Standard Model Physics Results at the LHC

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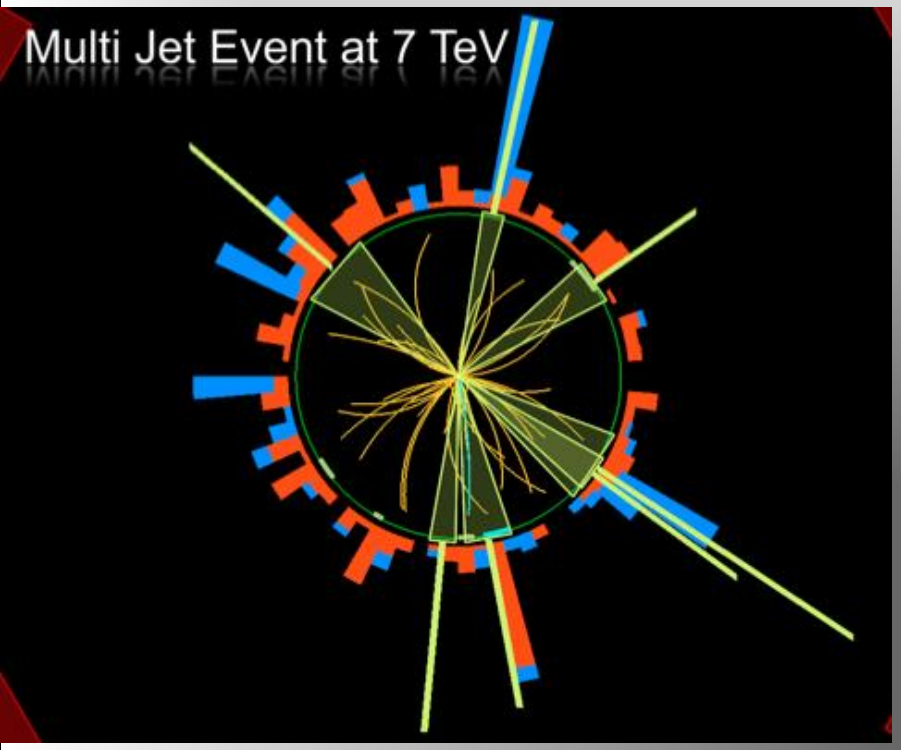
The first CERN Philippines School 2014



Outline

- Introduction
- Soft QCD Processes
- Hard QCD Processes
- Electroweak Processes
- The top quark
- New particles discovered…
- Summary

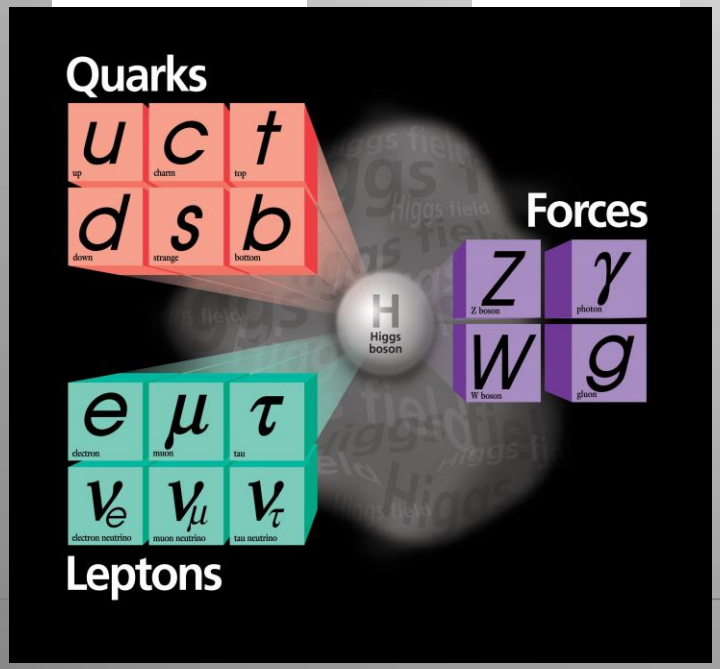
The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

Fermions

Bosons

Matter particles



Force particles

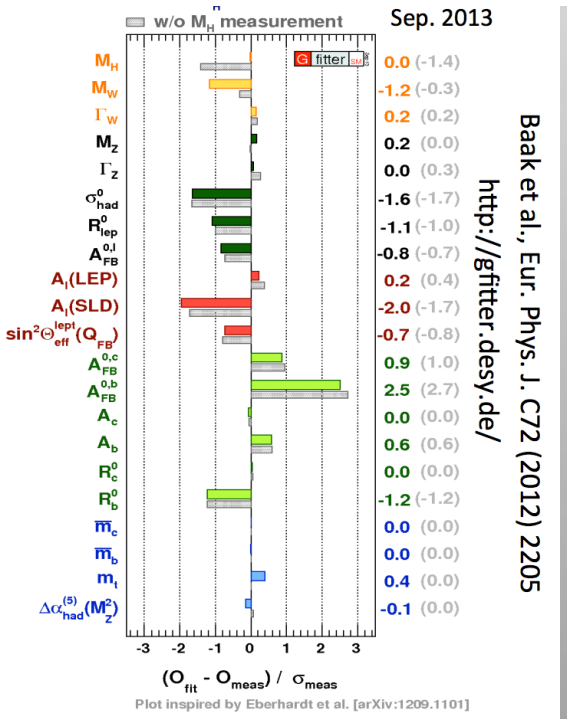
The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

The Standard Model

It is a very successful theory describing the fundamental interactions
Is it complete? Does it show cracks?
We study Standard Model processes at the highest energies in the lab

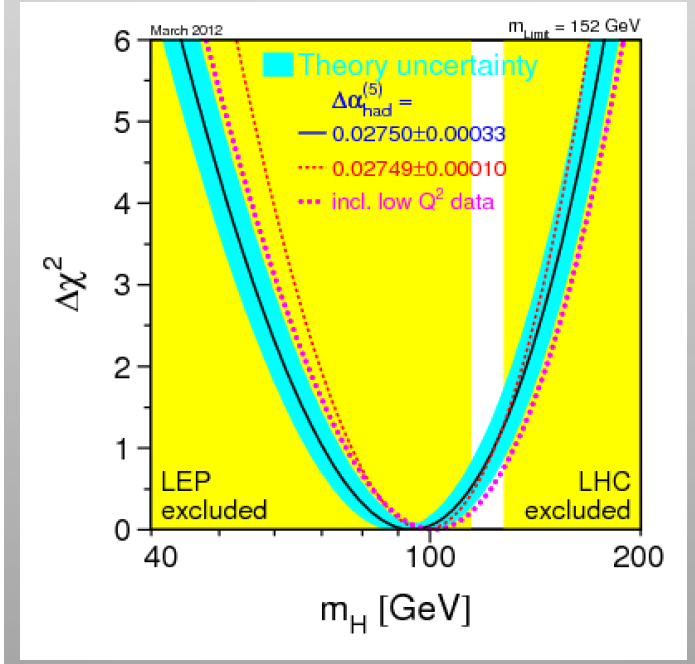
Precision measurements



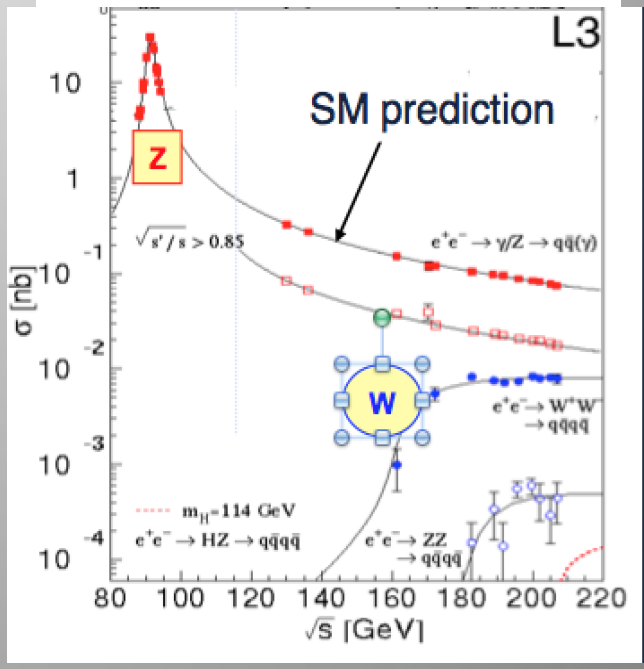
Baak et al., Eur. Phys. J. C72 (2012) 2205
http://gfitter.desy.de/

No deviations > 3 σ !
➔ SM consistent!

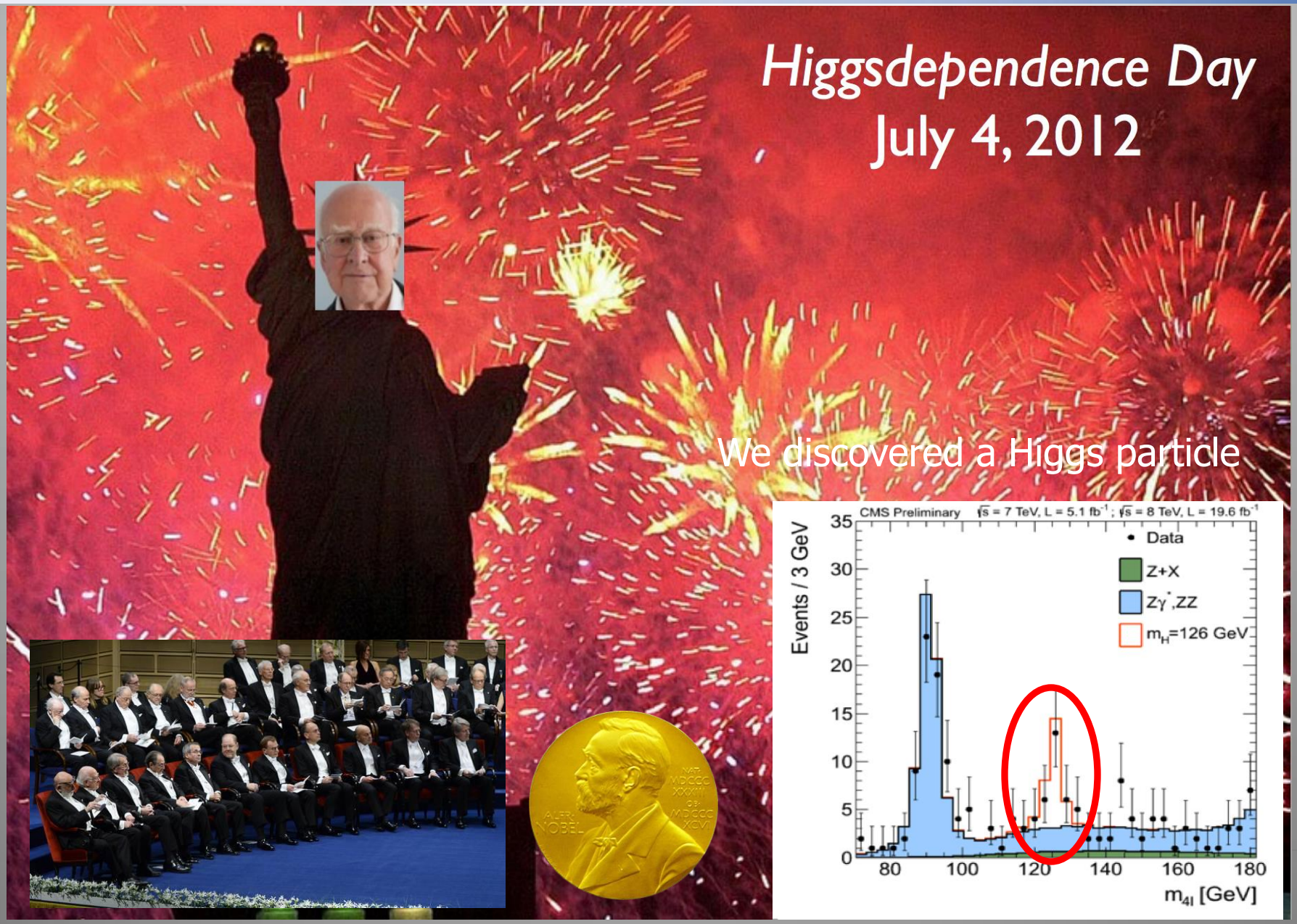
Higgs prediction



W and Z cross sections



4th of July 2012…



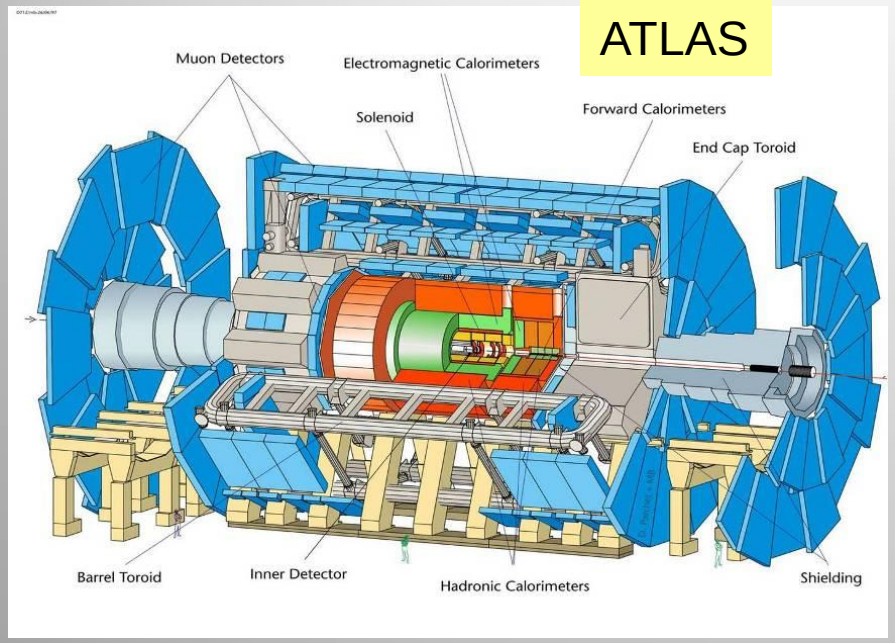
Lecture Plan

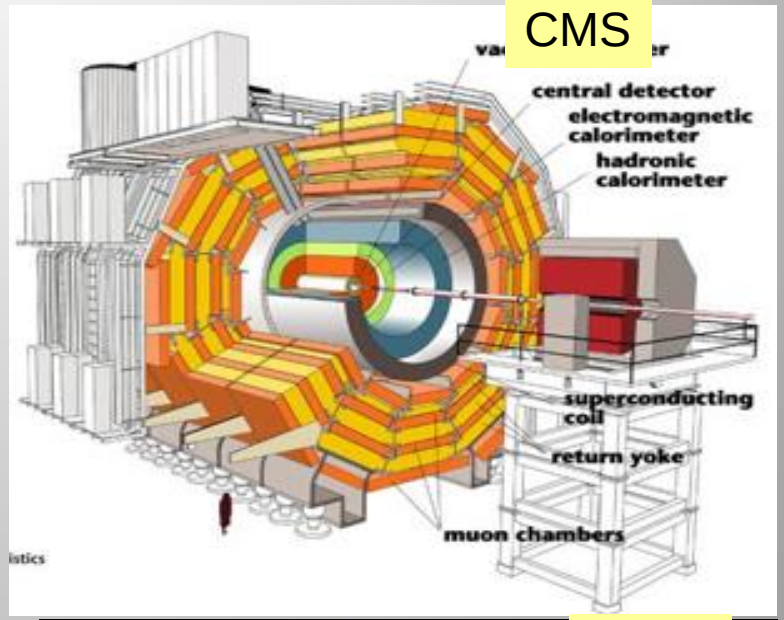
Overview of the 3 lectures in the next days

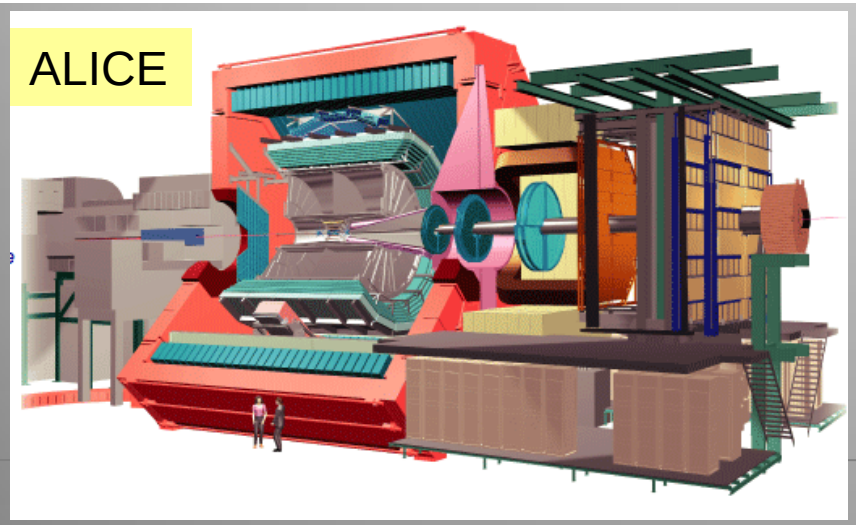
- Lecture 1: The study of standard model processes at the LHC
- Lecture 2: Searching for Beyond the Standard Model at the highest energies
- Lecture 3: The next ultimate challenge: identifying Dark Matter in the Universe, and its connection to Supersymmetry

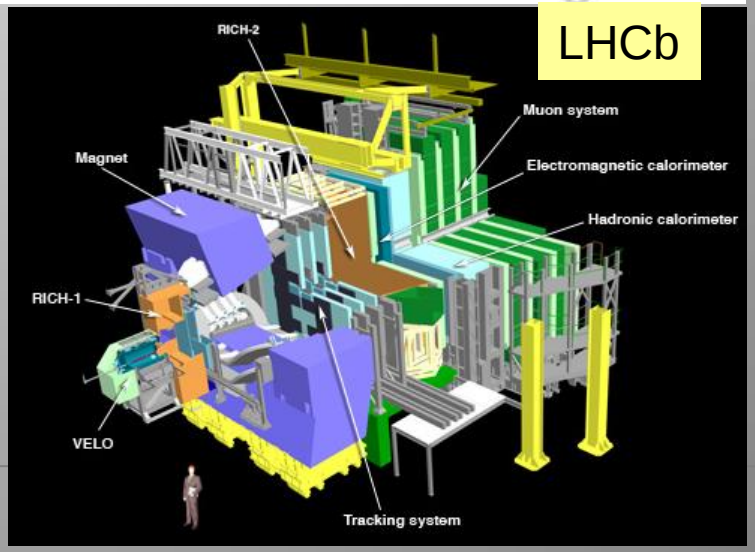
Experiments at the LHC

The Four Main LHC Experiments

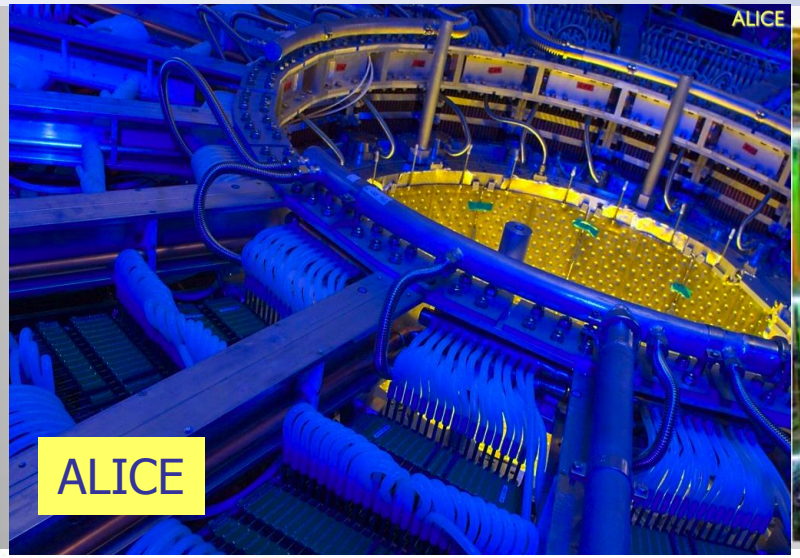


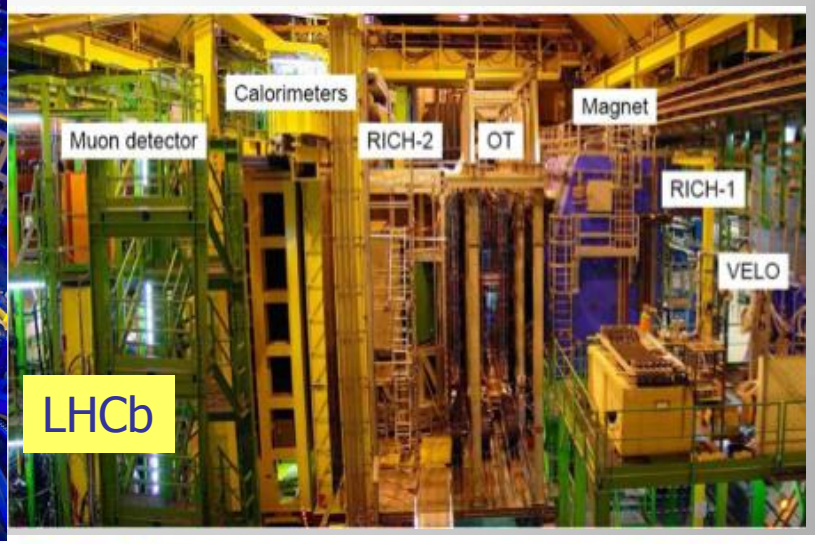




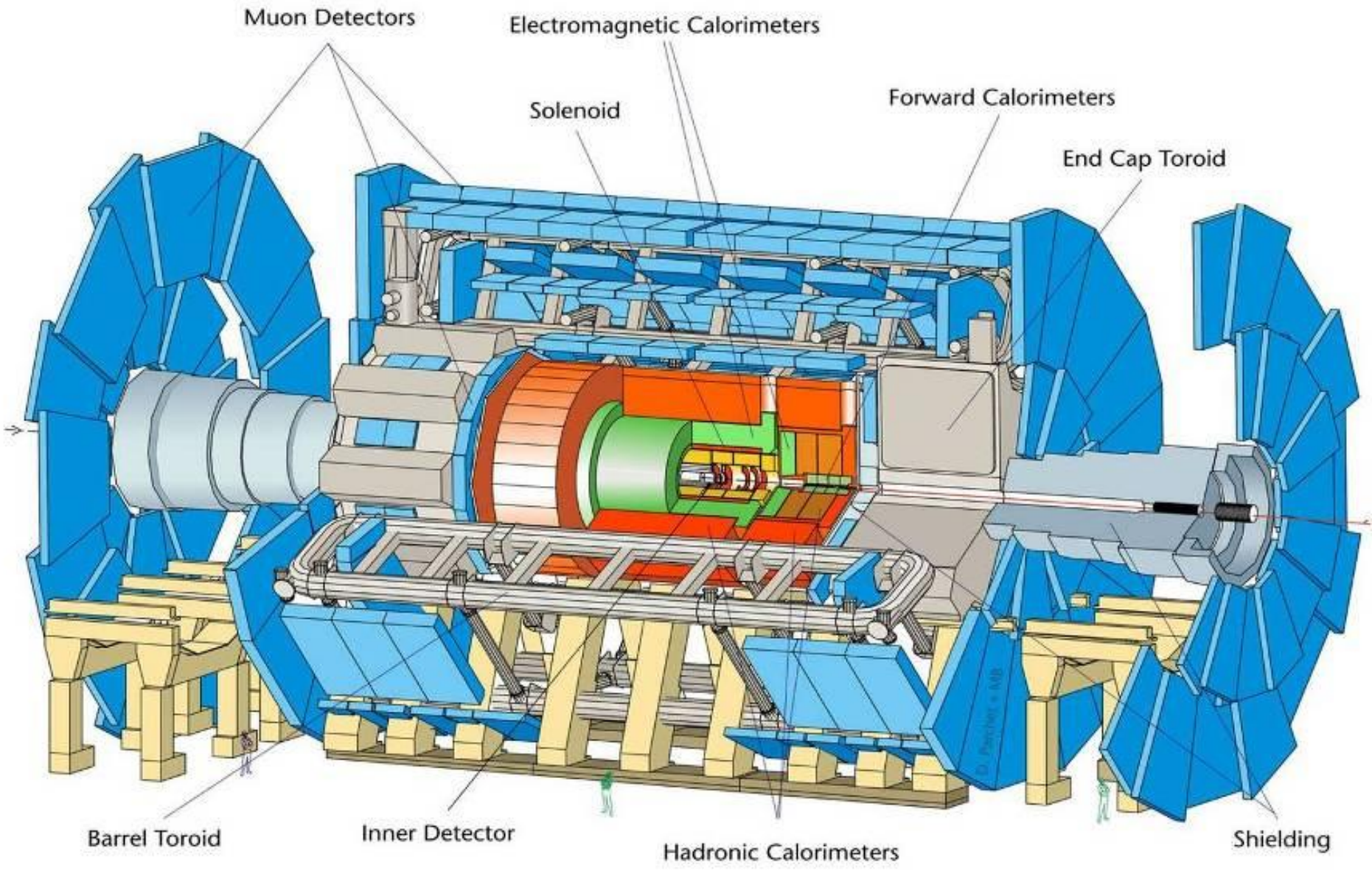


…and in real life..



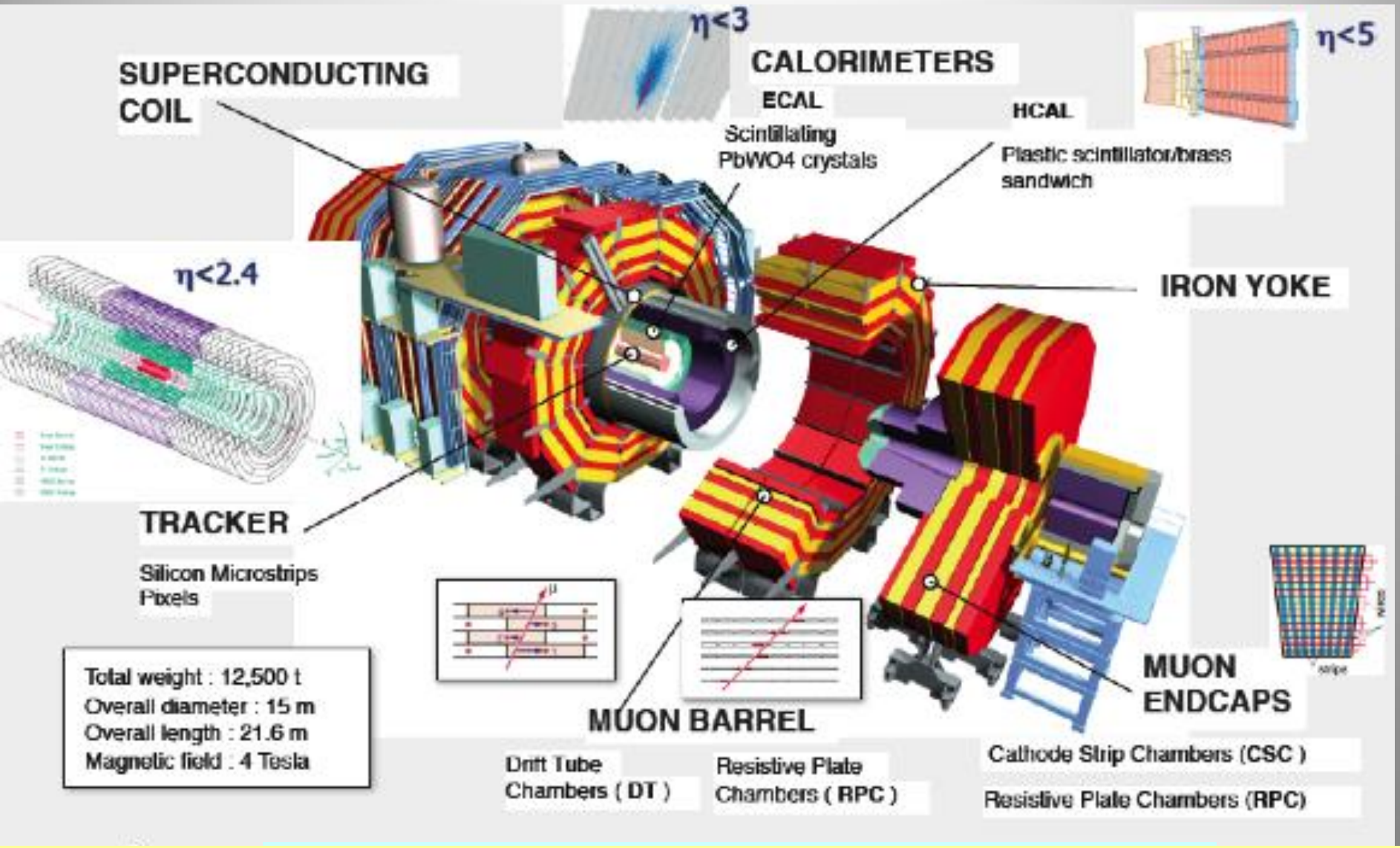


Eg..: ATLAS & CMS construction started >12 years ago



Length = 55 m Width = 32 m Height = 35 m but spatial precision ~ 10-100 μm

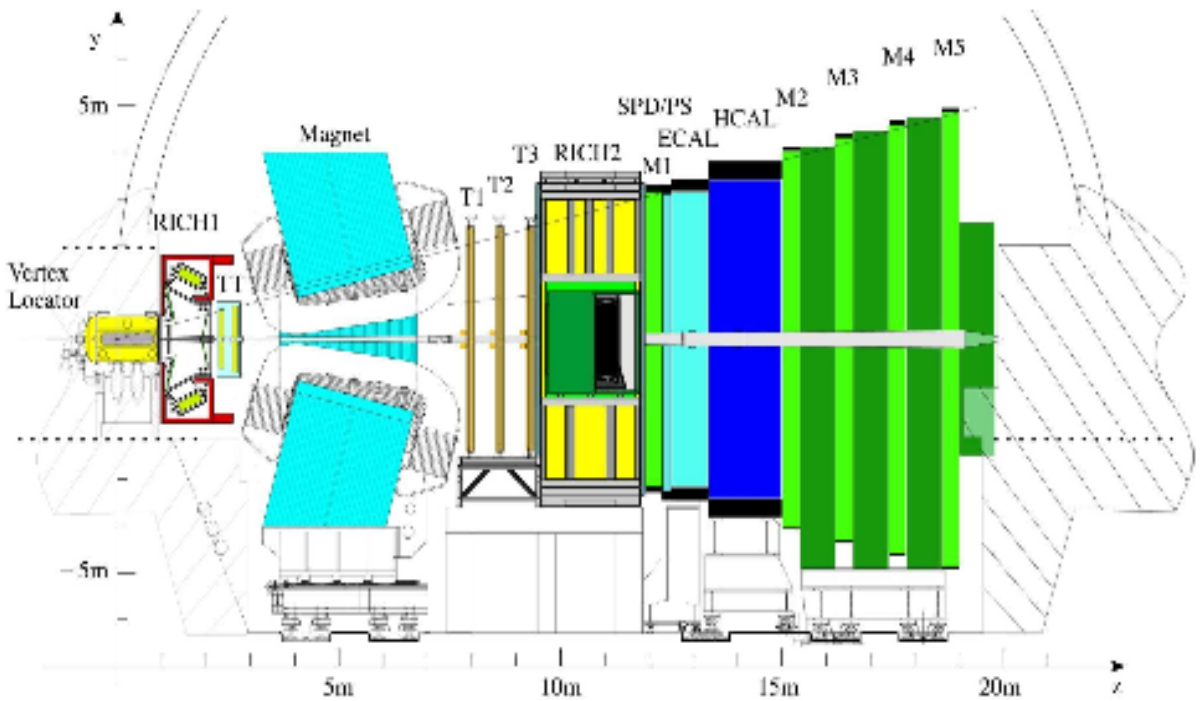
The Modular Design of CMS



Length = 22 m Width = 15 m Height = 15 m but spatial precision ~ 10-100 μm

LHCb: b-Physics at the LHC

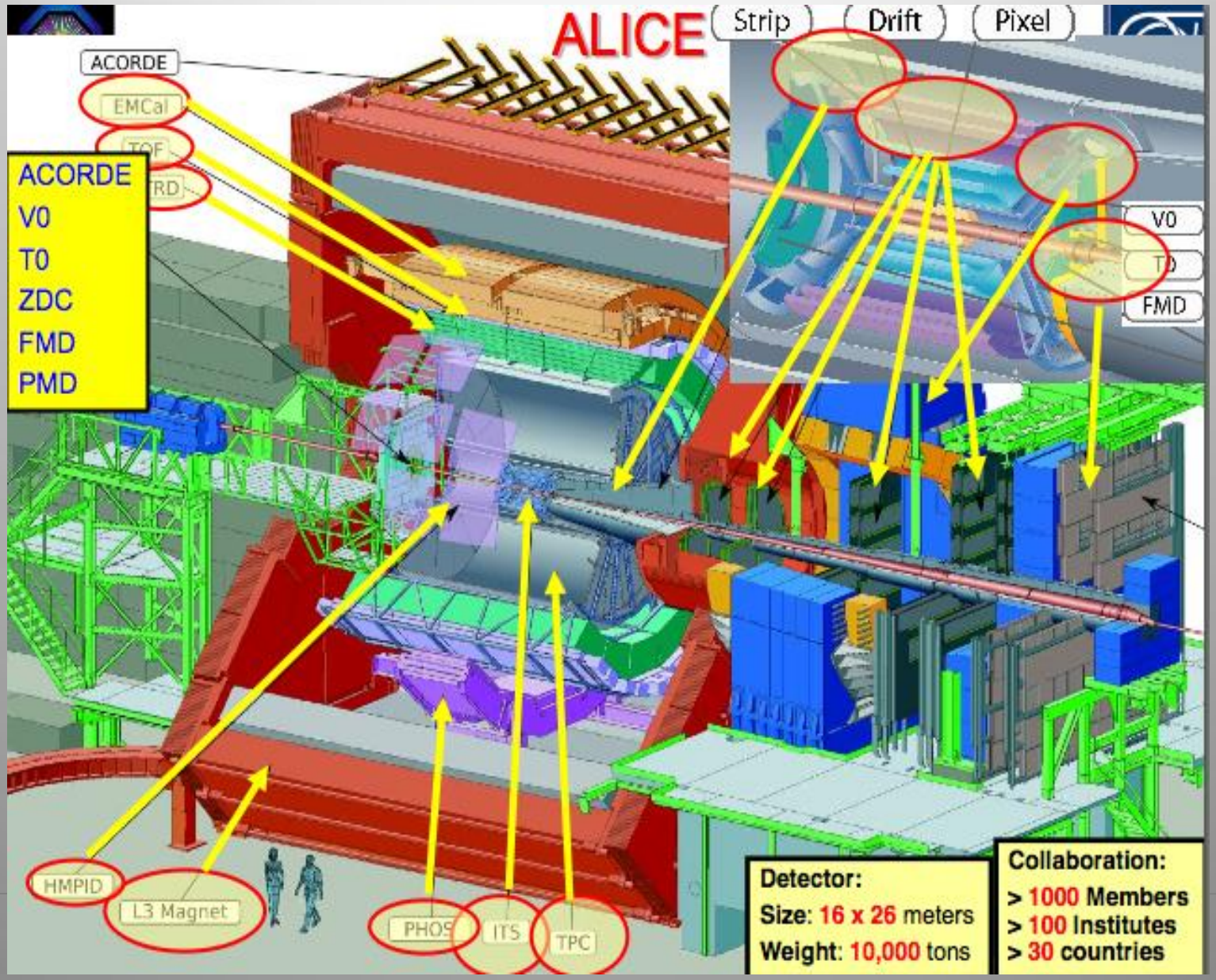
...and more...



Most relevant attributes for results to be shown today

- Forward acceptance ($2 < \eta < 5$) and down to very low p_T
- Precise vertexing (VELO) – hit resolution of down to 4 μm achieved; measurements 8mm from beam-line
- RICH system providing hadron id between 2 and 100 GeV/c
- High performance muon system

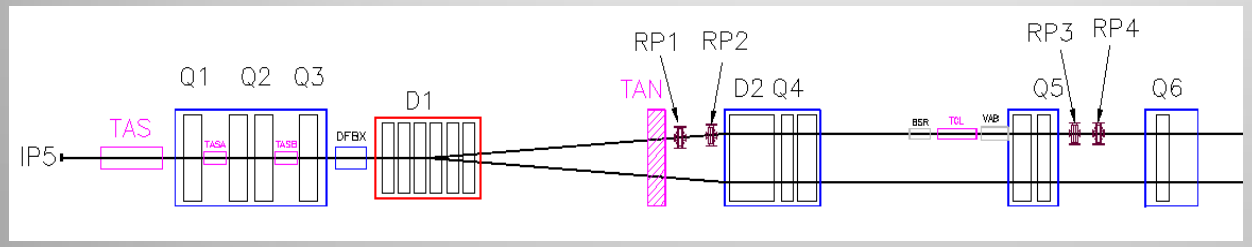
Heavy Ion Physics at the LHC

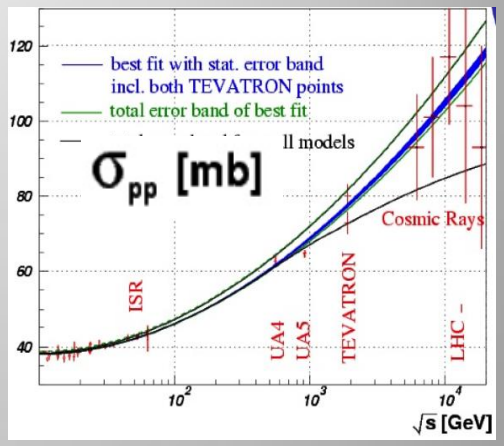


Smaller Experiments: TOTEM & LHCf

TOTEM: measuring the total, elastic and diffractive cross sections
Add Roman pots (and inelastic telescope) to CMS interaction regions (200 m from IP)

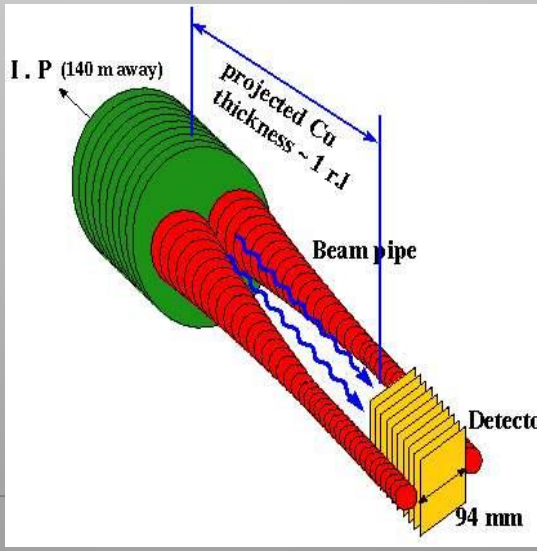
TOTal and Elastic cross section Measurement

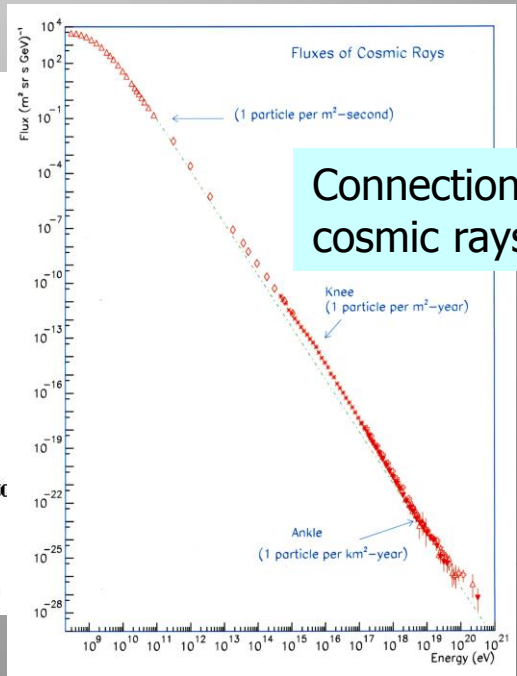




LHCf: measurement of photons and neutral pions in the very forward region of LHC

Add a EM calorimeter at 140 m from the Interaction Point (of ATLAS)

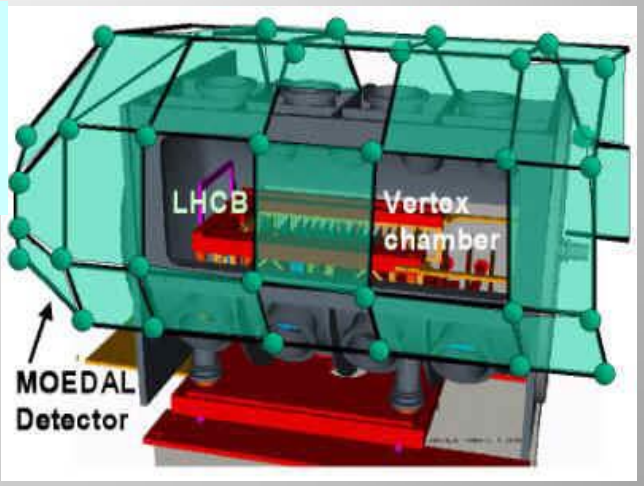


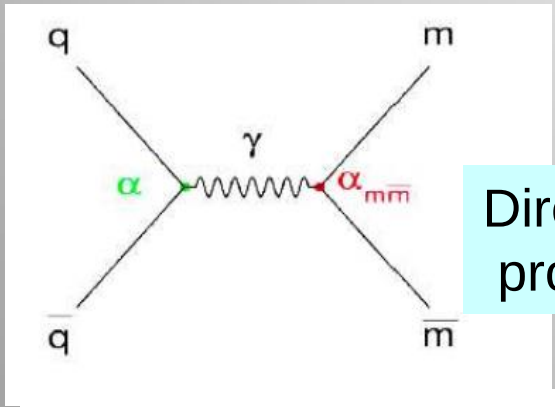


Connection with cosmic rays

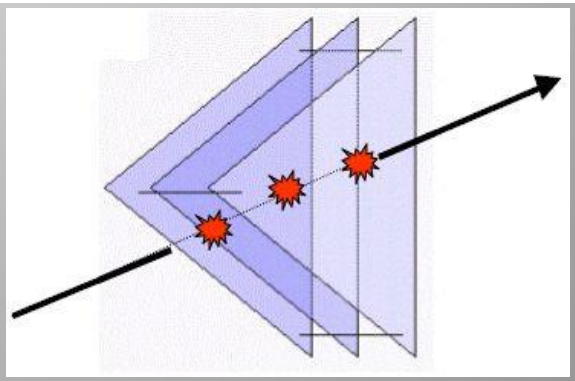
MOEDAL: MOnopole and Exotics Detector at the LHC

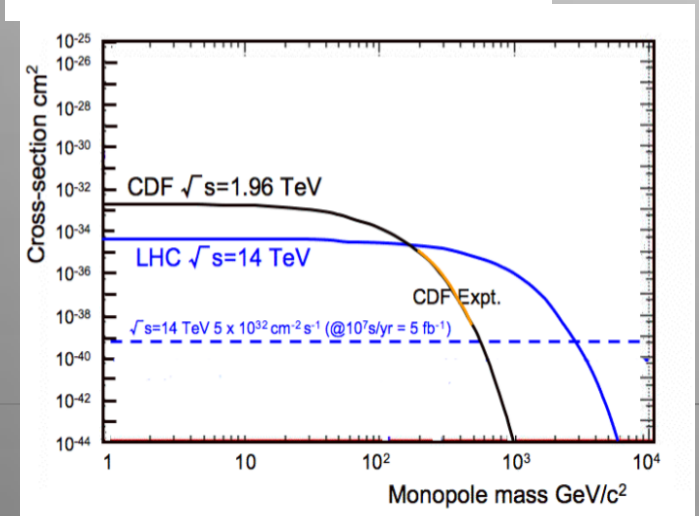
Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”





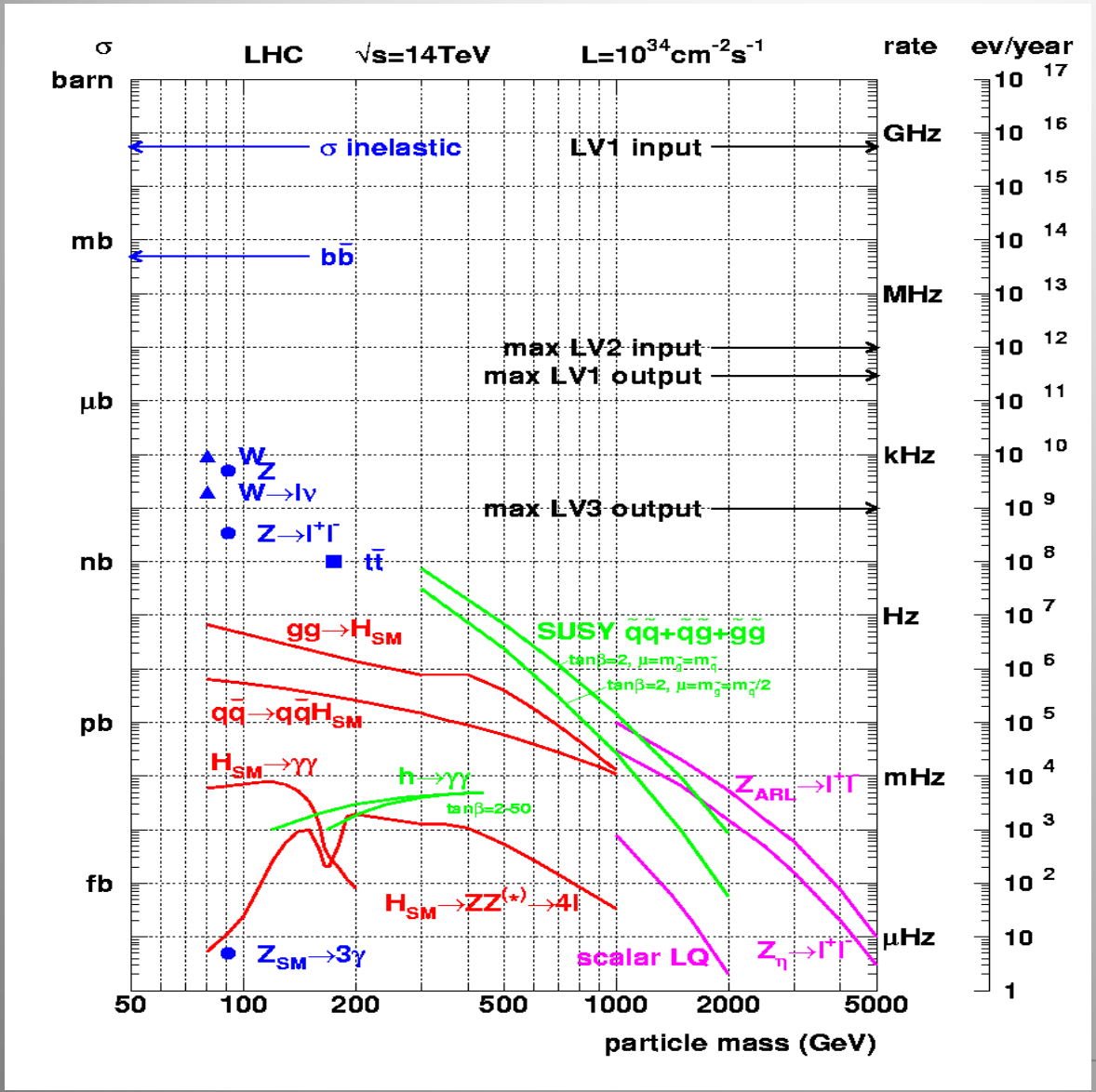
Direct Monopole production





Remove the sheets after some running time and inspect for ‘holes’

Cross sections at the LHC

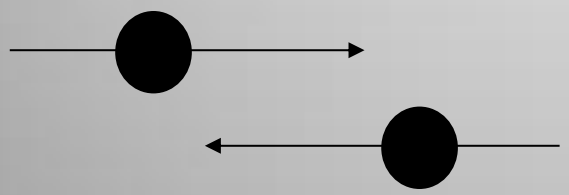


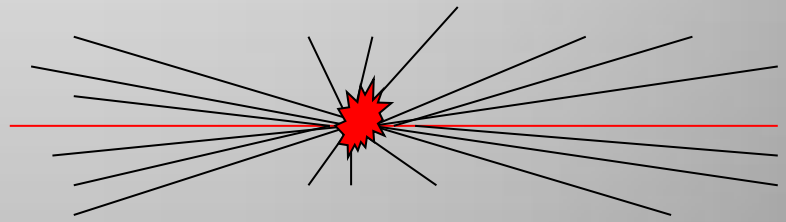
"Well known" processes, don't need to keep all of them …

New Physics!!
This we want to keep!!

Proton-proton Collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "
→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)
→particles in final state have large longitudinal momentum but small
→transverse momentum (scattering at large angle is small)





$< p_T > \approx 500$ MeV of charged particles in final state

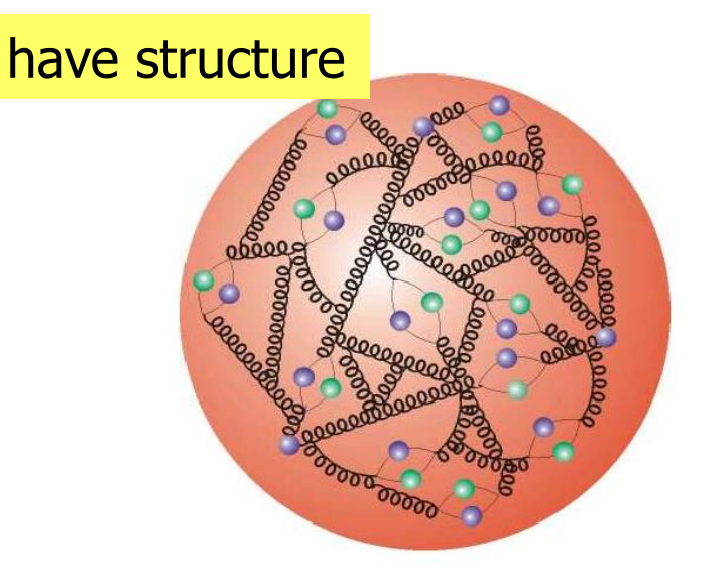
Most energy escapes down the beam pipe.

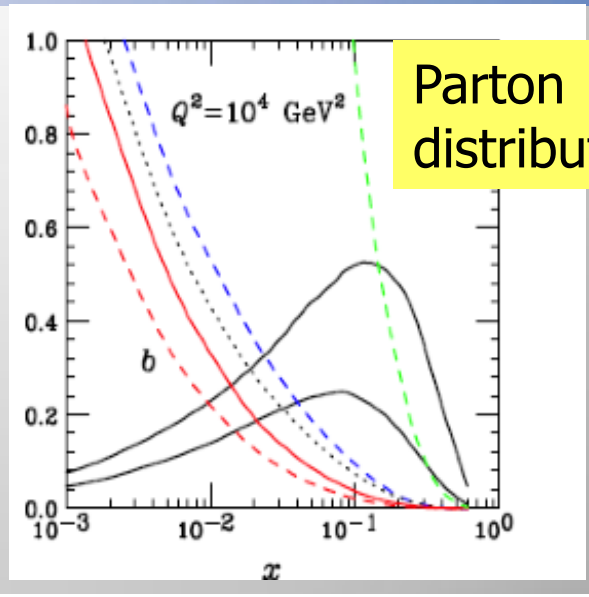
These are called soft events…

A minimum bias data event sample is dominated by soft events

pp collisons : complications

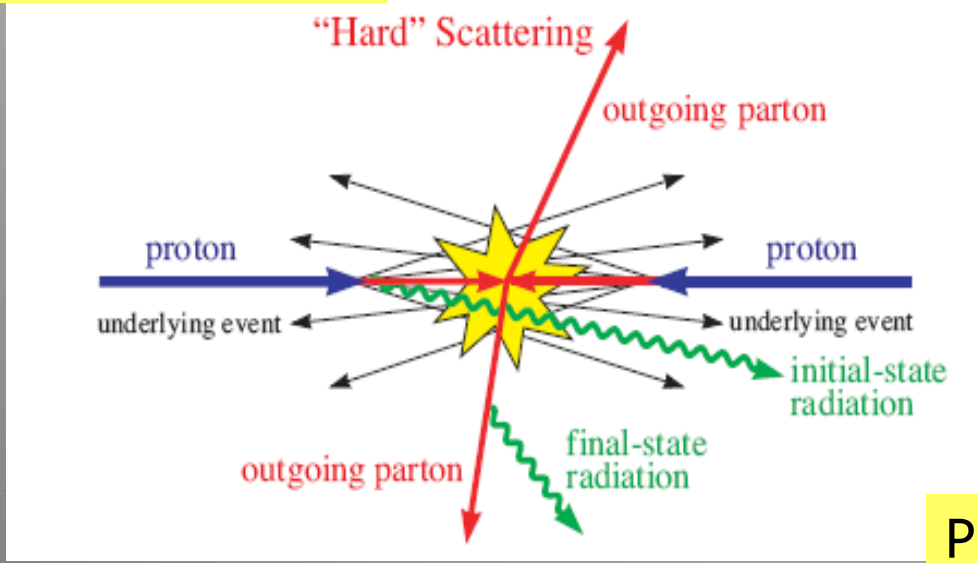
Protons have structure





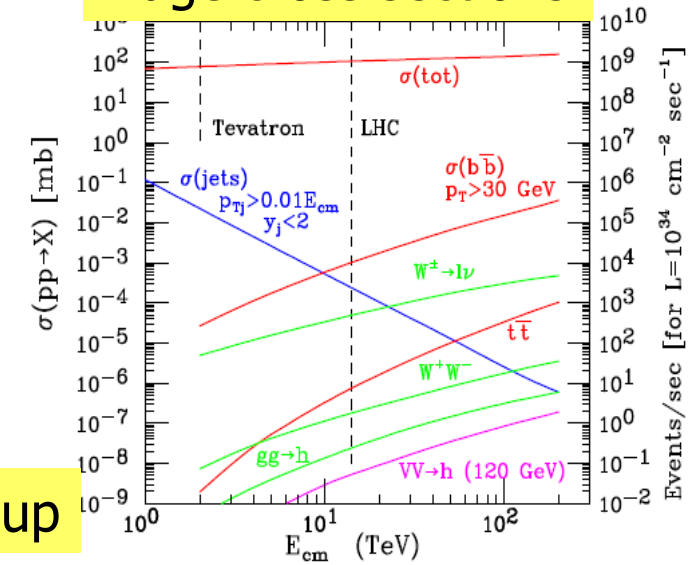
Parton distributions

Underlying event



Scattering cross sections for various SM processes:

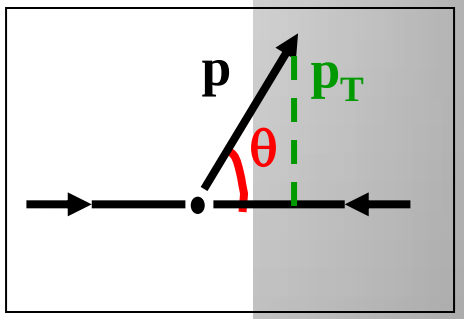
Huge cross sections



Pile-up

Kinematic Variables for pp Scattering

- Transverse momentum, p_T and $E_T = E \sin\theta$
  - Particles that escape detection (0) have $p_T=0$
  - Visible transverse momentum =0
    - Very useful variable!
- Longitudinal momentum and energy, p_z and E
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - Not so useful variable
- Angle:
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η



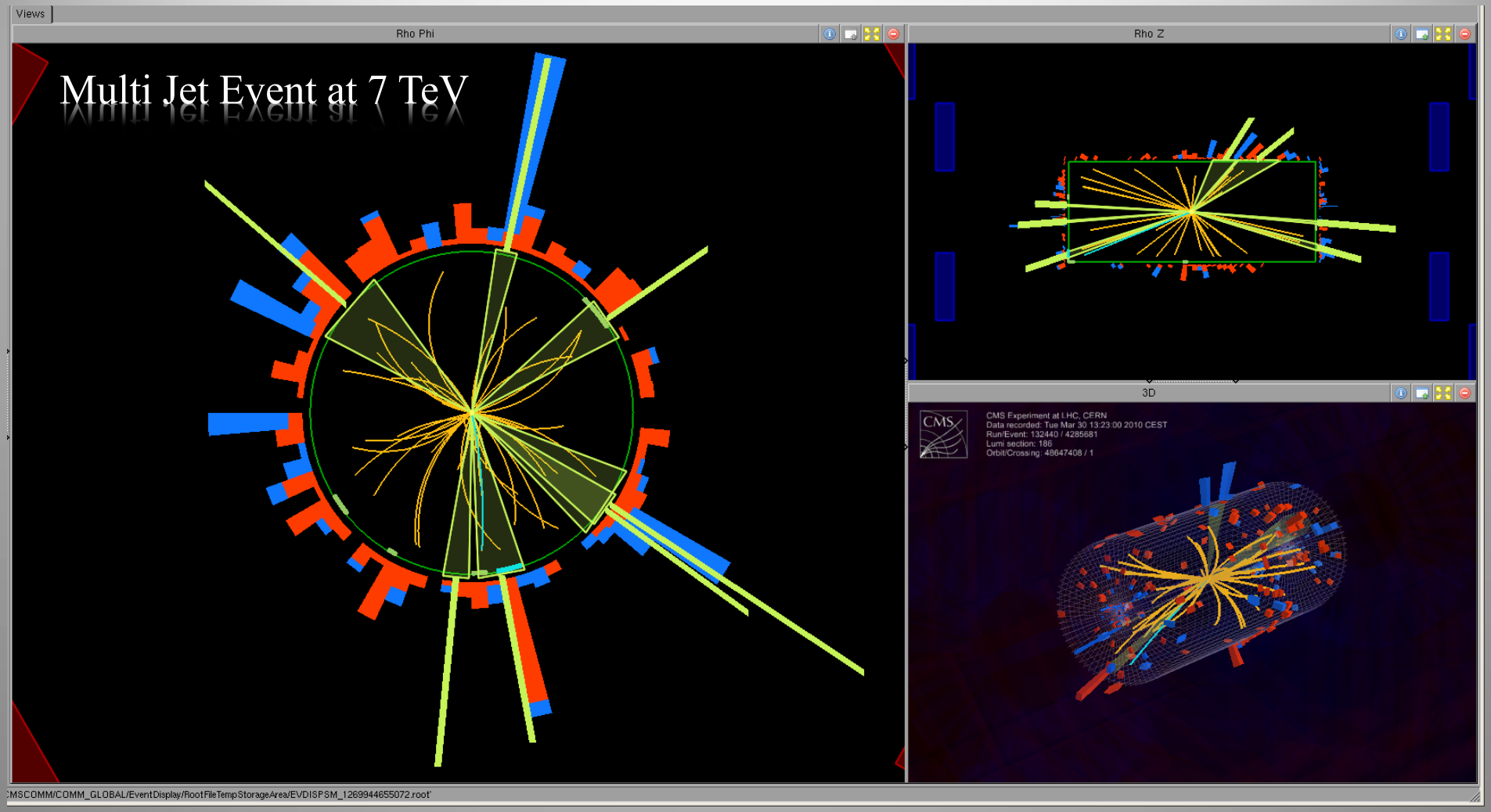
$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

For M=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

- Missing E_T and P_T: : Vectorial sum of all transverse momenta

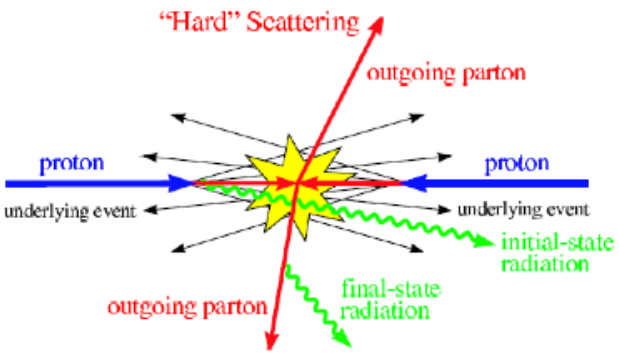
2010: First Collisions at 7 TeV



A Brave New World….

Physics Results In Chronological Order

- Studies of general characteristics of “minimum bias” events (our future pile-up)
- Study of the underlying event in collisions with a hard scattering
- Jet physics & QCD
- B-physics/charm physics
- W,Z boson production at 7 TeV
- Top quarks at 7 TeV
- Higgs discovery: a brand new particle at the LHC
- Searches for new physics: The future!
- …



Underlying event

Physics
Soft Physics and QCD

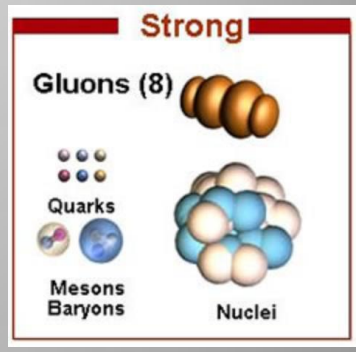
QCD

QCD plays a major role in basically every topic under discussion at this Symposium. For precision physics, or discovery physics we need to understand the role of QCD corrections: QCD is all around us at the LHC

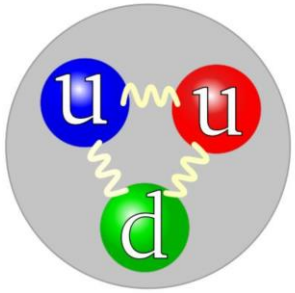
Quantum chromodynamics

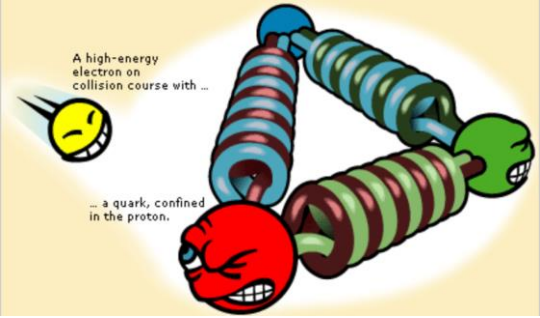
From Wikipedia, the free encyclopedia

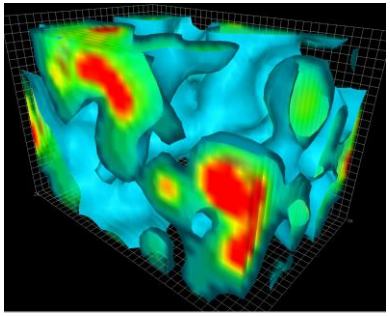
In theoretical physics, **quantum chromodynamics** (**QCD**) is a theory of the strong interaction (color force), a fundamental force describing the interactions between quarks and gluons which make up hadrons (such as the proton, neutron or pion). It is the study of the **SU**(3) Yang–Mills theory of color-charged fermions (the quarks). QCD is a quantum field theory of a special kind called a non-abelian gauge theory, consisting of a 'color field' mediated by a set of exchange particles (the gluons). The theory is an important part of the Standard Model of particle physics. A huge body of experimental evidence for QCD has been gathered over the years.



$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \sum_f \bar{\psi}_i^{(f)} \left(i \not{D}_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)}$$







First Data: Study of the Strong Force

Motivations for QCD

Satisfactory model for strong interactions: non-abelian gauge theory SU(3)

$$U^\dagger U = U U^\dagger = 1 \quad \det(U) = 1$$

Hadron spectrum fully classified with the following assumptions

- hadrons (barions,mesons): made of spin 1/2 quarks
- each quark of a given flavour comes in N_c=3 colors
- SU(3) is an exact symmetry
- hadrons are colour neutral, i.e. colour singlet under SU(3)
- observed hadrons are colour neutral ⇒ hadrons have integer charge

$$\begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix}$$

LHC early physics

<u>LHC</u>

Highest energy & luminosity: operating regime such that even early data have a potential for many discoveries

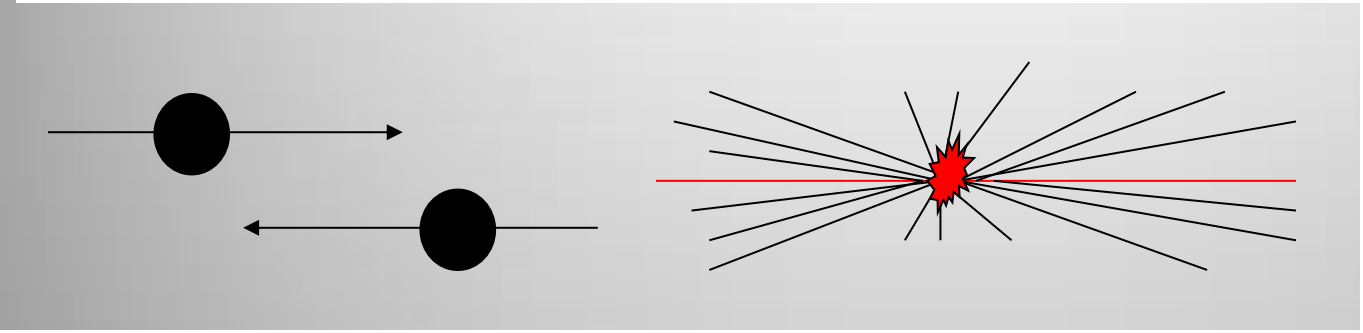
One of today's most addressed question:
What one can do with early LHC data?

The answer to this question very much depends on beam control, detector understanding/performance and control over QCD

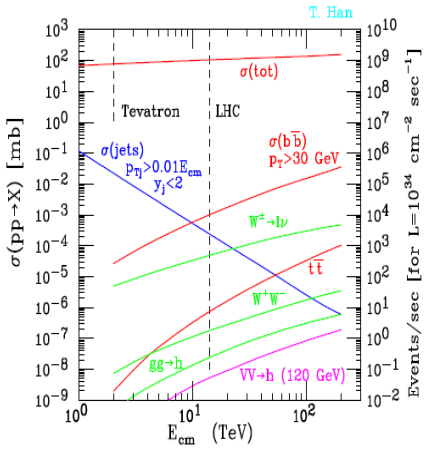
Soft QCD Dynamics

Understanding Soft Collisions

Most collisions at the LHC do not involve a hard scattering scale: these are so called soft collisions. They make up most of a "minimum bias" event sample



Scattering cross sections for various SM processes:



- Detailed studies of multi-particle production in pp
- Monte Carlos tunes, eg for describing the pile-up

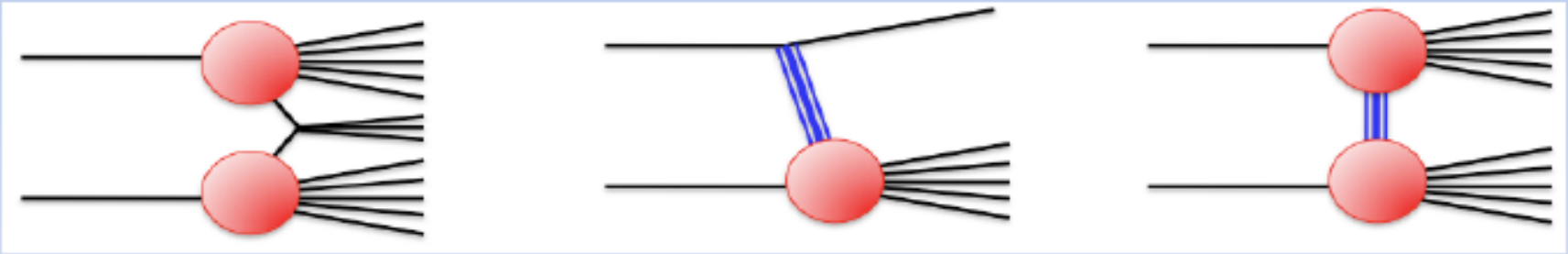
Pile-up 2012!!
Much more in 2015+

Total pp Cross Section

Dominated by soft collisions (ie no hard scattering in the events)
The elastic cross section is pp -> pp
The inelastic cross section has several components:

Inelastic p-p collisions are the result of a combination of non-diffractive and diffractive events:

$$\sigma_{\text{total-inelastic}} = \sigma_{\text{ND-inelastic}} + \sigma_{SD} + \sigma_{DD}$$

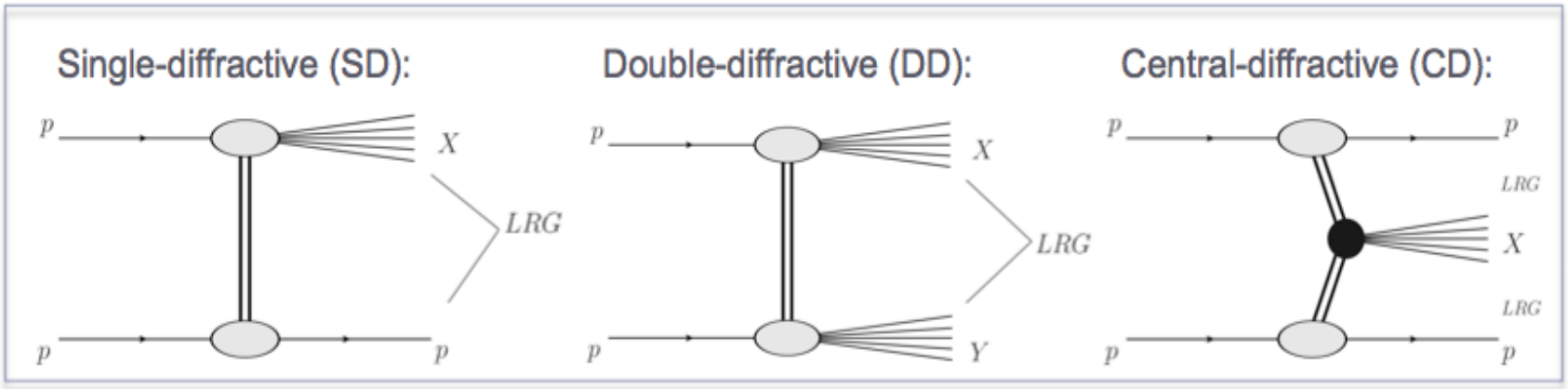


Non-Diffractive (**ND**) Single-Diffractive-Dissociation (**SD**) Double-Diffractive Dissociation(**DD**)

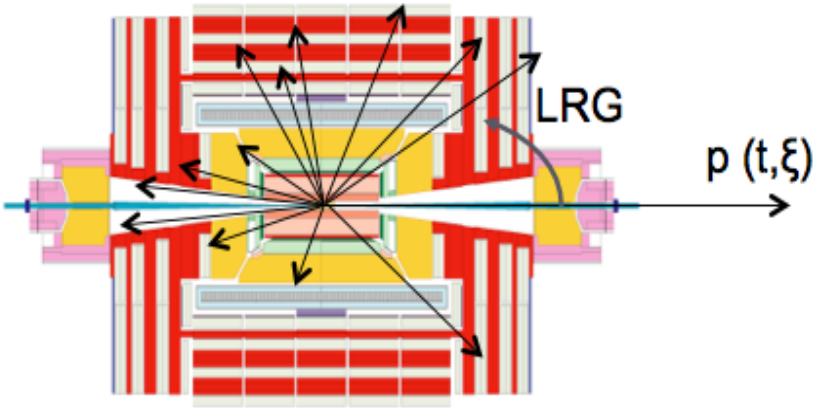
Pythia@7TeV σ~49 mb σ~14 mb σ~9 mb

What are the total pp cross section and total inelastic pp cross sections at the new high energy frontier of 7/8 TeV (in the laboratory)?

The Diffractive Component



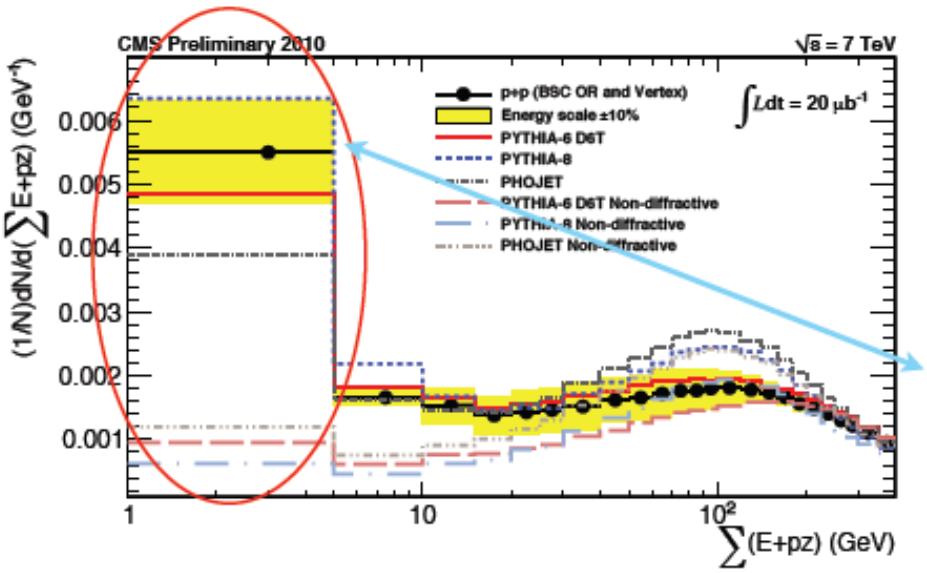
Sketch of single-diffractive event:



LRG: Large Rapidity Gap

- Diffractive events correspond to large fraction of the hadron-hadron cross section;
- Modeling of soft diffraction generator specific;
- Defining and constraining diffractive component (and their evolution with √s) important ingredient in the tuning of MC generators at the LHC.

The Diffractive Component



$\xi \sim \sum(E + p_z)$ when proton scattered in z-plus directions.

$\xi \sim \sum(E - p_z)$ when proton scattered in z-minus directions.

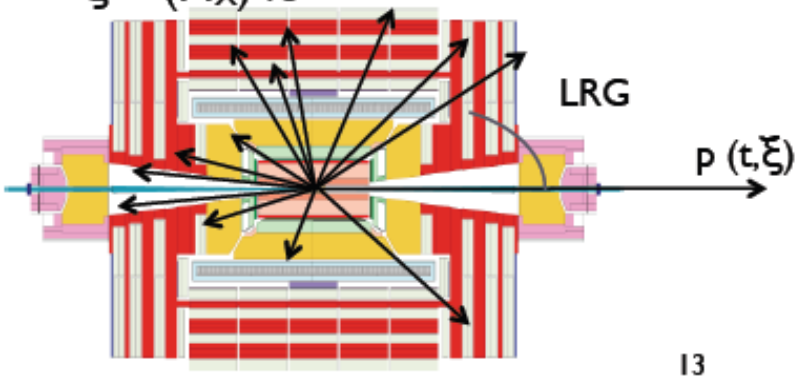
Inclusive diffractive cross section peaks at small values of ξ: $\sigma \sim 1/\xi$.

Observation of diffractive peak in data.

Main systematic effect due to ±10% energy scale variation.

N.B. Plots are uncorrected

$\xi = (M_X)^2/s$

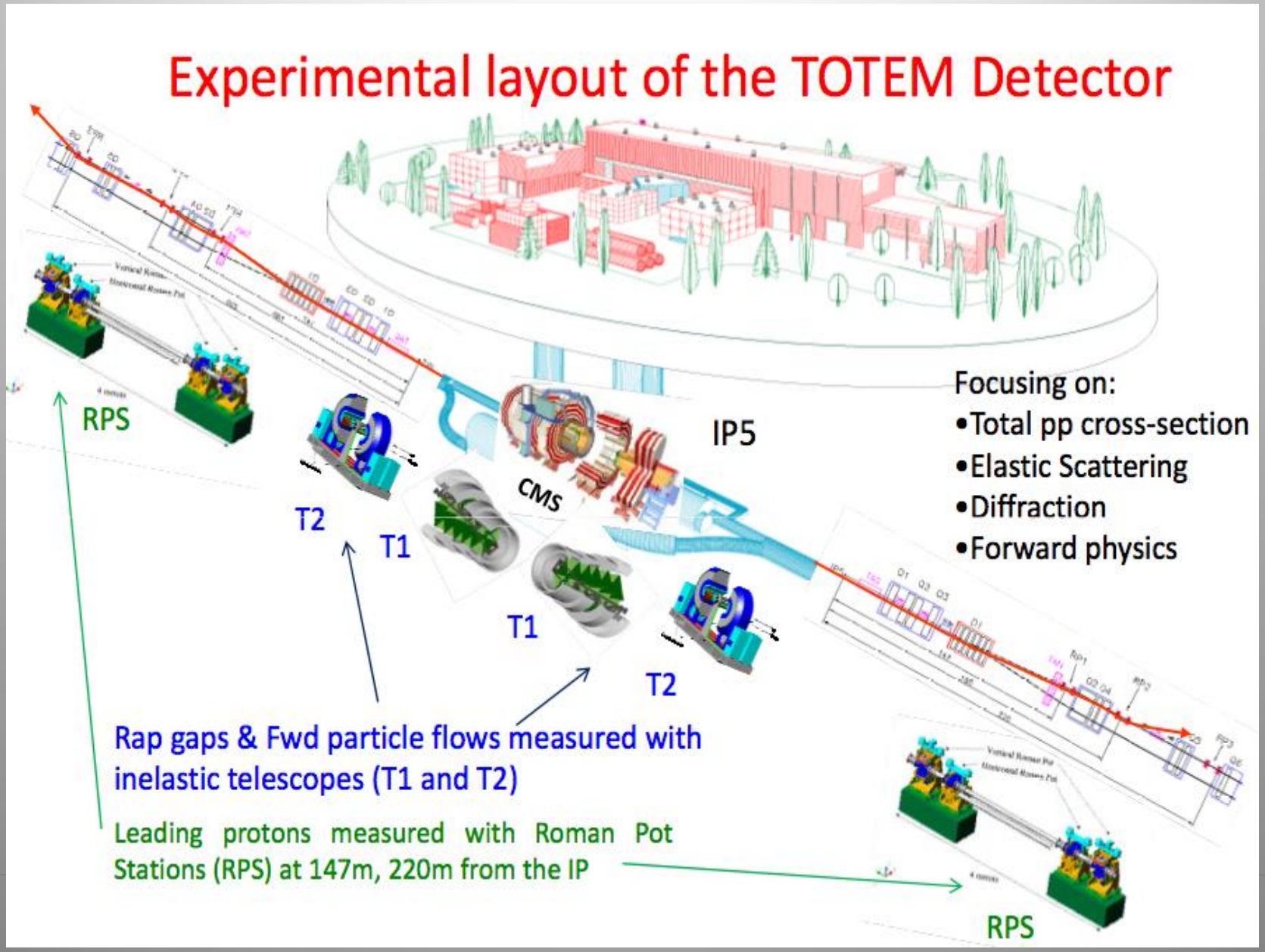


CMS PAS FWD-10-001

CMS PAS FWD-10-007

+ hard diffractive scattering (jets, W/Z) low-x QCD, exclusive processes

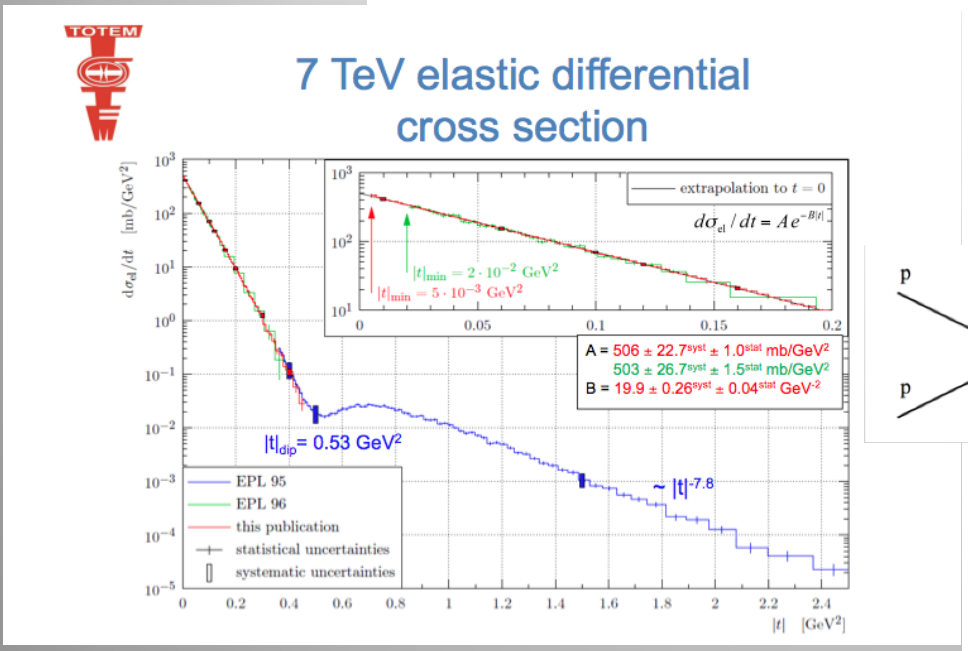
CMS + TOTEM

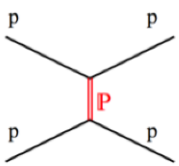

Experimental layout of the TOTEM Detector
RPS
T2
T1
CMS
IP5
T1
T2
Focusing on:
•Total pp cross-section
•Elastic Scattering
•Diffraction
•Forward physics
Rap gaps & Fwd particle flows measured with inelastic telescopes (T1 and T2)
Leading protons measured with Roman Pot Stations (RPS) at 147m, 220m from the IP
RPS

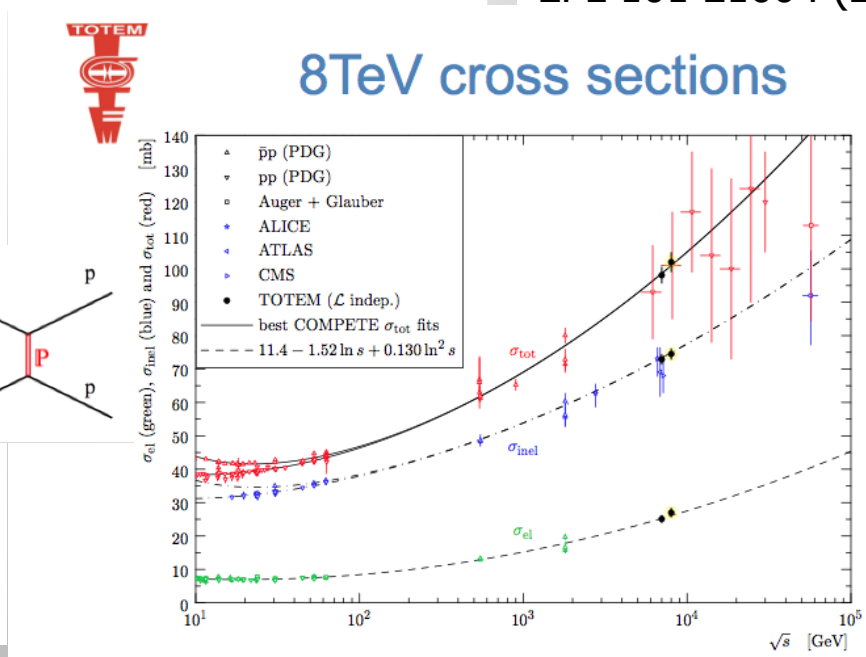
Elastic/Total pp Cross Section

TOTEM = Roman Pots + Forward Detectors
TOTEM uses the same IP as CMS (IP5)

EPL 101 21004 (2013)







$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt|_0}{N_{el} + N_{inel}}$$

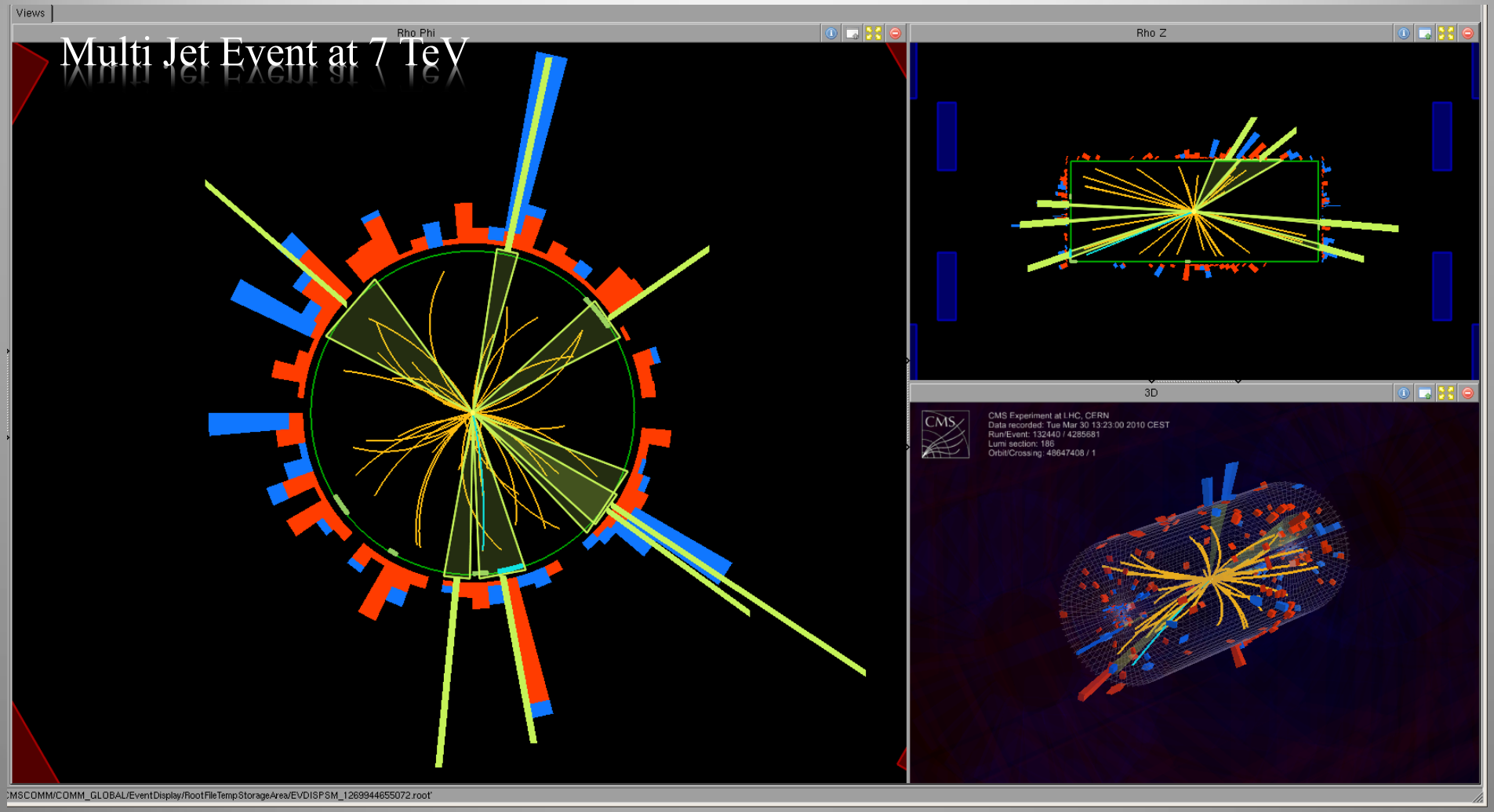
$$\sigma_{tot} = (101.7 \pm 2.9) mb$$

$$\sigma_{inel} = (74.7 \pm 1.7) mb$$

$$\sigma_{el} = (27.1 \pm 1.4) mb$$

Future: •High beta measurements for Coulomb-Nuclear interference, ALFA

Characteristics of Collisions at 7/8 TeV



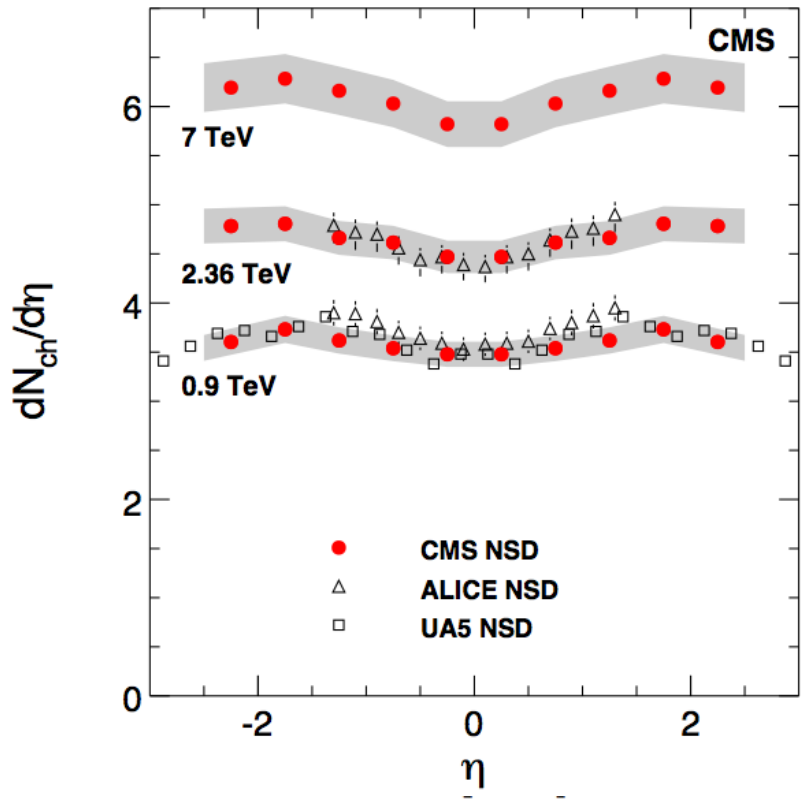
Central particle density, charged particle multiplicities, correlations

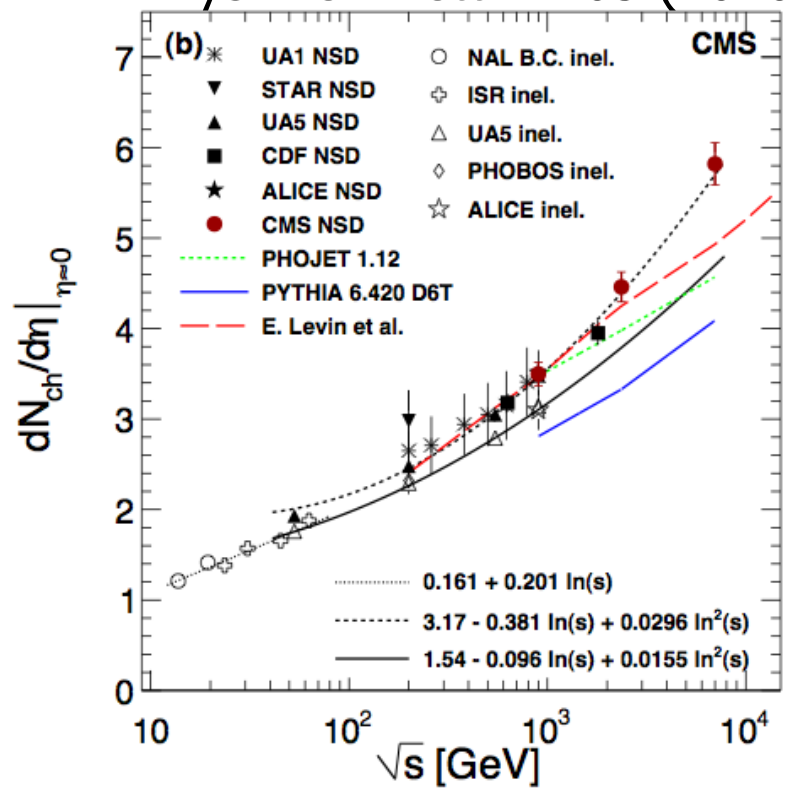
Charged Particles

pseudo-rapidity density of charged hadrons at √s = 7 TeV

Minimum bias events Non-Single Diffractive event selection

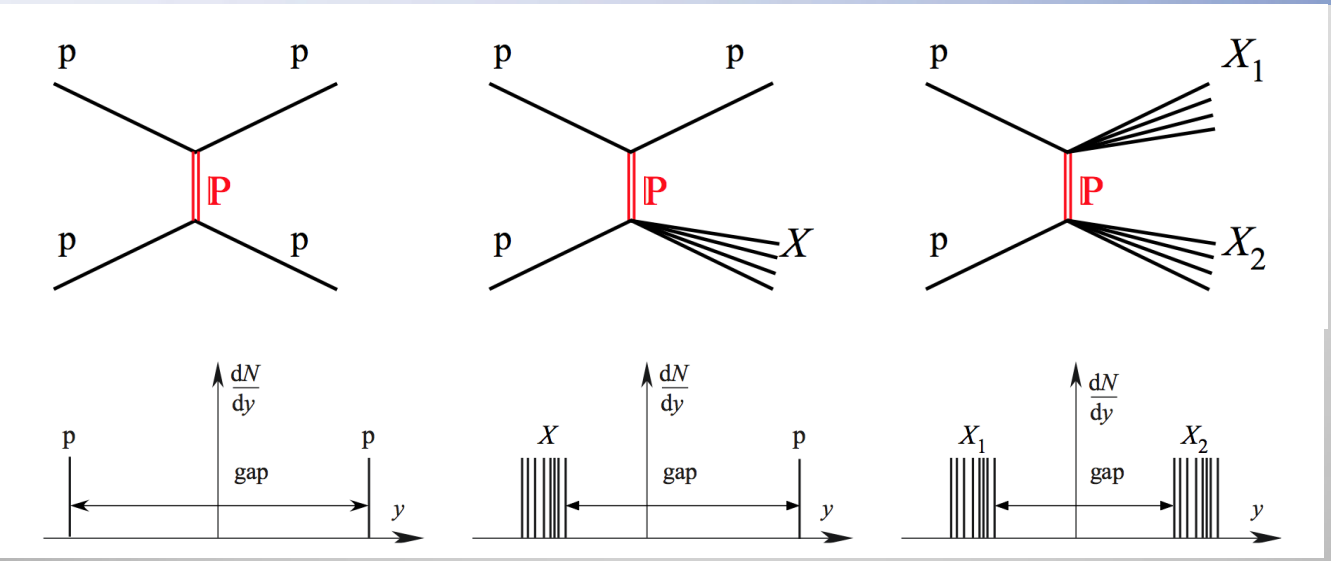
Phys. Rev. Lett. : 105 (2010)





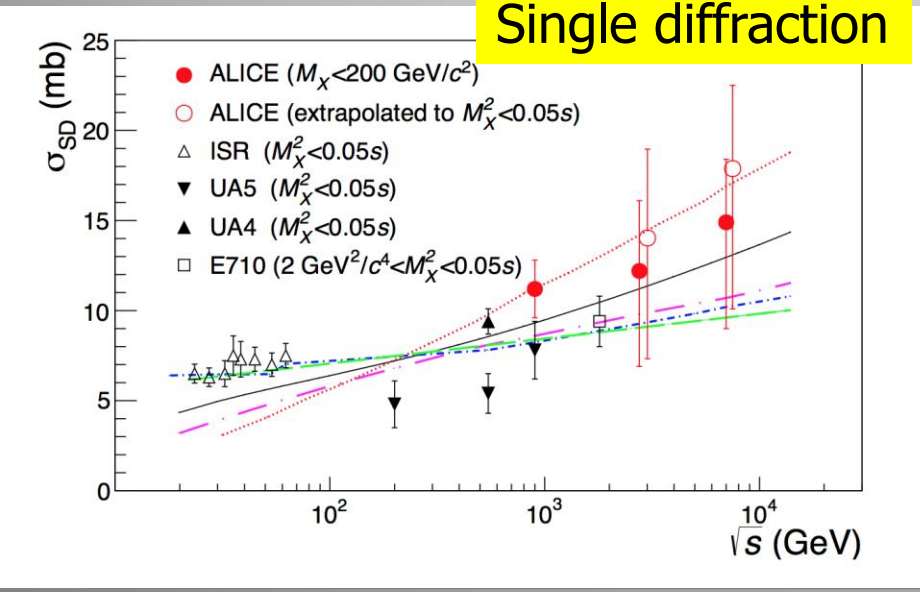
Rise of dN/dη in data stronger than currently used models

Diffractive Cross Sections

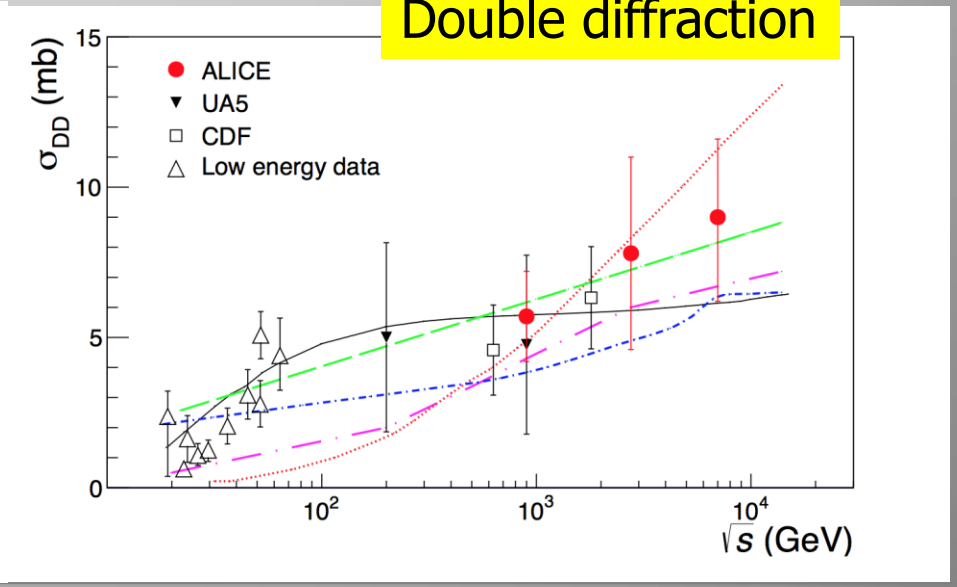


arXiv:1208.4968

Single diffraction

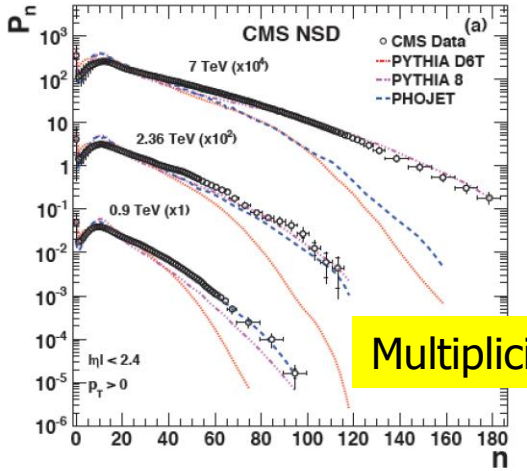


Double diffraction

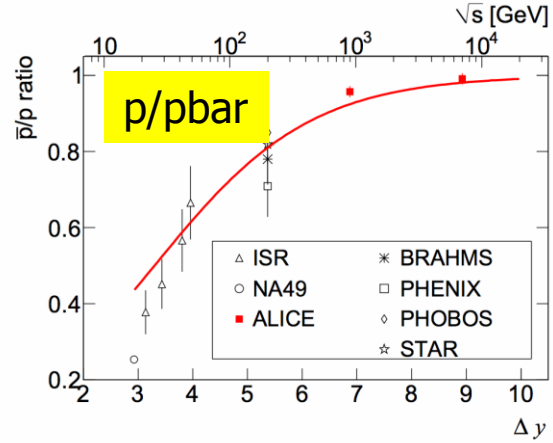


Understanding Particle Production

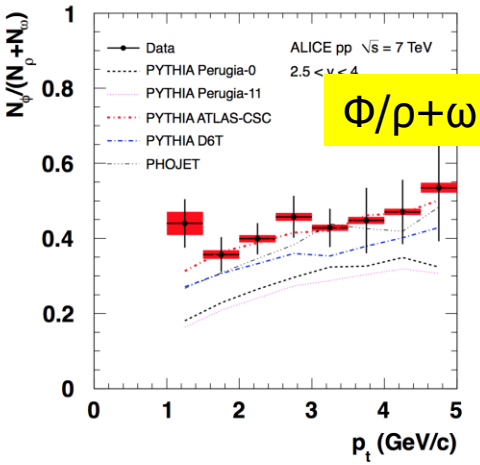
- Single particles, multiplicities etc. vs phenomenological models…
- LHC detectors are excellent and complementary for such studies



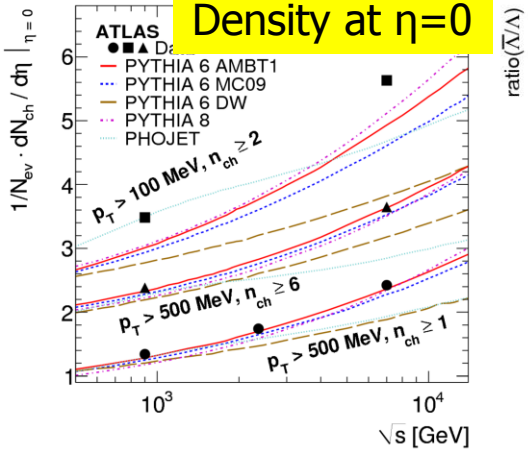
Multiplicities



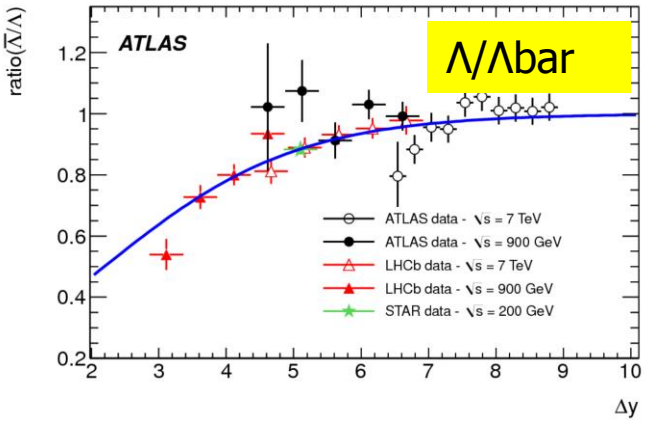
p/pbar



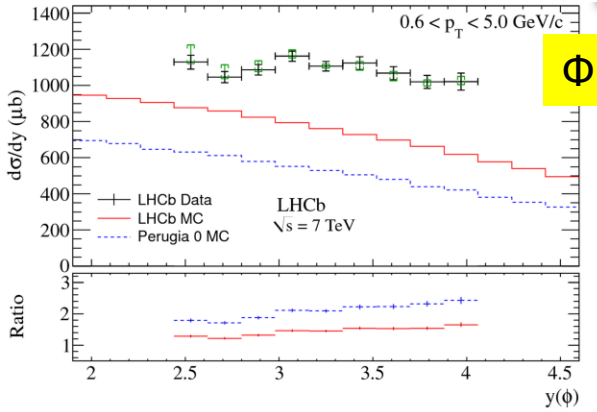
Φ/ρ+ω



Density at η=0



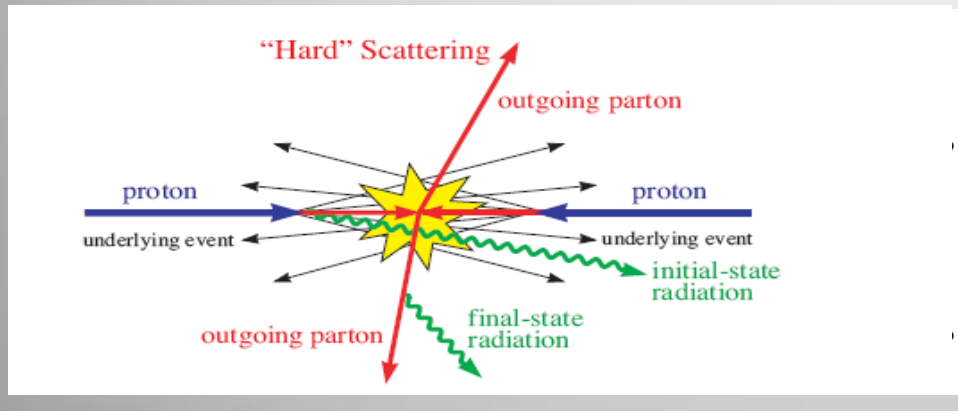
Λ/Λbar

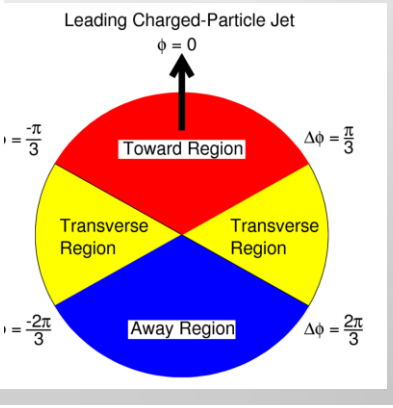


Φ

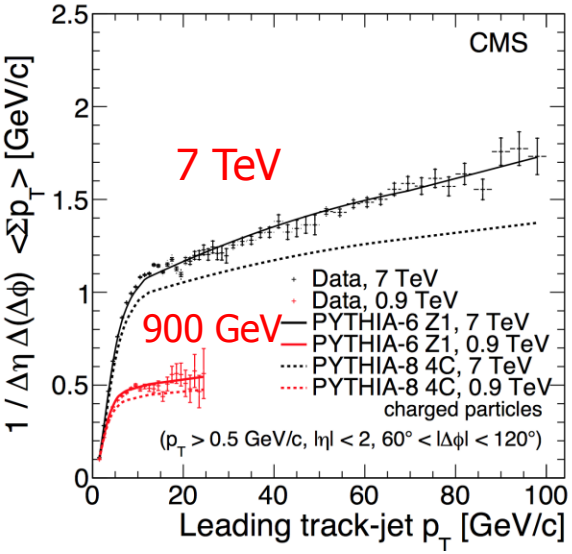
Underlying Event Studies

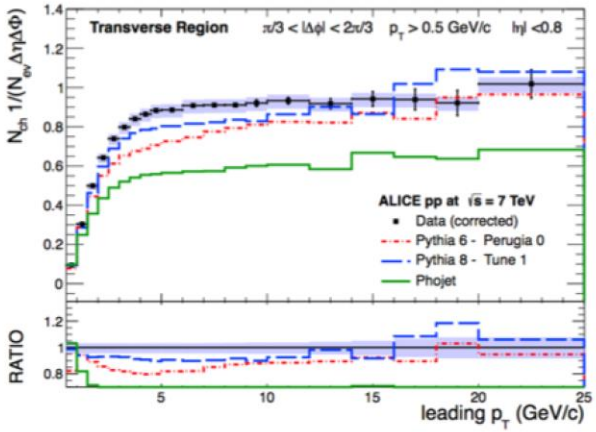
An important systematic effect for precision measurements, eg top mass
All central detectors have made measurements in the 'transverse' region:

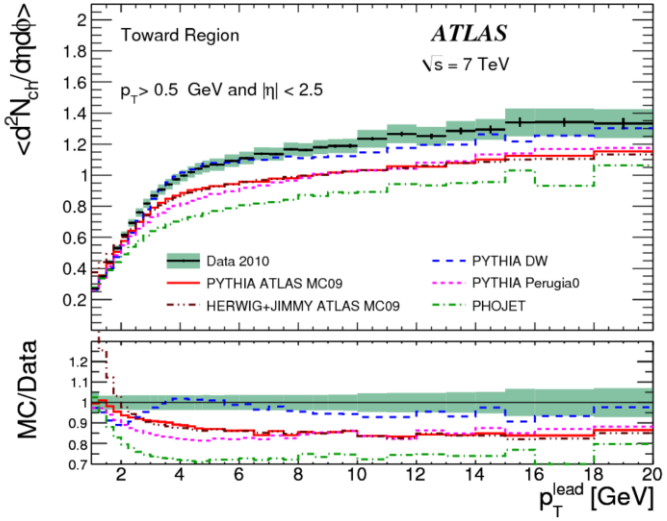




Measure the particle flow in transverse region as function of the hard scale



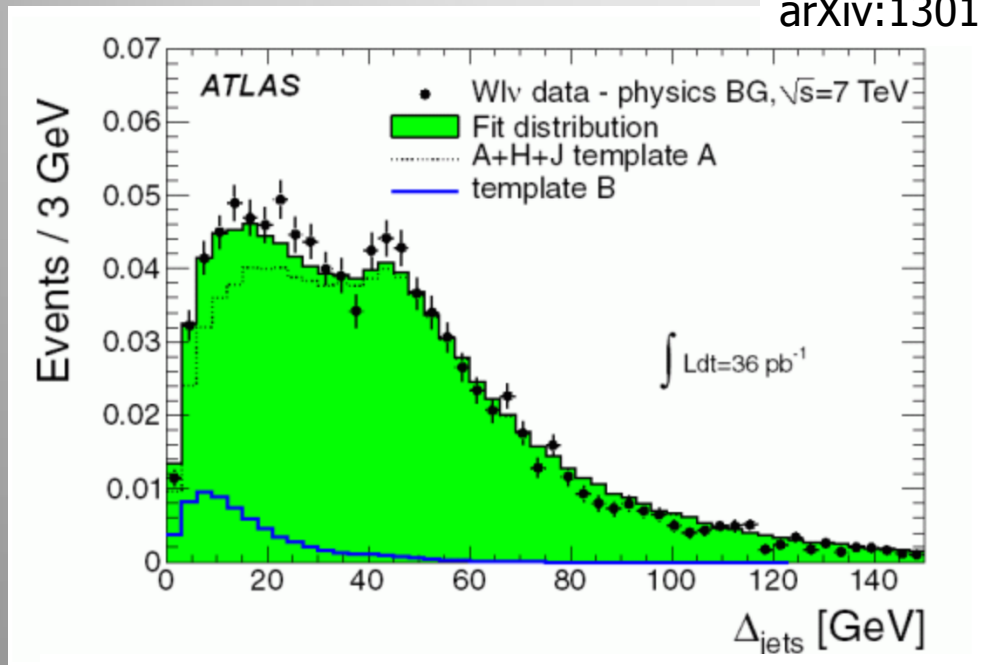




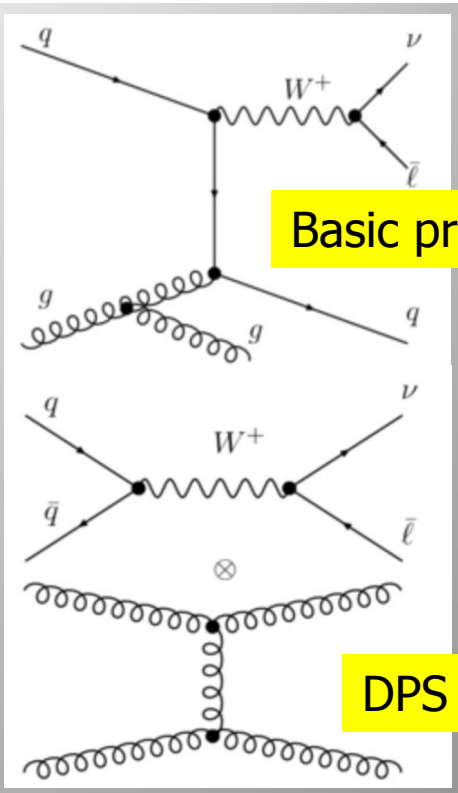
Double Parton Scattering

Example: angular correlations study of W+ 2jet events: The fraction of the cross section attributed to DPS= 0.08 ± 0.01 (stat.) ± 0.02 (sys.)

arXiv:1301.6872

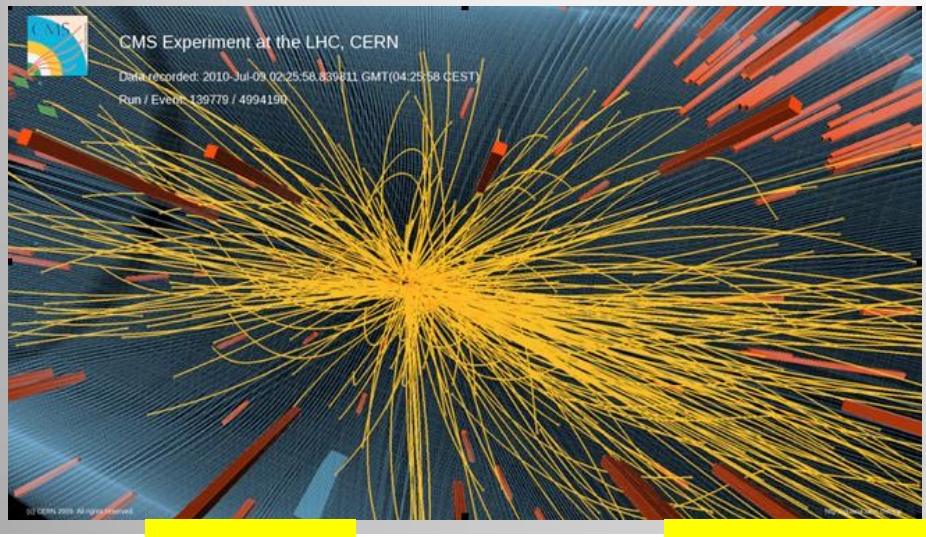


Difference between the transverse momenta of the two jets (p_T > 20 GeV)



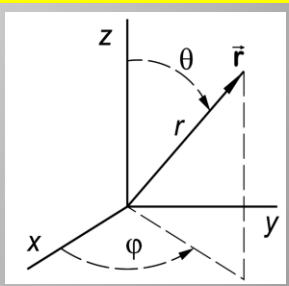
DPS can be important for searches where after cuts only a few events remain…

Correlations Between Produced Particles

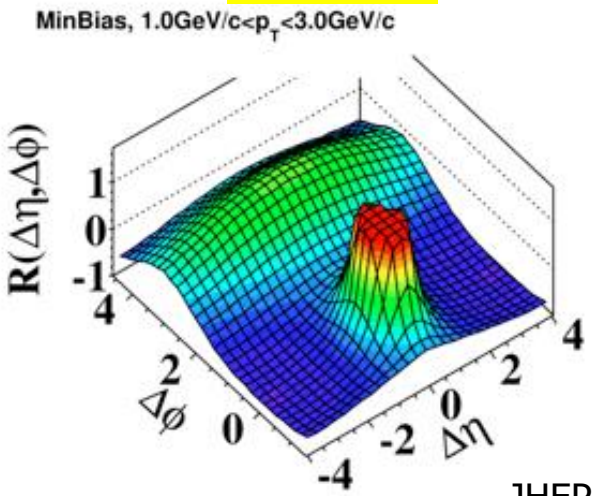


- Select high multiplicity events
- Study the correlation between two charged particles in the angles φ (transverse): Δφ and θ (longitudinal): Δθ

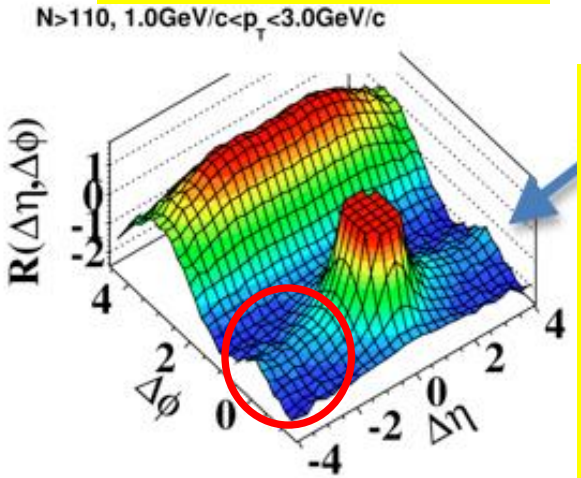
η= -ln tanθ/2



All events



High multiplicity events



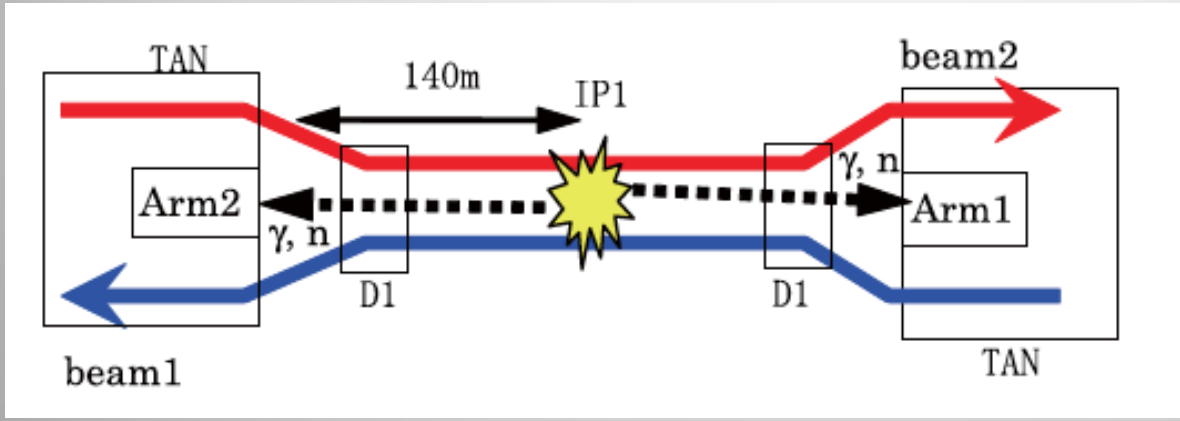
JHEP 1009 (2010) 091

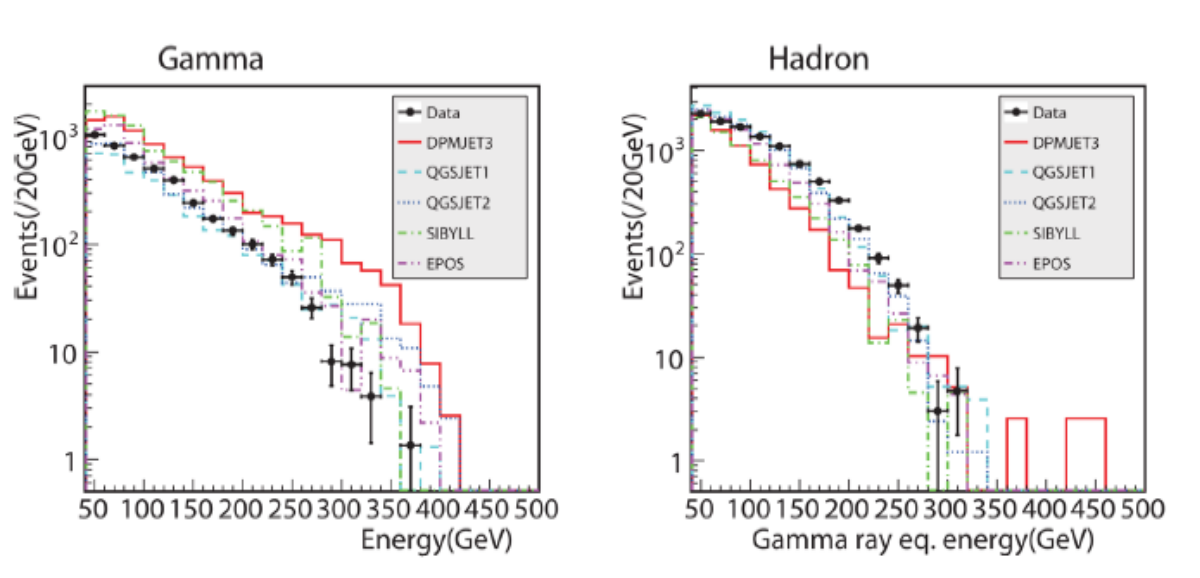
A new phenomenon in the 'stronge force'?

- Multiple interactions?
- Glass condensates?
- Hydrodynamic models?

…

Very Forward measurements: LHCf



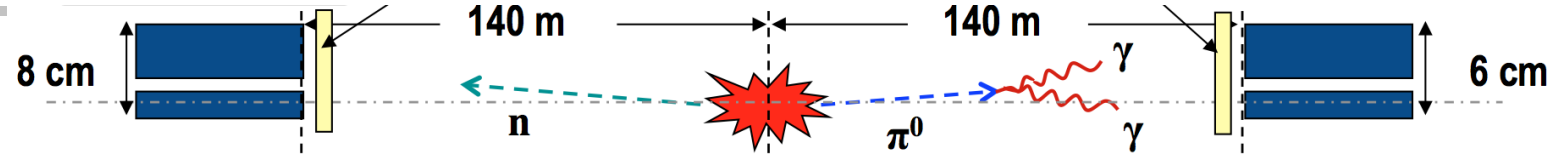


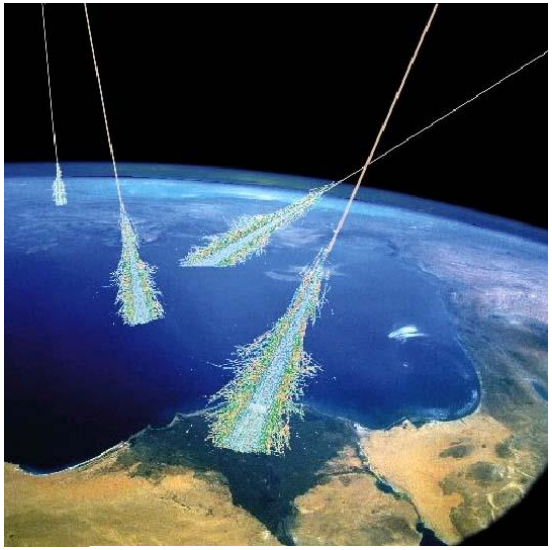
Models have difficulties to reproduce the very forward "zero degree" emitted energies

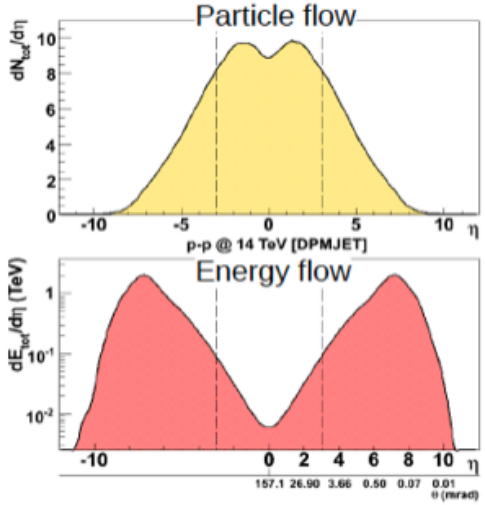
Very important for cosmic ray experiments

Forward Particles Measurements

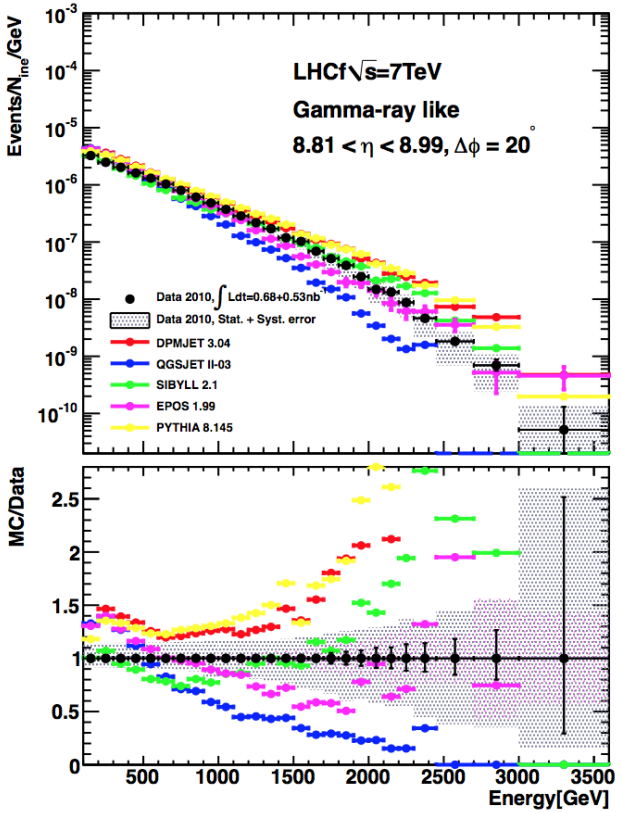
- LHCf uses the same Interaction Point as ATLAS (IP1)
- LHCf has forward detectors at zero degrees seen from the IP (140 away from the IP): Measure the forward photons/pions for cosmic ray studies







DESY-PROC-2012-03



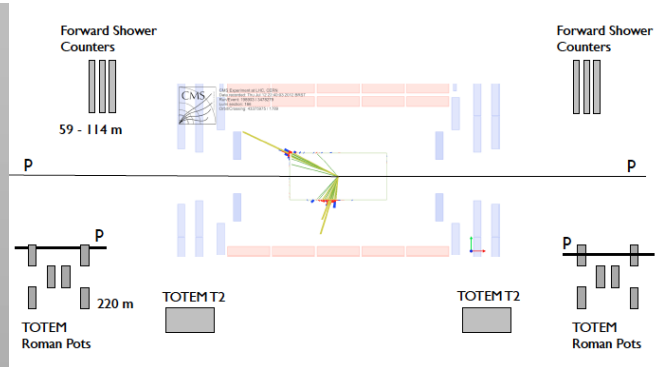
Forward gamma measurement compared to Monte Carlos for Cosmic Ray studies

No model reproduces the data well !!

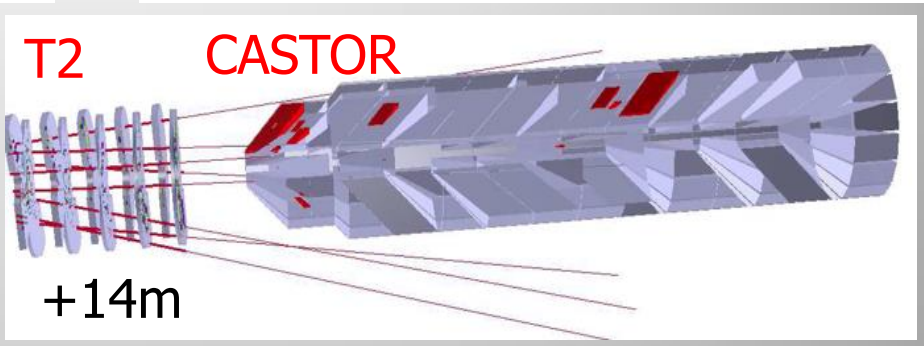
Future Option: CMS + TOTEM

Since end of 2011: "Common data taking of CMS with TOTEM"

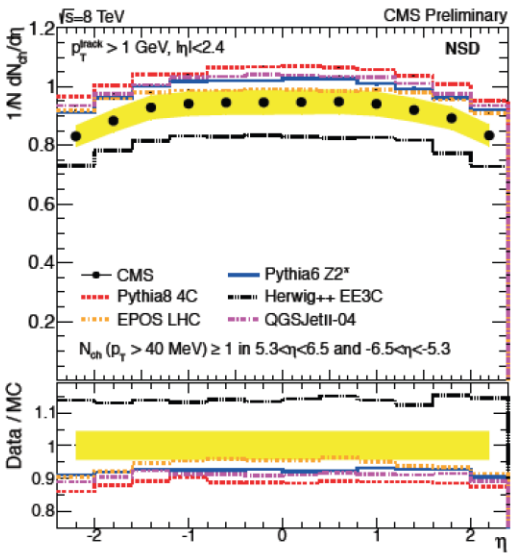
RP (TOTEM) + Central Di-jet (CMS)

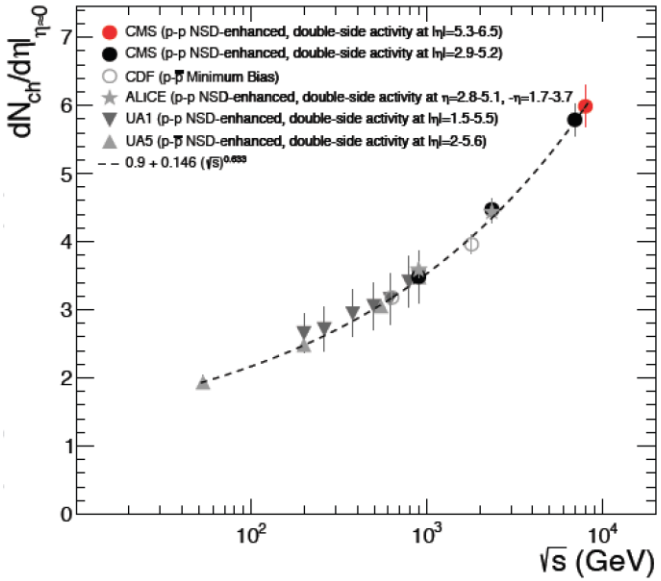


T2 (TOTEM) + CASTOR (CMS)

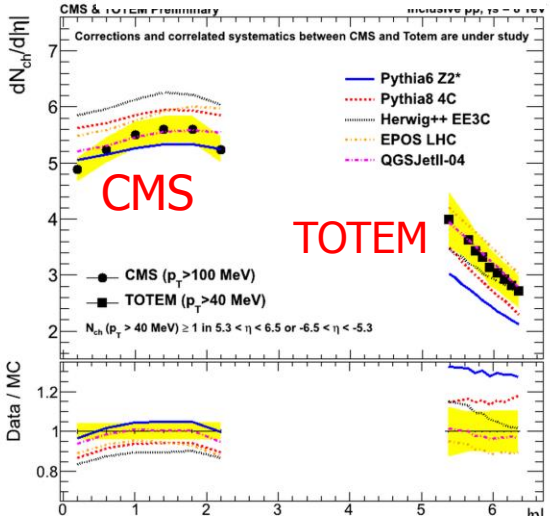


CMS central energy flow with TOTEM T2 tag





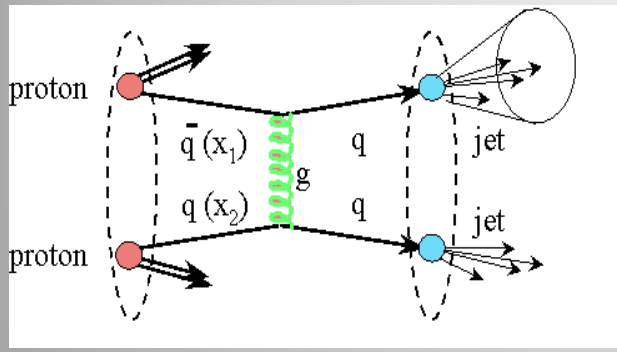
CMS PAS FSQ-12-026

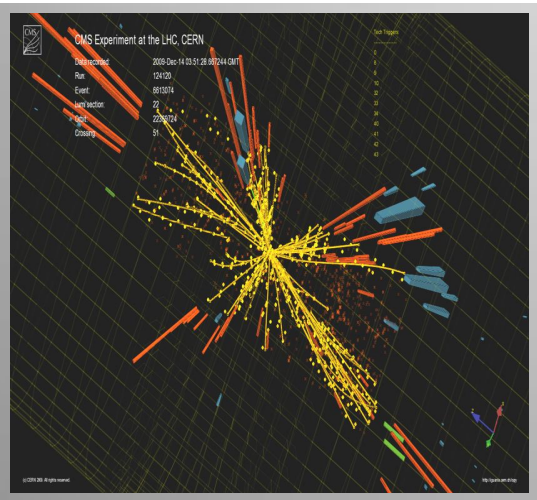


Pseudo-rapidity η

Hard Probes in QCD

Strong Interaction: Jets Production!

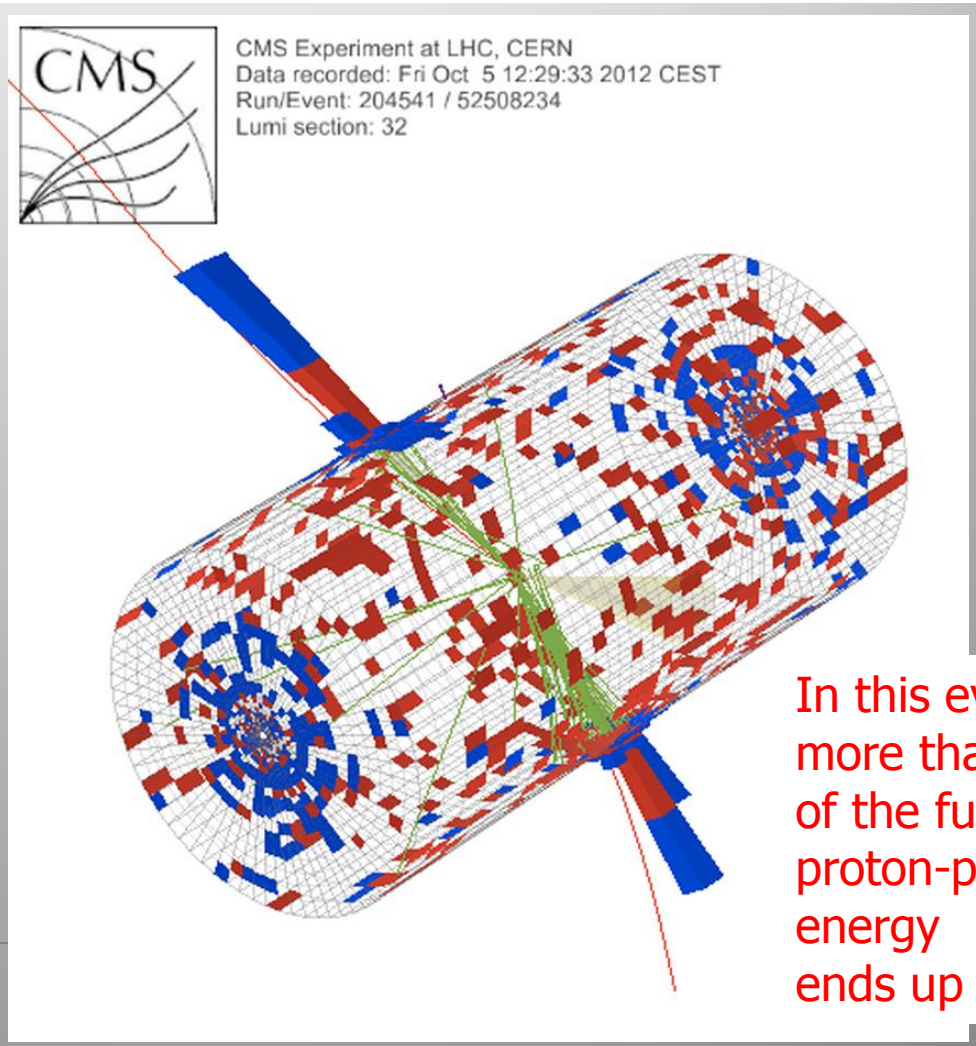




Jets of particles emerge after a high energy parton-parton scattering

Study the strong force using jet production

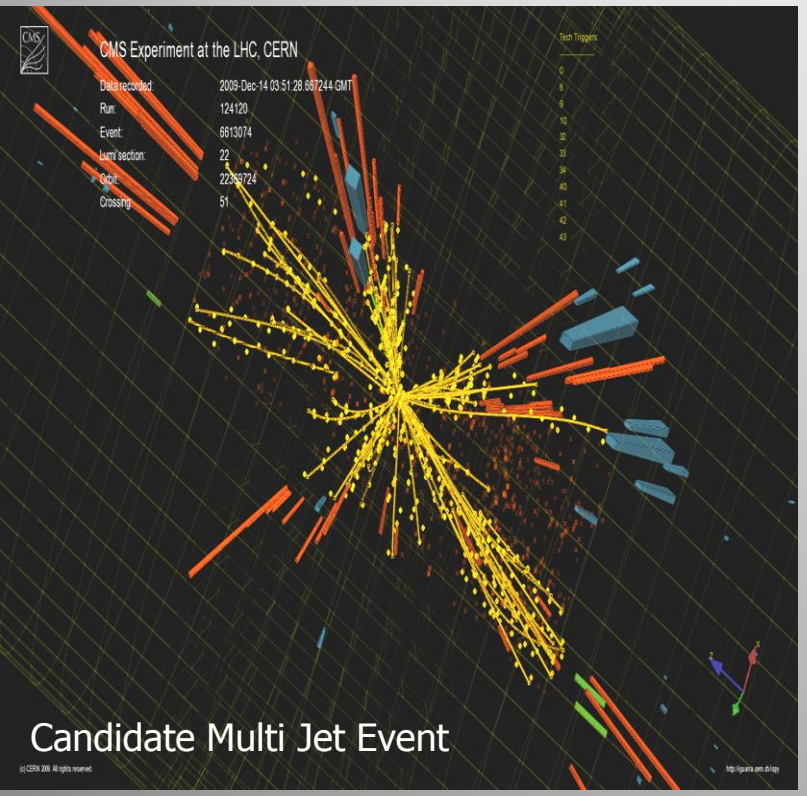
Di-jet invariant mass = 5.15 TeV (R=1.1 jets)

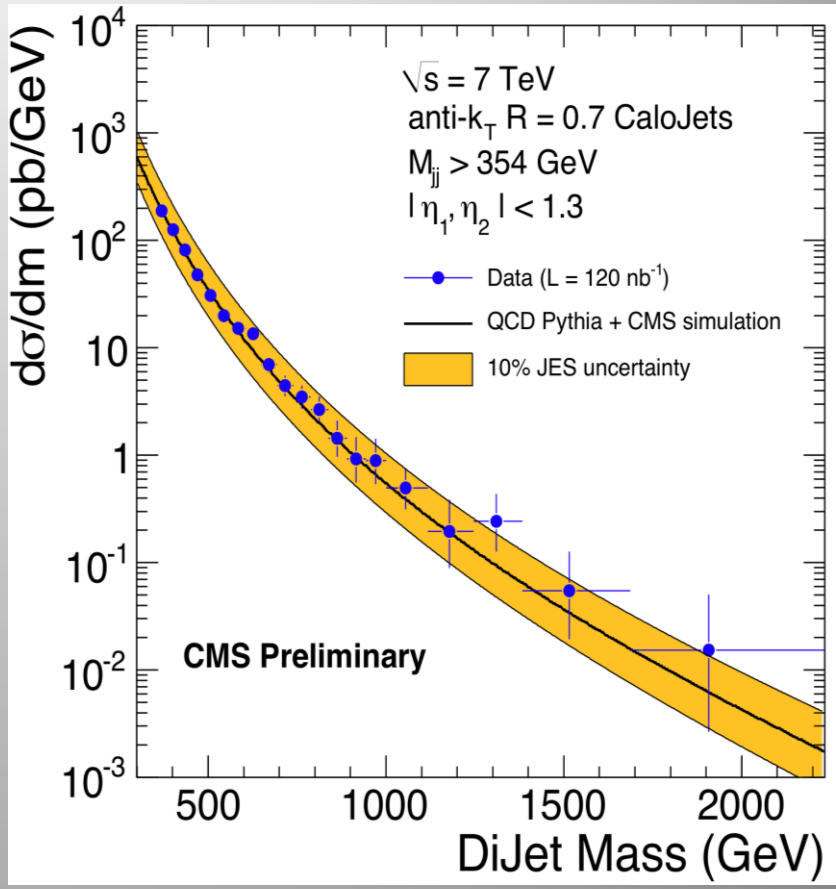


In this event more than 60% of the full proton-proton energy ends up in jets

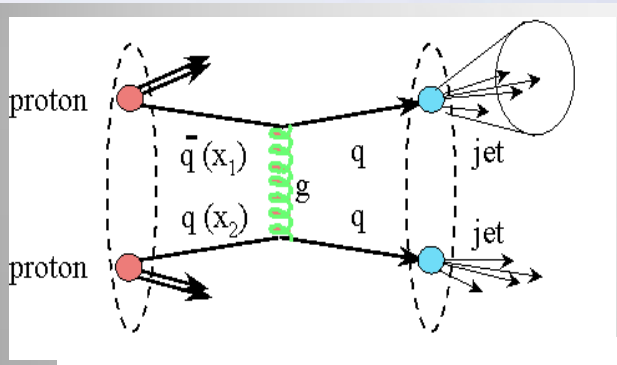
Jets!

LHC probes a new regime eg with jets





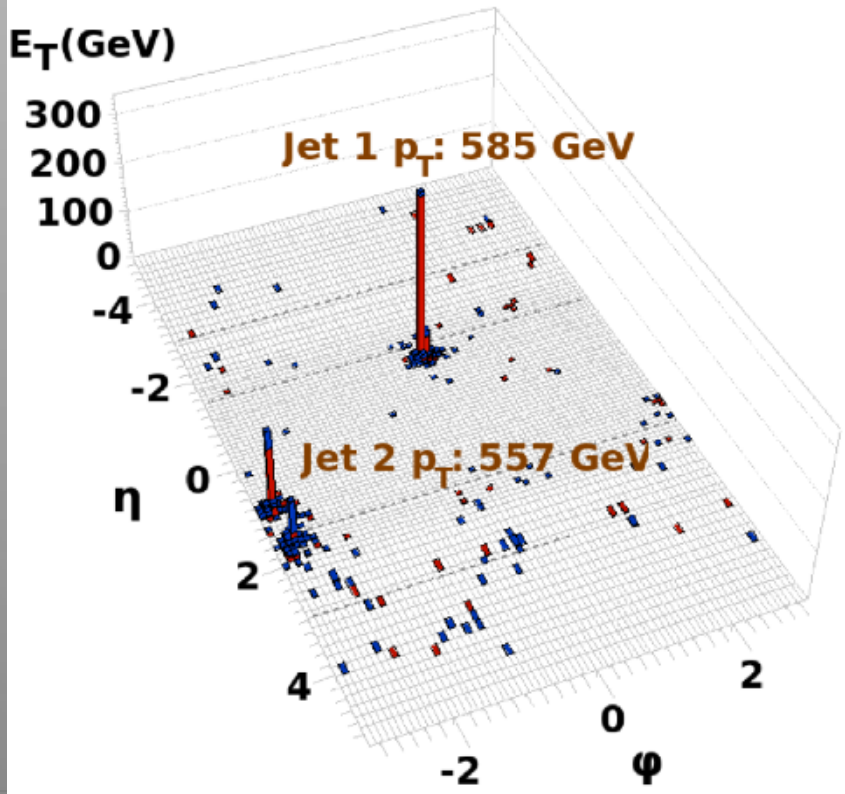
Jet Production at 7 TeV

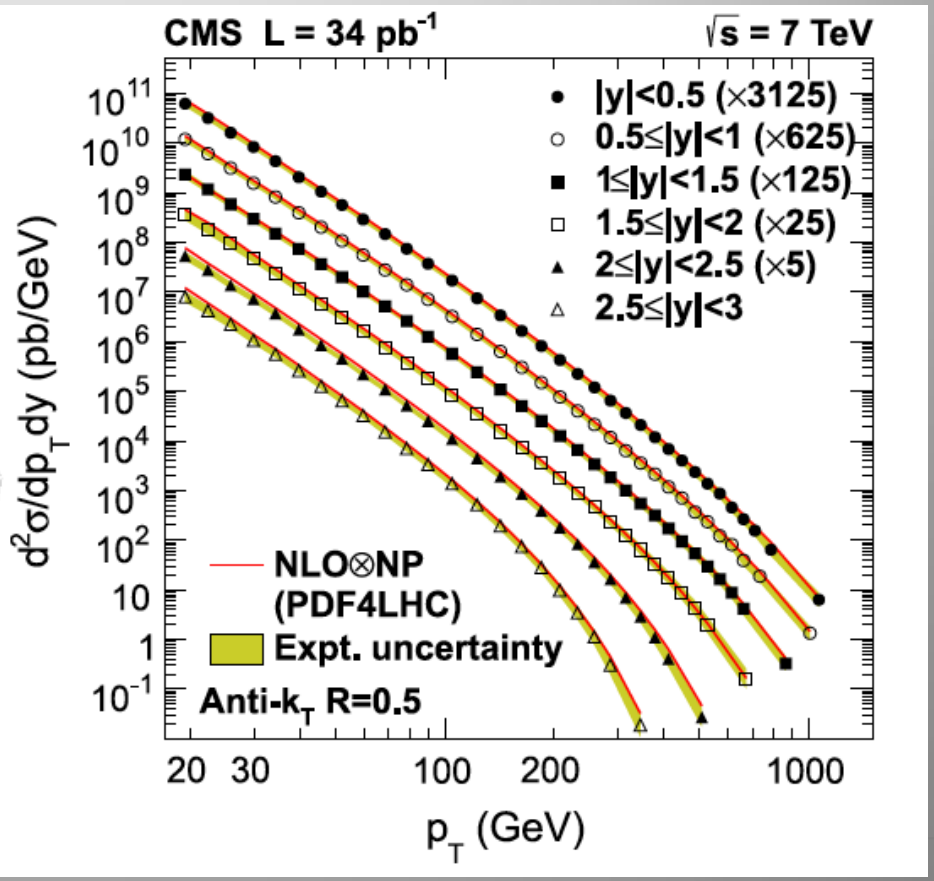


The data are spanning:

-20 GeV < p_T < 1200 GeV and $|\eta| < 4.4$

-Up to 10 orders of magnitudes in cross-sections



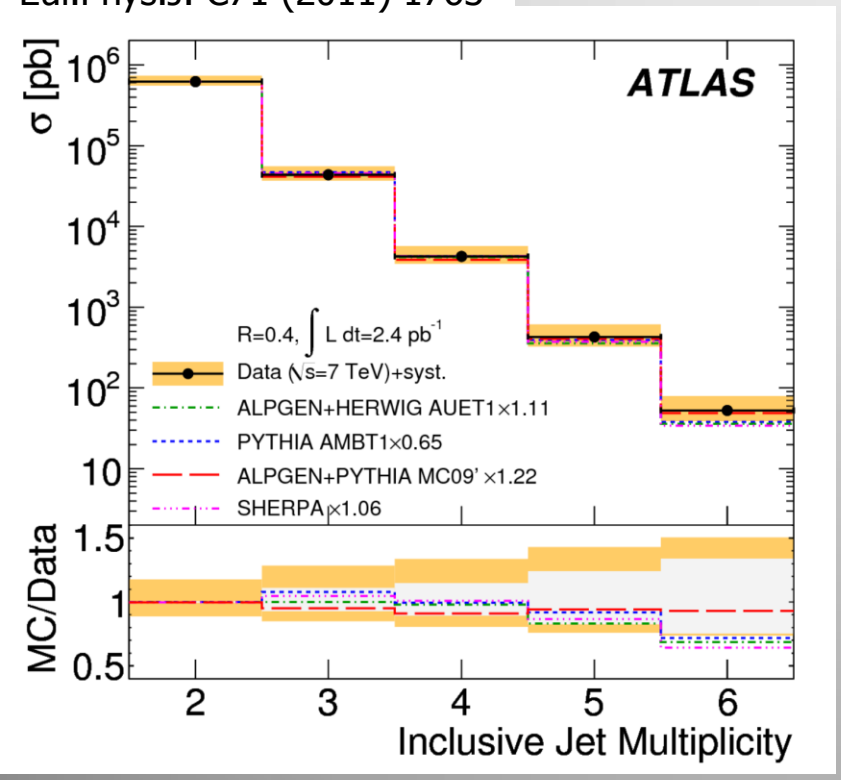


Early Measurements of Multi-jets

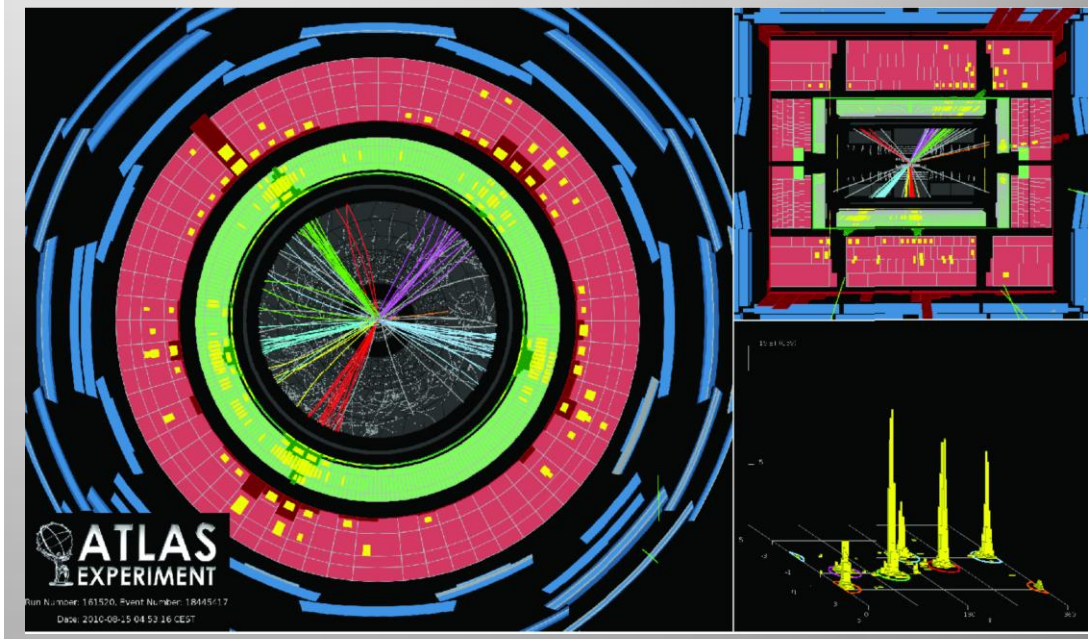
Early 2010 data…

Jet Multiplicity distribution

Eur.Phys.J. C71 (2011) 1763



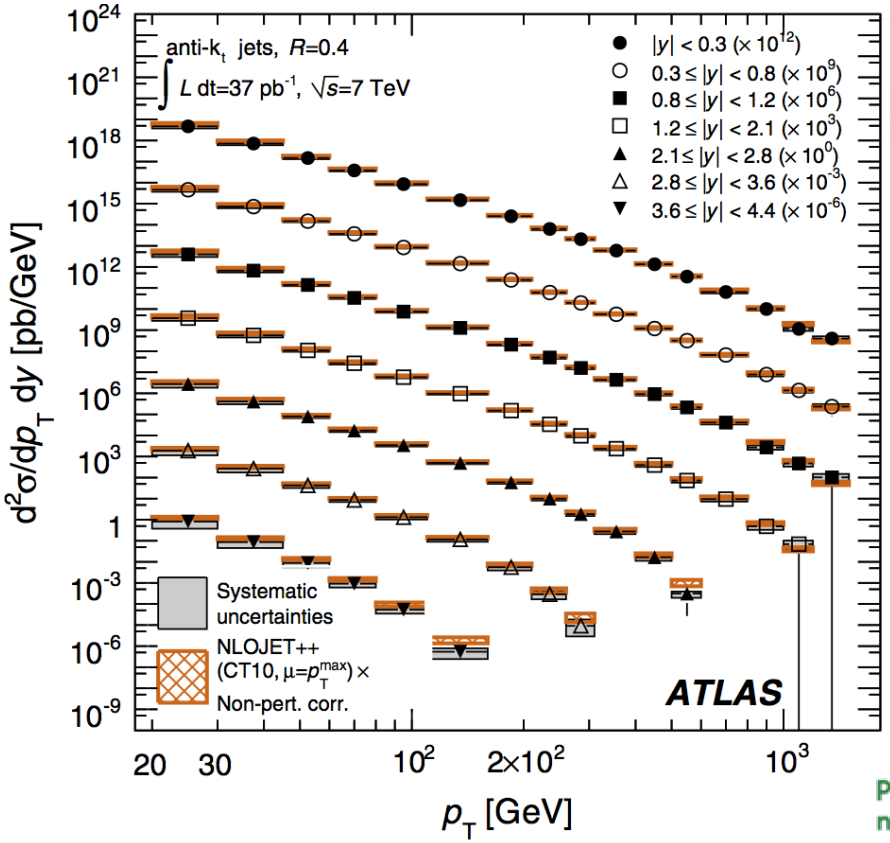
A six jet event



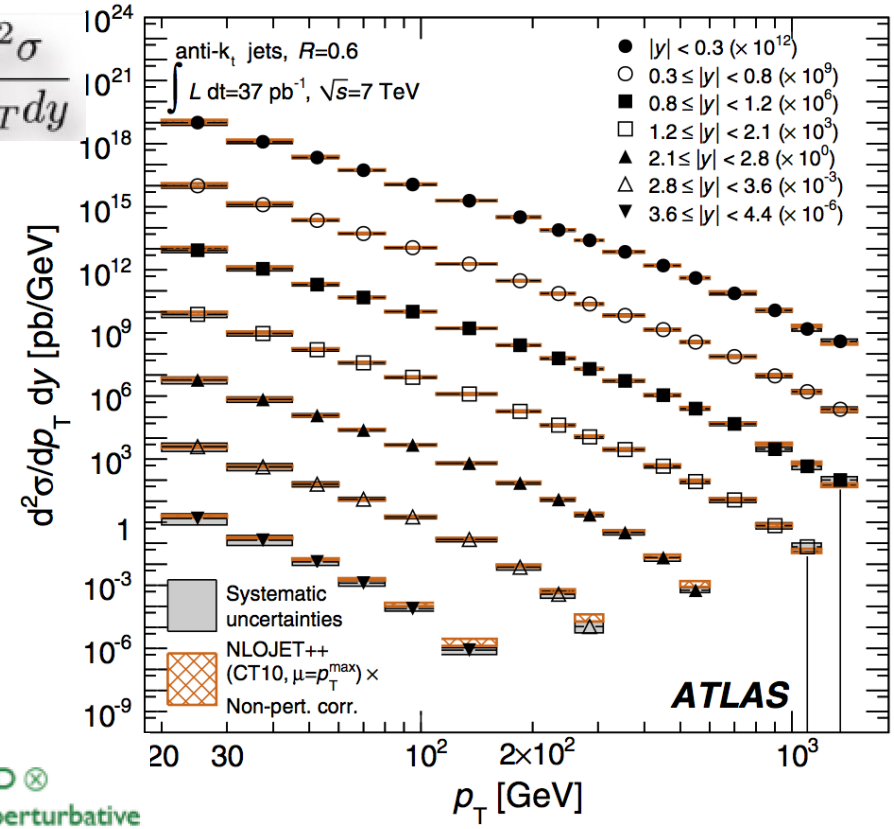
Multi-jet distribution in good agreement with theory - LO matrix elements plus matched parton showers - apart from normalization

Inclusive Jet Production (7 TeV)

Phys.Rev. D86 (2012) 014022



$$\frac{d^2\sigma}{dp_T dy}$$



pQCD ⊗ non-perturbative corrections

Agreement with NLO calculations over the full range, up to 2 TeV jets

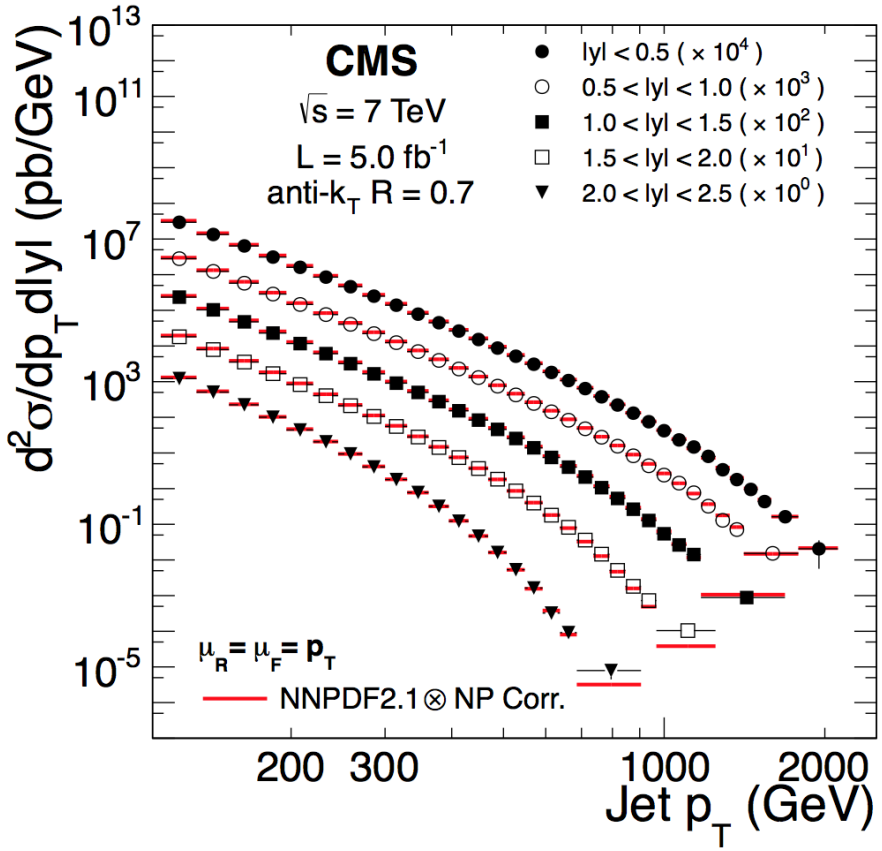
The anti-kT jet algorithm is used in most studies. The 'cone' chosen for this algorithm is different for ATLAS and CMS -> no direct comparison possible

ATLAS uses R=0.4 and R=0.6

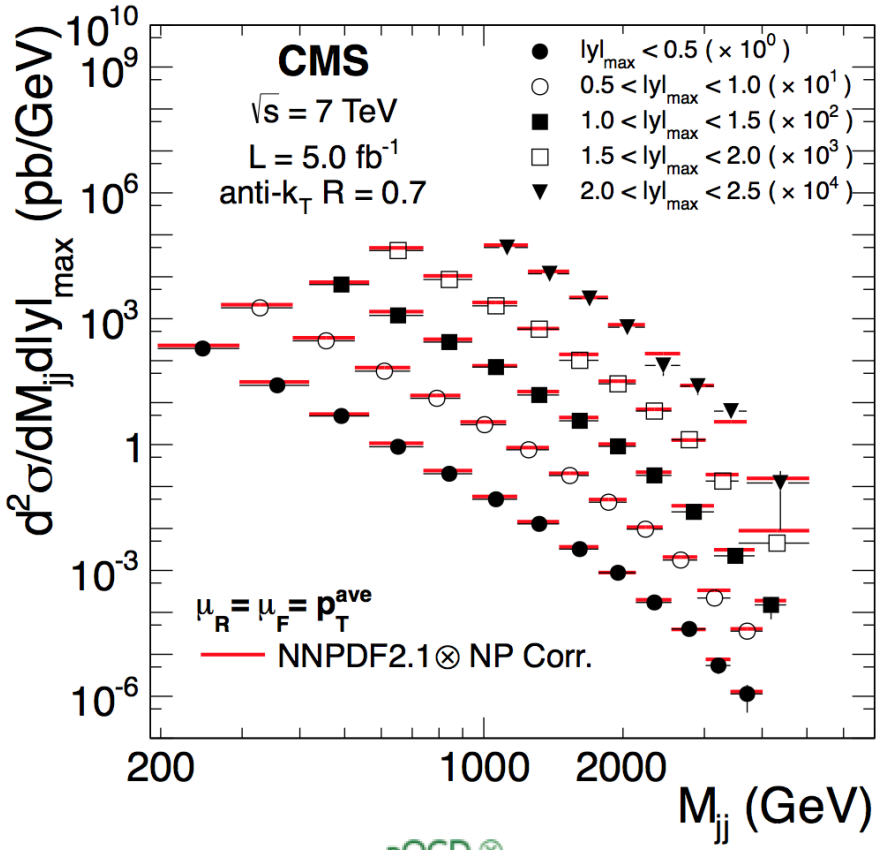
Inclusive Jet Production (7 TeV)

arXiv:1212.6660

$$\frac{d^2\sigma}{dp_T dy}$$



$$\frac{d^2\sigma}{dM_{JJ}d[|y|_{max}, y^*]}$$

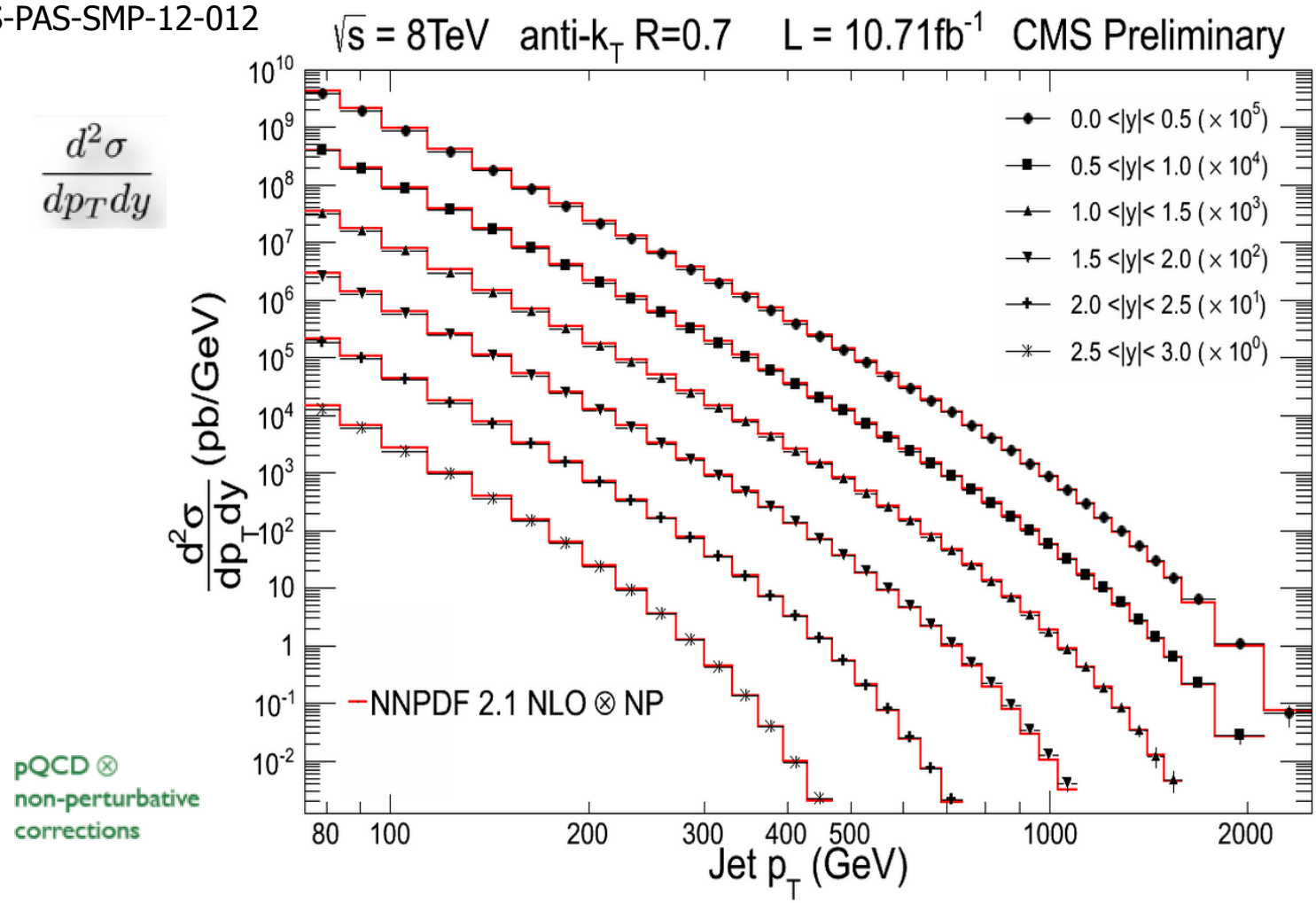


pQCD ⊗ non-perturbative corrections

...and CMS uses R=0.5 and R=0.7...

Inclusive Jet Production (8 TeV)

CMS-PAS-SMP-12-012



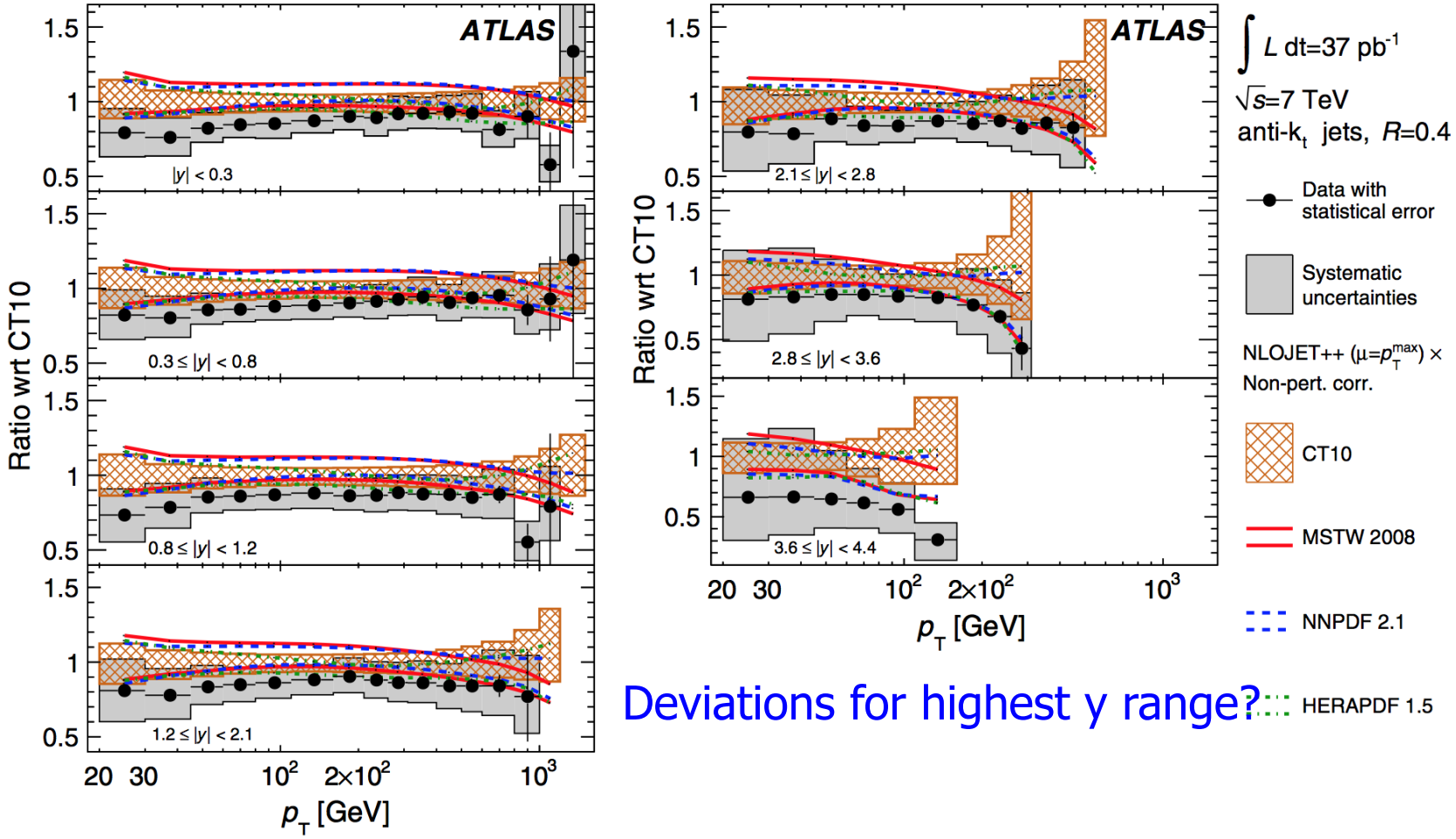
$$\frac{d^2\sigma}{dp_T dy}$$

pQCD ⊗
non-perturbative
corrections

Agreement with NLO calculations over the full range, up to and beyond 2 TeV jets

Inclusive Jet Production

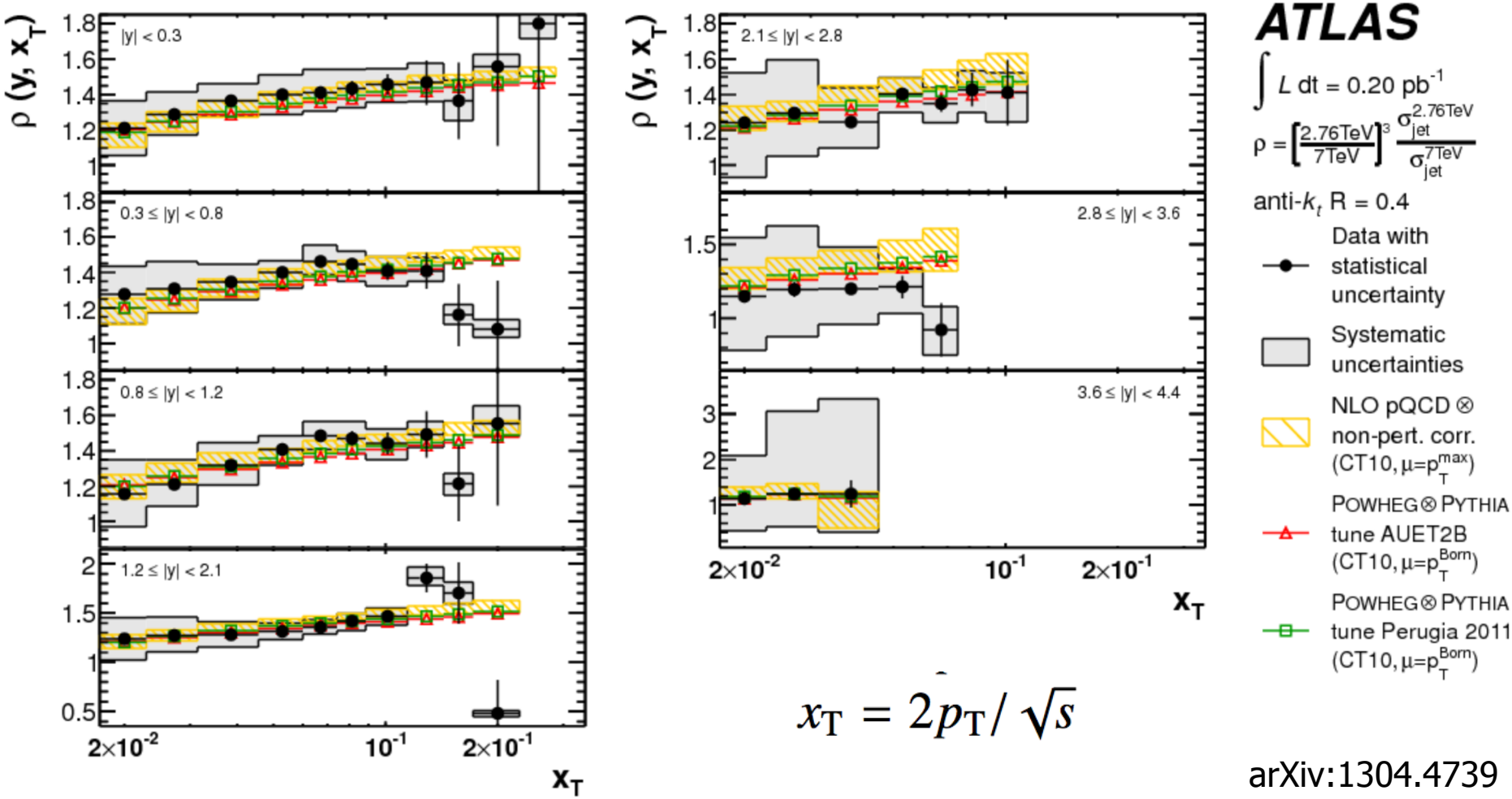
Comparison with NLO calculations with the data in some detail, for different proton structure function parameterizations.



Deviations for highest y range?

Jets Measurements at Two Energies

Data from proton-proton collisions at 2.76 TeV and 7 TeV



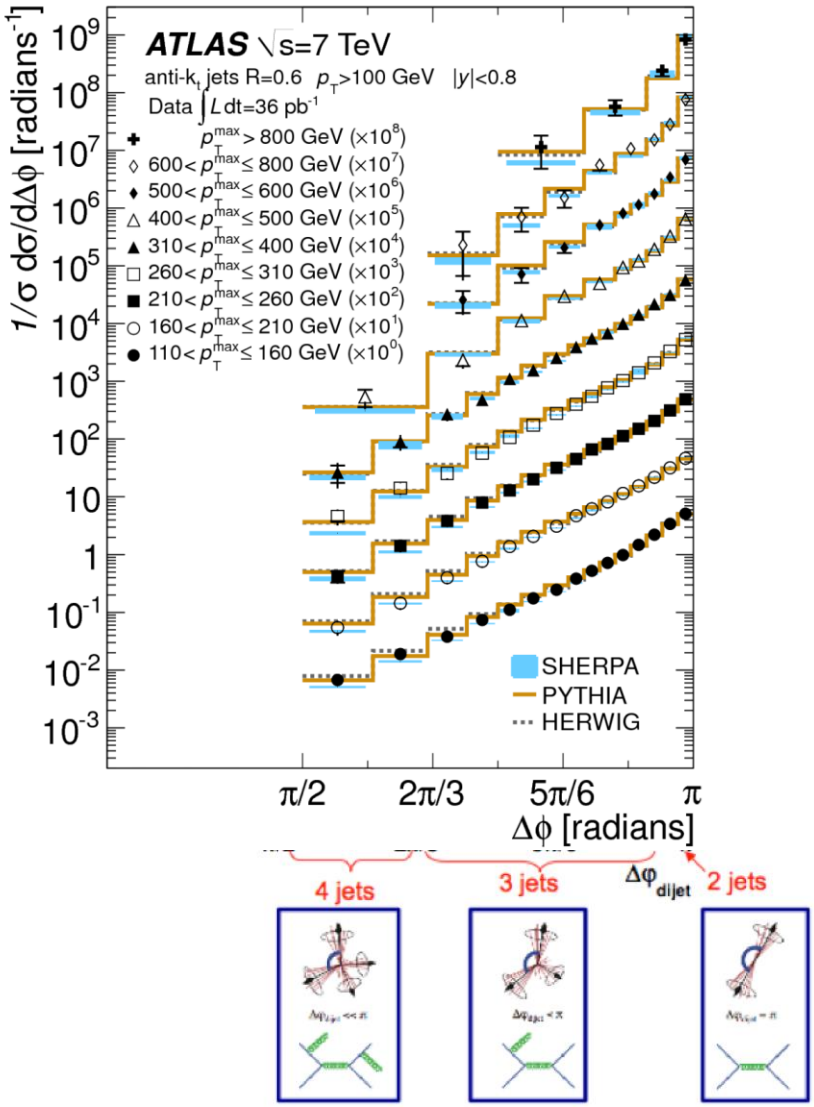
$$x_T = 2p_T/\sqrt{s}$$

arXiv:1304.4739

Some systematics ~ cancel in the ratio

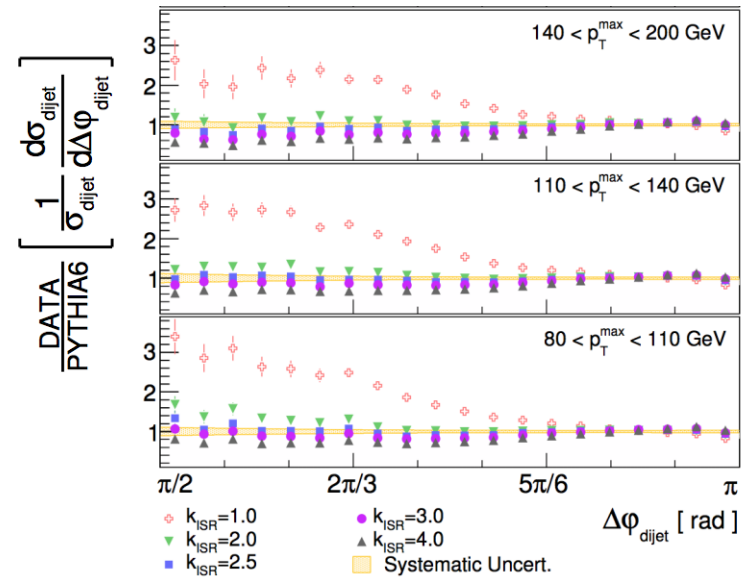
Azimuthal Correlations Between Jets

PRL 106 (2011) 172002



Azimuthal correlations between the two most leading jets are sensitive to the QCD radiation in the event, both initial and final rad.

PRL 106 (2011) 172002



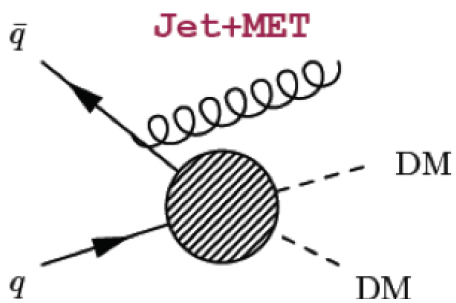
Initial state radiation (ISR) became very important for certain searches at the LHC!!

The Dark Matter Connection

Searches for mono-jets (mono-photons) can be used for

Direct searches for Dark Matter (DM)

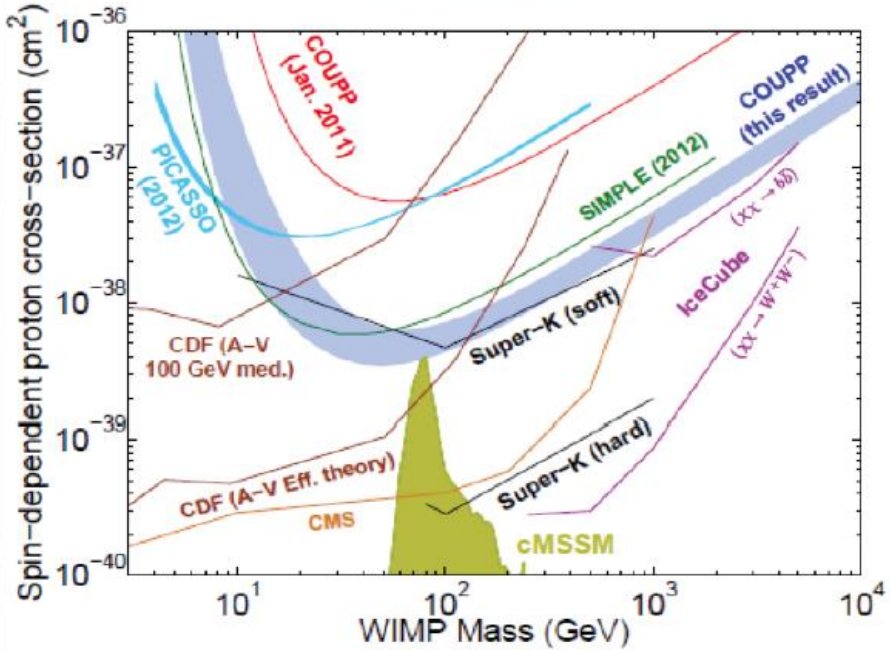
-> Spin dependent and spin independent cross sections of DM with matter



Effective contact interaction approach

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

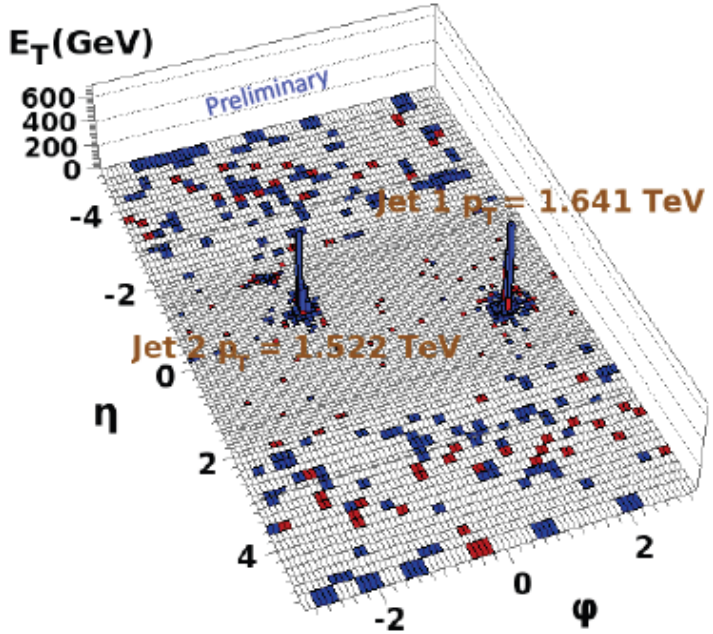


Collider searches are very competitive!!

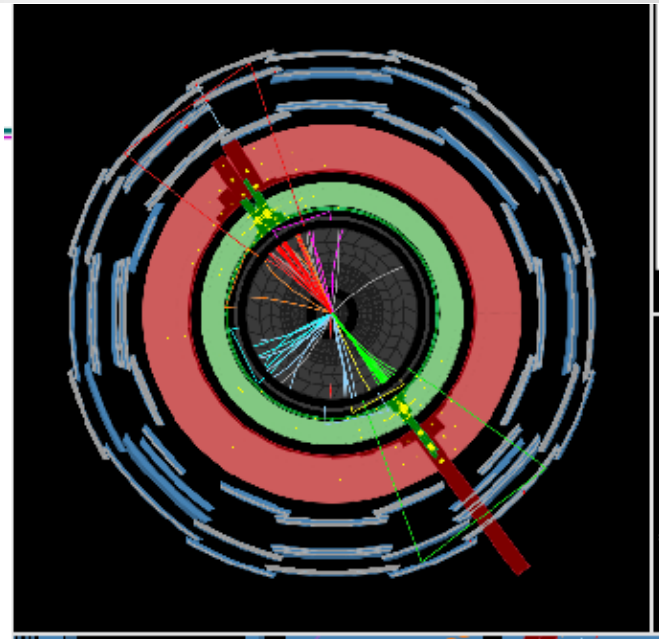
Similarly some SUSY searches with compressed spectra rely on ISR, for the for trigger: AMSB with semi-stable gauginos arxiv:1202.4847 (ATLAS)

Do we control ISR well enough so that we can rely on it for searches?

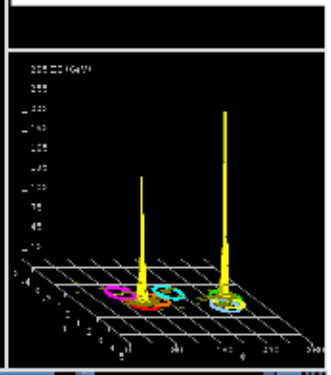
High p_T Dijet Events

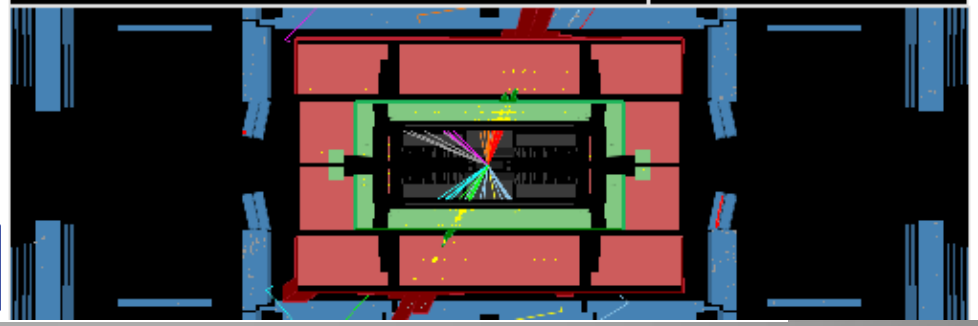


❖ Well balanced dijet event

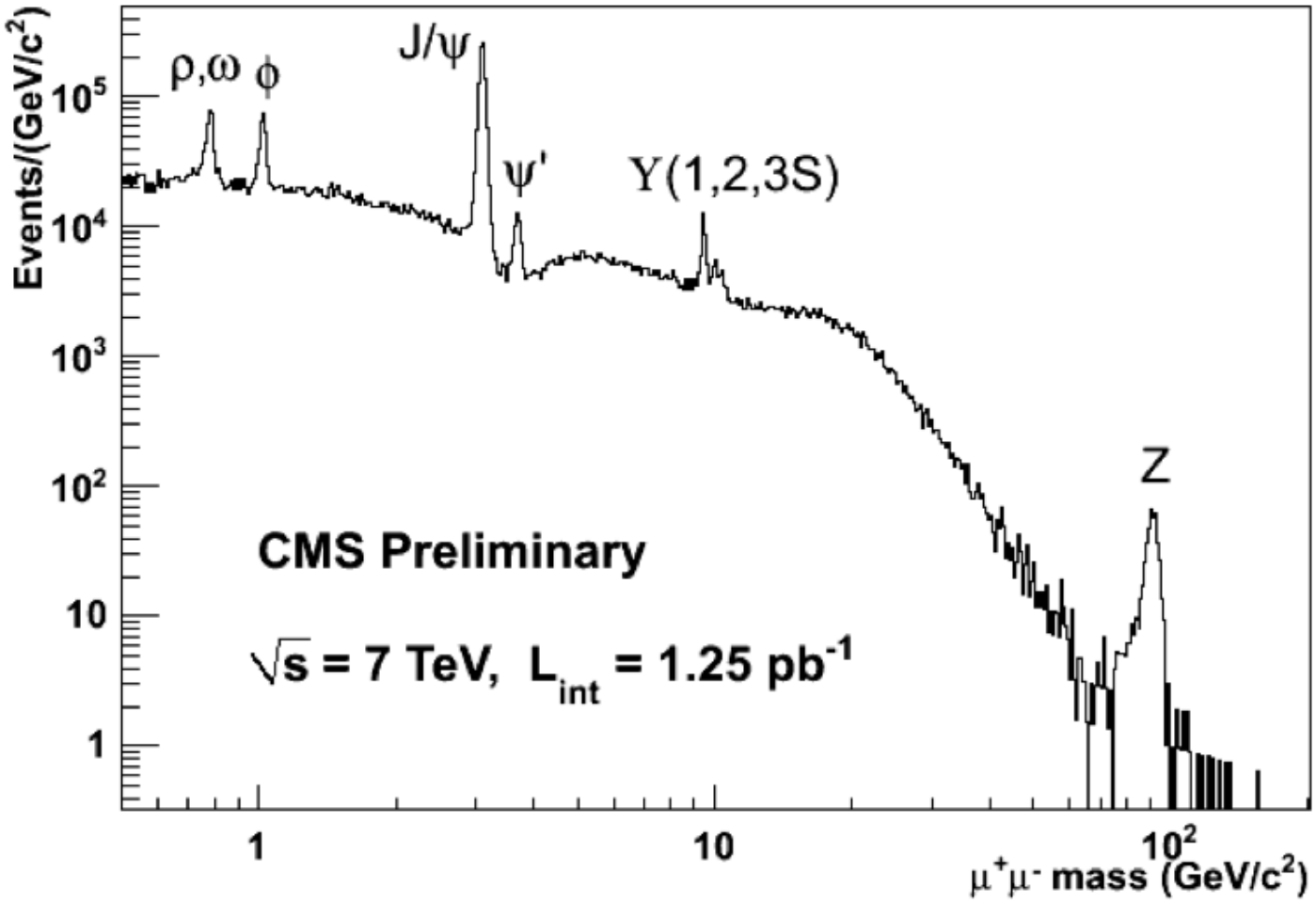


Very high energy jet event
m_{jj} = 4040 GeV
p_T^{j1} = 1850 GeV
p_T^{j2} = 1840 GeV
ATLAS-CONF-2011-081





Resonances → μμ

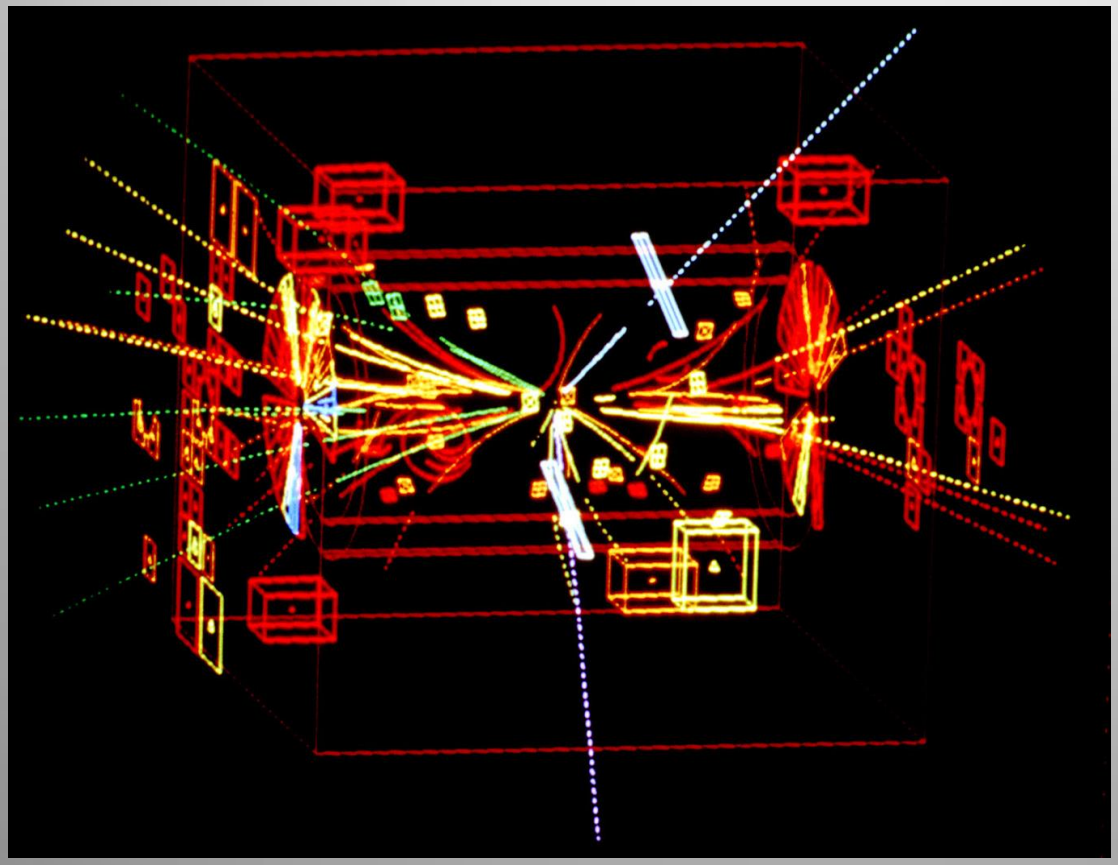


Remember: CMS = Compact Muon Solenoid!!

Electroweak Hard Probes

Discovery of the W & Z Bosons

Discovery of the Z and W bosons in UA1/UA2 (1983)



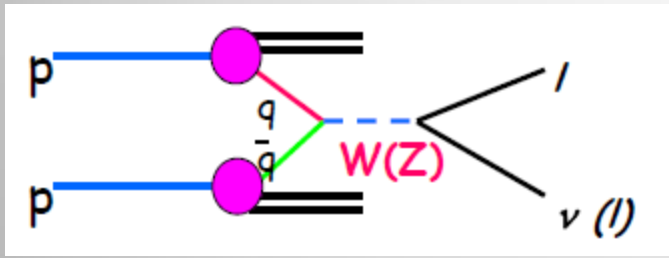
'Picture' of the first

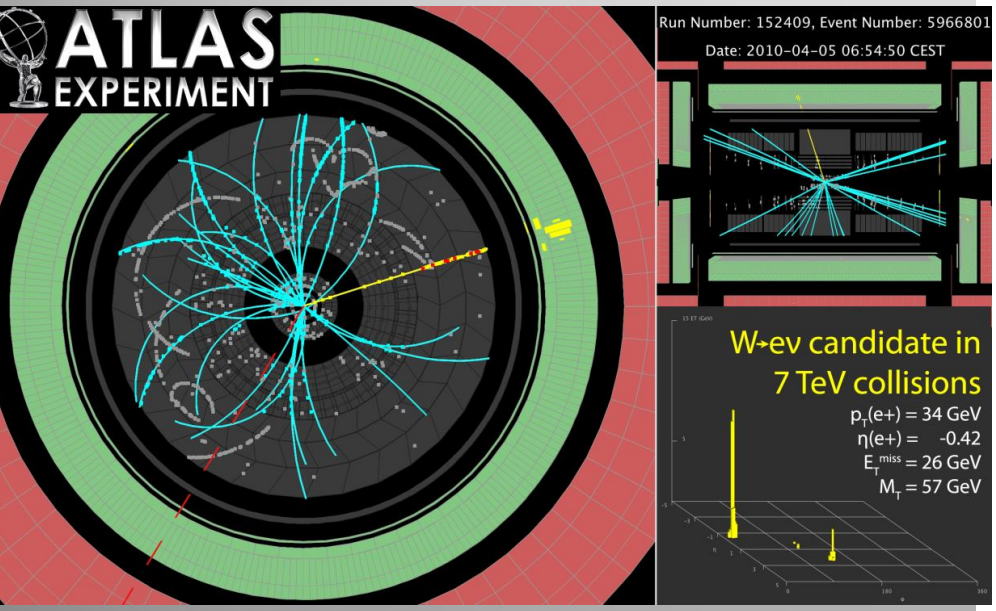
$$pp \rightarrow Z + X$$
$$\rightarrow e^+e^- + X$$

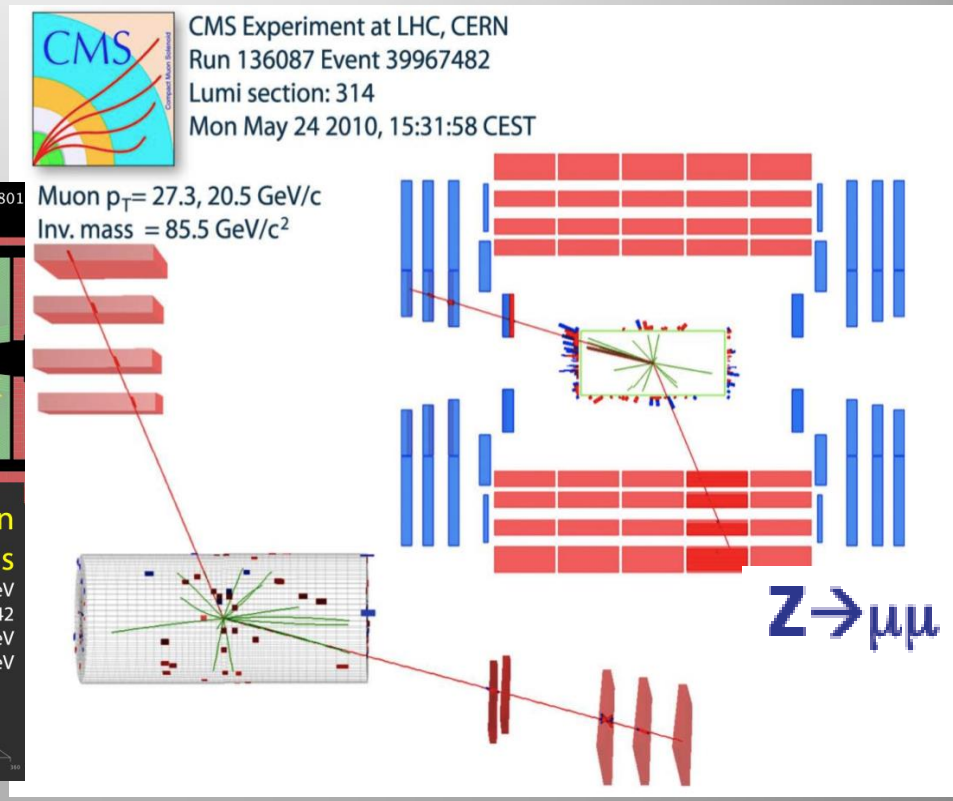
event in the UA1detector at the SppS accelerator for a centre of mass energy ($\sqrt{s}$) = 630 GeV

(30/4/1983)
Success story of the SppS machine at CERN rebuilt from a fixed target machine to a collider

Heavy Boson Production





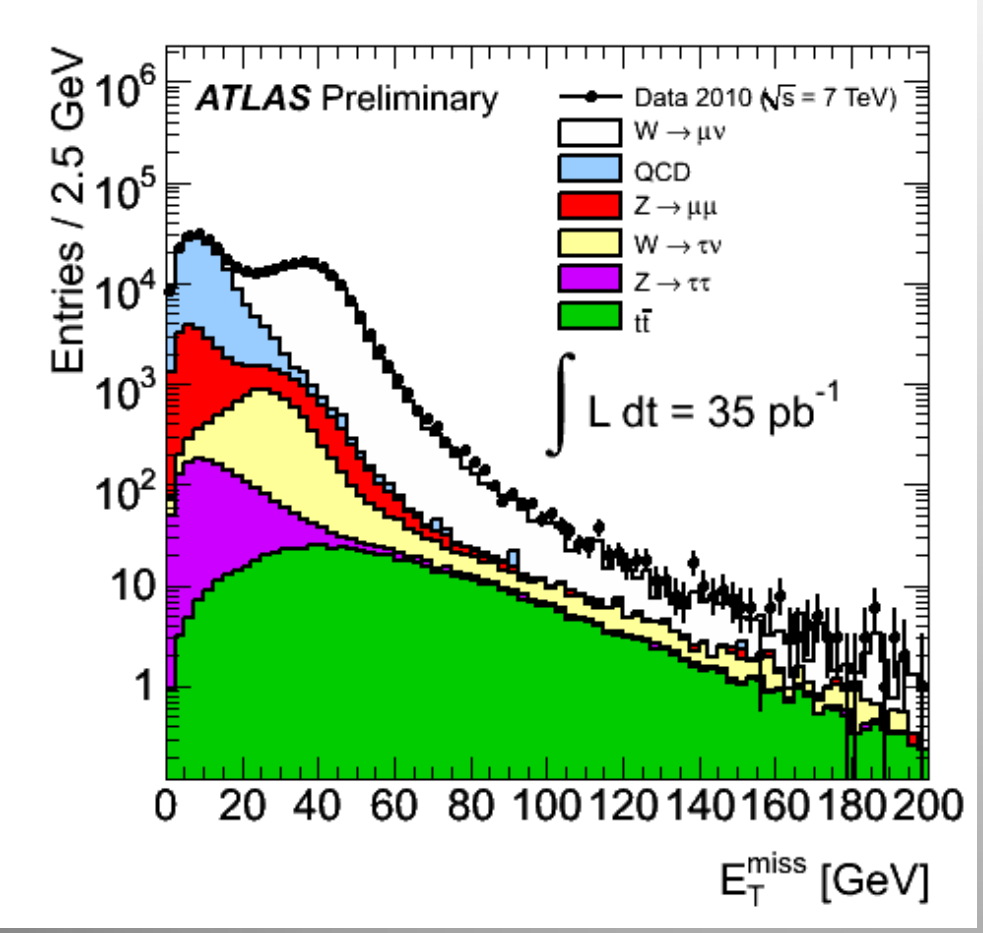


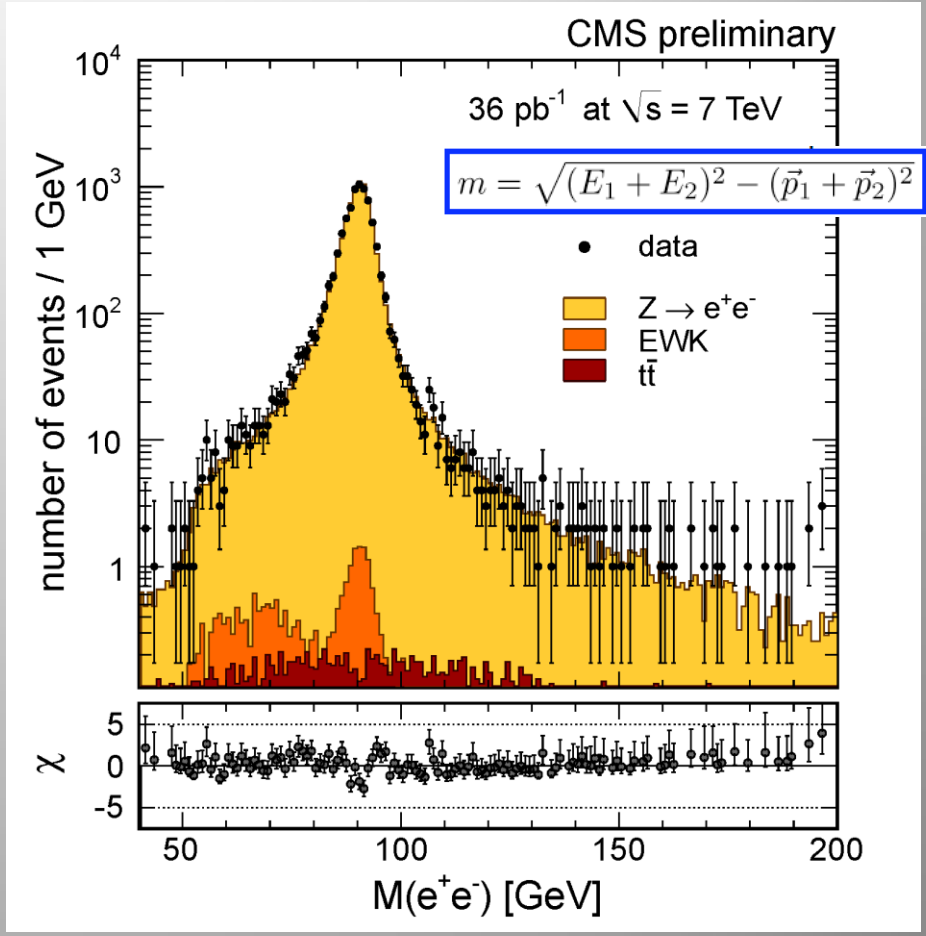
The first W & Z bosons showed up in May 2010 in the experiments

Now: about 30M W and 3M Z events/fb^{-1} for analysis (e+μ final states)

W and Z Boson Production

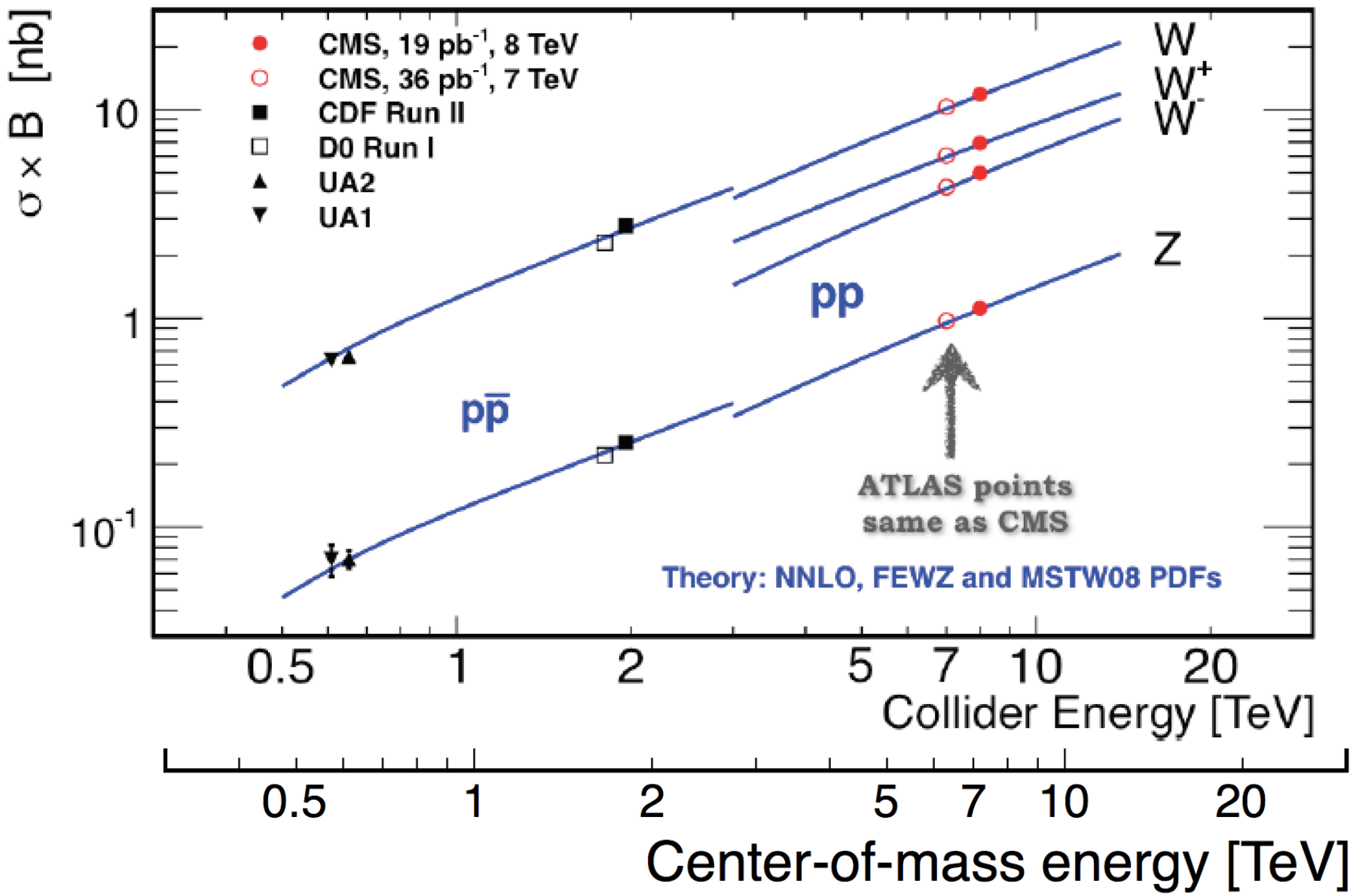
Sub. to JHEP
arXiv:1107.4789[hep-ex]



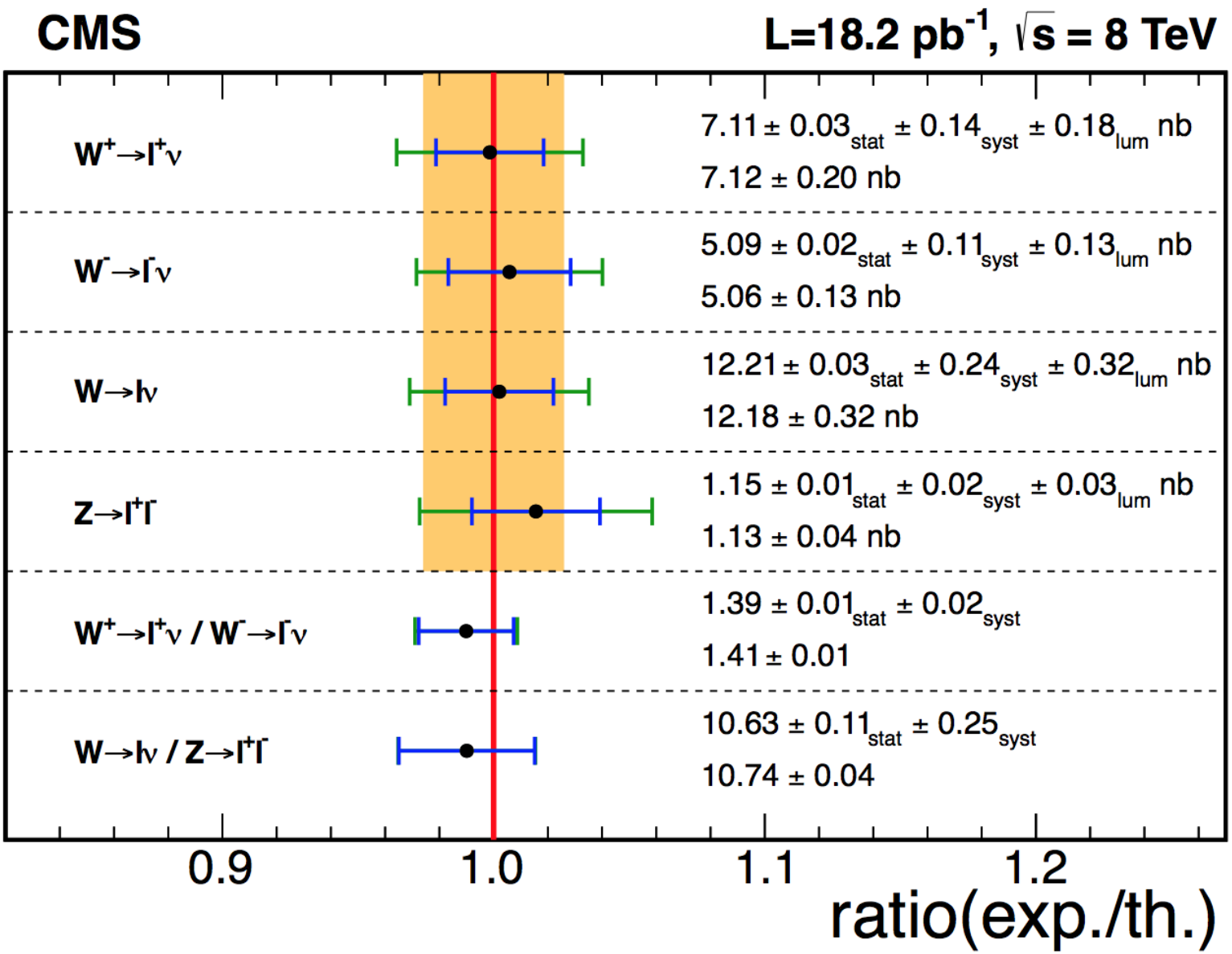


Missing transverse energy from the W → μ + ν decays

Z peak (di-lepton pair mass distributions)


σ × B [nb]
CMS, 19 pb^{-1}, 8 TeV
CMS, 36 pb^{-1}, 7 TeV
CDF Run II
D0 Run I
UA2
UA1
W
W$^+$
W$^-$
Z
pp
p$\bar{p}$
ATLAS points
same as CMS
Theory: NNLO, FEWZ and MSTW08 PDFs
10
1
10^{-1}
0.5
1
2
5
7
10
20
Collider Energy [TeV]
Center-of-mass energy [TeV]

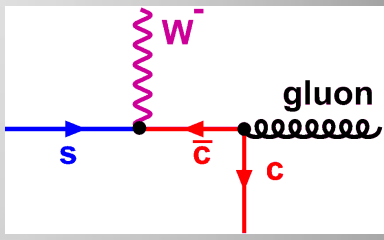
Electroweak: Summary Plot 8 TeV



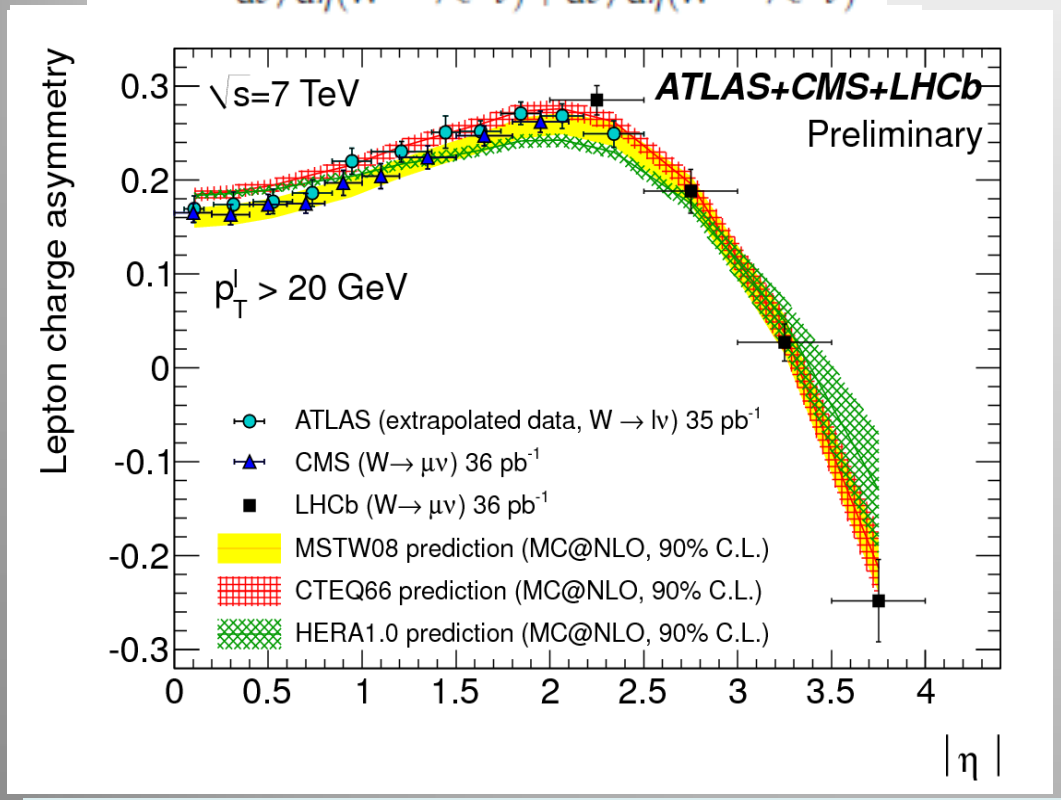
Electroweak: access to proton PDFs

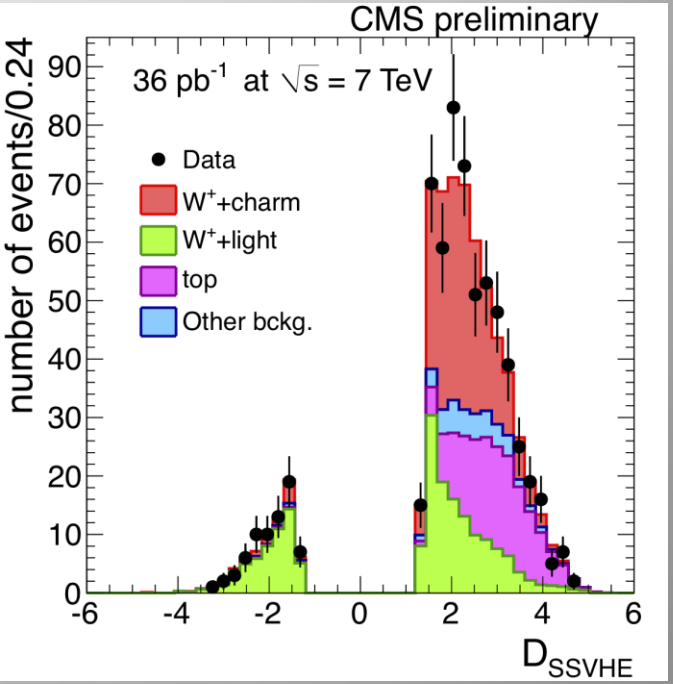
PAS EWK-11-005, 013

W+charm



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





$R^{\pm}_c = \sigma(W^+c)/\sigma(W^-c) = 0.92 \pm 0.19(\text{stat.}) \pm 0.04(\text{syst.})$

$R_c = \sigma(Wc)/\sigma(W+\text{jets}) = 0.143 \pm 0.015(\text{stat.}) \pm 0.024(\text{syst.})$

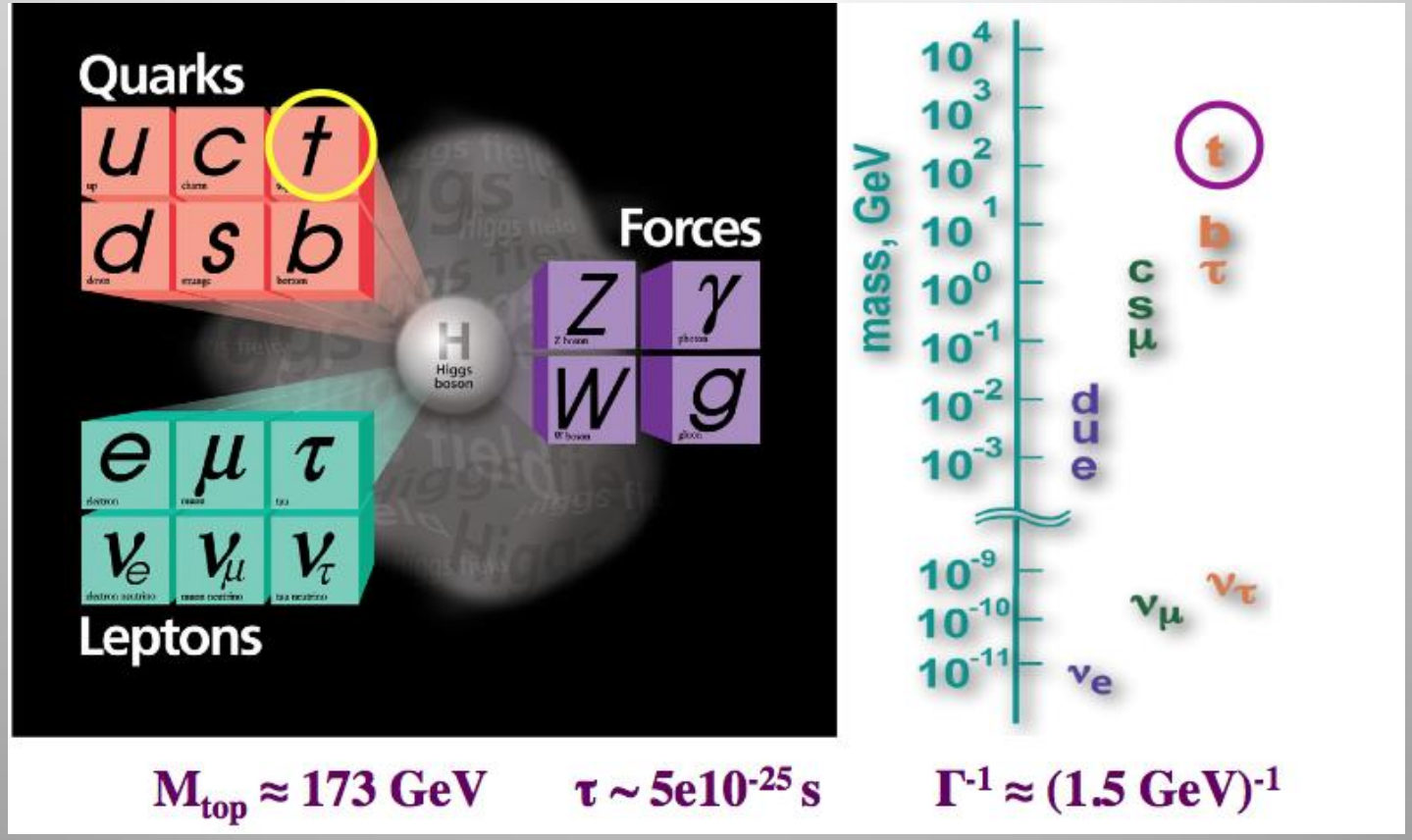
NLO predictions:

$R^{\pm}_c = 0.91 \pm 0.04$ $R_c = 0.13 \pm 0.02$

Secondary vertex decay length discriminator

Top Quark Physics

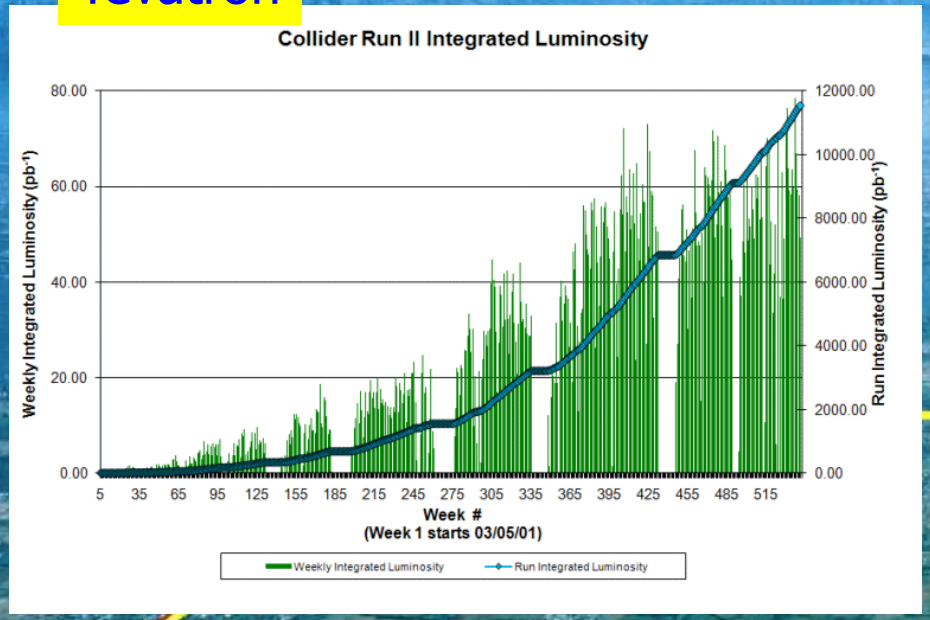
Top Quark Physics



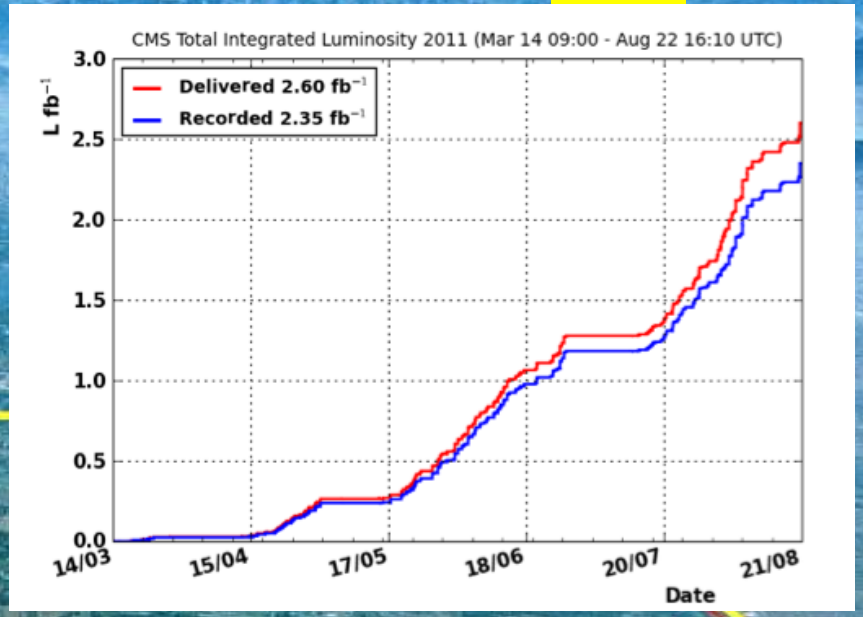
$M_{top} \approx 173$ GeV $\quad \tau \sim 5e10^{-25}$ s $\quad \Gamma^{-1} \approx (1.5\ \text{GeV})^{-1}$

- The heaviest known elementary particle: ~173 GeV
- Coupling to the Higgs ~1 → Special role in EWK symmetry breaking?
- Special sector to searches for new physics

Tevatron



LHC



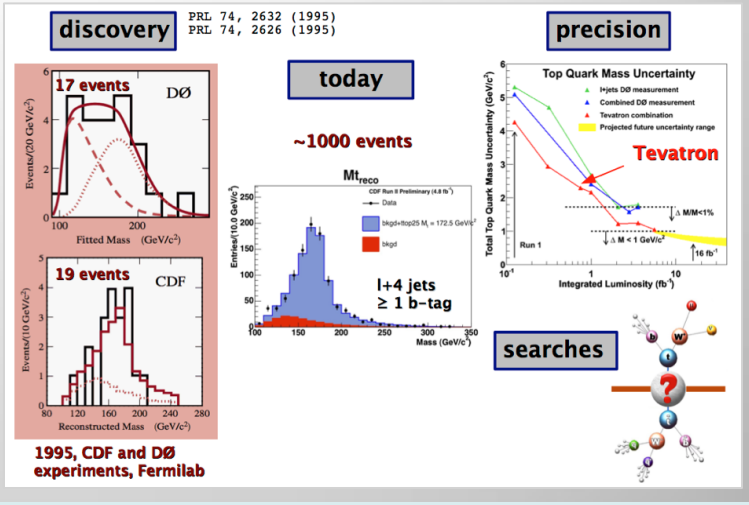
Energy 1.96 TeV
Int. Luminosity: 12 fb^{-1}
Age: ~25 years
Events/exp (5.4 fb^{-1})
350 ee eμμ
3500 lepton + jets

Energy 7 TeV
Int. Luminosity: ~5 fb^{-1}
Age: ~1.5 years
Events/exp (1fb^{-1})
2.5K ee eμμ
15K lepton+jets

Short History of TOP

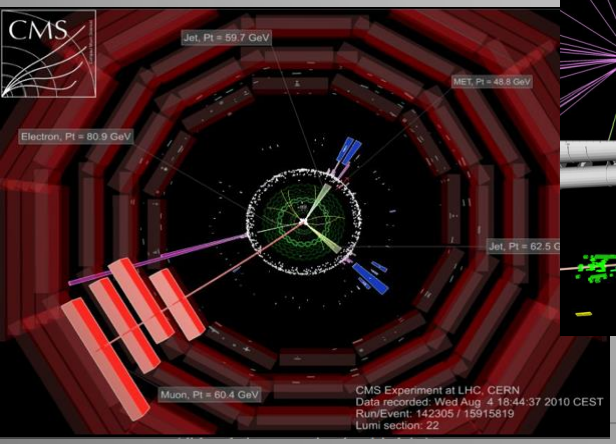
1995: Discovery of the top quark

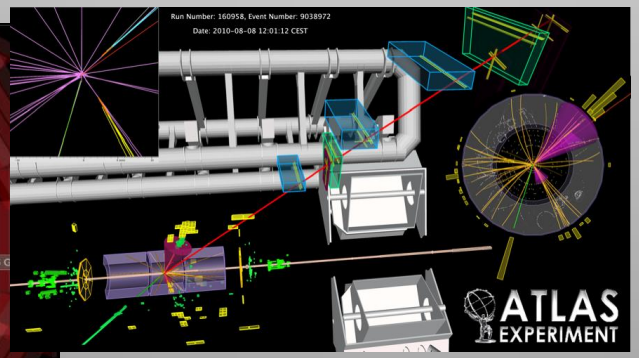
- in 1995 D0 and CDF observed and excess of events consistent with $p\bar{p} \to t\bar{t} \to W^+bW^-\bar{b}$

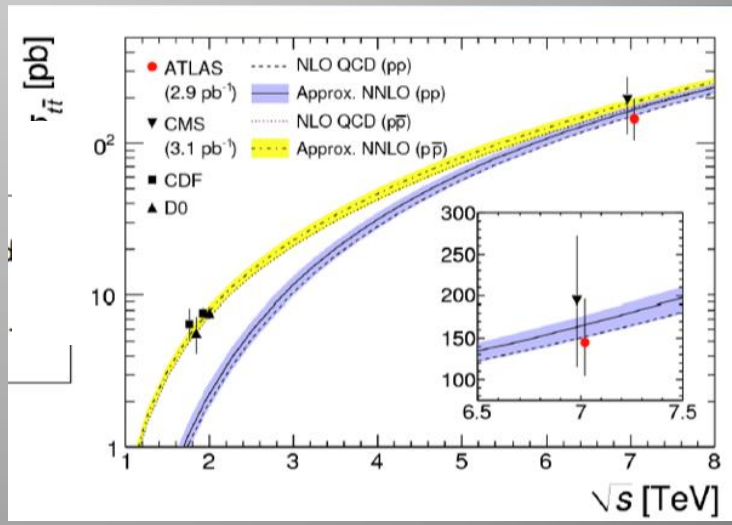


2009: Discovery of the single top production

July 2010: First top in Europe





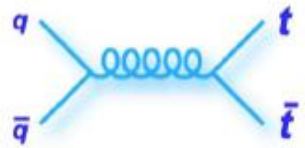


By end 2010: LHC top measurements

Top Production

- Gluon fusion

- Quark-antiquark annihilation



	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

Predicted cross sections (see E. Laenen)

For $m_t = 172.5$ GeV

$\sqrt{s} = 1.96$ TeV: $\sigma(pp \to t\bar{t})_{NNLOapprox} = 7.46^{+0.48}_{-0.67}$ pb

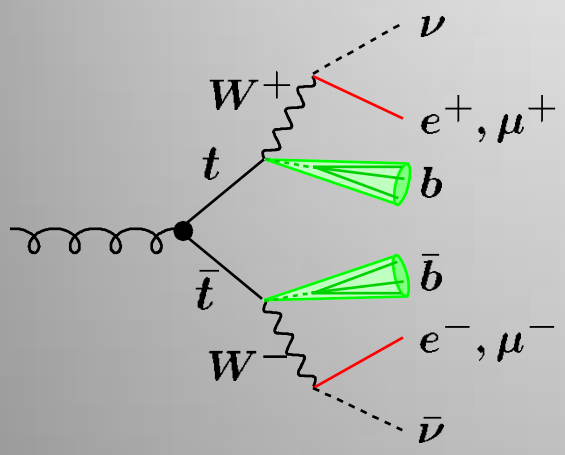
$\sqrt{s} = 7$ TeV: $\sigma(pp \to t\bar{t})_{NNLOapprox} = 164.6^{+11.4}_{-15.7}$ pb

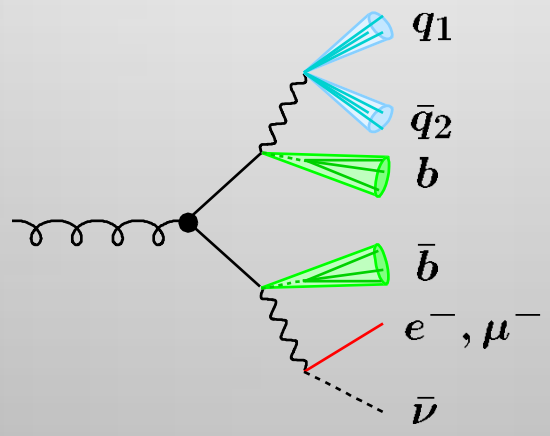
.

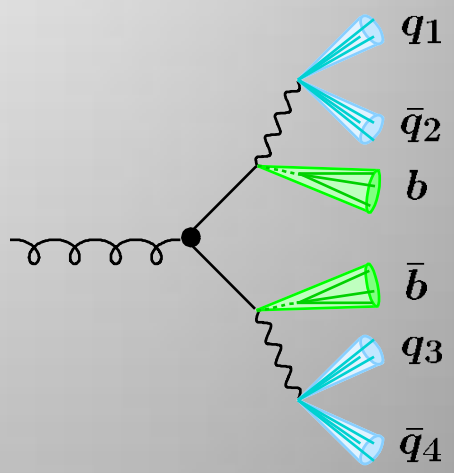
Langenfeld et al. PRD 80, 054009 (2009)
Aliev et al., Comp. Phys. Comm. 182, 1034 (2011)
Kidonakis, Phys. Rev. D82, 114030 (2010)
Ahrens et al., JHEP 1009, 097 (2010) arXiv:1105.5824

Top Decays

$$Br(t \to W^+ b) \sim 100\%$$





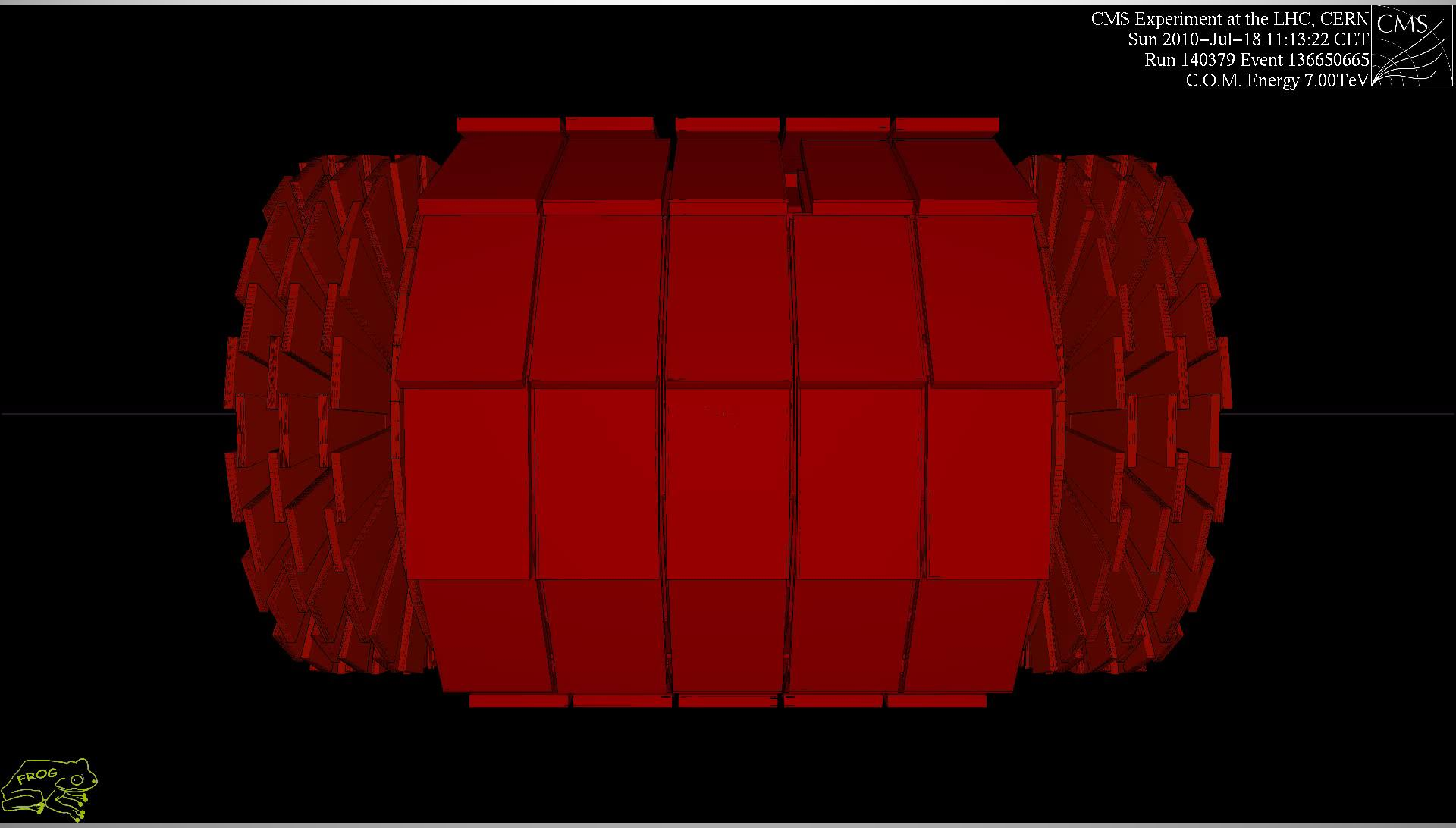


Dilepton
- 2 lepton
- 2 *b*-jet
- MET

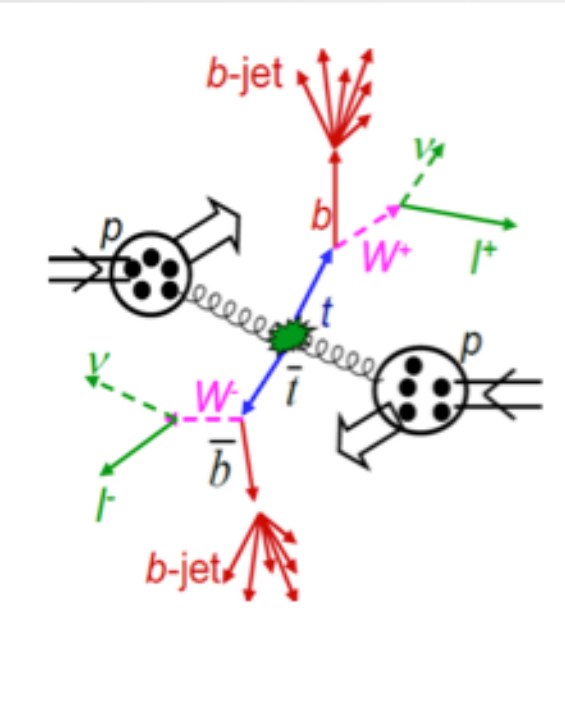
Lepton+Jet
- 1 lepton
- 4 jet(2 *b*-jet)
- MET

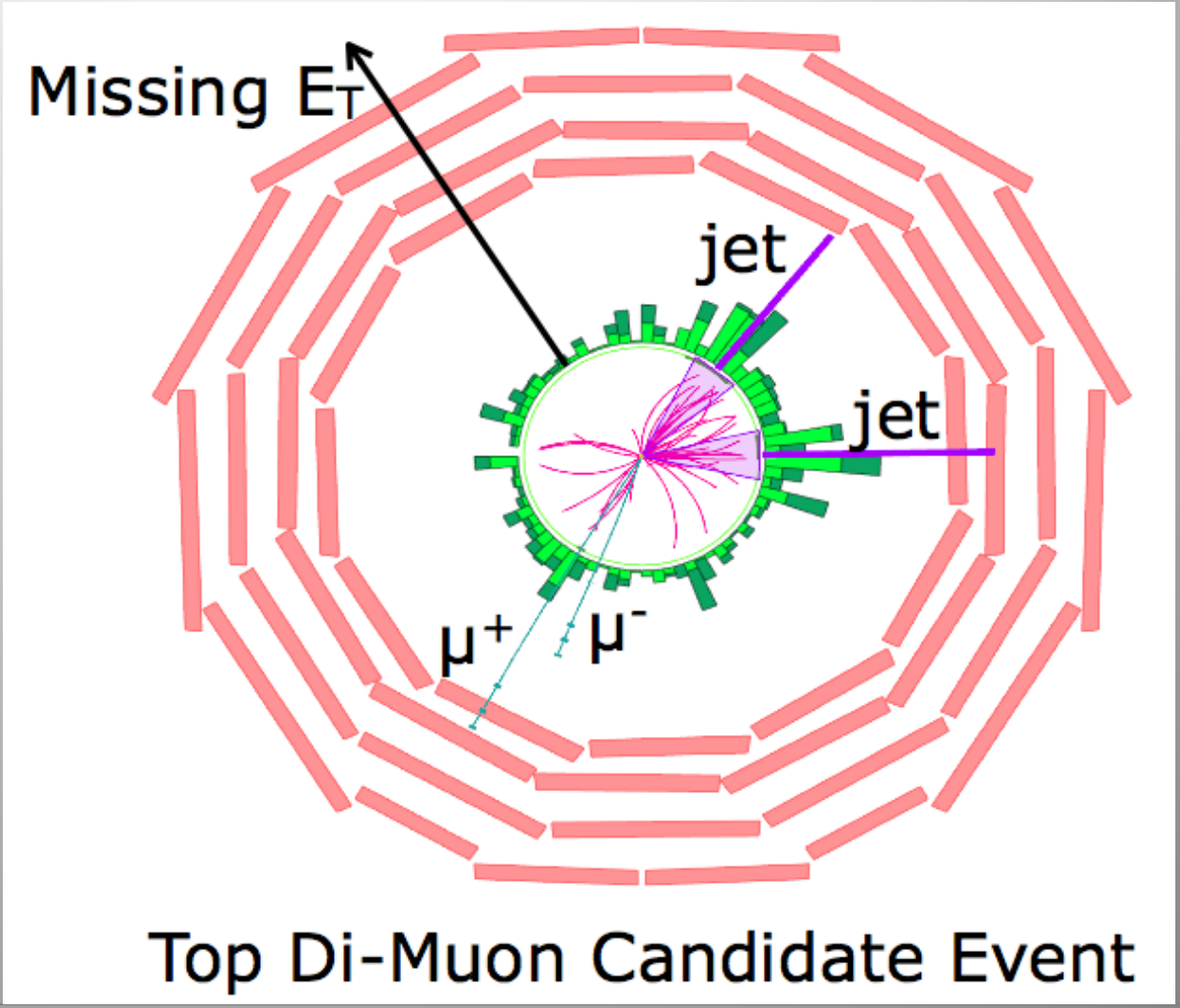
All Hadronic
- 6 jet(2 *b*-jet)

Categorise tt events into 3 decay types according to W decay mode

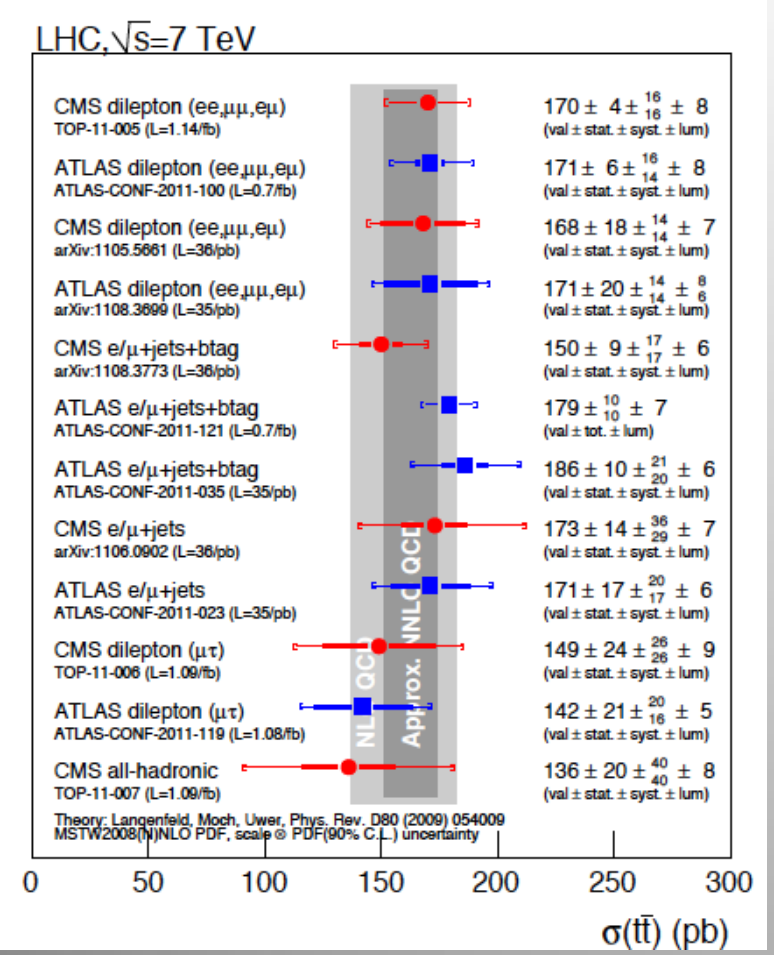

CMS Experiment at the LHC, CERN
Sun 2010−Jul−18 11:13:22 CET
Run 140379 Event 136650665
C.O.M. Energy 7.00TeV
CMS
FROG

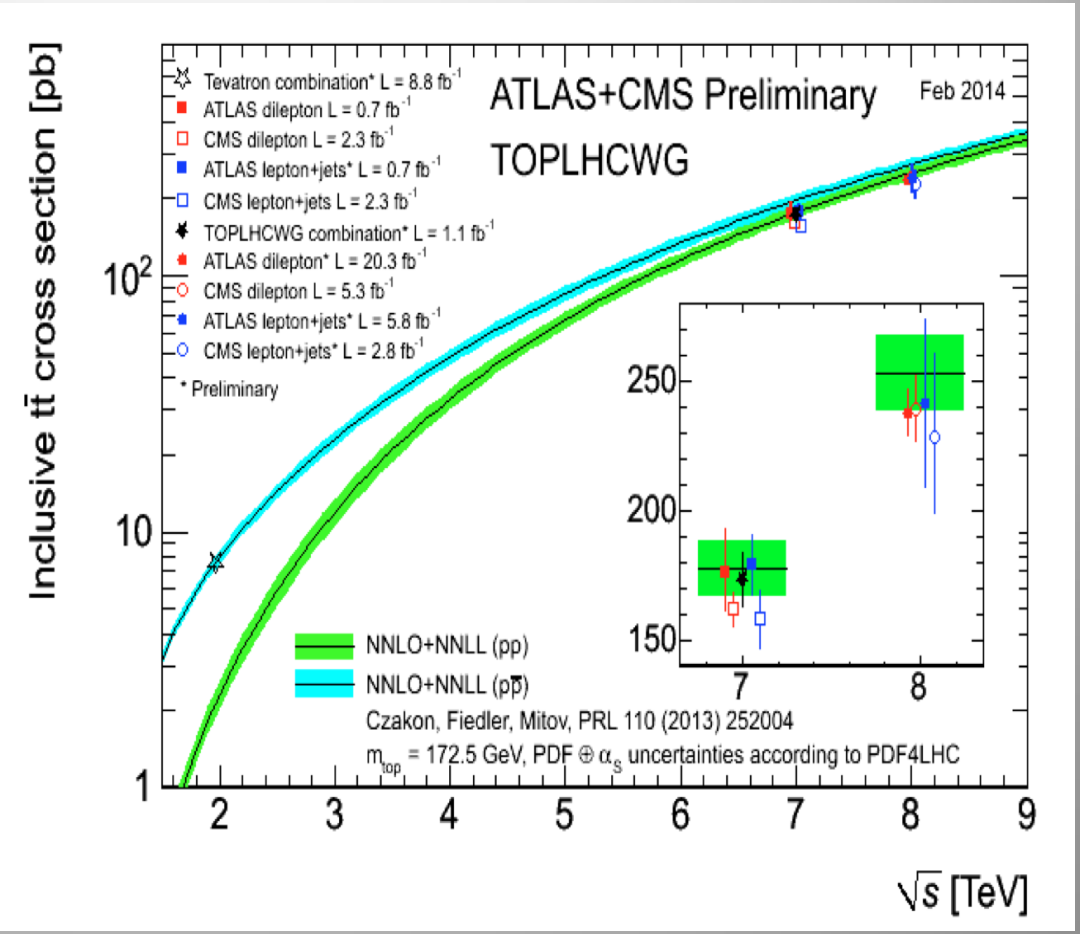
Candidate Event for Top Production





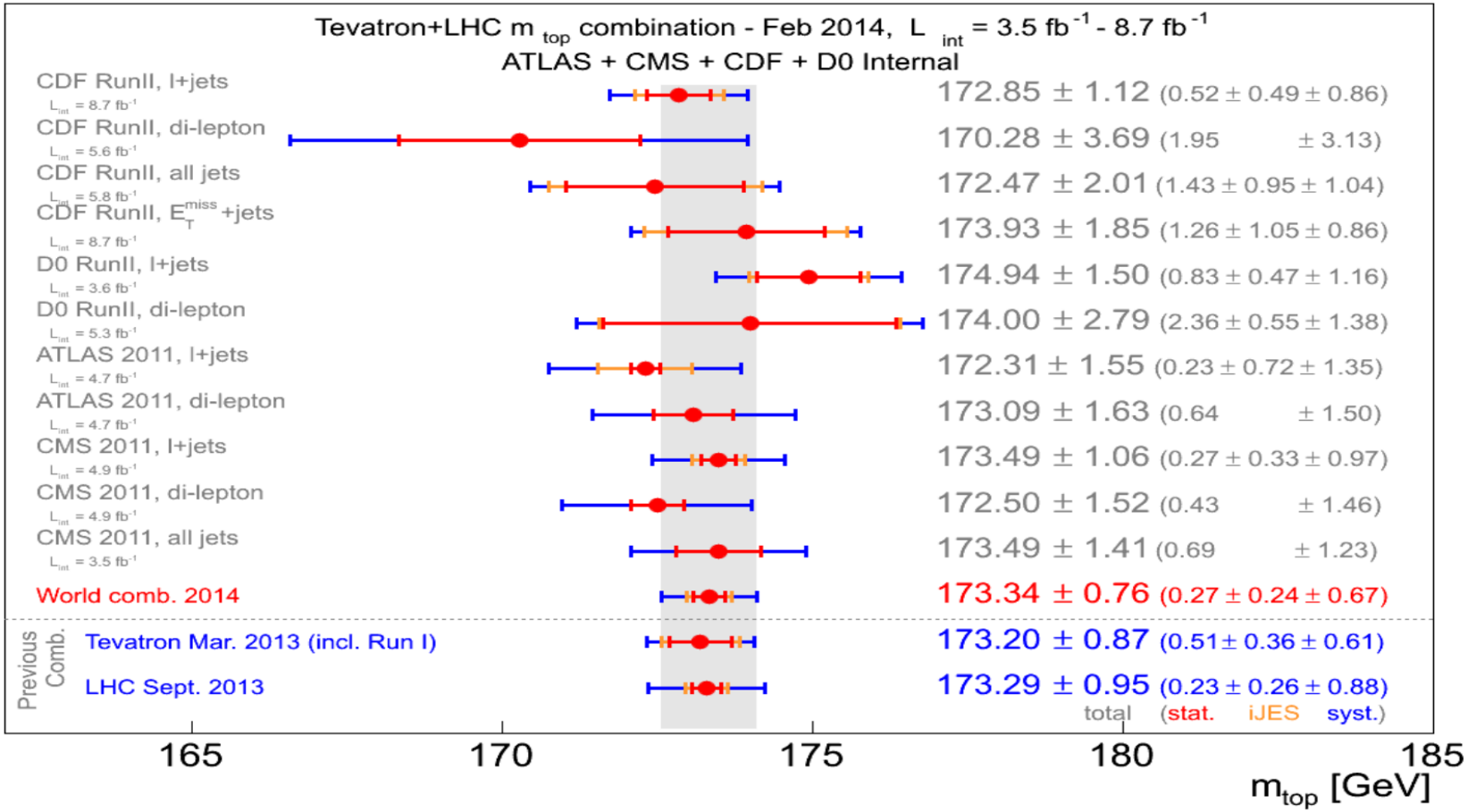
Top Pair Production at 7/8 TeV





ATLAS and CMS have also made first single top cross-section measurements in agreement with NLO QCD expectations. Present precision ~ 6%

The Mass of the Top Quark



Using Tevatron and LHC data combination of the mass measurements

- Combination performed using BLUE

$m_t = 173.34 \pm 0.27\ (\text{stat.}) \pm 0.24\ (\text{iJES}) \pm 0.67\ (\text{syst.})\ \text{GeV}$

$$m_t = 173.34 \pm 0.76\ \text{GeV}$$

The best value on the top mass to date!!

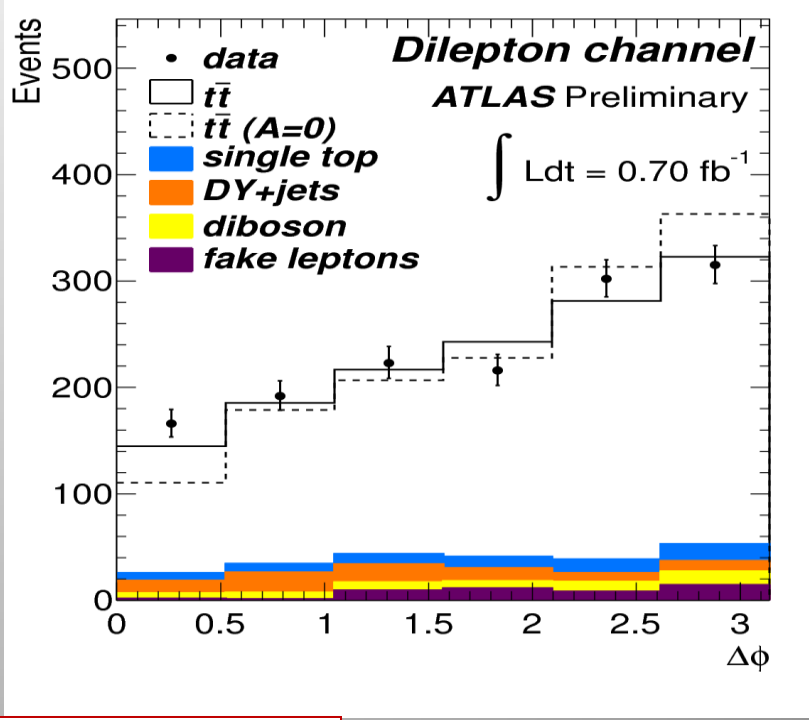
Examples of Top Quark Properties

Many property measurements performed or in progress

- Top cross section
- Top mass determination
- Top decays
- Charge asymmetries
- Spin correlations
- Top and W polarization
- Top anti-top mass difference
- Top Higgs couplings
- Search for new physics with top

…

ATLAS t-tbar spin correlation as measured in di-lepton events (Δφ between leptons in azimuthal plane in the t-tbar lab frame)



$C_{\text{helicity}} = 0.34^{+0.15}_{-0.11}$ (SM predicts ~ 0.32)

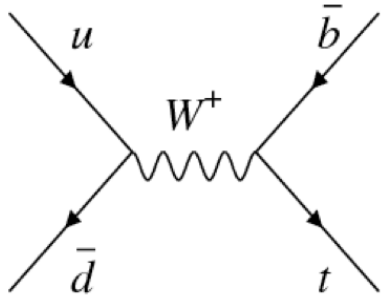
Competitive with TeVatron Measurements…

Single Top Production

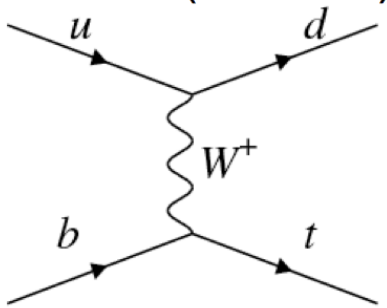
Electroweak production of the top quark

- Single top quark production by charged-current electroweak interactions
- LO classification:

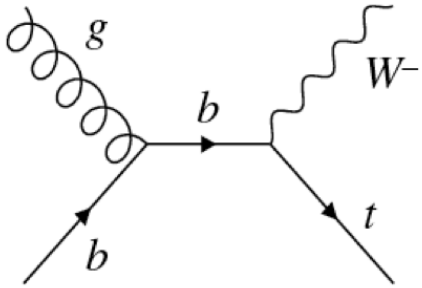
s-channel



t-channel (dominant)



Wt associated production channel



NLO+NNLO with m_t = 173.3 GeV at 8TeV @LHC

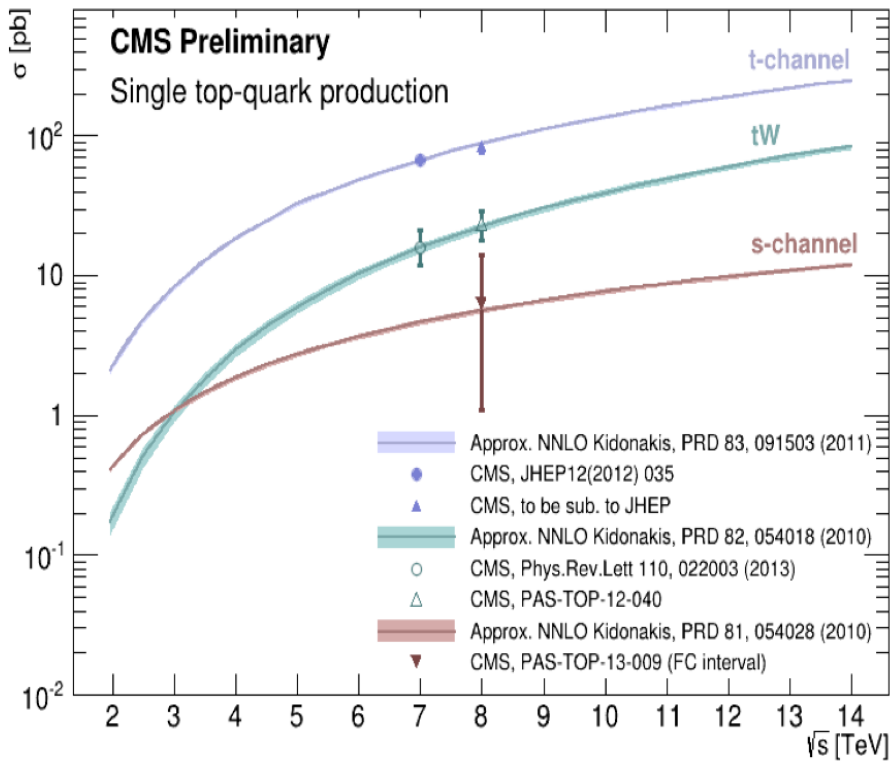
[1] $\sigma_s = 5.6 \pm 0.2$ pb

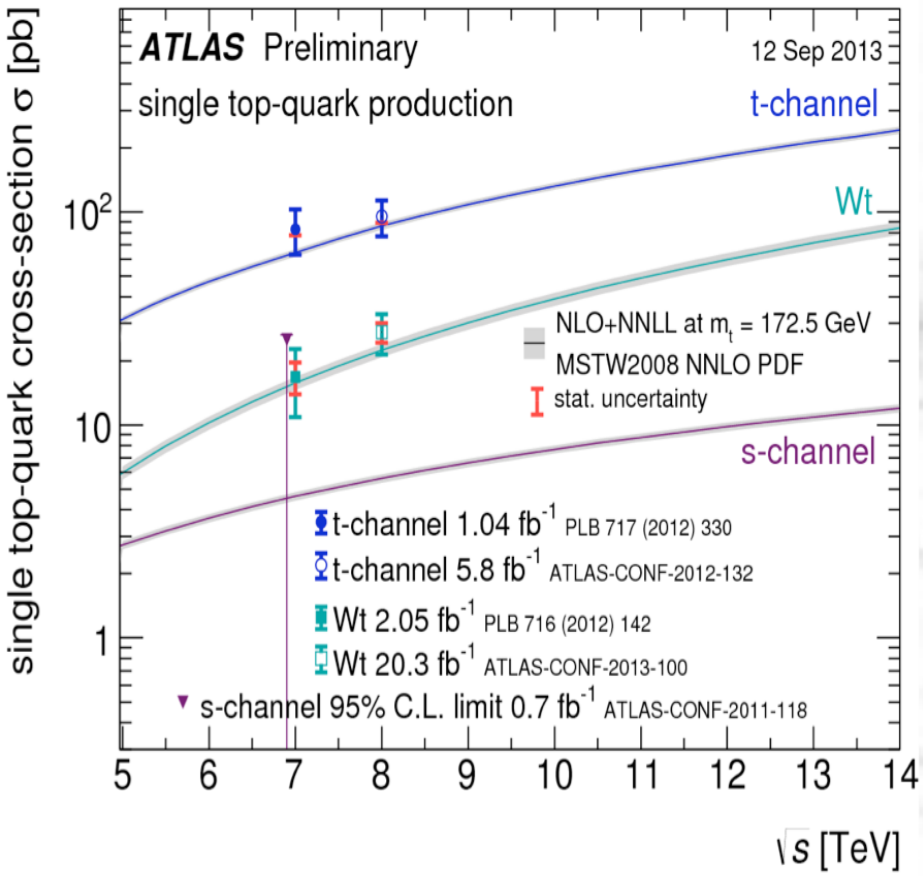
[2] $\sigma_t = 87.8^{+3.4}_{-1.9}$ pb

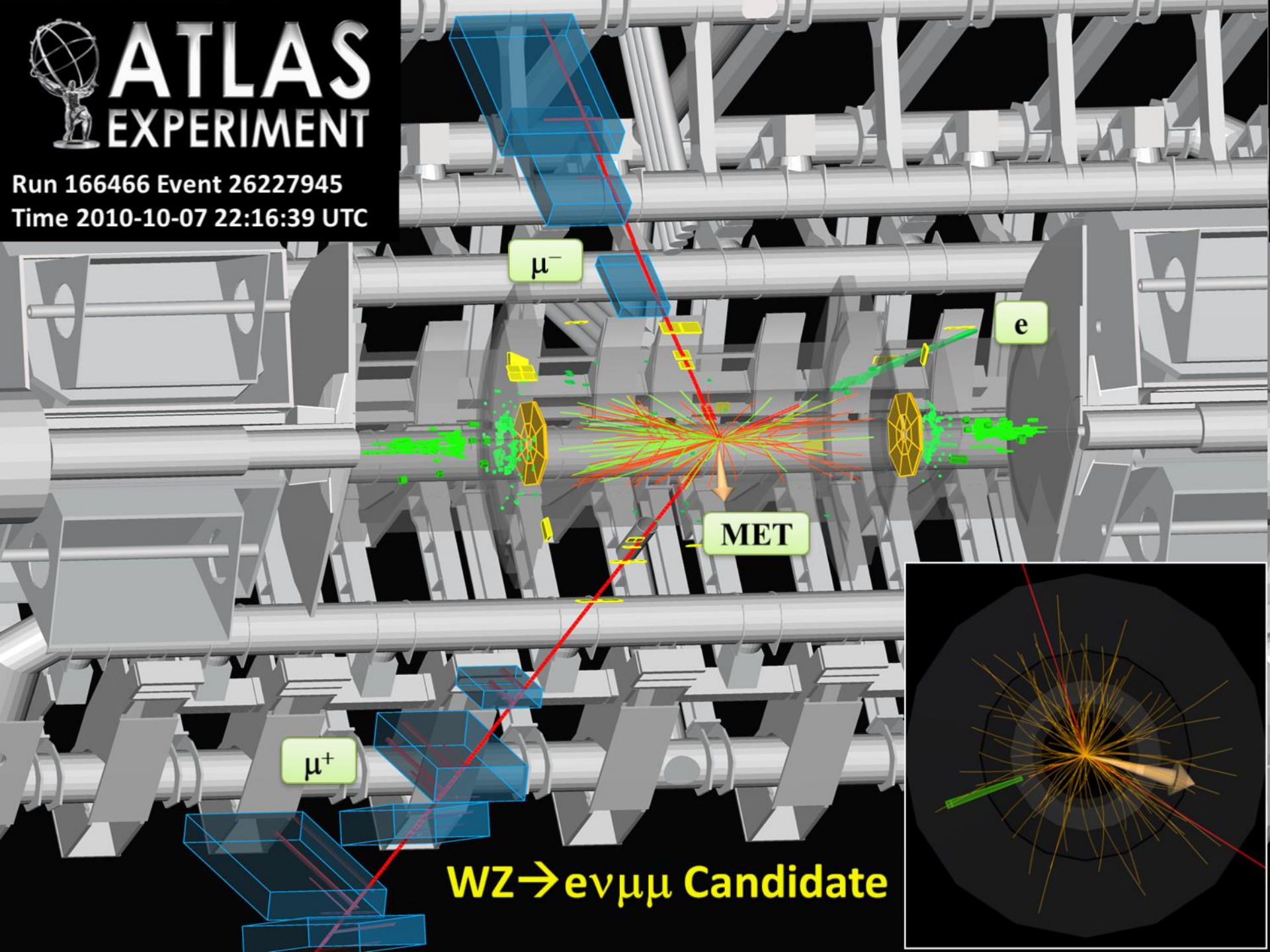
[3] $\sigma_{Wt} = 22.4 \pm 1.5$ pb

- $\sigma_{singletop}$ proportional $|V_{tb}|^2$, probes the electroweak Wtb vertex
- Measuring polarization observables tests the left-handed nature of the charged-current
- Sensitivity to different manifestations of BSM physics

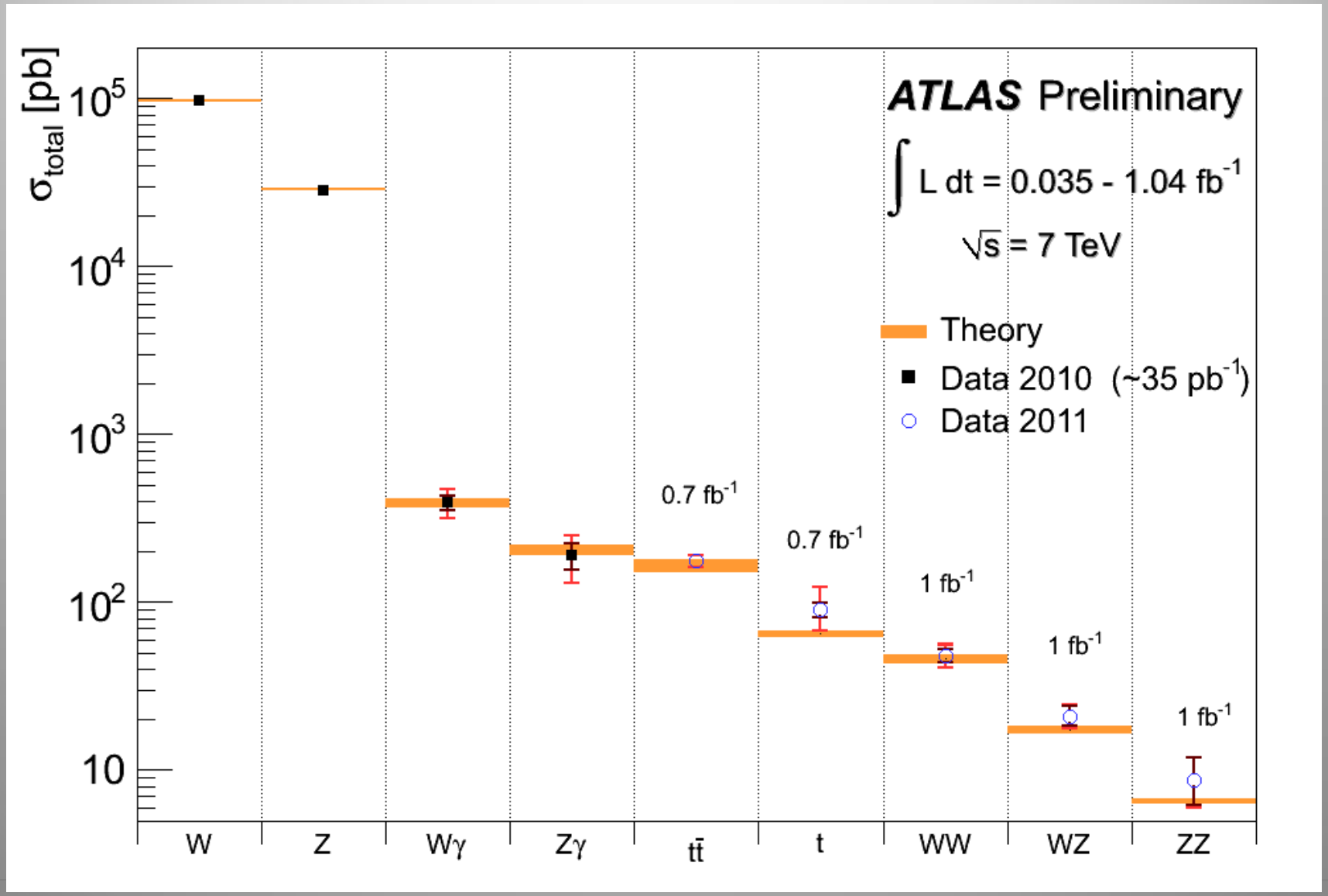
Single Top Production



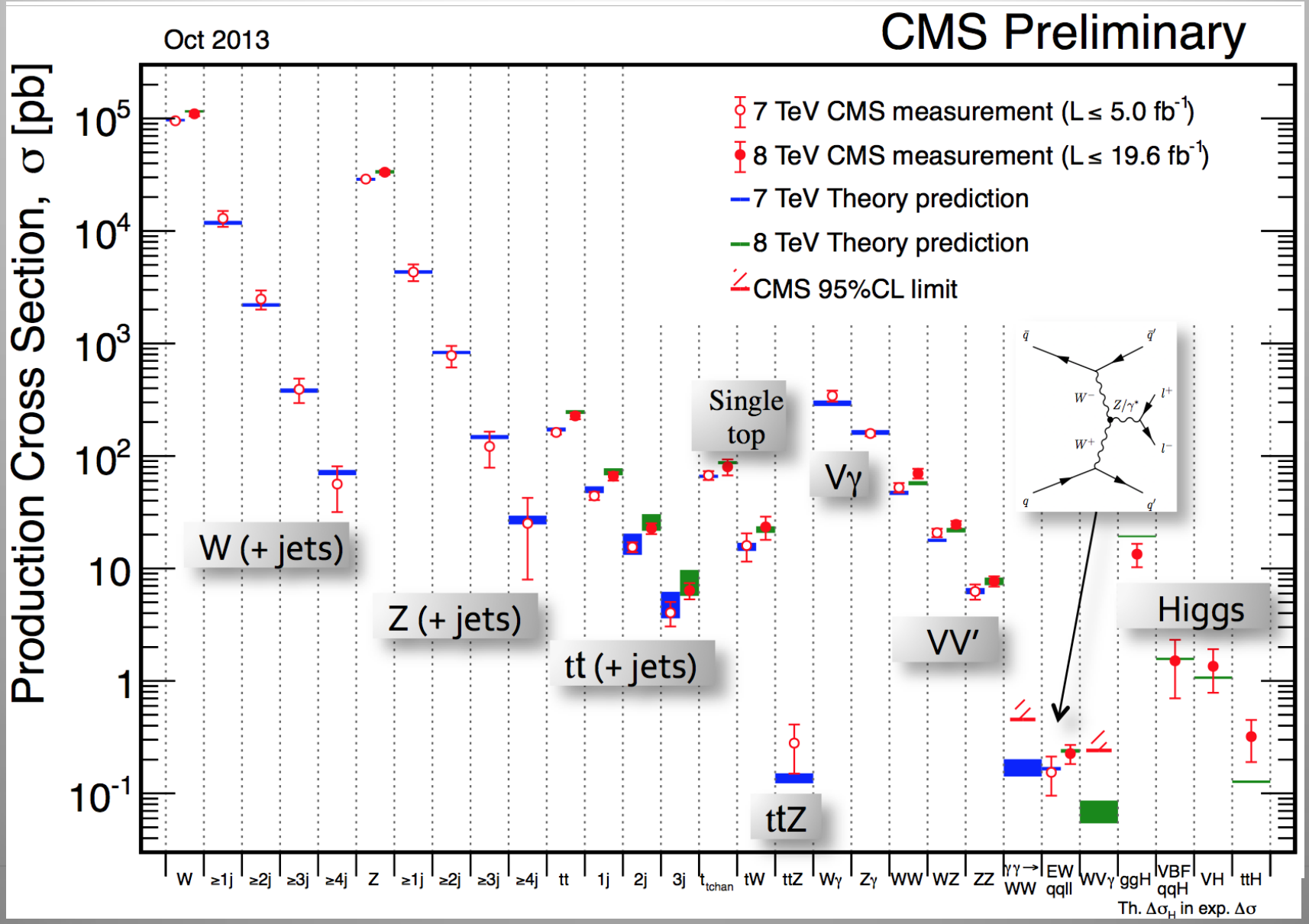



ATLAS
EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate

Measured Cross sections at 7 TeV

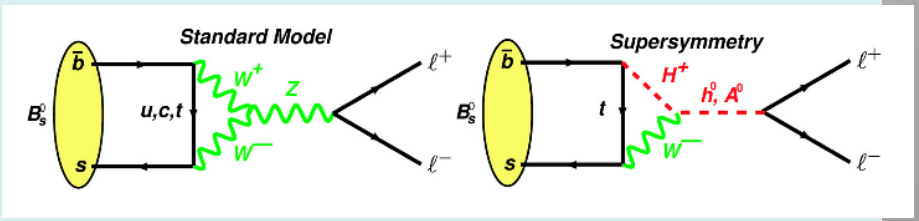


Measured Cross sections at 7/8 TeV



Search for $B_{s(d)} \rightarrow \mu\mu$ (CMS)

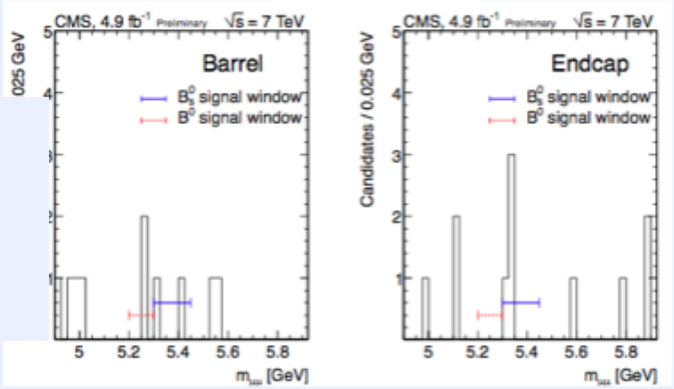
- Decays are highly suppressed in the SM
  - BR($B_s \rightarrow \mu\mu$): $(3.6 \pm 0.2) \times 10^{-9}$, $B_d \rightarrow \mu\mu$: $(1.0 \pm 0.1) \times 10^{-10}$
- Indirect sensitivity to new physics
  - MSSM: BR$\propto (\tan\beta)^6$



- Blind analysis
  - $B^+ \rightarrow J/\psi\ K^+$ used for normalization
  - $B^0 \rightarrow J/\psi\ \phi$ used as control regions for efficiencies
  - Events observed in the unblinded windows are consistent with bkg. plus SM expectations.
- CMS BR Limits at 95% CL (2011)

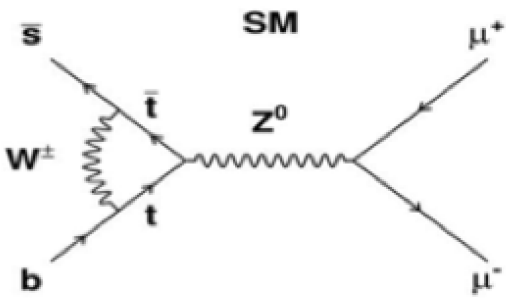
upper limit (95%CL)	observed	(median) expected
$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

2011 data



Rare Decays: B_s to μμ Decays

2013

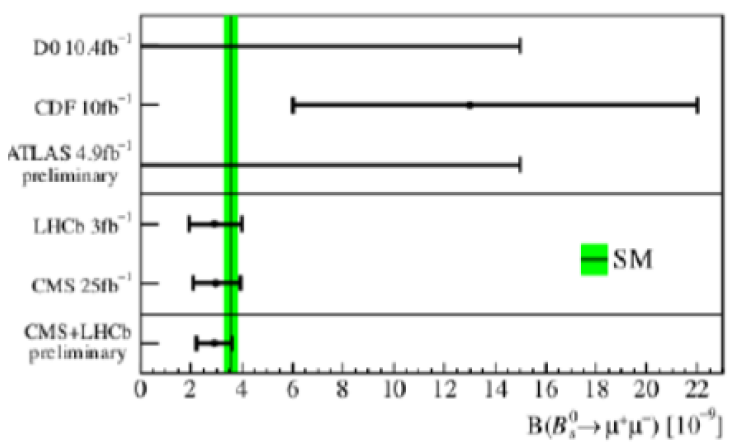


- A B_s particle is a particle consisting of a beauty-quark and strangeness-quark, with a mass of ~ 10 GeV
- Three B_s particles in a million will decay into two muons. This decay has been chased since 25 years.
- New physics modifies these Standard Models predictions

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.56 \pm 0.29 \times 10^{-9}$$

Observation:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$



Results from LHCb +CMS experiment combined

Heavy Flavor Physics: Spectroscopy

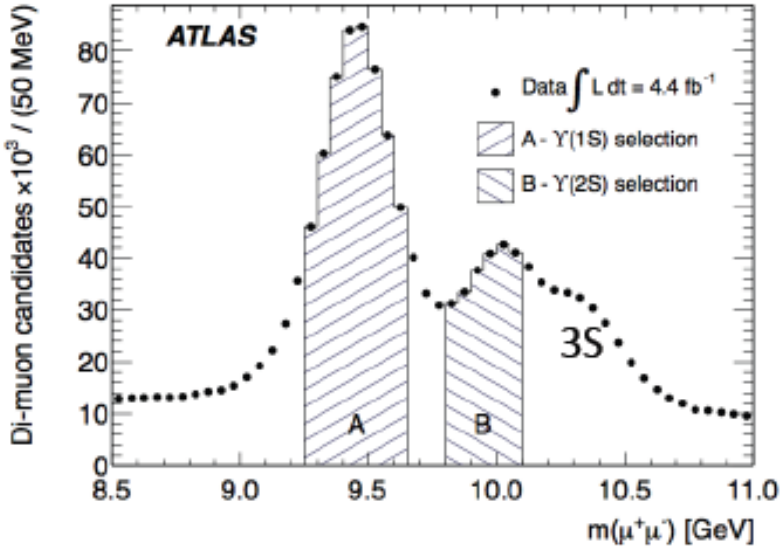
Observation of a New χ_b State

bottom anti-bottom state

- Quarkonium physics, test of QCD
- $\chi_b(1P)$, $\chi_b(2P)$ seen and measured by CUSB, CLEO, ARGUS, CDF 1982-2004
- Radiative decays

$$\chi_b(nP) \rightarrow \Upsilon(1,2S)\,\gamma$$

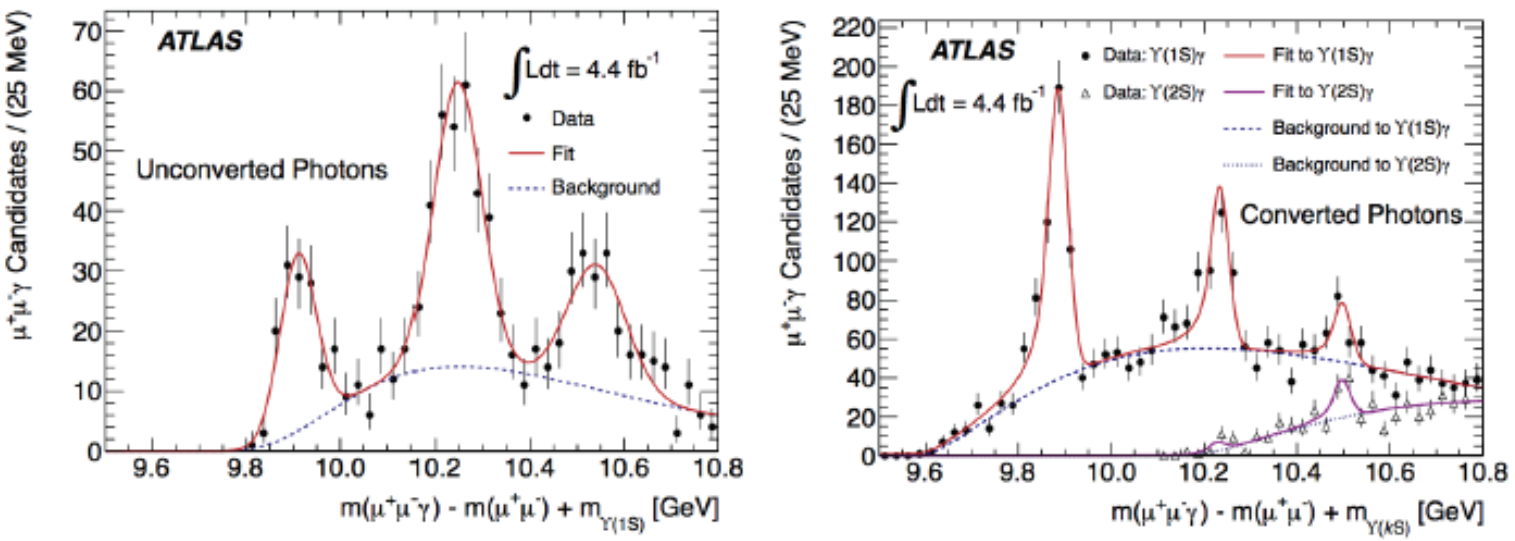
$$\Upsilon(1,2S) \rightarrow \mu^+\mu^-$$



- "Loose" muons $\eta<2.3$, $p_T>4$ GeV
- $p_T(\mu^+\mu^-)>12$ (20) GeV converted (unconv.) Υ's
- "Loose" Υ's from shower shape, little in HCAL or e^+e^- pairs with vertex $P(\chi^2)>1\%$ and 40 mm from beam

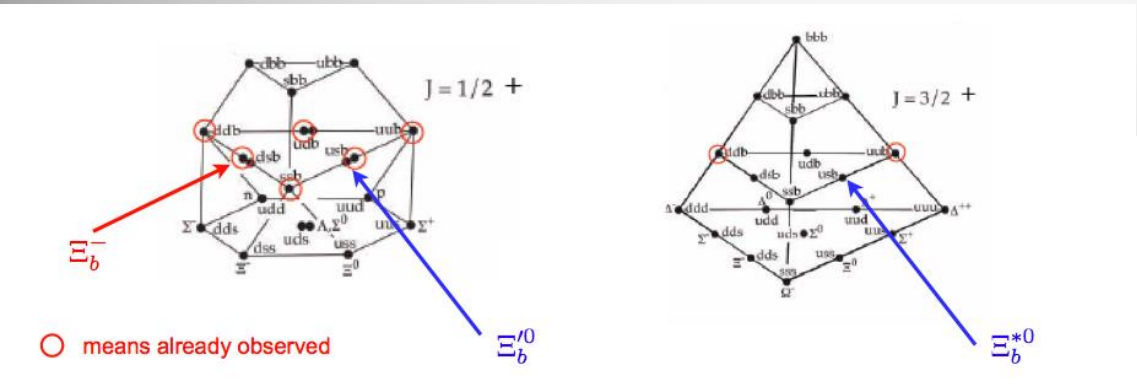
Heavy Flavor Physics: Spectroscopy

"ATLAS Discovers its first new particle"

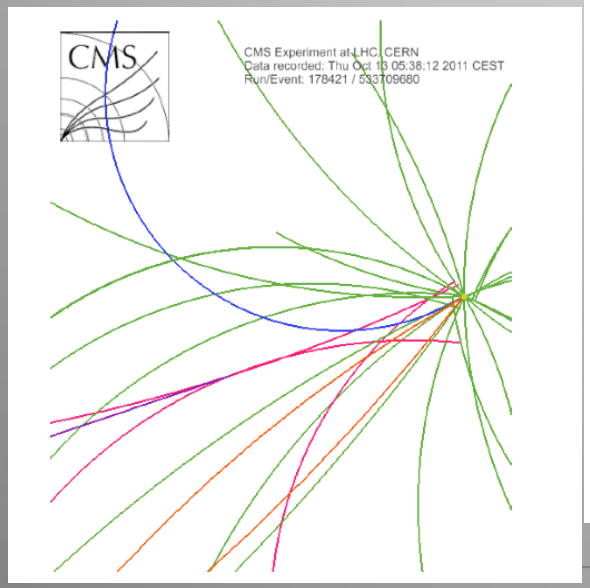


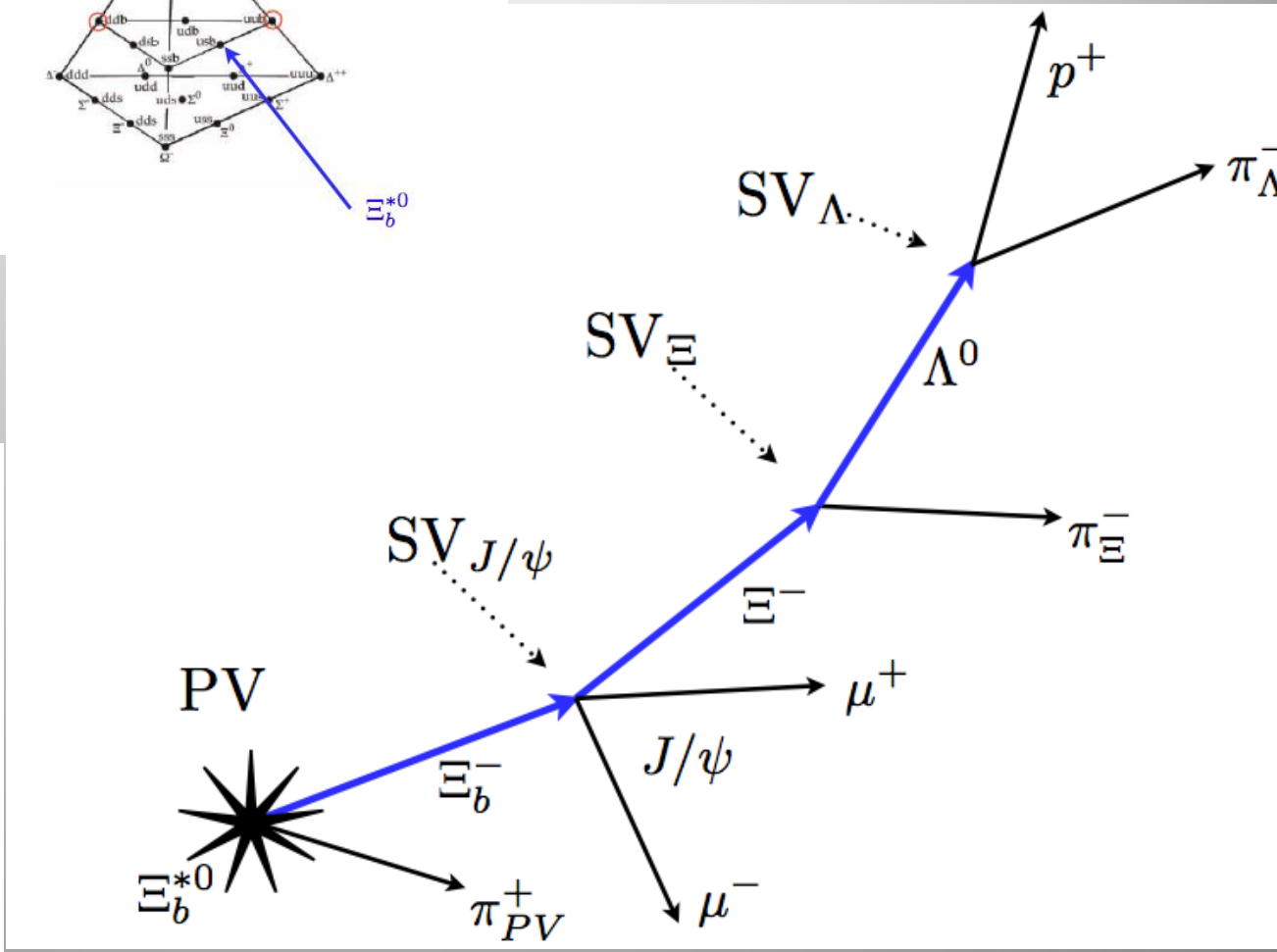
- Hyperfine splittings taken from previous experiments for $\chi_b(1P)$ and χ_b (2P)
  - Taken from theory (12 MeV) for previously undetected χ_b (3P)
- Over 6σ (!) in each converted/unconverted category (log-likelihood ratio)
- Mass barycenter (GeV):
  - Unconverted: 10.541 ± 0.011 (stat) ± 0.030 (syst)
  - Converted : 10.539 ± 0.004 (stat) ± 0.008 (syst) ← Taken as final result
  - Converted systematics dominated by signal and background model assumptions

Searching for a New Particle: $\Xi_b^{\star 0}$

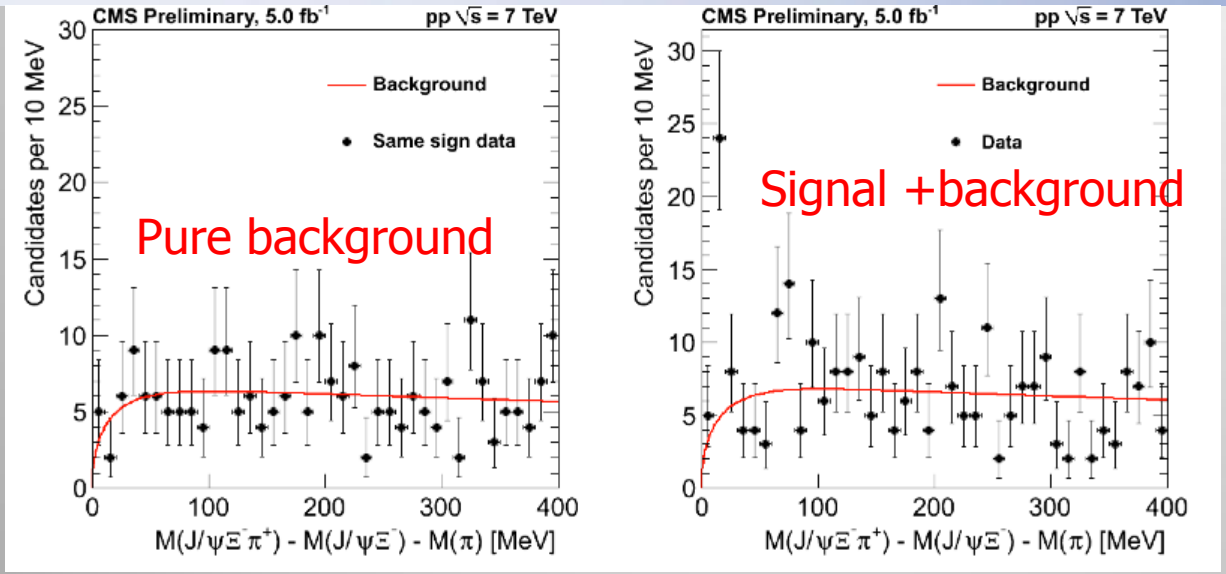


Quarks content : usb

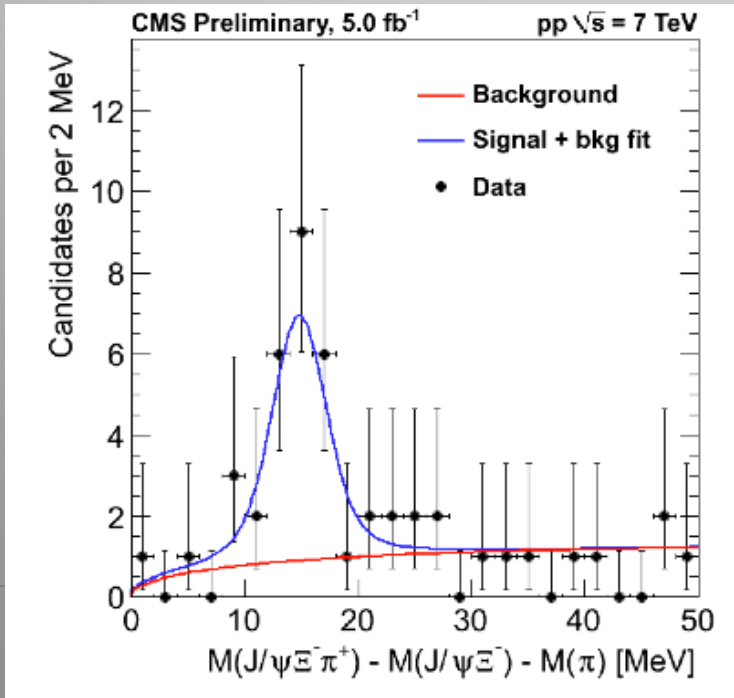




Searching for a New Particle: $\Xi_b^{\star 0}$



Signal and background



Final signal plot
24 events in the 'peak'

Both ATLAS and CMS have observed new particles !

But the particle we really want to see is THE HIGGS

Summary of the First Lecture

- The LHC is a very diverse machine. It allows for many Standard Model (SM) measurements in QCD and EWK.
- It is important to verify the Standard Model predictions with measurements at 7/8 TeV. Surprises could show up.
- The rich data of the LHC allows for new kind of tests of the Standard model, never done before
- At least one results was unexpected: the ridge in proton-proton collisions. More unexpected results may show up
- On July 4th we found a brand new particle that 'completes' the Standard model: The Higgs particle (See lectures from A. David). However, it implies physics beyond the SM!!