PRINCETON UNIVERSITY

Precision Measurements at the LHC:
Luminosity and W/Z Cross Section Measurements with CMS

And the Observation of EW Production of Same-Sign W boson pairs

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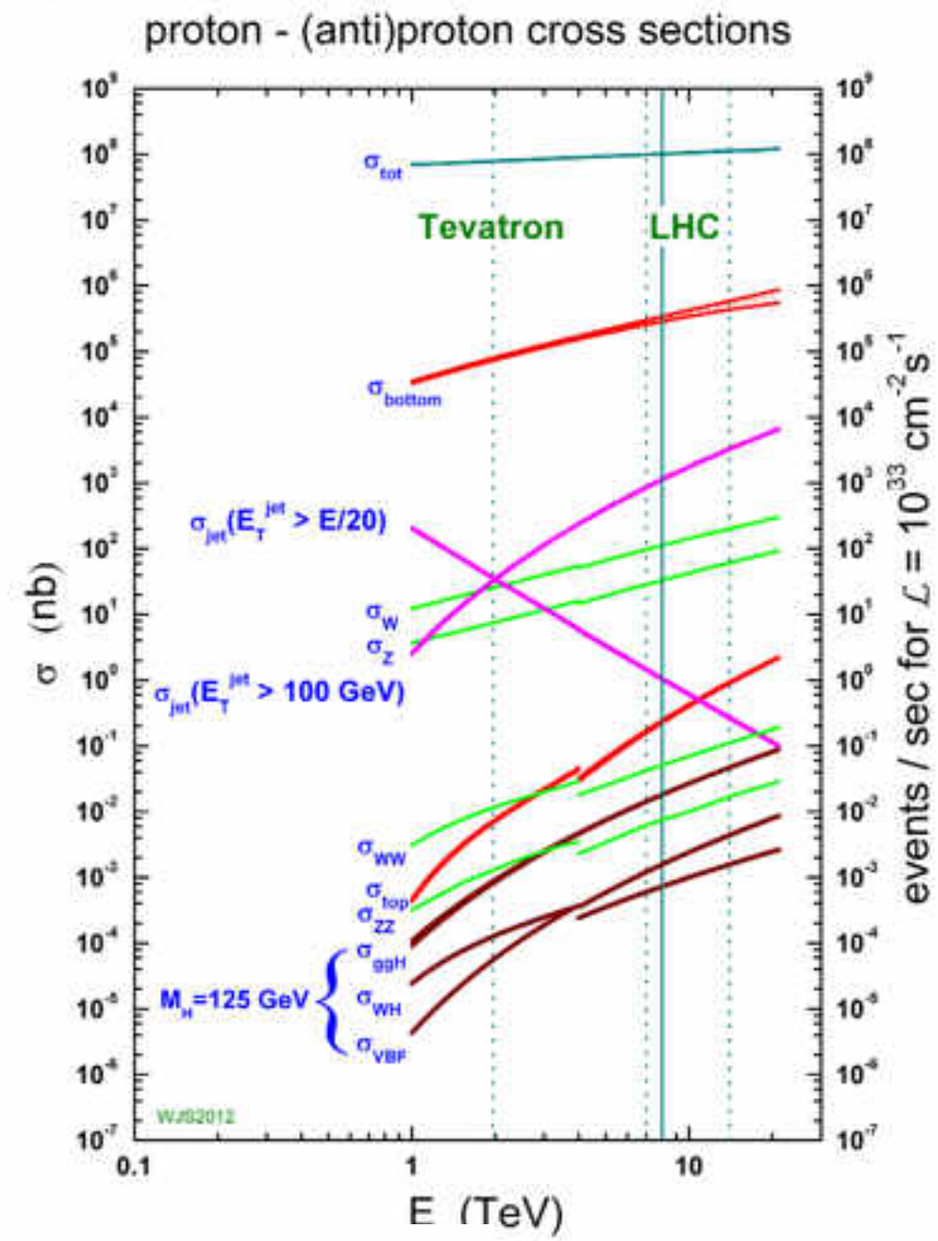
Prague Seminar

Luminosity is a measure for how often we throw dice at the LHC

Intro 1

- **Luminosity is reference for all cross section measurements at the LHC and a design parameter for accelerators**
- $$\sigma_p = \frac{R_p}{\mathcal{L}}$$
- **Cross section inferred from measured rate R_p of physical process and measured luminosity L**

  Luminosity measurement often introduces largest systematic uncertainty



- ***Goal:*** **probe theoretical prediction:**

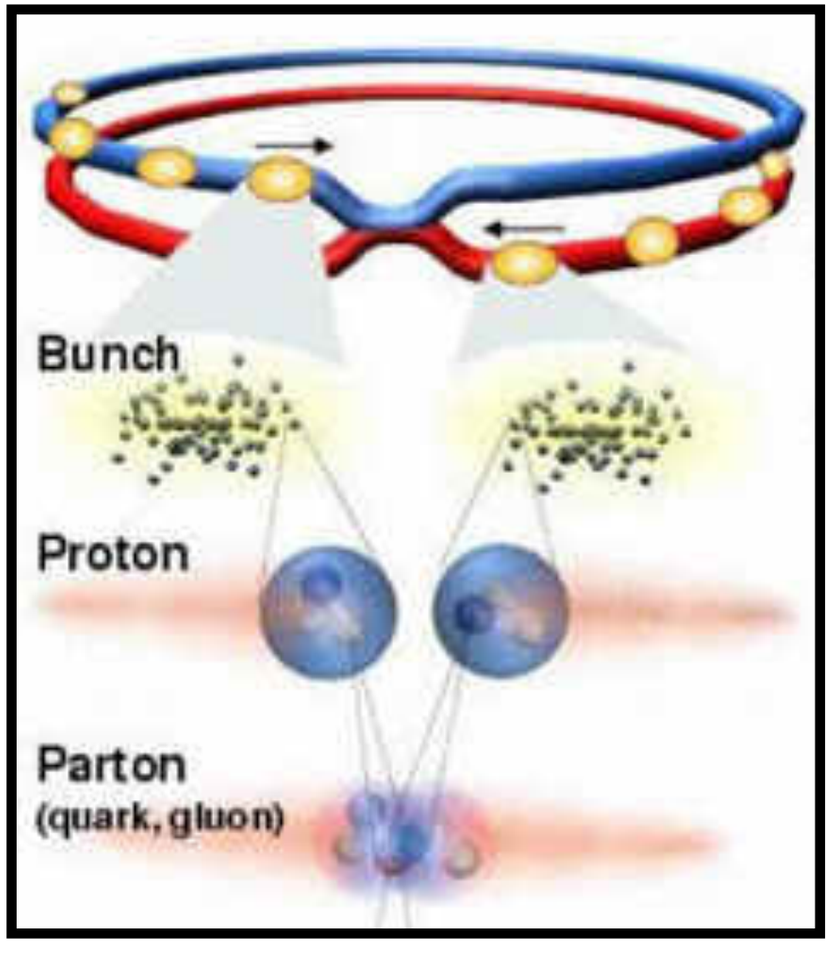
$$\sigma_{p_A p_B \to n} = \sum_q \int dx_a dx_b f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \hat{\sigma}_{ab \to n}$$

Intro 2

- **At LHC protons are distributed over bunches, per bunch instantaneous luminosity given by**

$$\mathcal{L} = \frac{f_{LHC} N_1 N_2}{2\pi\sigma_x\sigma_y}$$

f : 11245 Hz
N: 10^{11}
σ : 15 μm



Intro 3

- **At LHC protons are distributed over bunches, per bunch instantaneous luminosity given by**

$$\mathcal{L} = \frac{f_{LHC} N_1 N_2}{2\pi\sigma_x\sigma_y}$$

f : 11245 Hz
N: 10^{11}
σ : 15 μm

- **In practice, beam width estimates from machine parameters (emittance, beam optics) imprecise**

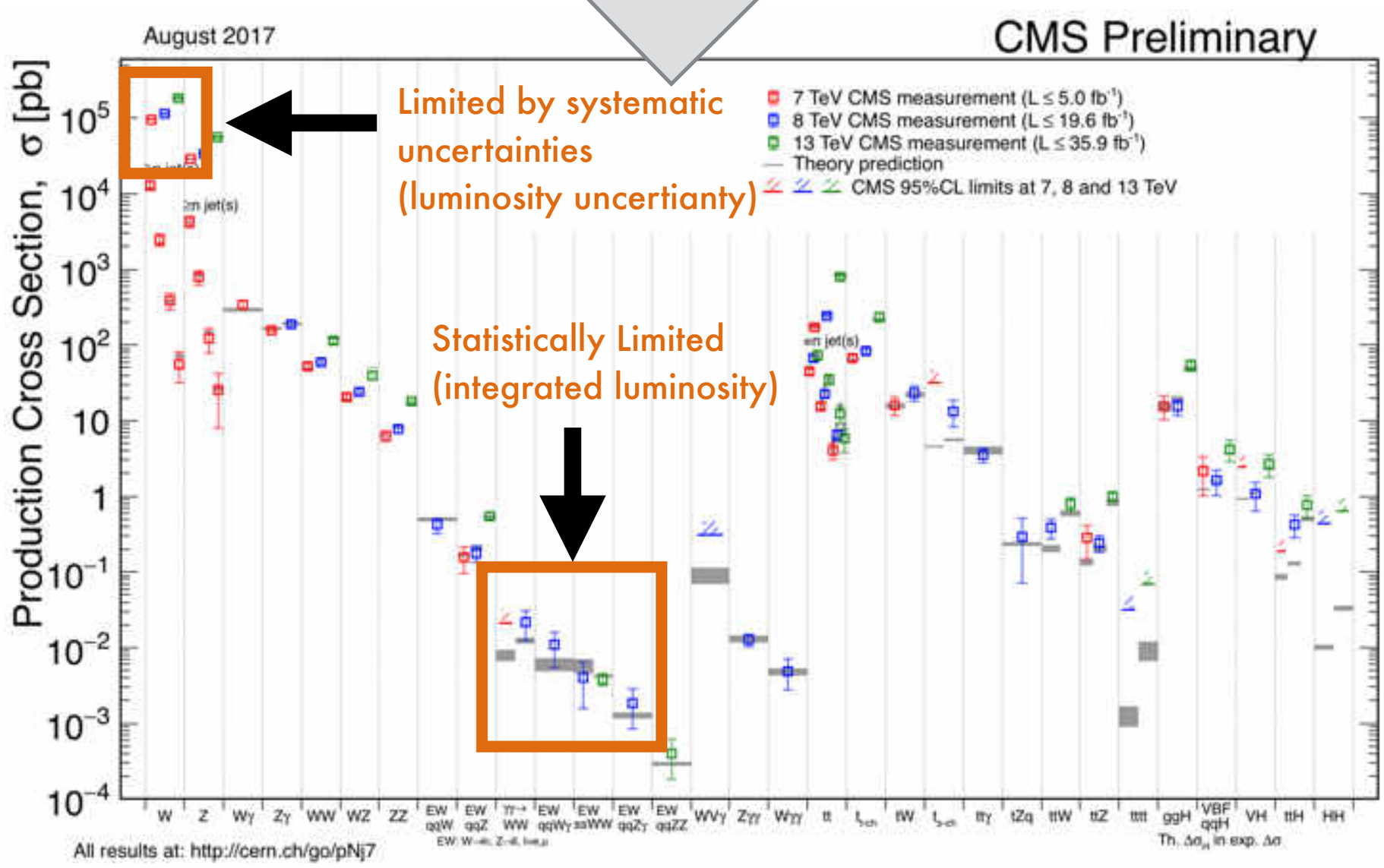
- **Luminosity is measured independently from high rate (R_A) "algorithms" in the detector by means of a calibration constant**

$$\sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_{\mathcal{A}}}\sigma_{\mathcal{A}}^{vdM}$$

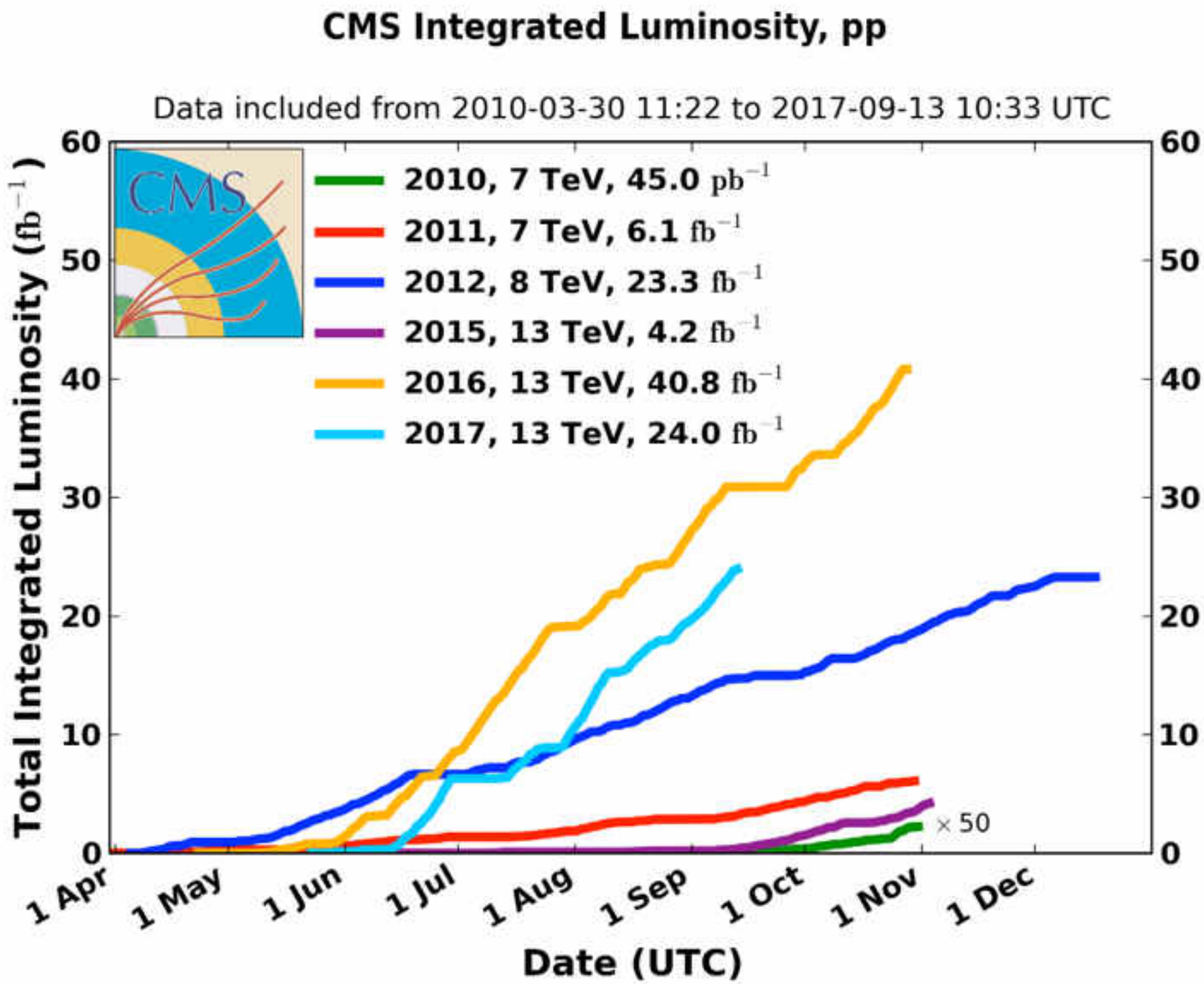
determined from van-der-Meer scans

Cross Section Summary

$$\sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_{\mathcal{A}}}\sigma_{\mathcal{A}}^{vdM}$$



Luminosity Timeline



LHC exceeds expectations: 17 Hz/nb achieved in 2017

Overview

First part: Luminosity Measurement

$$\sigma_p = \frac{\int R_p dt}{\int \mathcal{L} dt} = \boxed{\frac{N_p}{\epsilon A}} \boxed{\frac{\sigma_{\mathcal{A}}^{vdM}}{\int R_{\mathcal{A}} dt}}$$

Part 2:
Cross Section Measurement

Part 1:
Luminosity Measurement

Second part:

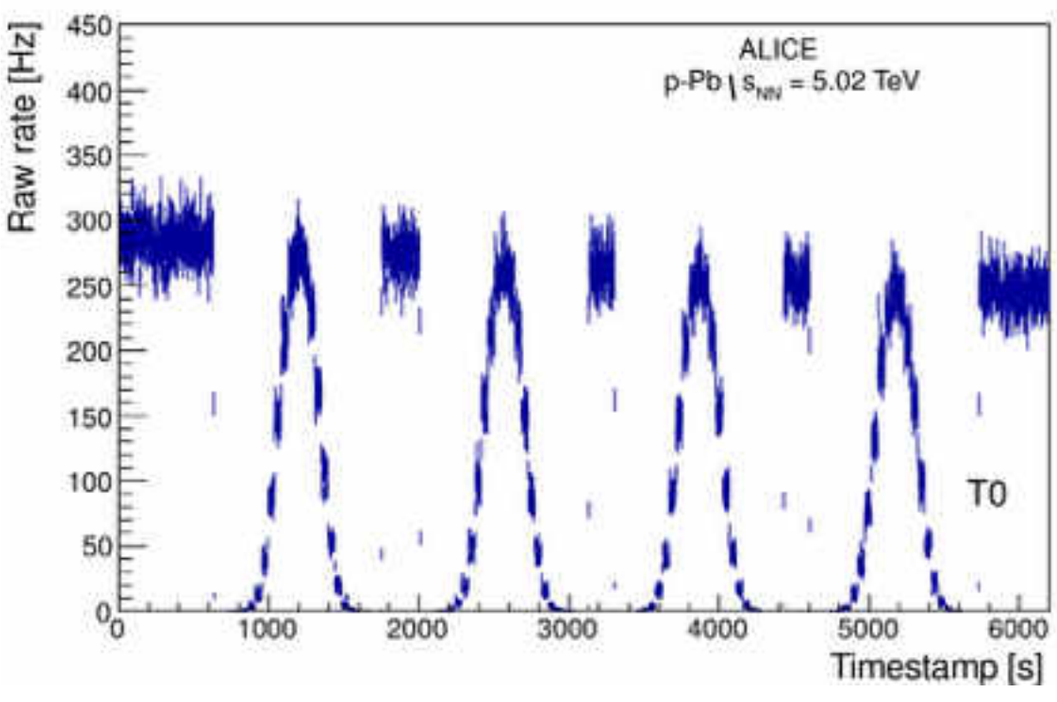
a.) W/Z cross section measurement (high cross-section)

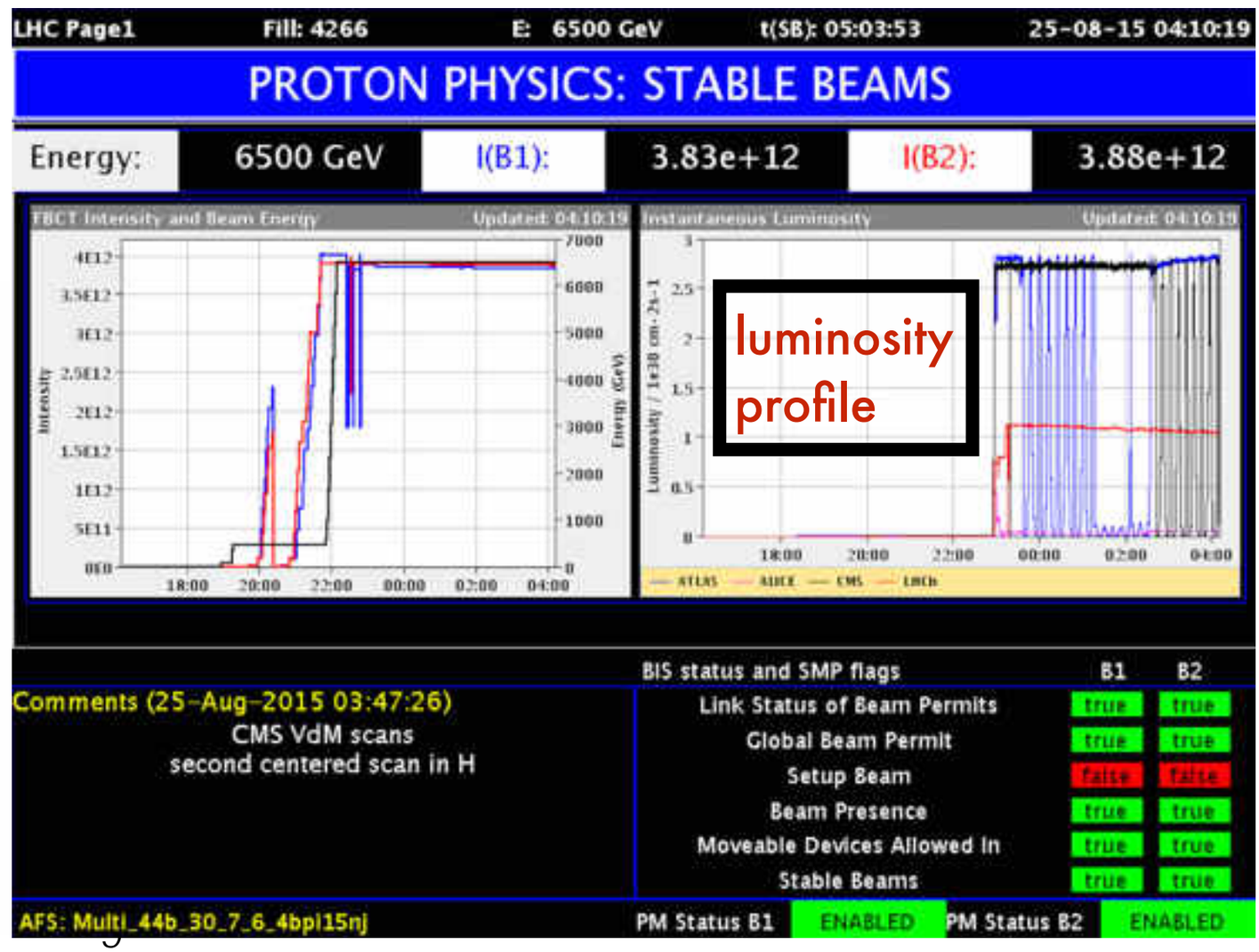
b.) EW production of same-sign W boson pairs (VBS, low cross section)

Luminosity Scale Estimation

- **Absolute luminosity scale is measured with special LHC machine set-up, pioneered by Simon van der Meer (1968, ISR-PO/68-31)**
  - **Beams are scanned across each other in the transverse plane**

$$\sigma_{\mathcal{A}}^{vdm} = \frac{R_{\mathcal{A}}}{\mathcal{L}}$$





Luminosity Scale Estimation

- **New van der Meer scans are performed every time when we change the center-of-mass energy 5, 7, 8, 13 TeV, and special Heavy Ion Programs**

- **Beams are scanned across each other in the transverse plane to measure the beam overlap integral**

$$\mathcal{L} = N_1 N_2 \nu_{\mathrm{rev}} O_I \qquad O_I = \int_{-\infty}^{\infty} \rho_1(x,y)\rho_2(x,y)\, dx\, dy$$

  - **For simple gaussian beams**

$$\mathcal{L} = \frac{f_{LHC} N_1 N_2}{2\pi\sqrt{\sigma_{x,1}^2 + \sigma_{x,2}^2}\sqrt{\sigma_{y,1}^2 + \sigma_{y,2}^2}} = \frac{f_{LHC} N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

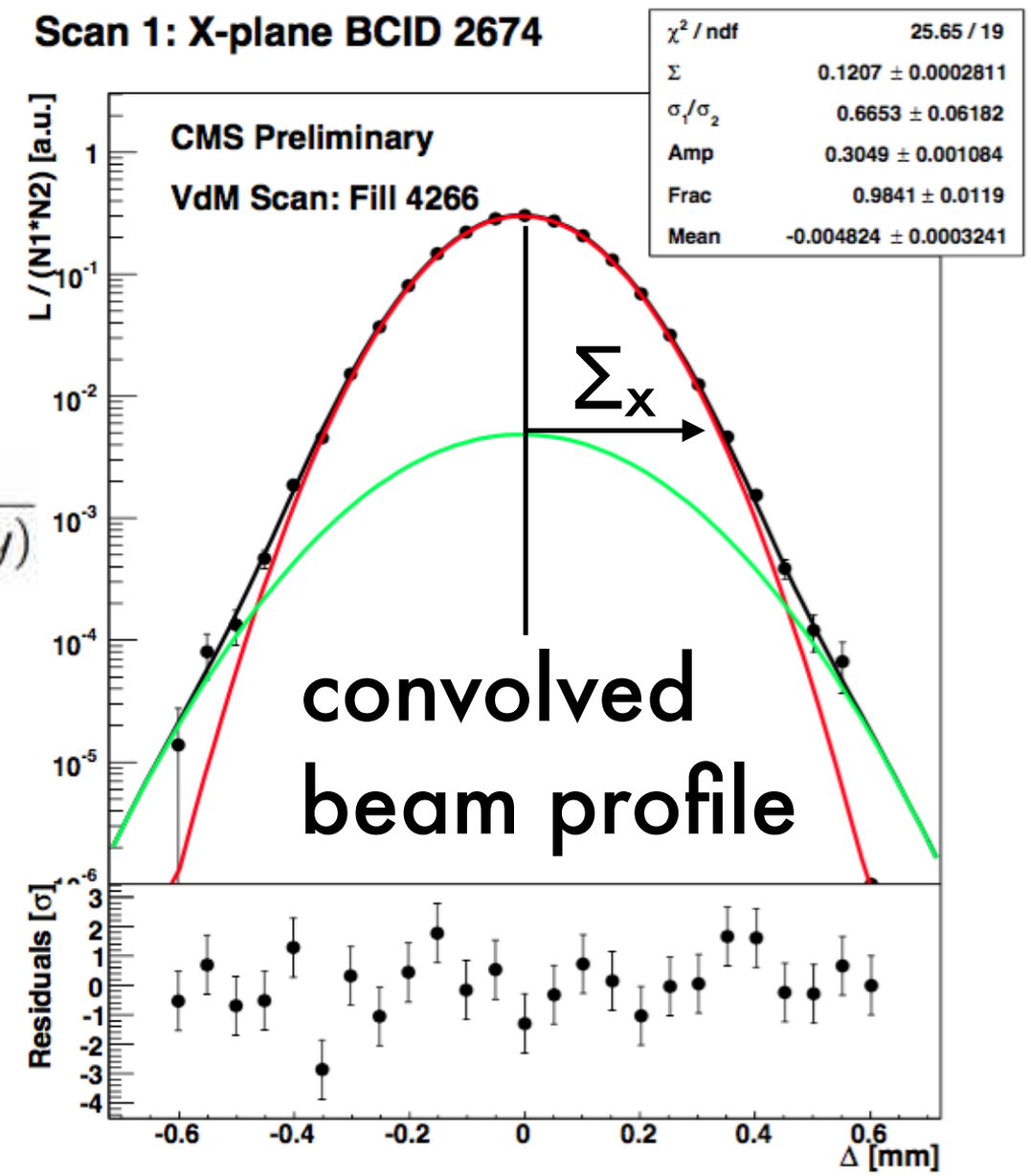
- **denominator is product of convolved widths of the two bunches**

Luminosity Scale Calibration

- **Formula can also be derived more generically, under assumption of factorizability**

$$O_I = \int_{-\infty}^{\infty} \rho_1(x)\rho_2(x)\,dx \times \int_{-\infty}^{\infty} \rho_1(y)\rho_2(y)\,dy$$

$$\mathcal{L}(\Delta x_0, \Delta y_0) = N_1 N_2 f \frac{R(\Delta x_0, \Delta y_0) R(\Delta x_0, \Delta y_0)}{\int_{-\infty}^{\infty} R(\Delta x, \Delta y_0)\,d(\Delta x) \int_{-\infty}^{\infty} R(\Delta x_0, \Delta y)\,d(\Delta y)}$$



- **convolved bunch widths measured from scan curve cross section (calibration constant) derived**

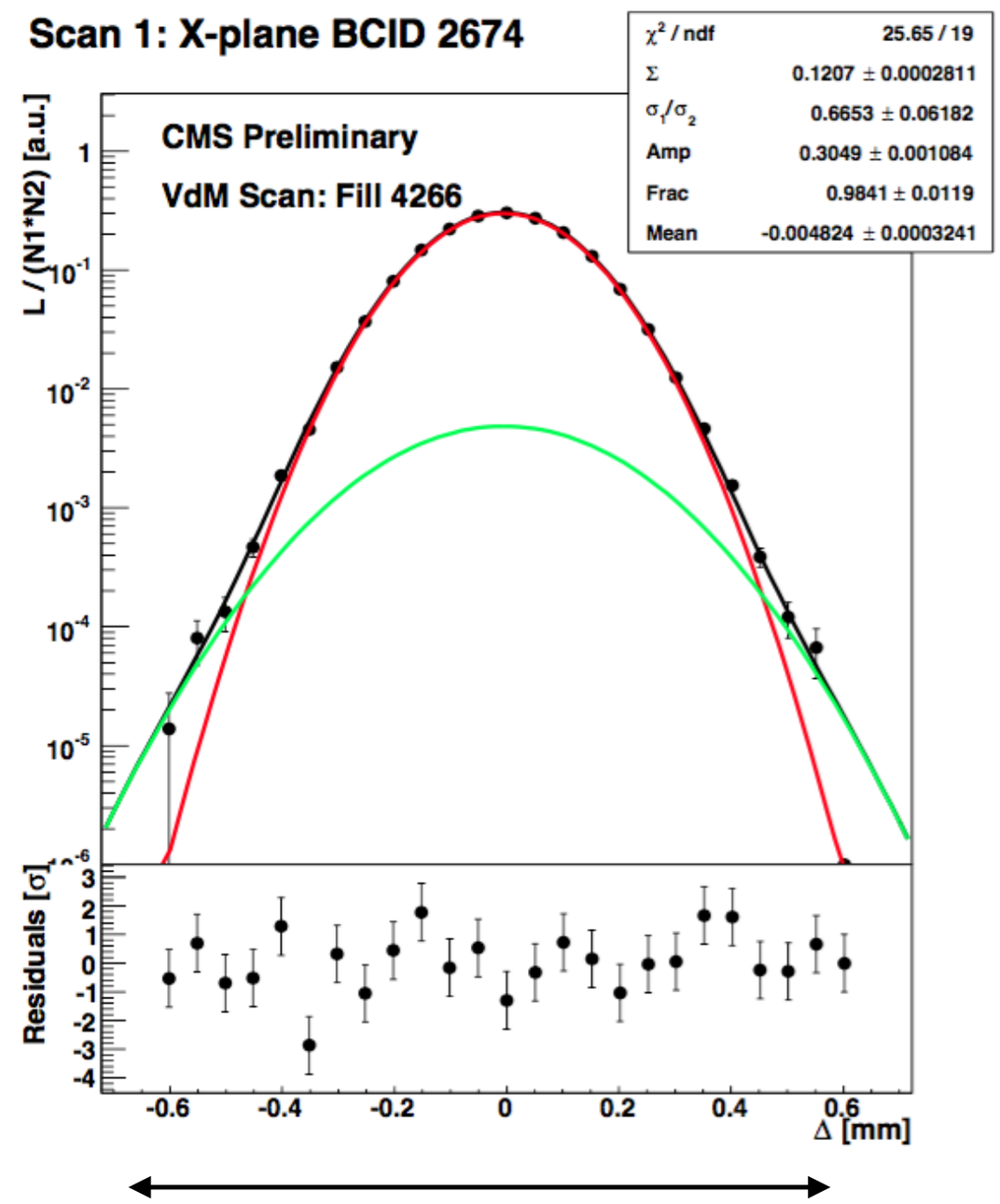
$$\sigma_{\mathcal{A}}^{vdM} = \frac{2\pi \Sigma_x \Sigma_y R_{\mathcal{A}}(0)}{N_1 N_2 f_{LHC}}$$

Experimental Effects

$$\sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_{\mathcal{A}}} \cdot \frac{2\pi \Sigma_x \Sigma_y R_{\mathcal{A}}(0)}{N_1 N_2 f_{LHC}}$$

-Length (separation) scale of beams
-Assumption on factorizability
-Beam-Beam effects
-Bunch current normalisation

Normalization	XY-Correlations
	Beam current calibration
	Ghosts and satellites
	Length scale
	Orbit Drift
	Beam-beam deflection
	Dynamic-β



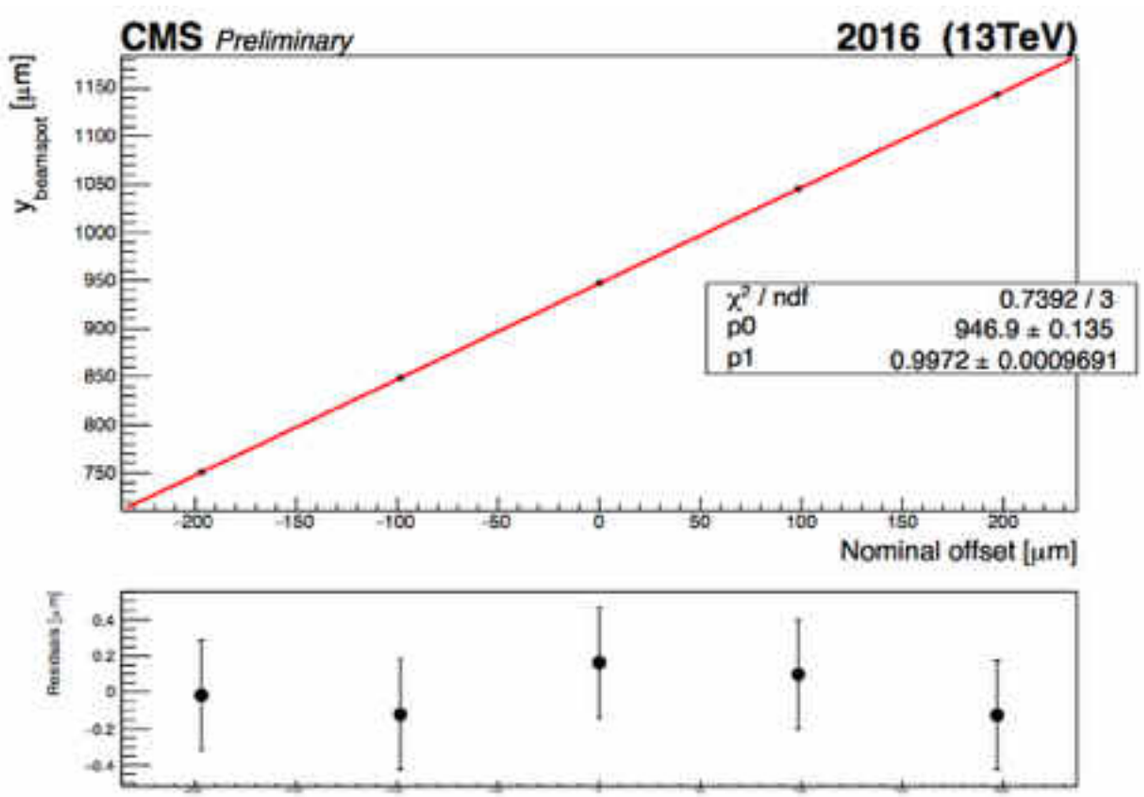
beam-beam separation

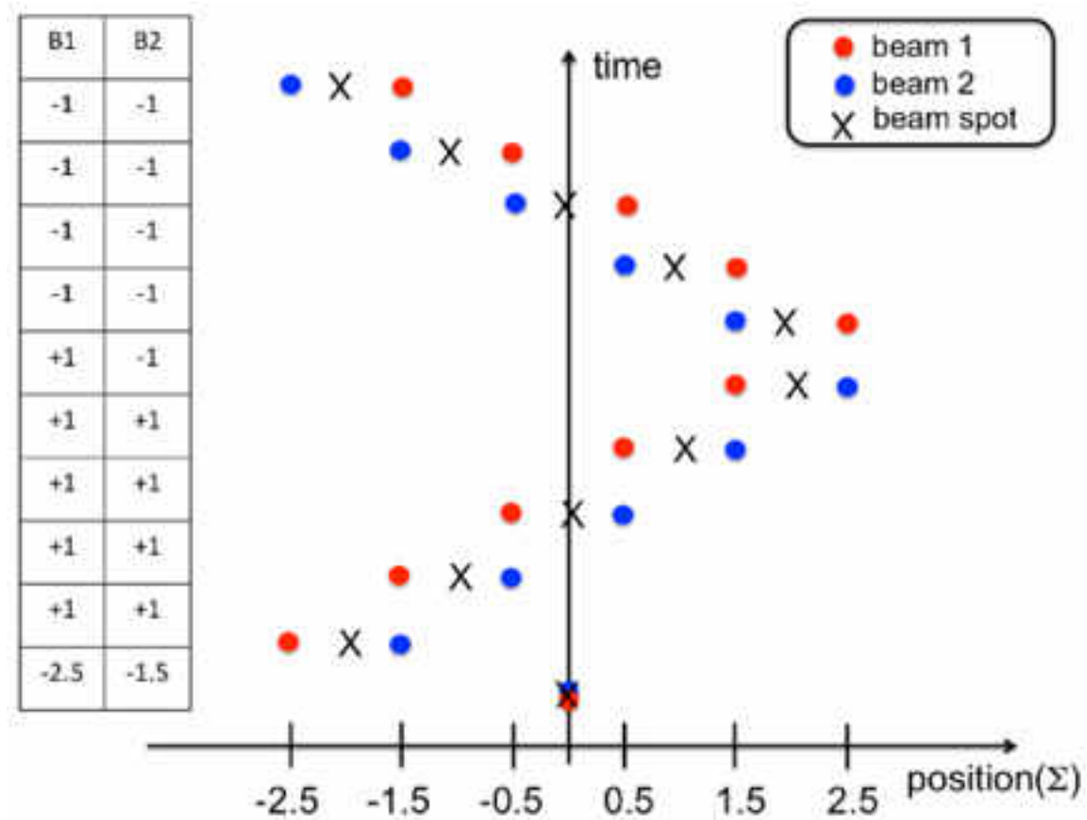
Length Scale

- **distance scale of beam movements are calibrated to distance scale to CMS tracking detector**

Currents in steering dipole magnets (orbit bumps) → **Beam positions** → **vertices in Tracker**

- **Specific "length scale scans"**



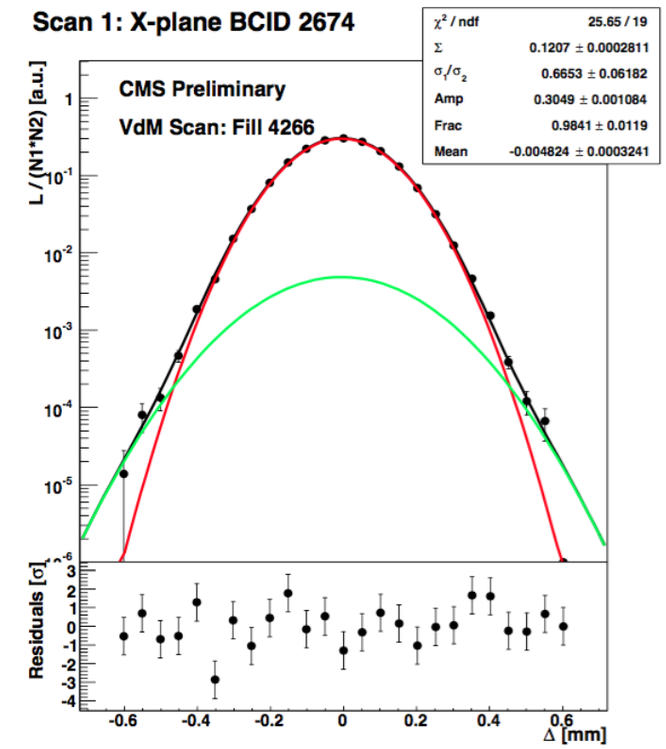


Beam-Beam Effects, Orbit Drift

- **Other effects changing the beam separation**

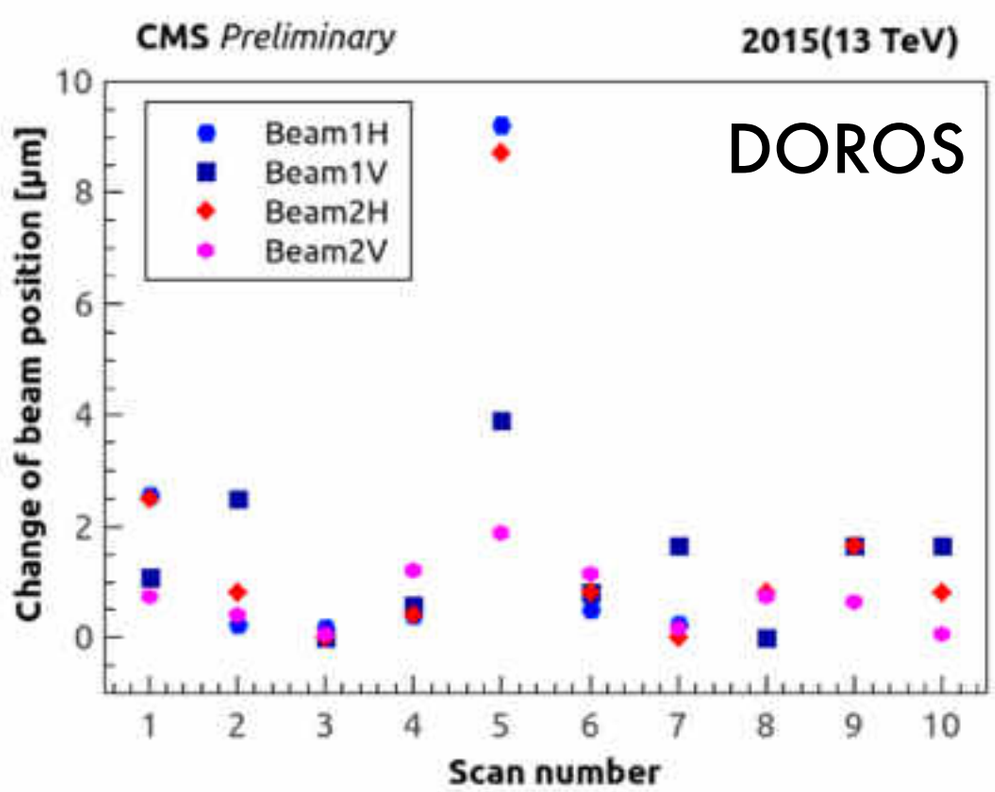
- **Beam-Beam effects:**

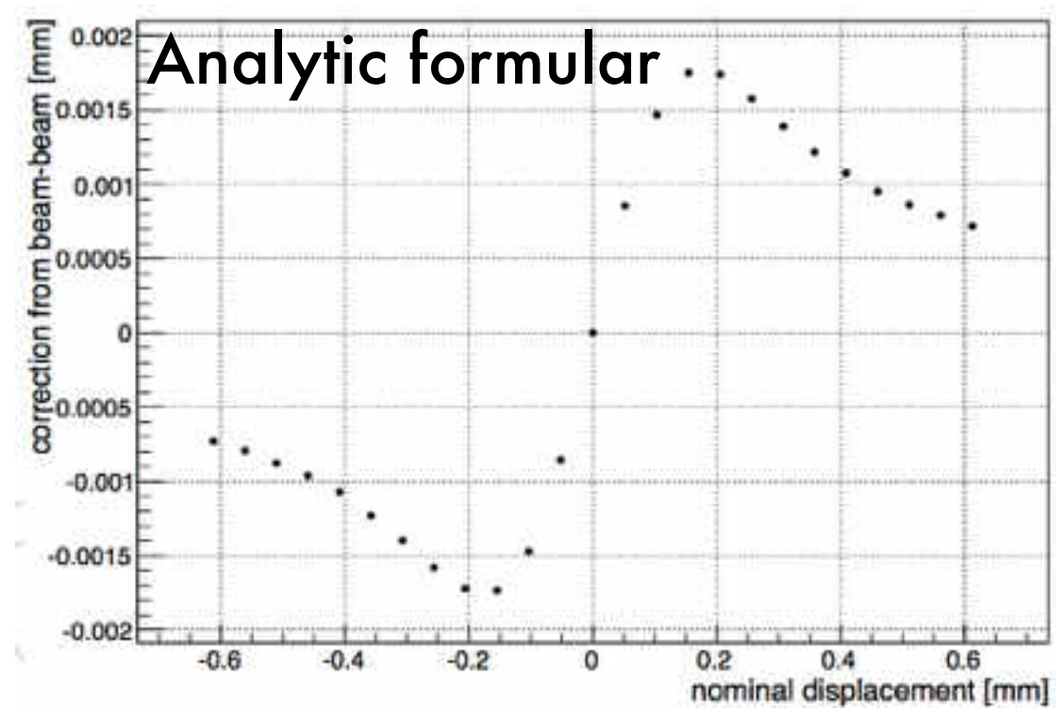
  - **Electromagnetic force of proton charges in colliding bunches introduce a "kick/beam-deflection" and can change the shape (de-focussing, dynamic-β <0.5%)**



- **Orbit Drift: Beams may drift from fixed orbit**

beam-beam separation



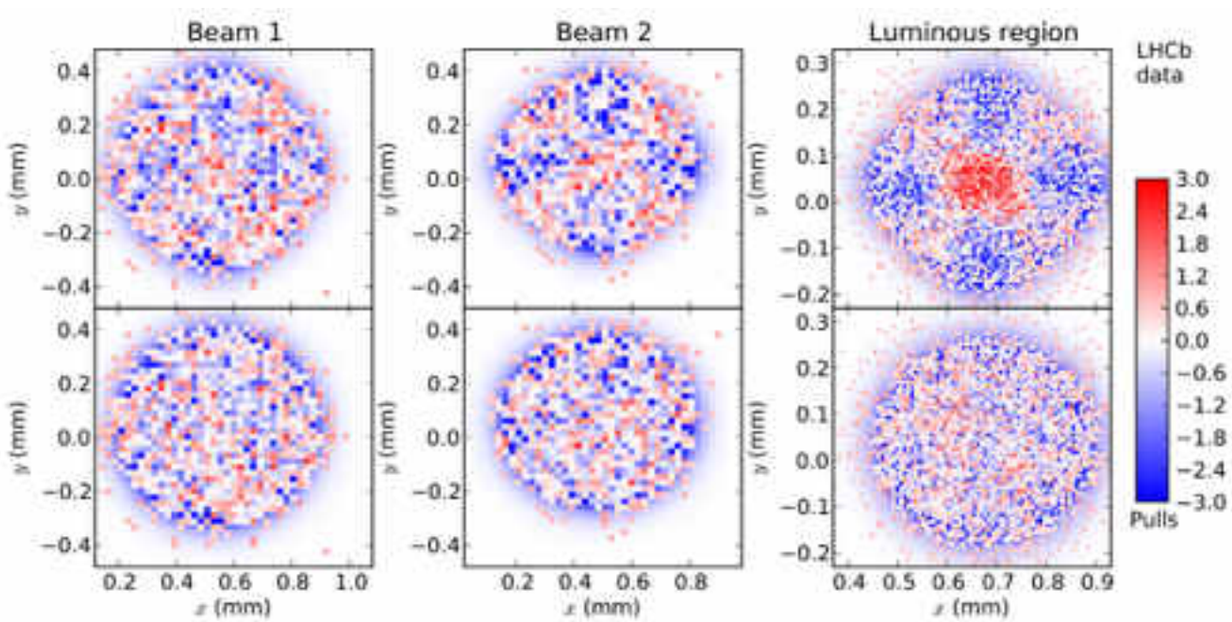


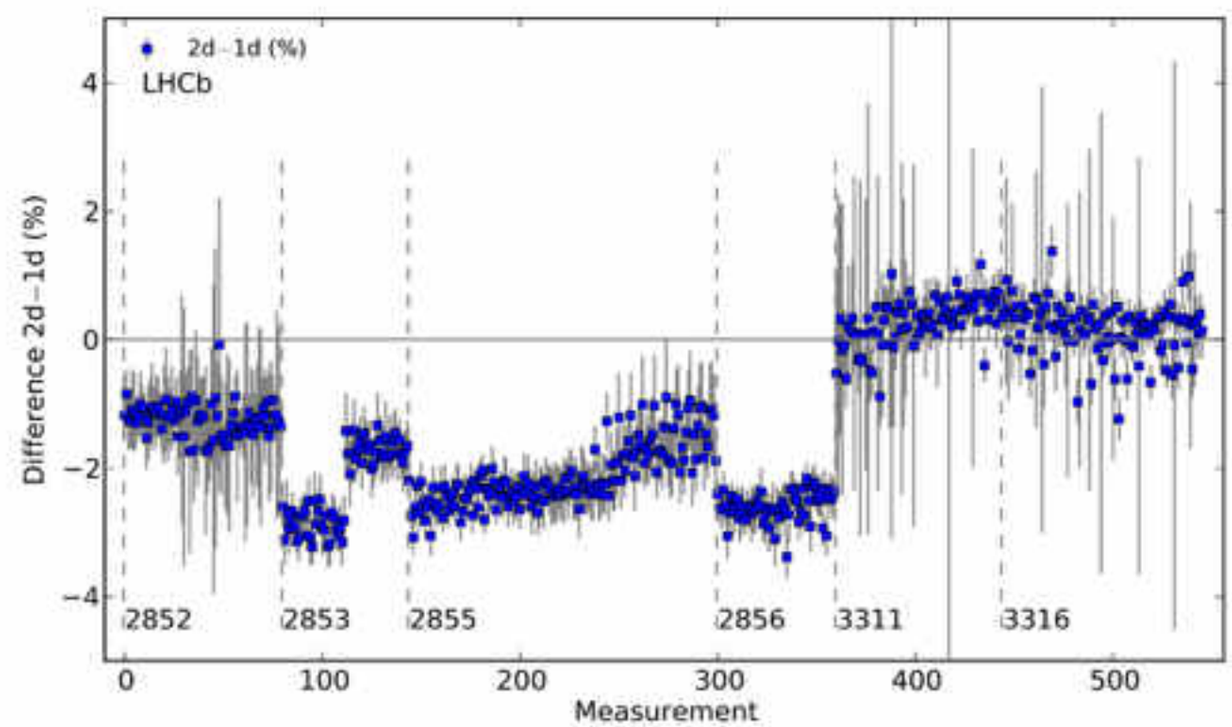
Beam Shapes (Non-Factorization)

- **assumption of factorizability of the beam shapes not perse true**

$$\boxed{O_I \overset{?}{=} \int_{-\infty}^{\infty} \rho_1(x)\rho_2(x)\,dx \times \int_{-\infty}^{\infty} \rho_1(y)\rho_2(y)\,dy}$$

- **tests performed by LHCb collaboration in Run-1 using beam-gas imaging technique**
- **collision vertex position distribution, to infer 3-dimensional bunch shape**





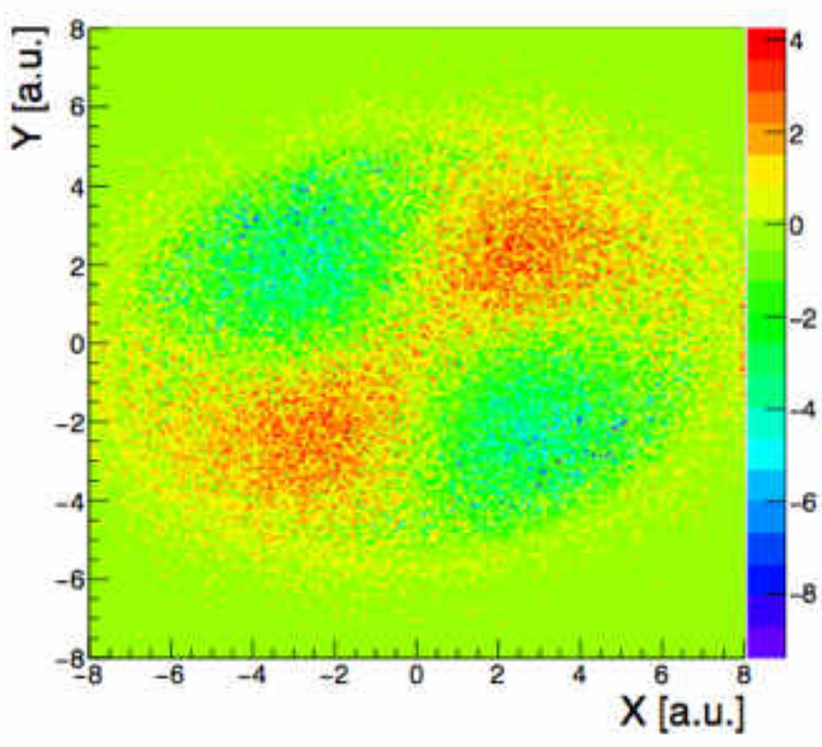
Beam Shapes (Non-Factorization)

- **CMS detector not suitable to measure beam-gas interaction vertices (forward tracks)**

- **However can use one beam to "image" the other**

  - **Beam Imaging: introduced in JINST P03018, 1103.1129**

- **Keep one beam fixed in the coordinate system of the detector, move other beam across**



pull per bin in transverse plane

(simulation)

$$\sum_n n^{vtx}(x,y;n\Delta x)\Delta x = \sum_n \rho_1(x,y)\rho_2(x+n\Delta x,y)\Delta x \otimes V$$

$$= \left[\sum_n \rho_1(x,y)\rho_2(x+n\Delta x,y)\Delta x\right] \otimes V$$

$$\approx \left[\int_{\Delta x} \rho_1(x,y)\rho_2(x+\Delta x,y)\, d(\Delta x)\right] \otimes V$$

$$= \rho_1(x,y)(\mathcal{M}_x\rho_2)(y) \otimes V.$$

resolution for vertex position

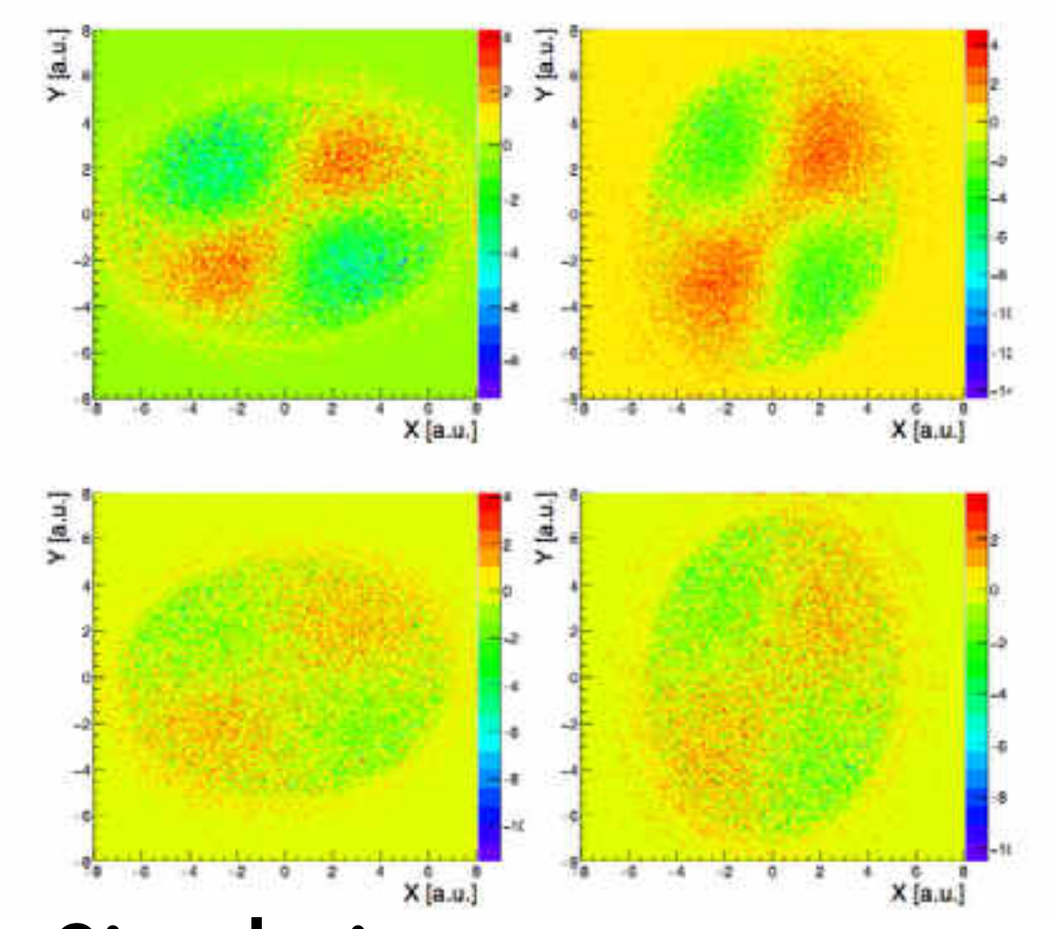
Beam Shapes

- **repeat scans with the other beam kept fixed, scan in *X* and *Y***

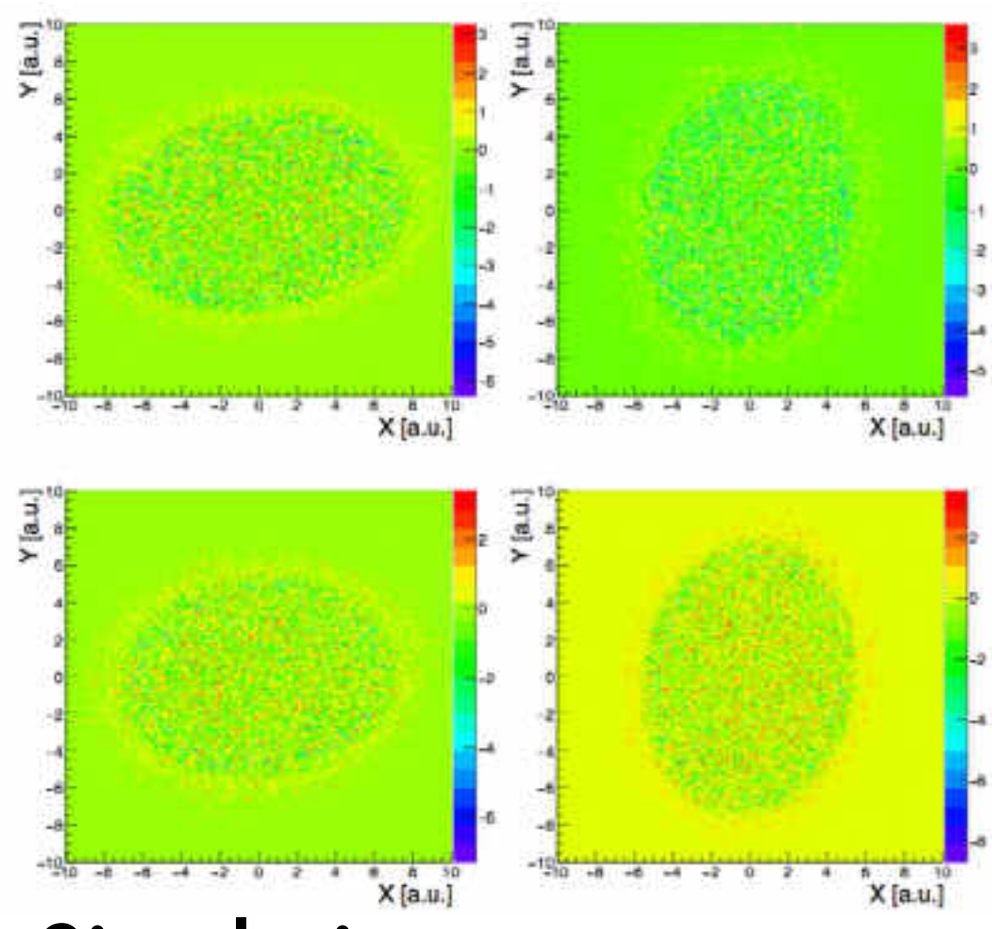
  - **4 vertex distribution in the transverse plane, fit simultaneously**

$$b_i(x,y) = w_i g_{i,N}(x,y) + (1-w_i) g_{i,W}(x,y)$$ <= beam shape model

$$g_{i,j}(x,y) = \frac{1}{2\pi\sigma_{i,j,x}\sigma_{i,j,y}\sqrt{1-\rho_{i,j}^2}} \exp\left(\frac{-1}{2(1-\rho_{i,j}^2)}\left[\frac{x^2}{\sigma_{i,j,x}^2} + \frac{y^2}{\sigma_{i,j,y}^2} - \frac{2\rho_{i,j}xy}{\sigma_{i,j,x}\sigma_{i,j,y}}\right]\right)$$



Simulation

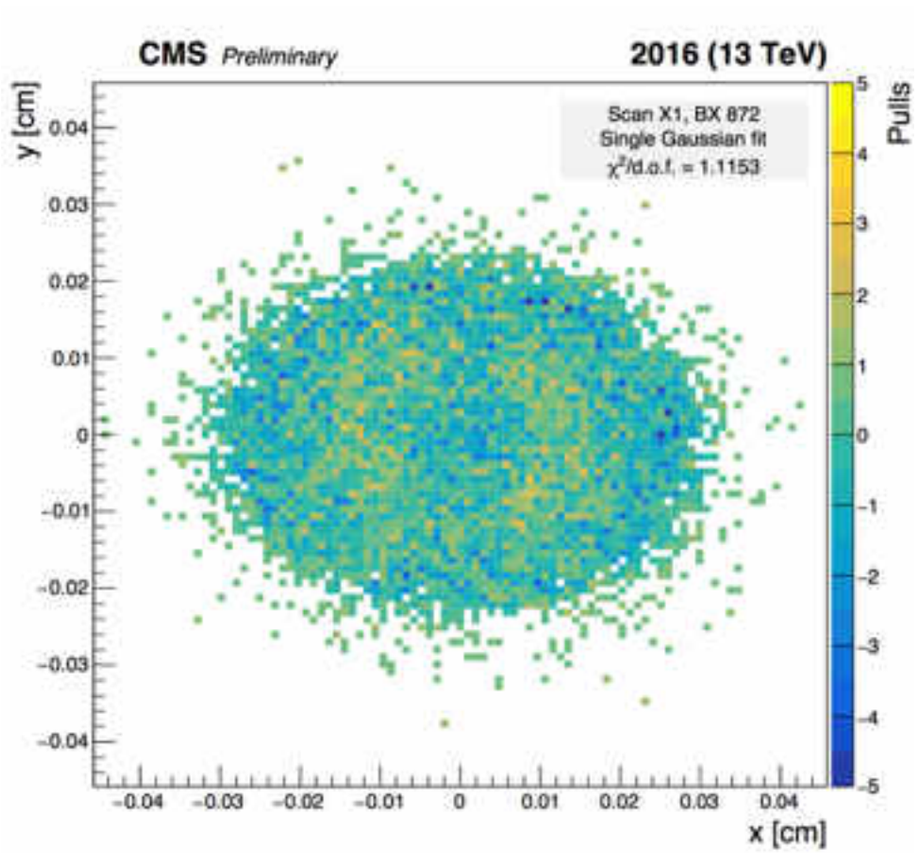


Simulation

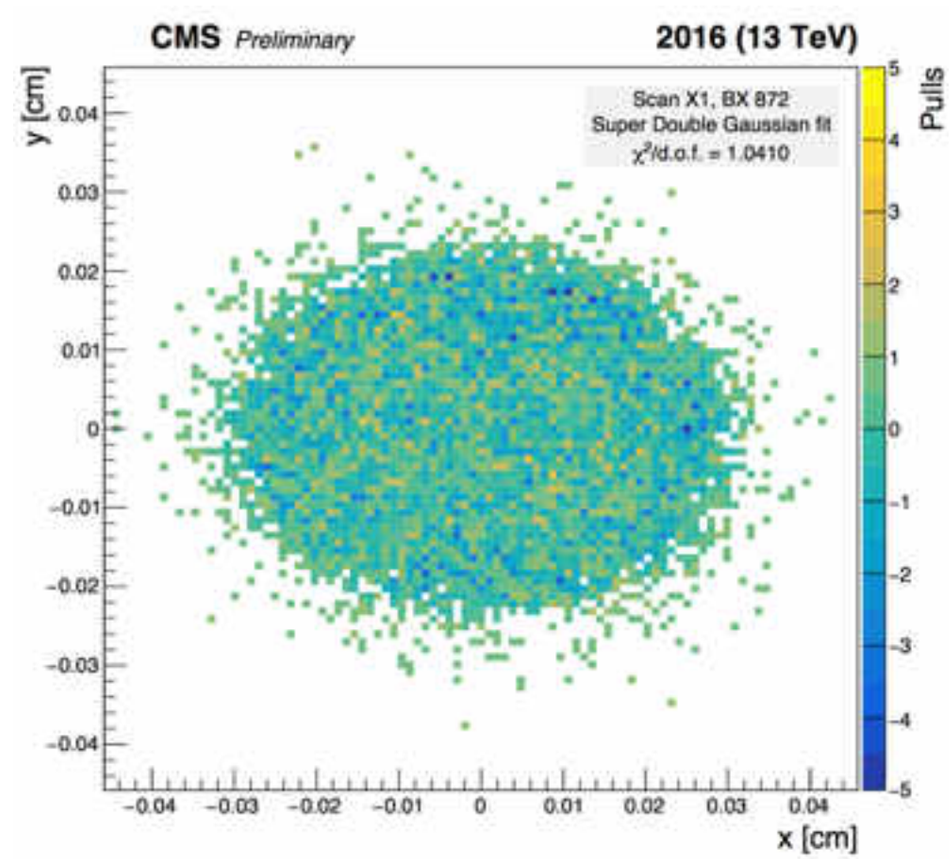
Beam Shapes

- **Beam Imaging scans performed in Run-2 vdM scan campaigns => non-factorization effects within ~1% observed**

  - **Once vertex reconstruction resolution understood, complementary beam overlap measurement can be obtained (decrease systematic uncertainties)**



comparison with fit-model assuming no XY-correlations

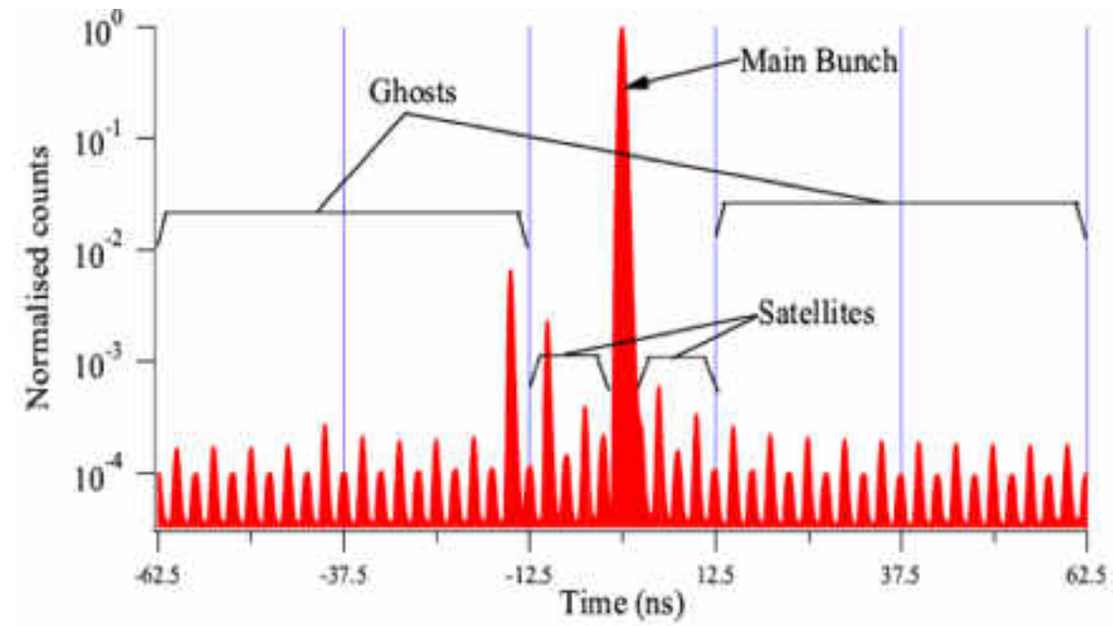


comparison with fit-model with XY-correlations Triple-Gaussian Model

Beam Currents

$$\sigma_p = \frac{R_p}{\mathcal{L}} = \frac{R_p}{R_{\mathcal{A}}} \cdot \frac{2\pi\Sigma_x\Sigma_y R_{\mathcal{A}}(0)}{N_1 N_2 f_{LHC}}$$

- Full per-beam intensity measured with 0.3% precision (Direct Current Transformer, 10% uncertainty in 2010)



- **per-bunch population measured with Fast BCT (25ns integration window), absolute scale not well calibrated, cross calibrated to DCCT**

- **spurious charges estimated with Longitudinal Density Monitor based on synchrotron radiation**

$$N^j(t) = N^j_{FBCT} \frac{N_{DC}(1 - f_{ghost})}{\sum_j N^j_{FBCT}} (1 - f^j_{sat.})$$

- Independent measurement performed by LHCb experiment (Beam-Gas)

Luminosity Rate Algorithms

- **CMS operates 5 luminometers to measure luminosity, based on complementary algorithms and detector technology**

- **Forward detectors, independent from CMS DAQ:**

Pixel Luminosity Telescope (online)
New installed detector for RunII, rate measurement based on telescope occupancy

Forward Hadron Calorimeter (online)
already used in RunI based on occupancy

Beam Condition Monitor (diamond sensors, online)
already used during RunI, based on number of MIPs

- **A suitable rate algorithm is pile up independent (low detector occupancy), not filling scheme dependent (no out-of-time response) and is operationally stable (no radiation damage)**

  - **So far for precise CMS offline measurements Pixel Cluster Counting with is used, and monitored using Muon Track rates in Drift Tubes**

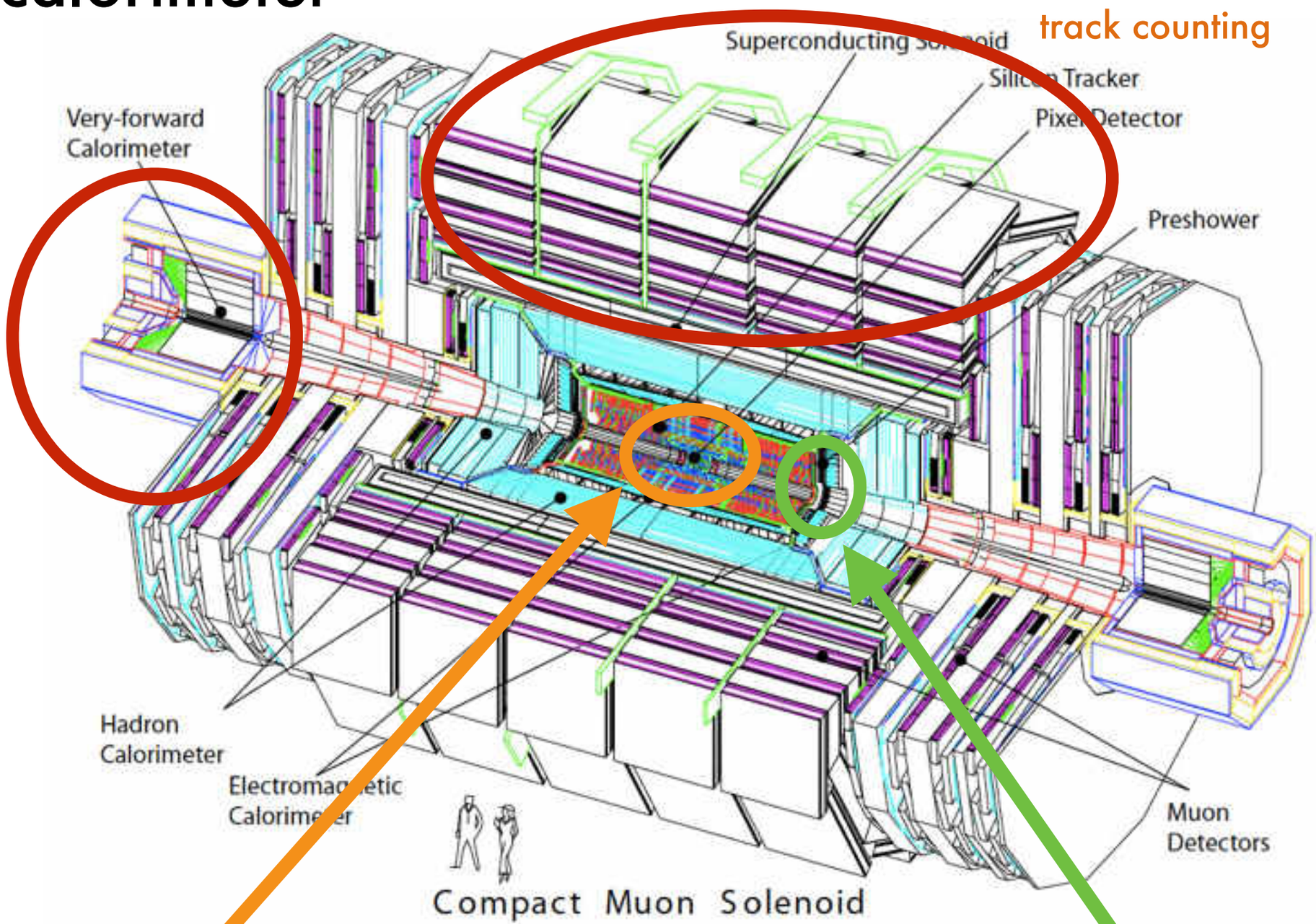
Luminosity Rate Algorithms

Forward calorimeter

occupancy

Muon Drift Tubes

track counting

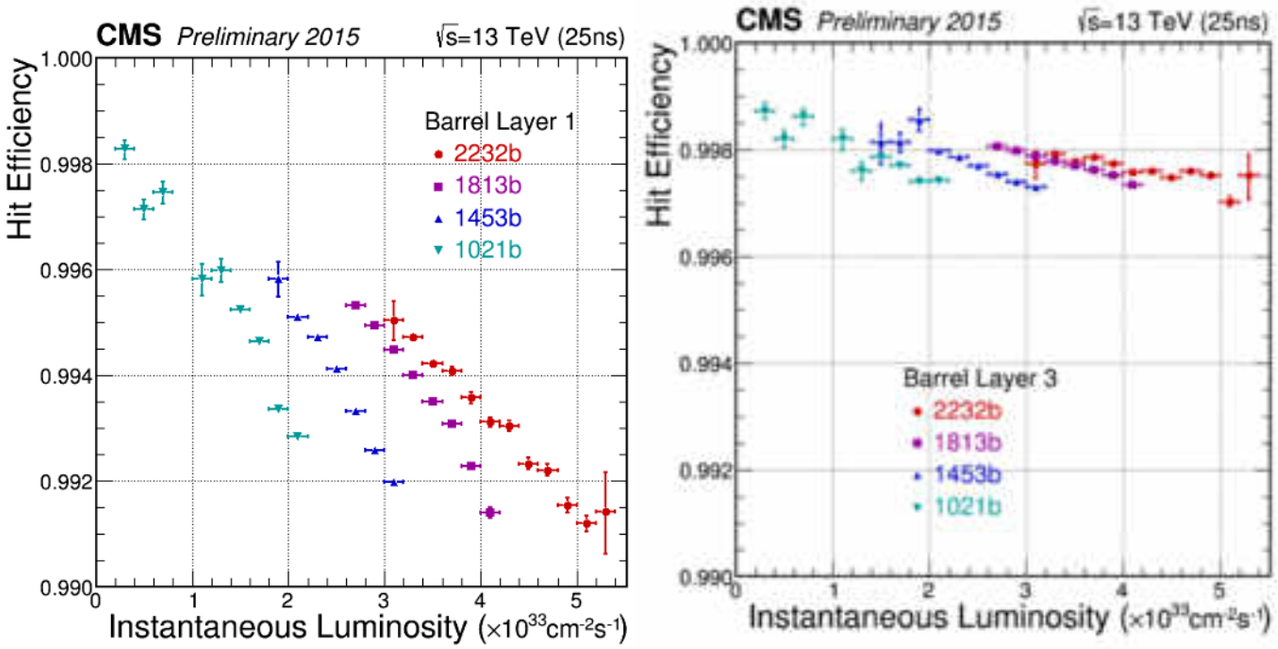


Silicon Pixel Detector

PLT, BCM1f

Pixel Cluster Counting

- **Algorithm for Silicon Pixel Detector is based on Pixel Cluster Counts (Rates)**
  - **66M channels, <0.1% occupancy at 10^{34} $cm^{-2}s^{-1}$,very good stability over time, linear response up to high pile up**
- **However, limitations from maximum trigger rates during data-taking (lower statistics), per bunch luminosity measurements being commissioned**
- **Only modules operational during the entire year used**



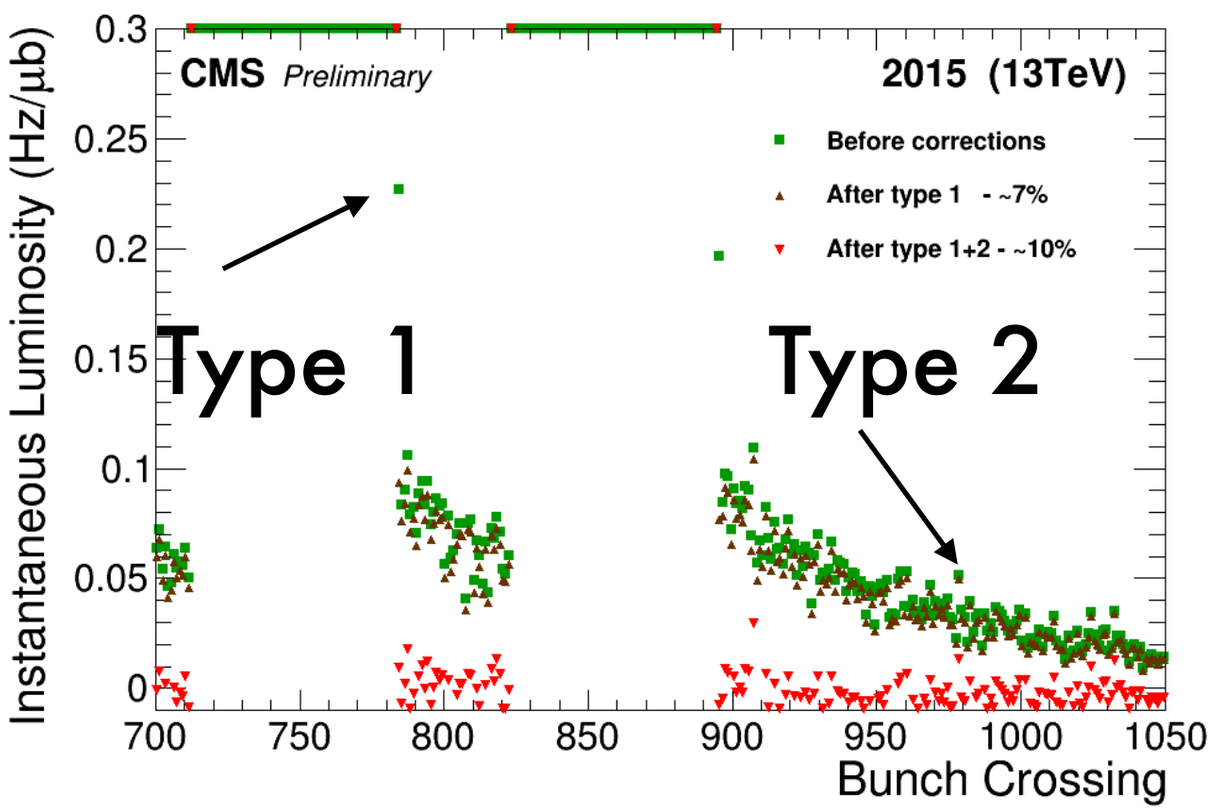
(a) Barrel Layer 1 (c) Barrel Layer 3

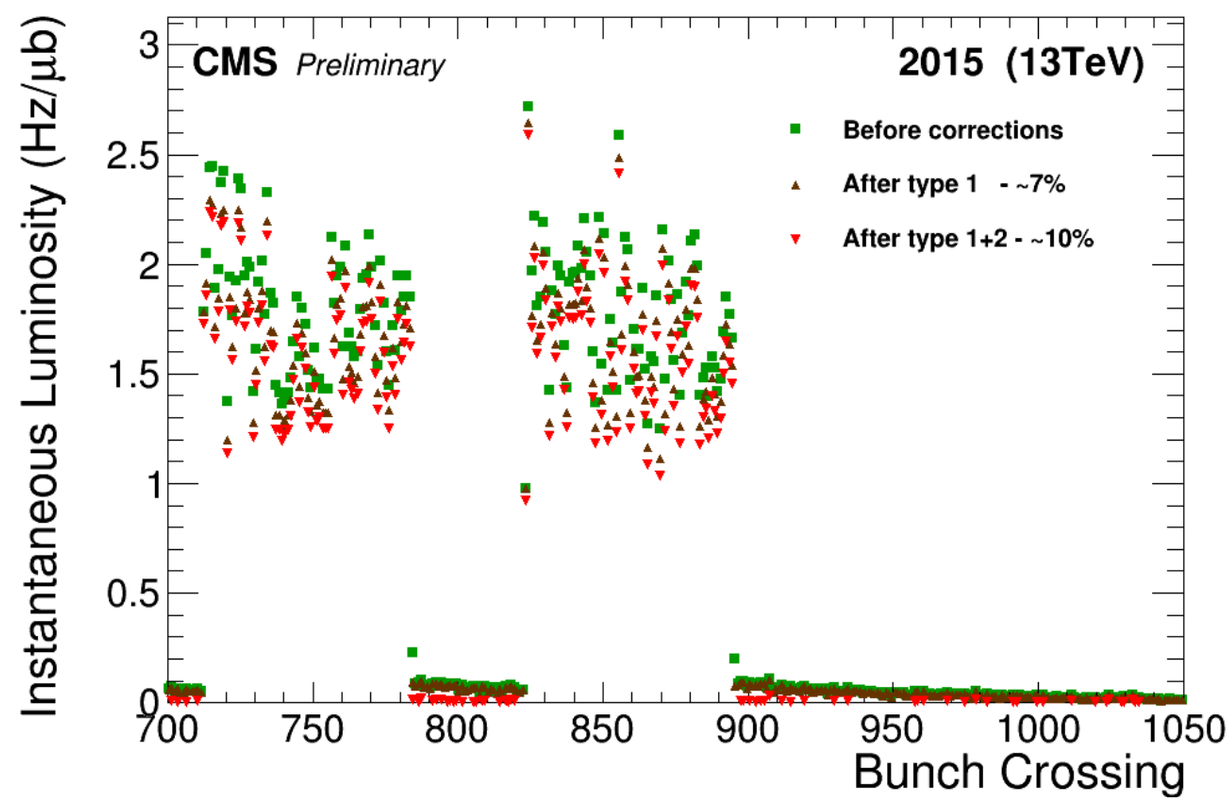
Pixel Cluster Counting

- **PCC has two Out-Of-Time response effects leading to bias of the true rate measurement**

  1. **Spill-Over/Time-Walk of electronic pixel signal leaking into next bunch slot (Type 1)**

  2. **<u>Afterglow</u>, exponential decay of activated material surrounding the detector (Type 2)**

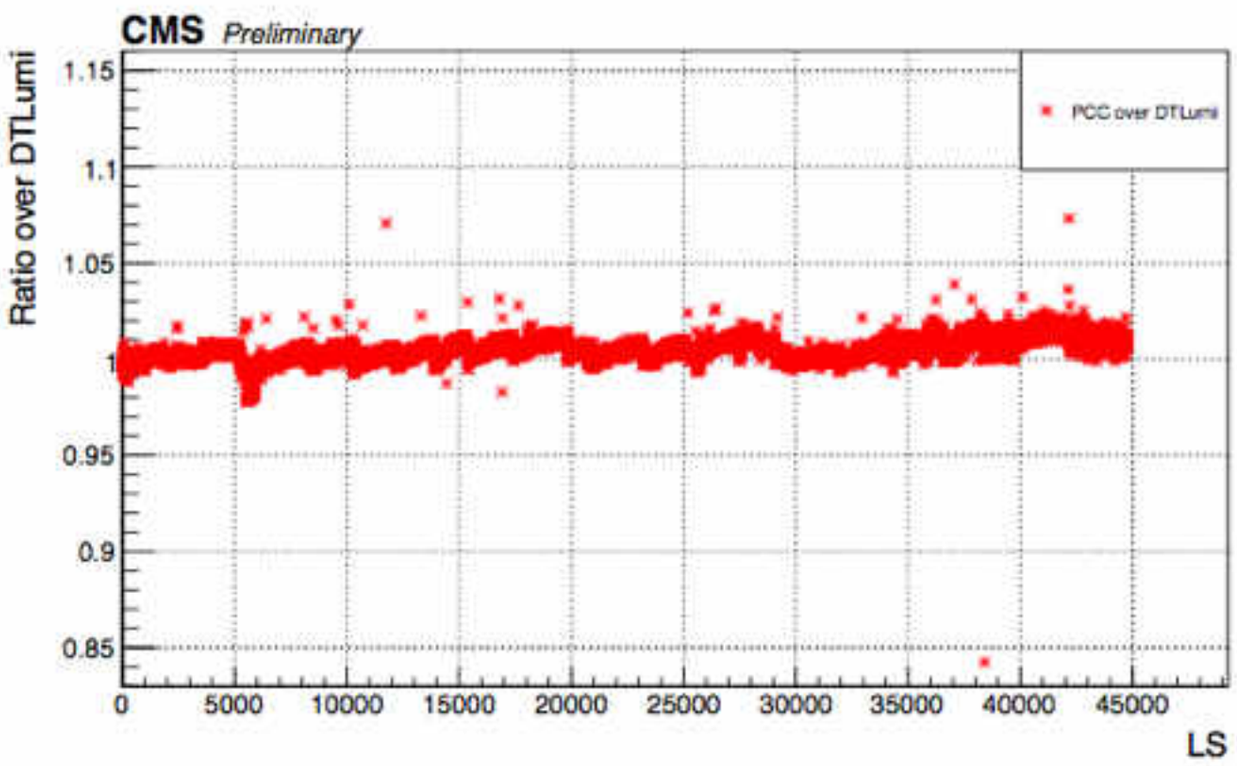


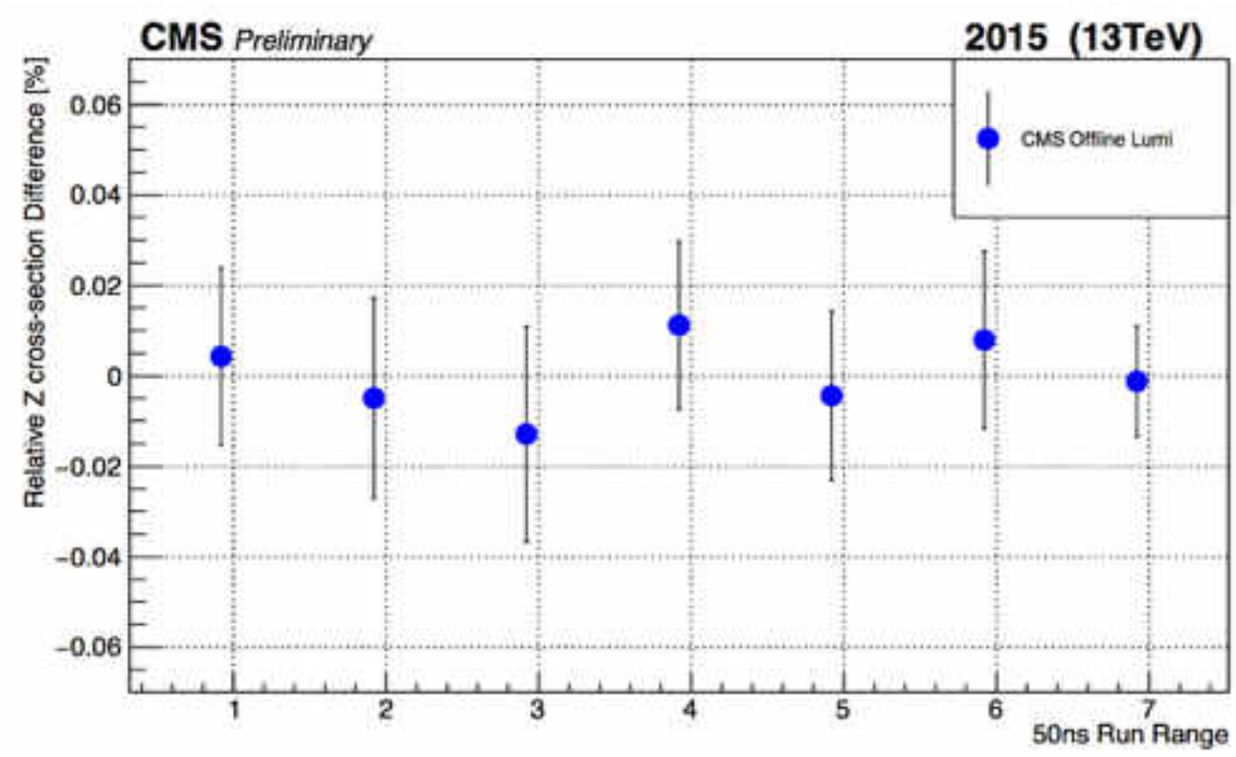


PCC from Random Triggers

Stability Reference

- **Reference to cross check stability of the Silicon Pixel detector to be determined**
  - **is there a more stable detector?**
- **Experimental approach: use complementary rate measurements**
  - **Drift Tube Muon Rates, Z Boson Rate after efficiency corrections**





Systematic Uncertainties

	Systematic	Correction (%)	Uncertainty (%)
Integration	Stability	-	1
	type 1	7 – 9	0.6
	type 2	0 – 4	0.7
	CMS deadtime	-	0.5
	Dynamic Inefficiency	-	0.4
Normalization	XY-Correlations	1.1	1.5
	Beam current calibration	-	0.3
	Ghosts and satellites	-	0.2
	Length scale	-0.5	0.5
	Orbit Drift	-	0.4
	Beam-beam deflection	1.8	0.4
	Dynamic-β	-	0.5
	Total		2.3

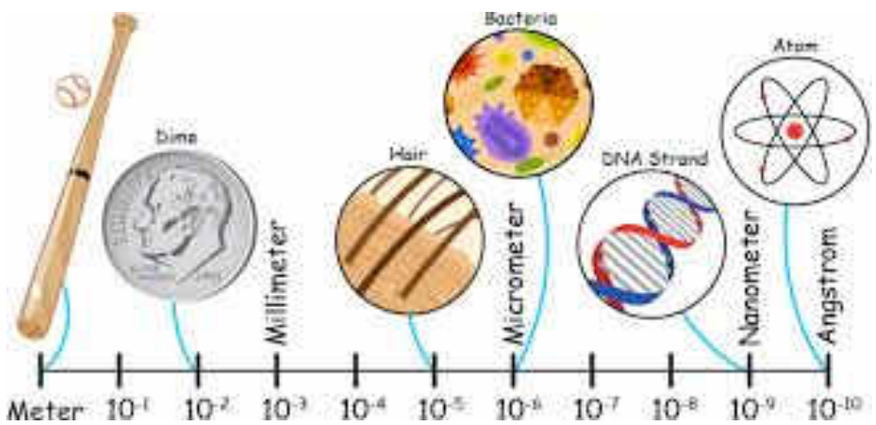
LUM-15-001

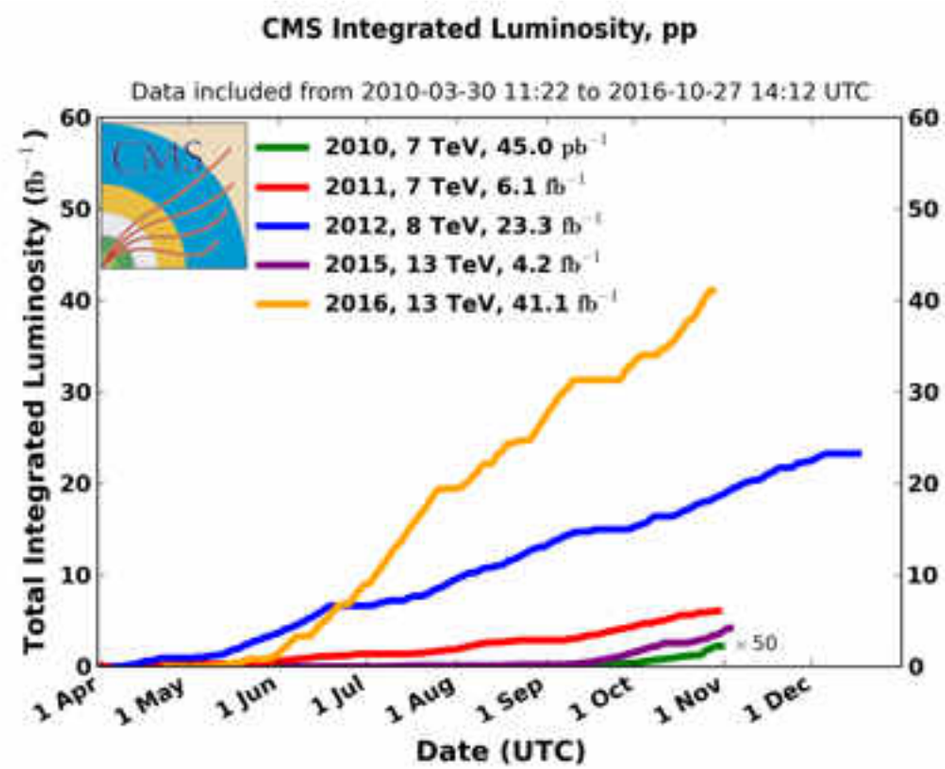
$$\sigma_p = \frac{\int R_p dt}{\int \mathcal{L}} = \frac{N_p}{\epsilon A}\left(\frac{\sigma_{\mathcal{A}}^{vdM}}{\int R_{\mathcal{A}} dt} \pm \Delta\mathcal{L}\right)$$

Fun Facts about Precision

- **the convolved beam widths are about 100μm**
  => Meaning with 2.7% uncertainty we can probe length sales of about 1μm

- **While the LHC probes scales of <10^{-19}m (EW Scale), control over the 10^{-6}m scale enter the cross section measurements**





- **At High Luminosity LHC target for total integrated luminosity: 3000/fb**

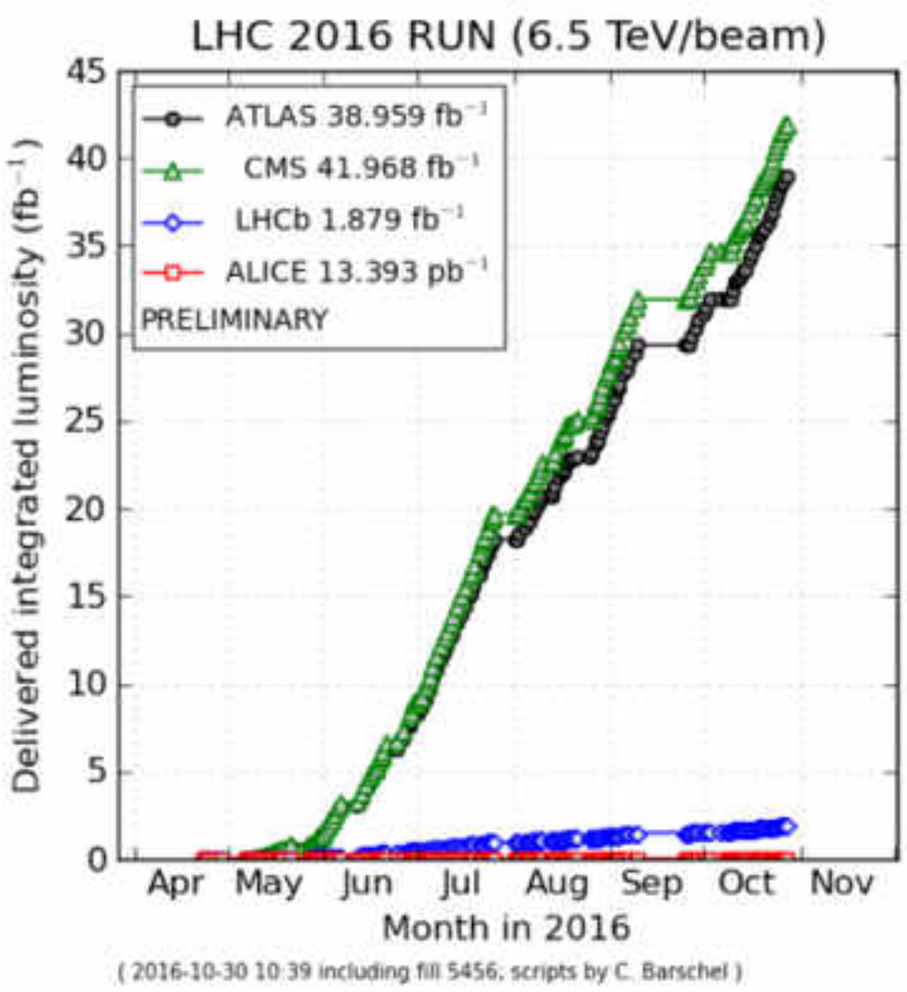
  - **2.3% uncertainty would translate into ± 69 fb^{-1} <= similar to the data collected from 2010 to 2016 (7 years of operation)**

Z Rate Measurements

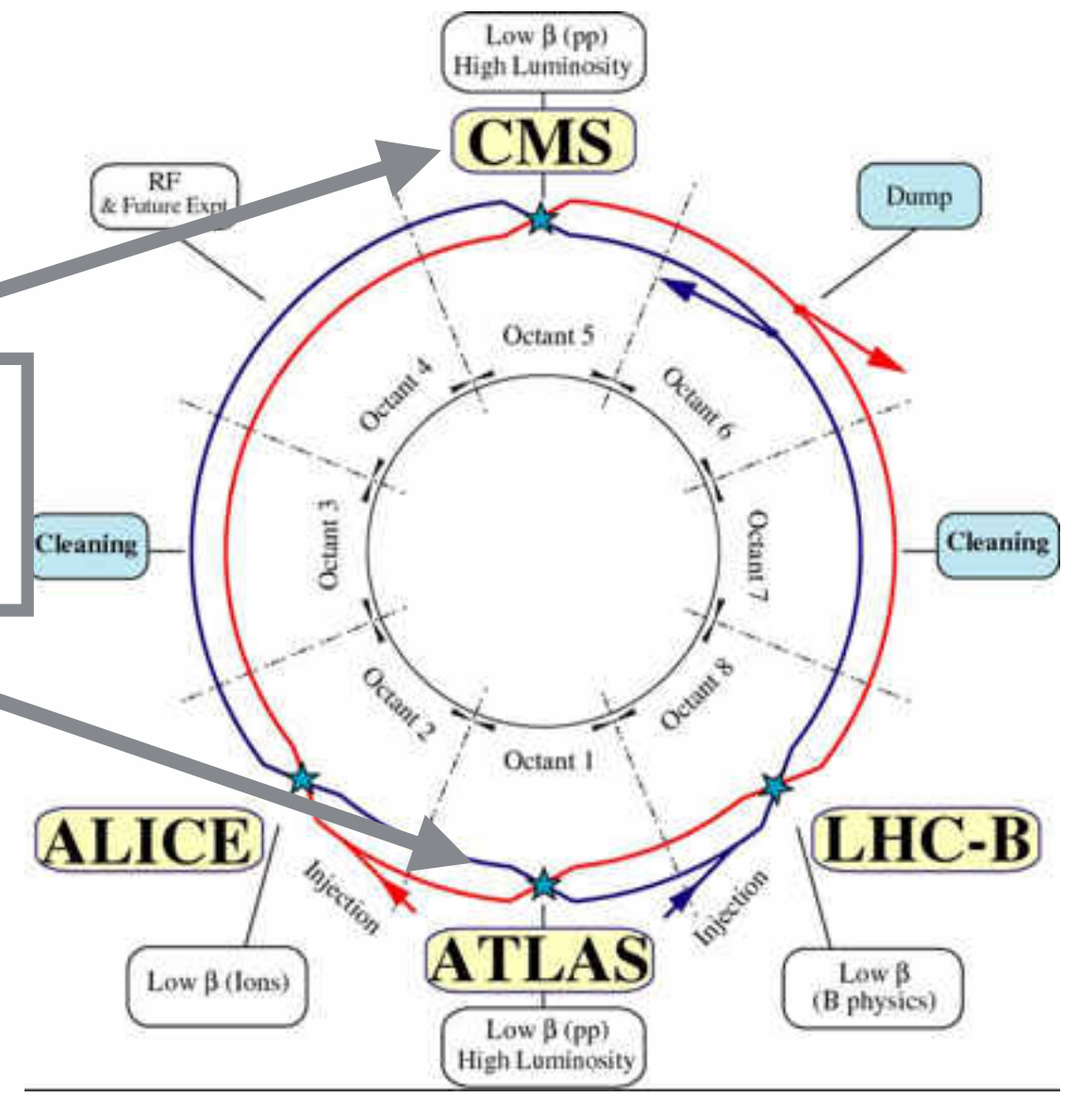
- **Does LHC deliver same amount of luminosity to ATLAS and CMS Experiments?**

  - **Z rate comparisons at both IPs (Reconstruction and DAQ efficiency corrected) as independent cross check**

    - **Independent to VdM calibration**

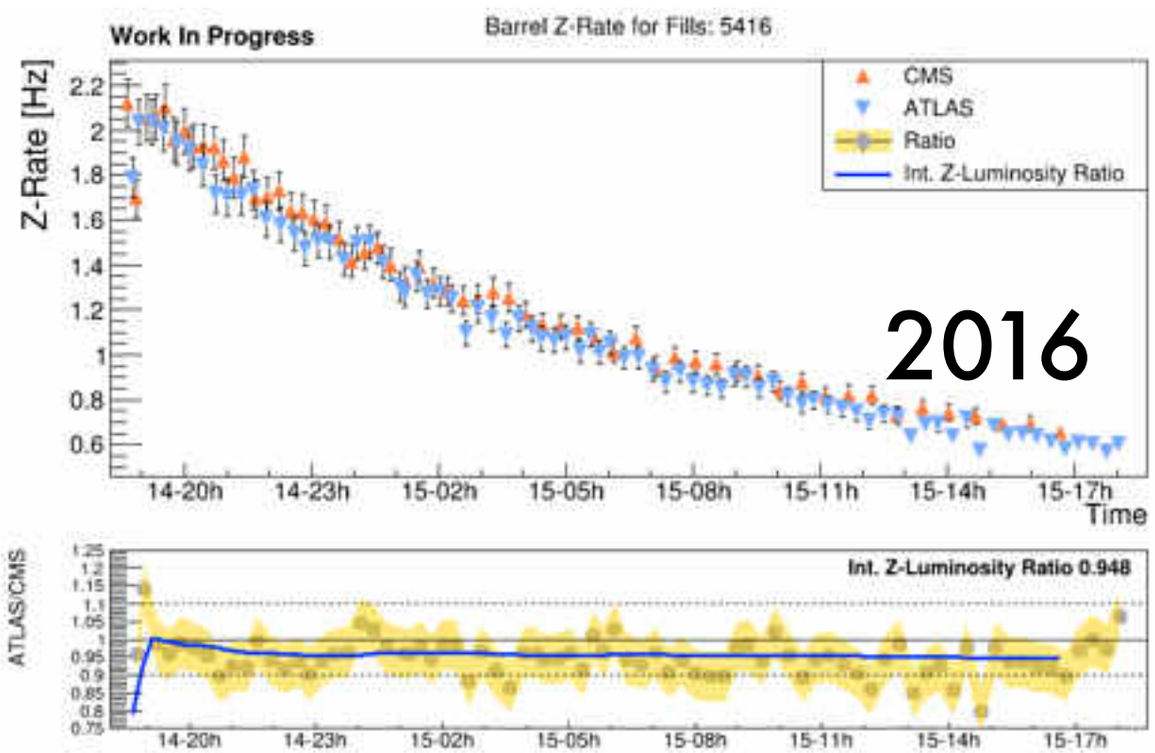


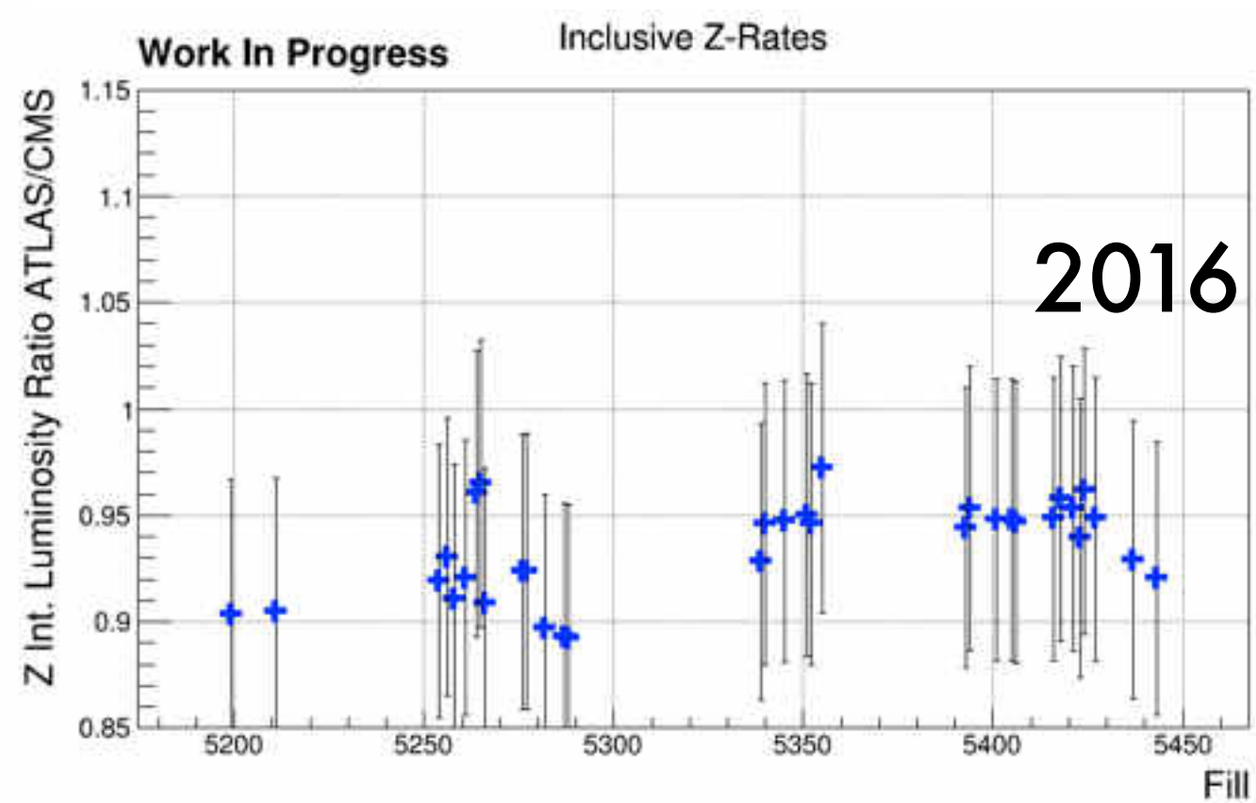
same Z cross-section



Z Rate Measurements

- **Z->μμ rate measurements performed in sub-datasets by ATLAS and CMS**
  - **same fiducial volume, direct comparison possible**
  - **corrections for data-taking efficiency applied by each experiment**





General Status

- **Luminosity measurements at the LHC is an active field of research**
  - **Great collective collaborational effort across all four experiments**
  - **many effects have been studied/understood during Run-1 though out Run-2, results are still being finalised**

	ALICE	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS	LHCb	ATLAS	CMS
Running period	2012 pp	2012 pp	2012 pp	2012 pp	2015 pp	2015 pp	2015 pp	2015 pp	2016 pp	2016 pp
$\sqrt{s}$ [TeV]	8	8	8	8	13	13	13	13	13	13
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%]	2.4	1.9	2.6	1.2	3.4	2.1	2.3	3.9 Prelim.	3.4 Prelim.	2.5

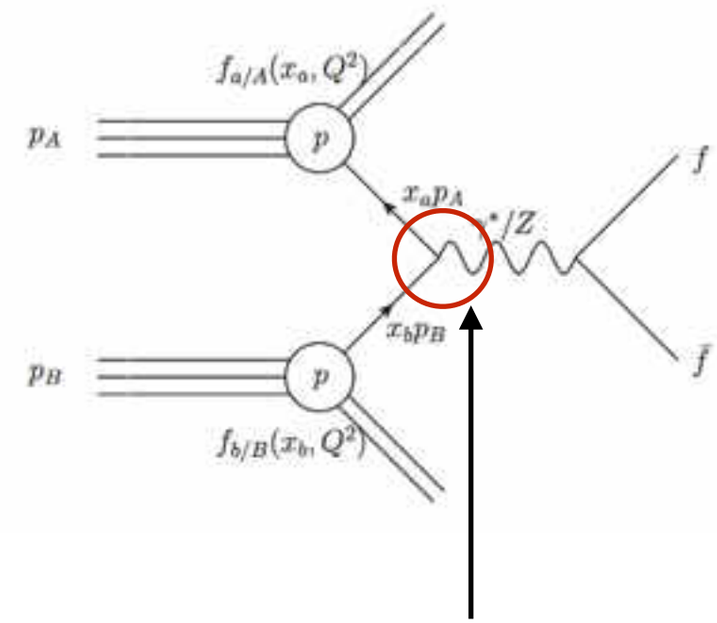
	ALICE	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS
Running period	2013 pp	2013 pp	2013 pp	2013 pp	2015 pp	2015 pp	2015 pp
$\sqrt{s_{NN}}$ [TeV]	2.76	2.76	2.76	2.76	5.02	5.02	5.02
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%]	3.8	3.1	3.7	2.2	2.1	5.4 Prelim.	2.3

Summary table borrowed of W. Kozancki and M. Gagliardi

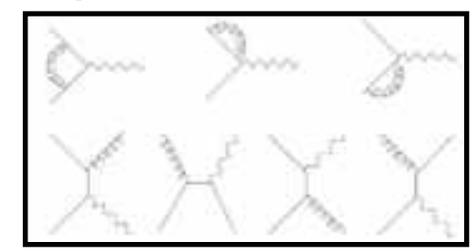
W/Z Cross Section Measurement

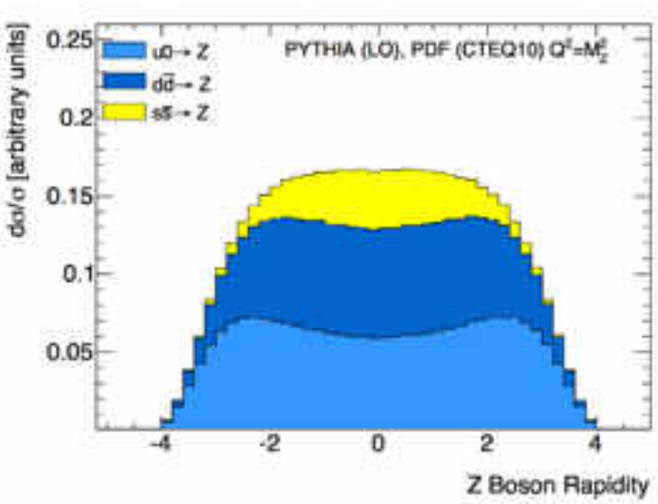
W/Z Cross section Measurement

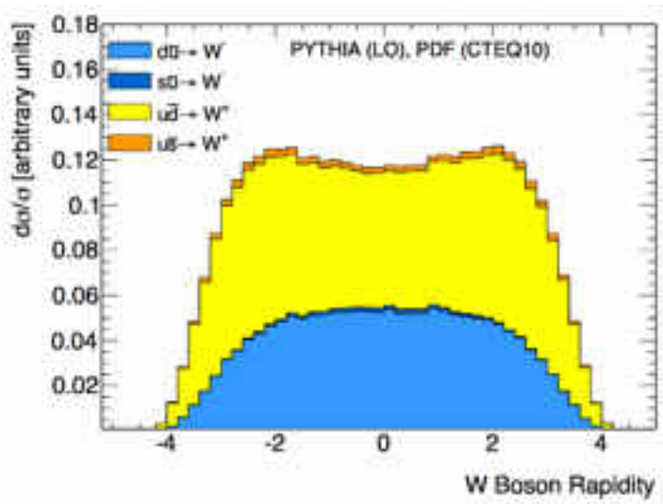
- **W/Z inclusive and differential cross section measurements probe:**
  - **QCD and EW higher order corrections**
  - **Parton Density Distributions of Proton**
  - **Background for BSM Searches**

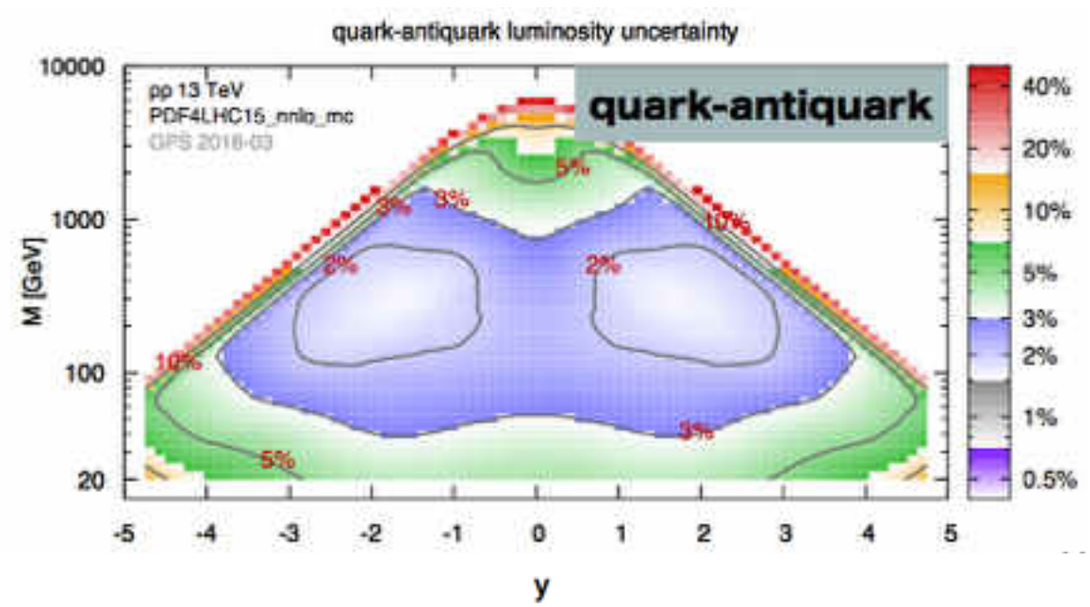


20-30% increase
LO-> NNLO









valence quarks interact with sea quarks

Overview

Signal Extraction, Background Estimation

$$\sigma_p = \frac{\int R_p dt}{\int \mathcal{L}} = \frac{N_p}{\epsilon A} \frac{\sigma_{\mathcal{A}}^{vdM}}{\int R_{\mathcal{A}} dt}$$

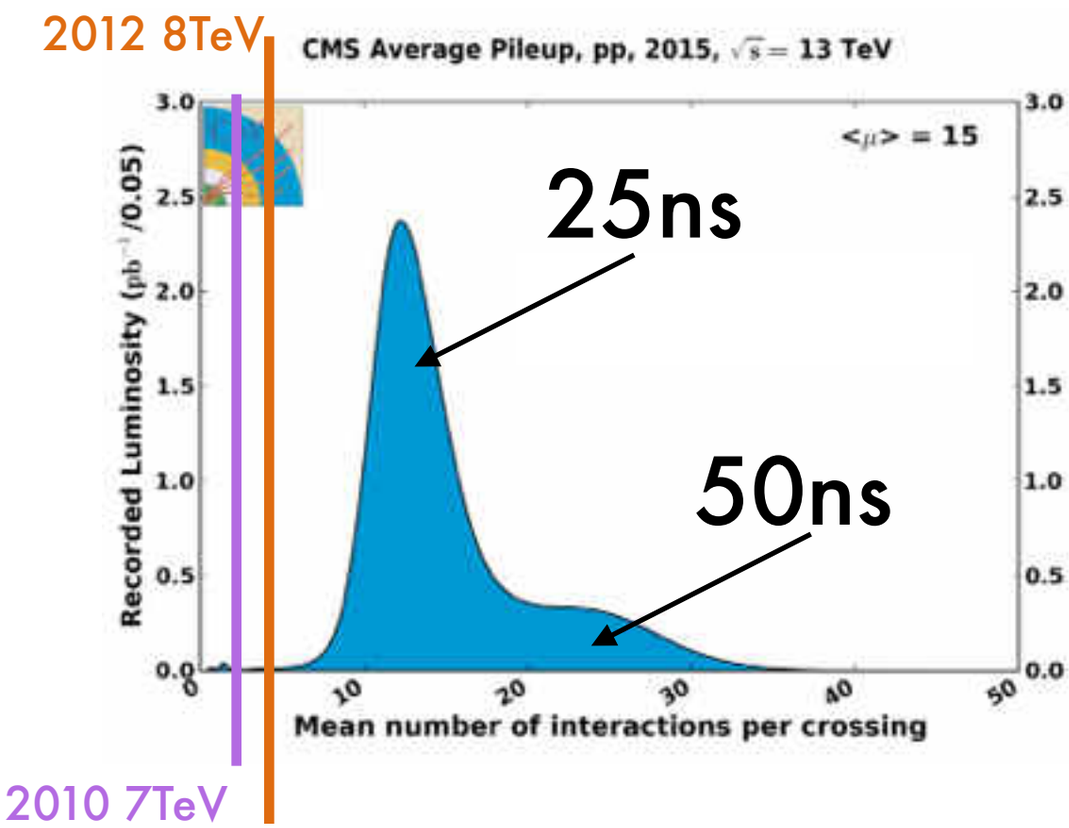
Event (Lepton) reconstruction & selection

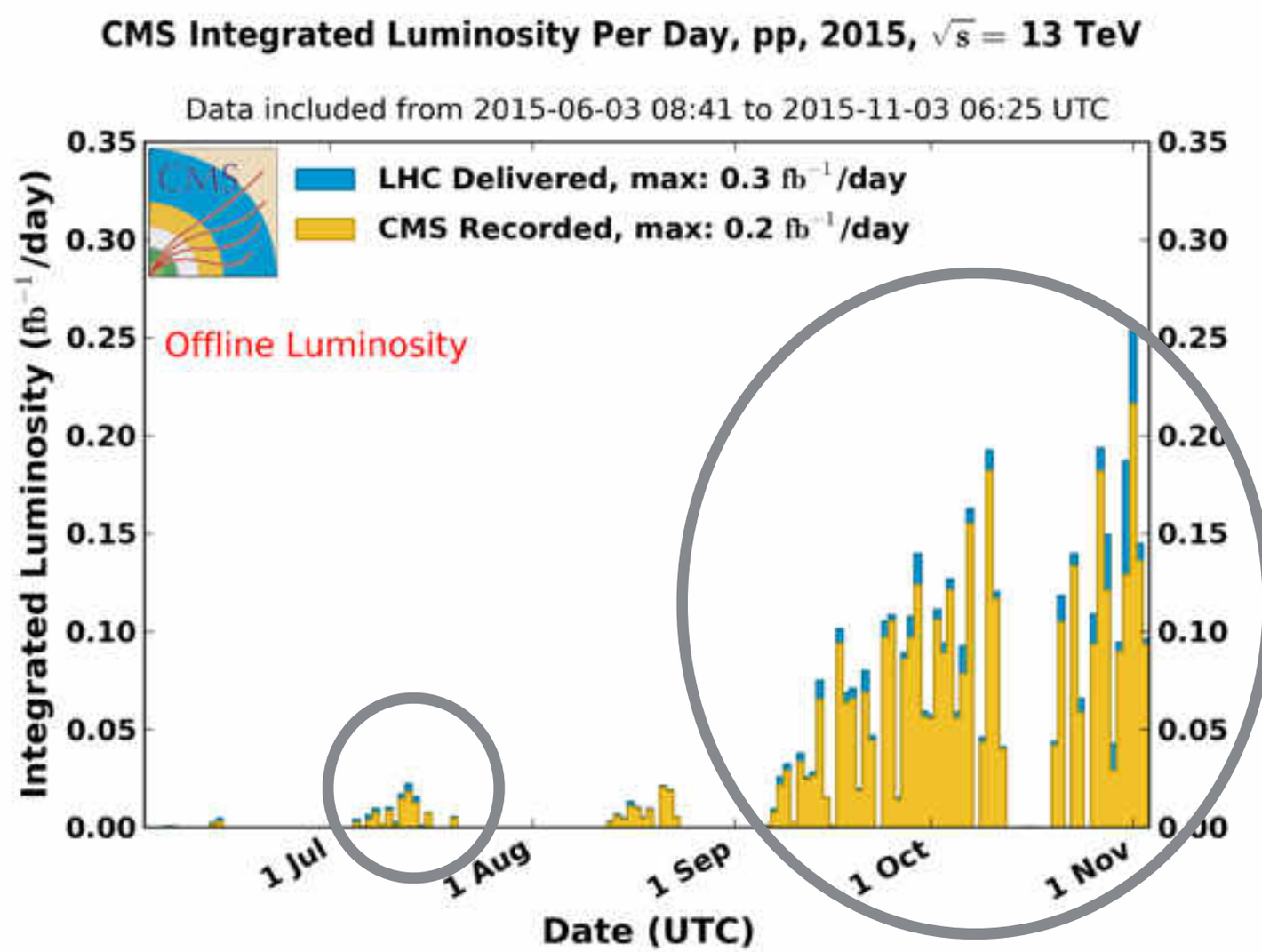
Detector acceptance, theoretical uncertainties

- **Results summarised in Physics Analysis Summaries SMP-15-004 (W/Z Inclusive) and SMP-15-011(Z differential)**
  Paper on 13 TeV W/Z cross sections in progress

Dataset and Conditions

- **Results based on 2015 dataset, two different periods**
  50ns bunch spacing 43/pb => ~ 30k Z→μμ events (cross section)
  25ns bunch spacing 2.3/fb => ~ 1.6M Z→μμ events (differential)





- **Experimental trick used during run one: low pile up**

  ▶ **not the case in Run-2**

Event Selection/Acceptance

- **Topology of Z events is characterised by two leptons of same flavour and opposite charge,**
- **Topology of W events: one lepton and missing transverse energy from neutrino escaping direct detection**
- **Acceptance obtained from simulation, fraction of events passing selection cuts on η and p_T**
  - **Baseline value obtained from aMC@NLO(+Pythia)**
- **Theoretical uncertainties enter:**
  - **(non-)perturbative QCD effects NNLO+NNLL RESBOS, DYRES, HORACE for EWK NLO, FEWZ for >NNLO by scale variations**
  - **impact of PDF uncertainties estimated from parameter variations**

Fiducial Volume

- Muon Channel:
  - p_T>25 GeV and |η|<2.4
  - Z selection: opposite charge, 60 GeV <$M_{\mu\mu}$<120 GeV
  - W selection: reject second muon with p_T>10 GeV
- Electron Channel:
  - E_T>25 GeV and |η|<2.5, excluding 1.44<|η|<1.5
  - Z selection: 60 GeV <M_{ee}<120 GeV
  - W selection: reject second electron with E_T>10 GeV

Lepton Selection Efficiency

- **Measured on data directly, using Tag-And-Probe technique**
- **Use Z-line mass shape, and count number of leptons failing and passing selection requirements**
- **performed in bins of (η,p_T)**

$$\epsilon = \frac{N_{pass}}{N_{pass} + N_{fail}}$$

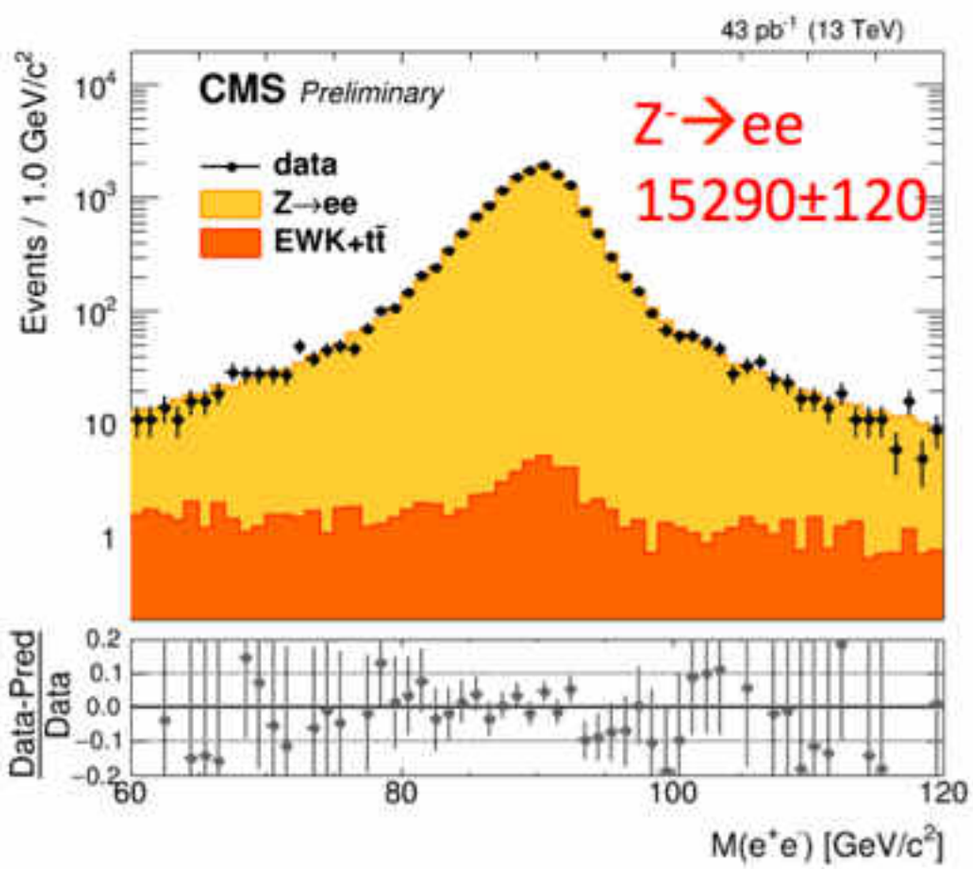
- **tracking, calorimeter cluster reconstruction lepton identification efficiency measured**
- **Uncertainty estimated from signal and background shape assumptions**
  - Signal: MC shape*Gaussian (default), Breit-Wigner*Cyrstal-Ball
  - Bkgr: Exponential (default), linear, ErrF*Exp, MC template from W+jets+QCD
  - N.B. statistic of the tag&probe sample affects systematic error

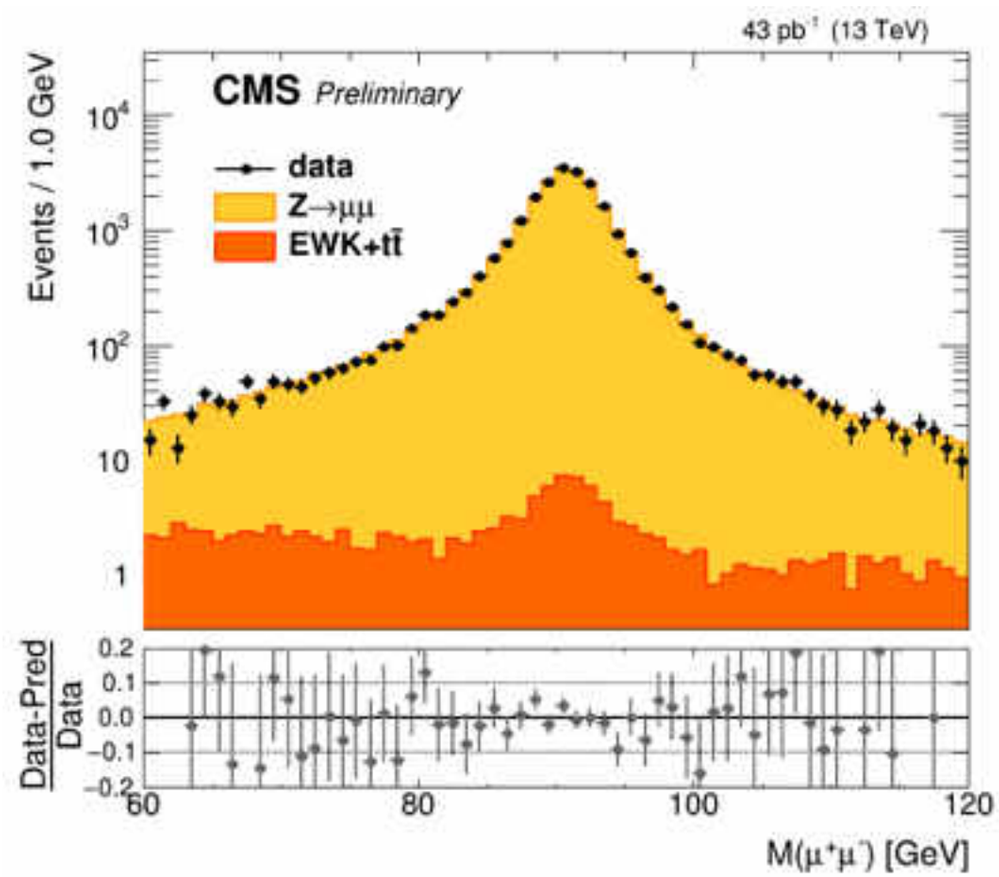
Z Boson Signal Extraction

- **Background subtracted yields (derived from simulation)**

Source	$Z \to e^+e^-$	$W^+ \to e^+\nu$	$W^- \to e^-\bar{\nu}$
Yields	15290 ± 120	122320 ± 980	98200 ± 950
Acceptance	0.33 ± 0.01	0.43 ± 0.01	0.44 ± 0.01
Efficiency	0.56 ± 0.01	0.58 ± 0.01	0.60 ± 0.01
Source	$Z \to \mu^+\mu^-$	$W^+ \to \mu^+\nu$	$W^- \to \mu^-\bar{\nu}$
Yields	23670 ± 150	167710 ± 830	131250 ± 910
Acceptance	0.36 ± 0.01	0.44 ± 0.01	0.46 ± 0.01
Efficiency	0.80 ± 0.02	0.78 ± 0.01	0.79 ± 0.01

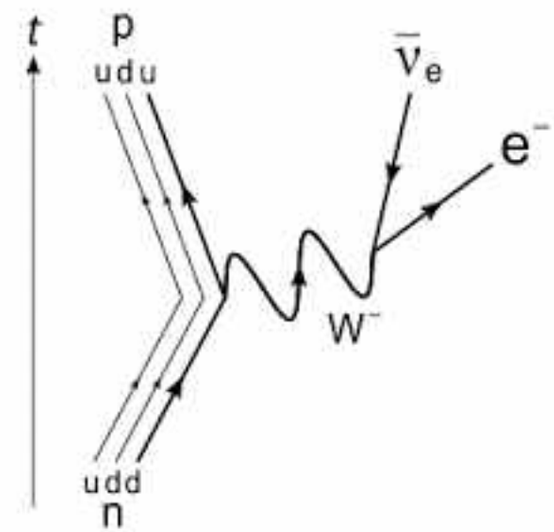
- **Background: 0.6% ttbar, W+Jets, WZ and $Z \to \tau\tau$ processes estimated from simulation**



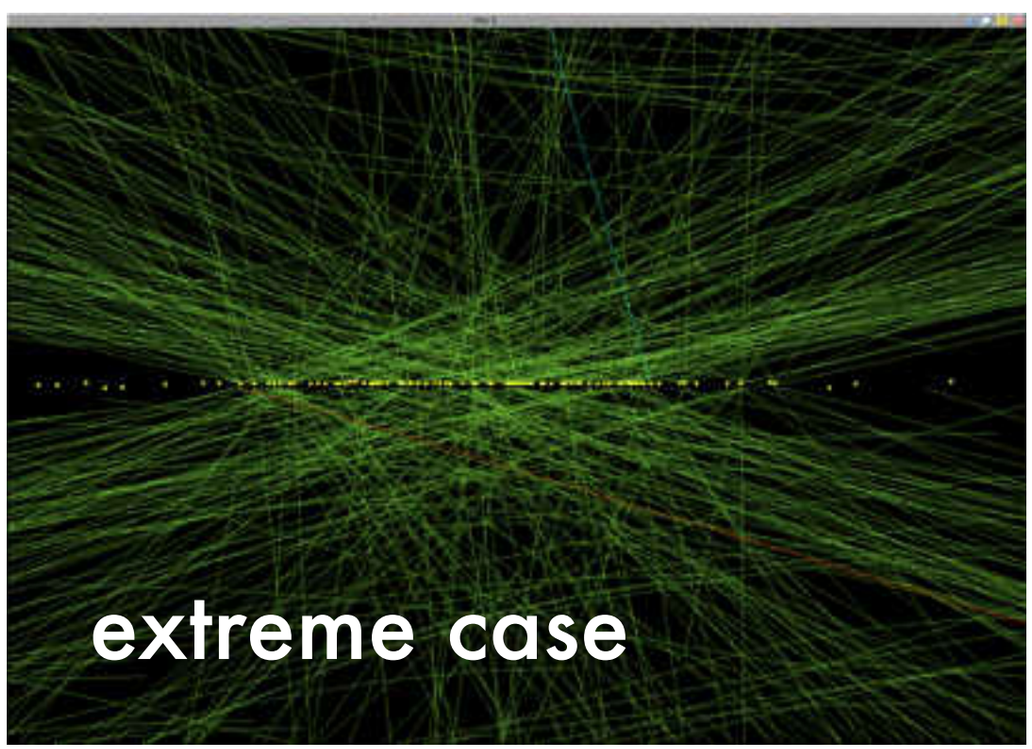


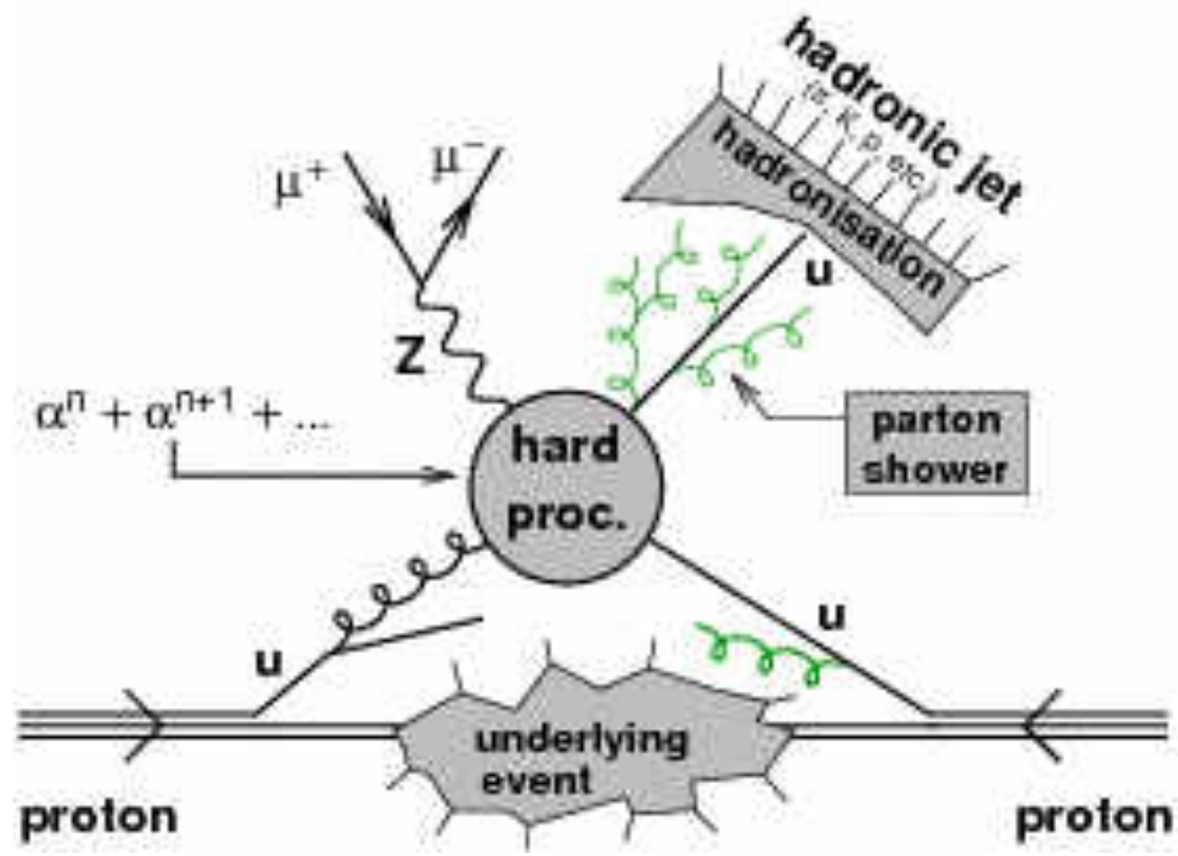
W Boson Signal Extraction

- **missing transverse energy distribution used to extract signal**
  - **Important to have precise missing transverse energy reconstruction**



- **two effects spoiling proper MET model in simulation: pileup contributions, "underlying event" model (proton remnant interactions)**

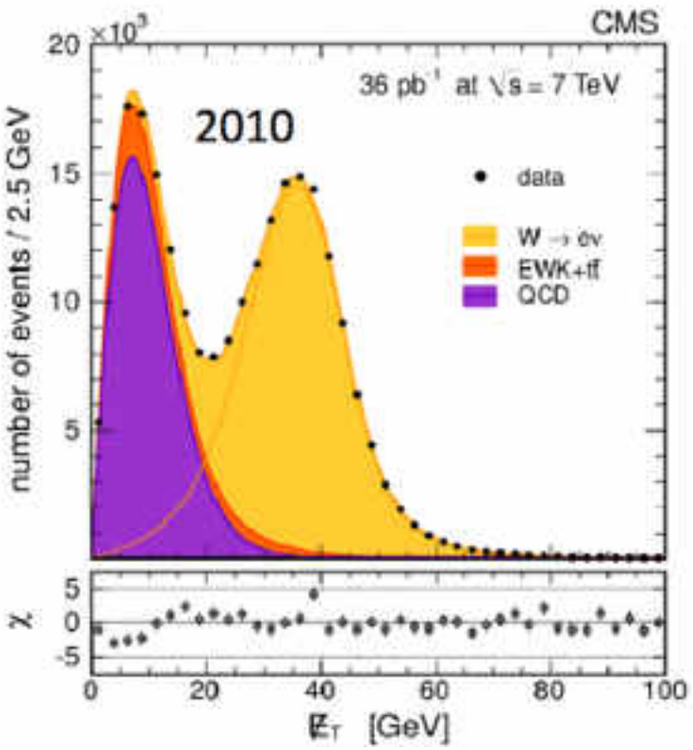


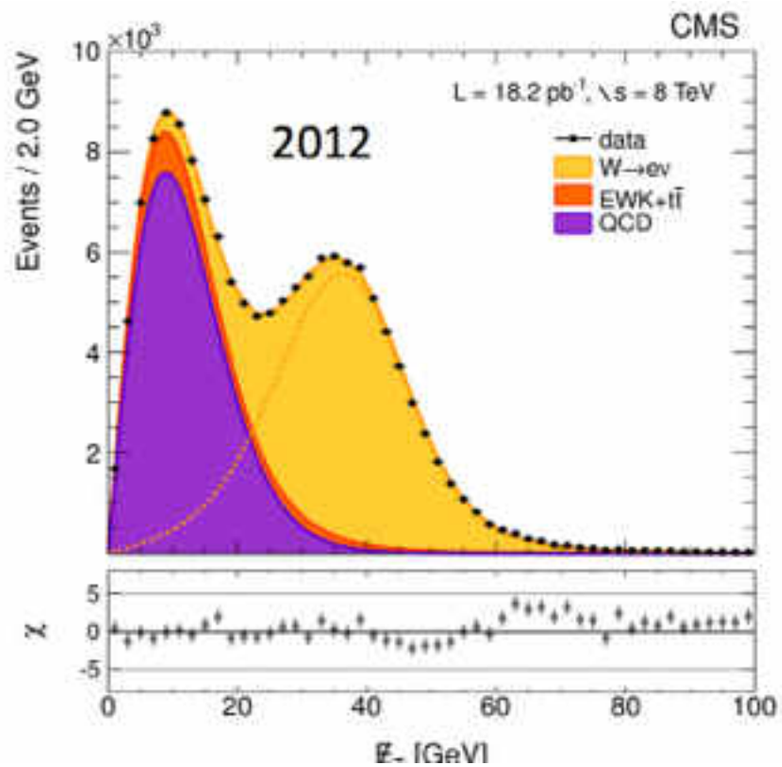


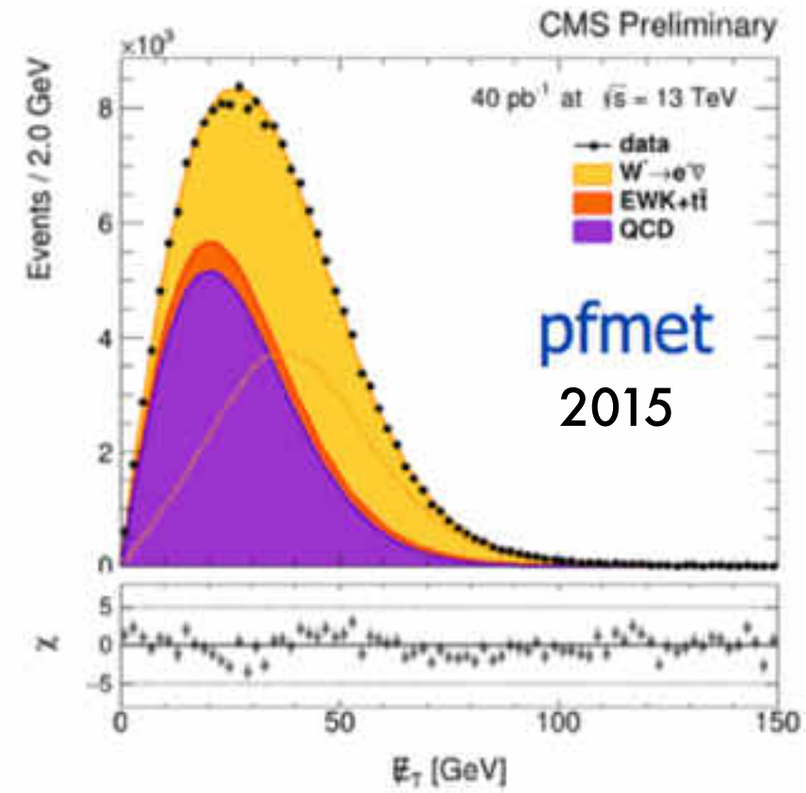
W Bosons Run-1

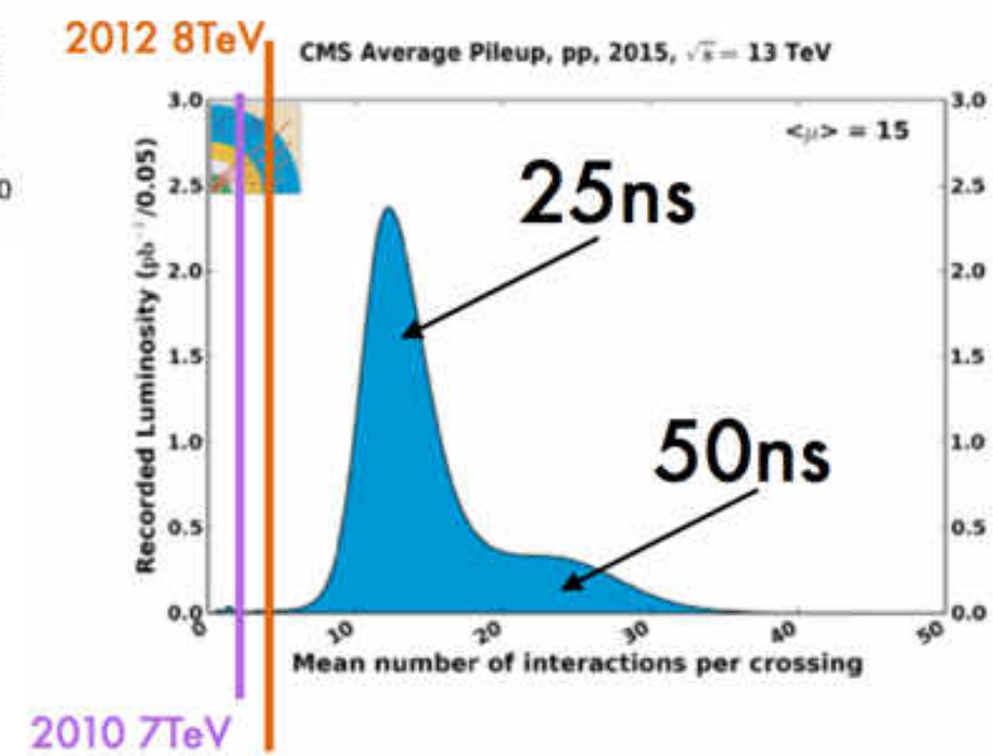
- **Good MET resolution is indeed crucial**

  - **Also here: luminosity is important to control**









- **QCD component is modelled using Rayleigh Distribution (no genuine MET)**

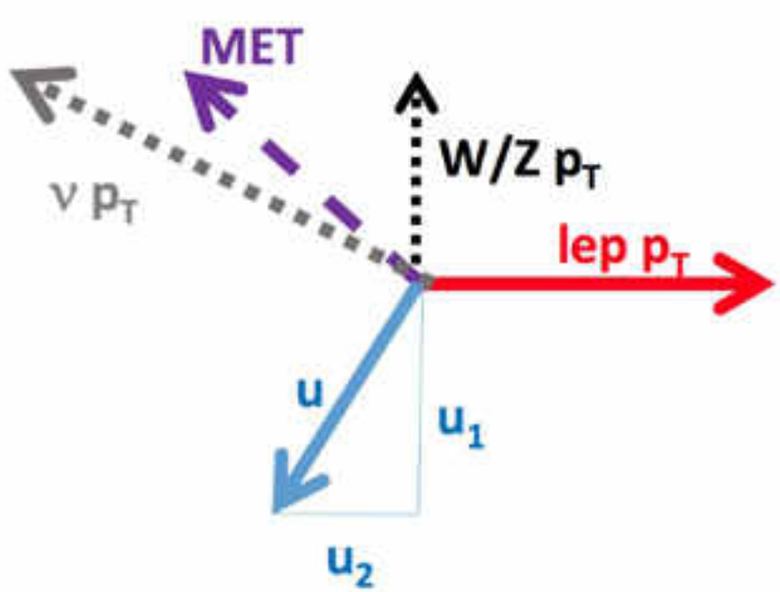
$$f_{\mathrm{QCD}}(E_{\mathrm{T}}^{\mathrm{miss}}) = E_{\mathrm{T}}^{\mathrm{miss}} \exp\left(-\frac{E_{\mathrm{T}}^{\mathrm{miss2}}}{2(\sigma_0 + \sigma_1 E_{\mathrm{T}}^{\mathrm{miss}})^2}\right)$$

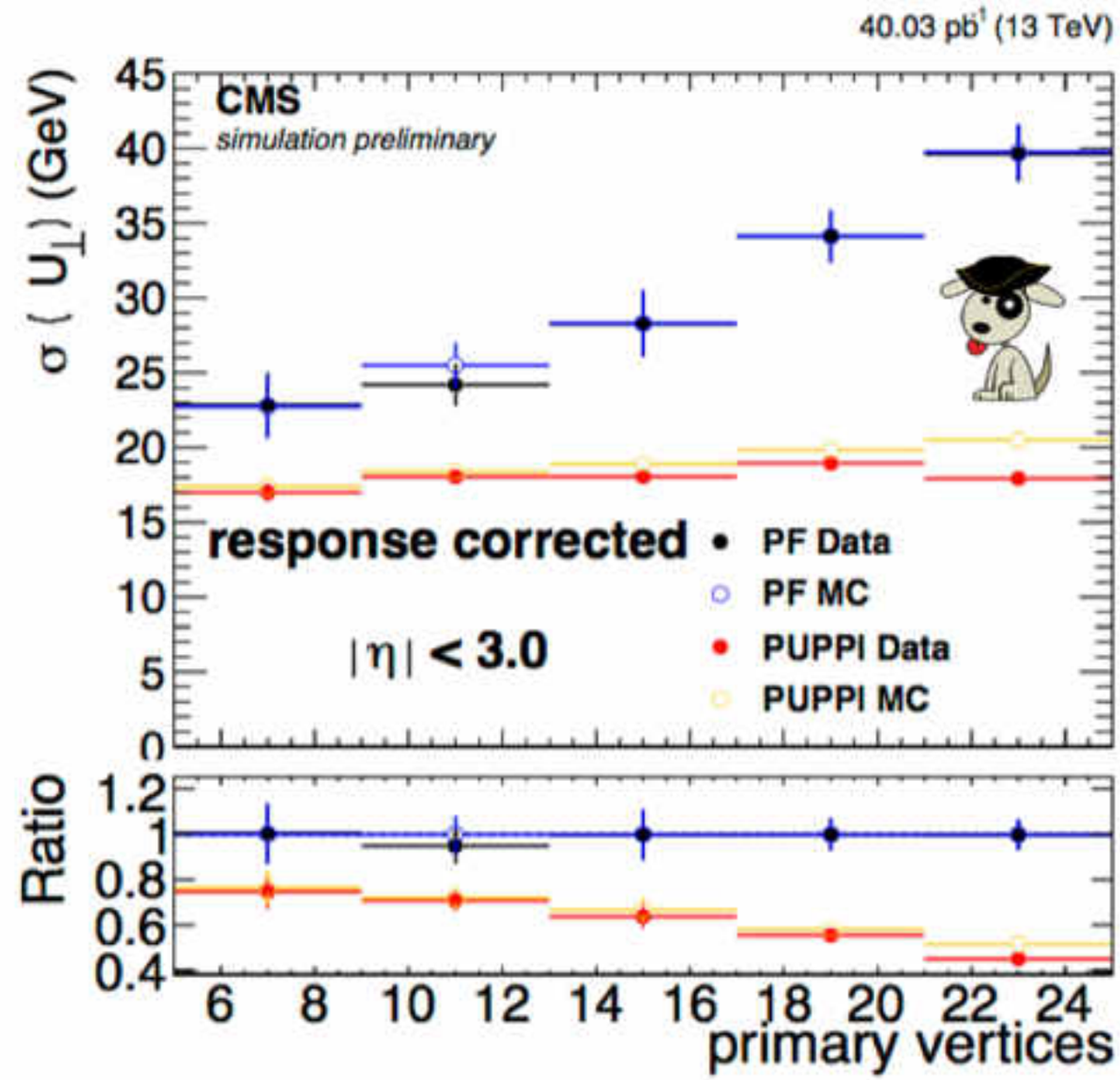
MET Recoil Corrections

- **Obtained improved resolution of missing transverse energy => <u>"PUPPI"</u> algorithm used to identify contributions from PU particles (arXiv:1407.6013)**

- **In addition: correct simulated hadronic recoil to the one observed in data in Z events**

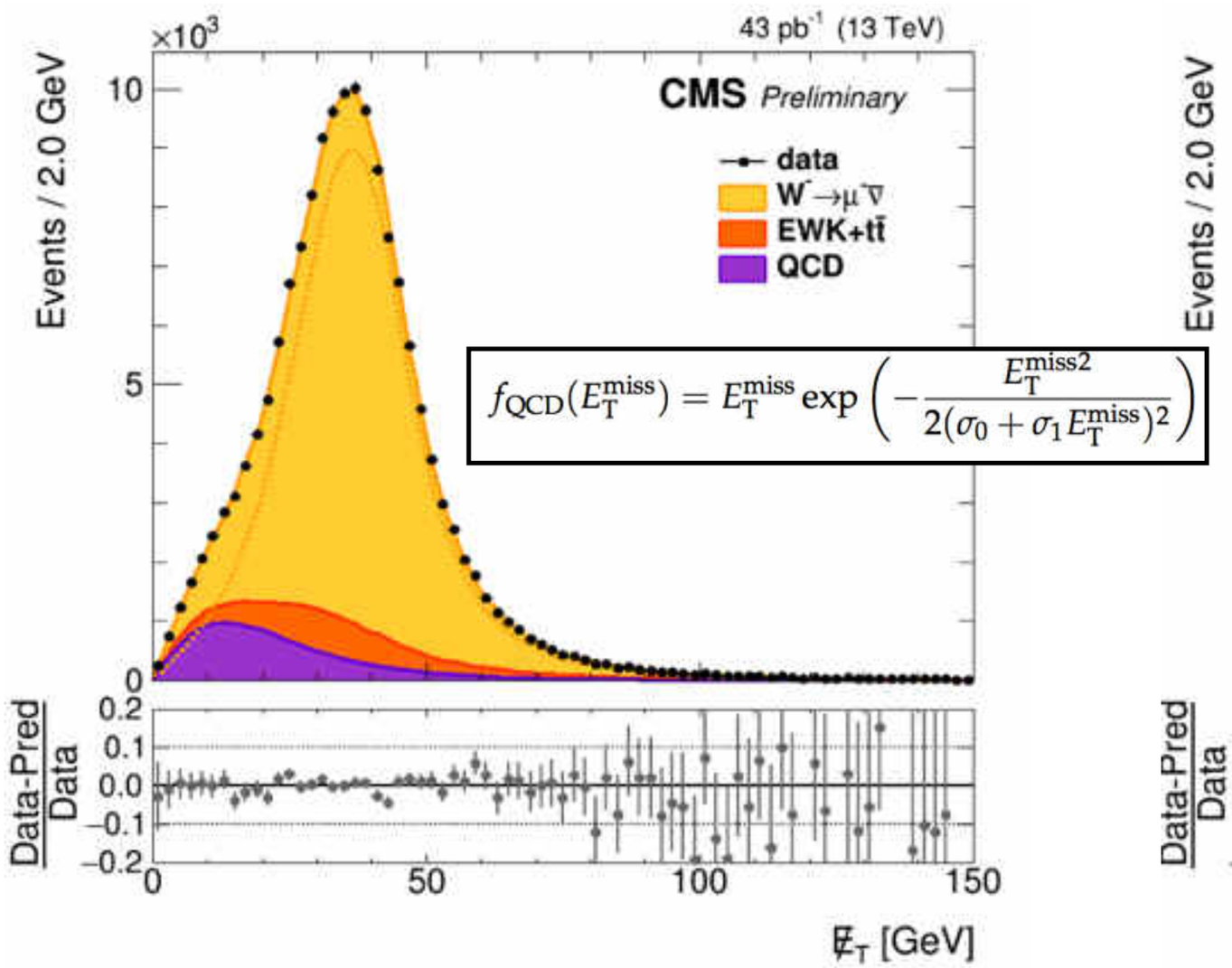
  - **apply to simulated W events**

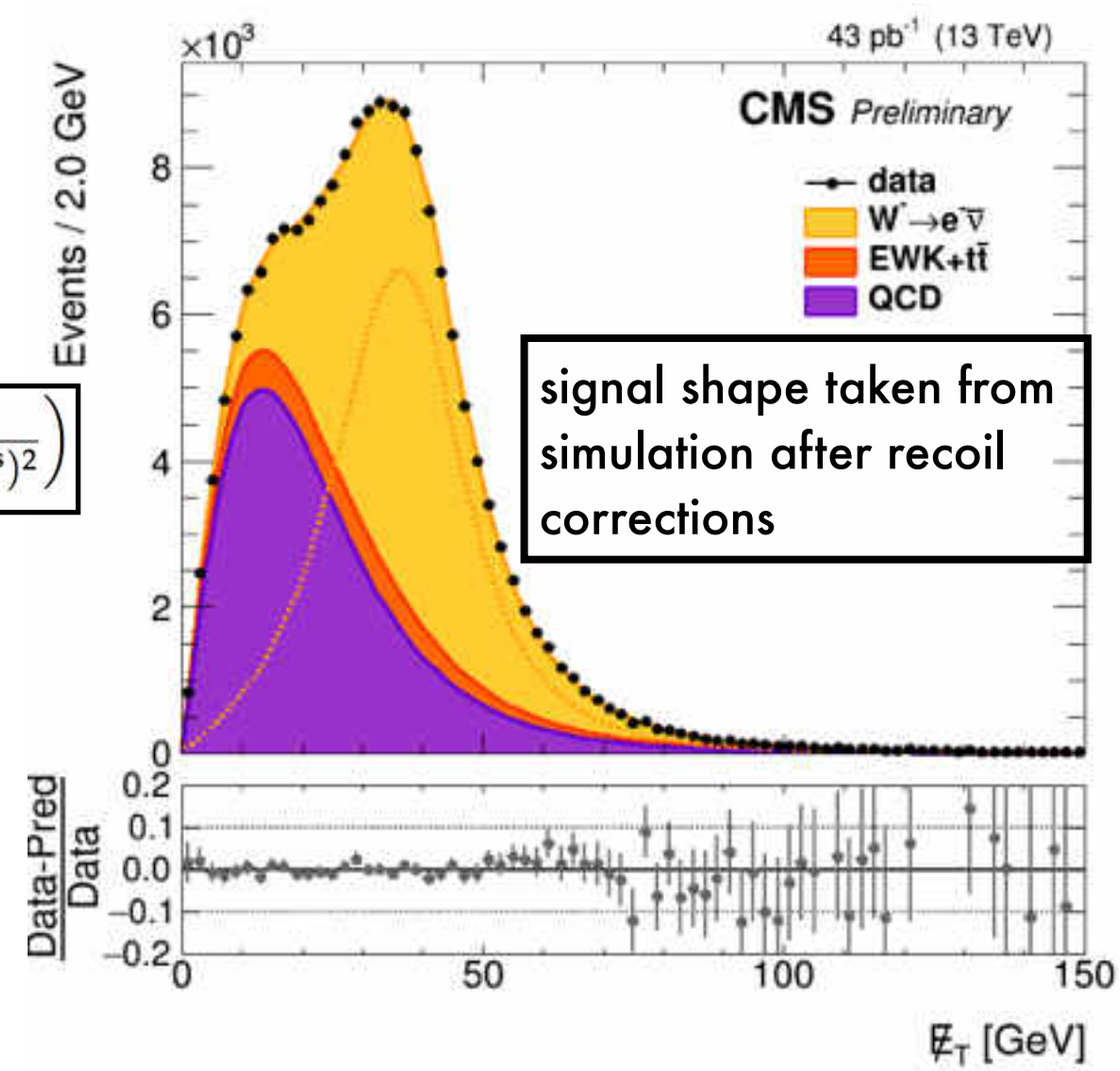




Signal Extraction

- **With improved resolution => signal extraction possible**





- **EW contributions, from Z→$\tau\tau$, W→τv, ttbar and DY with missing lepton**

Systematic Uncertainties

Muons, 50ns

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	1.9	1.7	1.8	0.3	2.2	0.6	0.6	0.6
Bkg. subtraction / modeling [%]	0.6	0.6	0.6	0.4	0.6	0.8	0.8	0.8
E_T^{miss} scale and resolution			shape		NA		shape	
Muon scale and resolution			shape		NA		shape	
Total experimental [%]	2.0	1.8	1.9	0.5	2.3	1.1	1.1	1.1
Theoretical Uncertainty [%]	2.0	1.7	1.3	2.3	1.5	2.0	1.9	1.6
Lumi [%]	4.8	4.8	4.8	NA	4.8	NA	NA	NA
Total [%]	5.6	5.4	5.3	2.3	5.5	2.3	2.2	1.9

- **Measurement limited by luminosity uncertainty (note: based on previous preliminary luminosity calibration)**
- **Otherwise experimental and theoretical uncertainties comparable in size**

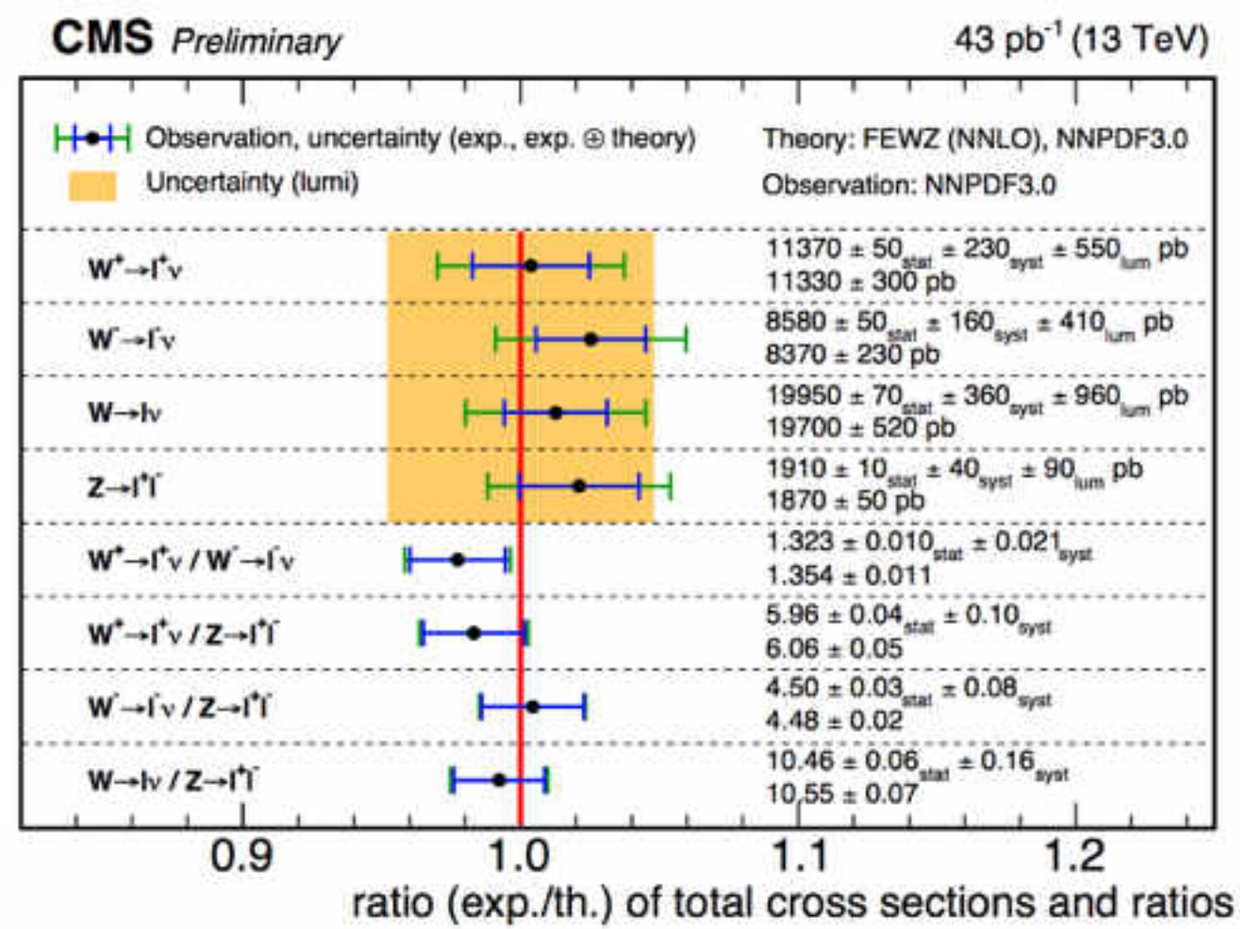
Total Inclusive Cross Sections

- **Cross section extrapolated from fiducial volume**

- **Good agreement with SM NNLO prediction**

  - **NNLO FEWZ cross section +NNPDF3.0**

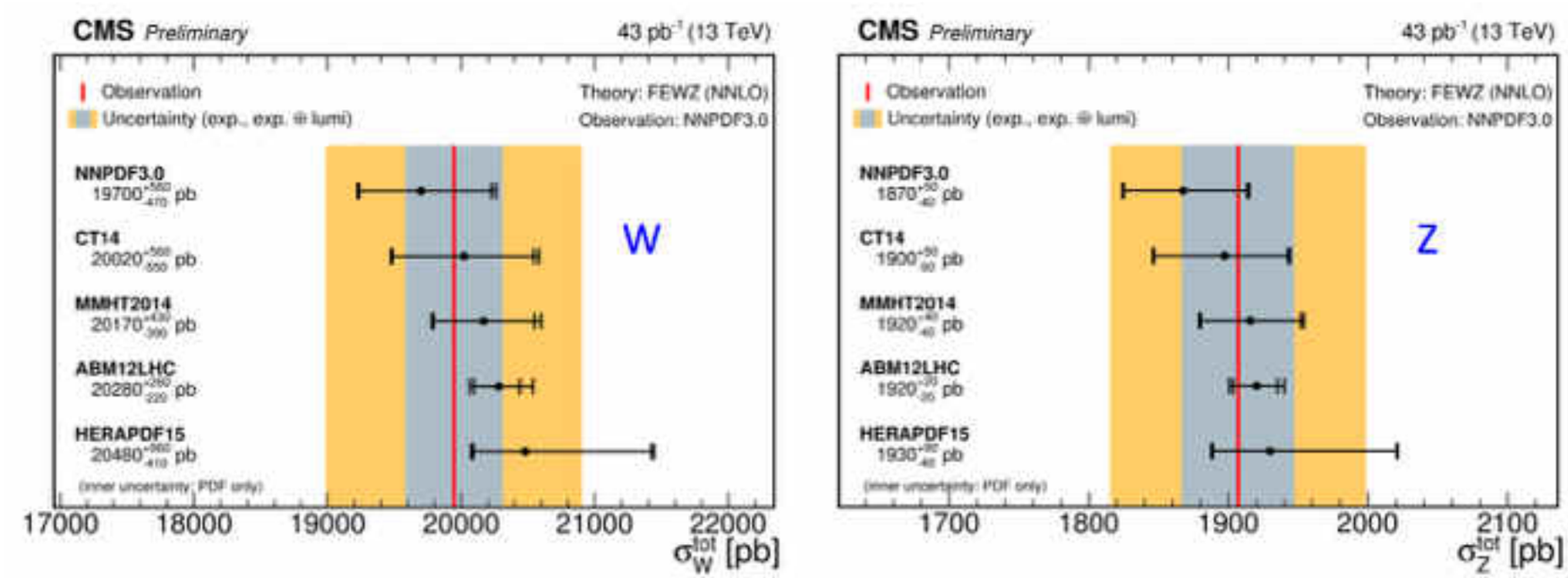
- **Theoretical uncertainties included from PDF and scale variation (dominated by PDF unc.)**



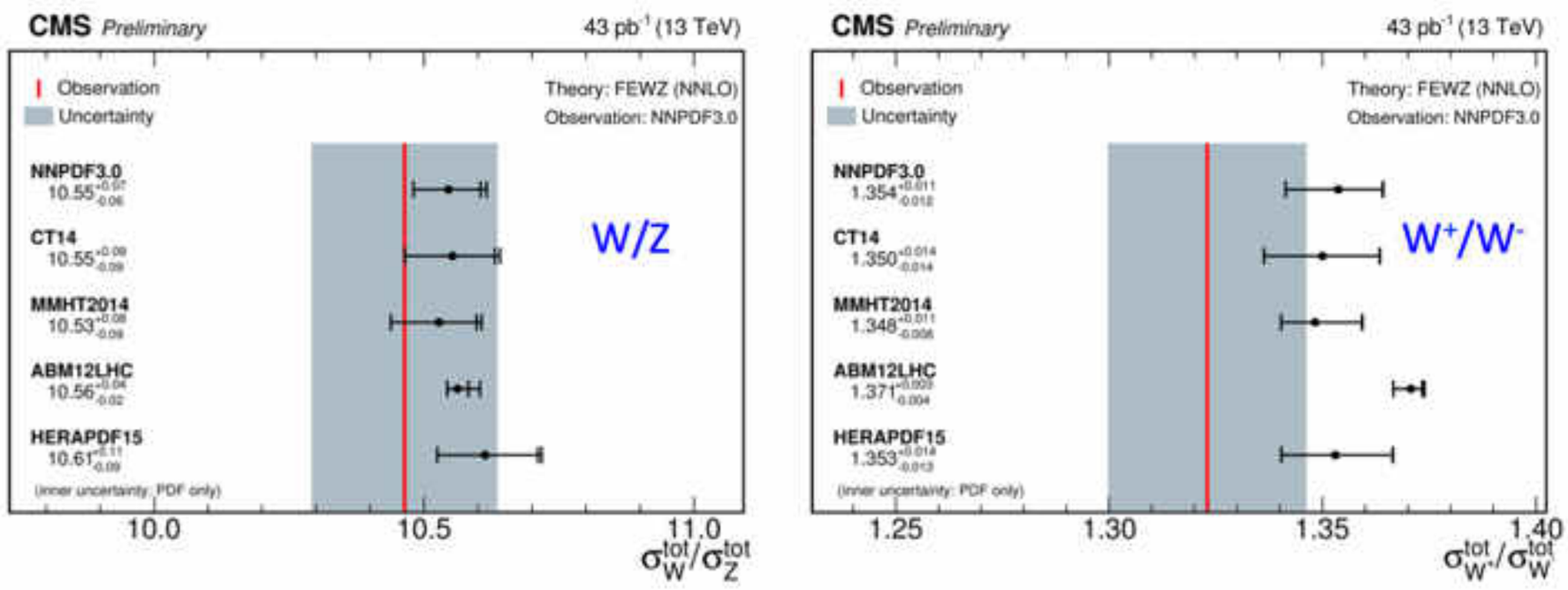
- **Z->μμ update with full dataset: 1870 ± 2 (stat) ± 35 (syst) ± 51 (lumi) pb**

Parton Distribution Functions

- **Comparison performed with different PDF sets**

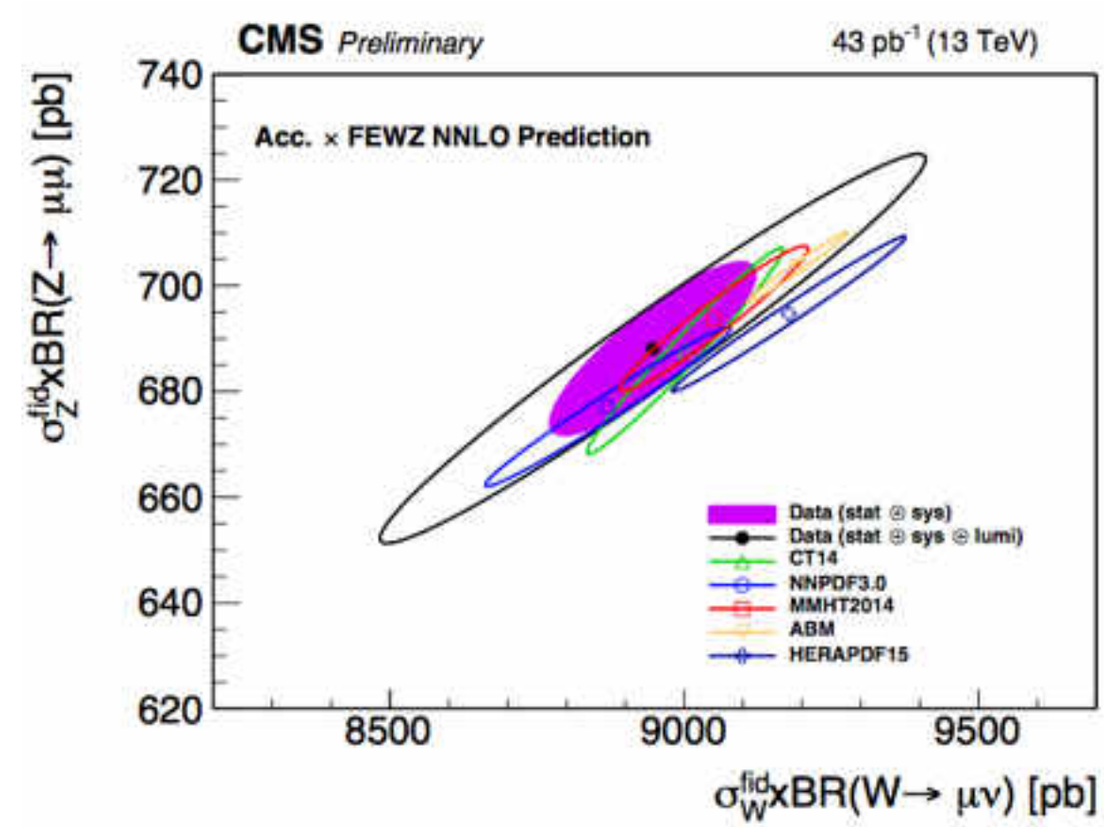


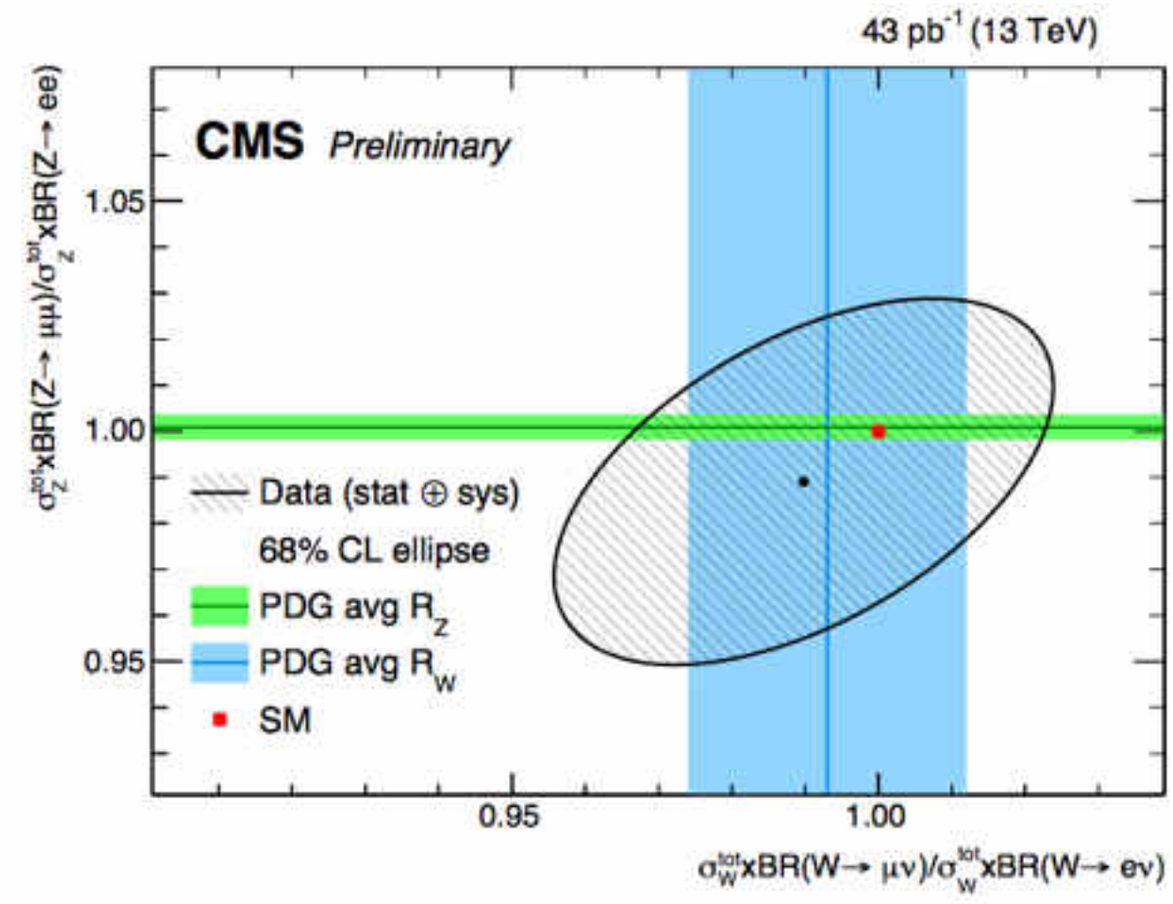
- **And ratios, part of the experimental uncertainties cancel**

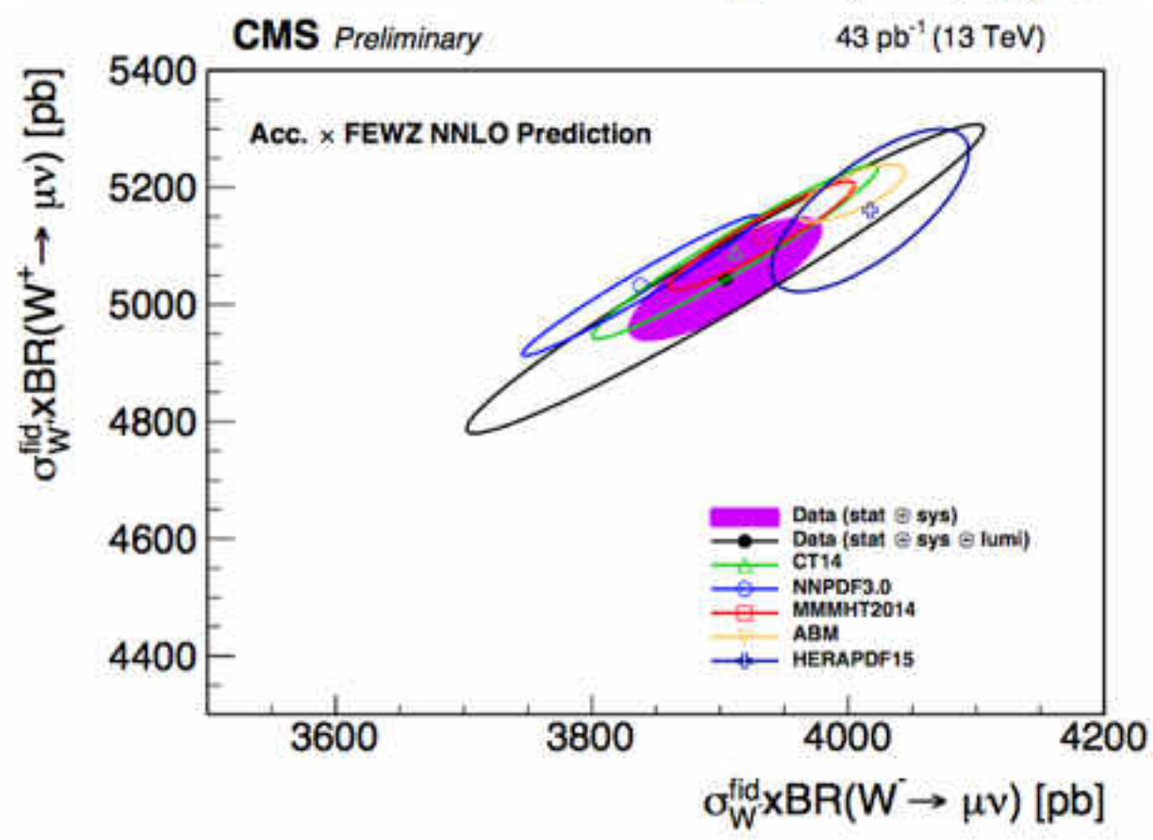


Lepton Universality, Relative PDF Comparisons

- **Relative scaling of cross sections for different PDF sets shown**
- **Universality of Electron and Muon couplings to vector bosons**

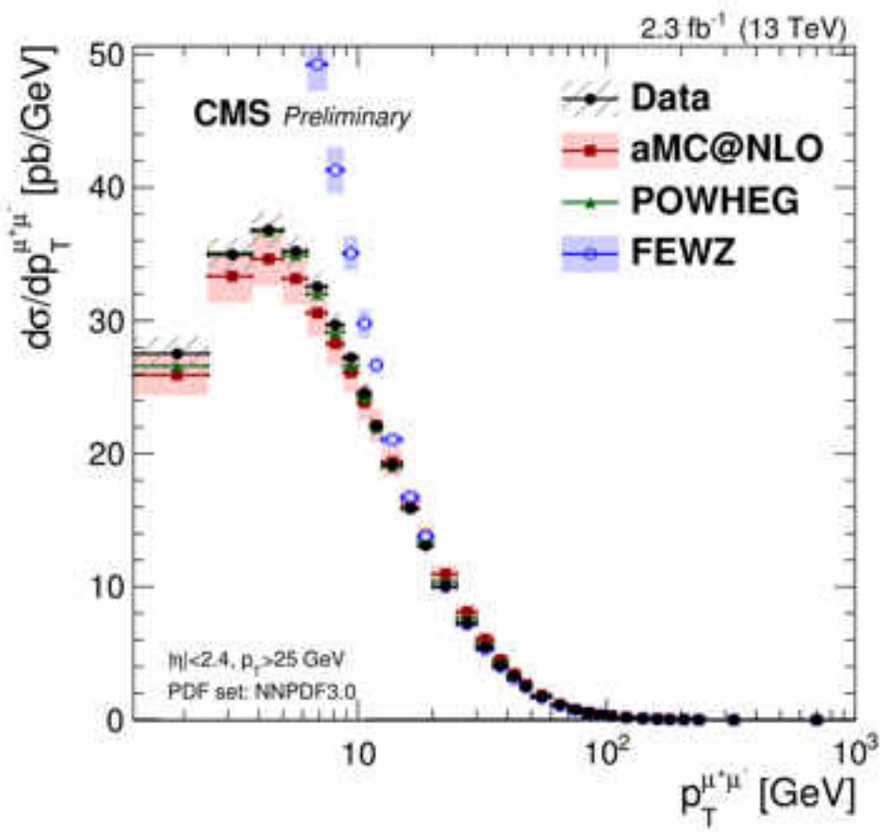


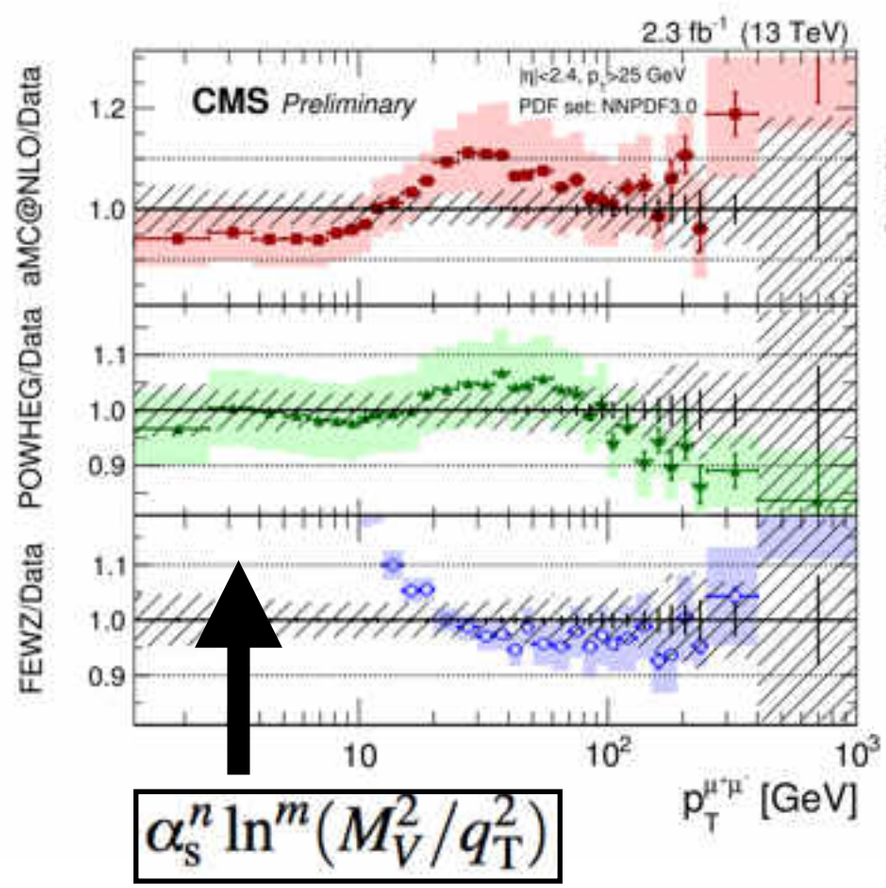


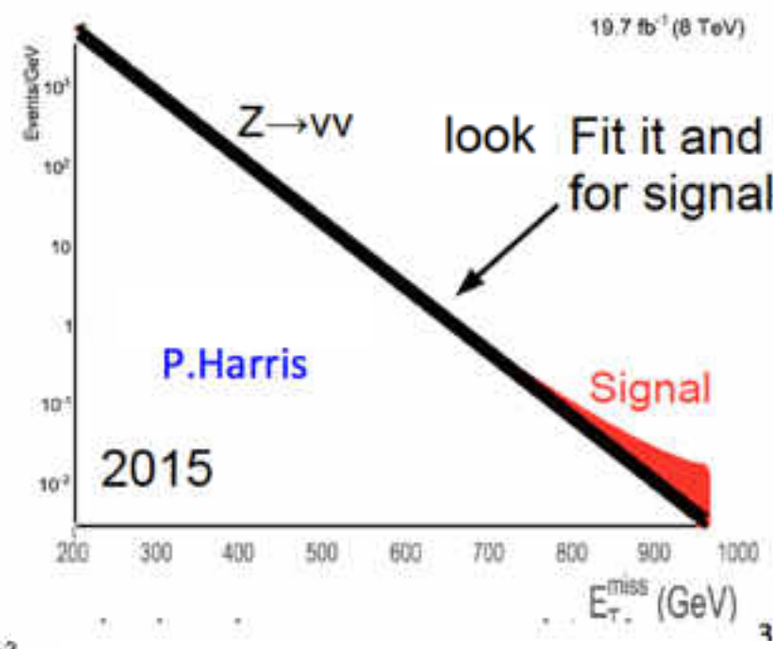


Differential Result

- **Absolute differential cross section measurements performed**
- **comparison with FEWZ and event generators (POWHEG,MADGRAPH)**
- **soft gluon emission (resummation) handled by PYTHIA, low pT probes NNLL calculations, high pT probes NNLO contributions**







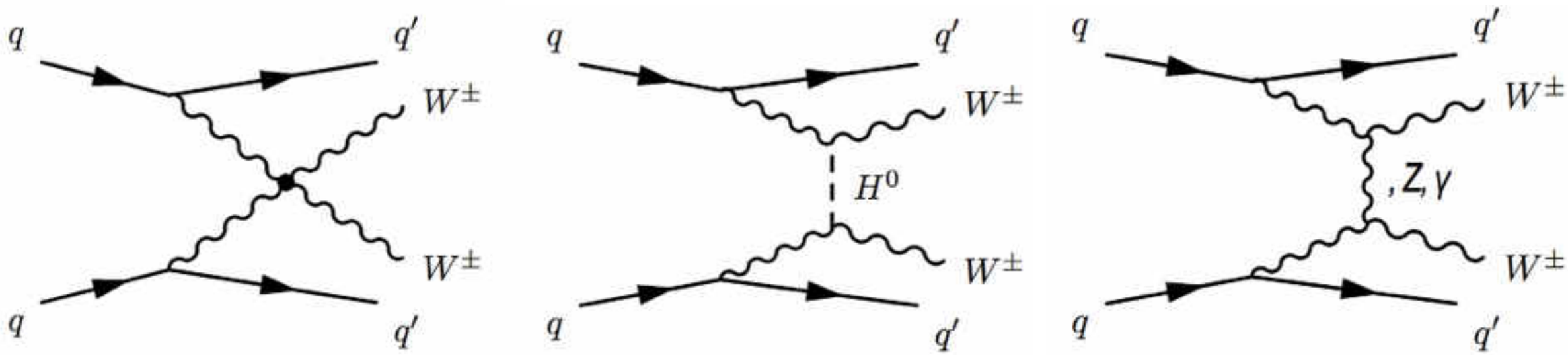
Observation of EW Production of same-sign W boson pairs

SMP-17-014

Vector Boson Scattering

- **Vector Boson Scattering is a crucial process to close to fully investigate Higgs mechanism**

  - **Higgs mechanism initially introduced to unitarize WW -> WW amplitude at the TeV-Scale**



$$\mathcal{M}_{\text{Higgsless}}(W_L^+W_L^- \to W_L^+W_L^-) \approx \mathrm{i}\frac{s+t}{v^2}$$

$$\mathcal{M}_{\text{SM}}(W_L^+W_L^- \to W_L^+W_L^-) \approx -\mathrm{i}\frac{m_H^2}{v^2}\left[2+\frac{m_H^2}{s-m_H^2}+\frac{m_H^2}{t-m_H^2}\right]$$

- **Probes so far unexplored operators in the SM Lagrangian (QGC,TGC)**

Run-1 History

Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

G. Aad *et al.* (ATLAS Collaboration)

Phys. Rev. Lett. **113**, 141803 (2014) – Published 3 October 2014

3.6σ observed
2.8σ expected

This Letter presents the first study of $W^{\pm}W^{\pm}jj$, same-electric-charge diboson production in association with two jets, using $20.3\ \mathrm{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 8\ \mathrm{TeV}$ recorded by the ATLAS detector at the Large Hadron Collider. Events with two reconstructed same-charge leptons ($e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, and $\mu^{\pm}\mu^{\pm}$) and two or more jets are analyzed. Production cross sections are measured in two fiducial regions, with different sensitivities to the electroweak and strong production mechanisms. First evidence for $W^{\pm}W^{\pm}jj$ production and electroweak-only $W^{\pm}W^{\pm}jj$ production is observed with a significance of 4.5 and 3.6 standard deviations, respectively. The measured production cross sections are in agreement with standard model predictions. Limits at 95% confidence level are set on anomalous quartic gauge couplings.

Study of Vector Boson Scattering and Search for New Physics in Events with Two Same-Sign Leptons and Two Jets

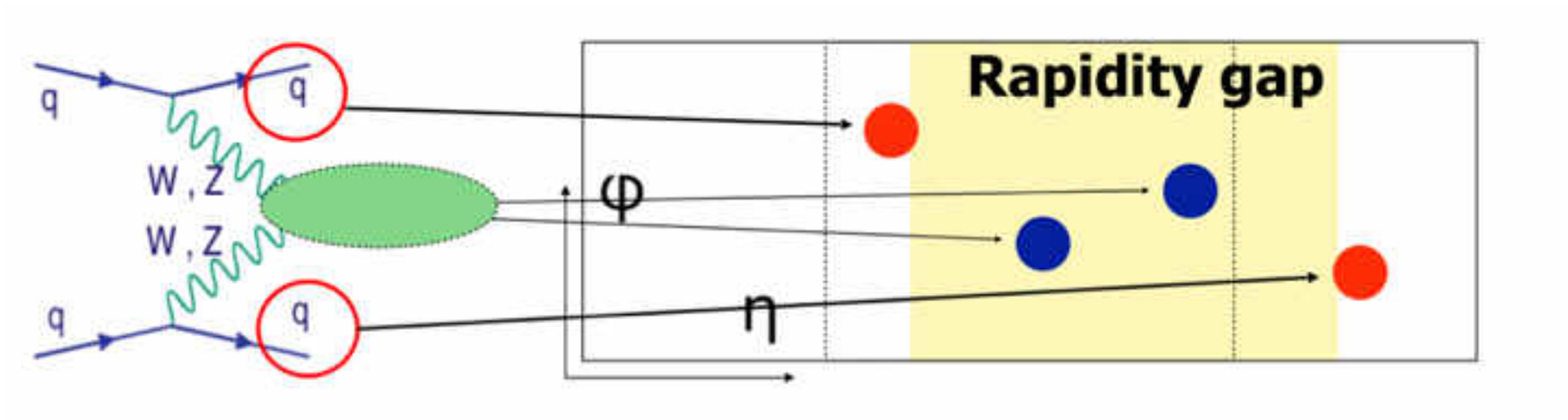
V. Khachatryan *et al.* (CMS Collaboration)

Phys. Rev. Lett. **114**, 051801 (2015) – Published 2 February 2015

2.0σ observed
3.1σ expected

A study of vector boson scattering in pp collisions at a center-of-mass energy of 8 TeV is presented. The data sample corresponds to an integrated luminosity of $19.4\ \mathrm{fb}^{-1}$ collected with the CMS detector. Candidate events are selected with exactly two leptons of the same charge, two jets with large rapidity separation and high dijet mass, and moderate missing transverse energy. The signal region is expected to be dominated by electroweak same-sign W-boson pair production. The observation agrees with the standard model prediction. The observed significance is 2.0 standard deviations, where a significance of 3.1 standard deviations is expected based on the standard model. Cross section measurements for $W^{\pm}W^{\pm}$ and WZ processes in the fiducial region are reported. Bounds on the structure of quartic vector-boson interactions are given in the framework of dimension-eight effective field theory operators, as well as limits on the production of doubly charged Higgs bosons.

Event Selection (Run-2 Analysis)



- **Exploit the VBS topology and clean same-sign lepton final state**
  - Trigger Selecton Single and Double Lepton Triggers, 99% efficiency
  - Two same-sign isolated leptons (electrons or muons) p_T>25,20 GeV letal<2.5
  - VBF selection: m_{jj} > 500 GeV $|\Delta\eta_{JJ}|$> 2.5 cut on max(z^*)< 0.75

- **Background rejection**
  - 3rd lepton veto (loose ID), >10 GeV
  - $|m_{ll}$ - m(Z)|>15 GeV
  - reject events with b-tagged jet
  - MET > 40 GeV

$$z_\ell^* = |\eta_\ell - (\eta_{j1} + \eta_{j2})/2| / |\Delta\eta_{jj}|$$

Event Yields

- **Leading background (64%) from non-prompt leptons top-pair production and W+Jets**
  - **Estimated from loose-to-tight fake rate method**
- **WZ (18%) and wrong-sign background estimated from the data**
- **Signal generated at LO using MG5, interference (QCD⊗EW) estimated using PHANTOM (overall < 5%), considered as systematic unc.**
  - **small ratio of QCD vs EW production**
  - **Best sensitivity to study VBS processes**

	e^+e^+	$e^+\mu^+$	$\mu^+\mu^+$	e^-e^-	$e^-\mu^-$	$\mu^-\mu^-$	Total
Data	14	63	40	10	48	26	201
Signal + total bkg.	19.0 ± 1.9	67.6 ± 3.8	44.1 ± 3.4	11.8 ± 1.8	38.9 ± 3.3	23.9 ± 2.8	205 ± 13
Signal	6.2 ± 0.2	24.7 ± 0.4	18.3 ± 0.4	2.5 ± 0.1	8.7 ± 0.2	6.5 ± 0.2	66.9 ± 2.4
Total bkg.	12.8 ± 1.9	42.9 ± 3.8	25.7 ± 3.4	9.4 ± 1.8	30.2 ± 3.3	17.4 ± 2.8	138 ± 13
Nonprompt	5.6 ± 1.7	24.9 ± 3.6	18.4 ± 3.3	5.0 ± 1.6	19.9 ± 3.2	14.2 ± 2.8	88 ± 13
WZ	3.0 ± 0.2	8.5 ± 0.3	4.4 ± 0.2	1.9 ± 0.2	5.2 ± 0.3	2.2 ± 0.1	25.1 ± 1.1
QCD WW	0.6 ± 0.1	1.7 ± 0.1	1.3 ± 0.1	0.2 ± 0.1	0.6 ± 0.1	0.4 ± 0.1	4.8 ± 0.4
$W\gamma$	1.4 ± 0.5	3.6 ± 0.9	0.2 ± 0.2	0.8 ± 0.4	2.3 ± 0.7	—	8.3 ± 1.6
Triboson	0.8 ± 0.2	2.2 ± 0.4	1.2 ± 0.3	0.3 ± 0.1	0.9 ± 0.3	0.5 ± 0.2	5.8 ± 0.8
Wrong sign	1.5 ± 0.6	1.4 ± 0.4	—	1.1 ± 0.5	1.2 ± 0.4	—	5.2 ± 1.1

Signal Extraction (First Observation)

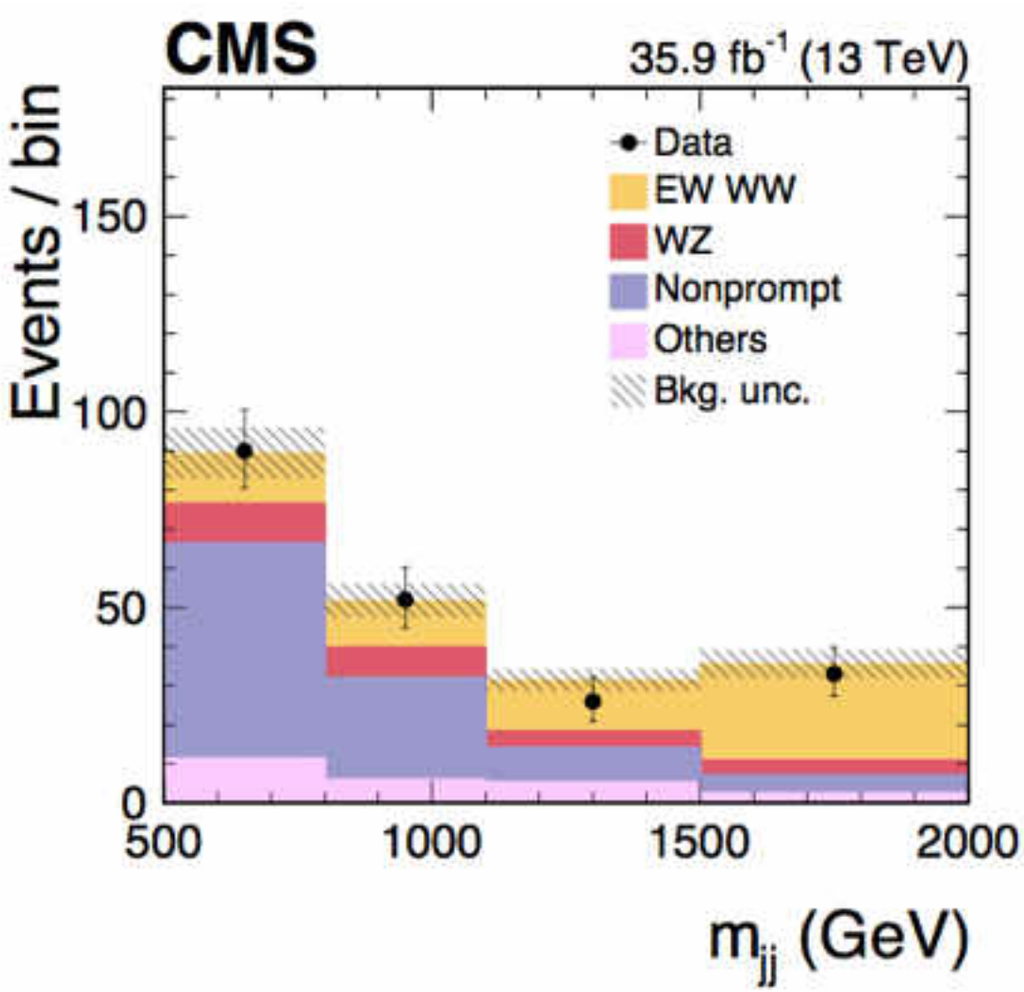
- **EW production of same-sign W boson pairs extracted using 2-dimensional fit in m_{ll} and m_{jj}, charge- and flavor-inclusive**

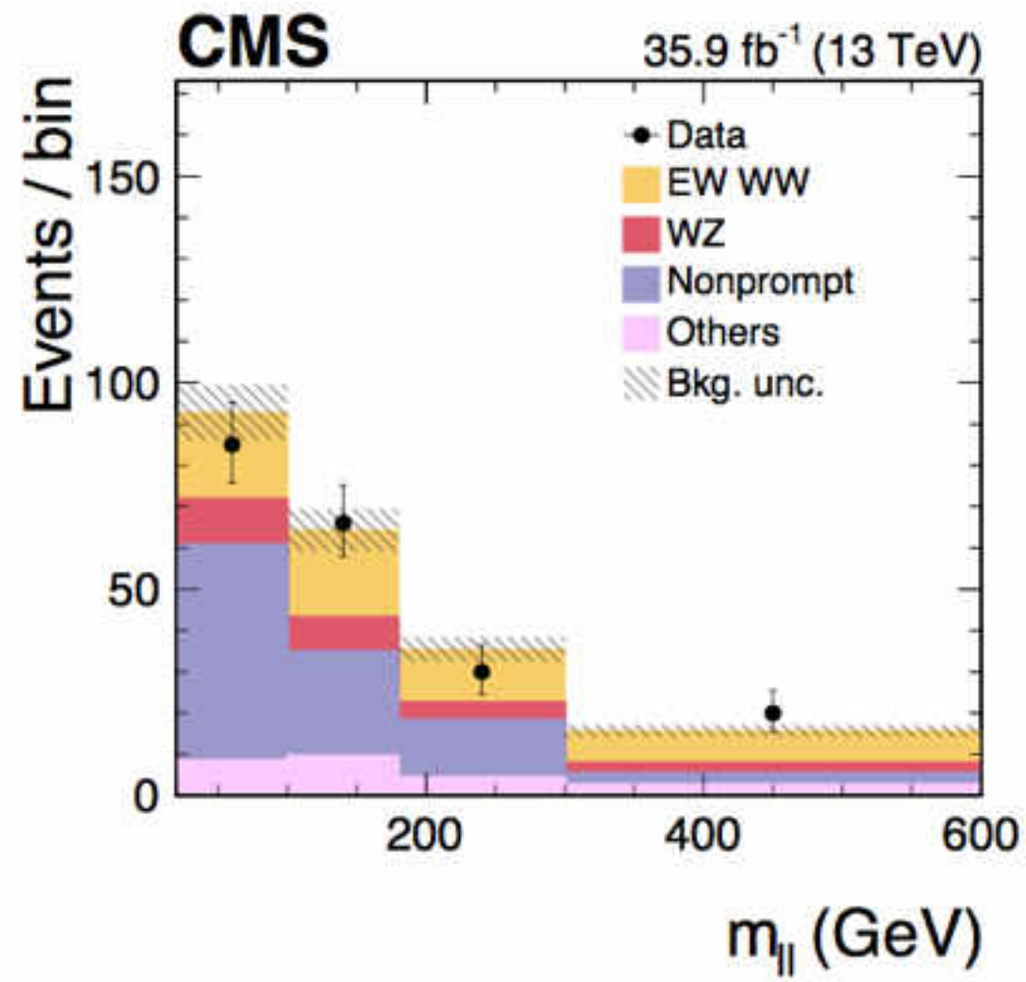
Measured fiducial cross section:

$3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})$ fb

5.5σ observed
5.7σ expected

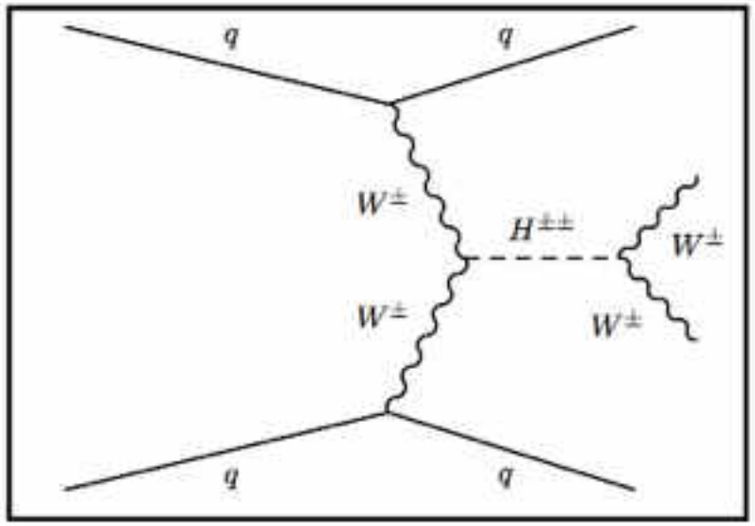
Signal Strength 0.90 ± 0.22





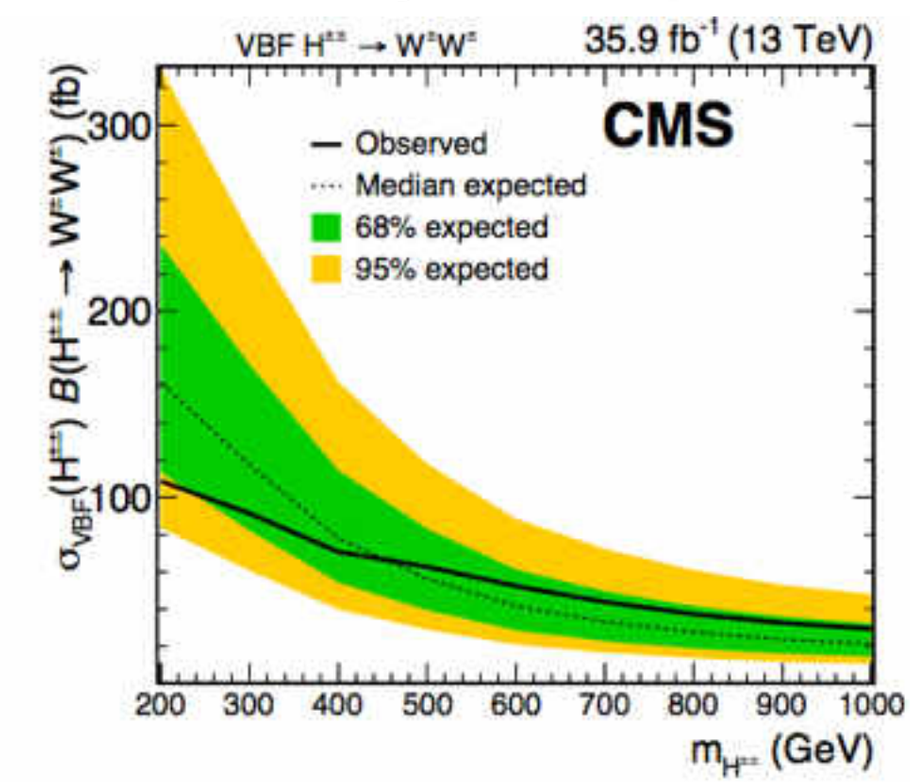
Beyond the SM Interpretation

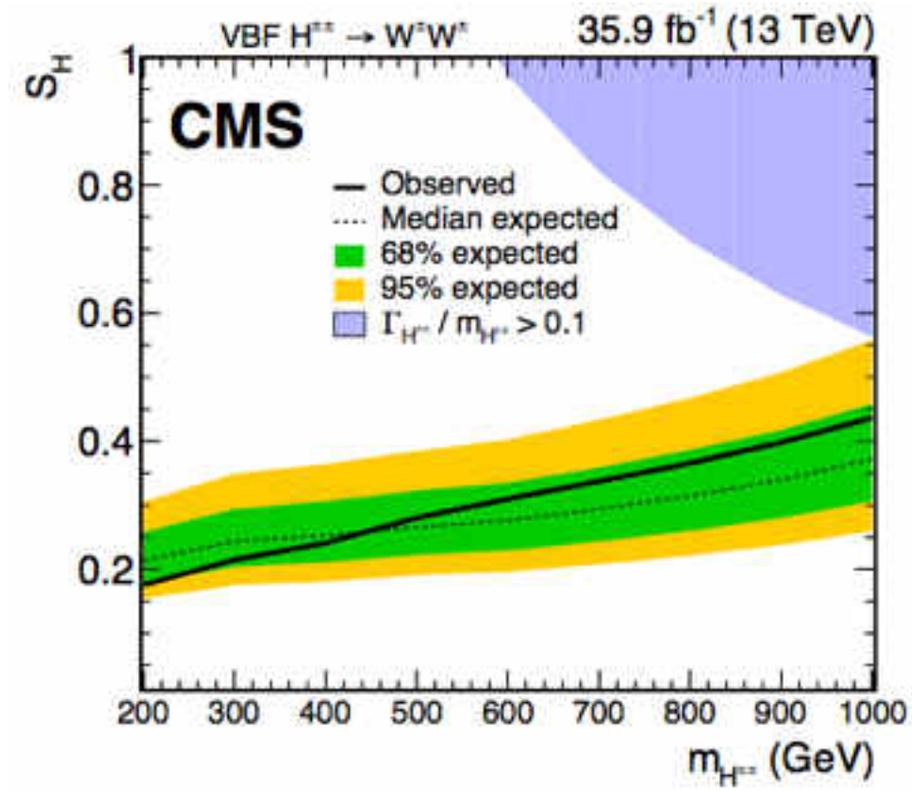
- **Excess of events could signal doubly charged Higgs production (fermiophobic)**



  - **Extended Higgs sector by SU(2) triplets (real&complex) custodial symmetry preserved at tree-level (Georgi-Machacek Model)**

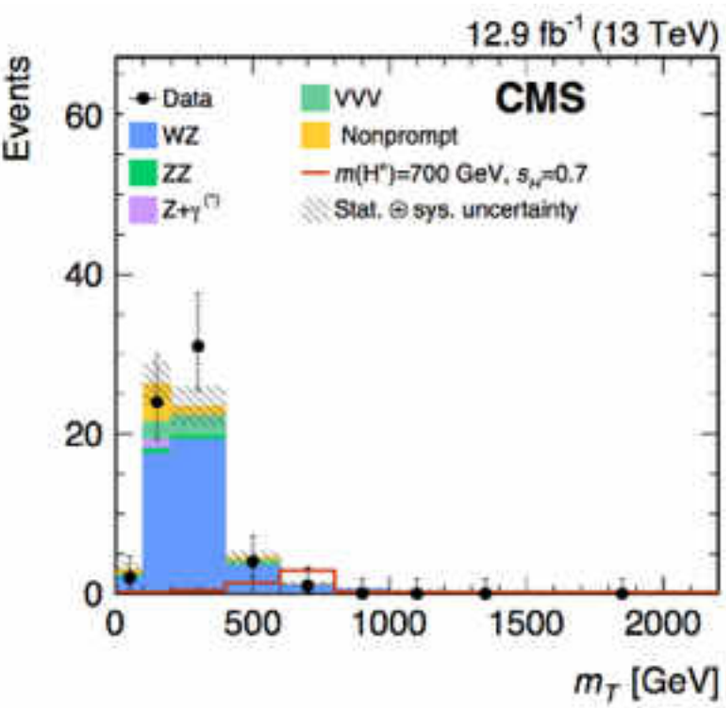
- **Model parameters are m(H^{++}) and sH, the fraction of the W mass generated by the triplet vev**

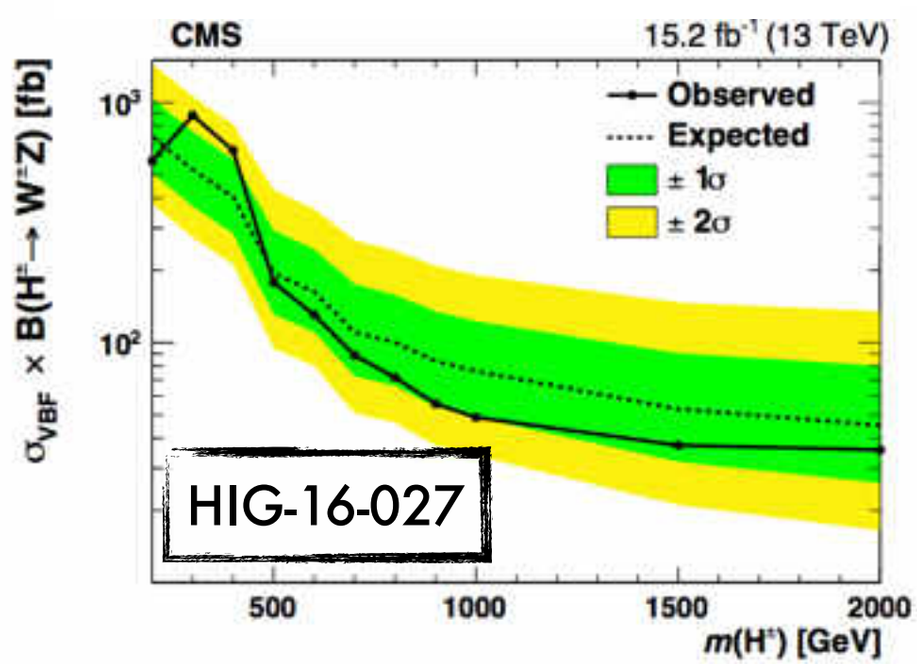


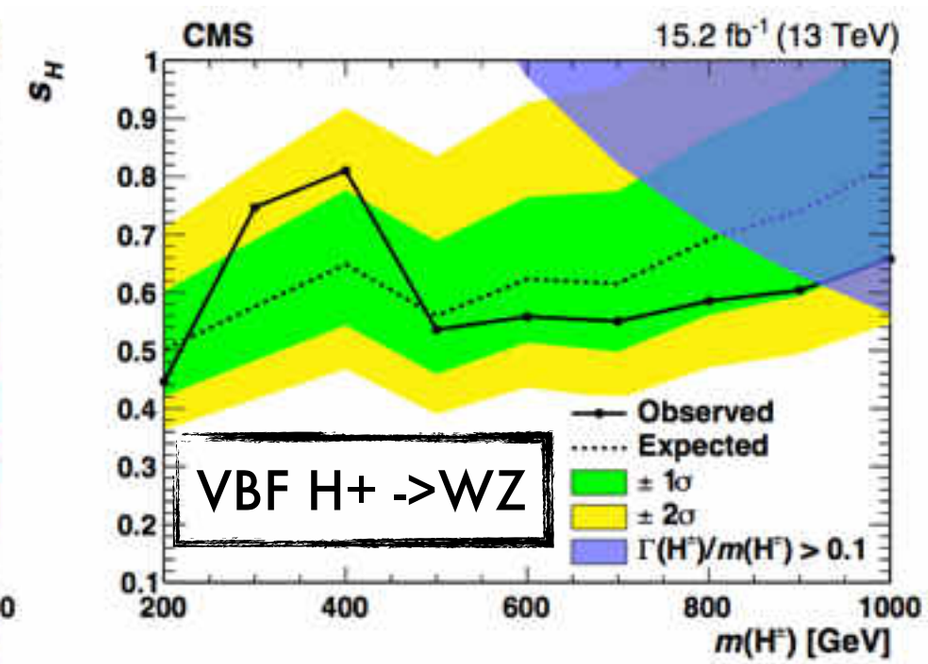


VBF WZ Production

- **EW production of pairs of W and Z boson just about to start being significant (QCD vs EW cross section: 70% vs 30%)**
  - **Establish search for charged Higgs bosons first, complementary to current focus of searches for charged Higgs bosons (fermiophobic)**
- **Similar to WW VBS, exploit VBF topology, fully leptonic final-state, on 2015 and 2016 data**



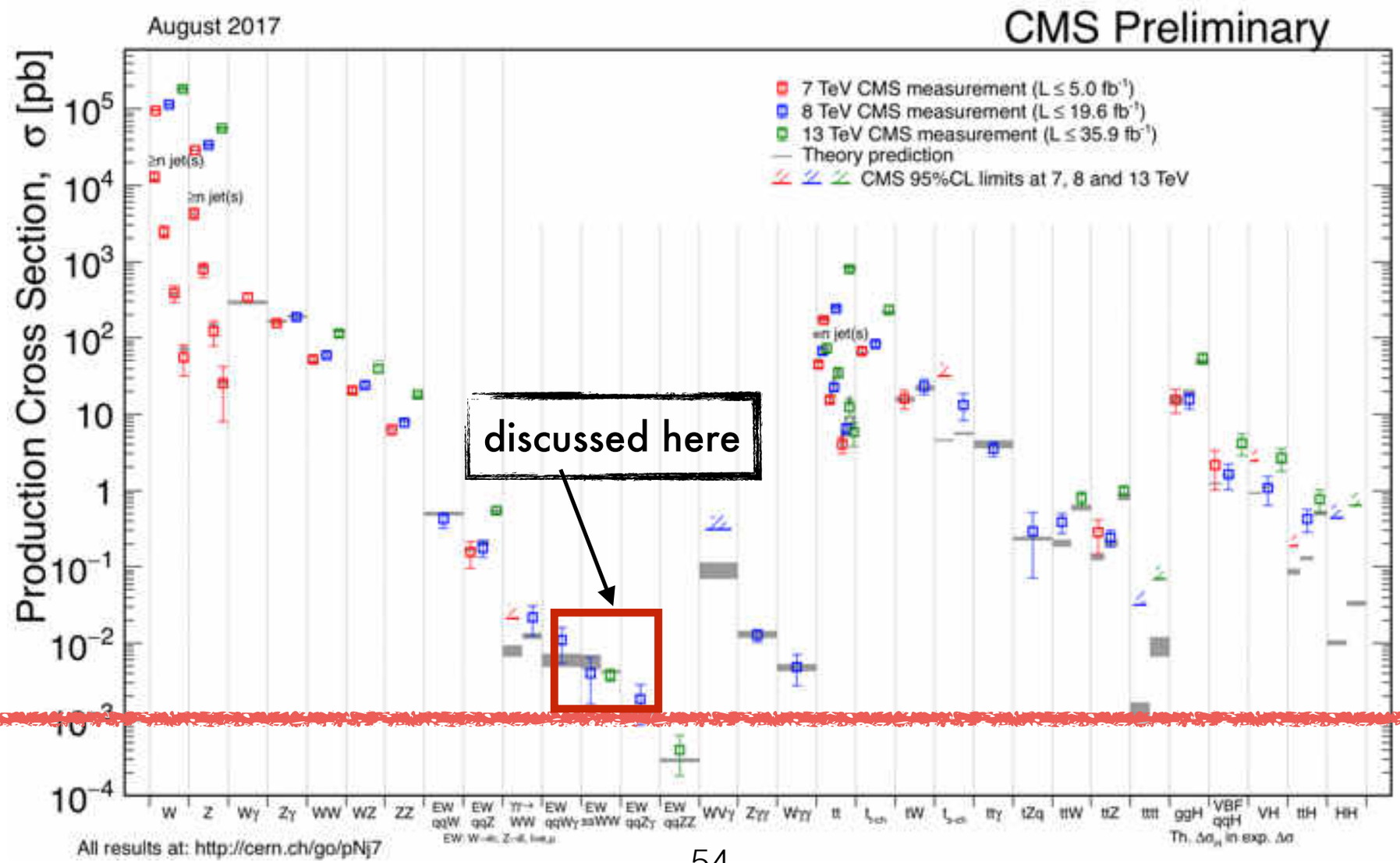




Statistical Precision at HL-LHC

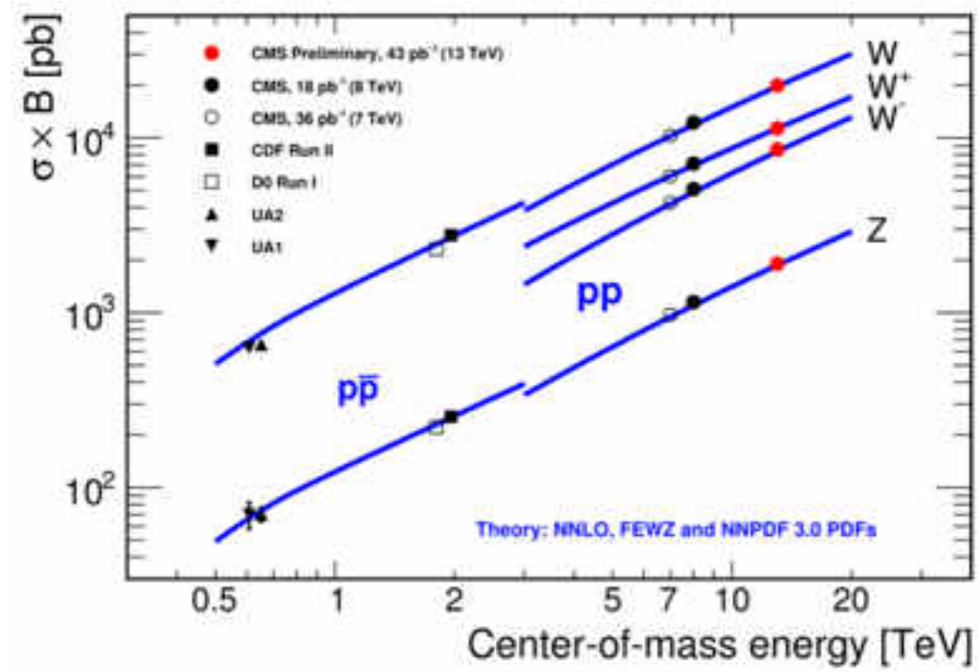
- **High-Luminosity LHC: Expect 3000fb^{-1} of data being collected until 2038, make naive statistical uncertainty estimate**
  (acceptances, branch ratios, efficiencies to be taken into account)

  - **$1/\sqrt{(\sigma * L)} \sim 1.8\%$ => for 3ab^{-1} measurements of processes with cross section above 1fb will be limited by systematic uncertainties (luminosity)**



Conclusions

$$\sigma_P = \frac{N_P}{\epsilon A \int R_{\mathcal{A}} dt}\left(\frac{2\pi \Sigma_x \Sigma_y R_{\mathcal{A}}(0)}{N_1 N_2 f_{LHC}}\right)$$



- **Elaborated on Luminosity measurements at the LHC**

- **Discussed W/Z boson production cross section as benchmark for precision measurements at the LHC**

  - **The measurement is dominated by systematic uncertainties**

  - **The luminosity estimate introduces one of the leading uncertainties**

- **First observation of EW same-sign WW production as benchmark for process with large statistical uncertainty with current luminosities**

- **With more data to come we will have more Standard Model processes with statistical uncertainty of <1%: Precision Higgs Physics**

But lets not wait until 2038! Interesting physics is around the corner

(and discussions on future accelerator projects in full swing)

Thank you for you attention!

Additional Material

Electron Systematic Uncertainties

Table 2: Systematic uncertainties in percent for the electron channel. "NA" means that the source either does not apply or is negligible.

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	2.1	2.0	2.1	0.6	2.5	1.2	1.0	1.0
Bkg. subtraction / modeling [%]	1.4	1.4	1.4	0.9	0.6	1.5	1.5	1.5
E_T^{miss} scale and resolution			shape		NA		shape	
Electron scale and resolution			shape		NA		shape	
Total experimental [%]	2.5	2.5	2.5	1.1	2.6	1.9	1.8	1.8
Theoretical uncertainty [%]	1.6	1.4	1.4	1.9	1.6	1.9	1.9	1.7
Lumi [%]	4.8	4.8	4.8	NA	4.8	NA	NA	NA
Total [%]	5.6	5.6	5.6	2.1	5.7	2.7	2.6	2.5

WWss Systematic Uncertainties

source	Signal	QCD WW	DPS WW	ZZ	WZ	Wrong sign	VVV	Non-prompt	$W\gamma$
Luminosity	2.5	2.5	2.5	2.5	-	2.5	2.5	-	2.5
Lepton efficiency	3.6	3.6	3.6	3.6	-	3.6	3.6	-	3.6
Momentum resolution	1.0	1.0	1.0	1.0	-	1.0	1.0	-	1.0
Trigger efficiency	1.0	1.0	1.0	1.0	-	1.0	1.0	-	1.0
Pile-up	0.5-2.0	0.5-2.0	0.5-2.0	0.5-2.0	-	0.5-2.0	0.5-2.0	-	0.5-2.0
b-tagging	0.5-3.0	0.5-3.0	0.5-3.0	0.5-3.0	-	0.5-3.0	0.5-3.0	-	0.5-3.0
JES	1.0-7.0	1.0-7.0	1.0-7.0	1.0-7.0	-	1.0-7.0	1.0-7.0	-	1.0-7.0
JER	1.0-3.0	1.0-3.0	1.0-3.0	1.0-3.0	-	1.0-3.0	1.0-3.0	-	1.0-3.0
PDF	1.0-5.0	1.0-5.0	1.0-5.0	1.0-4.0	-	-	-	-	-
EWK-QCD interference	1.0-4.0	-	-	-	-	-	-	-	-
QCD scales EWK	3.0-12.0	-	-	-	-	-	-	-	-
QCD scales VVV	-	-	-	-	-	-	10-25.0	-	-
QCD scales ZZ	-	-	-	3.0-10.0	-	-	-	-	-
WZ normalization	-	-	-	-	20.0-40.0	-	-	-	-
Wrong sign normalization	-	-	-	-	-	1.0-3.0	-	-	-
W + jets normalization	-	-	-	-	-	-	-	30.0	-
Statistics	2.0-7.0	10.0-20.0	15.0-70.0	1.0-17.0	1.0-15.0	7.0-60.0	10.0-70.0	10.0-90.0	30.0-90.0

DCCT (Fluxgate Sensor)

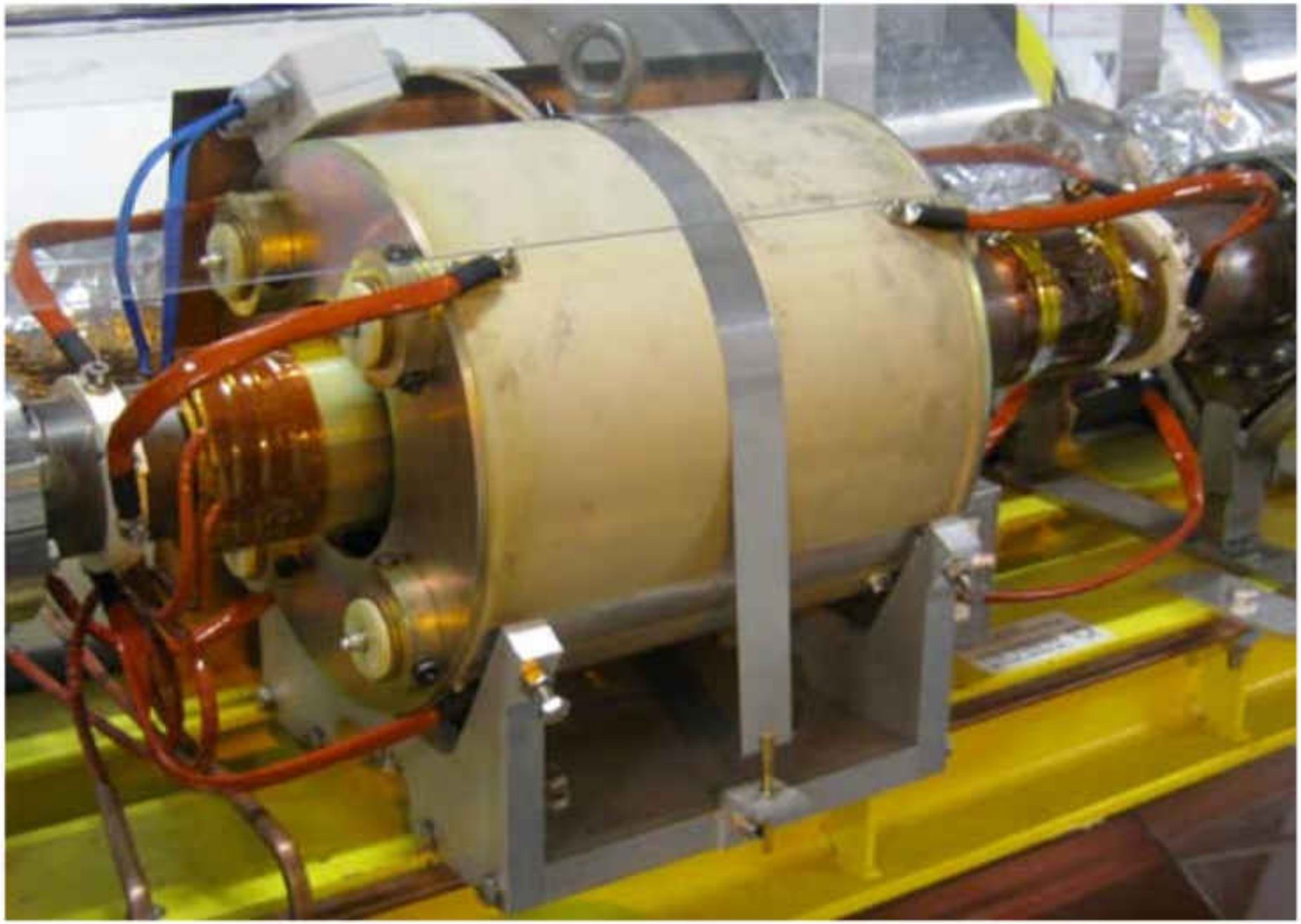
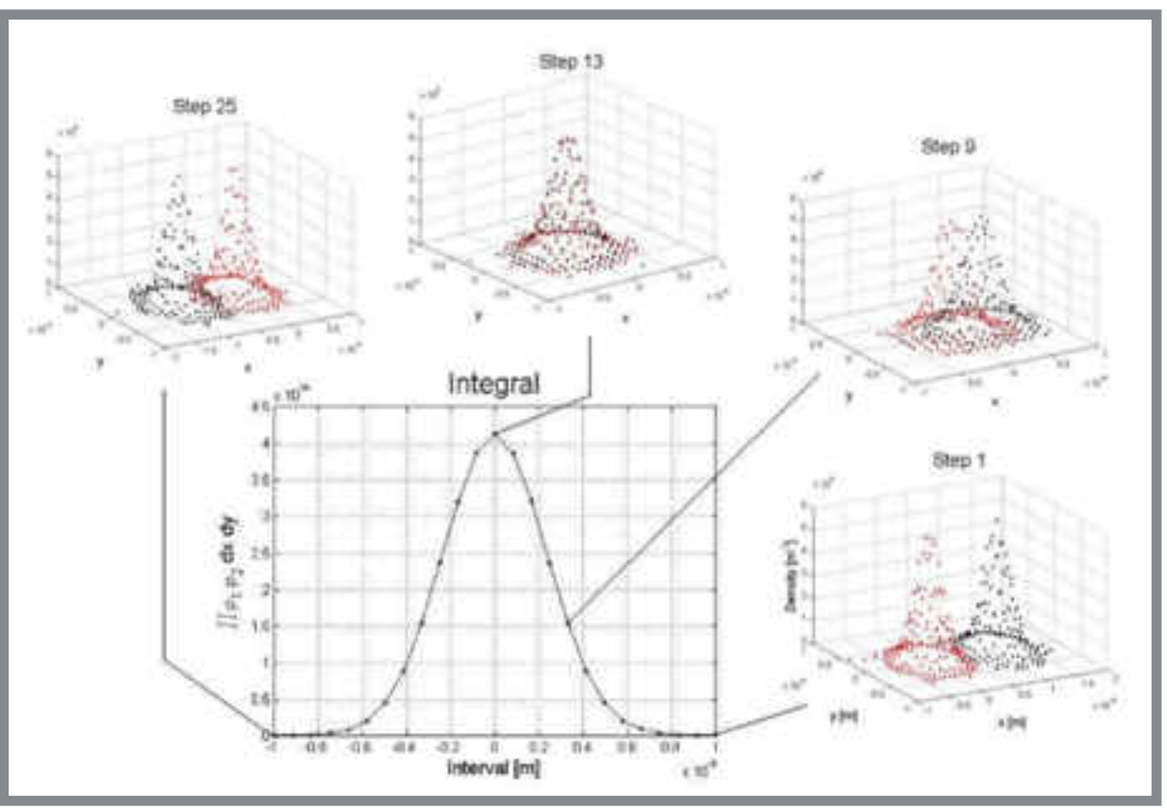


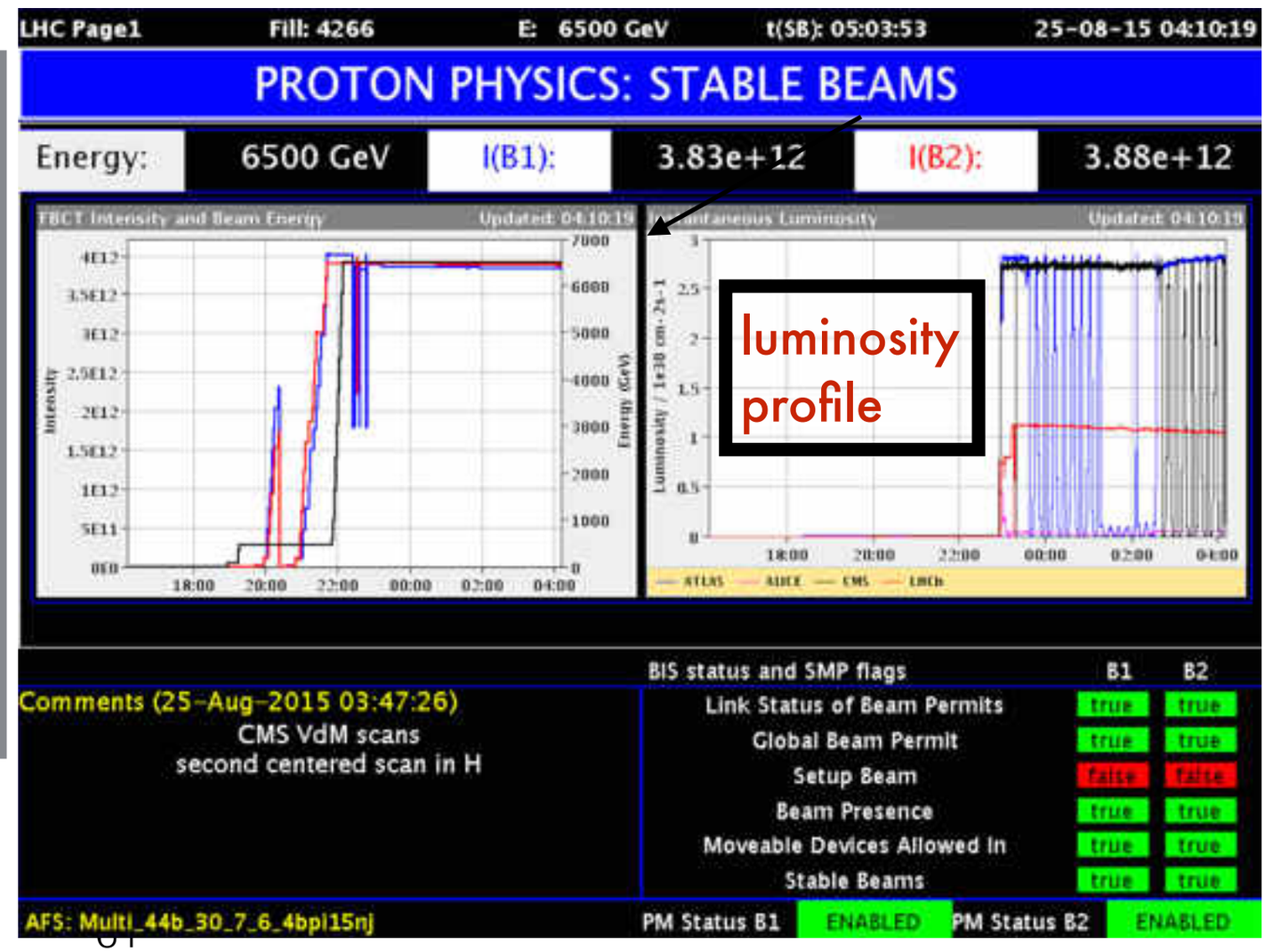
Figure 2: The DCCT with the connexions for the beam image current.

Luminosity Scale Estimation

- **Absolute luminosity scale is measured with special LHC machine set-up, pioneered by Simon van der Meer (1968, ISR-PO/68-31)**

  Beams are scanned across each other in the transverse plane





Luminosity Calibration

$$\mathcal{L}(\Delta x, \Delta y) = N_1 N_2 f \int_{-\infty}^{\infty} \rho_1(x,y)\rho_2(x+\Delta x, y+\Delta y)\, dx\, dy$$