Wybrane wyniki fizyki oddziaływań elektrosłabych z LHC

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Plan seminarium

1. Oddziaływania elektrosłabe
2. Działanie LHC w latach 2010-2012
3. Fizyka bozonów ***W*** i ***Z***
4. Fizyka kwarku ***t***
5. Podsumowanie

} Dane *p-p* 2010 - 2011 (punkty 3–4)

Unifikacja oddz. e-m i słabych w SU(2)xU(1)

- Leptony i kwarki niosą hiperładunek: $Y = 2(Q - I_3)$
- 4 bezmasowe pola:

  W^1, W^2, W^3 (stała sprzężenia g, słaby prąd izospinowy SU(2))

  B^0 (stała sprzężenia g', słaby prąd hiperładunkowy U(1))

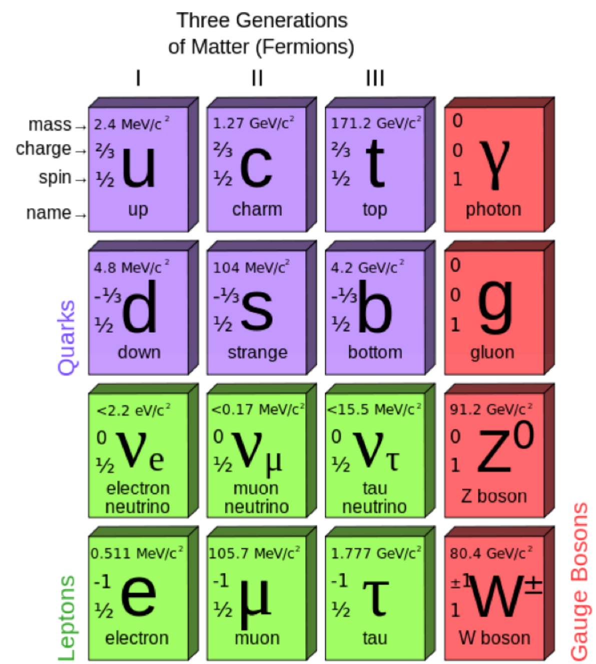
- Po spontanicznym złamaniu symetrii:

  W^+, W^-, Z^0 (masywne), γ (bezmasowy foton)

$$\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}$$

$$\begin{pmatrix}W^+ \\ W^-\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & -i \\ 1 & +i\end{pmatrix}\begin{pmatrix}W^1 \\ W^2\end{pmatrix}$$

$$e = g\sin\theta_W, \quad g/g' = \tan\theta_W$$



- Dublety ($I_3=\pm\frac{1}{2}$) fermionów lewoskrętnych, np. (ν_L, e^-_L), (u_L, d'_L)
- Singlety ($I_3=0$) fermionów prawoskrętnych, np. e^-_R, ν_R, u_R, d_R

Oddziaływania elektrosłabe

Lagranżjan oddziaływań elektrosłabych w MS (z 1 dubletem skalarów Higgsa):

$$\mathcal{L}_{EW} = \boxed{\mathcal{L}_K} + \boxed{\mathcal{L}_N} + \boxed{\mathcal{L}_C} + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

Część kinetyczna i masowa:

$$\mathcal{L}_K = \sum_f \overline{f}(i\partial\!\!\!/ - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + m_W^2 W^+_\mu W^{-\mu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \frac{1}{2}m_H^2 H^2$$

Prądy neutralne (γ, Z^0):

$$\mathcal{L}_N = eJ_\mu^{em}A^\mu + \frac{g}{\cos\theta_W}(J_\mu^3 - \sin^2\theta_W J_\mu^{em})Z^\mu$$

$$J_\mu^{em} = \sum_f q_f \cdot \overline{f}\gamma_\mu f \quad \longleftarrow \quad \text{electromagnetic current}, \quad q_f = \text{electric charge}$$

$$J_\mu^3 = \sum_f I_f^3 \cdot \overline{f}\gamma_\mu \frac{1-\gamma^5}{2} f \quad \longleftarrow \quad \text{neutral weak current}, \quad I_f^3 = \text{weak isospin}$$

Prądy naładowane ($W^\pm$):

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}}\left[\overline{u}_i\gamma^\mu \frac{1-\gamma^5}{2}\underbrace{\mathbf{V}_{ij}^{\mathbf{CKM}} d_j}_{d_i'} + \overline{\nu}_i\gamma^\mu\frac{1-\gamma^5}{2}e_i\right]W_\mu^+ + h.c.$$

Oddziaływania elektrosłabe

Lagranżjan oddziaływań elektrosłabych w MS (z 1 dubletem skalarów Higgsa):

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

Samooddziaływanie pola Higgsa (3- i 4-punktowe):

$$\mathcal{L}_H = -\frac{g m_H^2}{4 m_W} H^3 - \frac{g^2 m_H^2}{32 m_W^2} H^4$$

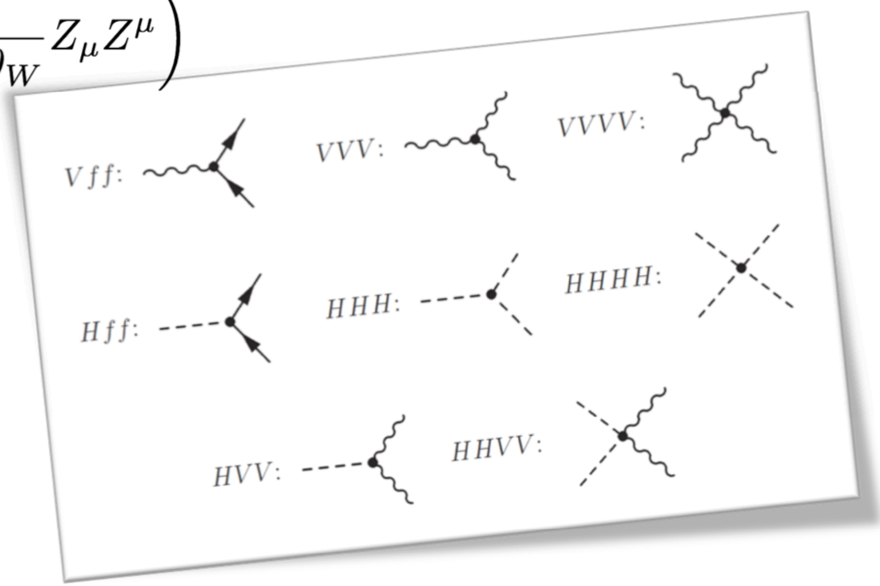
Oddz. pola Higgsa z bozonami wektorowymi:

$$\mathcal{L}_{HV} = \left(g\, m_W H + \frac{g^2}{4} H^2 \right) \left(W_\mu^+ W^{-\mu} + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \right)$$

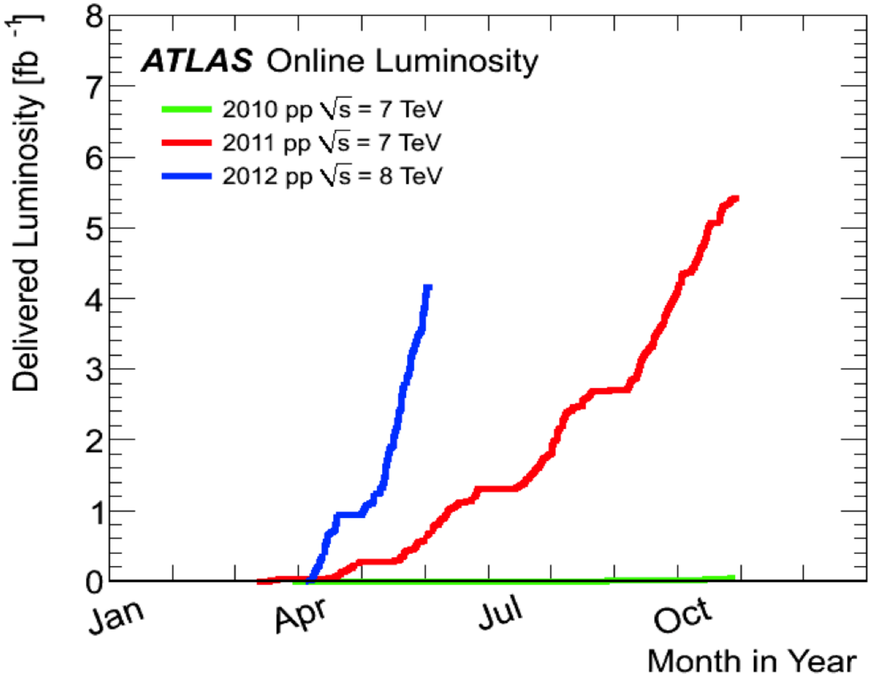
Samooddziaływanie bozonów wektorowych (3- i 4-punktowe)

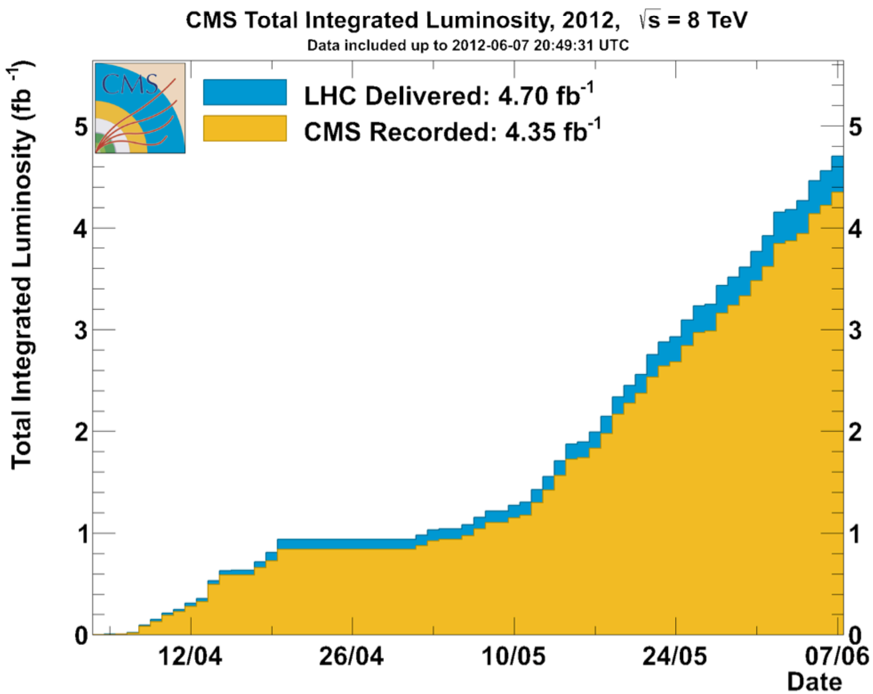
Oddz. pola Higgsa z fermionami:

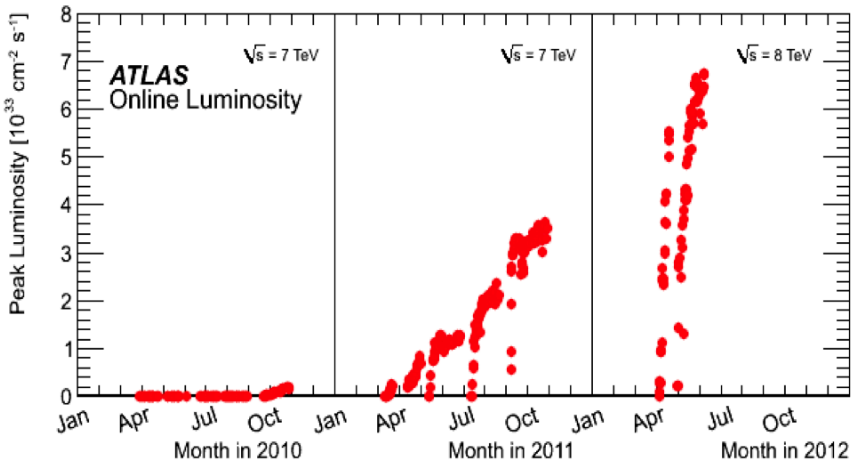
$$\mathcal{L}_Y = -\sum_f \frac{g\, m_f}{2 m_W} \bar{f} f H$$

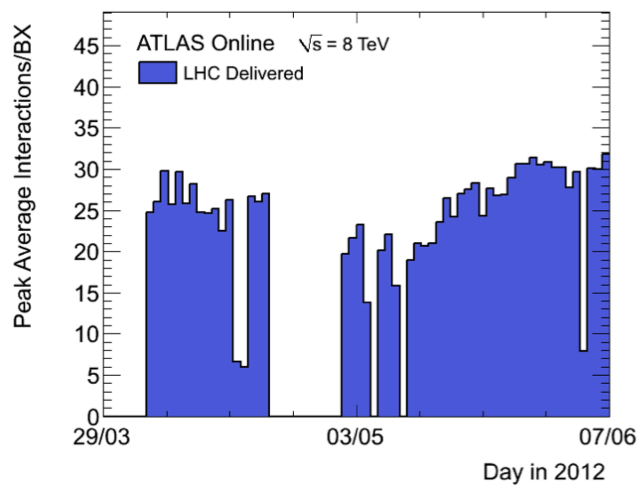


Działanie LHC w latach 2010-2012









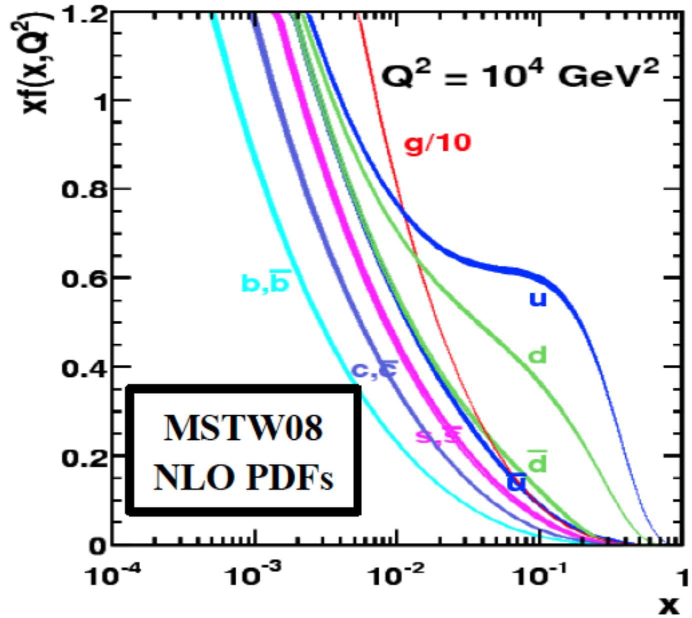
Działanie LHC w latach 2010-2012

			ATLAS, CMS	**LHCb**	*Jednostki*
7 TeV	**2010**	Scałkowana świetlność / exp	**45, 43**	**37**	pb^{-1}
		Maksymalna świetlność	**2.1×10^{32}**	**1.6×10^{32}**	$cm^{-2}s^{-1}$
		Średni pile-up	**3.5**	**3.2**	int / BX
	2011	Scałkowana świetlność / exp	**5.3, 5.6**	**1.1**	fb^{-1}
		Maksymalna świetlność	**3.7×10^{33}**	**8×10^{32}**	$cm^{-2}s^{-1}$
		Średni pile-up	**17**	**3.8**	int / BX
8 TeV	**2012** (kwiecień – maj)	Planowana scałkowana świetlność / exp	**~ 15**	**~ 1.5**	fb^{-1}
		Scałkowana świetlność / exp	**~ 4.0**	**~ 0.4**	fb^{-1}
		Maksymalna świetlność	**6.7×10^{33}**	**4×10^{32}**	$cm^{-2}s^{-1}$
		Średni pile-up	**31**	**3.7**	int / BX

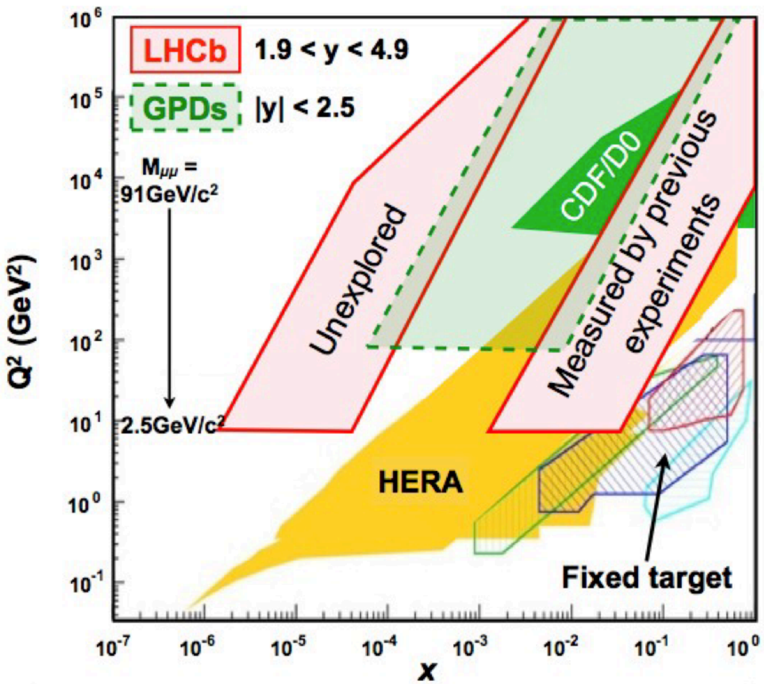
Fizyka *W* i *Z* w LHC

- W and Z production at LHC proceeds at the hard scattering level and first order via collisions of a valence quark (u,d) and a sea antiquark (Q≈100 GeV):

$$u+\bar{d}(\bar{s})\to W^{+} \qquad u+\bar{u}\to Z$$
$$d+\bar{u}(\bar{c})\to W^{-} \qquad d+\bar{d}\to Z$$



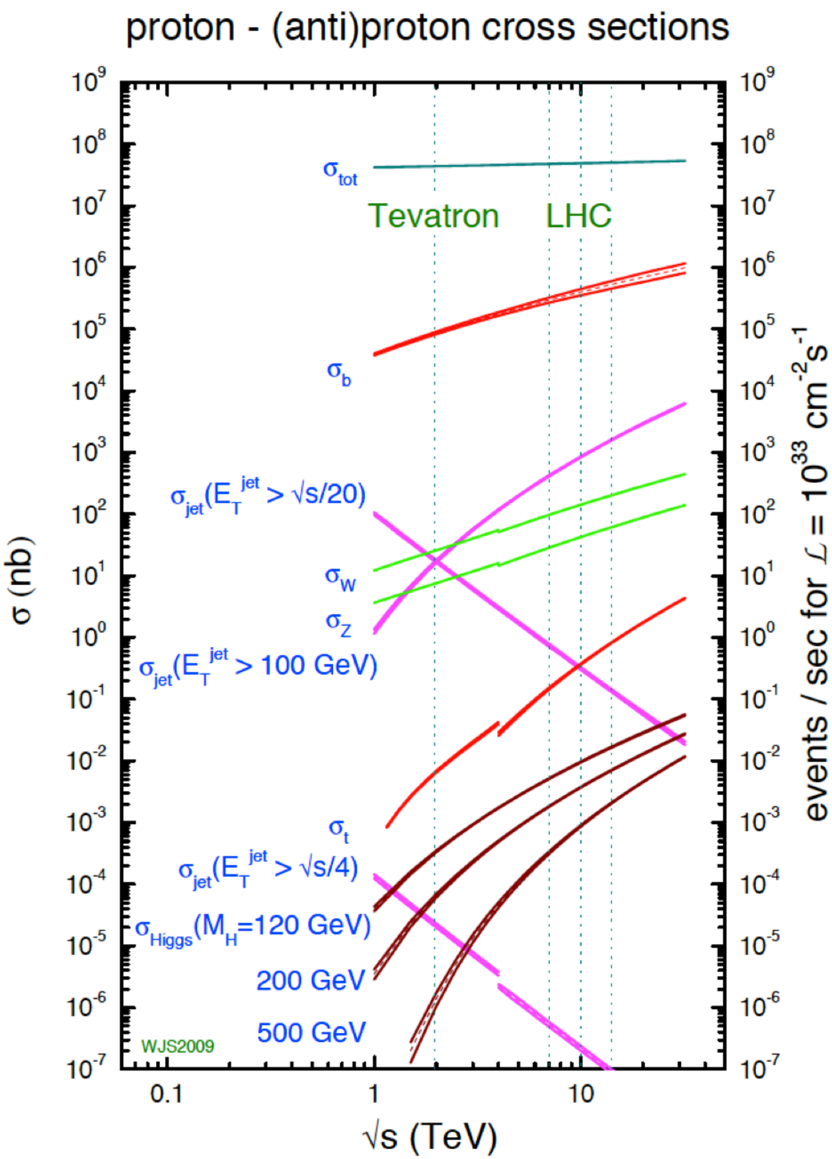
- LHC parton density fractions in this process are typically $10^{-4} < x < 10^{-1}$, so sea-sea $q\bar{q}$ contributions are also important



- Cross sections at LHC are a factor of 3 higher than at the Tevatron. We expect: $\sigma(W)^{*}B(W\to l\nu) \approx 10$ nb, and $\sigma(Z)^{*}B(Z\to l^{+}l^{-}) \approx 1$ nb

J. Alcaraz EPS-HEPP 2011

Fizyka ***W*** i ***Z*** w LHC



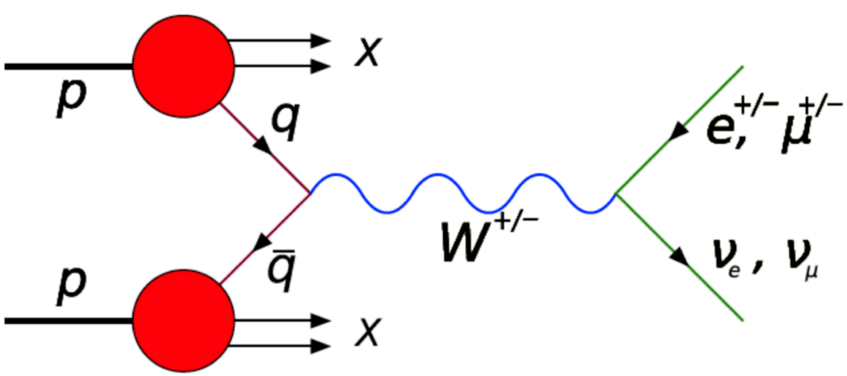
- Standard candles for detector commissioning, monitoring and performance
  - alignment and calibration (source of "prompt" muons)
  - energy and momentum resolution and scales (Z constraints)
  - lepton efficiency determination (tag-and-probe with Z events)
  - MET studies (W and Z similarities)
  - luminosity monitoring/determination
- Precise determination/tests of SM parameters/predictions given relatively low theoretical uncertainties
- Precise determination of the Parton Distribution Functions (PDF) - crucial for understanding physics at hadron colliders
- Main background for various Higgs and BSM searches

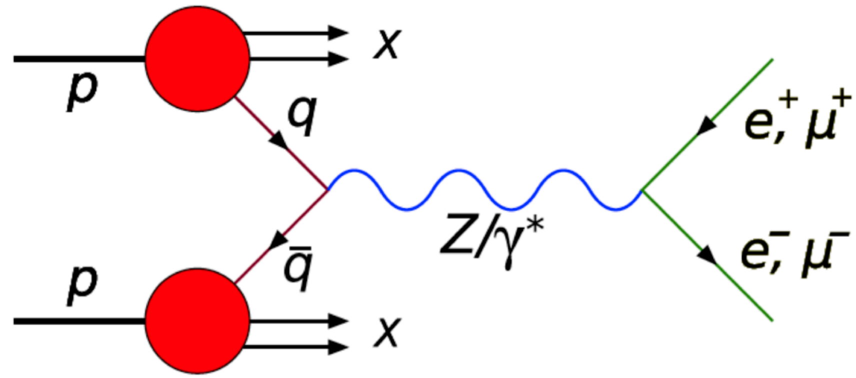
S. Stoynev LHC EWWG - May 2012

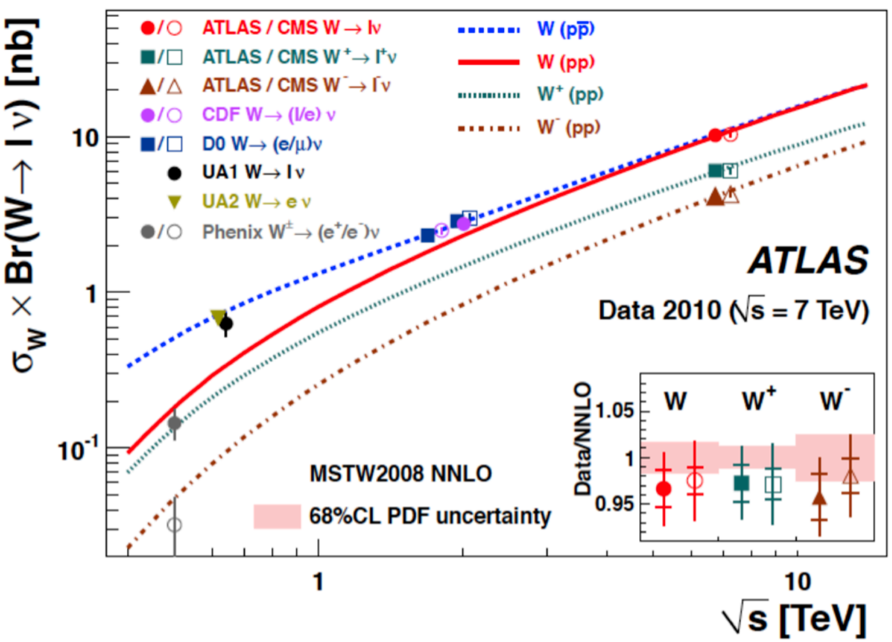
Analizy *W,Z* w ATLAS, CMS, LHCb

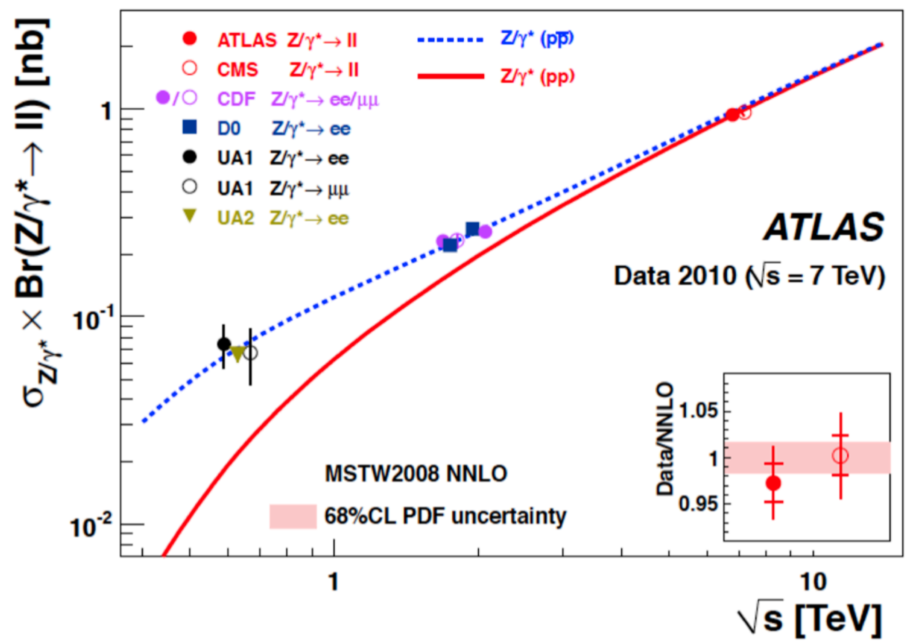
- Pomiary inkluzywne *W* / *Z*: **$24\ pb^{-1} - 1.6\ fb^{-1}$**
  - $\sigma\times BR(W)$ i $\sigma\times BR(Z)$ (uniwersalność leptonowa w rozpadach *W* i *Z*)
  - Rozkłady różniczkowe $(d\sigma/d|y_Z|$ dla $Z\to\ell^+\ell^-,\ d\sigma/d|\eta_\ell|$ i $A_C(\eta_\ell)$ dla $W\to\ell\nu_\ell)$
  - Gęstość kwarków *s* $(r_s = 0.5(s+\bar{s})/\bar{d}$ z kanałów: $Z\to\ell^+\ell^-,\ W^-\to\ell^-\bar{\nu}_\ell,\ W^+\to\ell^+\nu_\ell)$
  - Polaryzacja τ (kanał: $W\to\tau_{had}\nu_\tau$)
  - Polaryzacja *W* (kanały: $W^-\to\ell^-\bar{\nu}_\ell,\ W^+\to\ell^+\nu_\ell$)
  - Kąt mieszania Weinberga ($\sin^2\theta_W$ w kanale $Z\to\ell^+\ell^-$)
- W/Z + dżety: **$\leq 2.1\ fb^{-1}$**
  - $\sigma(W+\geq$ n-jets) i $\sigma(Z+\geq$ n-jets) (całkowite, różniczkowe)
  - *V* + HF-jets (W+c, W+b, Z+b, Z+2b)
- Kanały dwubozonowe: **$\leq 4.7\ fb^{-1}$**
  - Wγ, Zγ, WW, WZ, ZZ
  - Limity na aTGC

Inkluzywna produkcja *W* i *Z*









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Inkluzywna produkcja ***W*** i ***Z***

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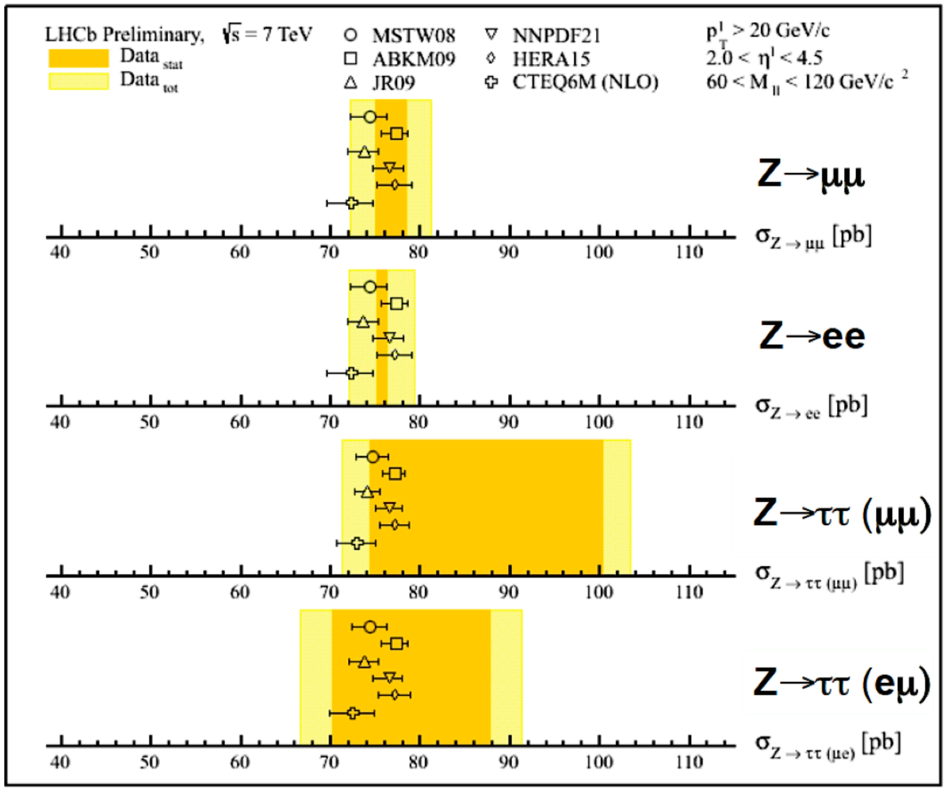
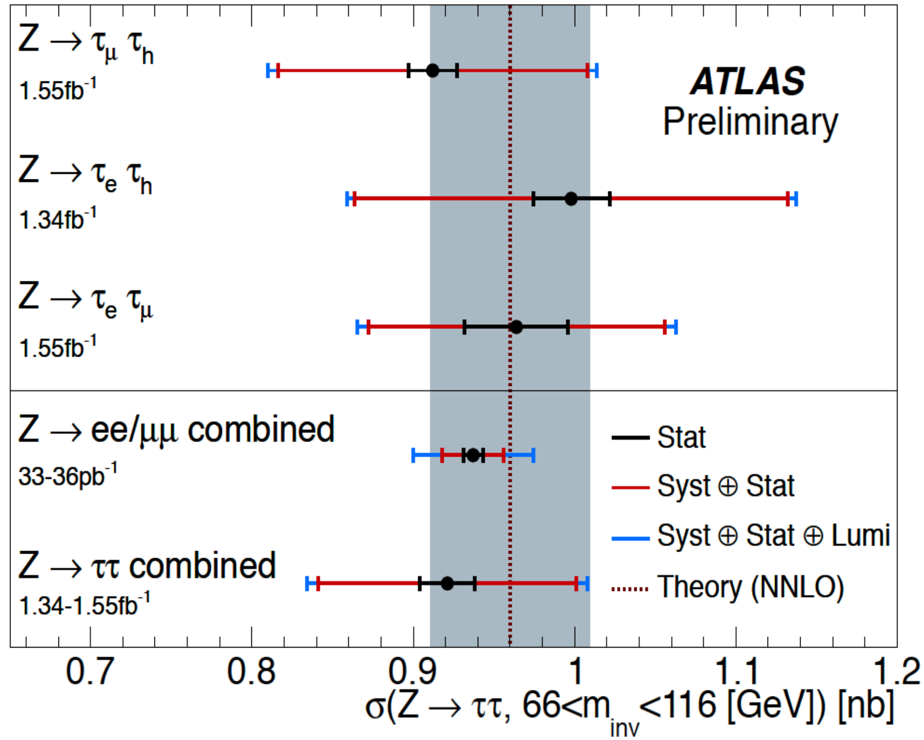
LHCb $37pb^{-1}$

NNLO (DYNNLO) PDF uncertainties at 68% CL





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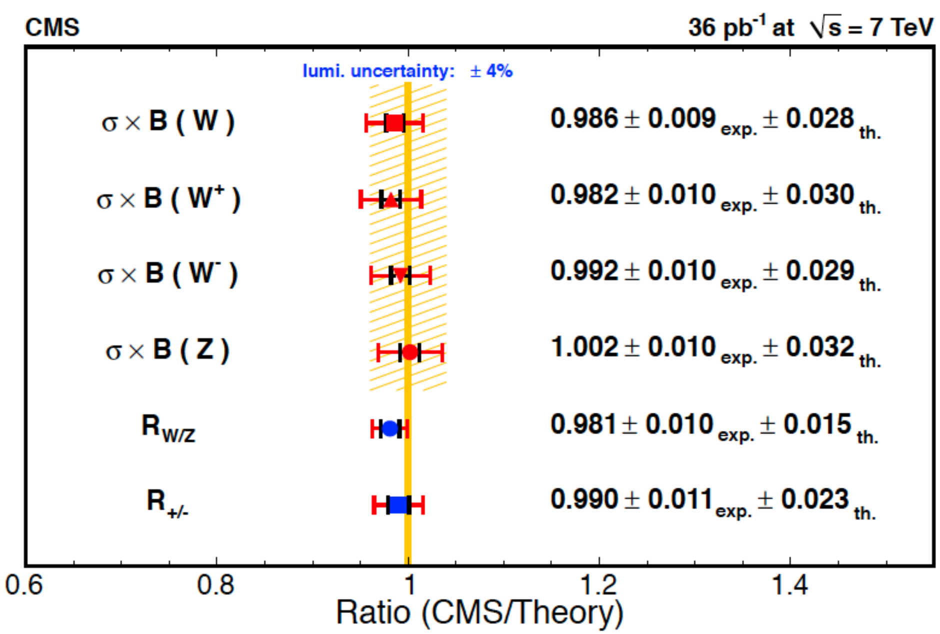
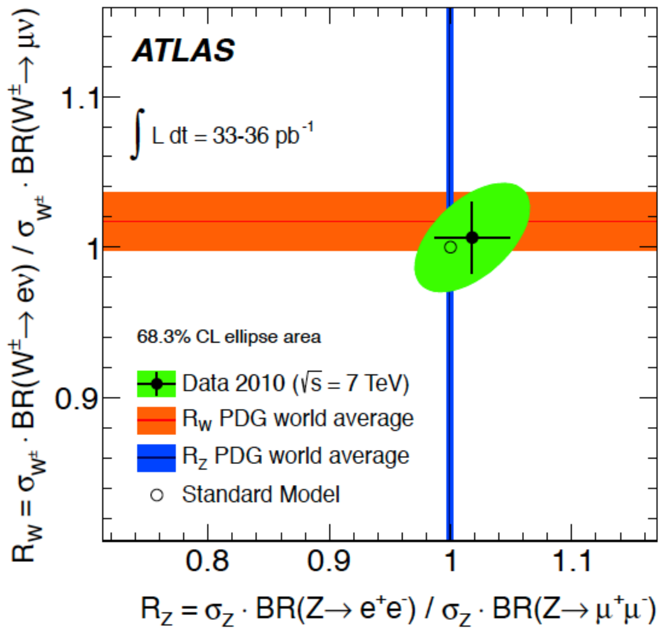
Inkluzywna produkcja ***W*** i ***Z***

- Cross section for inclusive production and leptonic decays, $W \to \ell\nu$ and $Z \to \ell\ell$ reached experimental accuracy of few % in $\ell = e, \mu$ channels with 2010 data
- QCD prediction at NNLO: precision test of proton PDFs and the SM
- Maximising sensitivity using ratios and correlation information; avoid extrapolation in theory comparison
- $e - \mu$ universality in W decays confirmed to 2%





Inkluzywna produkcja *W* i *Z*

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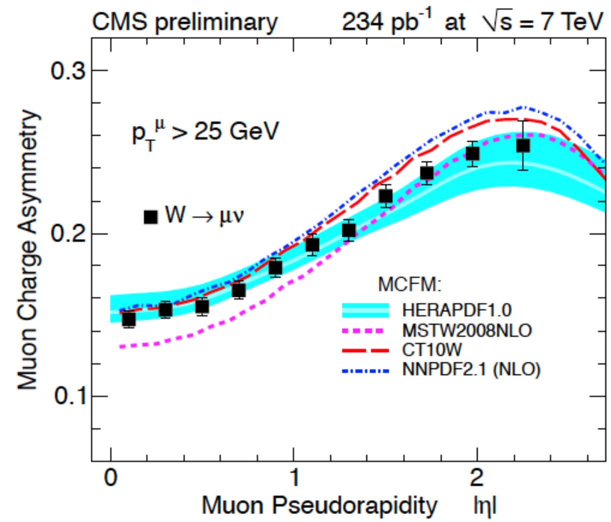
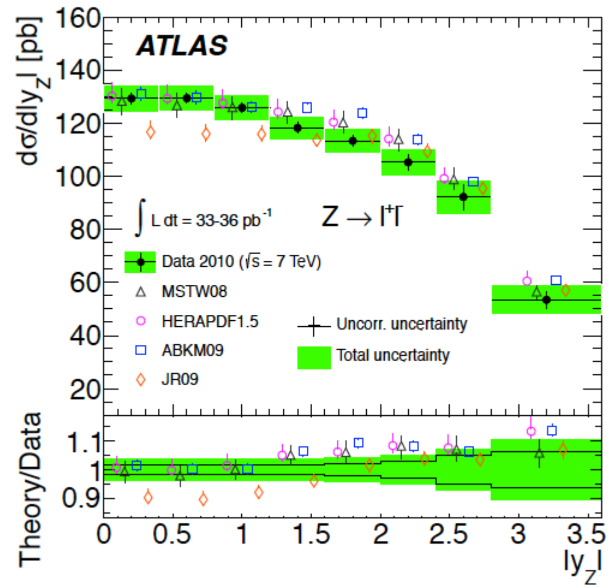
- Boson rapidity y directly linked to parton momentum fractions $x_{1,2} = M_{W,Z}/\sqrt{s} \cdot e^{\pm y}$
- W: charged lepton pseudo-rapidity η_ℓ used
- CMS:
  - *W lepton charge asymmetry* $A(\eta) = (\mathrm{d}\sigma^+(\eta) - \mathrm{d}\sigma^-(\eta))/(\mathrm{d}\sigma^+(\eta) + \mathrm{d}\sigma^-(\eta))$
  - *normalised Z rapidity* $1/\sigma \cdot \mathrm{d}\sigma/\mathrm{d}y$
- ATLAS: absolute differential cross sections for Z, W^+, W^- with correlation information
- Comparison to theory at NLO and NNLO shows broad agreement, but also indicates sensitivity to PDFs





arXiv:1109.5141→PRD; arXiv:1110.4973→PRD; JHEP04(2011)050; CMS PAS EWK-11-005

Inkluzywna produkcja *W* i *Z*

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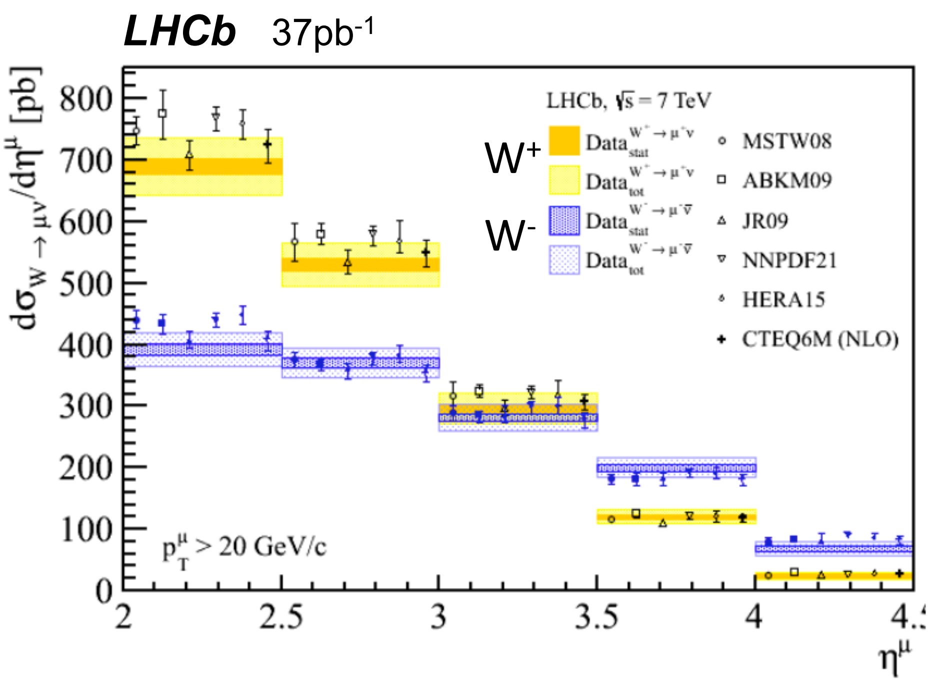
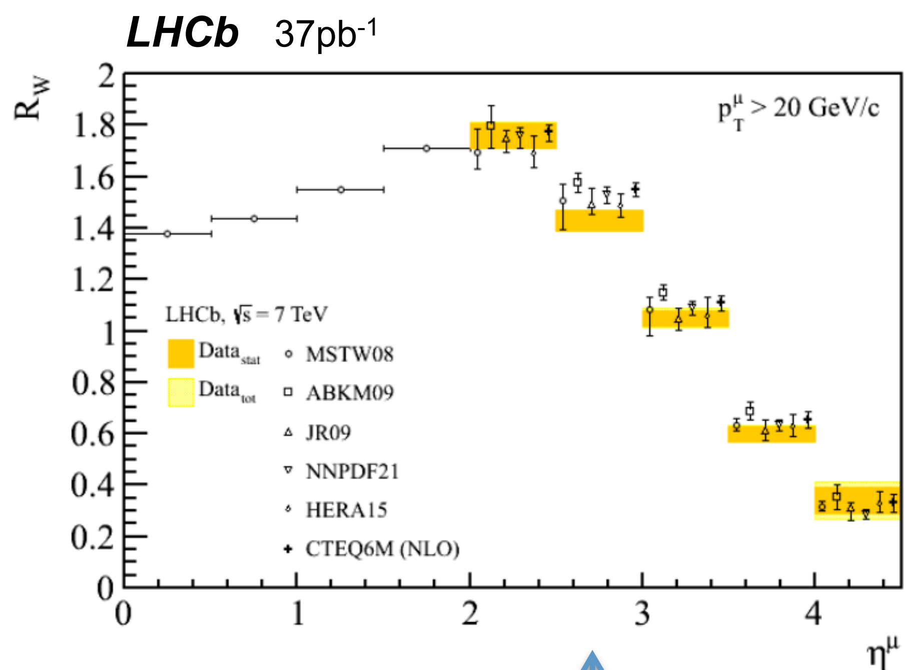
arXiv: 1204.1620





Differential W+ and W- cross-sections as a function of muon η
Ratio of W+ to W- production as a function of muon η

(note: full correlation matrix available for W+,W-,Z results)

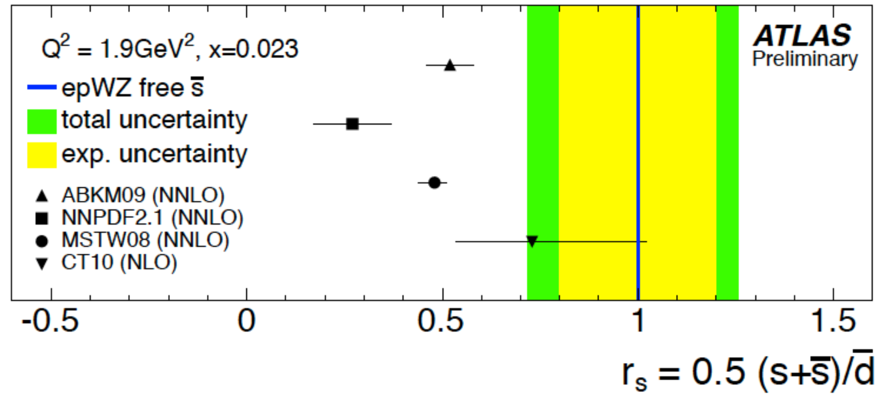
Pomiar gęstości kwarku *s*

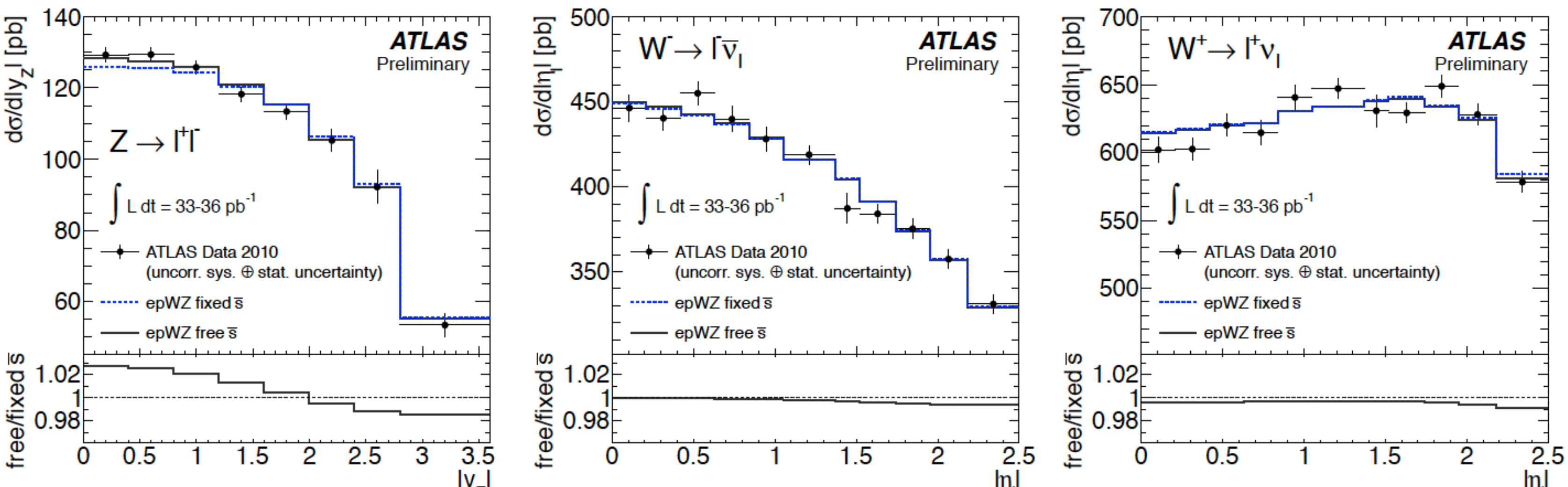
- ATLAS performed NNLO QCD fit to Z, W^+, W^- + HERA ep DIS cross sections: significant tension for Z observed when suppressing strange by 50% at low scale $1.9\,\mathrm{GeV}^2$

- Fit with free strange sea gives no supression

$$r_s = 1.00 \pm 0.20_{\mathrm{exp}}\,{}^{+0.16}_{-0.20}\,\mathrm{sys}$$

for (x=0.023, Q^2=1.9GeV^2)





ATLAS-STDM-2011-43 → PRL

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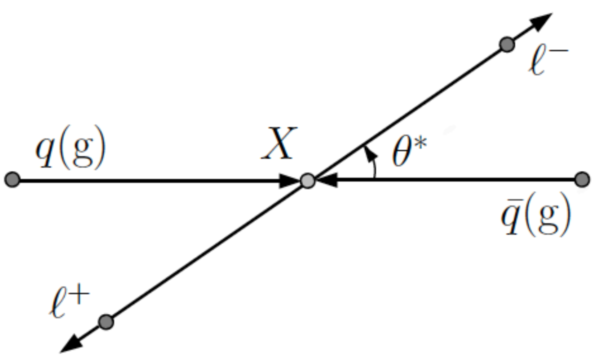
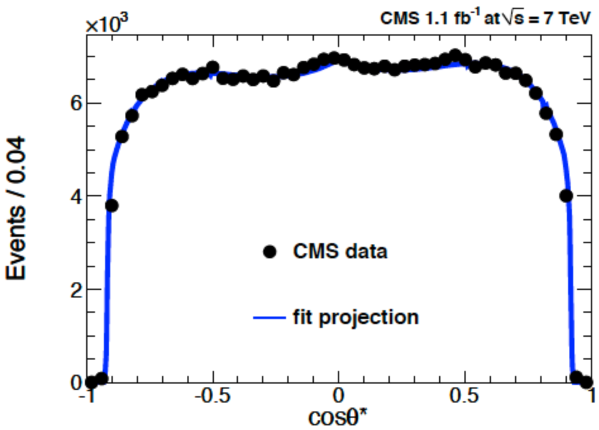
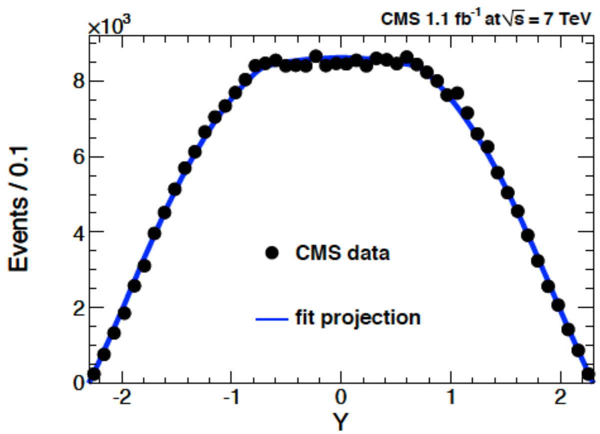
Pomiar $sin^2\theta_W$

- Fundamental parameter of the SM, world average has 0.1% accuracy, but contains results with few σ tension
- CMS has used large amount of Z/γ^* to measure $\sin^2\theta_{\rm eff}$ from the *forward-backward asymmetry* in the $q\bar{q} \to Z/\gamma^* \to \mu^-\mu^+$ process
- Quark direction more likely in boost direction: three dimensional fit in decay angle $\cos\theta^*$, mass m and rapidity y to disentangle forward/backward direction on statistical basis
- Result with $\sim 1\%$ precision: $\sin^2\theta_{\rm eff} = 0.2287 \pm 0.0020_{\rm stat} \pm 0.0025_{\rm syst}$

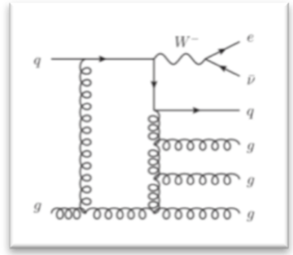


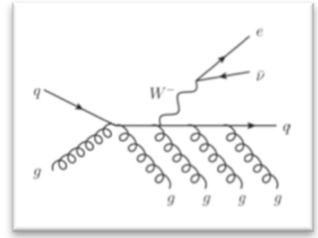




PRD 84, 112002 (2011)

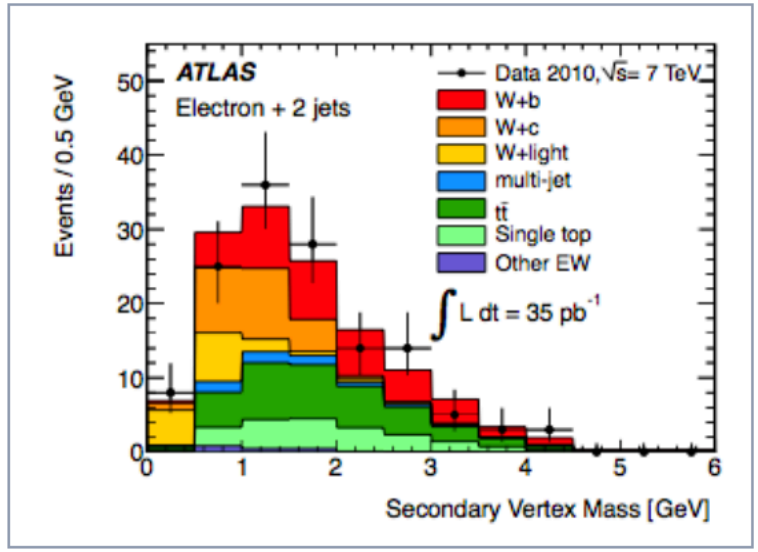
W + b

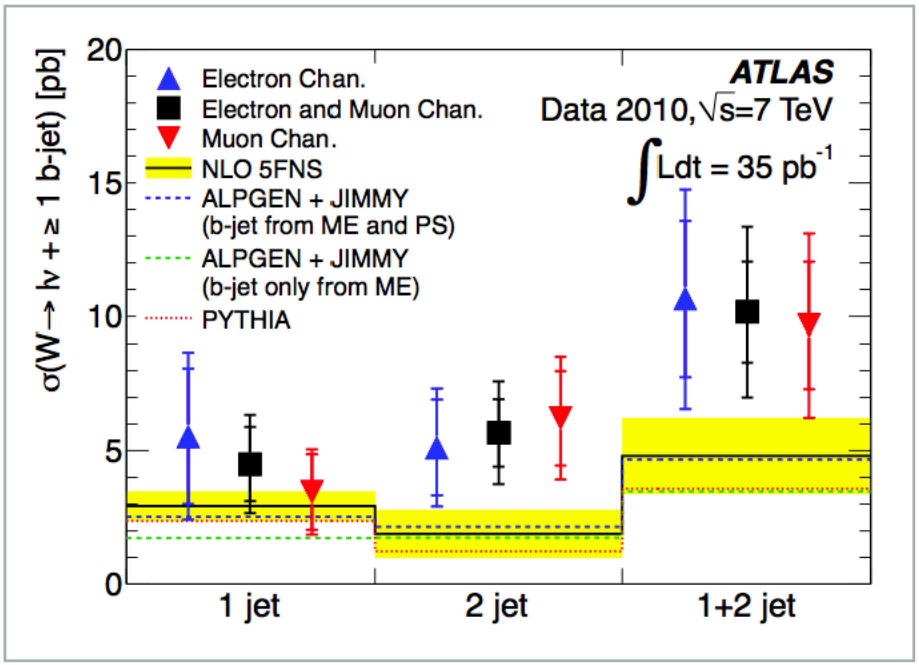




"Tension" in data/MC comparisons

- **W+b**
  - ATLAS observe 'tension' in cross-section
    - **~1.5 sigma**
    - NLO(5FNS) and LO (Alpgen+Jimmy)





Event fitted yield is corrected for detector effects with MC LO matched prediction for Wjets (including heavy flavour) from **ALPGEN**.
Uncertainty ~20% stat and ~25% syst.
Dominant systematics
- B-tagging & m(SV) templates ~16%
- Top background ~12%
- QCD background ~7%
- W+b-jet modeling ~10%
- Jet+b-jet energy scale ~7%

Non-perturbative correction 0.93±0.07

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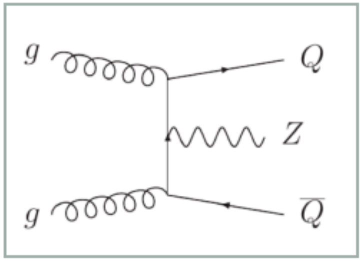
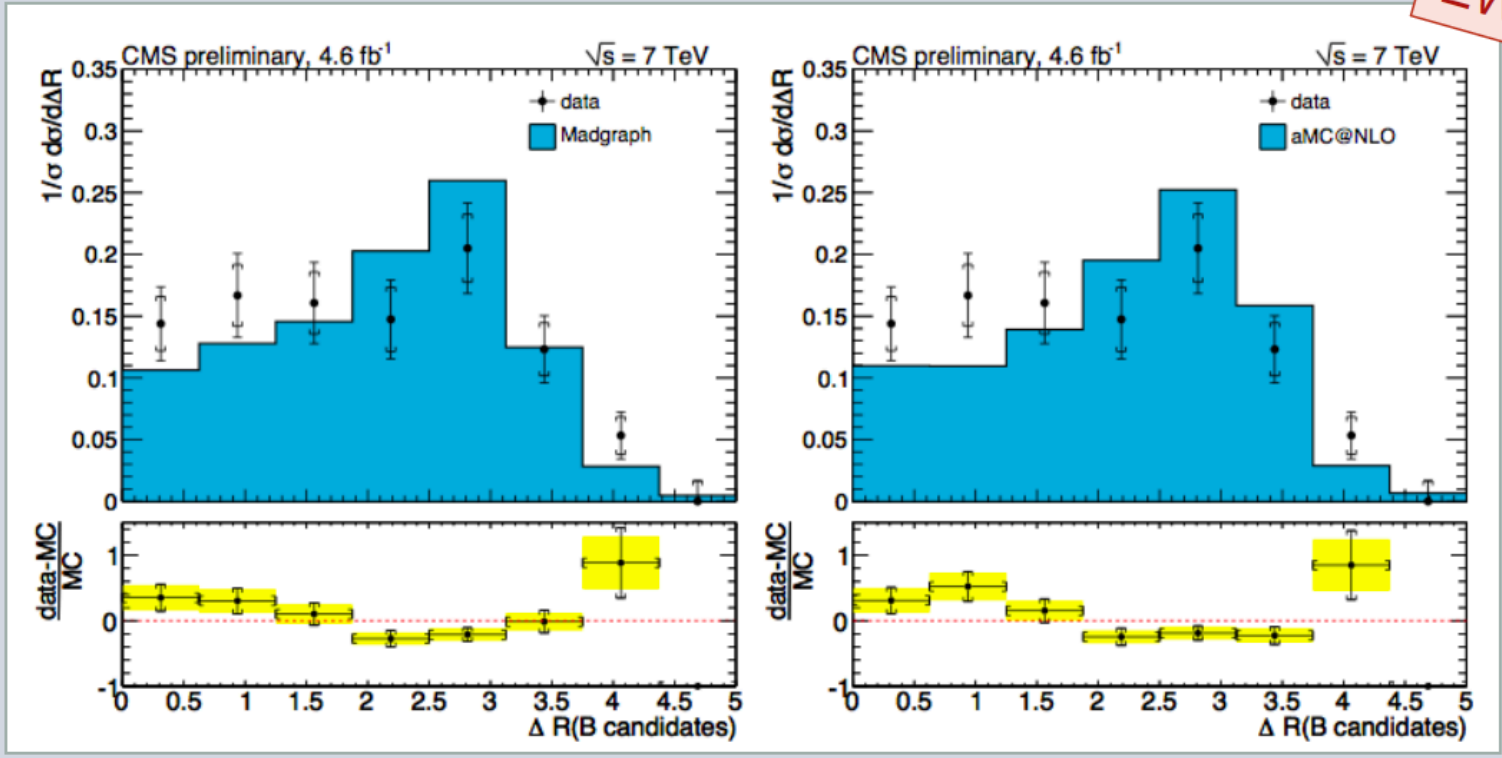
Z + 2SV



"Tension" in data/MC comparisons

- **ΔR(b1,b2): angle between the two displaced vertices of the b-hadrons**
  - Not using b-jets, but "Inclusive Vertex Finder" to find displaced vertex
    - ➢ Sensitivity at **small angles**

EWK-11-015



➢ **General shape disagreement**

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Produkcja ***VV*** i ***VV'*** w LHC

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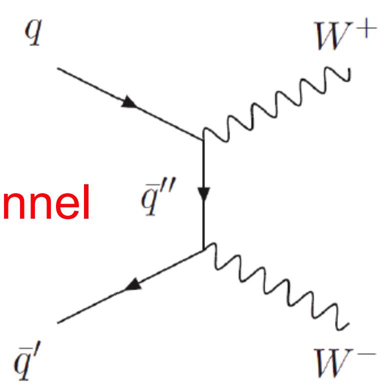
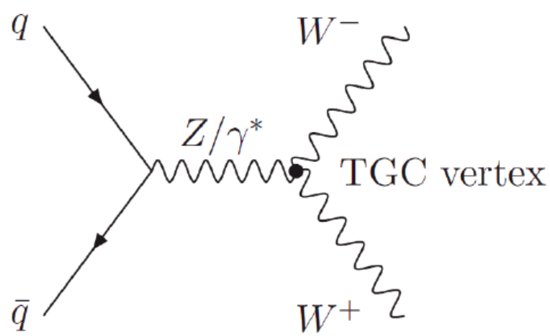
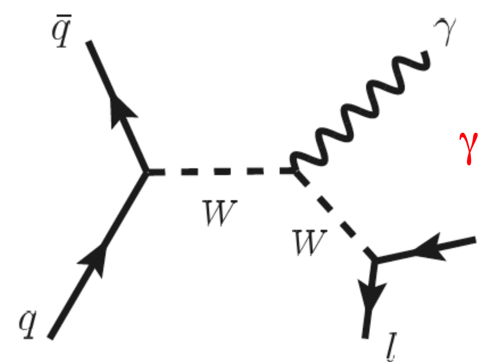
- Main production diagrams for di-bosons are in general t-channel quark exchange and FSR for γ
- In the standard model s-channel contribute with triple gauge coupling (TGC) due to non-Abelian $SU(2)_L \times U(1)_Y$ structure:
  - Allowed for $WW\gamma$ and WWZ vertices
  - Not allowed for “neutral” ZZZ, $ZZ\gamma$ or $Z\gamma\gamma$ vertices
- Select phase space with enhanced TGC contribution, limits on anomalous TGCs (aTGCs); cross sections compared to NLO predictions (both fiducial and total)
- Important irreducible background to some Higgs channels

t-channel





s-channel



γ FSR

Pomiary *VV* i *VV'* w LHC

Final states with electrons and muons:

- Small branching ratios
- Clean signatures
- Low QCD backgrounds

	σ_{NLO} (pb)	e/μ BF
WW	46	4.7%
WZ	17.2	1.5%
ZZ	6.5	0.5%
Wγ	333 (*)	22%
Zγ	205 (*)	6.7%

(*) includes phase space cuts for definition of prompt photon: E_t^{γ} >15 GeV, ΔR>0.7, isolation

W and Z signatures:

- **W:** one high p_T lepton (e/μ) + missing transverse energy (M_{ET}) from the neutrino
- **Z:** two high p_T leptons (e/μ) with opposite charges and same flavor

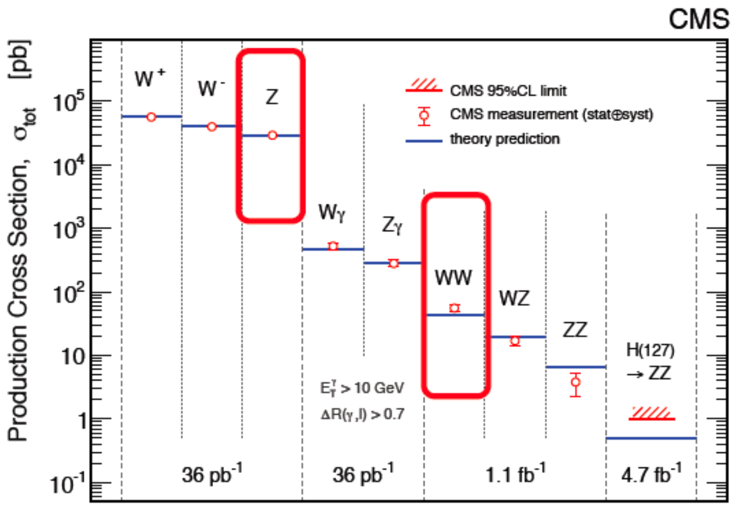
Main backgrounds:

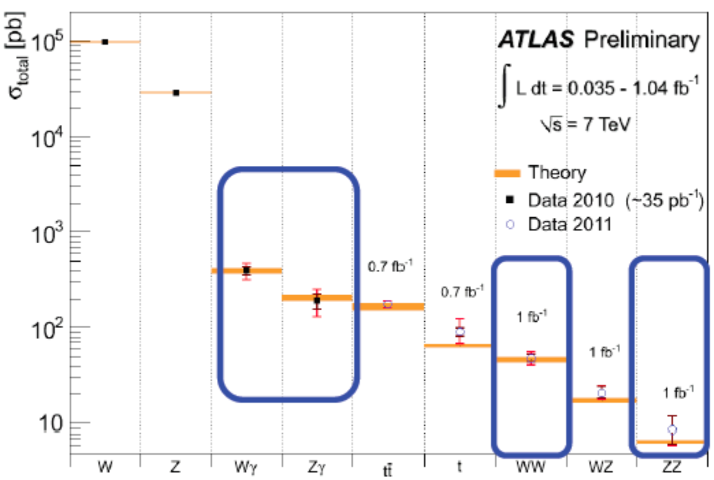
- **Top:** ttbar and Wt (t →Wb)
- **QCD multi-jets, W+jets** (jets faking leptons)
- **Drell-Yan:** Z/γ* →$l^+ l^-$
- **Diboson:** other modes

Major backgrounds estimated with data driven techniques

J. Malcles Moriond QCD 2012

Pomiary *VV* i *VV'* w LHC





J. Malcles Moriond QCD 2012

Moriond 2011 with ≈ 35 pb^{-1}

First measurements of Wγ, Zγ, and WW production at the LHC

EPS 2011 with ≈ 1 fb^{-1}

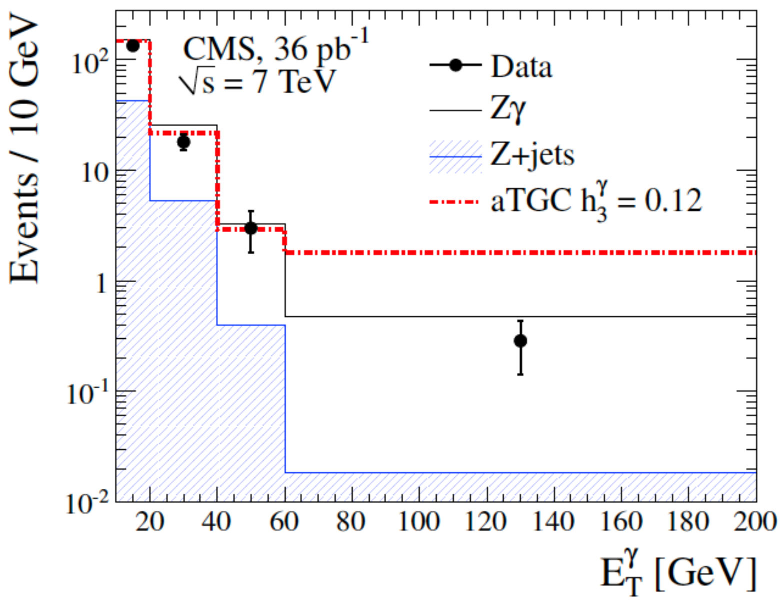
- First measurements of WZ and ZZ production cross-sections at the LHC
- Updated results on WW production

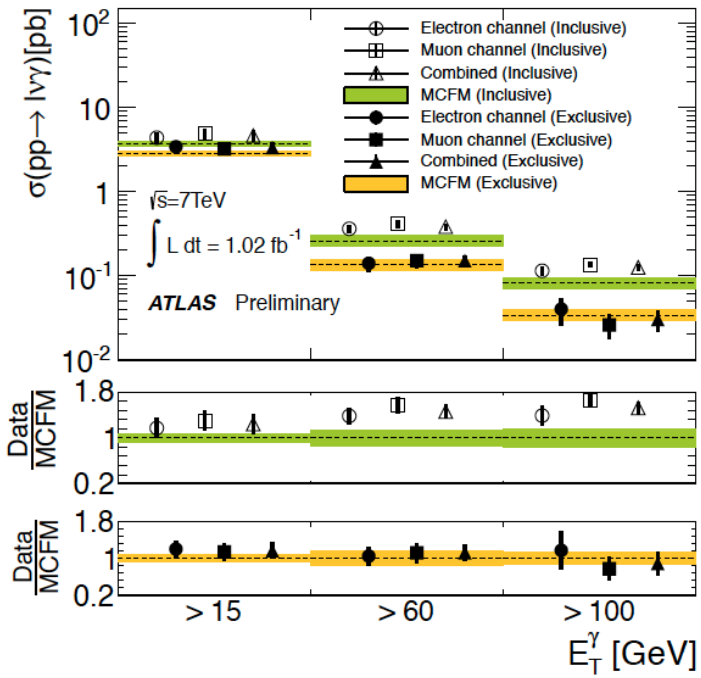
Moriond 2012: results with ≈ 1 to 5 fb^{-1}

- **Updated Wγ, Zγ (≈1fb^{-1}, ATLAS)**
- **Updated WW (≈5fb^{-1}, ATLAS)**
- **Dijet mass spectra in W+2 or 3 jets (≈5fb^{-1}, CMS)**
- **Updated ZZ→4l and first ZZ→2l2ν (≈5fb^{-1}, ATLAS)**
- **Bonus: observation of Z→4l (≈5fb^{-1}, CMS)**

Produkcja $W^{\pm}\gamma$ i $Z\gamma$

- Highest cross section di-boson processes: typical Z or W selection, additional isolated photon with $\Delta R(\ell, \gamma) > 0.7$ and $p_T^\gamma > 10..15$ GeV
- Cross sections with $\sim 10..15\%$ uncertainty, mostly good agreement with NLO predictions (especially in *exclusive* selection, jet veto)
- aTGCs on $WW\gamma$ and $ZZ\gamma, Z\gamma\gamma$ vertices on similar level as Tevatron and LEP analyses



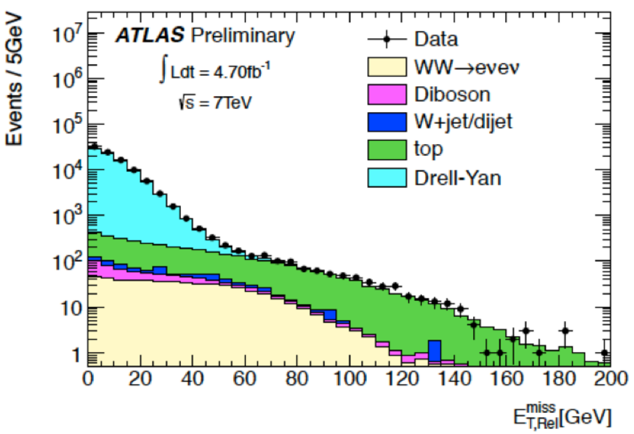


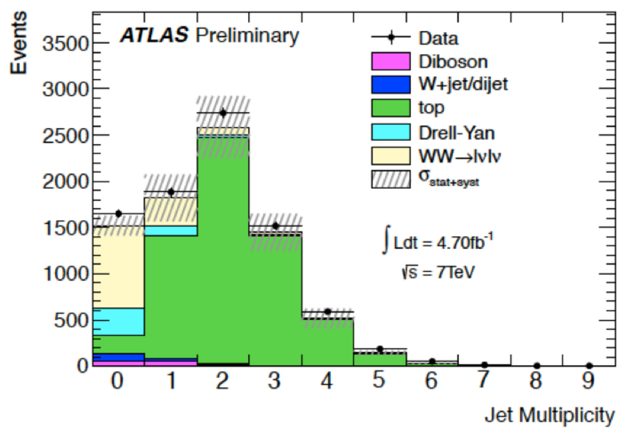
JHEP 09 (2011) 072; to be submitted to PLB; PLB 701 (2011) 535-555

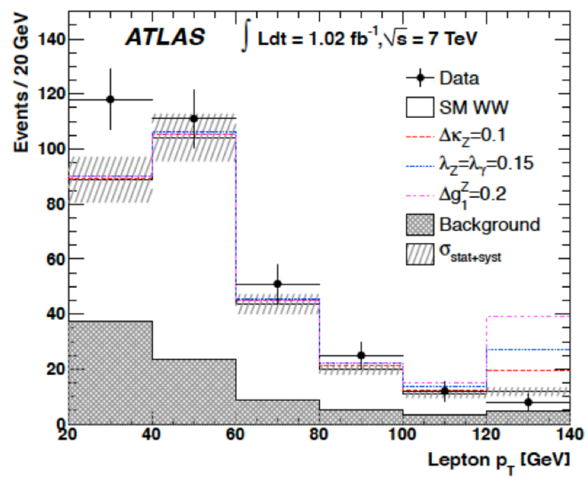
Produkcja W^+W^-

J. Kretzschmar Moriond EWK 2012

- Measured in leptonic channels $2e2\nu, 2\mu2\nu, e\mu2\nu$
- Large Drell-Yan bkg. (esp. in like-flavour channels): $\not{E}_T$ relative to lepton/jets; Z mass window veto; Top background controlled with jet/b-jet/soft muon tag vetos
- Cross section precision $\sim 10..15\%$ (largely systematic): ATLAS and CMS $\sim 1\sigma$ above NLO prediction
- aTGC limits sensitive to high leading lepton p_T: limits in between Tevatron and LEP







ATLAS-STDM-2011-24 → PLB; ATLAS-CONF-2012-025; CMS-PAS-EWK-11-010

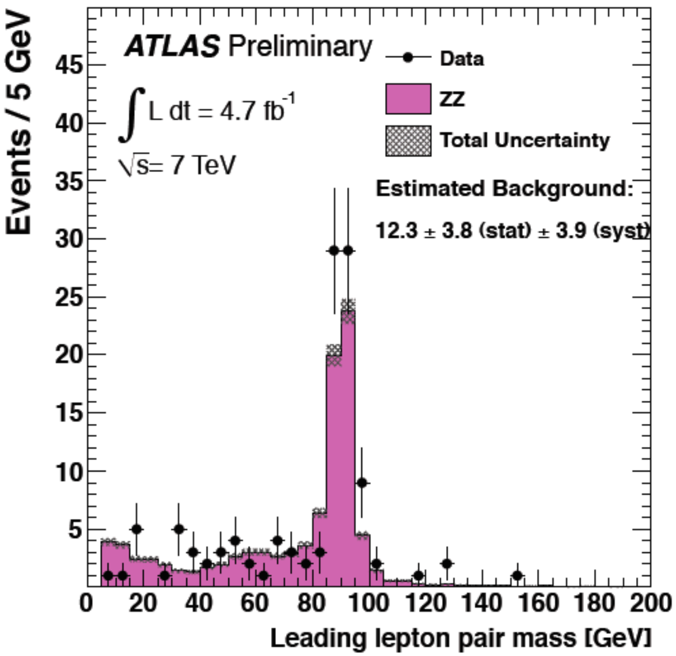
Produkcja ZZ

Cross-section: dominated by statistical uncertainties

$$\sigma^{\text{fid}}_{ZZ\to\ell^+\ell^-\ell^+\ell^-} = 21.2^{+3.2}_{-2.7}\,(\text{stat})\,^{+1.0}_{-0.9}\,(\text{syst})\,\pm 0.8\,(\text{lumi})\,\text{fb} \quad \text{fiducial}$$

$$\sigma^{\text{tot}}_{ZZ} = 7.2^{+1.1}_{-0.9}\,(\text{stat})\,^{+0.4}_{-0.3}\,(\text{syst})\,\pm 0.3\,(\text{lumi})\,\text{pb} \quad \text{total}$$

- Fiducial phase space defined with cuts that mimic analysis acceptance
- Fiducial cross section extrapolated to the full phase space using kinematic distributions predicted from SM (NLO) + BR
- Consistent with NLO SM predictions
  - 19.0 ± 1.0 fb (fiducial)
  - 6.5 ± 0.3 pb (total)



W+2(3) dżety : masa m_{jj}

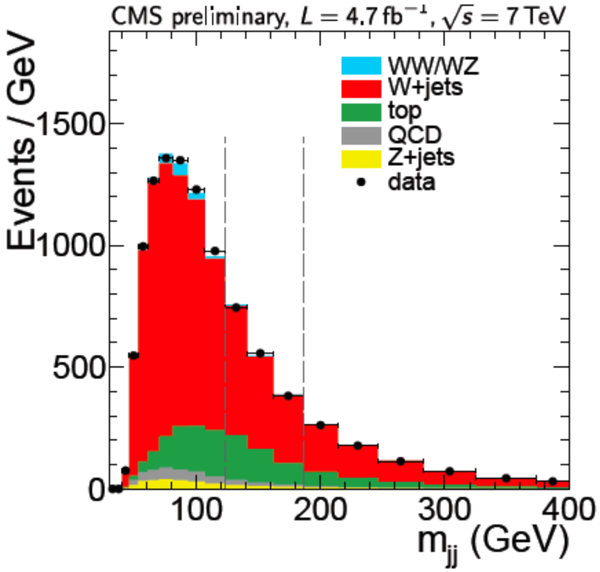
ML fit to the m_{jj} distribution:

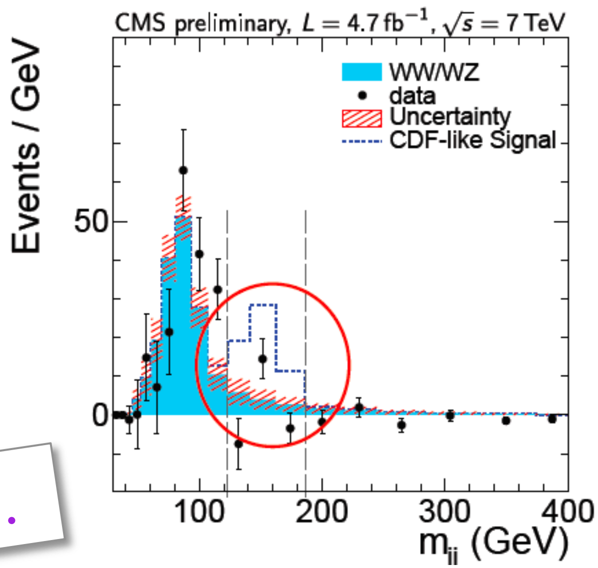
- Mass region [123-186] GeV excluded from the fit
- Templates taken from MC, except:
  - Multijets: from control sample (lepton failing isolation)
  - W+jets: combination of three MC shapes with scales varied by factors 2 and ½, weights free in the fit
- Normalizations:
  - W+jets: free in the fit
  - Others: with a gaussian constraint
    - Multijets: mean and sigma from fit to M_{ET} distribution in data
    - Others: mean from MC, sigma from theo. errors

Results:

- **Diboson signal after other backgrounds removal**
- **No evidence for resonant enhancement**

J. MALCLES 01/02/2012





No CDF-like signal…

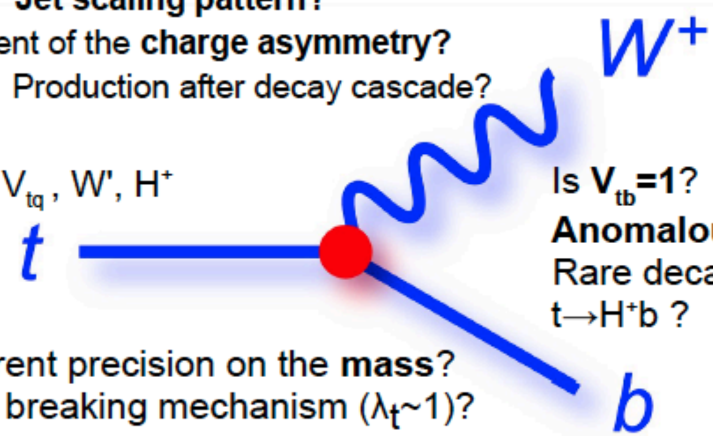
Fizyka kwarku *t* w LHC

P. Silva Moriond EWK 2012

The LHC has delivered >10^6 top quarks last year – what have we learnt?

Top pair production: consistent with QCD prediction?
- **Spin correlations?** **Jet scaling pattern?**
- Differential measurement of the **charge asymmetry?**
- Resonant production? Production after decay cascade?

Single top production: V_{tq}, W', H^+



Is $\mathbf{V_{tb}=1}$?
Anomalous couplings in Wtb vertex?
Rare decays by **FCNC** to γq, qZ, qg?
$t \to H^+ b$?

Can we improve the current precision on the **mass**?
Privileged role in EWSB breaking mechanism (λ_t~1)?
CPT invariance in the top sector: $m_{top}=m_{anti\text{-}top}$?

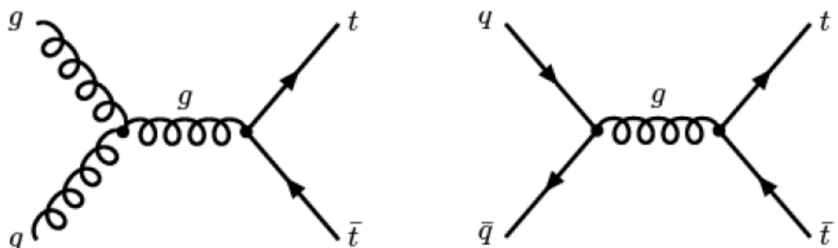
Is the **charge** of the decay products compatible with 2/3e?
Is the **width** of the prompt decay compatible with Γ_t~1.3 GeV?

Many unknowns: unique sample for precision measurements and exploration of deviations from the SM at the LHC.

Przewidywania dla 7 TeV

P. Silva Moriond EWK 2012

Top pair production



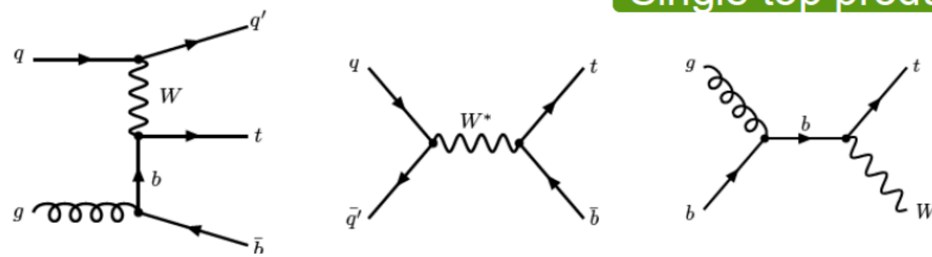
85 % 15 %

165^{+11}_{-16} pb

Aliev, M. et al
arXiv/hep-ph:1007.1327

≈ 165 pb

Single top production



$64.57^{+2.09}_{-0.71}\ {}^{+1.51}_{-1.74}$ pb

Kidonakis,N.
PRD83:091503,2011

$4.63 \pm 0.07^{+0.19}_{-0.17}$ pb

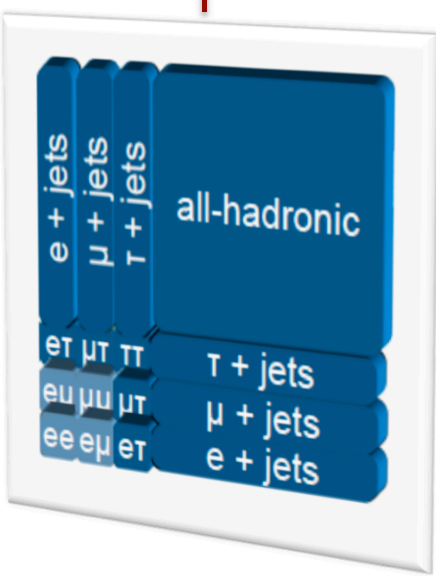
Kidonakis,N.
PRD81:054028,2010

$15.74 \pm 0.40^{+1.10}_{-1.14}$ pb

Kidonakis,N.
PRD82:054018,2010

t-channel s-channel tW-channel

≈ 65.6 + 4.6 + 15.7 pb



Analizy *t* w: ATLAS i CMS

- Produkcja par $t\bar{t}$:
  - Przekrój czynny $(\text{kanały}: ee, e\mu, \mu\mu, \mu\tau,\ e/\mu + \text{jets},\ \text{all hadronic})$ **≤ 1.1 fb⁻¹**
  - Masa $(\sigma_{t\bar{t}},\ \text{kanały}: ee, e\mu, \mu\mu,\ e/\mu + \text{jets},\ \text{all hadronic})$ **≤ 4.7 fb⁻¹**
  - Różnica mas $\Delta m_t = m_t - m_{\bar{t}}$ **≤ 1.1 fb⁻¹**
  - Testy pQCD $(\text{rozkłady}: N_{jets},\ p_T(t\bar{t}),\ M_{t\bar{t}},\ p_T(t),\ \eta(t),\ p_T(\ell),\ \eta(\ell),\ M_{\ell\ell})$
  - Ładunek elektryczny (wykluczenie modeli z $|Q|=4/3e$)
  - Asymetria ładunkowa (całkowita, różniczkowa)
  - Korelacje spinowe
  - Stosunek rozgałęzień $BR(t \to Wb)/BR(t \to Wq)$ **≤ 2.2 fb⁻¹**
  - Rzadkie rozpady z FCNC: $t \to qZ$
  - Polaryzacja bozonu *W* **≤ 2.2 fb⁻¹**
- Produkcja pojedyncza kwarku t:
  - Przekrój czynny (obserwacja: kanał t, kanał "tW", limit: kanał s) **≤ 2.1 fb⁻¹**
  - Rzadka produkcja z FCNC: $qg \to t$
- Poszukiwania 4. generacji kwarków $(\text{limity}: m_{t'},\ m_{b'},\ m_T,\ m_B)$

Przekrój czynny na $t\bar{t}$

P. Silva Moriond EWK 2012

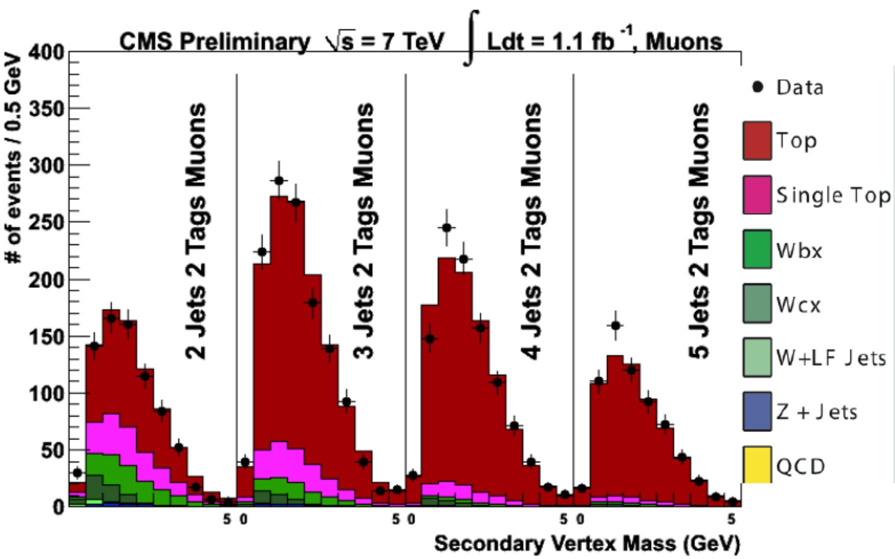
- Main backgrounds:
  - **QCD multijets** (rejected with m_T/MET, can be controlled from sidebands)
  - **W+jets** (in particular Heavy Flavor)

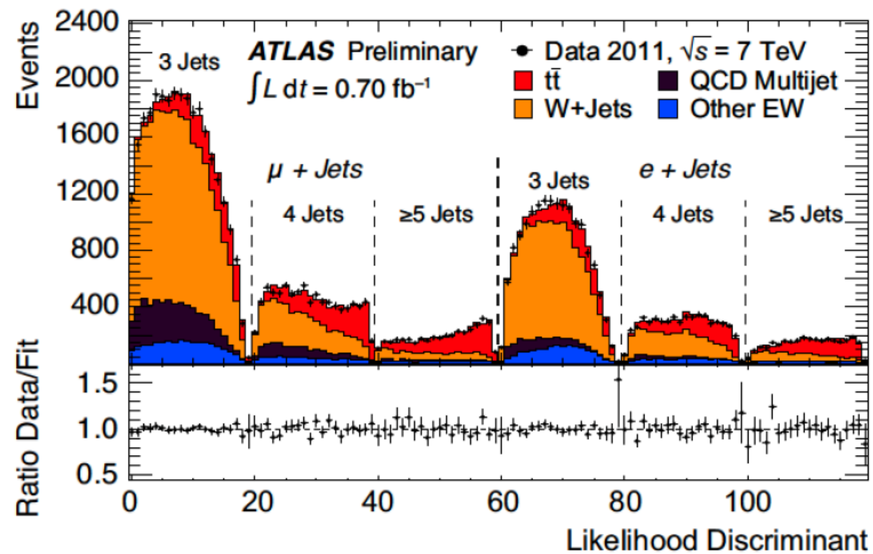
e/μ + jets

- **Use kinematics to discriminate top**

b-driven: mass of secondary vertex

topology driven: η_l, jet momentum tensor/H_T





- **Categorize events and extract σ_{tt} from fit**
  - W+HF normalization included in fit
  - Systematics treated as nuisance parameters (e.g. ISR/FSR, Q^2, b-tag efficiency)

Results

ATLAS

$$179.0 \pm 3.9(\text{stat}) \pm 9.0(\text{syst}) \pm 6.6(\text{lumi})$$

CMS

$$164.4 \pm 2.8(\text{stat}) \pm 11.9(\text{syst}) \pm 7.4(\text{lumi})$$

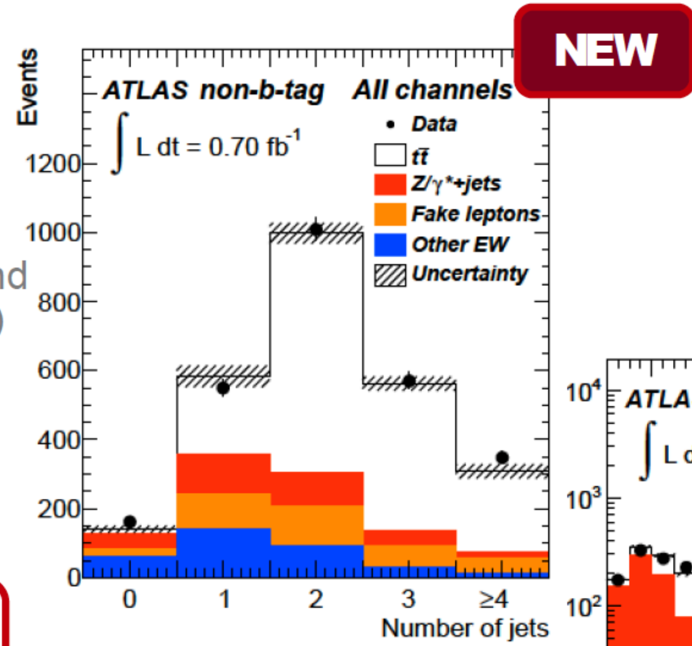
dileptons

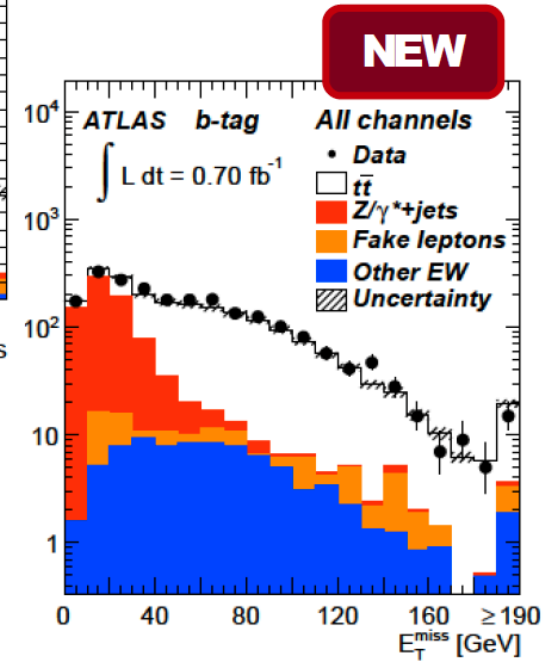
Przekrój czynny na $t\bar{t}$

- **Cleanest signature**
- Main **backgrounds**:
  - **Drell-Yan** (Z-window is vetoed in ee/μμ and used to rescale DY contribution from data)
  - **Single top tW** and **dibosons** (from MC)
  - Residual **fake leptons** (controlled from sidebands using fake rate/efficiency)

"Signal is visible" even without requiring E_T^{miss} or b-tags

- **Main systematics**: jet energy scale, pileup (through E_T^{miss}), signal modeling, tW contribution
- Cross section measured from profile likelihood fit or from cut and count technique ▶



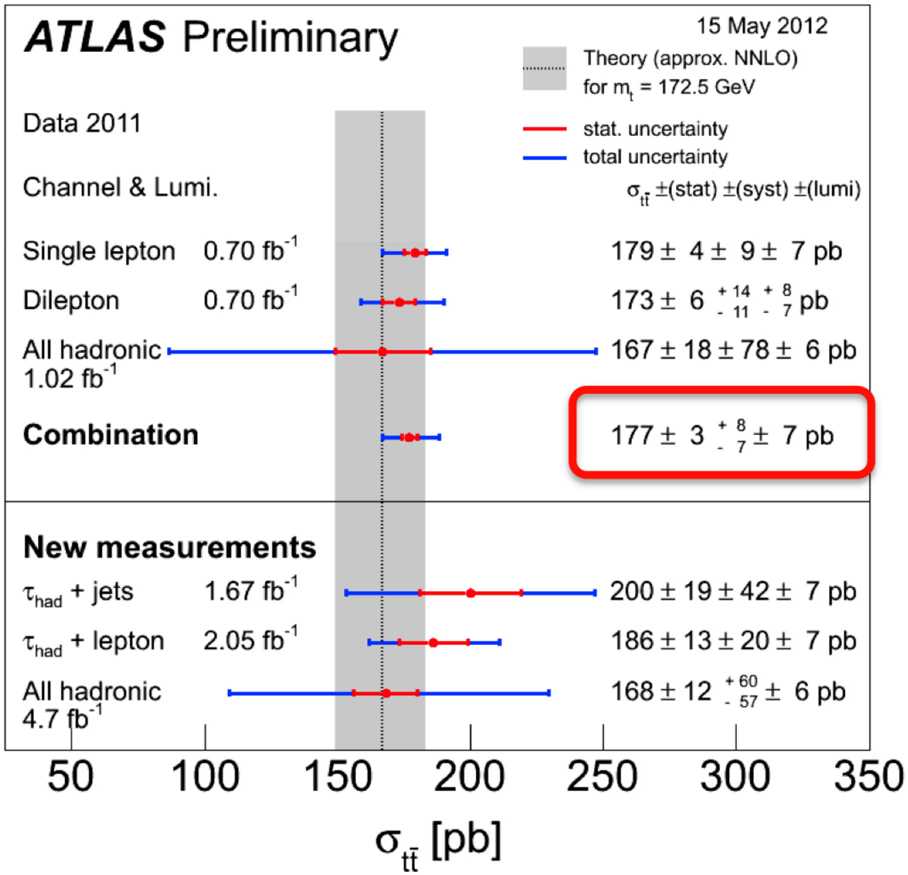


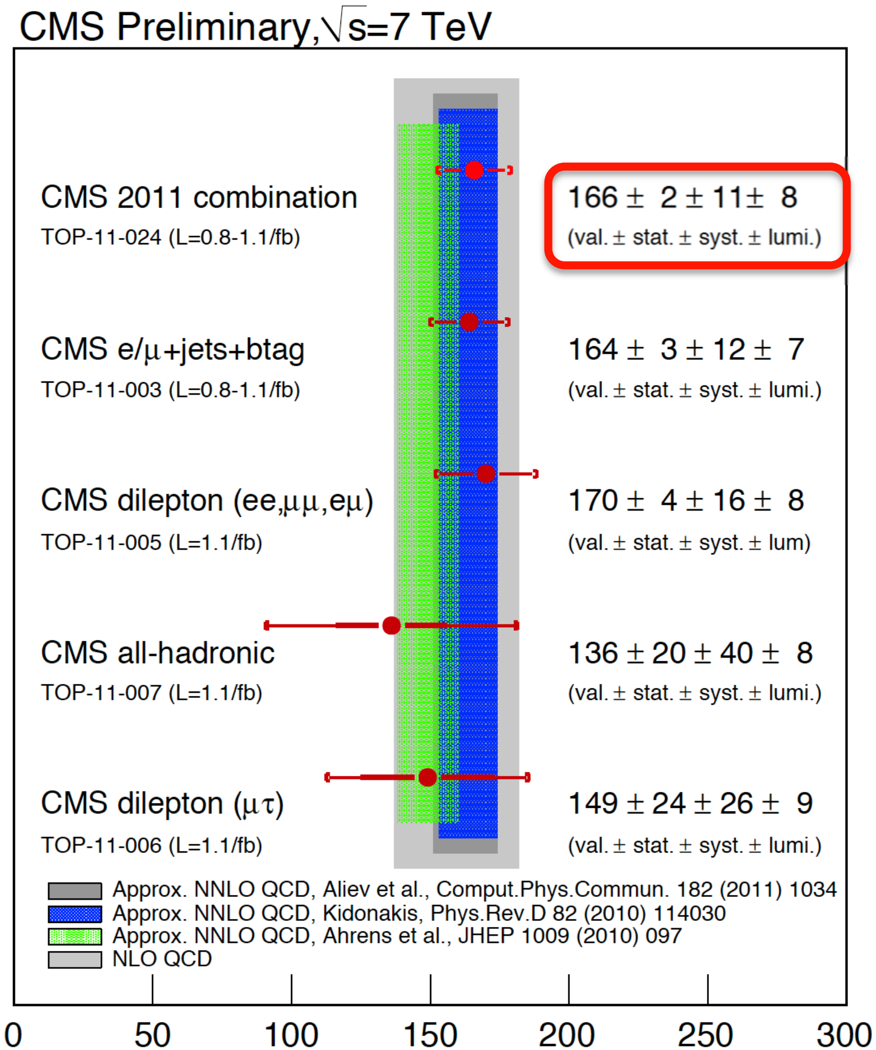
Results

ATLAS	$176 \pm 5(\mathrm{stat})^{+14}_{-11}(\mathrm{syst}) \pm 8(\mathrm{lumi})$
CMS	$169.9 \pm 3.9(\mathrm{stat}) \pm 16.3(\mathrm{syst}) \pm 7.6(\mathrm{lumi})$

P. Silva Moriond EWK 2012

Przekrój czynny na $t\bar{t}$





ATLAS CONF-2012-024 (+update)   CMS PAS-TOP-11-024

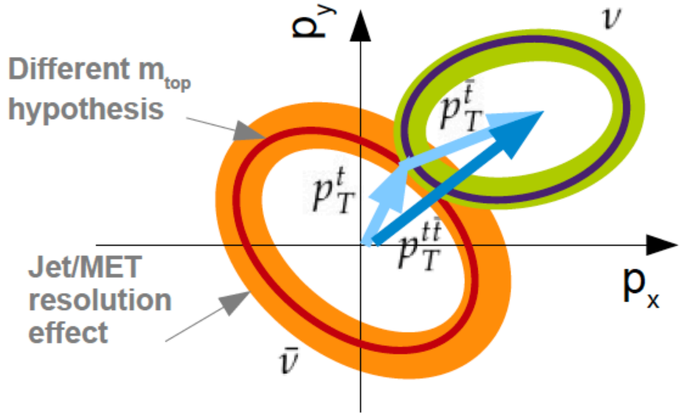
Theor. uncertainty: 8% (approx. NNLO)

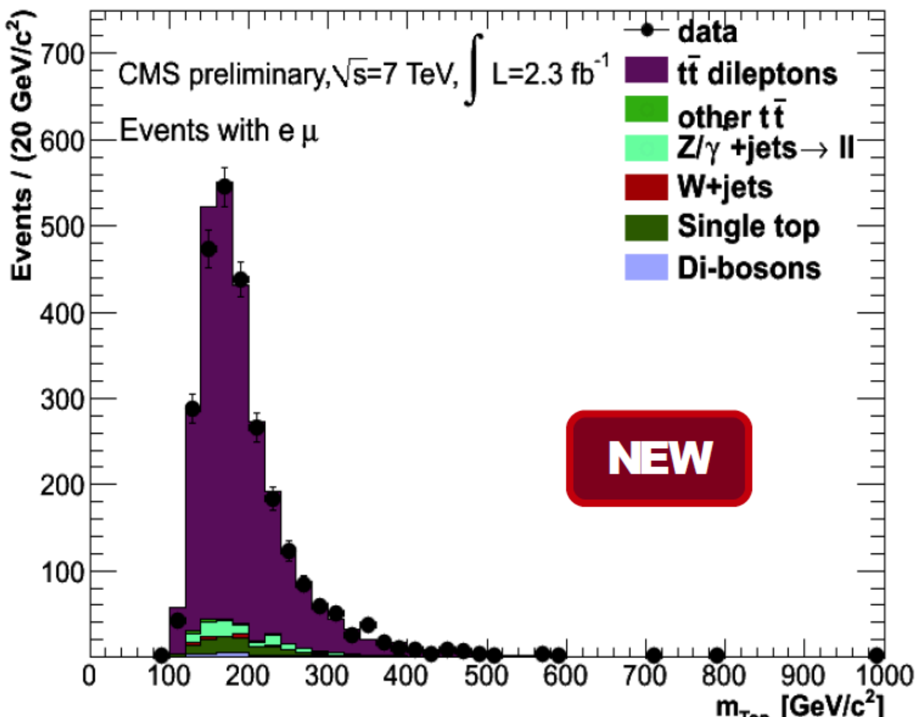
Exp. uncertainty: 6% (ATLAS), 8% (CMS)

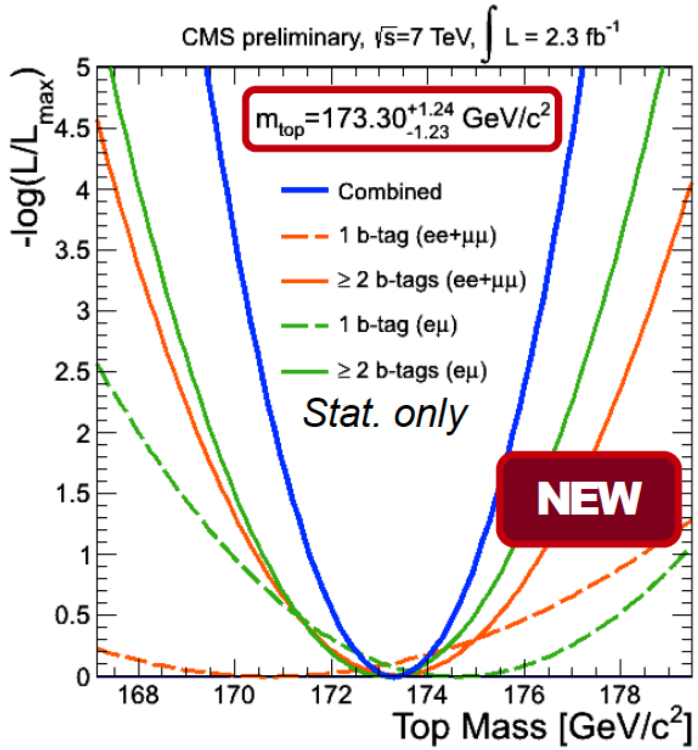
Main systematics: MC signal & ISR / FSR QCD modelling, JES, lepton ID & b-tagging efficiencies dileptons

Masa m_t

- One degree of freedom in the kinematics
  - Up to 8 possible solutions per event ▶
- **KINb method**: eq. solved numerically several times
  - most probable combination is picked up
- **Measure:** 173.3 ± 2.8 (stat ⊕ syst) GeV
  - dominated by JES uncertainty
  - **most precise up-to-date in the dilepton channel**







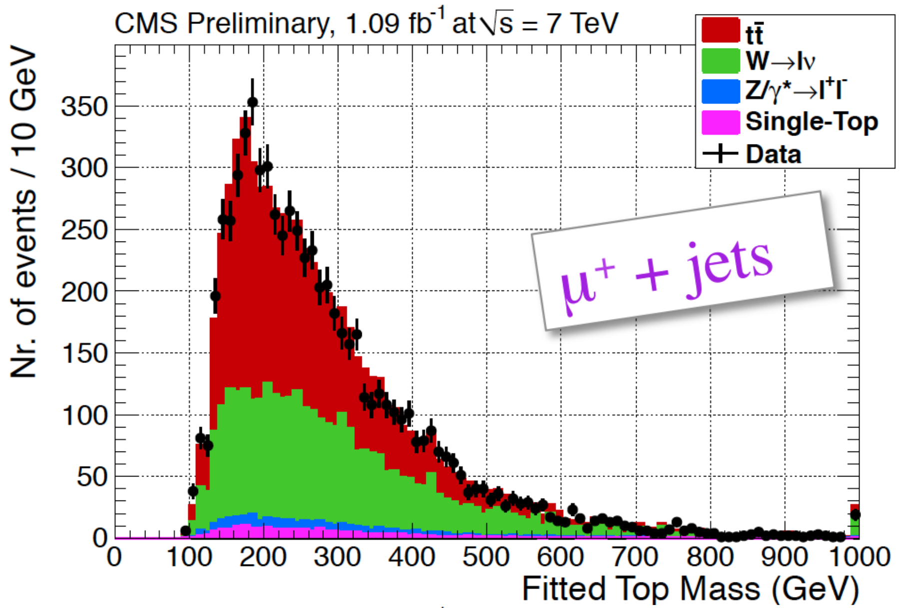
Różnica $\Delta m_t = m_t - m_{\bar{t}}$

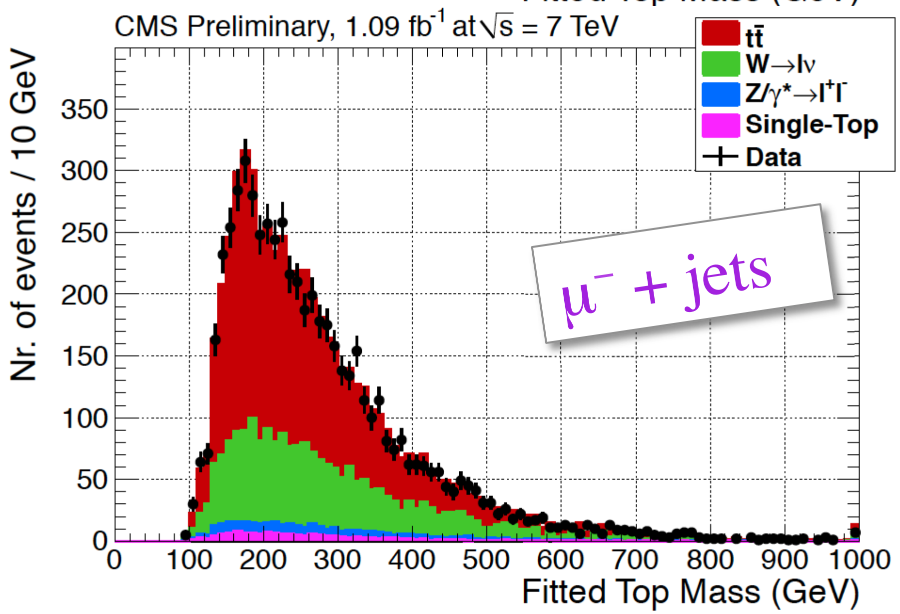
- **Test CPT invariance in the top quark sector: $m_{top}=m_{anti\text{-}top}$?**
- Compare μ^++jets vs μ^-+jets samples
- Mass reconstructed from hadronic side
  - Use kinematic fit (including resolutions)
  - Choose combination with lowest χ^2
- Final measurement from ideogram method (combine event-per-event likelihood for μ^- and μ^+ separately)
- **Most systematic effects cancel out**
- Measurement is stat. limited
- **World's best so far!**

Results

$$\Delta m_t = -1.2 \pm 1.2\,(\text{stat.}) \pm 0.5\,(\text{syst.})\ \text{GeV}$$

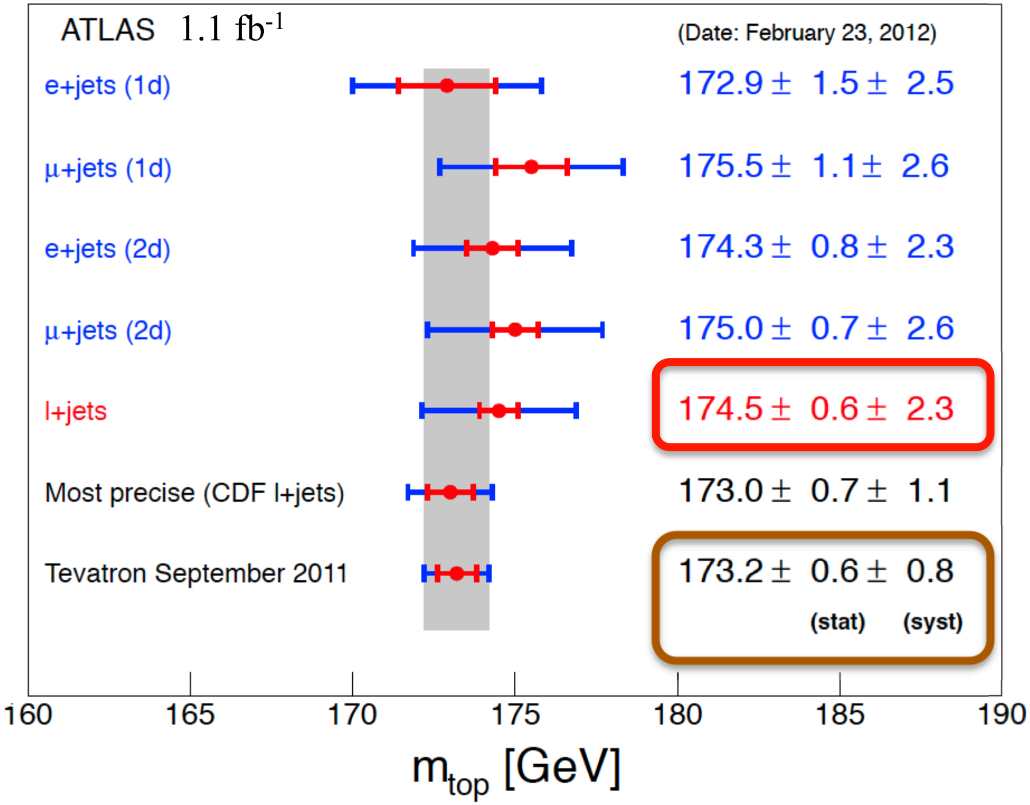
- Result is consistent with the SM

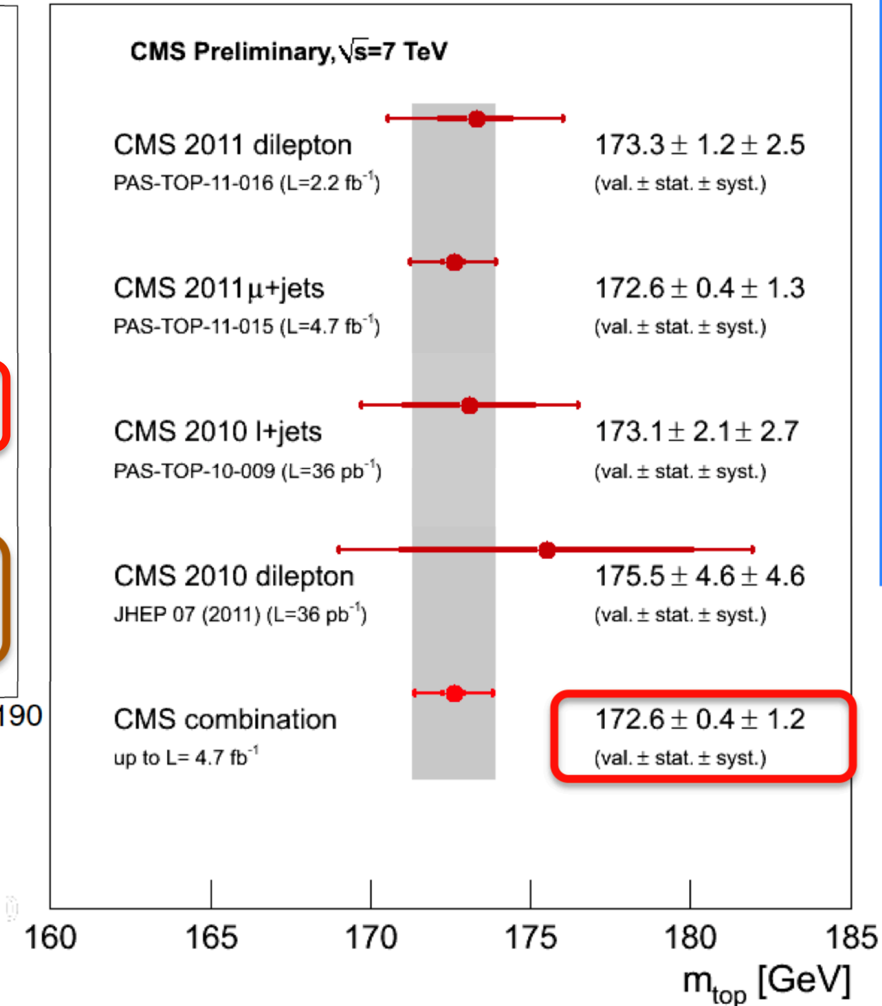




Masa m_t

CERN-PH-EP-2012-003 CMS PAS-TOP-11-018





LHC is catching up with Tevatron

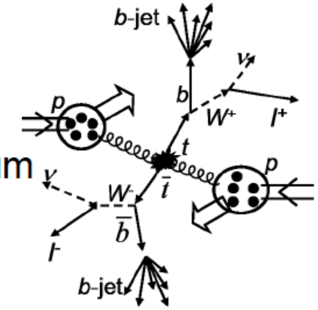
→ e.g. world's best: dilepton m_t , Δm_t

In progress: ATLAS internal and ATLAS+CMS combinations

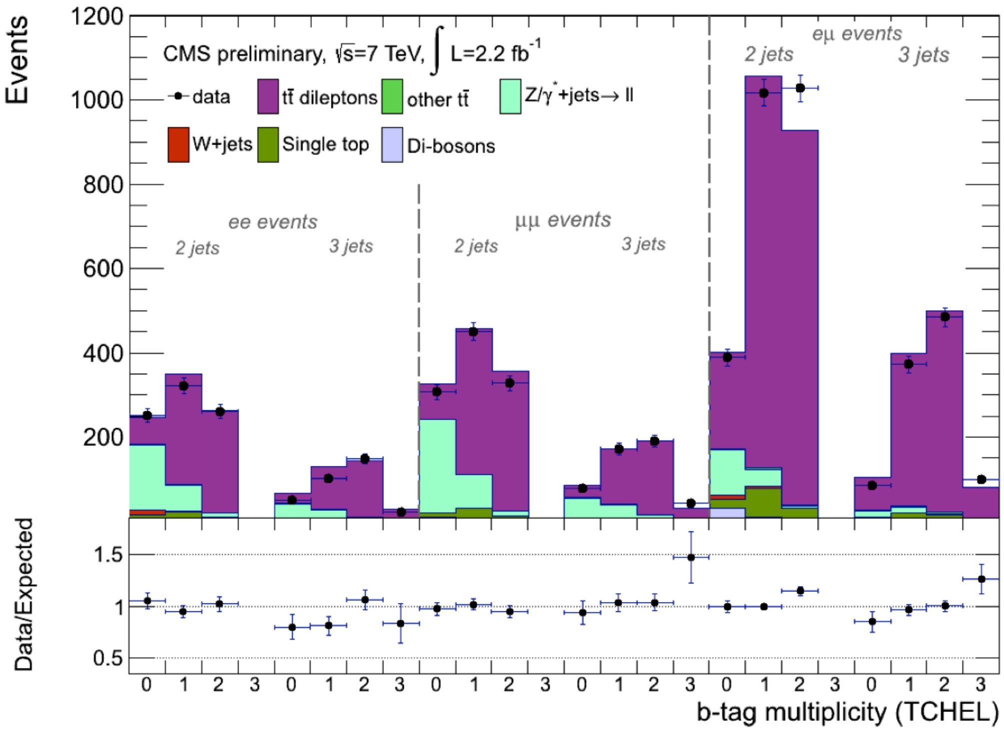
Main systematics: JES (jets, b-jets), ISR / FSR QCD modelling

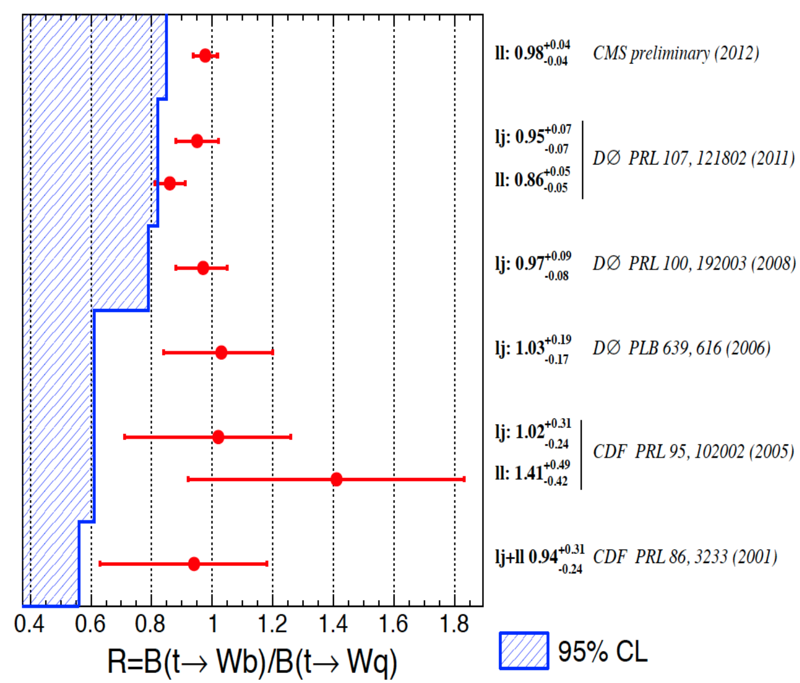
dileptons $BR(t \to Wb)/BR(t \to Wq)$

- Some tension between SM and D0 measurement: $R_{\mathrm{dileptons}} = 0.86 \pm 0.05 \;(\mathrm{stat} \oplus \mathrm{syst})$
  cf. PRL107:121802,2011
- **Measurement is fully data-driven**
  - b-tagging multiplicity is parametrized as function of R, ε_b, ε_q, top contributions
  - number of reconstructed $t \to Wq$ is estimated from lepton-jet invariant mass spectrum

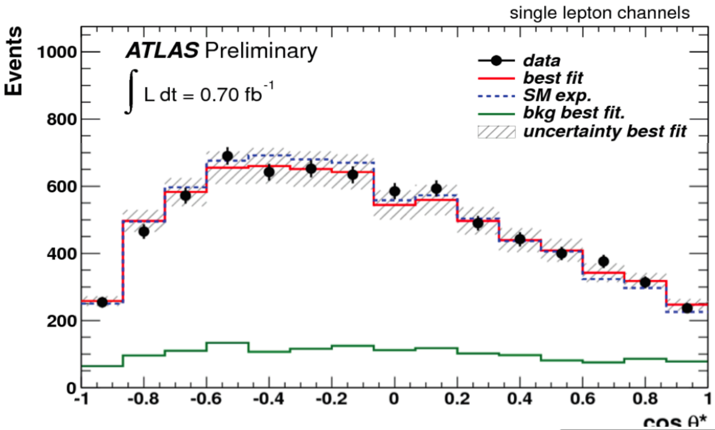


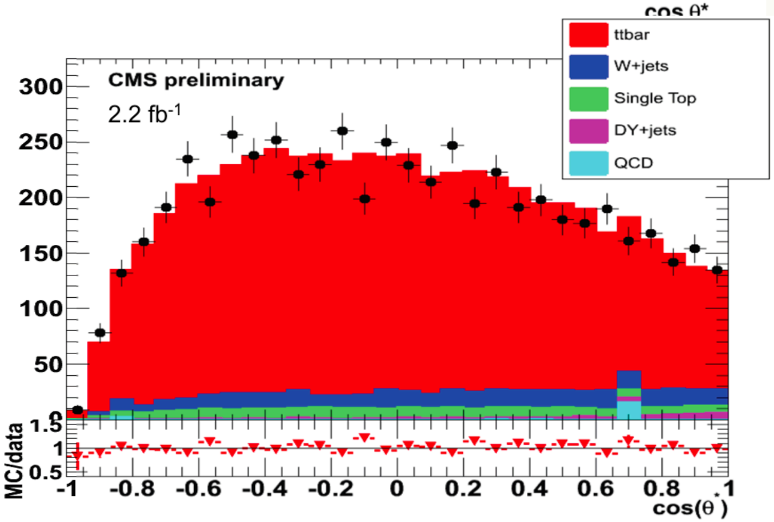
- $R = 0.98 \pm 0.04 \;(\mathrm{stat} \oplus \mathrm{syst})$
  - lower endpoint of the confidence interval @ 95% CL after requiring R<1 is **R>0.85**





Polaryzacja bozonu *W*



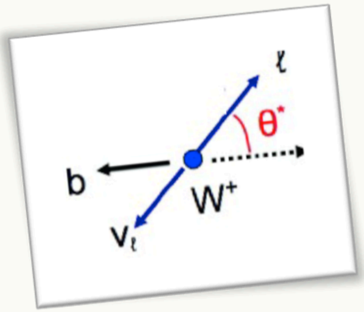


e/μ+jets, dileptons

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}(1-\cos^2\theta^*) F_0$$

How

- θ*: Angle between $\vec{p}$(lep) in W rest-frame and $\vec{p}$(W) in top rest-frame
- Kinematic fit to event
- Remove background
- Unfold to particle-level

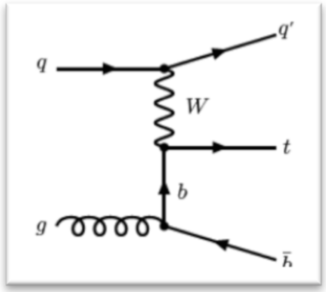


Polarisation	Predicted NNLO	Measured ATLAS	Measured CMS
F_R	0.0017 ± 0.0001	$0.09 \pm 0.04(\text{stat}) \pm 0.09(\text{syst})$	$0.040 \pm 0.035(\text{stat}) \pm 0.044(\text{syst})$
F_L	0.311 ± 0.005	$0.35 \pm 0.04(\text{stat}) \pm 0.04(\text{syst})$	$0.393 \pm 0.045(\text{stat}) \pm 0.029(\text{syst})$
F_0	0.687 ± 0.005	$0.57 \pm 0.07(\text{stat}) \pm 0.09(\text{syst})$	$0.567 \pm 0.074(\text{stat}) \pm 0.047(\text{syst})$

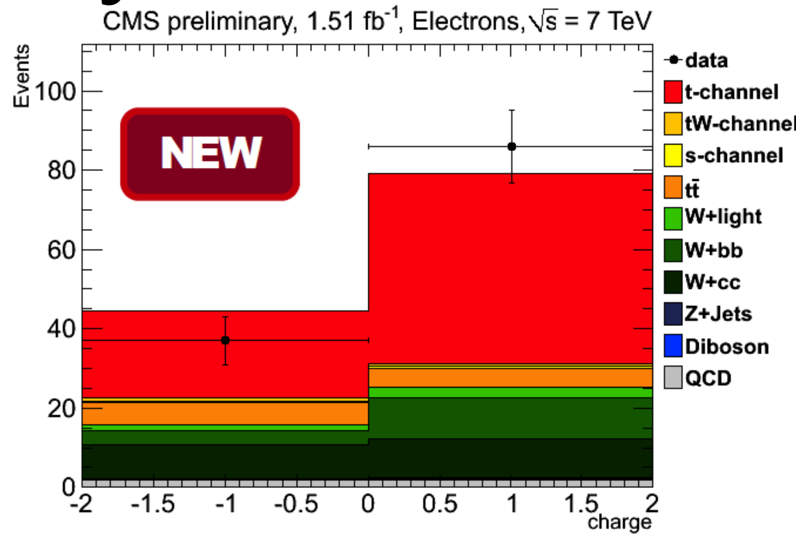
t-channel

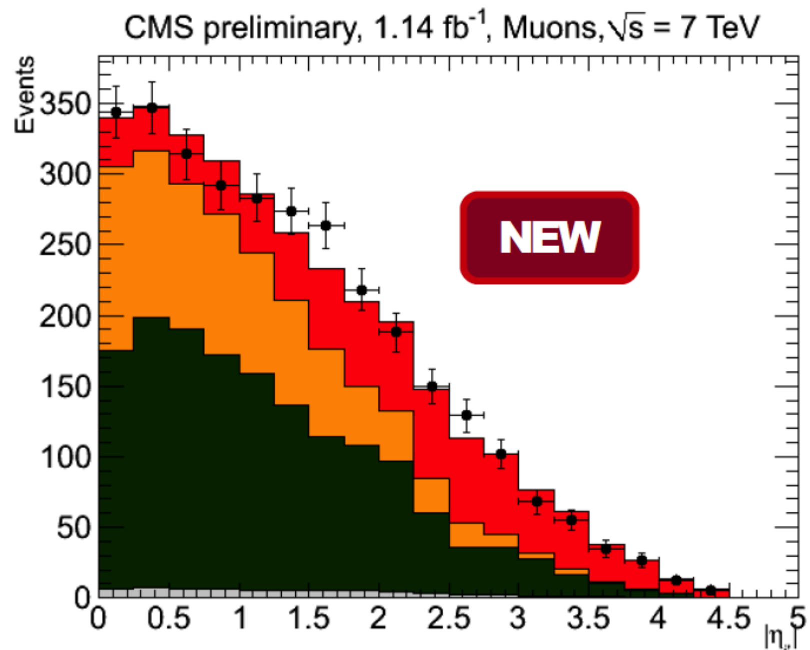
Pojedynczy *t*

- **Dominant production channel**
  - **1 central, isolated lepton** + E_t^{miss}
    expect **N(l⁺) ≈ 1.9 N(l⁻)**
  - 1 b jet + **1 forward recoil jet**



- Main backgrounds:
  - **Multijets**: fit to E_T^{miss}, or m_T spectrum with template from lepton selection side-band
  - **W+jets** (heavy flavor): fit from the discriminator output or re-scaled from selection sideband (e.g. failing $m_{l\nu b}$ requirement)
- Measurement stems from 2 cross-checks:
  - **fit to angular variables as** $\eta_{j'}$ – robust approach ▶
  - multivariate analysis exploiting fully signal topology and maximizing significance (for CMS: not yet updated with 2011 data cf. CMS-PAS-TOP-10-008)

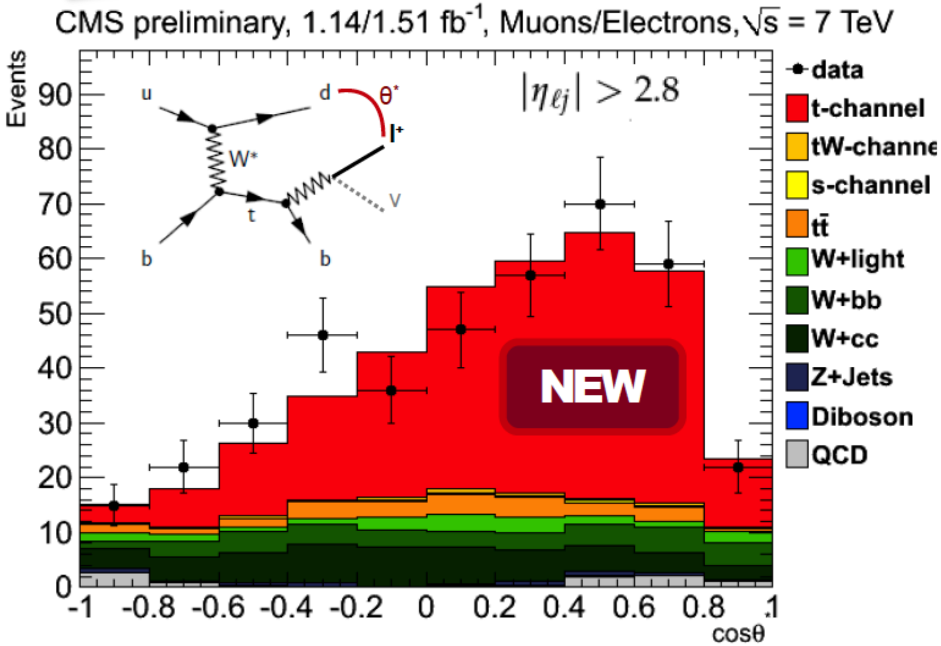


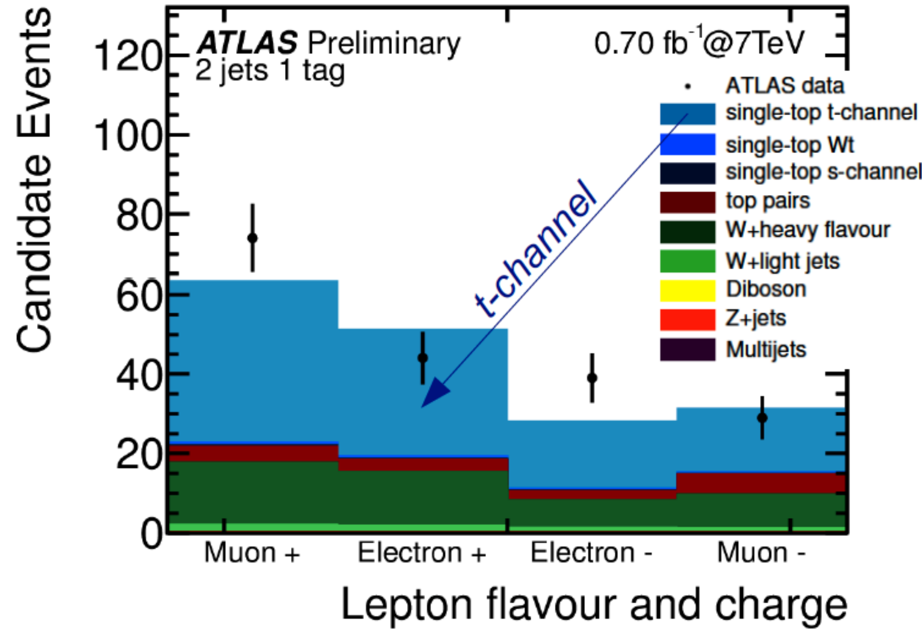


P. Silva Moriond EWK 2012

t-channel

Pojedynczy *t*





Results

CMS

$$70.2 \pm 5.2(\text{stat}) \pm 10.4(\text{syst}) \pm 3.4(\text{lumi})\ \text{pb}$$

ATLAS

$$90 \pm 9(\text{stat})^{+31}_{-20}(\text{syst})\ \text{pb}$$

- **Leaving discovery phase: precision measurements just around the corner!**
  - Using expected th. cross section CMS obtains: $|V_{tb}| = 1.04 \pm 0.09(\text{exp}) \pm 0.02(\text{th})$
  - More to come: polarization, differential measurements

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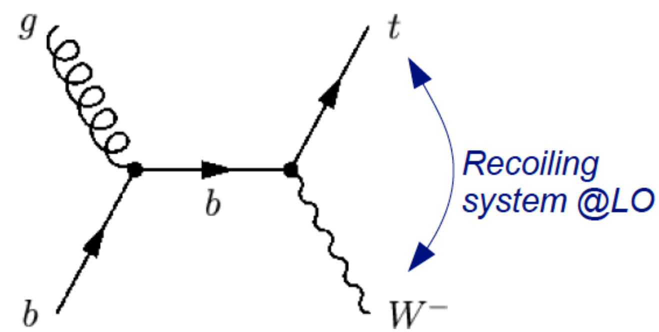
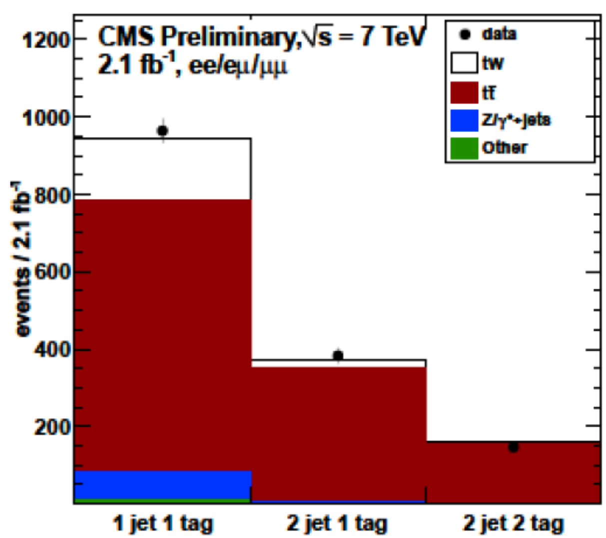
tW-channel

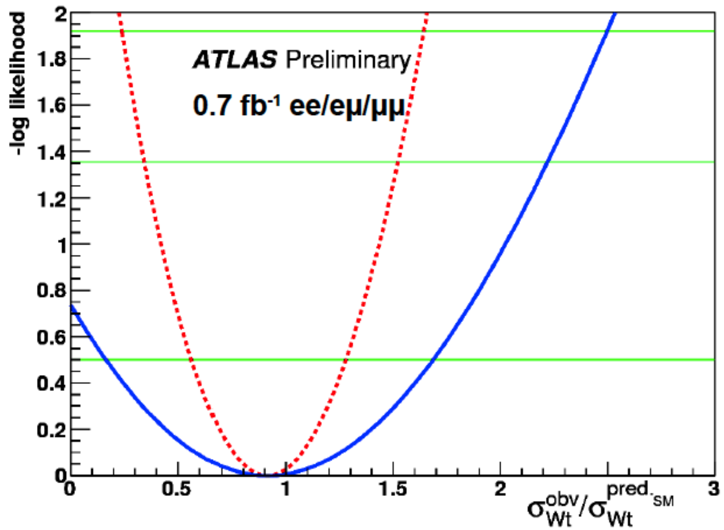
Pojedynczy *t*

- **Final state: 2 leptons+1 b-jet+E_T^{miss}** (at LO similar to tt dileptons with only 1 b-jet)
- Signal discrimination
  - 2nd b-jet veto is applied for signal region
  - **Balance:** $|\sum_{leptons} \vec{p}_T + \vec{p}_T^{\,b-jet} + \vec{E}_T^{miss}| < 60\ GeV$
  - Categorize events to constrain tt and ε_b



- Use **max. likelihood fit for σ(tW):**





Results

CMS

$22^{+9}_{-7}(\mathrm{stat} \oplus \mathrm{syst})\ \mathrm{pb}$

(significance=2.7σ)

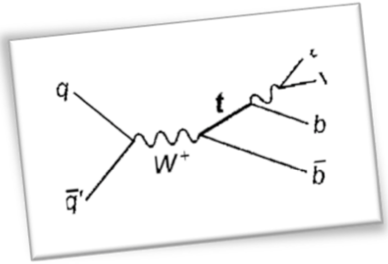
ATLAS

$14.4^{+5.3}_{-5.1}(\mathrm{stat})^{+9.7}_{-9.4}(\mathrm{syst})\ \mathrm{pb}$

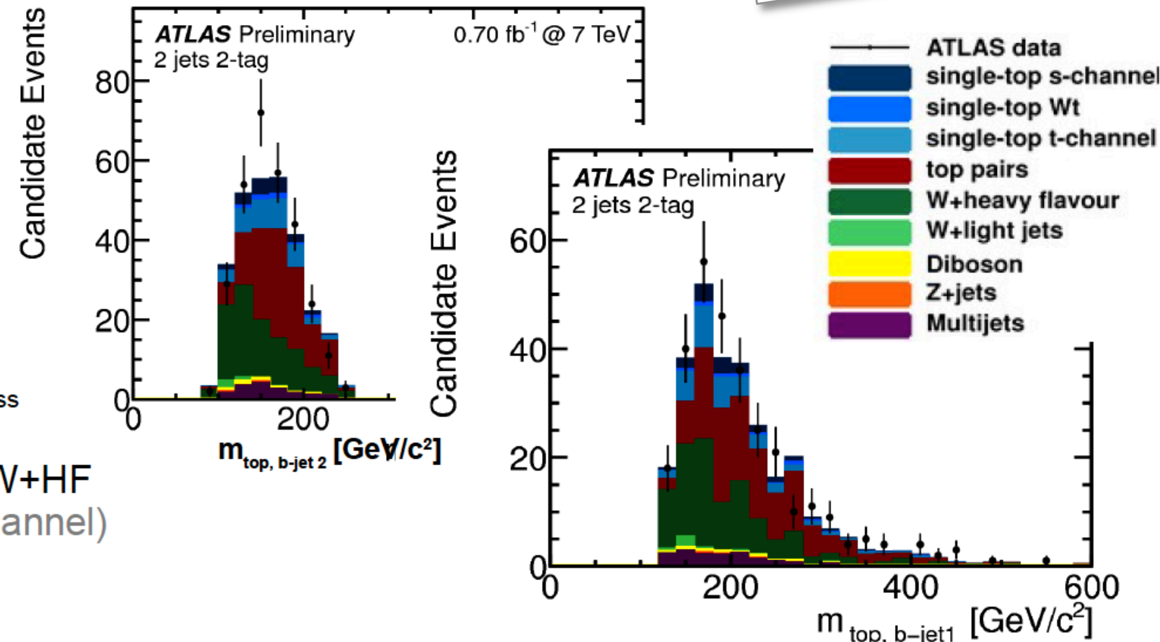
(significance=1.2σ)

Pojedynczy *t*

s-channel



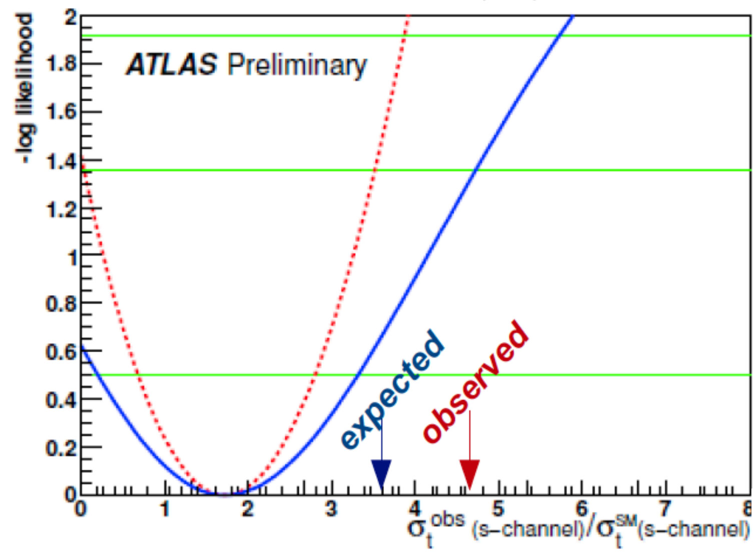
- **Lowest cross section, may reveal new physics:**
  - W' , massive $H^\pm \rightarrow t + b$
- Signature: 1 lepton+2 b-jets+E_T^{miss}
  - Contaminated by QCD multijets, W+HF and top pair events (similar to t-channel)
- **Categorize according to b-tag multiplicity and analyze kinematics**
  - Jet kinematics, invariant mass of objects, etc.
  - Apply sequential cuts maximizing $S/B^{1/2}$
  - Exp. S/B=16/296 → interpret statistically



Results

ATLAS

< 26.5 pb (20.5 pb exp.) @ 95%CL



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Podsumowanie

- Obfita produkcja bozonów W i Z w LHC:
  - Precyzyjne pomiary różniczkowych przekrojów czynnych (czułe na gęstości partonów, np. kwarku s)
  - Studiowanie produkcji z dużym p_T(W/Z) lub z wieloma dżetami
  - Przekroje czynne na produkcję dwubozonową wyszły z „fazy obserwacji"
  - Precyzja pomiaru $\sigma(\mathbf{t\bar{t}})$ porównywalna z niepewnościami NLO
  - Generalna zgodność obserwacji z dostępnymi przewidywaniami NLO oraz NNLO
- Pomiary parametrów MS:
  - Kąt mieszania Weinberga (1%)
  - Pomiary m_t zaczynają być konkurencyjne w stosunku do Tevatron-u (np. dilepton m_t, Δm_t)
  - Wykluczenia anomalnych sprzężeń trójbozonowych dorównują tym z LEP-u i Tevatron-u
- Plany na 2012:
  - Na konferencjach letnich powinny pojawić się uaktualnione analizy z pełną statystyką zebraną w roku 2011 (ATLAS, CMS: 5 fb^{-1}, LHCb: 1 fb^{-1})
  - Kombinacja wyników z LHC
  - Konieczność dostosowania analiz do zwiększonej świetlności przy 8 TeV
  - Dodatkowe kanały poszukiwań fizyki poza MS (np. FCNC w single-top)

BACKUP

Dostępne wyniki

- **ATLAS**:

  https://twiki.cern.ch/twiki/bin/view/AtlasPublic

- **CMS:**

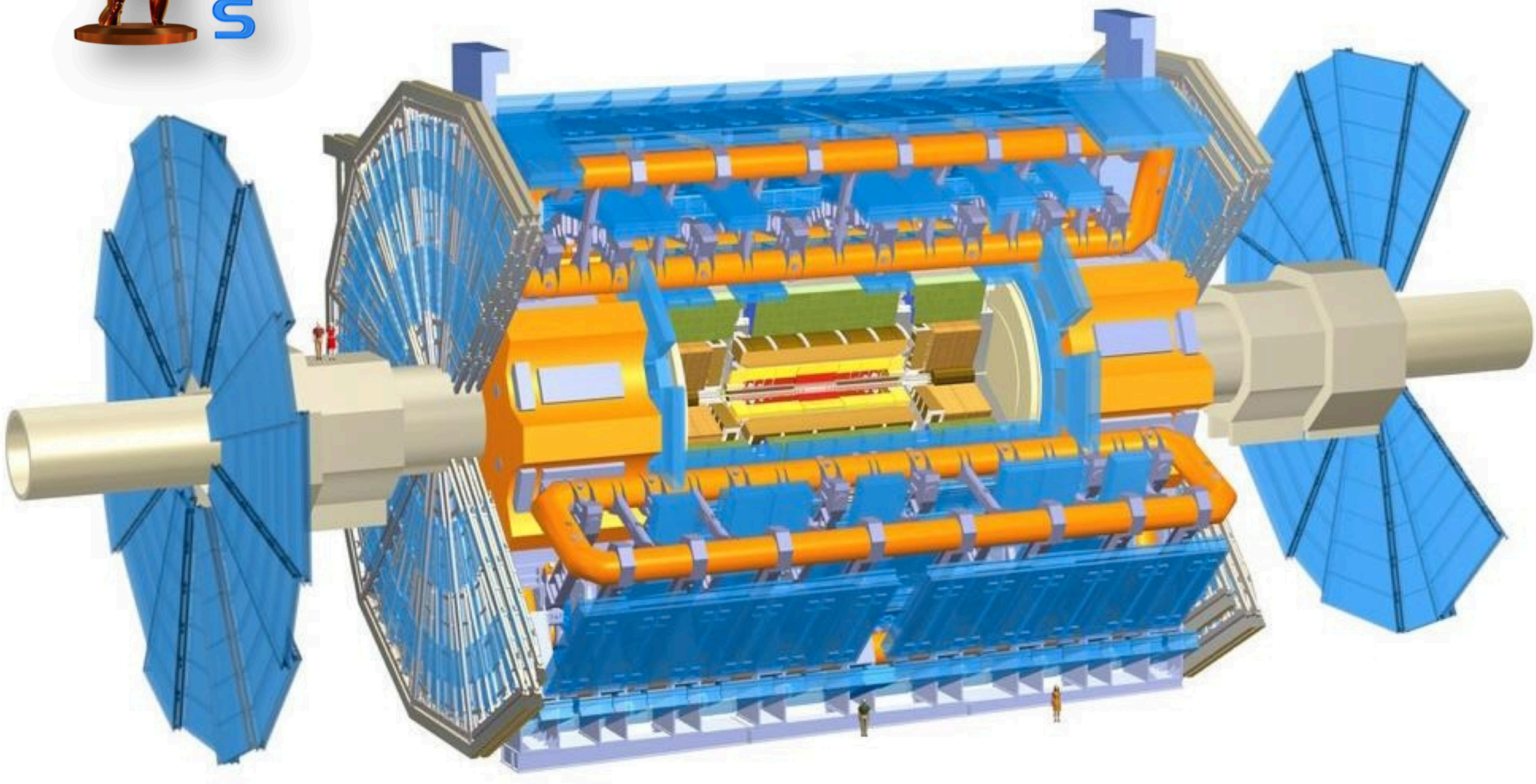
  http://cms.web.cern.ch/org/cms-papers-and-results

- **LHCb:**

  http://lhcb.web.cern.ch/lhcb/lhcb_page/physics_results/recent_lhcb_results/Default.html

Detektor ATLAS

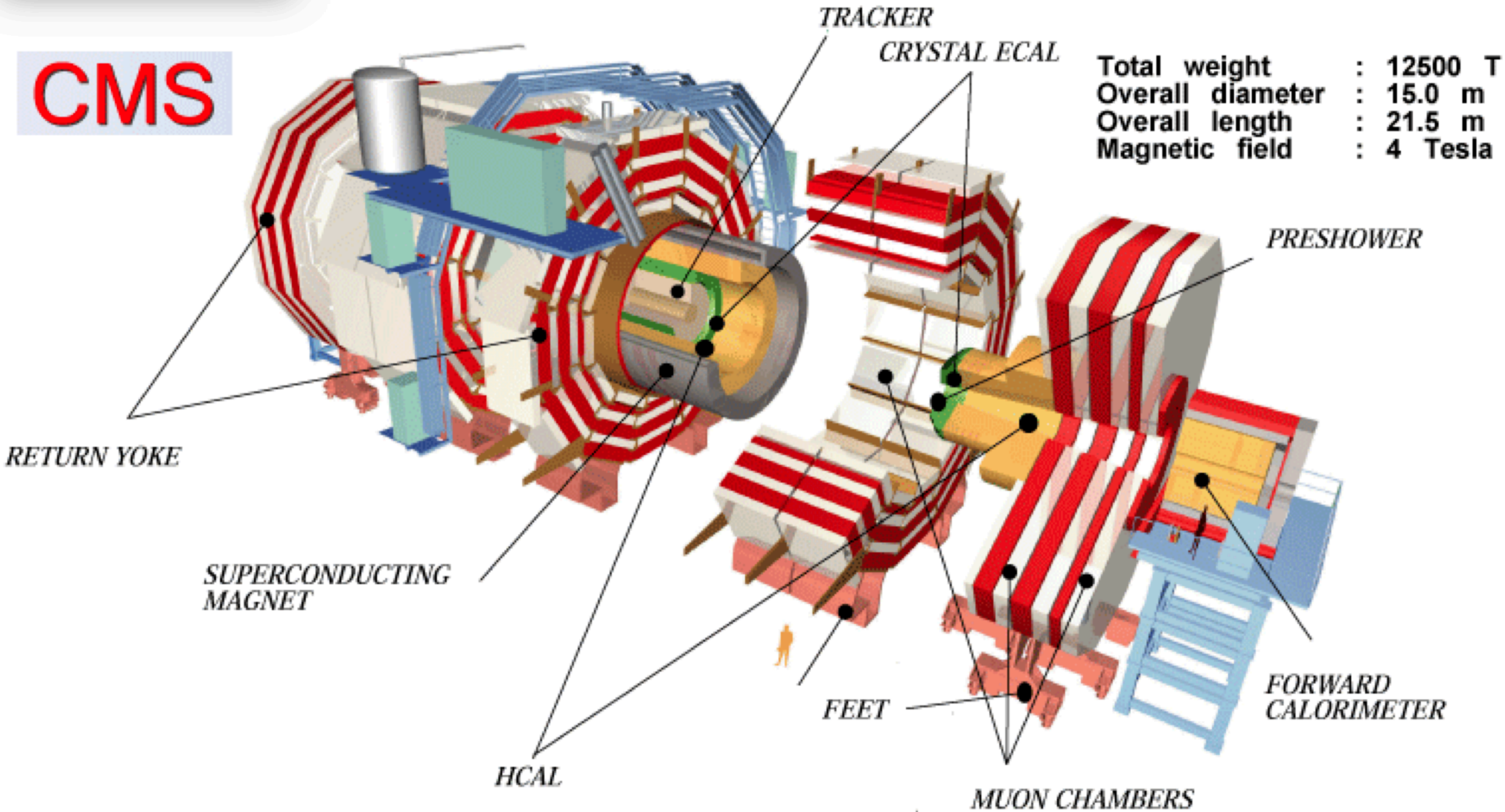
A T**oroidal **L**HC **A**pparatu**S



Detektor CMS

***C**ompact **M**uon **S**olenoid*

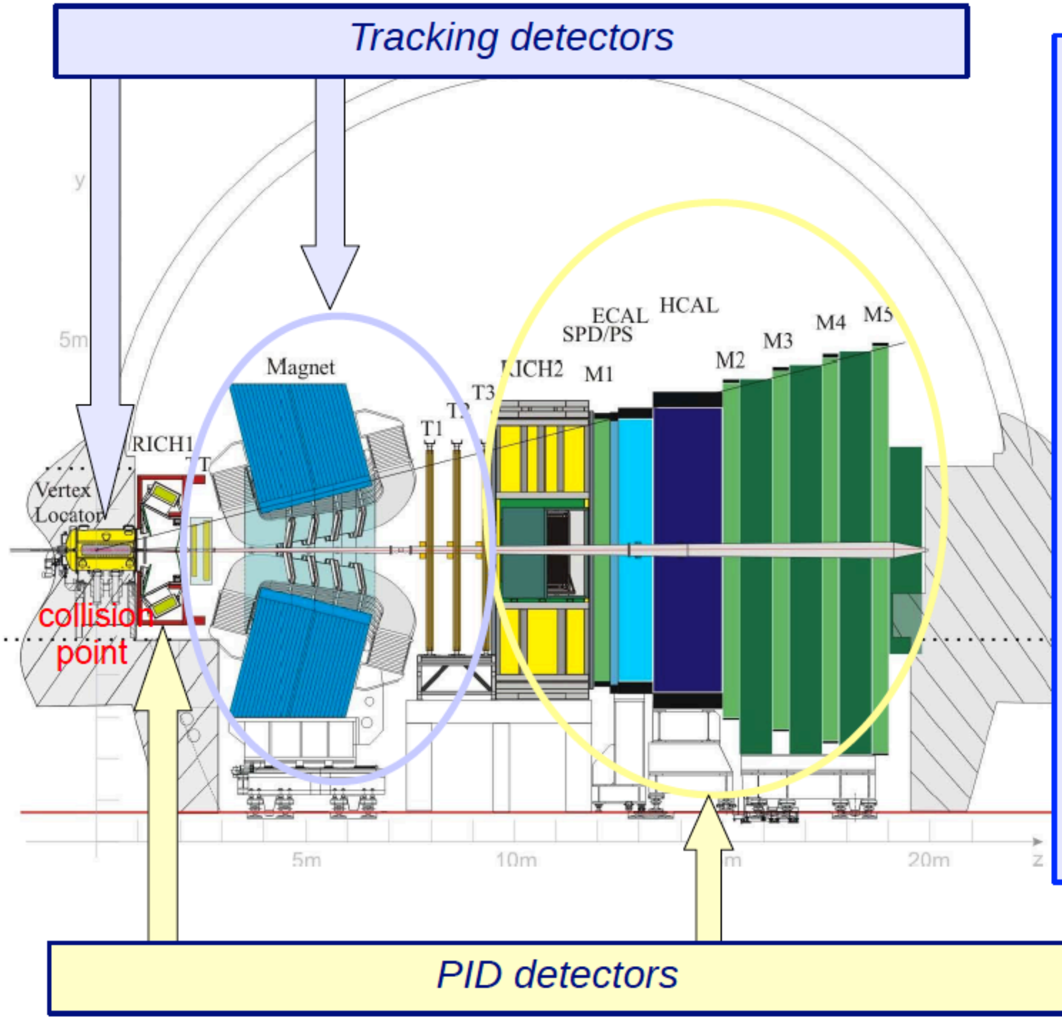
CMS



Detektor LHCb

Large Hadron Collider beauty

=> *LHCb spectrometer: combination of tracking and PID detectors covering full acceptance*



- *Forward spectrometer with planar detectors: optimized for the forward peaked heavy quark production at the LHC*
- *covers about 4% of the solid angle, but captures around 40% of the heavy quark production cross-section*
- *Detector acceptance: $1.9<\eta<4.9$ fully covered by the tracking system → unique at the LHC*
- *Size: 10m high, 13m wide, 21m long*
- *Weight: ~5600 tons*
- *Number of r/o channels: ~10^6*
- *Designed to run at a moderate luminosity: large pile-up complicates identification of the B decay vertex and flavor tagging*

Selekcja ***W*** i ***Z*** (ATLAS)

A.Lewis LHC EWWG – May 2012

- single lepton trigger
- $p_T^\ell > 20 GeV$
- μ channel: $|\eta^\mu| < 2.4$
- "central" e channel $|\eta^e| < 2.47$ (excluding calo. crack: $1.37 < |\eta^e| < 1.52$)

$W \to \ell\nu$

- single isolated lepton
- $E_T^{Miss} > 25 GeV$
- $m_T > 40 GeV$

$Z \to \ell\ell$

- 2 isolated leptons
- opposite charge
- $66 < m_{\ell\ell} < 116 GeV$

- For combination of e and μ channels extrapolate to common fiducial region: $|\eta_\ell| < 2.5$
- Complementary "Forward" $Z \to ee$ measurement:
  - One well identified electron in central region
  - One forward electron in range $2.5 \leq |\eta_e| \leq 4.9$

Pomiar $\sigma_{W/Z}$ (ATLAS)

$$\sigma_{fid} = \frac{N - B}{C_{W/Z}\mathcal{L}} \qquad \sigma_{tot} = \frac{\sigma_{fid}}{A_{W/Z}}$$

- Fiducial cross section, σ_{fid}, is corrected for efficiencies
- Efficiency factor $C_{W/Z} = \frac{N_{MC,rec}}{N_{MC,gen,cut}}$
  - corrected for data/MC differences using "Tag and Probe" method
- $N_{MC,gen,cut}$ defined at three different levels of QED FSR corrections
  - Born: Leptons before QED FSR
  - Bare: Leptons after QED FSR
  - Dressed: Bare lepton re-summed with all FSR photons within $\Delta R < 0.1$
- QED FSR correction factors published on HepData hepdata.cedar.ac.uk/view/ins928289/d16
- Total cross section, σ_{tot}, is corrected for acceptance
- Acceptance, $A_{W/Z}$, derived from MC
- Theoretical uncertainties for $C_{W/Z}$ and $A_{W/Z}$ by comparing
  - MC@NLO
  - Powheg+Pythia and Powheg+Herwig
  - Reweighting to different PDF sets
  - PDF eigenvector propagation

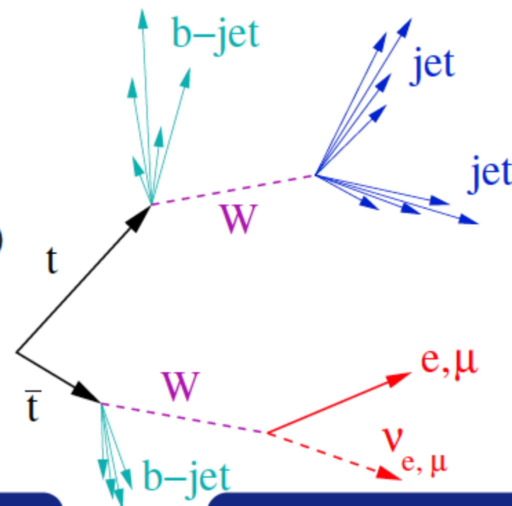
Lepton + jets ($t\bar{t} \rightarrow \ell\nu +$ jets)

One isolated lepton

- ATLAS & CMS : Single lepton trigger
- ATLAS (p_T >25/20 GeV (e/μ))
  - Calo isolation
    E_T (ΔR=0.2)<4 GeV
  - Track isolation for muons
    p_T (ΔR=0.3)<4 GeV
- CMS (p_T >45/35 GeV (e/μ))
  - I_{rel}(cone 0.3) <0.1/0.05 (e/μ)

b-tagging

- ATLAS & CMS: Analyzes with and without b-tagging
  - In this talk : untagged (ATLAS) and tagged (CMS)



Jets

anti-k_T algorithm

- ATLAS p_T >20 GeV, $|\eta| < 2.5$, R=0.4
- CMS p_T >30 GeV, $|\eta| < 2.4$, R=0.5

E_T^{miss}

- ATLAS from topological calorimeter clusters
  - > 35 GeV (25 GeV) e (μ)
  - Additional cut on $m_T(W)$ >25 GeV (e); $m_T + E_T^{miss}$ >60 GeV (μ)
- CMS using particle flow objects
  - No cut, used in likelihood

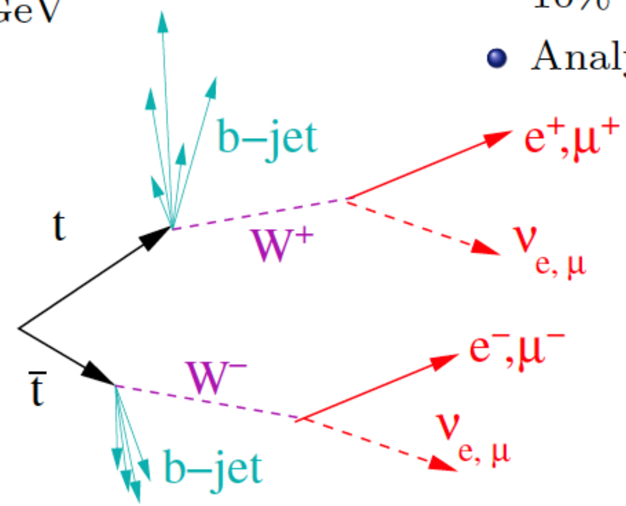
Dilepton - $t\bar{t} \to \ell^{\pm}\ell^{\mp} +$ jets

Two isolated lepton

- ATLAS & CMS use dilepton trigger
- Oppositely charged p_T >25/20 GeV (ATLAS/CMS)
- M_{ll} >15/12 GeV & $|M_{ll} - M_Z|$ >10/15 GeV (ATLAS/CMS)

≥1 b-tag

- ATLAS: Likelihood ratio of impact parameters and secondary vertex properties (70% eff., 1% mistag rate)
- CMS: $d_0/\sigma(d_0)$ based tagger (80% eff., 10% fake rate (MC))
- Analysis w/o b-tag by ATLAS



E_T^{miss} & H_T

- >60/30 GeV for ee/$\mu\mu$ (ATLAS/CMS)
  - >40 GeV for b-tag (ATLAS)
- H_T >130 GeV for eμ
  - H_T >140 GeV for b-tag (ATLAS)

Background

- Small background and branching ratio (6%)
  - Drell-Yan, W+jets

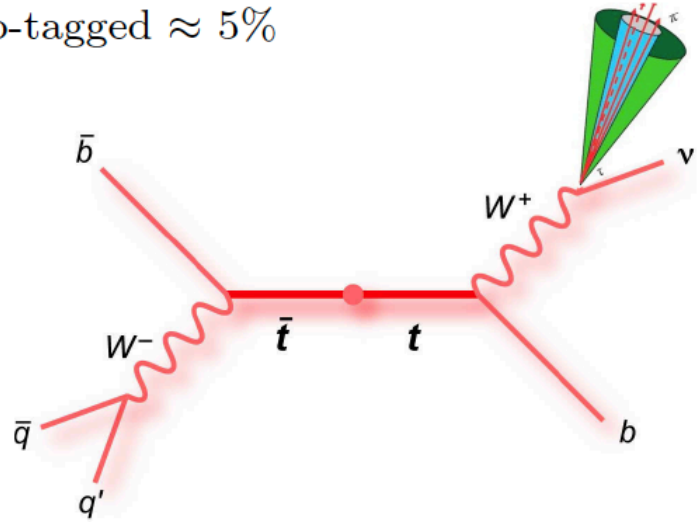
Tau + jets channel - $t\bar{t} \rightarrow \tau^{\pm}\mu^{\mp} +$ jets (ATLAS only)

≥ 2 b-tags

- 2 b-tag trigger
- Likelihood ratio of impact parameters and secondary vertex properties
- Eff. 60%, light jet rejection ≈ 340
- Probability for τ to be b-tagged $\approx 5\%$

$\tau_{\rm had}$ identification

- Select $\tau_{\rm had}$ candidate from standard jets
- 1 or 3 charged track associated with $\tau_{\rm had}$ candidate
- $p_{\rm T} > 40$ GeV, $|\eta| < 2.5$



$E_{\rm T}^{\rm miss}$ significance

- $S_{E_{\rm T}^{\rm miss}} \equiv E_{\rm T}^{\rm miss} / (0.5 \cdot \sqrt{\sum E_{\rm T}})$
- $S_{E_{\rm T}^{\rm miss}} > 0.8$

Jets

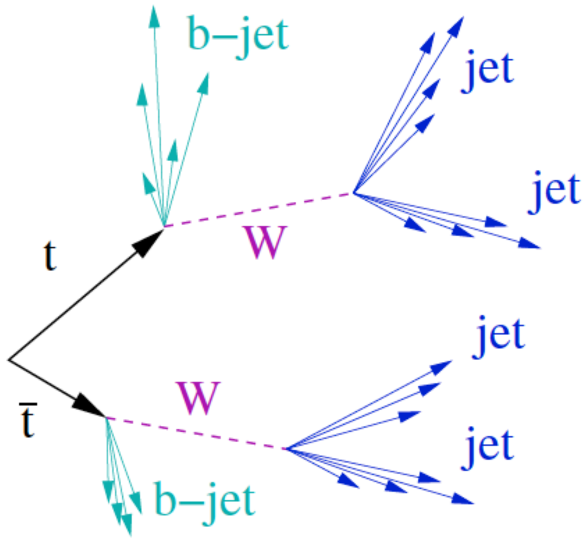
anti-$k_{\rm T}$ algorithm

- 5 jets with $p_{\rm T} > 20$ GeV, $|\eta| < 2.5$

All hadronic - $t\bar{t} \to$ all jets

Multijet trigger

- ATLAS: $\geq$ 5 jets with p_T>35 GeV
- CMS: Asymmetric 4 (p_T≥50GeV) + 5th jet (≥40 GeV) (+ 6th ≥30 GeV)



≥2 b-tags in signal region

- ATLAS: Neural network using the output weights of three taggers:
  - Secondary vertex finder (Kalman fitter)
  - Impact parameter based tagger
  - Likelihood of vertex properties
- CMS: Decay length significance $d_B > 2.0$, efficiency 38%, mis-tag 0.12%

≥6 jets

anti-k_T algorithm

- ATLAS: $\geq$ 5 jets p_T>55 GeV, $|\eta|$ <2.5, R=0.4
- CMS: ≥4 jets p_T>60 GeV + 5th jet (≥50 GeV) + 6th jet (≥40 GeV), $|\eta|$ <2.4, R=0.5

Signal extraction - Kinematic fit

- Exploit all hadronic event topology in kinematic fit
- Use mass distribution of top quark candidate for measurement

Podsumowanie $\sigma(t\bar{t})$

		Lumi. (fb)	$\sigma_{t\bar{t}}$ (pb)
Lepton + jets	ATLAS	0.70	$179.0 \pm 3.9(\text{stat.}) \pm 9.0(\text{syst.}) \pm 6.6(\text{lumi.})$
	CMS	0.80-1.09	$164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lum.})$
Dilepton	ATLAS	0.70	$183 \pm 6(\text{stat.})^{+18}_{-14}(\text{syst.})^{+8}_{-7}(\text{lumi.})$
	CMS	1.14	$169.9 \pm 3.9(\text{stat.}) \pm 16.3(\text{syst.}) \pm 7.6(\text{lumi.})$
Tau $+\mu$	ATLAS	1.08	142 ± 21 (stat.) $\pm^{20}_{16}$ (syst.) ± 5 (lumi.)
	CMS	1.09	148.7 ± 23.6 (stat.) $\pm$ 26.0 (syst.) ± 8.9 (lumi.)
Tau + jets	ATLAS	1.67	$200 \pm 19(\text{stat.}) \pm 43(\text{syst.})$
All hadronic	ATLAS	4.70	$168 \pm 12(\text{stat.})^{+54}_{-51}(\text{syst.}) \pm 7(\text{lum.})$
	CMS	1.09	$168 \pm 20(\text{stat.}) \pm 40(\text{syst.}) \pm 8(\text{lum.})$

- $\mathcal{O}(20)$ measurements by ATLAS + CMS in $\gtrsim 1$ year!
- Precision limited by systematics
  - World's most precise $t\bar{t}$ cross section measurement in lepton + jets channel
- Reached precision below theoretical uncertainties
- All results are consistent with the SM expectations

I .Aracena Moriond QCD 2012

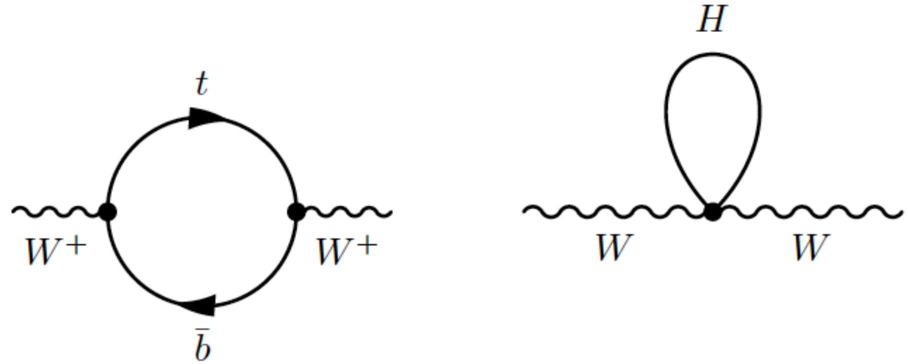
Masa bozonu *W*

The W boson mass is not an input parameter, but can be calculated

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

Loop Corrections

$$\Delta r(M_Z, M_H, m_t, \alpha_s, \ldots)$$

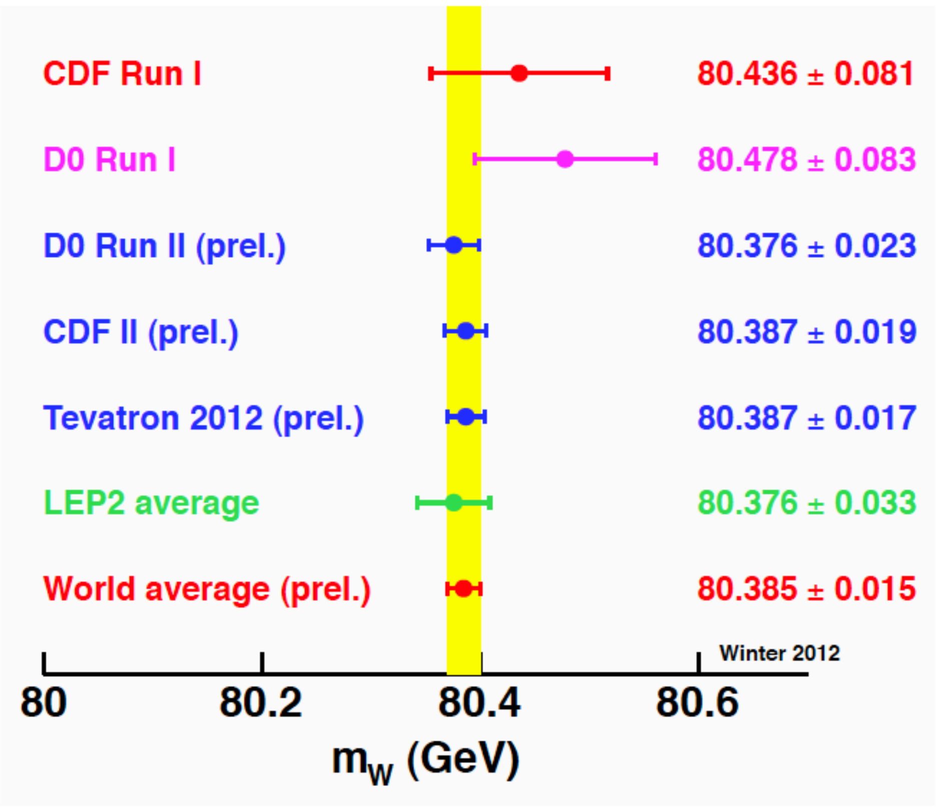


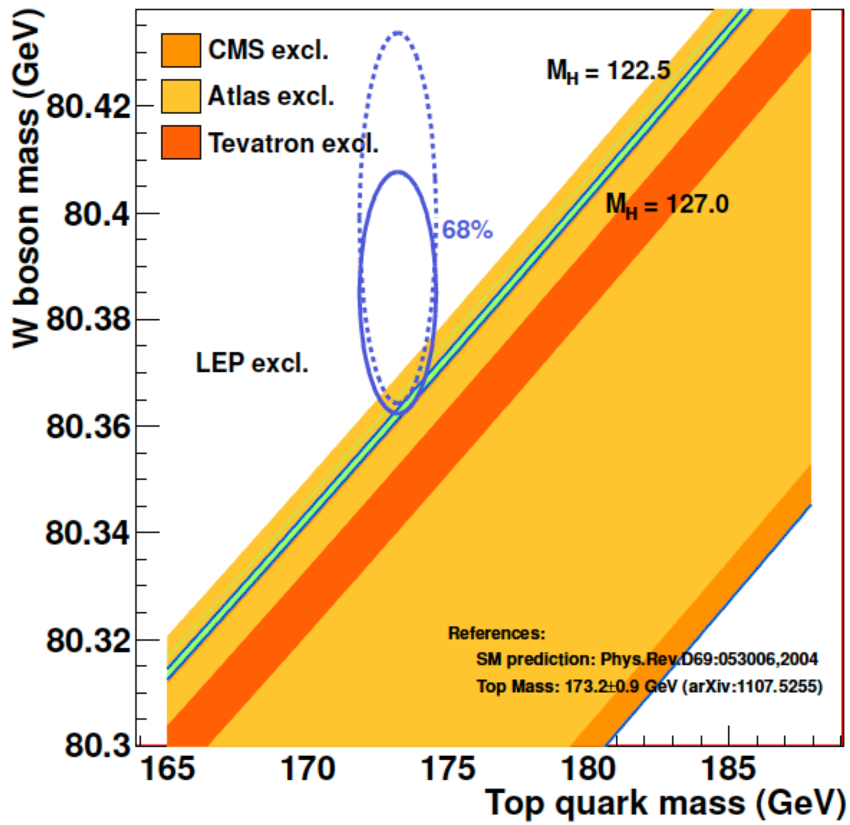
Indirect dependence	δM_W
$\delta M_H = 13\,GeV[114 \to 127]$	$-6.2\,MeV$
$\delta m_t = 1.8\,GeV[172.4 \to 174.1]$	$10.8\,MeV$
$\delta(\Delta\alpha^{(5)}_{HAD}) = 0.0002$	$-3.6\,MeV$
Current theoretical uncertainty	$4\,MeV$

SM prediction known to complete 2-loop order (and some 3-loop parts)
PHYS.REV.D69:053006,2004

Nowy pomiar m_W

(Preliminary) New World Average





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