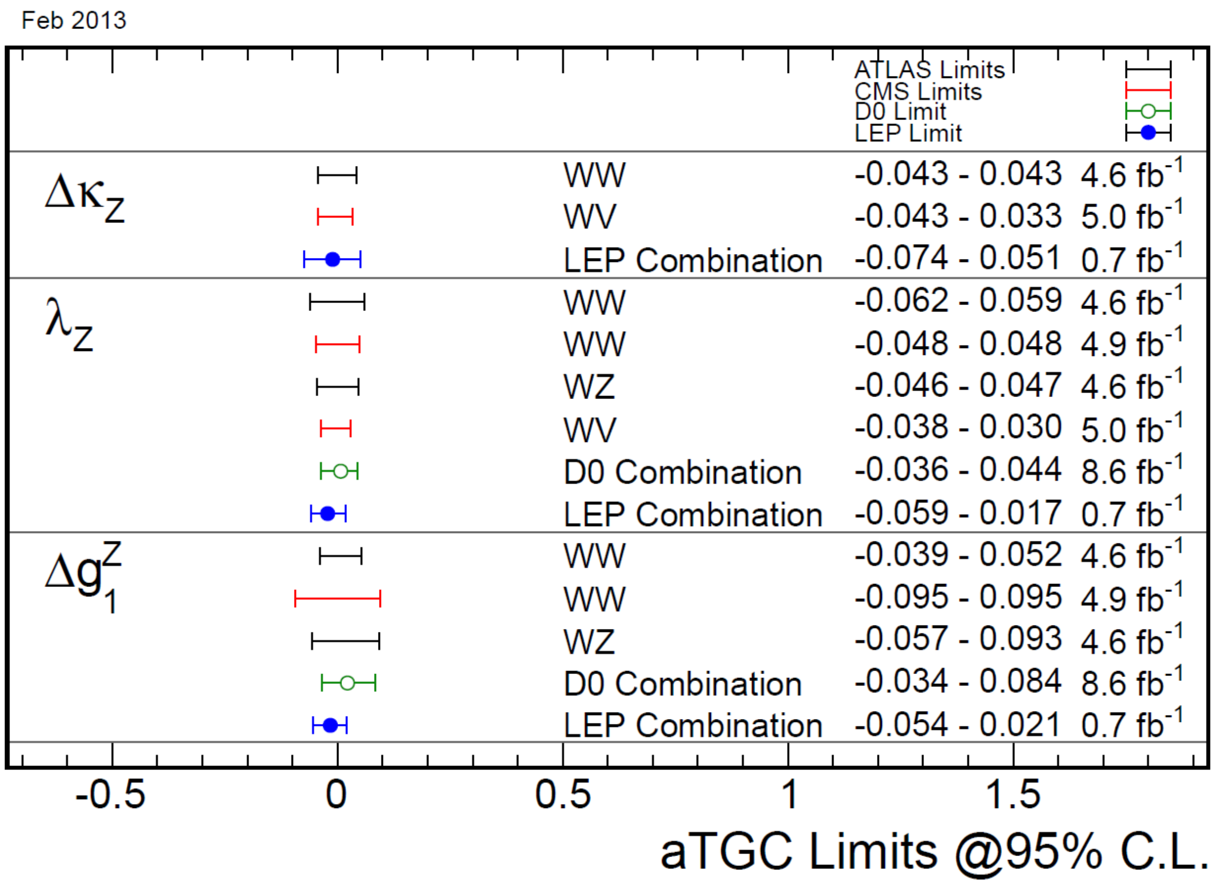
Wγ, γ PT

inclusive

exclusive 0-jet

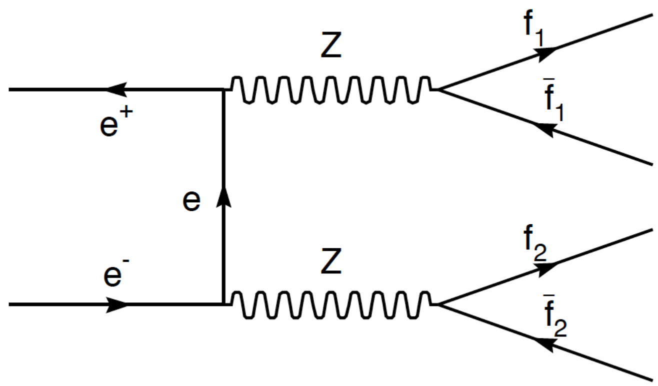
Charged aTGCs: World Summary

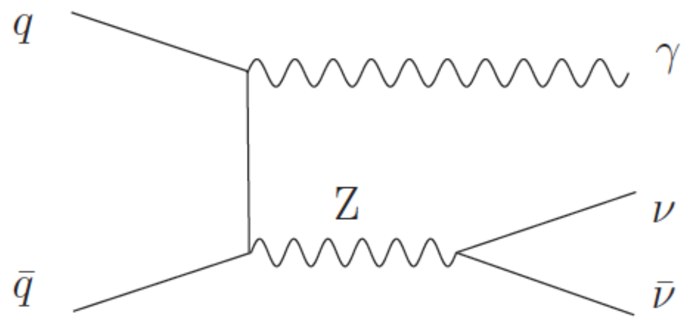
- Best single LHC 7 TeV measurements equal LEP2 or Tevatron combinations
- Semileptonic WW gives the best information on κ and λ, leptonic WW and WZ better for g.
- LHC 8 TeV will provide 2-3X better constraints, reaching LEP2 precision also for g

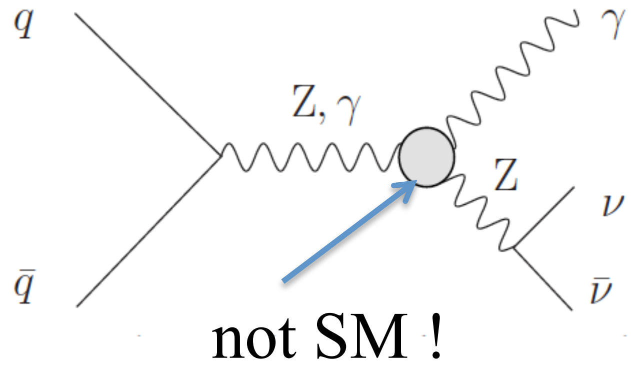


Anomalous Neutral couplings

- ZZZ, γZZ and γγZ trilinear couplings are not present in the Standard Model: ZZ and Zγ production does not take place through s-channel
- Anomalous couplings can be defined through effective lagrangians, two CP-conserving and two CP-violating couplings are defined
- The parametrization depends on the final state (*f* couplings for ZZ, *h* couplings for γZ)





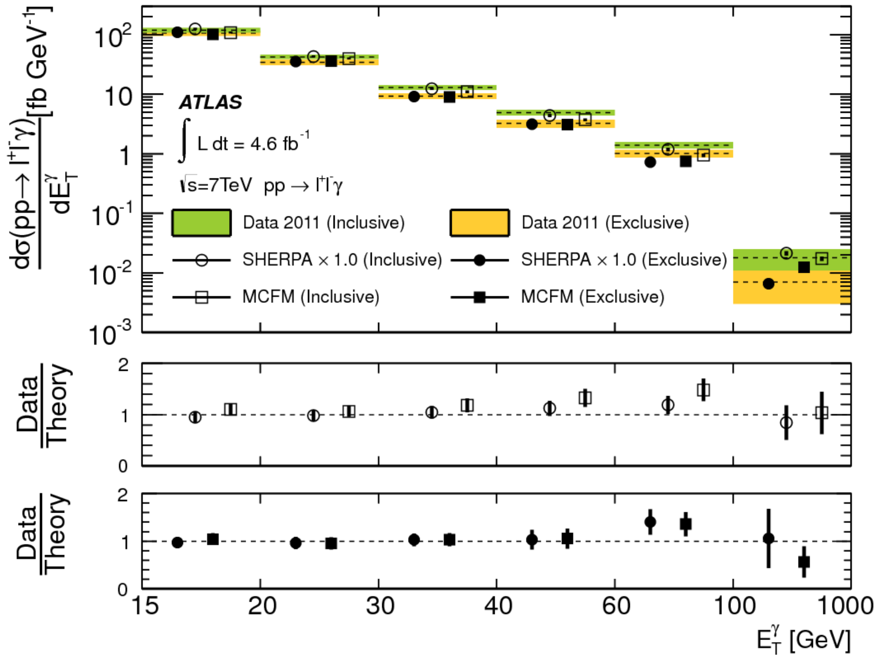


Zγ Production

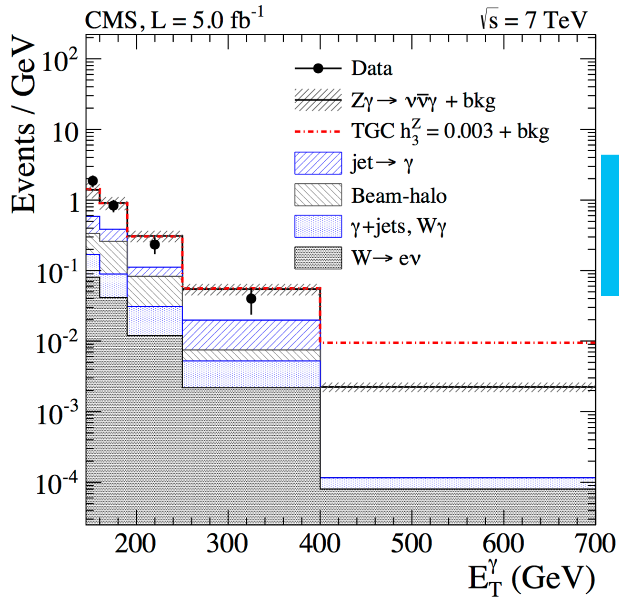
[JHEP 10 (2013) 164](#)

[PRD 89 (2014) 092005](#) [PRD 87 (2013) 112003](#)

Zγ → llγ
γ PT



- Thousands of dilepton-photon events at 7 TeV agree with SM
- MET-photon channel: Higher BR and low background at high PT gives superior (dim 8) TGC constraint



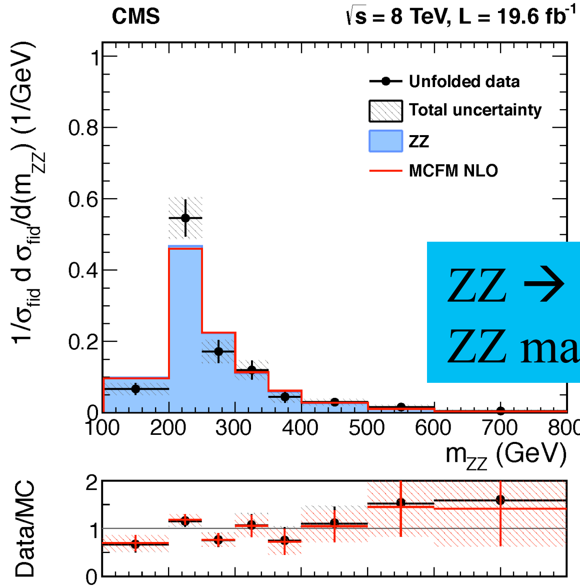
Zγ →MET+γ
γ PT

ZZ Production

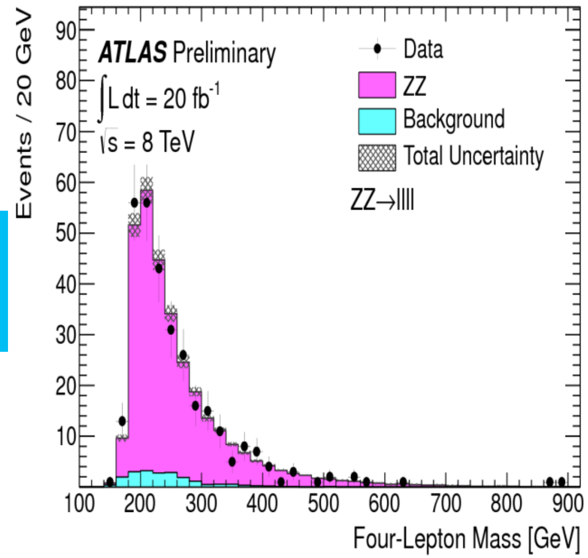
ATLAS-CONF-2013-020
CMS-PAS-SMP-12-016 arxiv:1406.0113

- ~300 ZZ to 4-lepton candidates observed at 8 TeV/experiment with SM rate and shapes

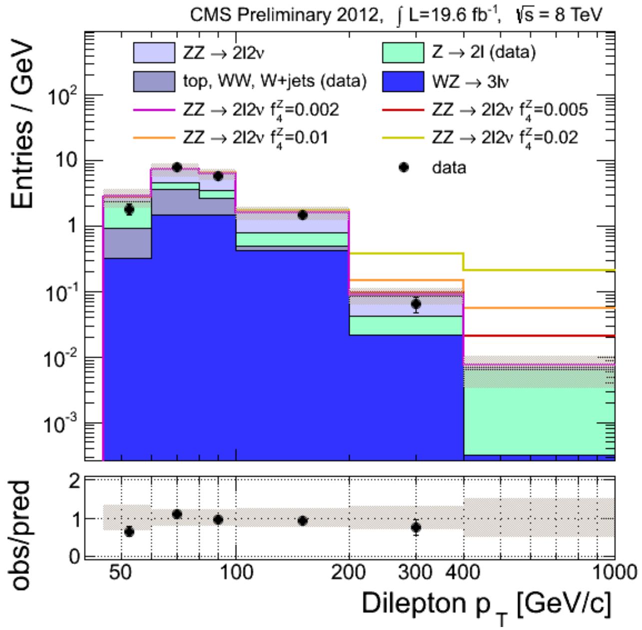
- ~200 ZZ to 2l2v candidates observed at 8 TeV, give best (dim 8) TGC constraint



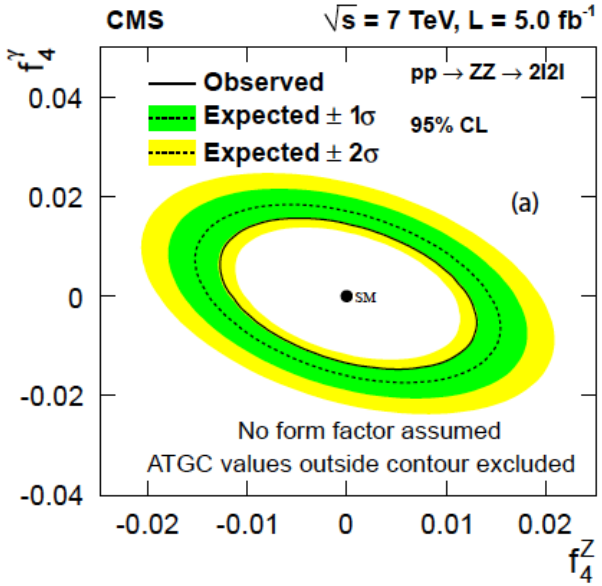
ZZ → 4l
ZZ mass

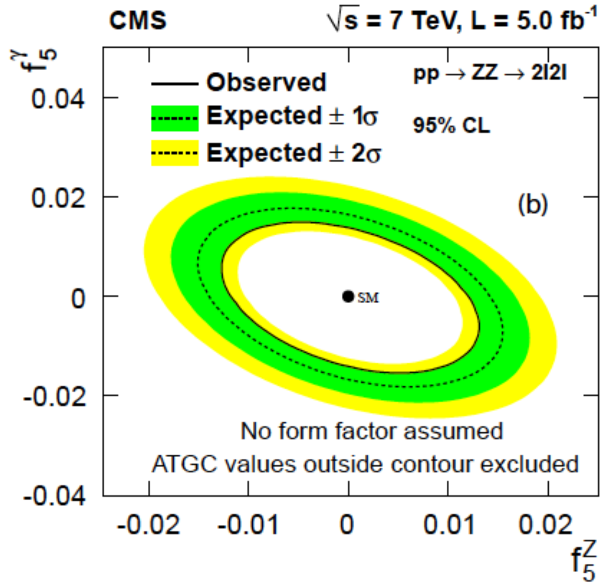


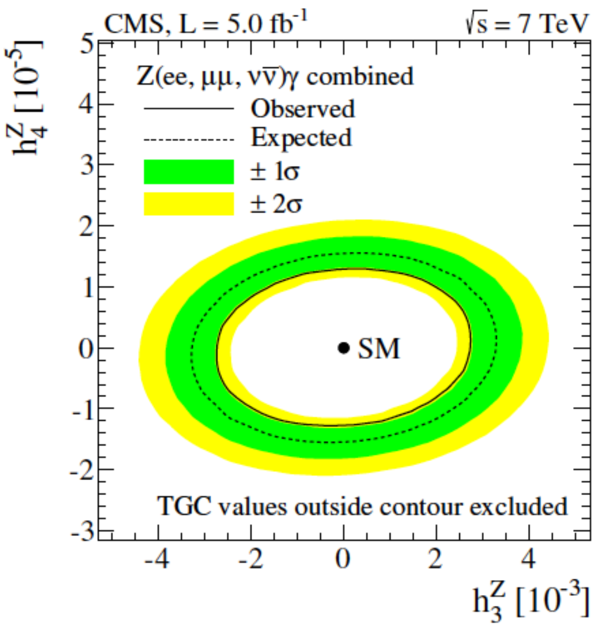
ZZ → 2l2v
Z PT

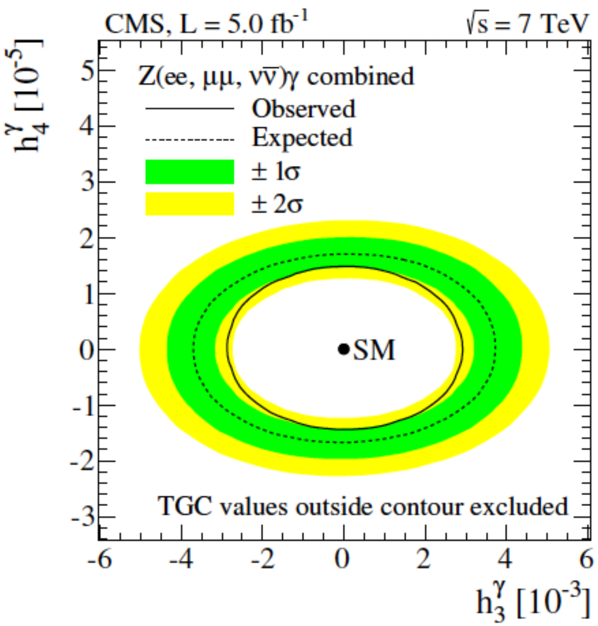


Limits on neutral couplings

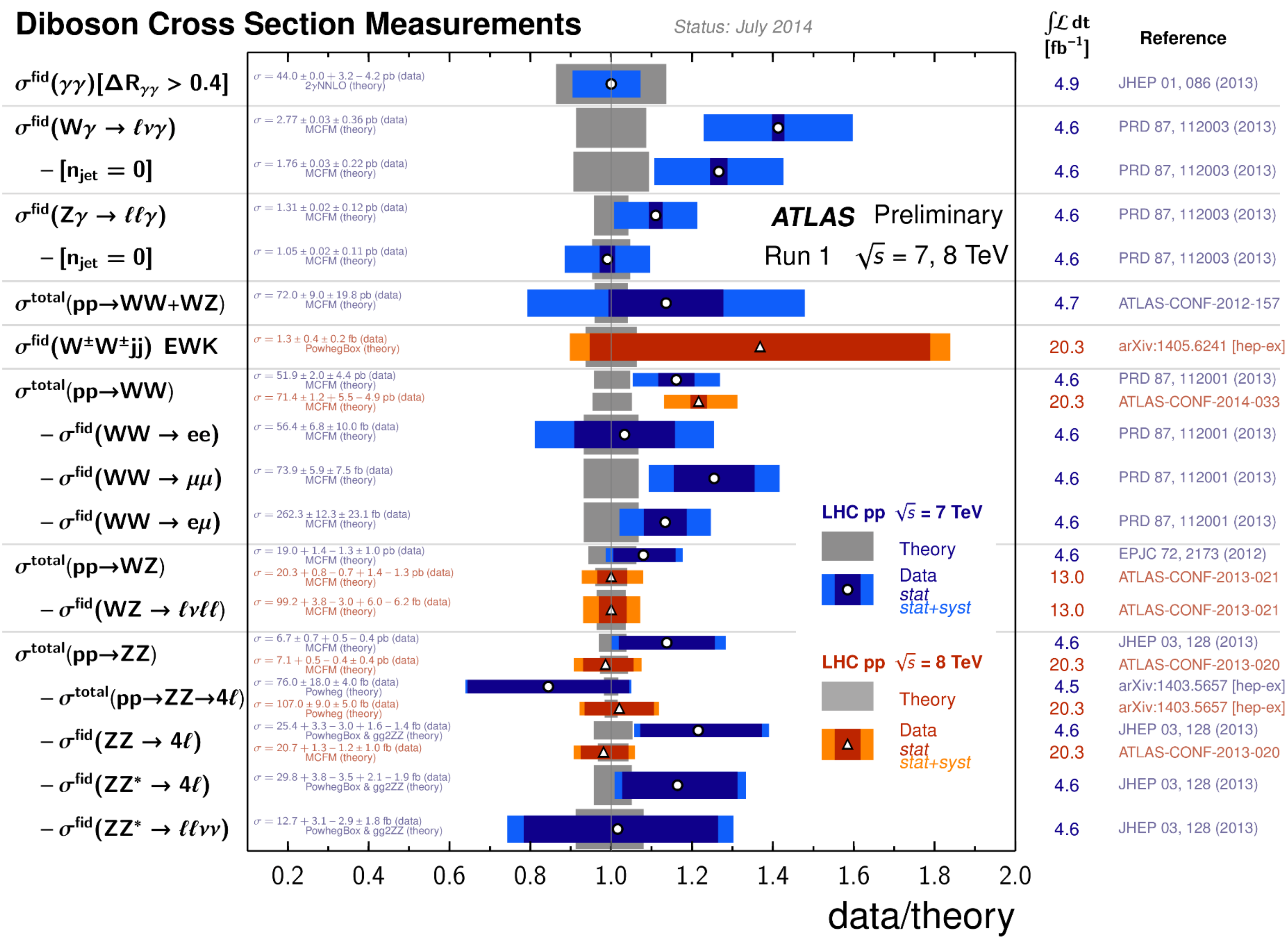


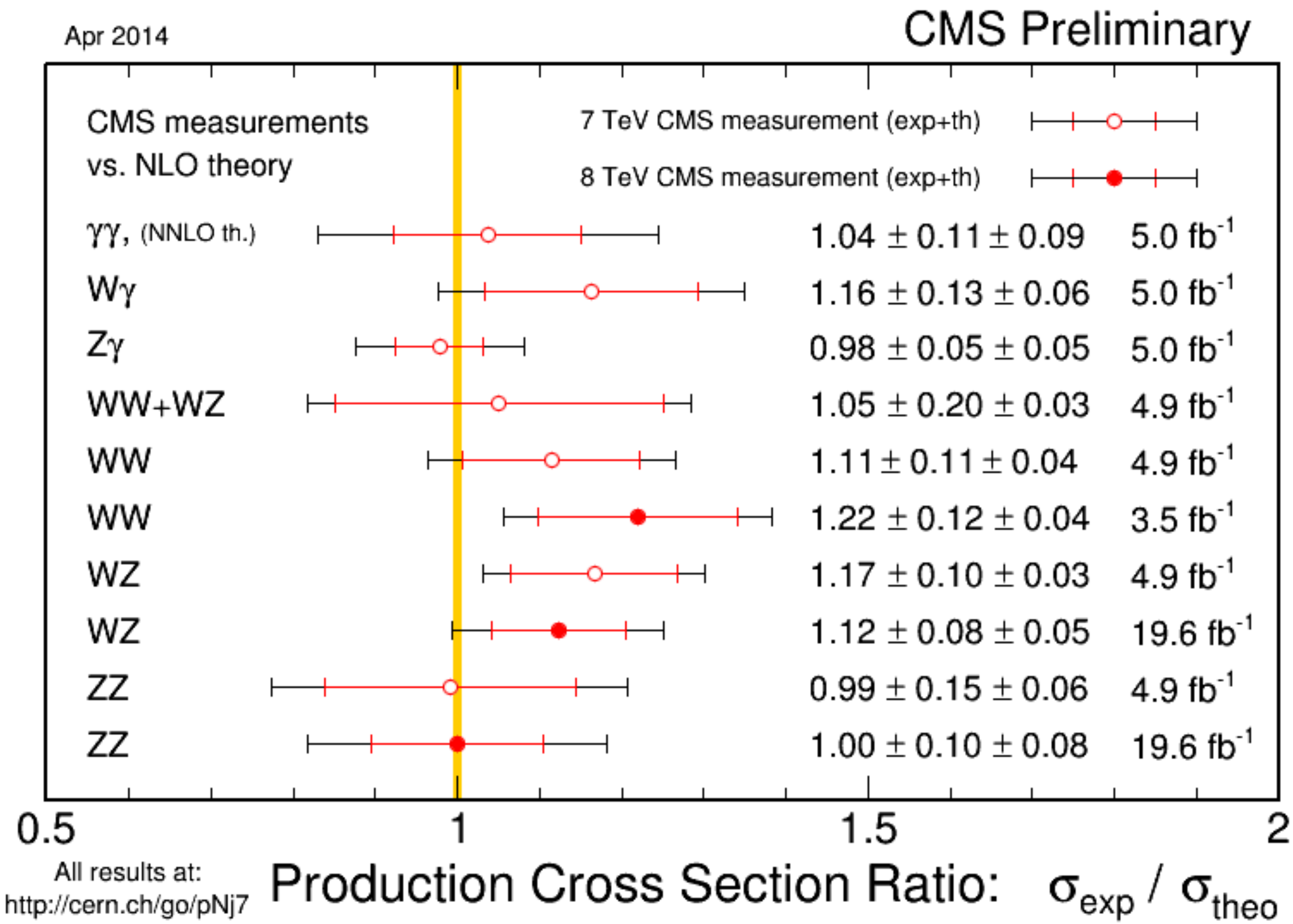




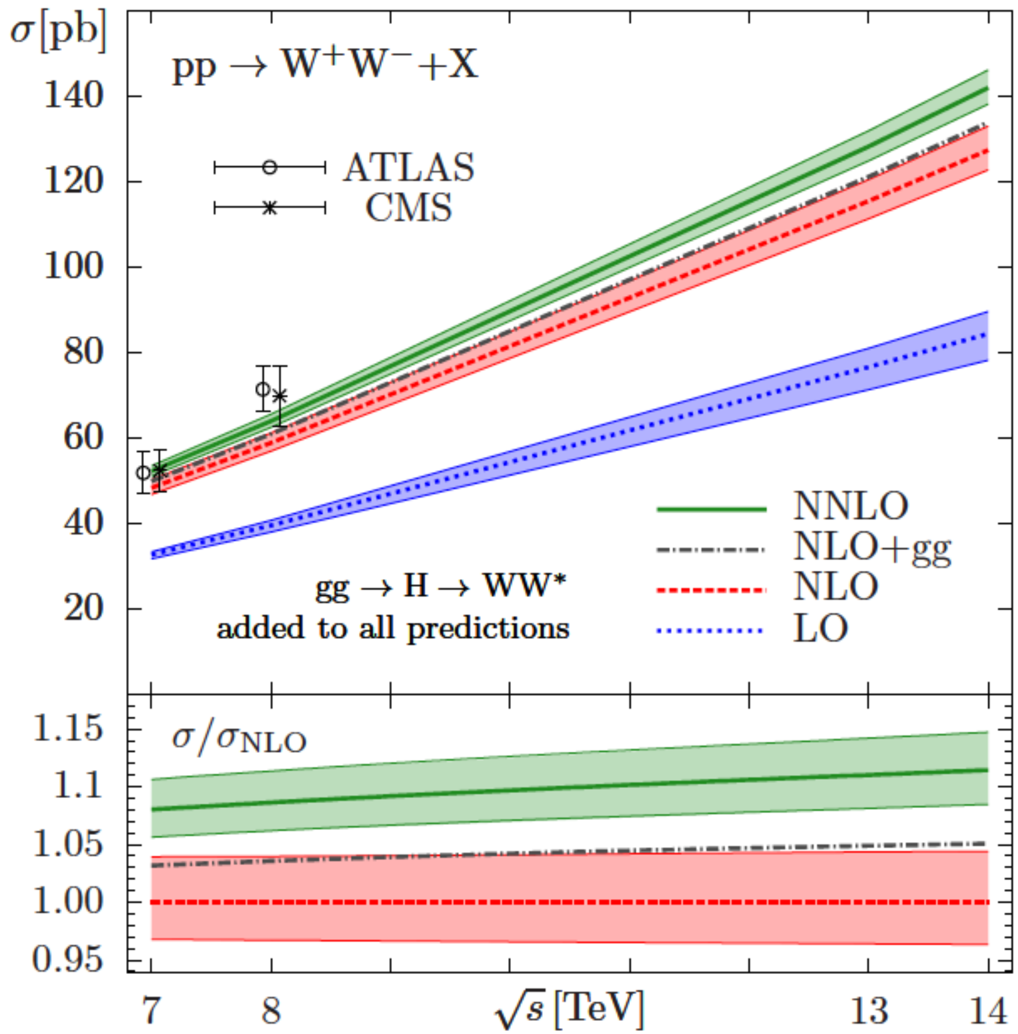


ATLAS Diboson Summary




Apr 2014
CMS Preliminary
CMS measurements
vs. NLO theory
7 TeV CMS measurement (exp+th)
8 TeV CMS measurement (exp+th)
γγ, (NNLO th.)
Wγ
Zγ
WW+WZ
WW
WW
WZ
WZ
ZZ
ZZ
1.04 ± 0.11 ± 0.09 5.0 fb-1
1.16 ± 0.13 ± 0.06 5.0 fb-1
0.98 ± 0.05 ± 0.05 5.0 fb-1
1.05 ± 0.20 ± 0.03 4.9 fb-1
1.11 ± 0.11 ± 0.04 4.9 fb-1
1.22 ± 0.12 ± 0.04 3.5 fb-1
1.17 ± 0.10 ± 0.03 4.9 fb-1
1.12 ± 0.08 ± 0.05 19.6 fb-1
0.99 ± 0.15 ± 0.06 4.9 fb-1
1.00 ± 0.10 ± 0.08 19.6 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

About WW production and higher orders



Gehrmann et al

Executive Summary

- W, Z inclusive cross sections measured at 7 and 8 TeV with a precision of 3% (≈uncertainty on lumi)
- W, Z differential cross sections start to have impact on PDF (e.g. charge asymmetry), heavy flavour sector coming into the game
- Jet physics probed over many order of magnitudes, precise measurement of α_s
- Sensitivity on charged triple gauge couplings reached LEP2 level, world best results for neutral TGC and QCG
- A roadmap for a precision measurement of M_W and $\sin^2\theta_W$ implies and efficient and smart use of LHC data to improve our knowledge of proton PDF