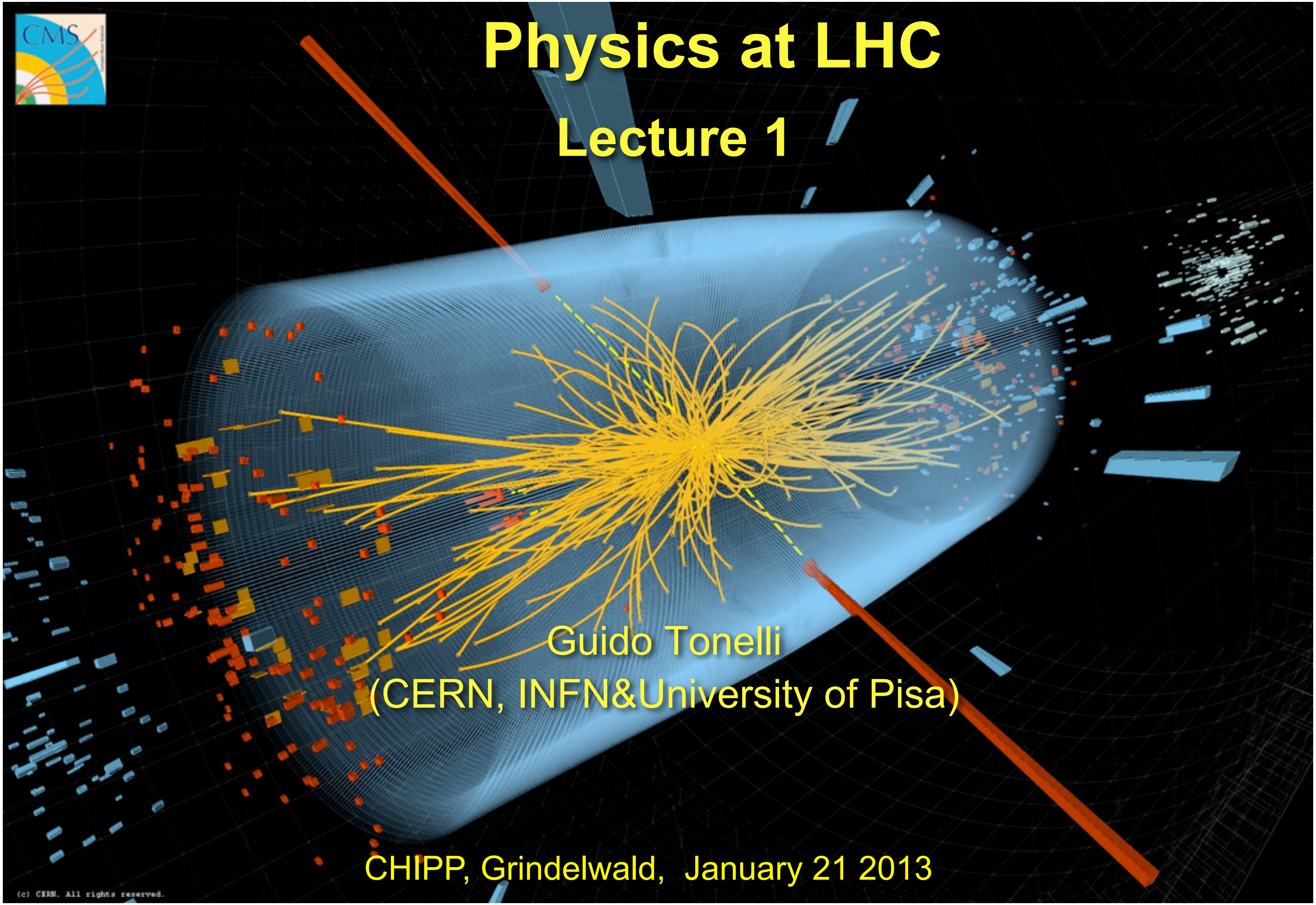
Physics at LHC

Lecture 1



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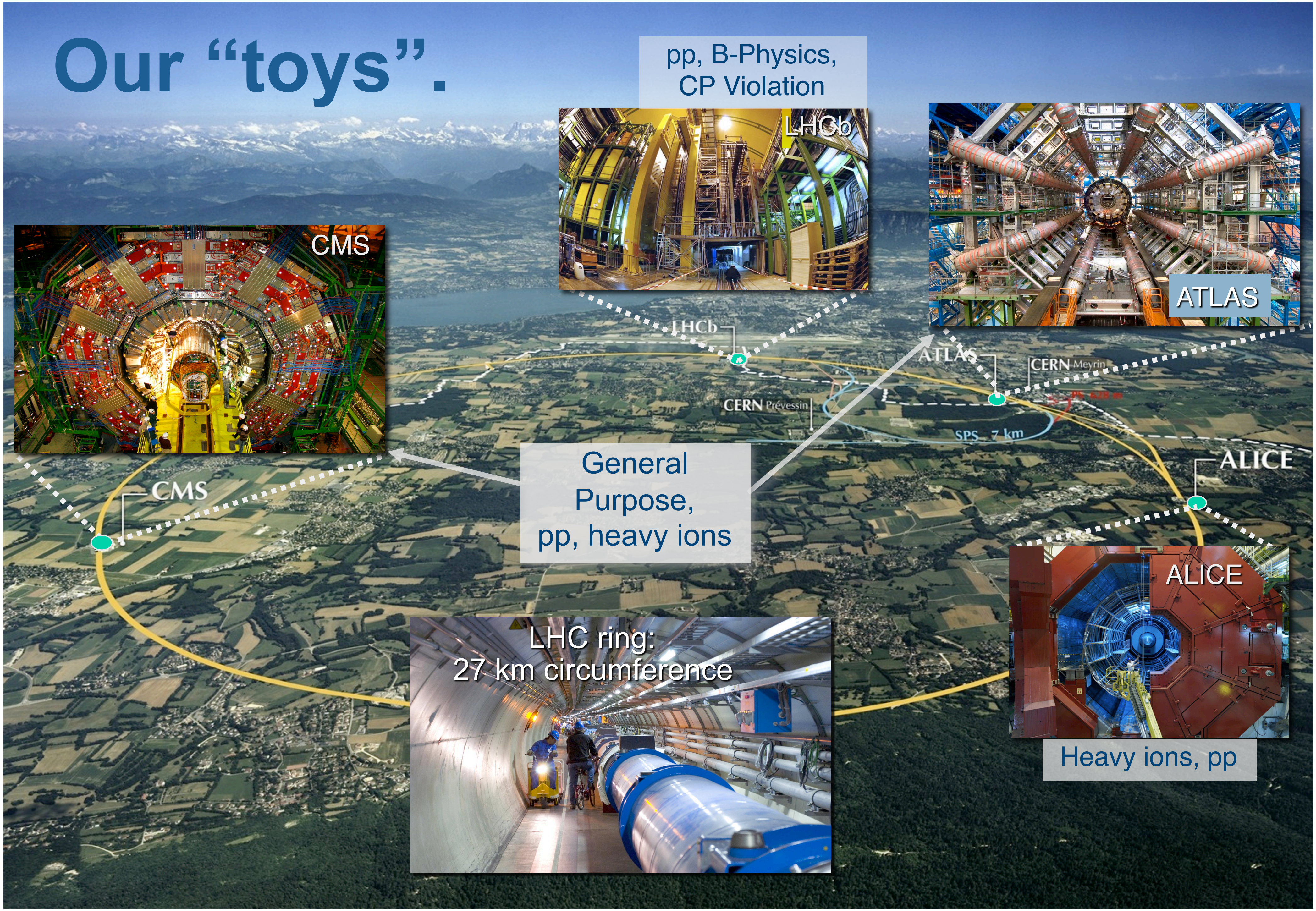
CHIPP, Grindelwald, January 21 2013

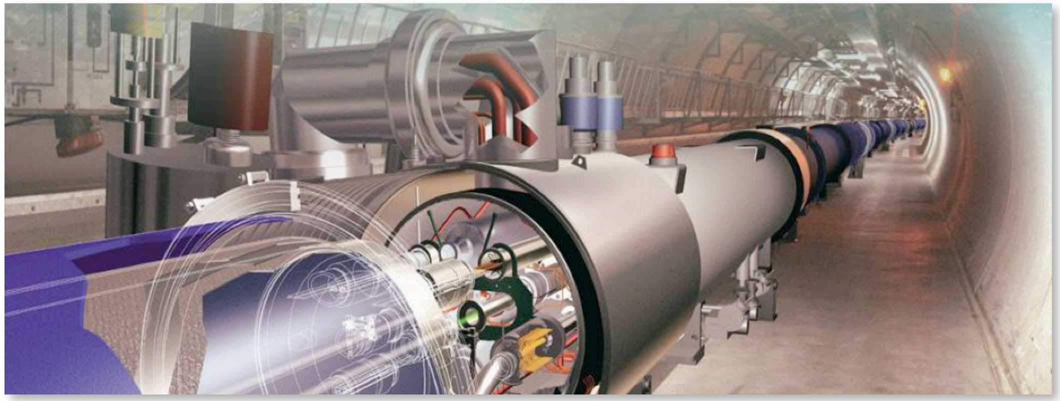
General Outline

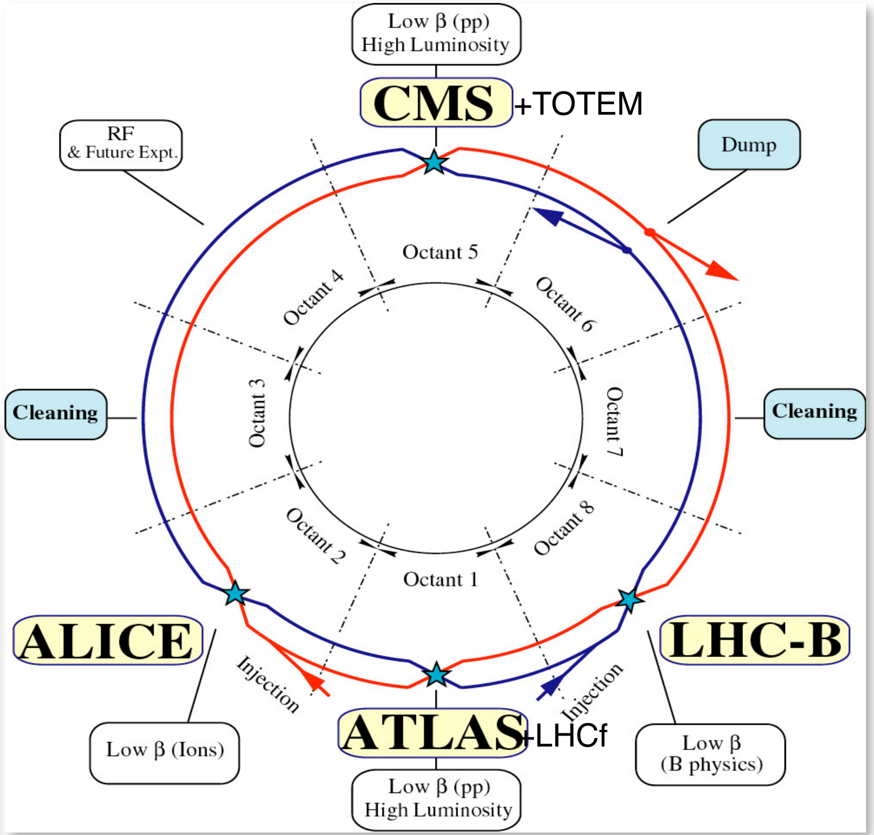
- Lecture 1 Introduction, low pt phenomena, jets anf photons
- Lecture 2 EWK and TOP results
- Lecture 3 Selected Exotica and SUSY searches
- Lecture 4 Higgs discovery and perspectives

Disclaimer 1: only pp physics (apologies for heavy ion physics and ALICE)
Disclaimer 2: mostly ATLAS and CMS (apologies to LHCb)
Disclaimer 3: still the set of results is too large to be covered in four lectures
Disclaimer 4: I have recycled many transparencies of CMS and ATLAS colleagues


Our "toys".
pp, B-Physics,
CP Violation
LHCb
CMS
ATLAS
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
CMS
General
Purpose,
pp, heavy ions
ALICE
LHC ring:
27 km circumference
Heavy ions, pp

The LHC : design parameters





1232 superconducting dipoles
15m long at 1.9 K, B=8.33 T
Inner coil diameter = 56 mm

max. beam-energy	7 TeV	(7x TEVATRON)
design Luminosity	10^{34} $cm^{-2}s^{-1}$	(>100x TEVATRON)
Bunch spacing	24.95 ns	
Particles/bunch	1.1 10^{11}	
Stored E/beam	362 MJ	

Also : Lead Ions operation
Energy/nucleon 2.76 TeV / u
Total initial lumi 10^{27} cm^{-2} s^{-1}

Unprecedented complexity:

10k magnets powered in 1700 electrical circuits

Basic relations 1)

$\mathcal{L}$ instantaneous luminosity is a measurement of the number of collisions that can be produced in an interaction point per cm^2 and per second. To calculate the number of events per second for a particular process we need also to consider the cross section and the branching ratio for the process:

event rate = σxBRx$\mathcal{L}$.

$$\mathcal{L} = \frac{N_b^2 n_b f_{\mathrm{rev}} \gamma_r}{4\pi\varepsilon_n\beta*} F$$

N_b = number of proton per bunch
n_b = number of bunches
f_{rev} = rotation frequency (~ 11Hz)
F = crossing angle factor
Rms transverse beam size =$\sqrt{\varepsilon\beta/\gamma}$
ε_n = renorm. transverse emittance
β^* = optics at beam crossing (m)
γ_r = relativistic factor

Basic relations 2)

$$\mathcal{L} = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi\varepsilon_n \beta*} F$$

$L = \int \mathcal{L} dt$ **integrated luminosity** is the integral of $\mathcal{L}$ over time and depends on the efficiency of the machine/duty cycle/luminosity lifetime etc.

If you consider the maximal instantaneous luminosity and a nominal time 10^7s/year it is advisable to use a typical 20—25% (Hubner) factor:

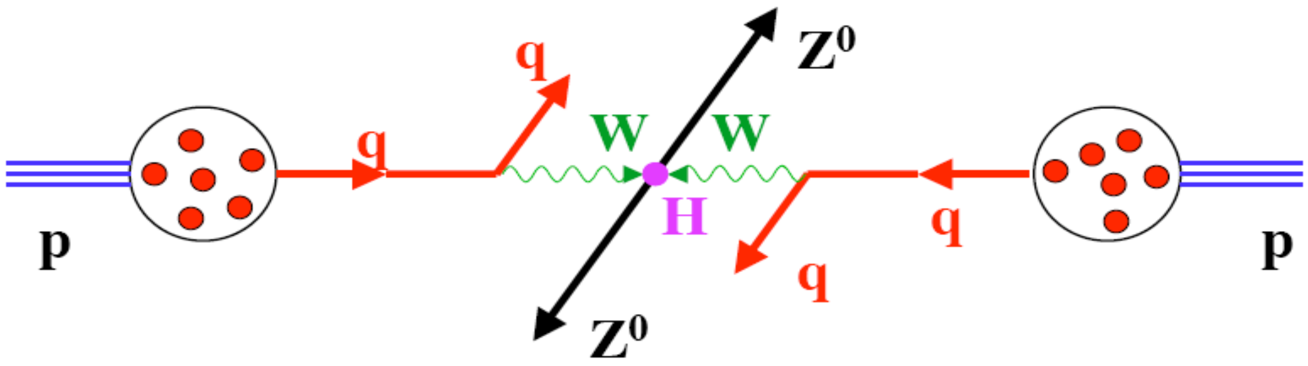
events/year = σx$\mathcal{L}$x10^7xBRx0.2.

e.g. H ~ 0.8 TeV (σ~100fb); H → ZZ → 4l (BR~10^{-3})

Events/year: 10^{-37}cm^{-2}x10^{34}cm^{-2} s^{-1} x10^7sx10^{-3}x0.2 ⇒ ~**2**

The Large Hadron Collider

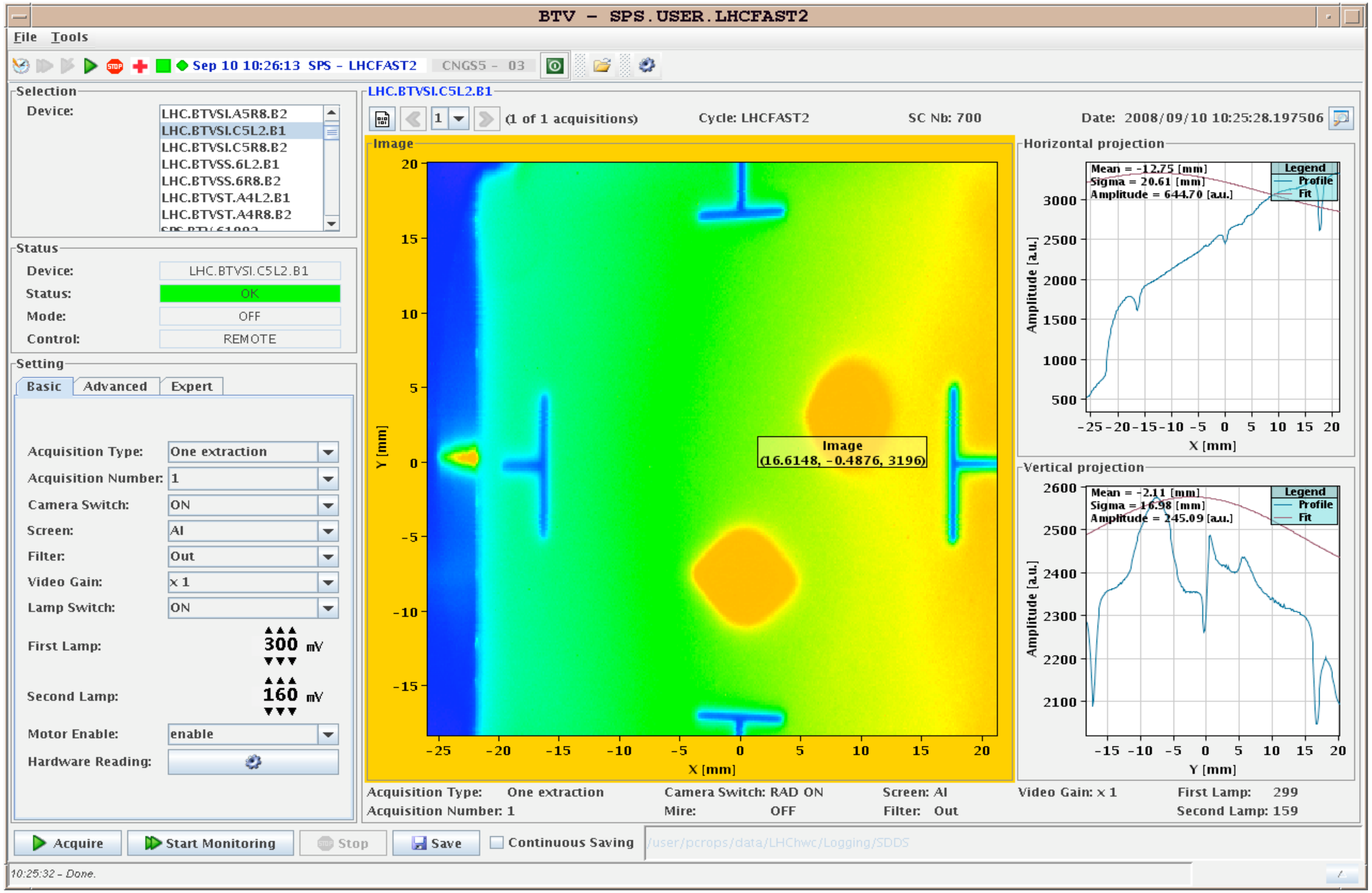
- A broad band exploratory machine
- May need to study W_L-W_L scattering at c.m. energy of ~ 1 TeV



- Need $E_W \sim 500$ GeV $\Rightarrow$ q ~ 1 TeV $\Rightarrow$ $\sqrt{s_{pp}} \sim 14$ TeV
- May need to discover a Higgs boson up to a $M_H \sim 1$TeV

10/09/2008: first beam in LHC

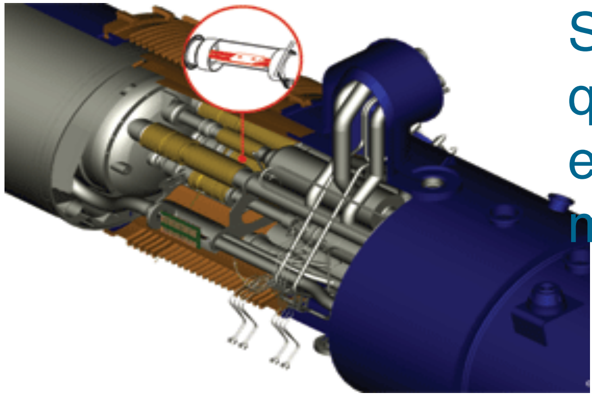
- 2 shots of clockwise beam: $2x10^9$ protons per beam



A lot of excitement in all control rooms

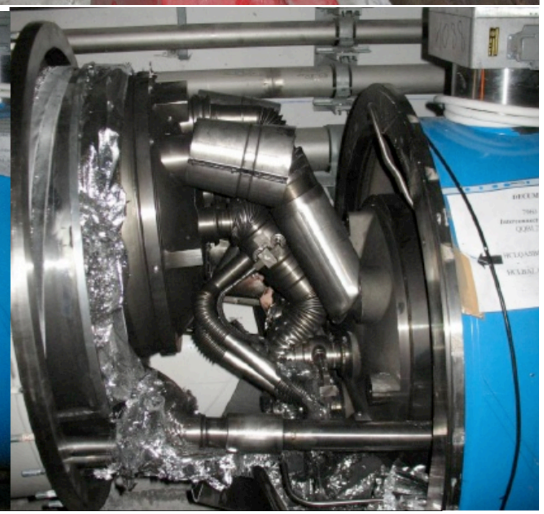
19/09/2008: our black friday

- An incident occurred during a powering test of one LHC sector for commissioning beam operation to 5 TeV. Massive helium loss in one arc of the tunnel; cryogenics and vacuum lost and important mechanical damage to tens of dipoles and quadrupoles
- The cause of the incident was determined to be a faulty electrical connection ("bus bar") between a dipole and a quadrupole.



Superfluid helium in quick expansion can easily displace a string of many 20t magnets…

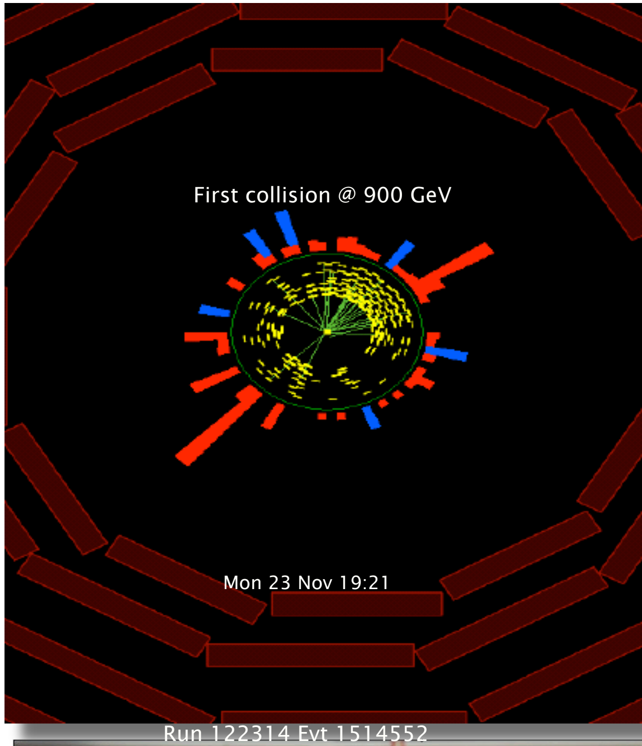
… and these are the consequences: ~1 year of work to replace/repair/re-check 53 magnets and to put in place any sort of test and all possible preventive actions to avoid the same incident could happen again.

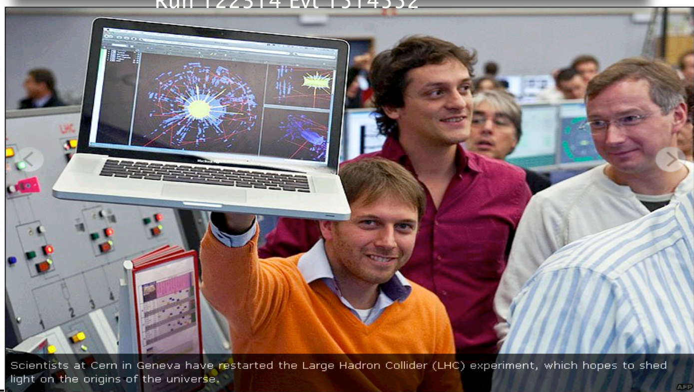


The LHC Start-Up in 2009

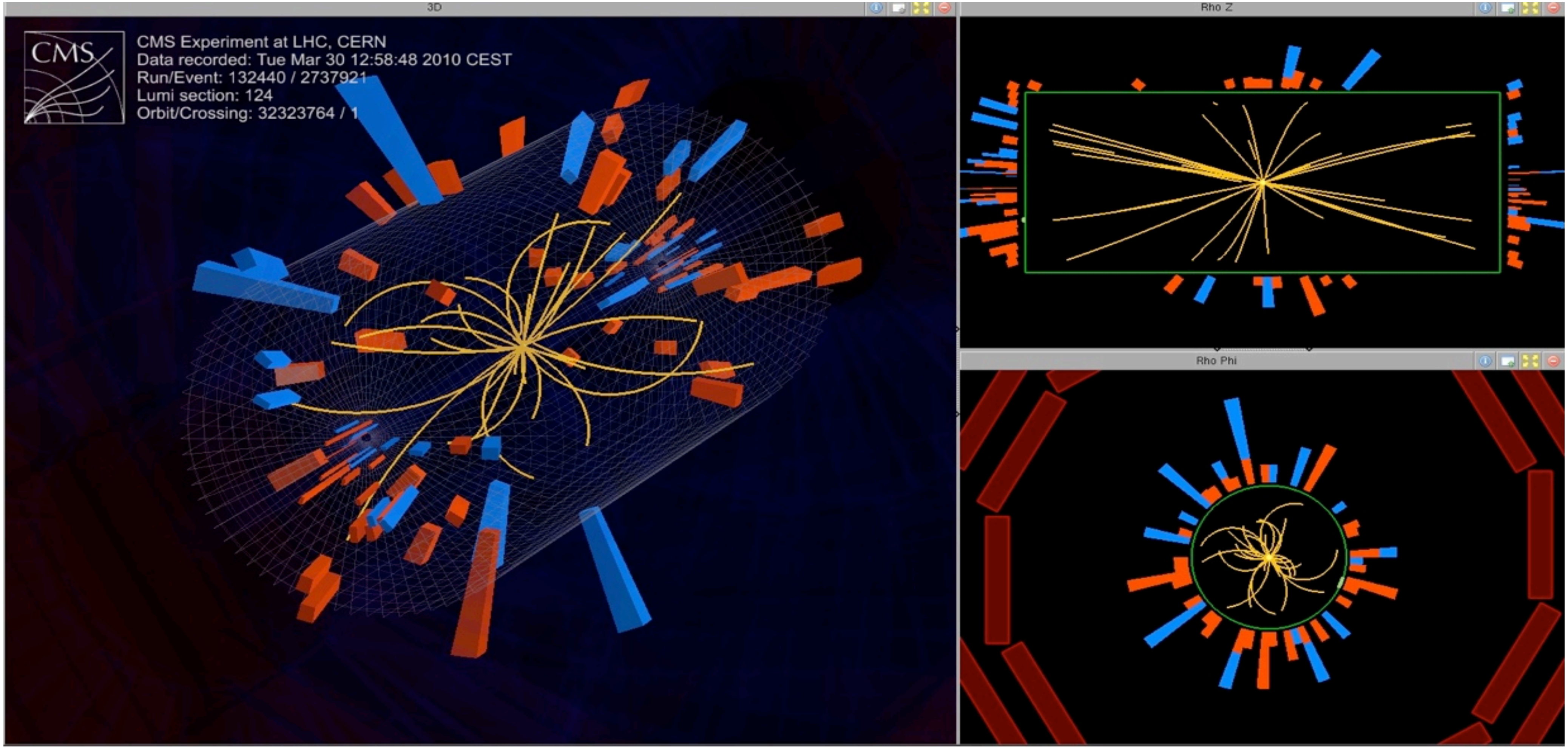
- Nov.20: Start of 2009 beam circulation
- Nov. 23: First collisions at 900 GeV
- Nov. 26: First results shown publicly at CERN!
- Dec.6: First physics fills
- Dec.8: Acceleration
  - both beams ramped to 1.18 TeV each
- Dec.11: Higher proton intensities (7E10)
  - Starting to accumulate luminosity at 900 GeV
- Dec.14, Collisions at 2.36 TeV !

First CMS Collision Event





First collisions in CMS at 7 TeV



within seconds: registered, reconstructed and displayed on screens

New plan for the LHC

- **2010: first physics run, 7TeV, L>2x10^{32}cm^{-2}s^{-1}, (40pb^{-1} delivered)**
- **2011: 7TeV, L>3.5x10^{33}cm^{-2}s^{-1} (>5.5fb^{-1} delivered)**
- **2012: 8TeV , L> 7.5x10^{33}cm^{-2}s^{-1}(>23fb^{-1} delivered)**

- **Since 2010 LHC is running smoothly and with excellent performance often exceeding the most optimistic expectations.**

- 2013-14: long shutdown to completely repair all the splices interconnecting the magnets and prepare the machine for 14 TeV.
- 2014-2015-2016: LHC at **13-14TeV** and **L> 10^{34}cm^{-2}s^{-1}**

LHC : Performance Limitations

Parameter/Effects	Limitations	Now
Beam energy limited by maximum dipole field. Industrially available technology.	7 TeV	3.5 -> 4 TeV
Bunch and total beam intensity beam-beam effect (tune spread), small allowed space in Q-space, collimators (impedance, collective instabilities), electron cloud, radiation	$N < 1.7\ 10^{11}$ $N_{nom} = 1.15\ 10^{11}$ $I < 0.85$ A	**$N \sim 1.5\ 10^{11}$**
Normalized emittance Limited by injectors and main dipole aperture	$\varepsilon_n < 3.75\ \mu m$	**1.9 - 2.4 μm**
Beam size at IP (β^*) Limited by (triplet) quadrupole aperture	$0.55\ m < \beta^* < 1\ m$ $\sigma \sim 17\ \mu m$	0.6 m $\sigma \sim 20\ \mu m$
Crossing angle Limited by (triplet) quadrupole aperture	300 μrad	290 μrad
Number of (colliding) bunches Limited by stored beam energy, electron cloud eff.	2808	1368
Luminosity	$1\ 10^{34}$	7.5×10^{33}

Legend:

N : particles/bunch

n : nr. of bunches

I : current / beam

$\varepsilon_n = \varepsilon\gamma$, ε : emittance

β^* : β at IP

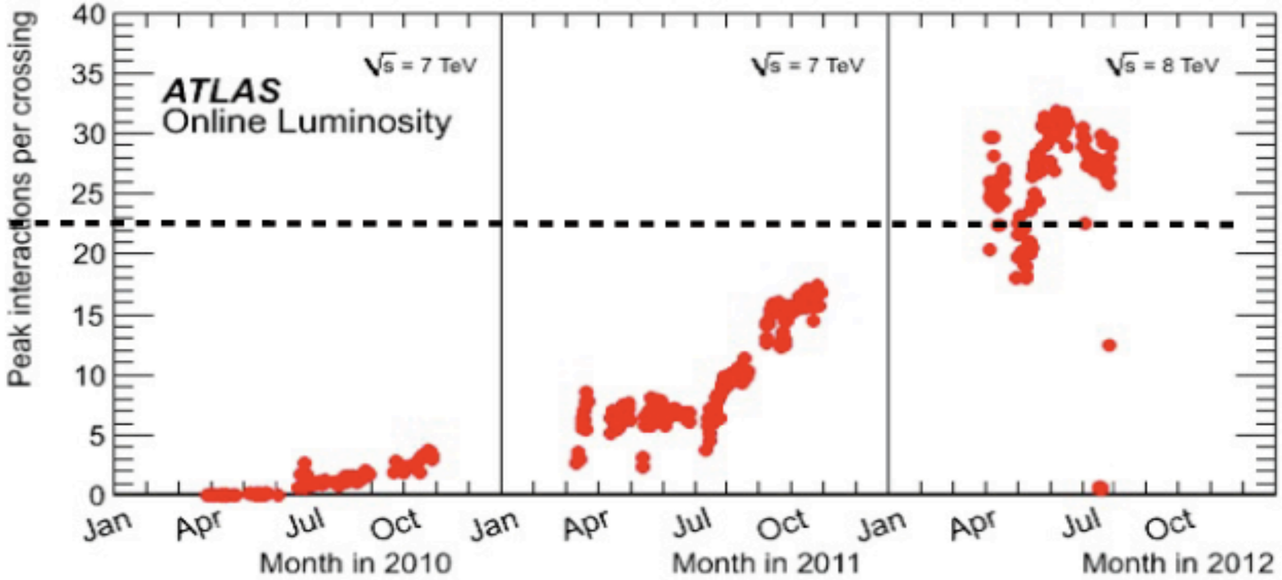
Beam size $\sigma^2 = \beta\varepsilon$

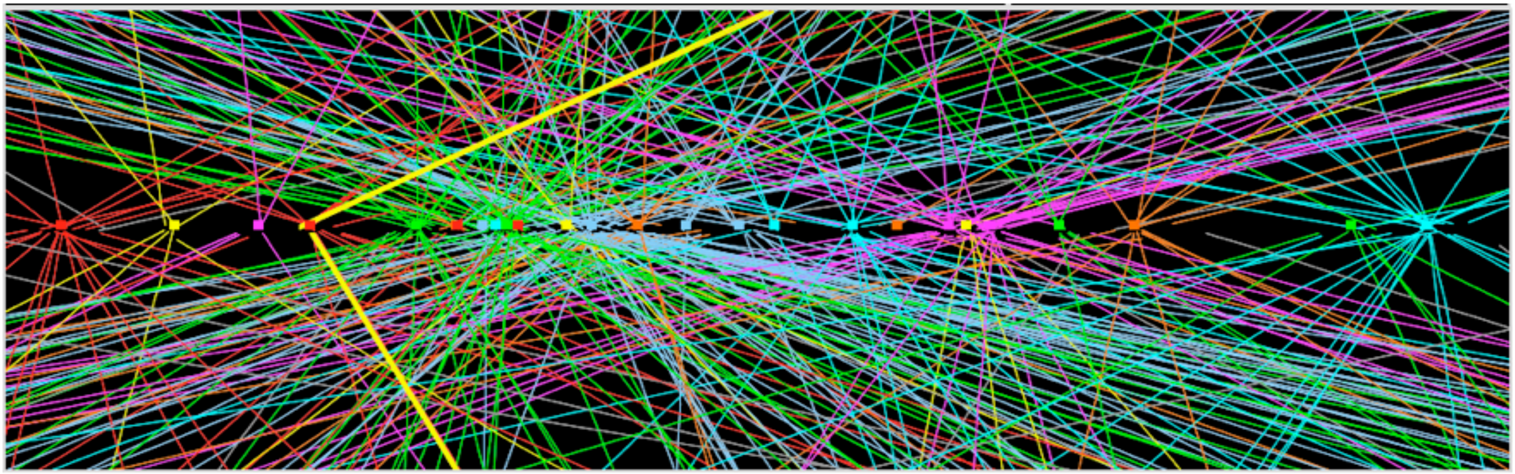
Q : tune (number of trans. oscil./turn)

Pile up: the price to pay to get high $\mathcal{L}$

Peak interactions per crossing

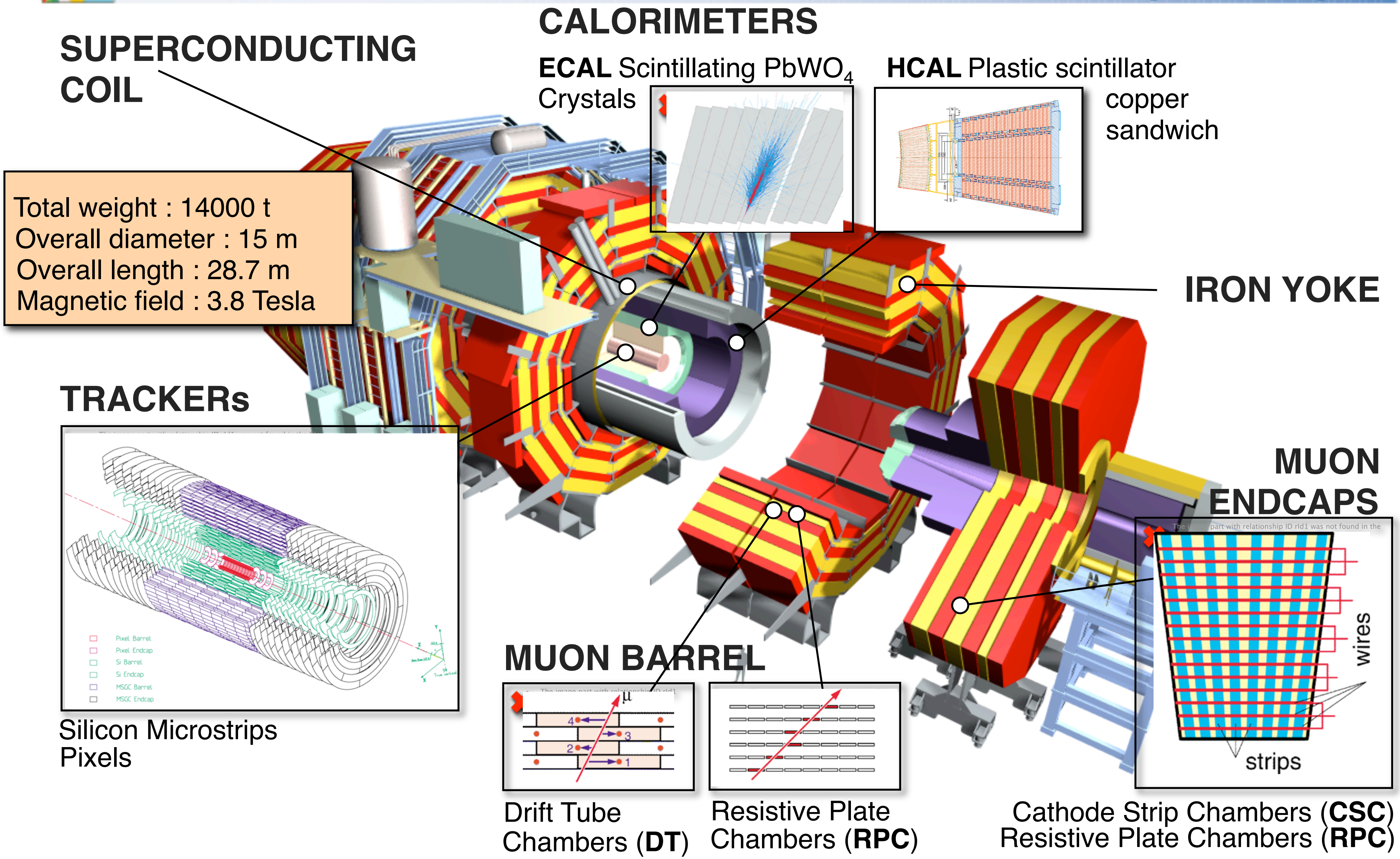
Design value: 23
for $L=10^{34}$ /cm^2 s



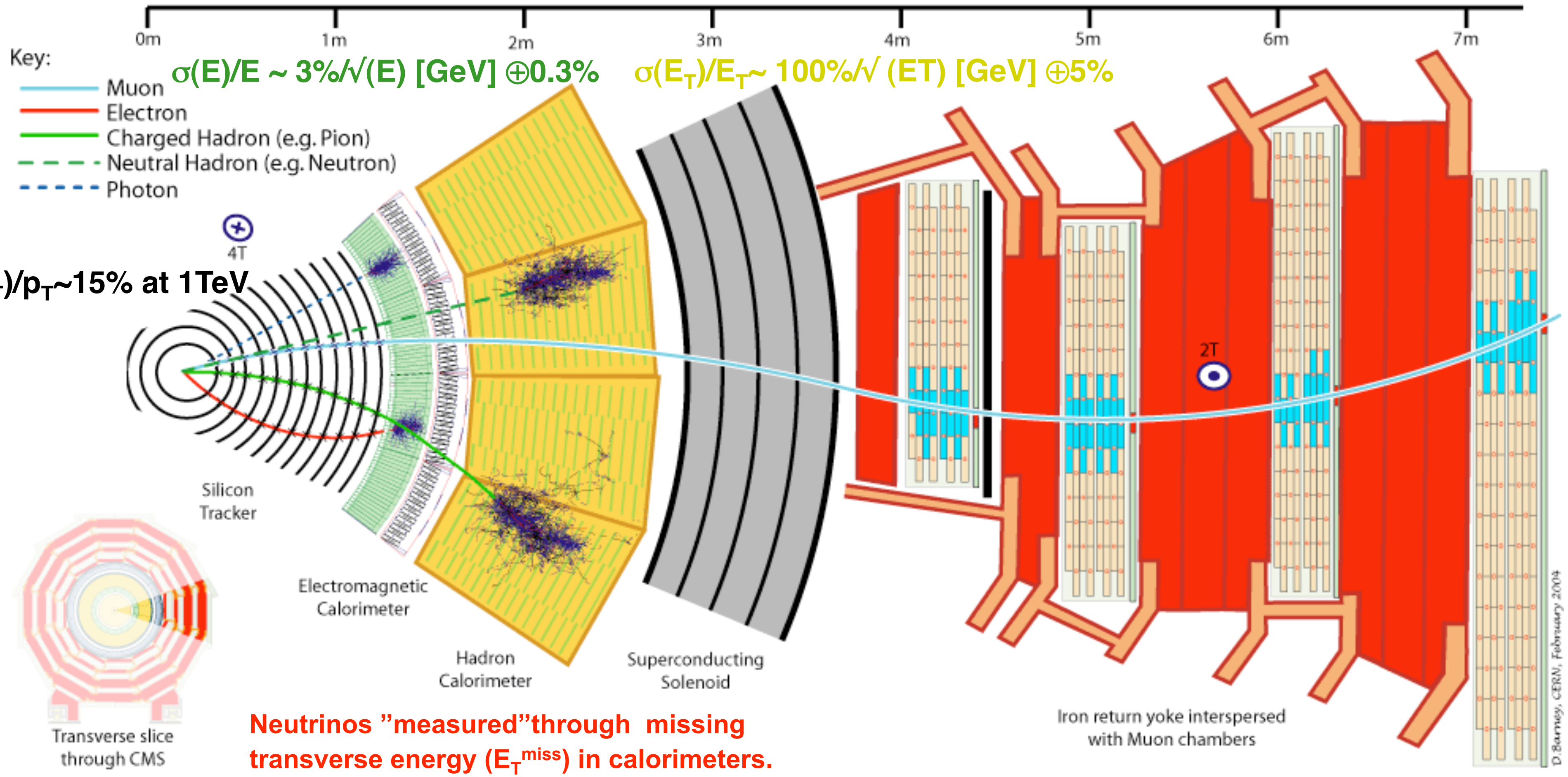


Z in μμ event
with 25 vertices

The Compact Muon Solenoid (CMS)



CMS conceptual design



$\sigma(E)/E \sim 3\%/\sqrt{(E)}$ [GeV] $\oplus 0.3\%$

$\sigma(E_T)/E_T \sim 100\%/\sqrt{}$ (ET) [GeV] $\oplus 5\%$

$\sigma(p_T)/p_T \sim 15\%$ at 1TeV

Neutrinos "measured" through missing transverse energy (E_T^{miss}) in calorimeters.

Fast detectors: 25-50ns bunch crossing
High granularity: 20-40 overlapping complex events
High radiation resistance: >10 years of operation

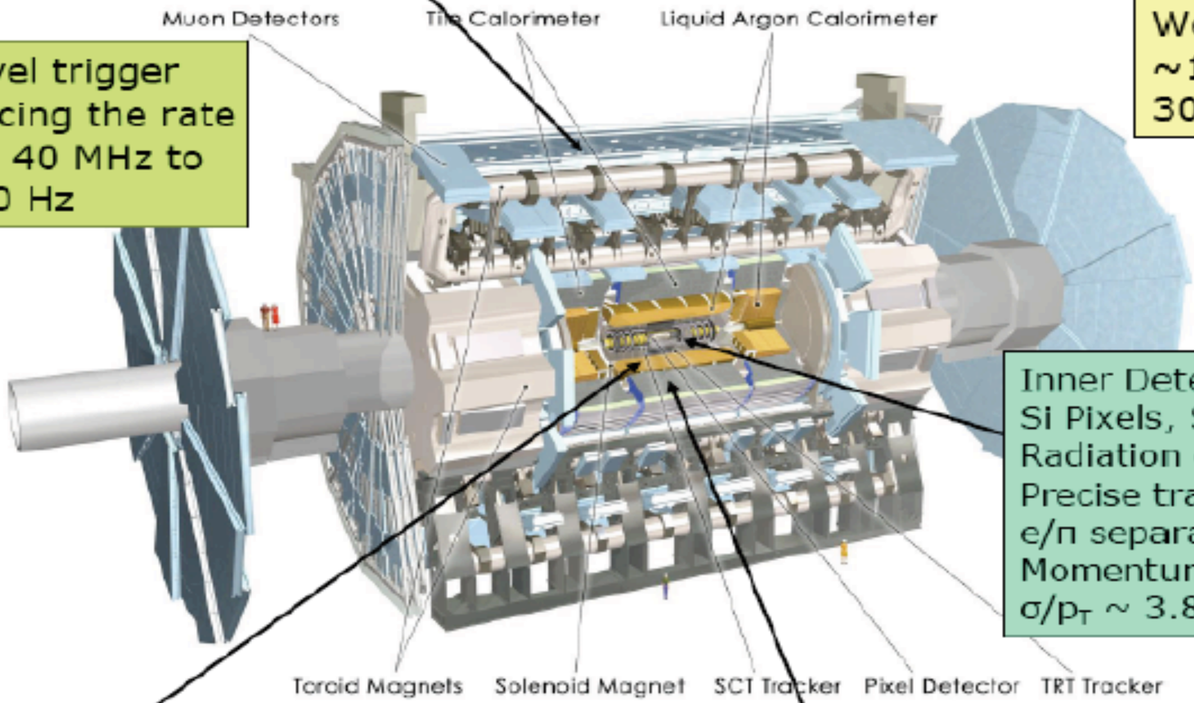
$\sigma(p_T)/p_T < 1\%$ @ 100GeV
$\sigma(p_T)/p_T < 10\%$ @1 TeV

The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz

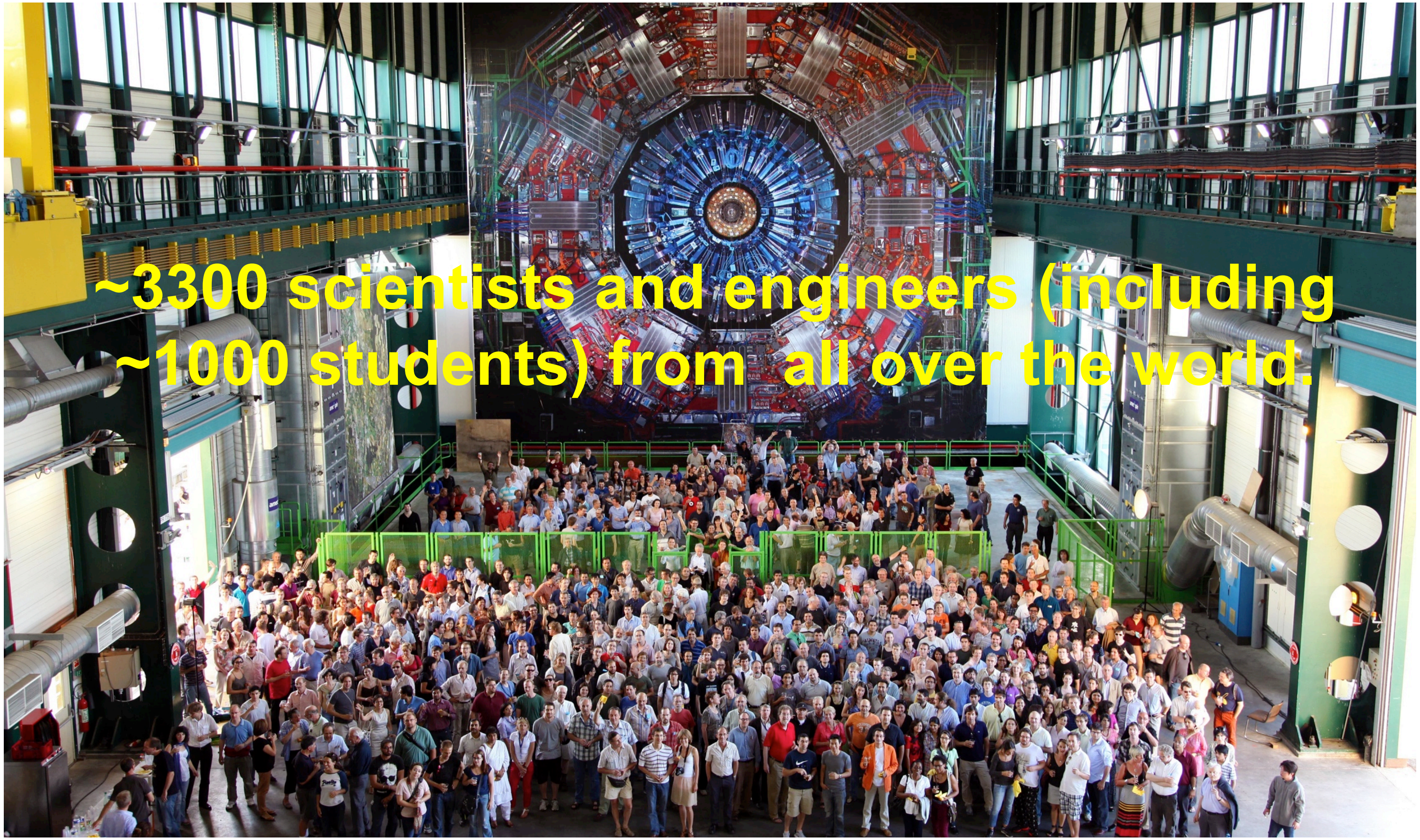


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Another key component: the people

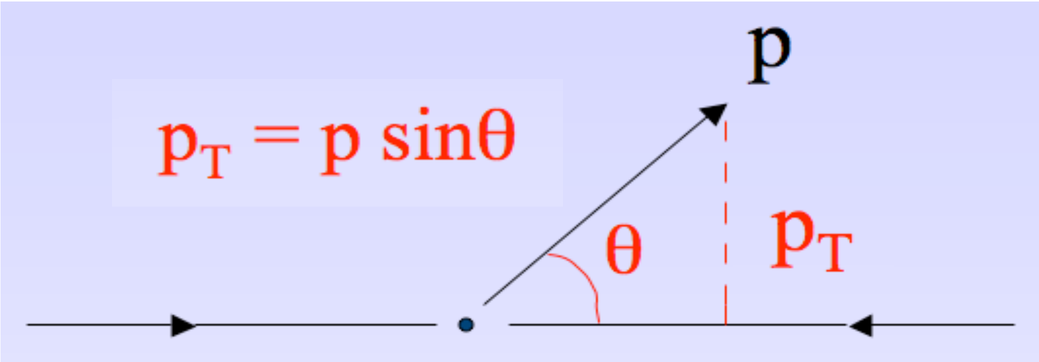


Collaborations strong of ~1000 students and post-doc can do incredible things facing challenges that were once considered "mission impossible".

Tools and Methods

Variables used in pp collisions

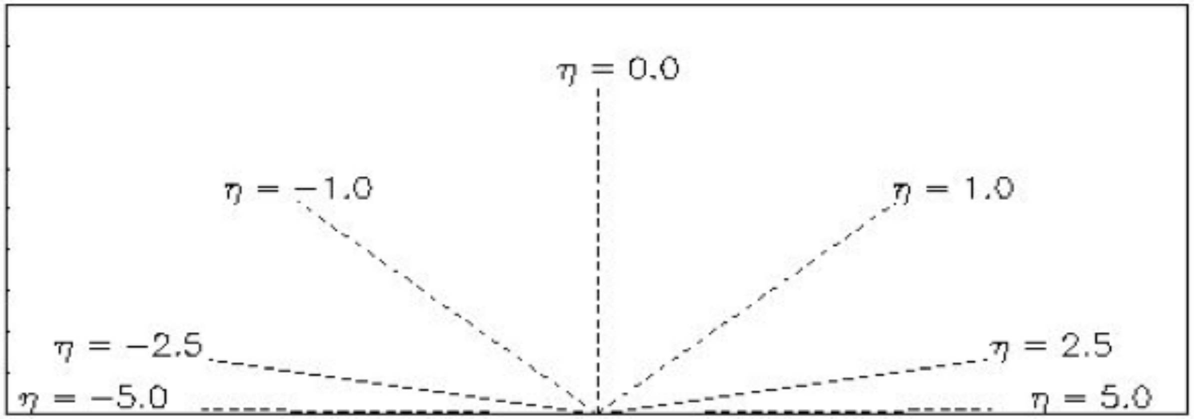
Transverse momentum



As a consequence of the collision kinematic, the longitudinal momentum p_Z is not known therefore we can use only the conservation of the transverse momentum, p_T, in the plane perpendicular to the beam.

Rapidity $y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right)$

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



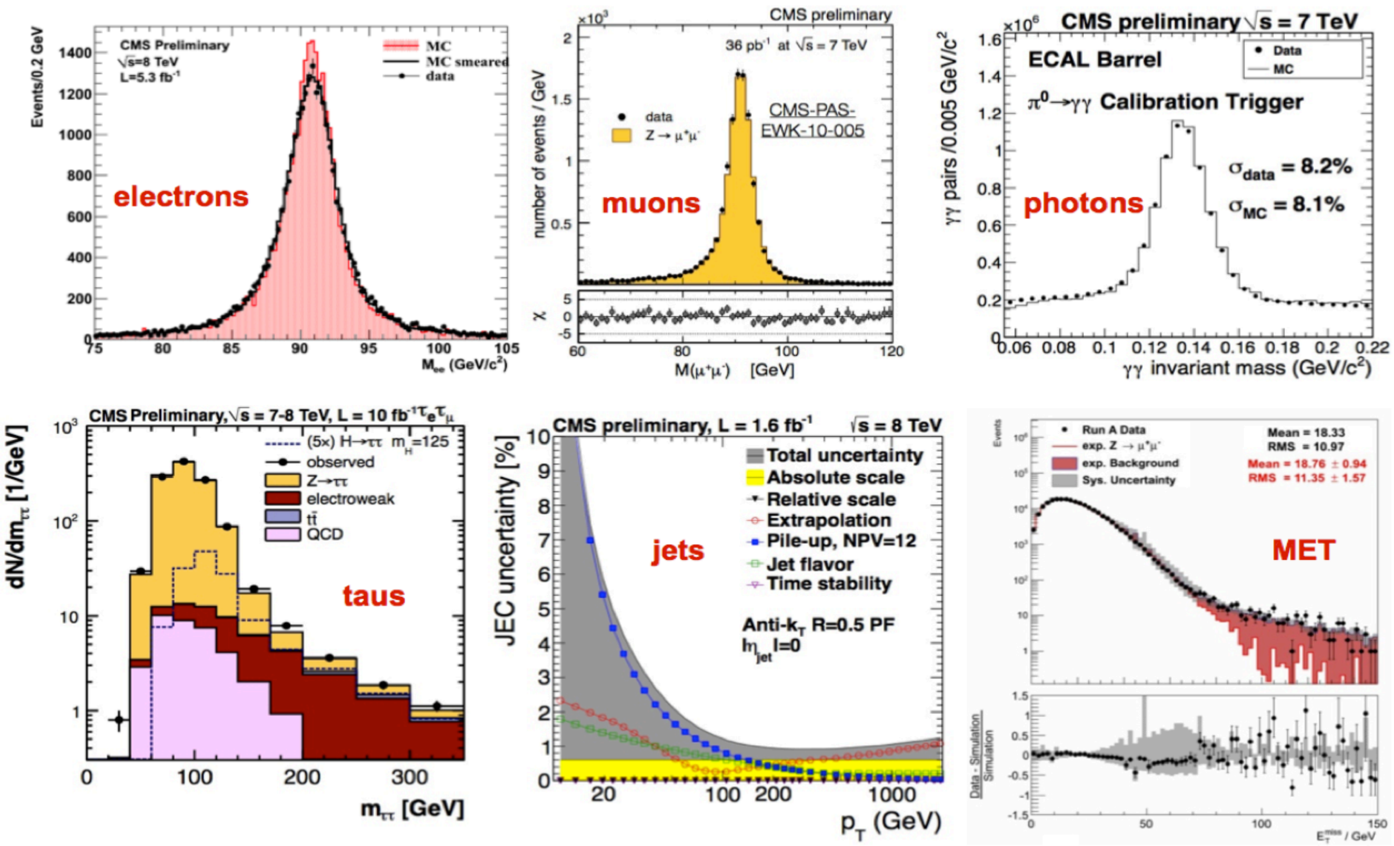
$\theta = 90^o \rightarrow \eta = 0$

$\theta = 10^o \rightarrow \eta \cong 2.4$
$\theta = 170^o \rightarrow \eta \cong -2.4$

$\theta = 1^o \rightarrow \eta \cong 5.0$

(Pseudo) rapidity is Lorentz invariant while the polar angle θ is not.

Performance, Object reconstruction



- non-showering electrons in barrel: resolution (reconstructed Z peak) close to 1 GeV
- muon momentum resolution: 1% for p_T < 100 GeV, 7-8% at 1 TeV
- pions mis-ID as muons: <0.5% for p_T > 2 GeV
- Tau ID eff. > 65% for p_T > 20 GeV, with mis-ID eff. of hadronic jets < 3%
- b-jet tagging eff. of 70% for p_T > 30 GeV, with mis-ID eff. of light-quark jets < 3%

Our Master Equation

Event rates (absolute, relative, differential)
Stat vs syst errors, backgrounds from data or MC?
Resolution, Energy Scale, Signal Significance

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \; L}$$

Proton-Proton Luminosity uncertainty < 5%

Experimental issues : Triggers, reconstruction, isolation cuts, low-p_T jets (jet veto) acceptance, efficiency determination (tag&probe)

Theoretical issues : p_T distributions at NLO + resummation; differential calculations for detectable acceptance.

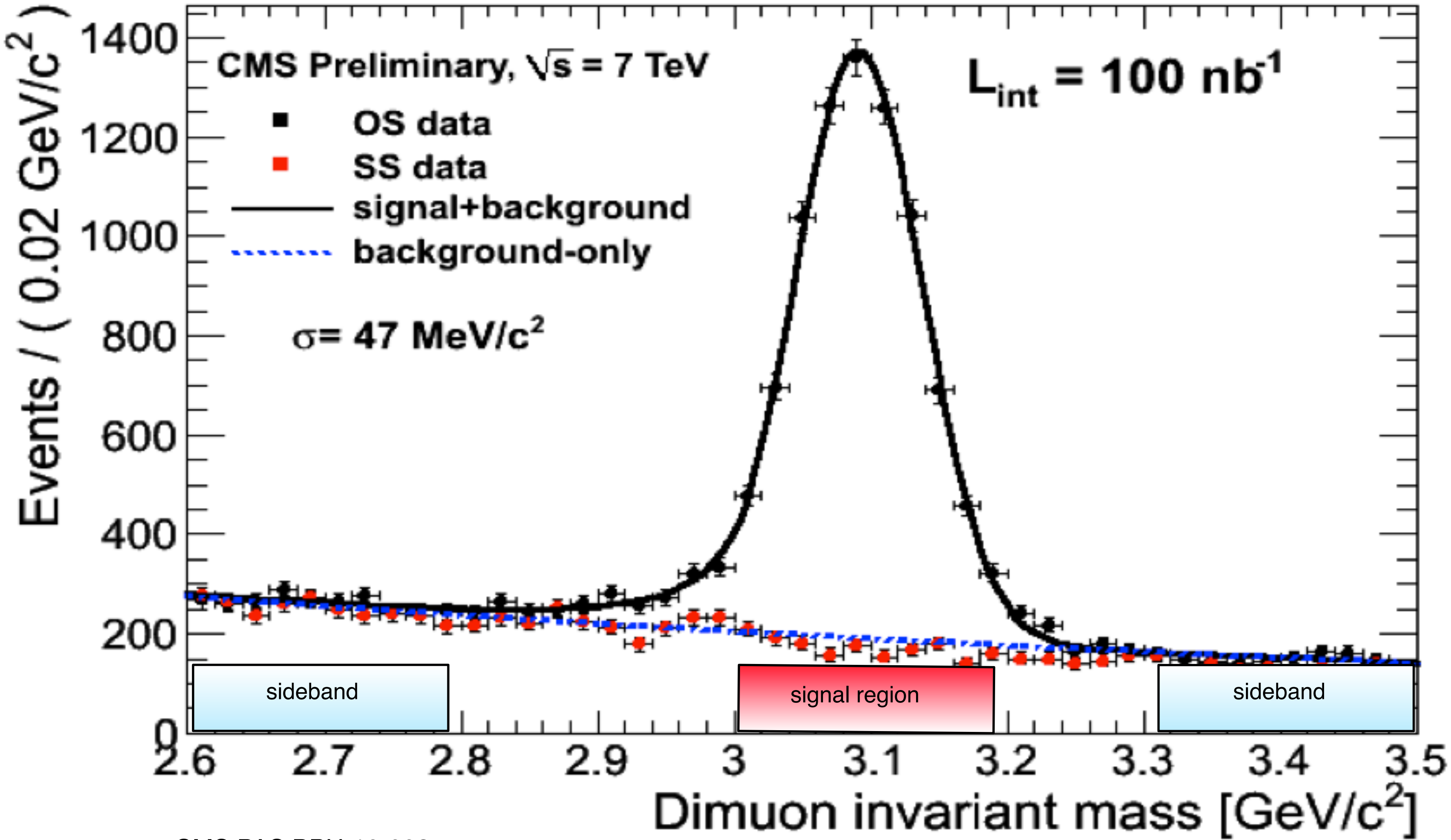
$$\sigma_{\text{theo}} = PDF(x_1, x_2, Q^2) \otimes \hat{\sigma}_{\text{hard}}$$

constrain, define uncertainties

HO calculations, implement in MC

Goal : test SM (in)consistency : $\sigma_{\text{exp}} \pm \Delta_{\text{exp}} \stackrel{?}{=} \sigma_{\text{SM}} \pm \Delta_{\text{th}}$

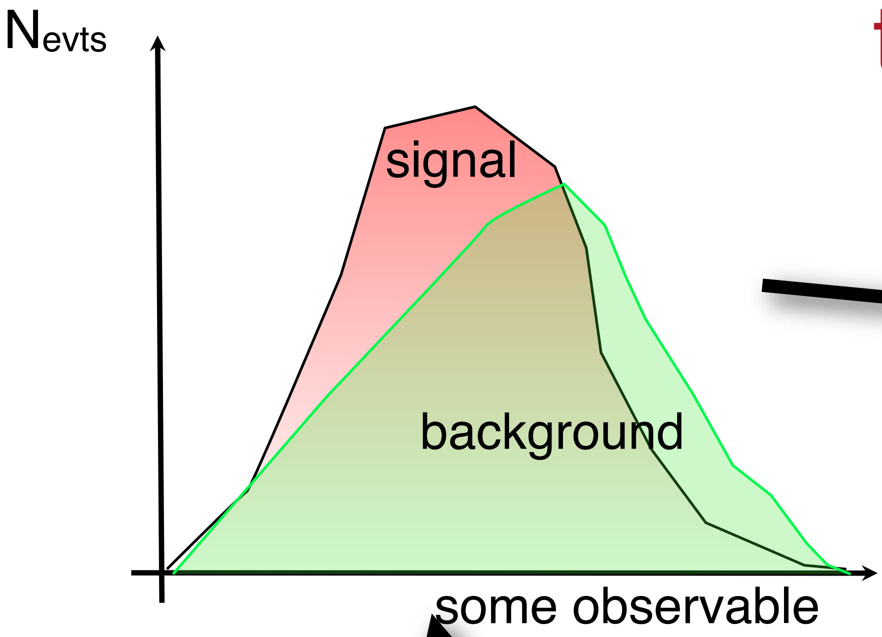
The "trivial" case : Sidebands



CMS PAS BPH-10-002

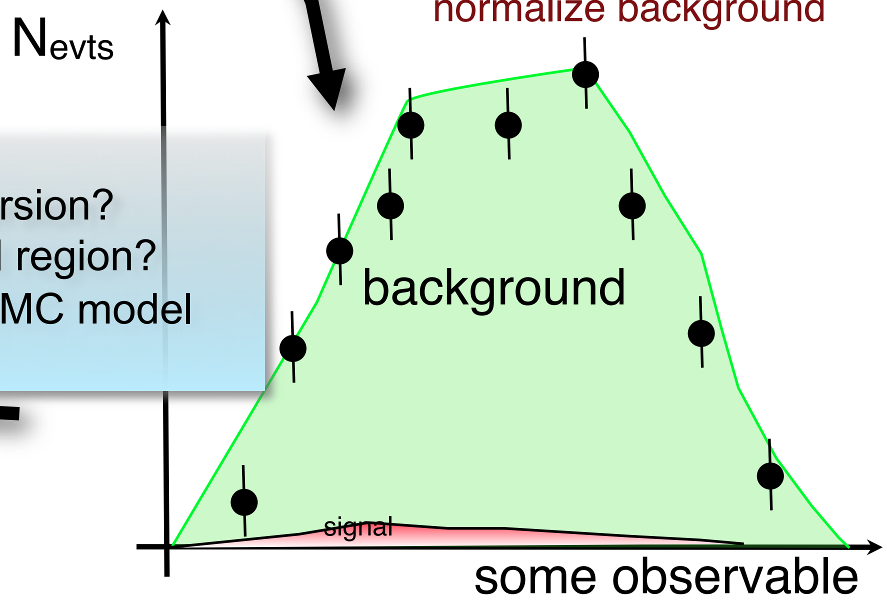
Data-Driven Background Estimates

the general idea



invert cuts :
from signal enhancement to background enhancement

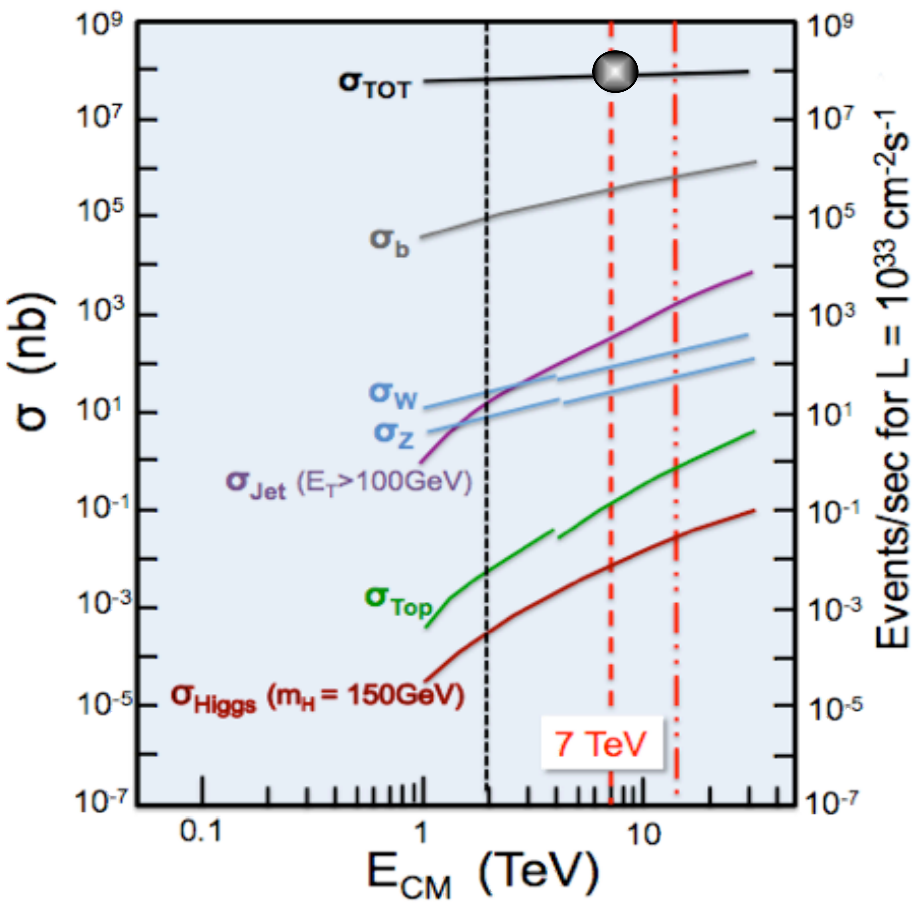
use data to
normalize background



Issues:
- is signal left after inversion?
- any bias in the control region?
- how well does theory/MC model the cut inversion?

going back:
use theory (MC) to compute change in background when inverting cuts; or use some well-motivated extrapolation, data only

Expected Physics : 1



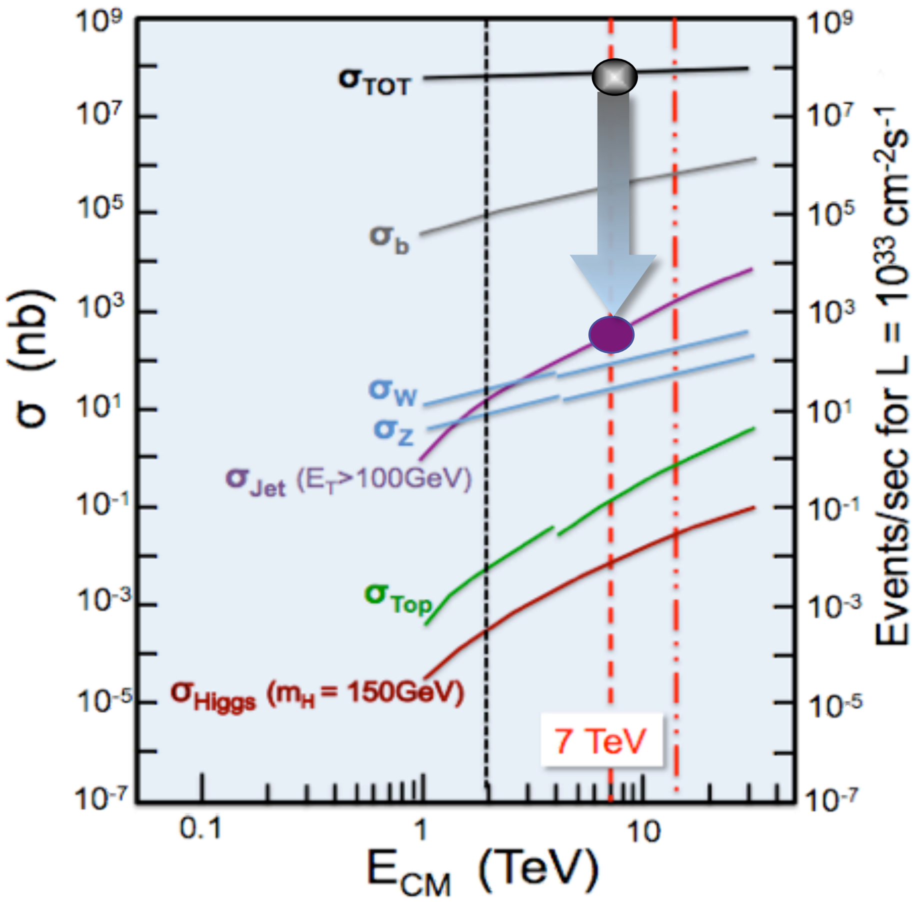
- Inelastic low-p_T pp collisions
  - Most processes are due to soft and semi-soft interactions between incoming protons
    - particles in the final state have large longitudinal, but small transverse momentum -> small momentum transfer:
      - several hundreds of MeV

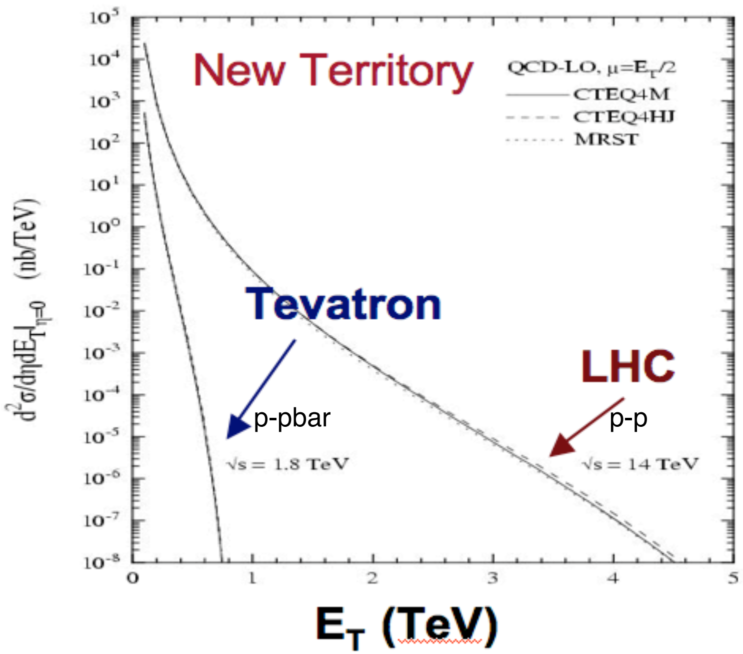
Low-p_T inelastic pp-collisions:
"Minimum Bias events"
Parameters (multiplicity etc) poorly known!
Important for tuning MC simulations,
and understanding of Pile-Up effects

- particle density:
  ~ 4 - 6 charged particles (pions) plus ~ 2 - 3 neutrals (π^0) per unit of pseudorapidity
  in the central detector region (and ~flat in rap)
- uniformly distributed in ϕ
- average p_T ~ few hundreds of MeV

Expected Physics : 2

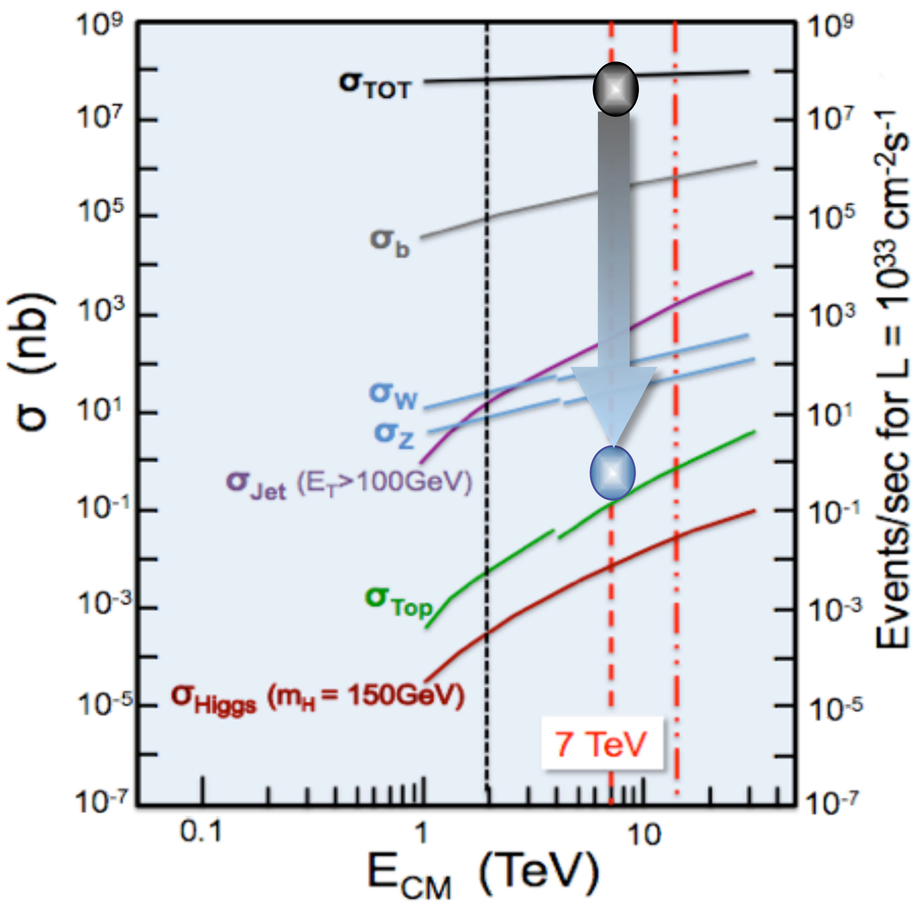
- Measure Jet cross sections
  - E_T^{Jet} > 500 GeV after a few months at startup
  - Going fast beyond the TEVATRON reach
    - early sensitivity to compositeness





- requires good understanding of jets (algorithms, production, jet energy scale), PDFs, pile-up, underlying event, ...
- Thus : good calorimetry!!

Expected Physics : 3



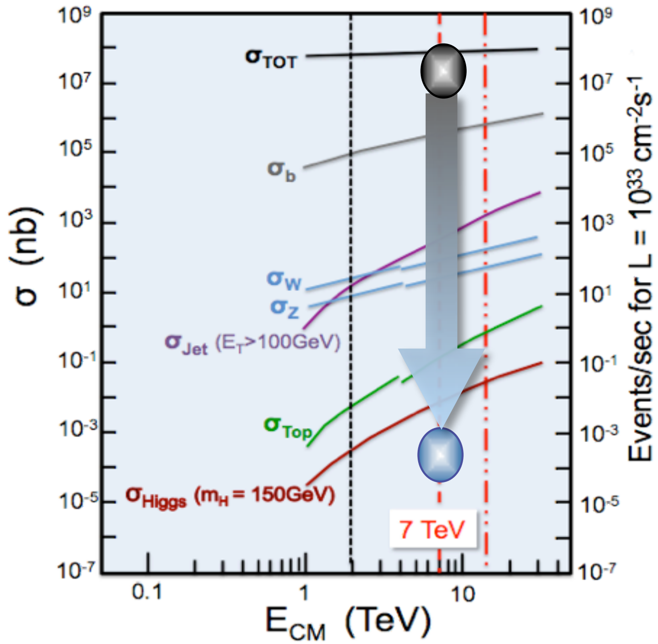
- The Electroweak Sector
  - test (re-establish the SM) and then go beyond
  - most SM cross sections are significantly higher than at the TEVATRON
    - eg. 100x larger top-pair production cross section
    - the LHC is a top, b, W, Z, ..., Higgs, ... factory

Important:
Concentrate on final states with high-p_T and isolated **leptons and photons** (+ jets)

Otherwise overwhelmed by QCD jet background!!

Goals

- Benchmark processes defining main machine/detector parameters
  - Basic processes relevant for studying electro-weak symmetry breaking (as seen in early days):
  - All cross sections (times BR) of order 1 - 100 fb : determines needed luminosities for sizable statistics



$$pp \to W^+W^- \to \mu^+\nu_\mu\,\mu^-\bar{\nu}_\mu$$

$$pp \to H \to ZZ \to \mu^+\mu^-\mu^+\mu^-$$

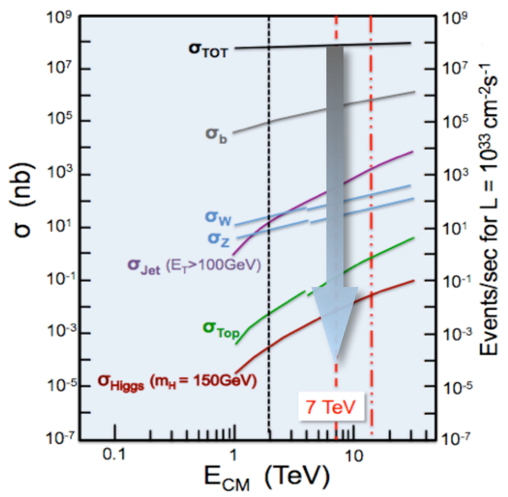
$$pp \to H \to ZZ \to \mu^+\mu^-\,\nu_\mu\bar{\nu}_\mu$$

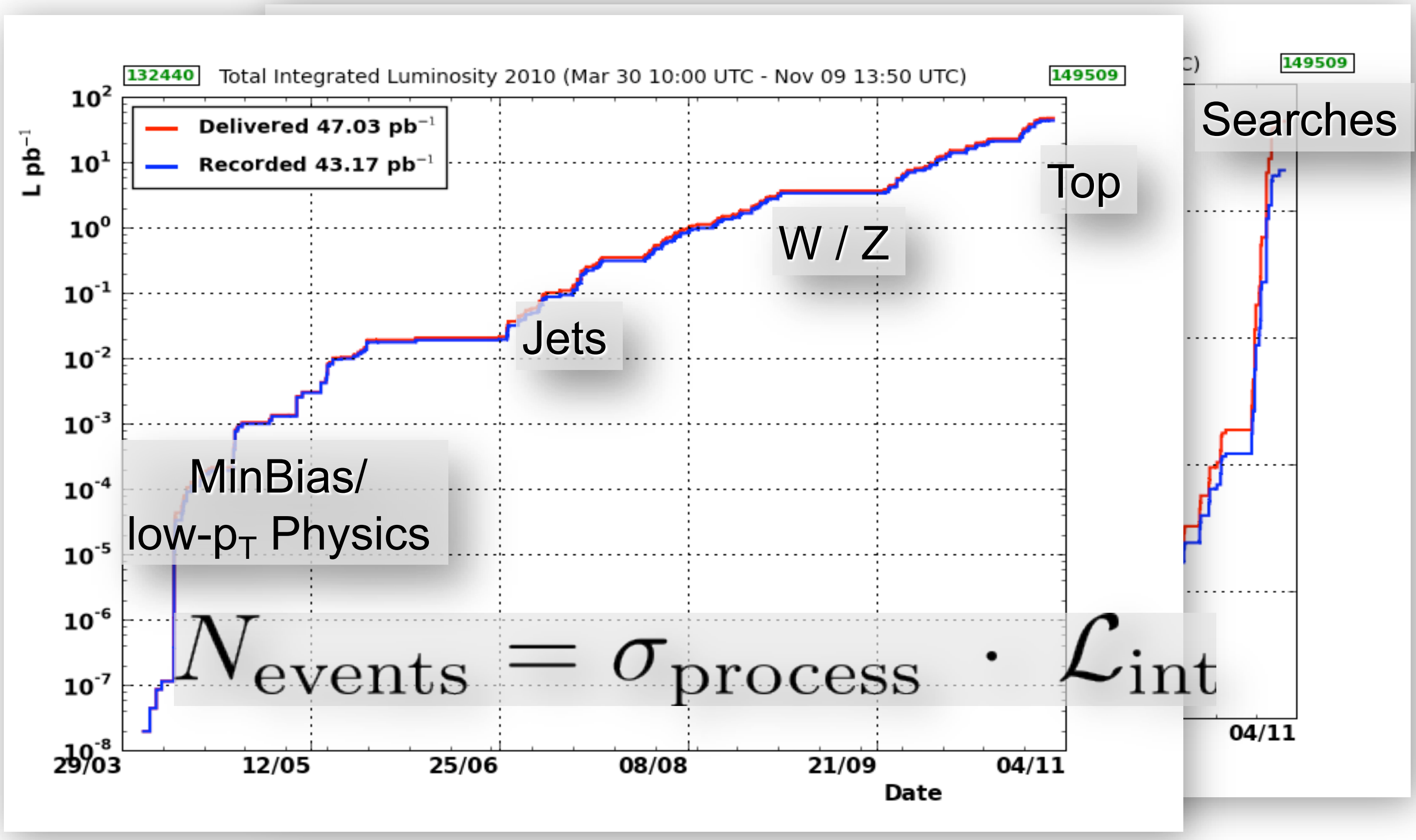
$$pp \to H \to \gamma\gamma$$

$$pp \to H\ \mathrm{jet\,jet}\quad (\mathrm{VBF})$$

$$pp \to Z' \to \mu^+\mu^-$$

As things appeared with time....





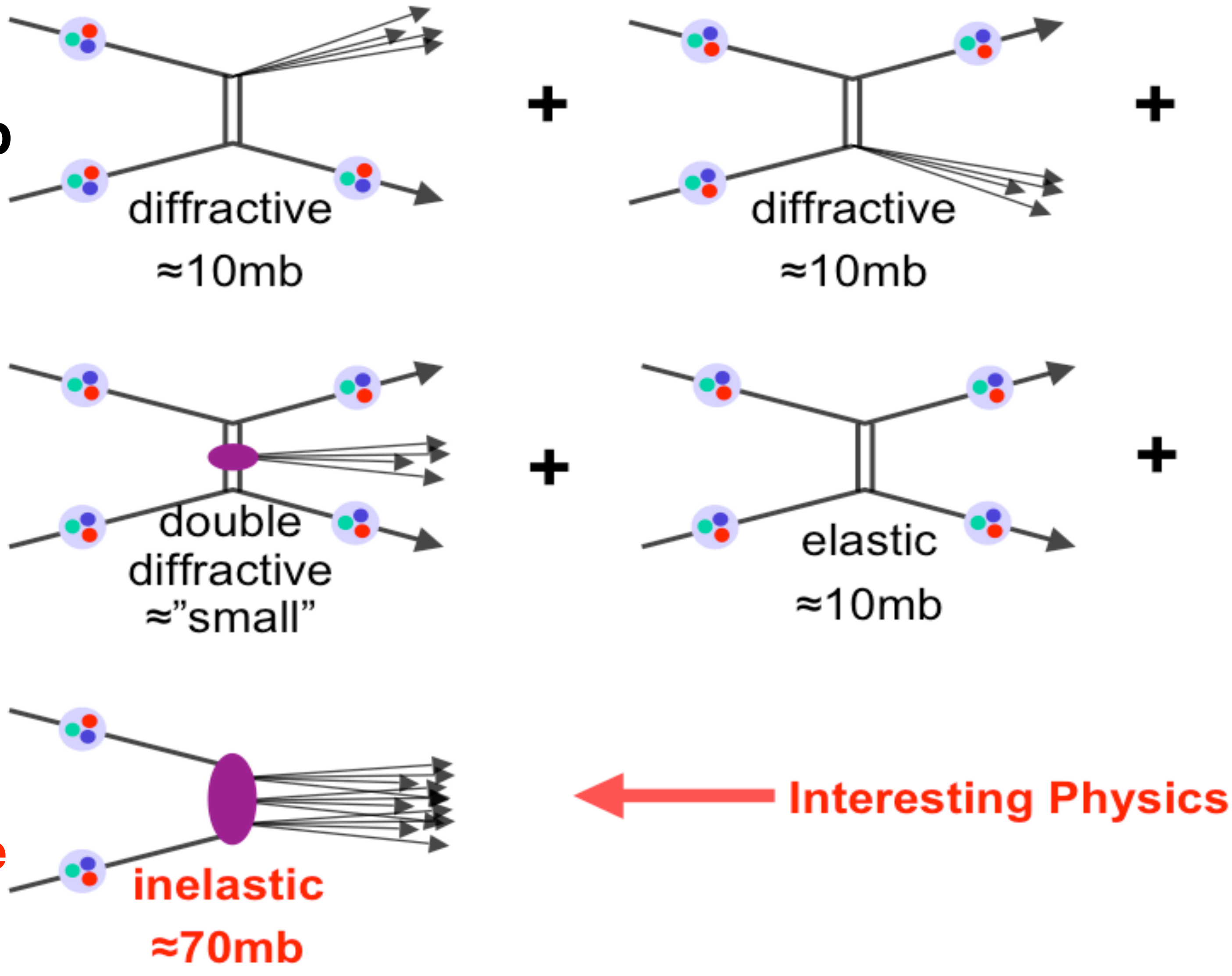
$$N_{\rm events} = \sigma_{\rm process} \cdot \mathcal{L}_{\rm int}$$

Measurements of "soft" processes (low p_T)

- Understand particle production in minimum-bias pp collisions
- Test and improve phenomenological models of non-pert. QCD effects
- Tune parameters of model implementations in Monte Carlo generators
- Understand the underlying event, tune parameters

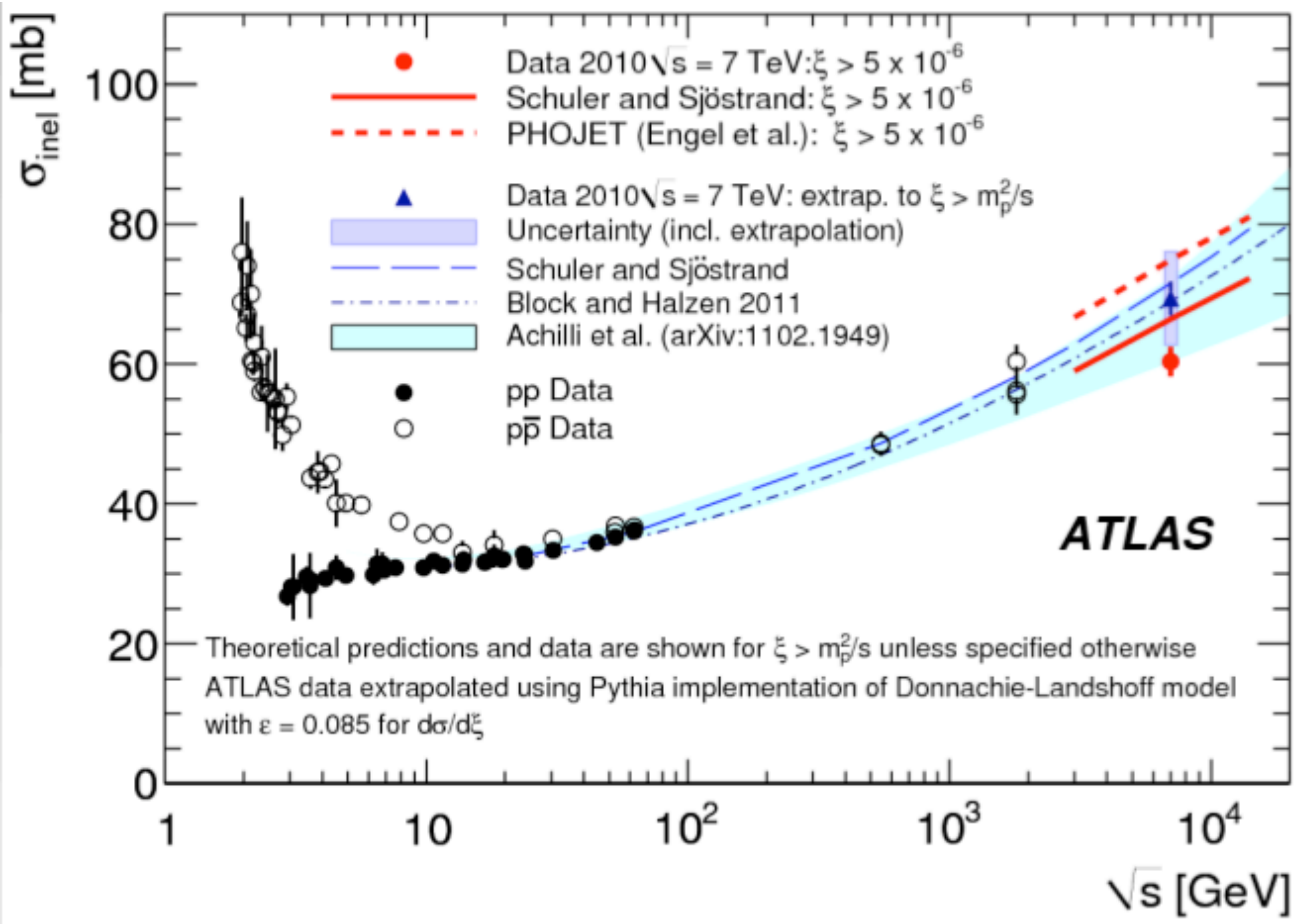
pp-interactions at the LHC

σ_{tot} ~100mb



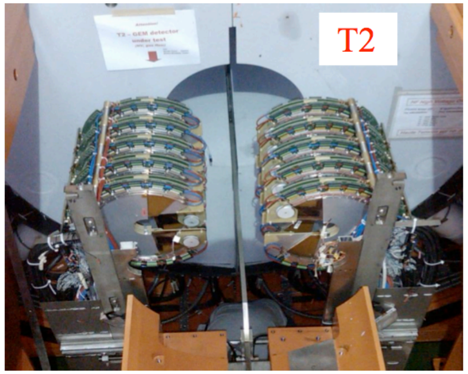
non-diffractive

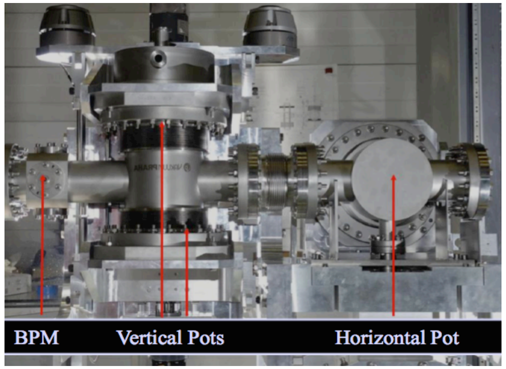
Total Inelastic Cross Section

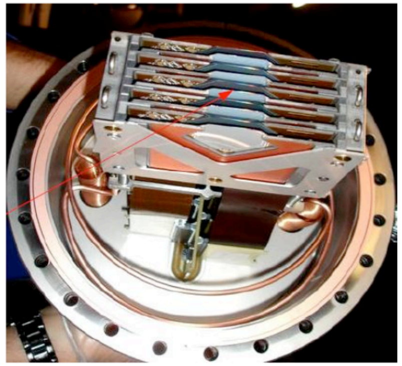


The full inelastic cross section is extrapolated to be **69.1±2.4(expt)±6.9(extr) mb.**
Data agree with most analytic calculations, lower than Phojet.

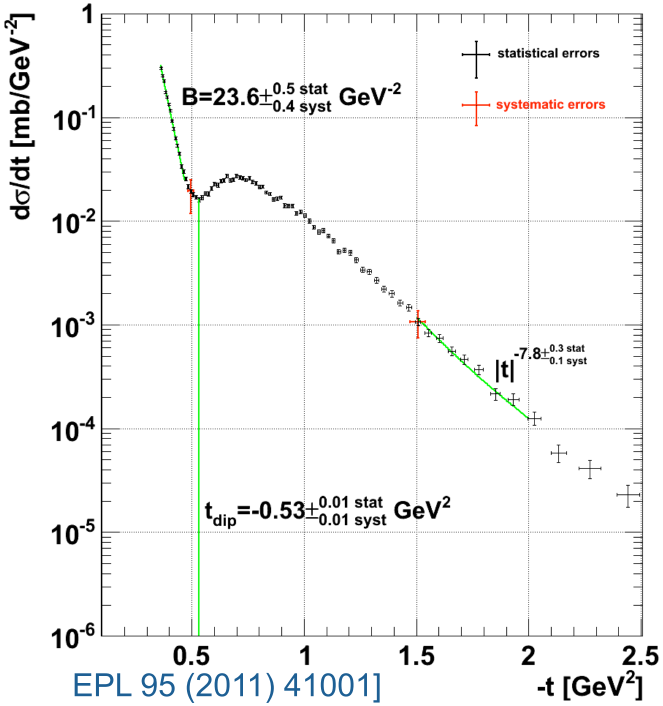
Totem $\sigma_{elastic}$ and σ_{tot}







pp elastic differential cross-section



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Elastic exponential slope:

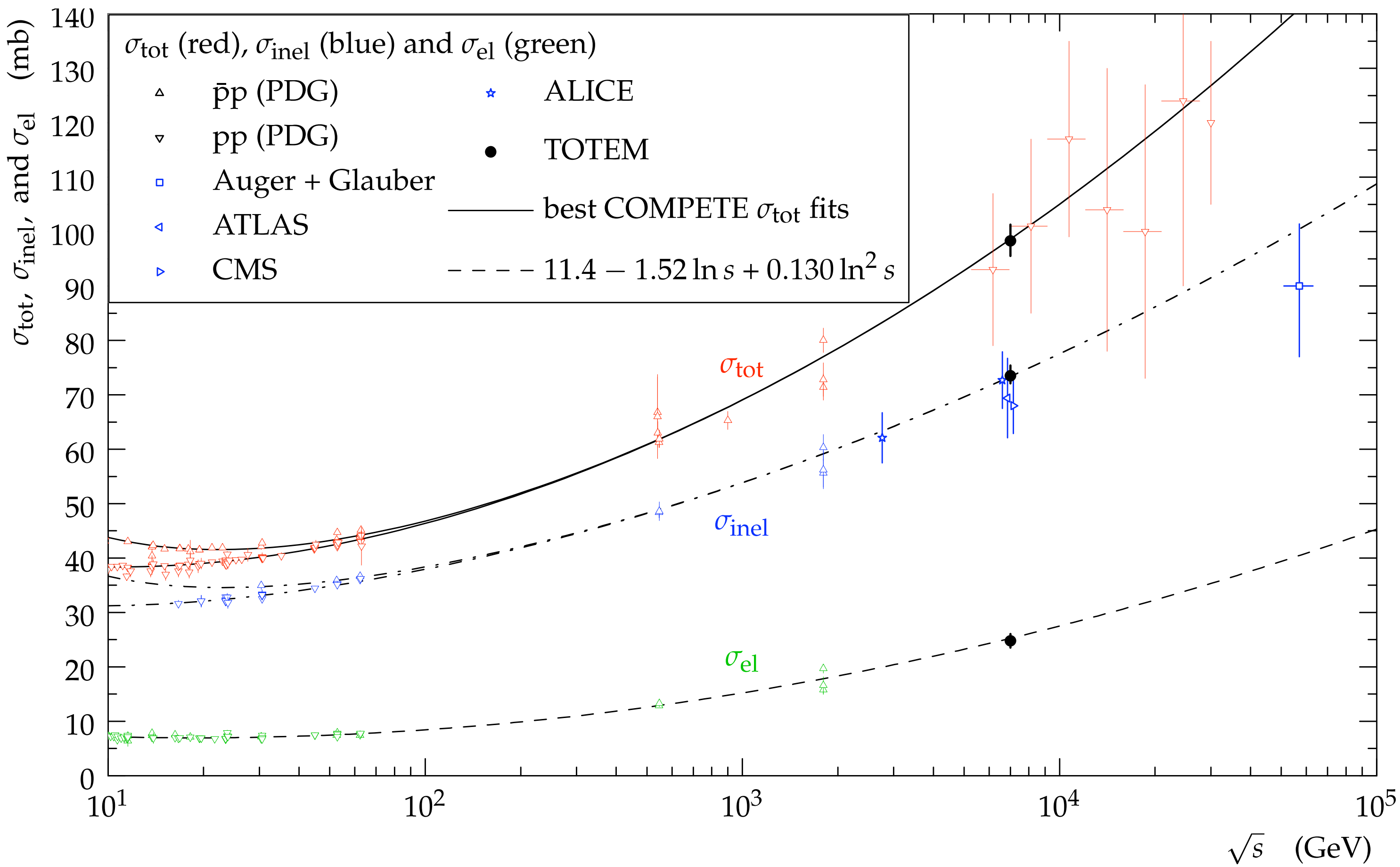
$$B\big|_{t=0} = (20.1 \pm 0.2^{(stat)} \pm 0.3^{(syst)})\ \mathrm{GeV}^{-2}$$

Elastic diff. cross-section at optical point :

$$\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = (503.7 \pm 1.5^{(stat)} \pm 26.7^{(syst)})\mathrm{mb} / \mathrm{GeV}^2$$

Optical Theorem, $\sigma^2_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{1}{L} \left(\frac{dN_{el}}{dt}\right)_{t=0}$ $\rho = 0.14^{+0.01}_{-0.08}$

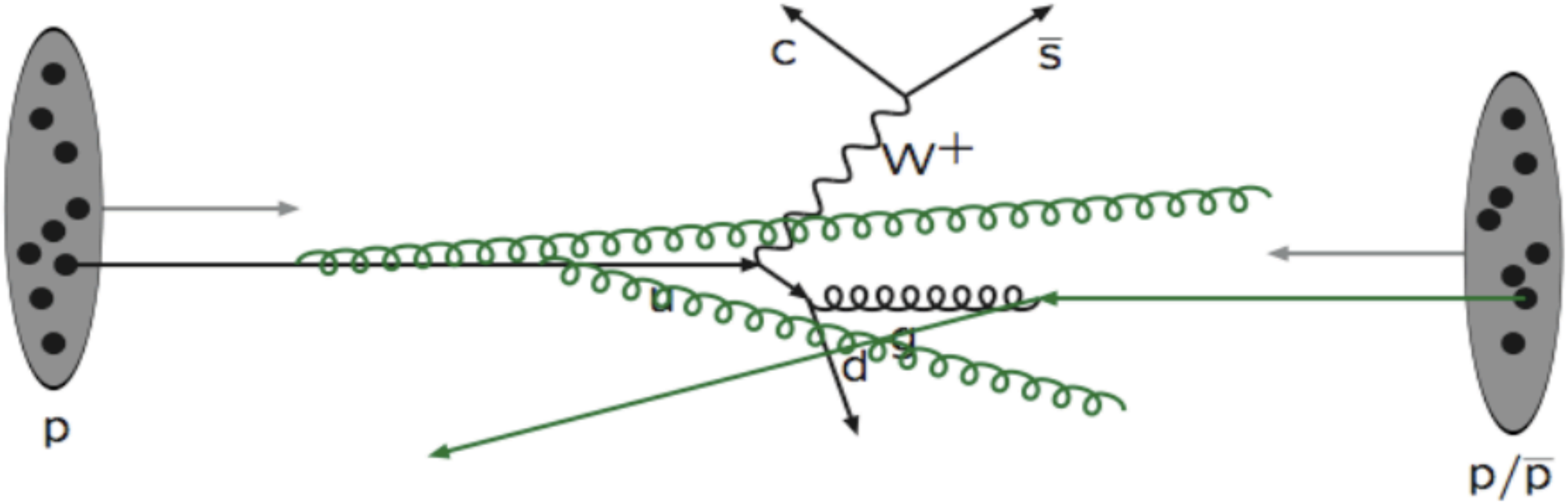
Totem $\sigma_{elastic}$, $\sigma_{inelastic}$ and σ_{tot}



EPL 96 (2011) 21002

$$\sigma_T = \left(98.3 \pm 0.2^{(\text{stat})} \pm 2.7^{(\text{syst})} \left[\begin{matrix}+0.8\\-0.2\end{matrix}\right]^{(\text{syst from }\rho)}\right) \text{mb}$$

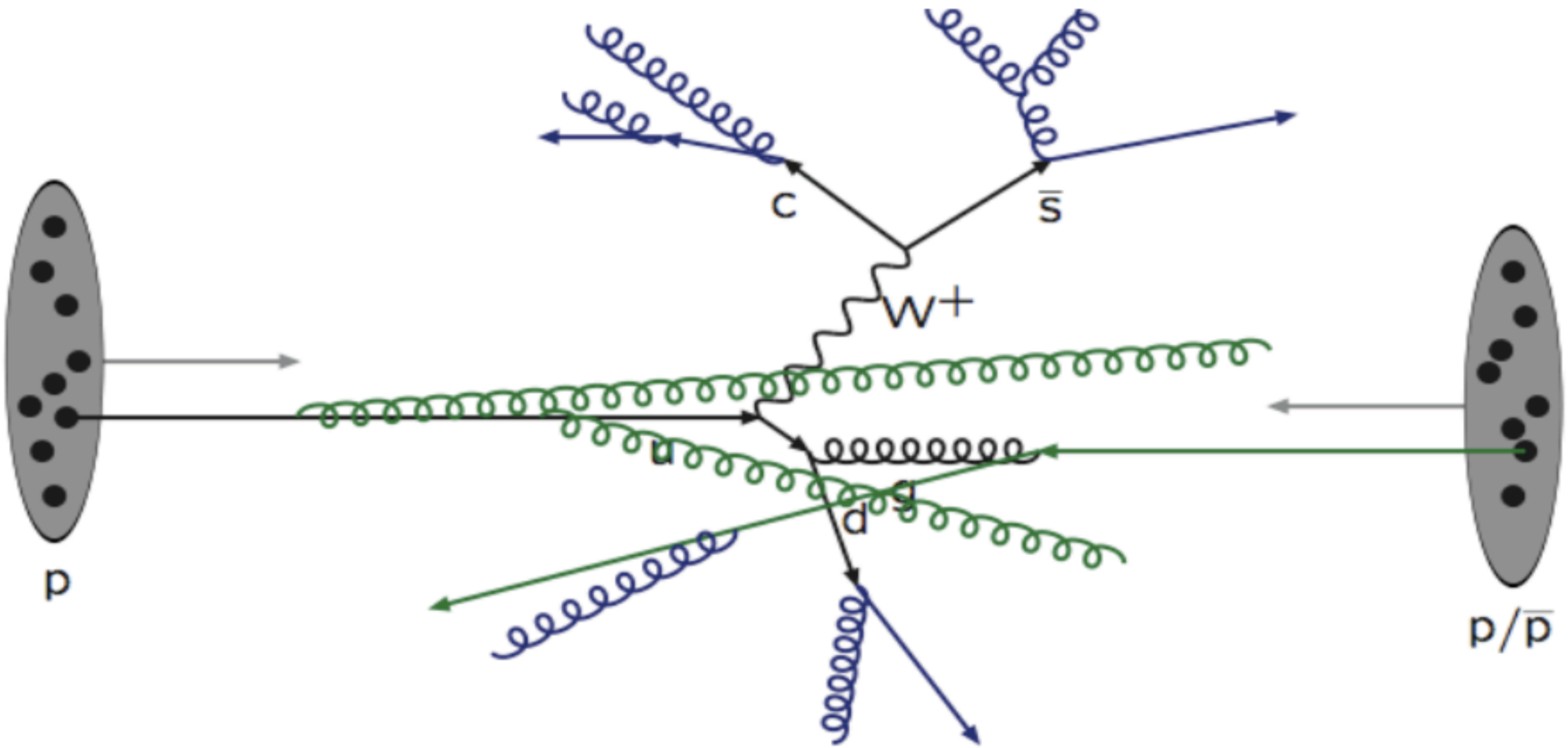
The structure of an event: ISR



One shower initiator parton from each beam may start off a sequence of branchings, such as q → qg, which build up an initial-state shower.

Initial state radiation: spacelike parton shower

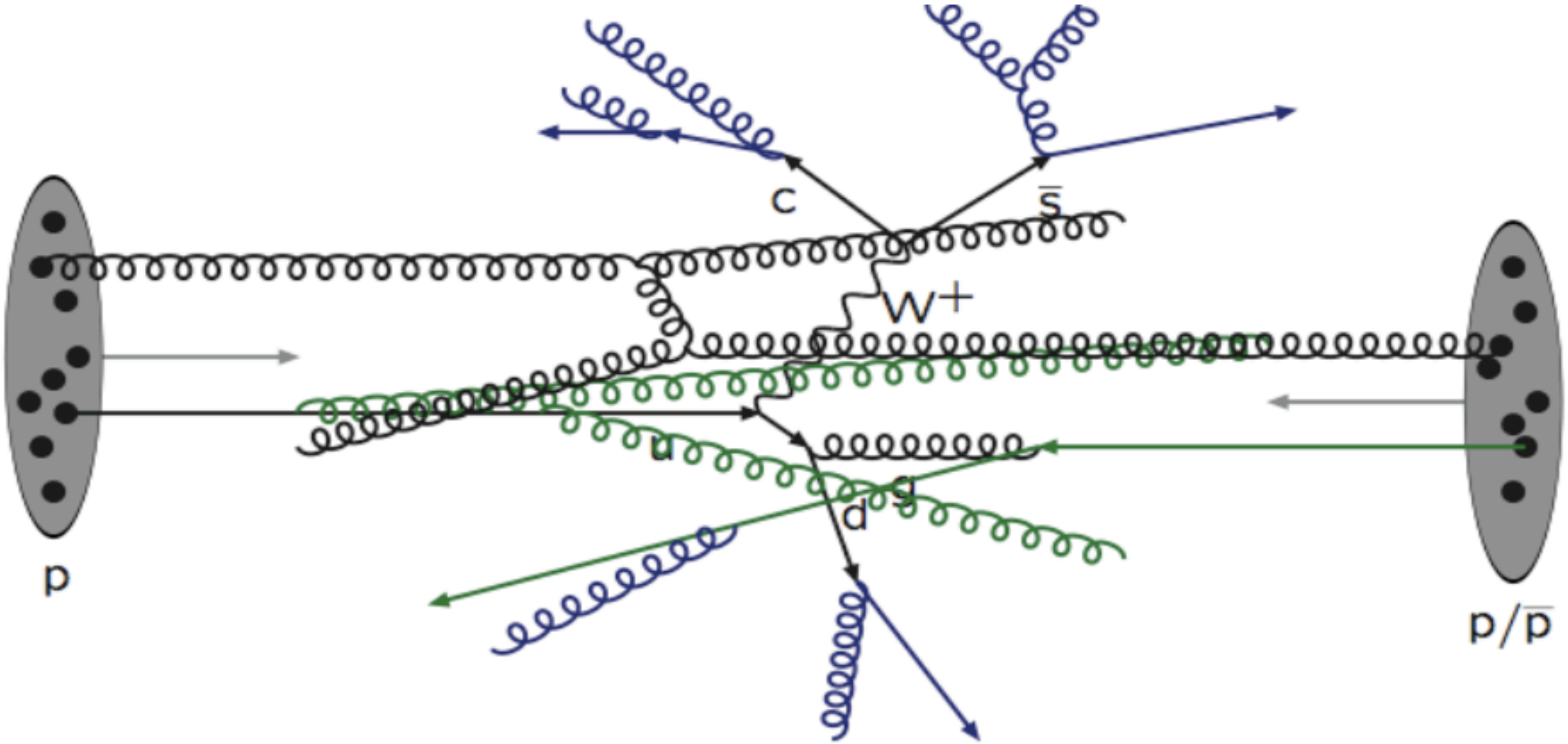
The structure of an event: FSR



The outgoing partons may branch, just like the incoming did, to build up final-state showers.

Final state radiation: timelike parton showers

The structure of an event: Pile up

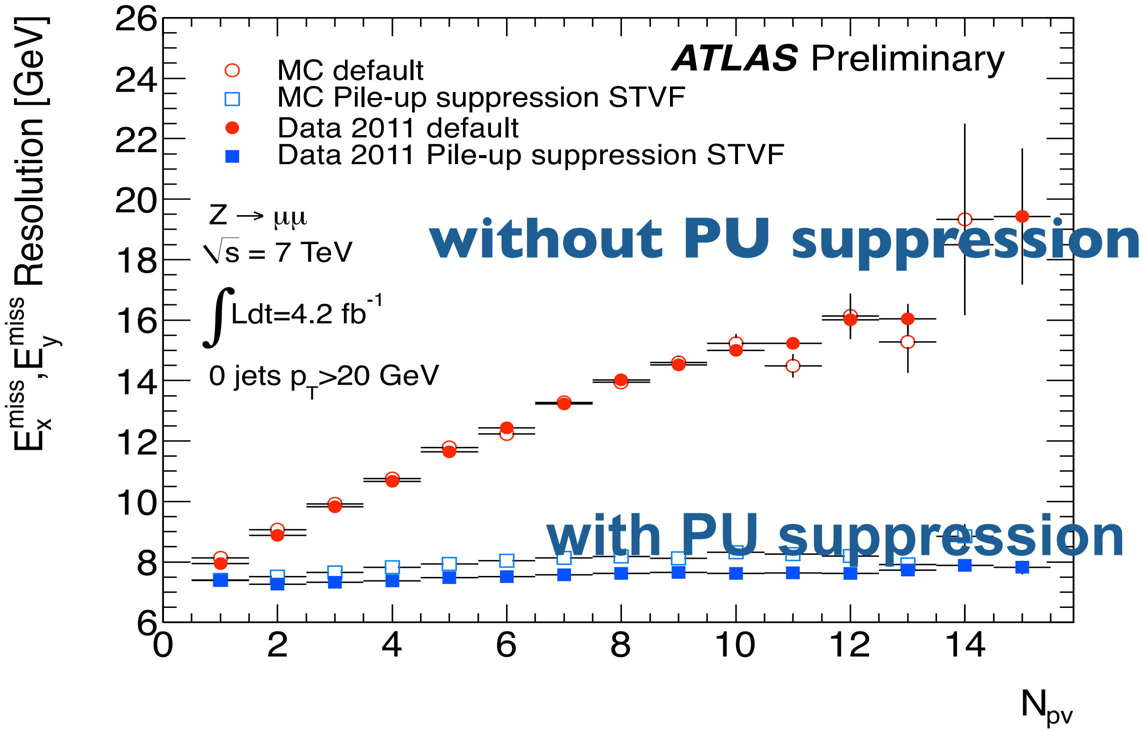


In addition to the hard process considered above, further semi-hard interactions may occur between the other partons of two incoming hadrons.

Challenge Pile up: example E_T^{miss}

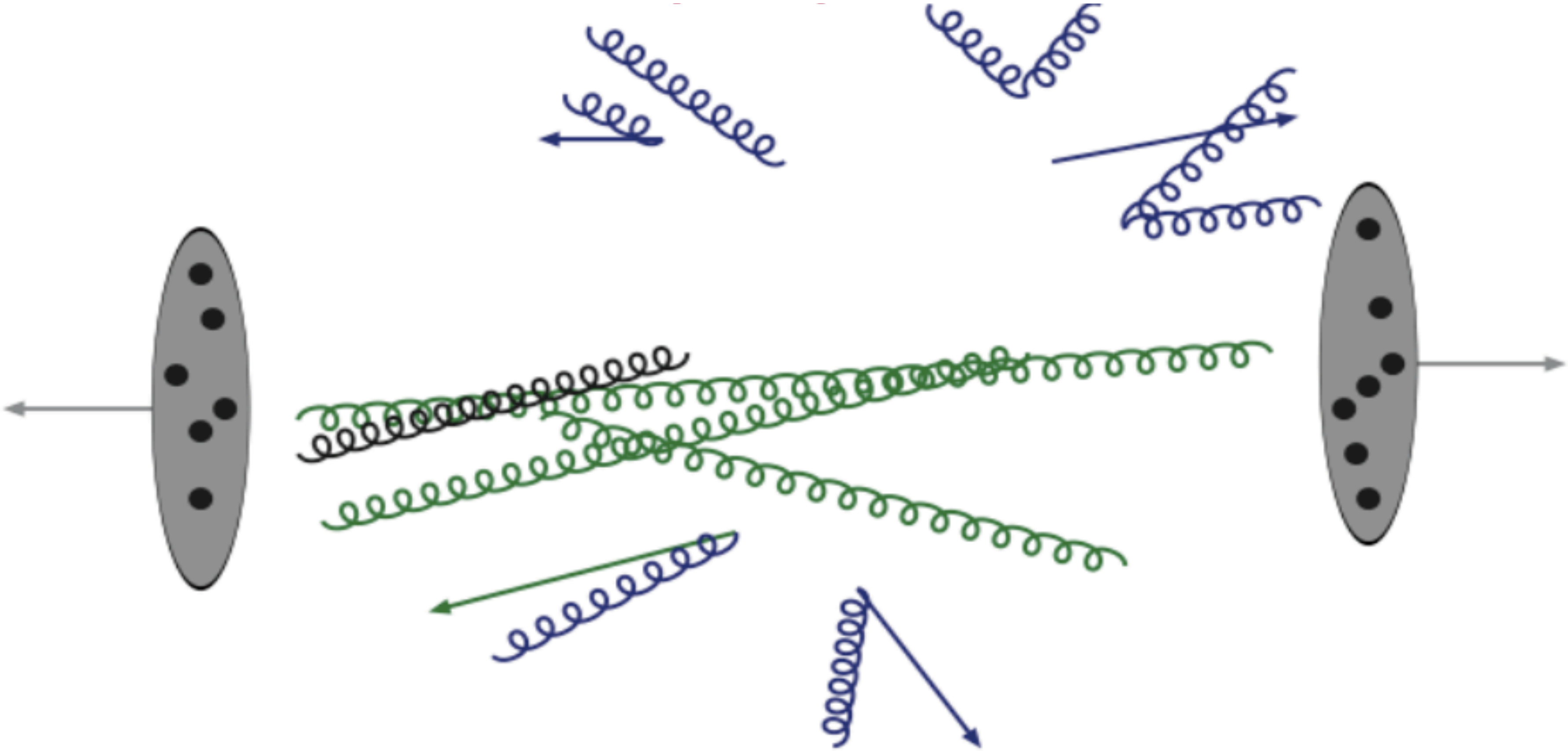
Important for quantities, affected by soft hadrons, for example;

$E_T^{miss} = -| \Sigma \mathbf{p}T |$



- Strict requirements on track vertexing
- Number of reconstructed vertices proportional to the pile-up
- Measure pile-up density event by event: Use it to subtract from the jets energy a pile-up term. do the same with isolation cones.
- For evaluation of the pile-up given the mismodelling of min bias, have to use data!

Underlying event

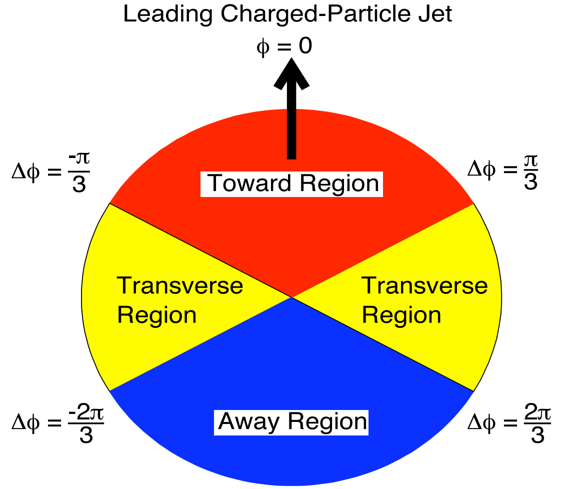


Proton remnants (in most cases coloured!) interact.

The underlying event consists of low p_T objects superimposed to the hard scattering products.

Underlying Event

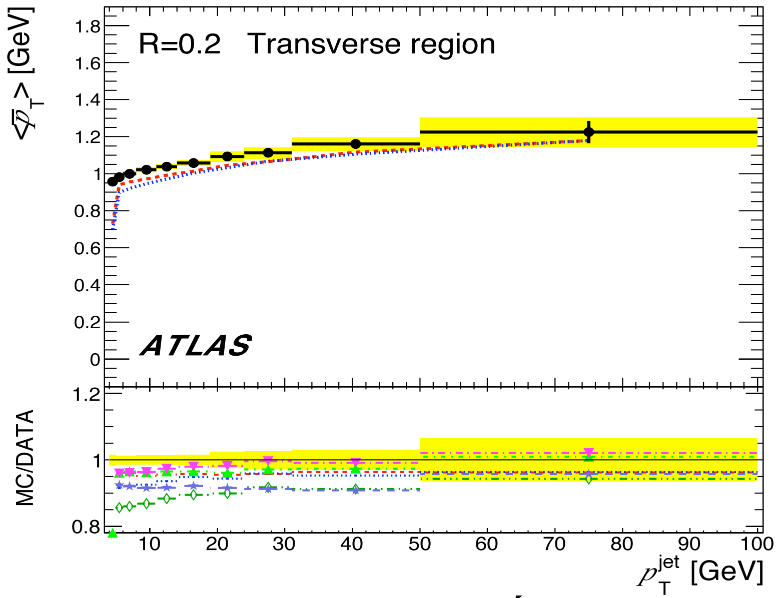
- Studying underlying event is crucial for understanding high p_T SM events at LHC.
- ingredient for many analyses. In fact they affect: the jet reconstructions and lepton isolation, jet tagging etc..



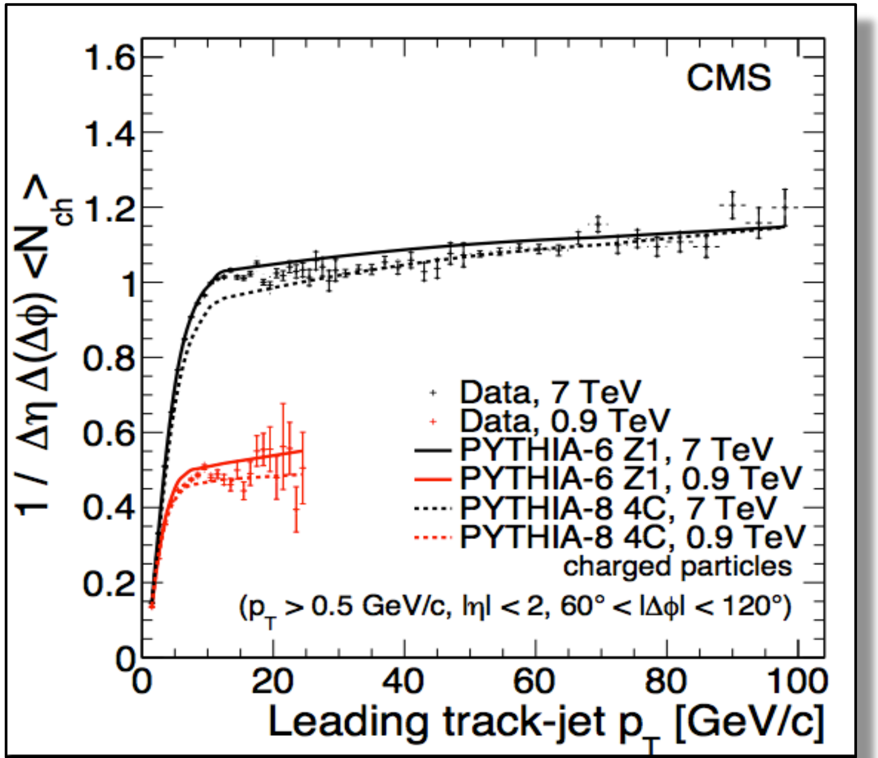
- One can look at charged track multiplicities

N_{ch} in transverse regions which are little affected by the high p_T objects.

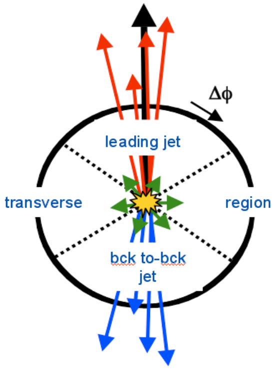
- Reasonably described by models



Underlying event



CMS JHEP 09 (2011) 109



Particle Production in the transverse region

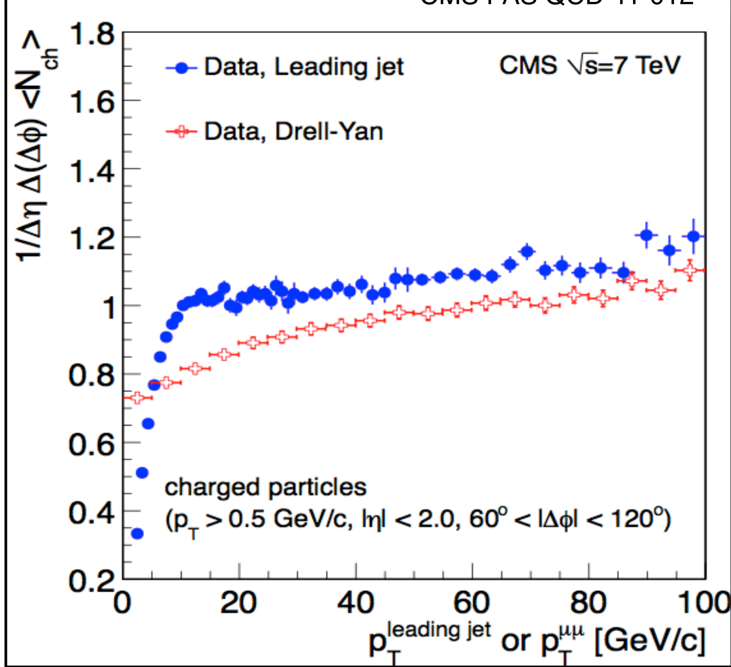
Remarks / Issues

•again, found that most/all of the pre-LHC tunes failed to give good description for the whole phase space

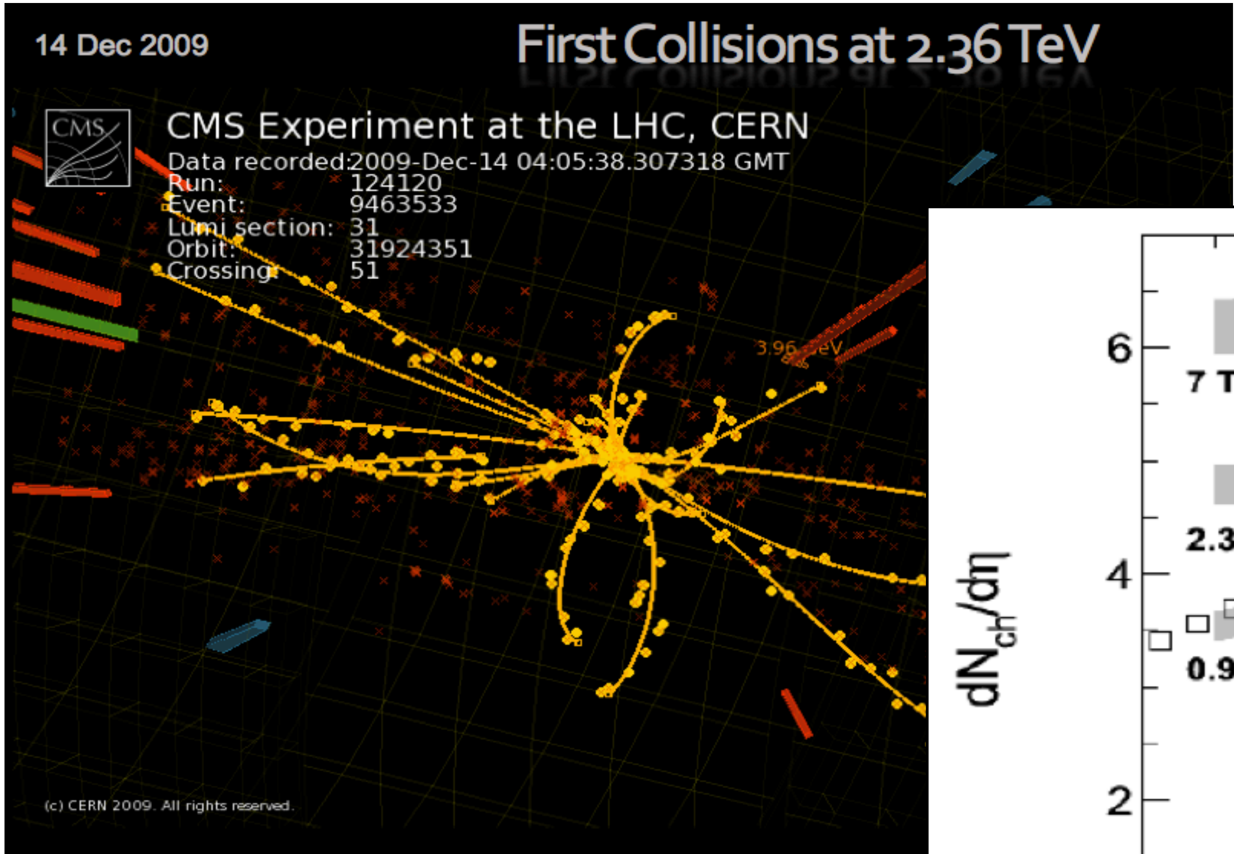
•generally, stronger particle production in transverse region observed than expected

•special LHC tunes obtained, now used for the big MC productions

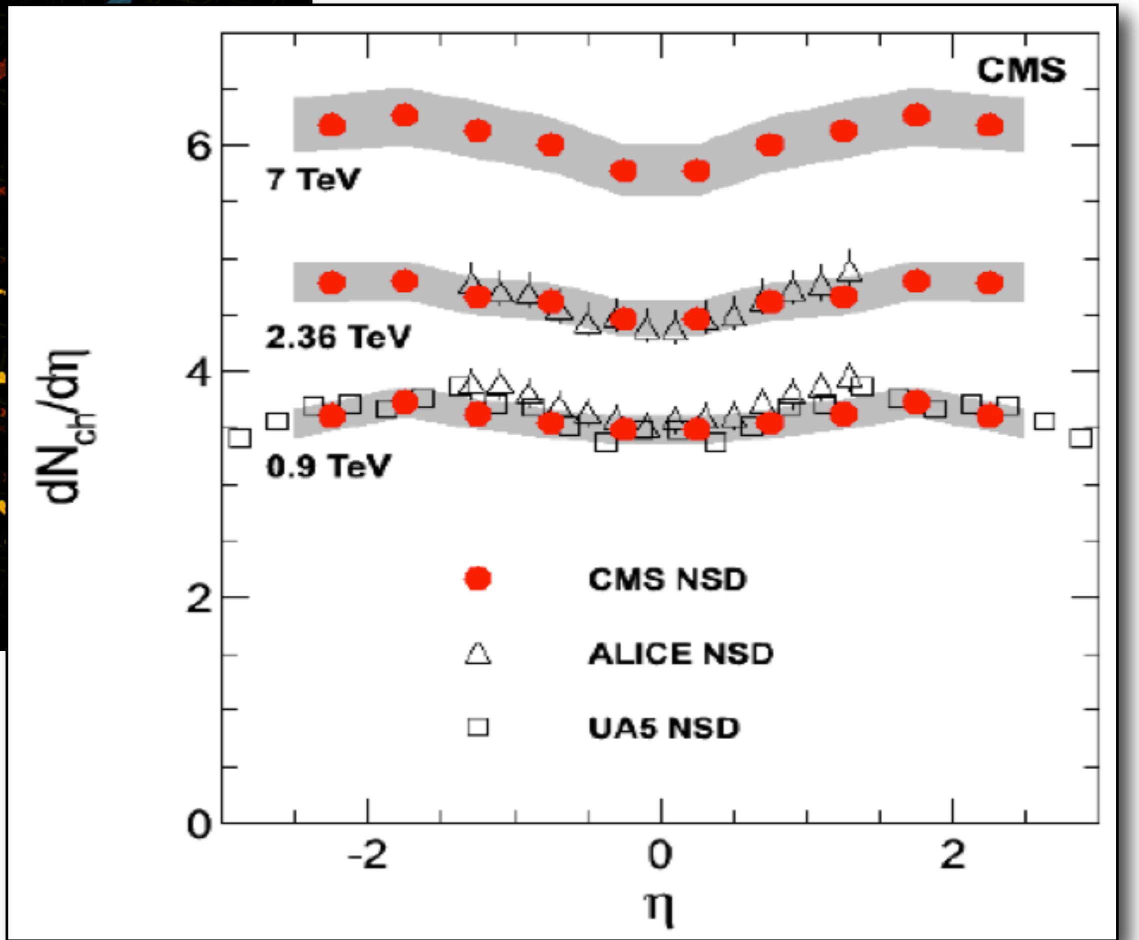
CMS PAS QCD-11-012



Minimum bias events.



- first publications by LHC experiments !

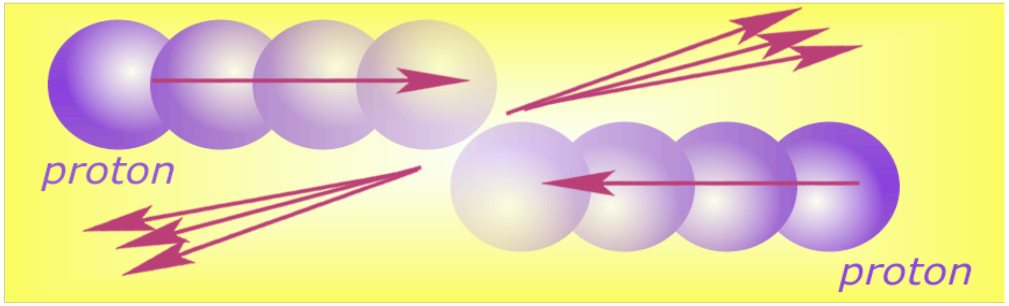


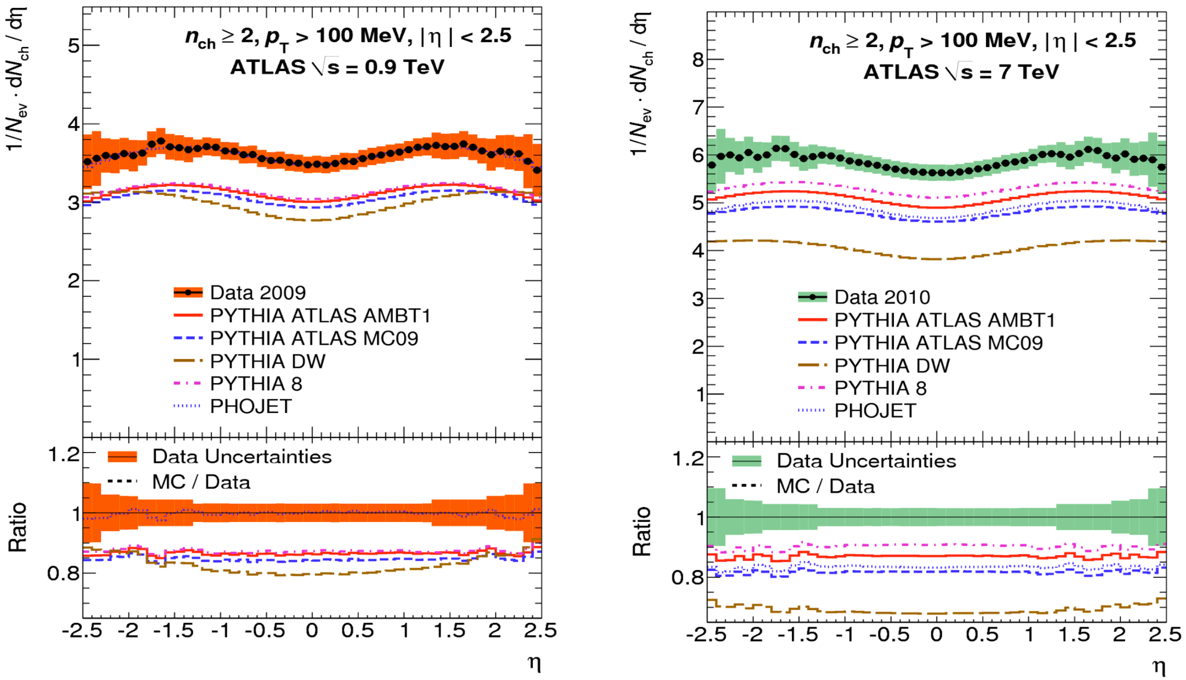
CMS PRL 105, 022002 (2010)

- dN/dη at 0.9, 2.36 and 7 TeV
  - correction for NSD (~6% corr. →2.5% syst)

Minimum bias events

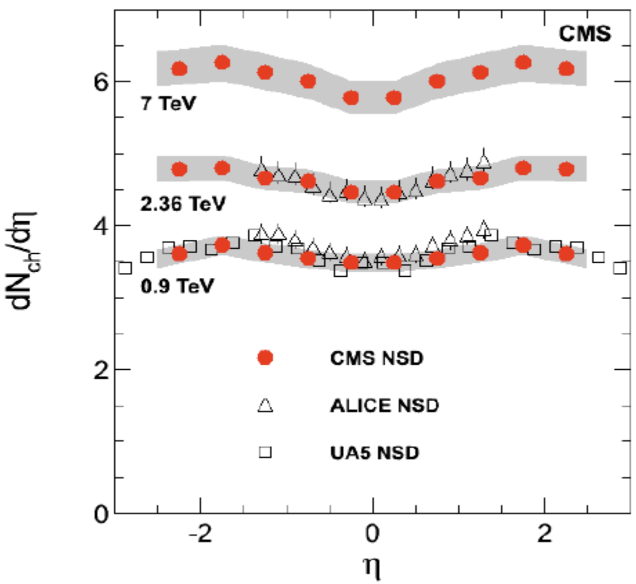
- Non head-on collisions, with only low p_T objects. Those are the majority of the events in which there is a small momentum transfer
  $$\Delta p \sim h/\Delta x$$
- Distributed uniformly in **η**: $dN/d\eta = 6$
- On average the charged particles in the final state have a p_T~500 MeV

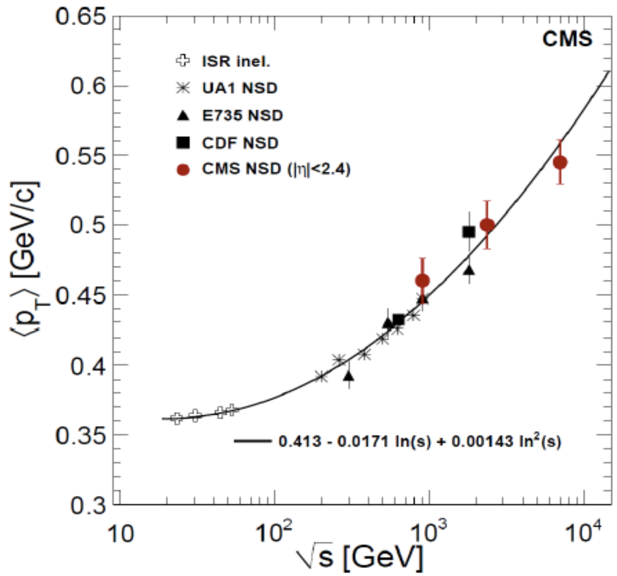


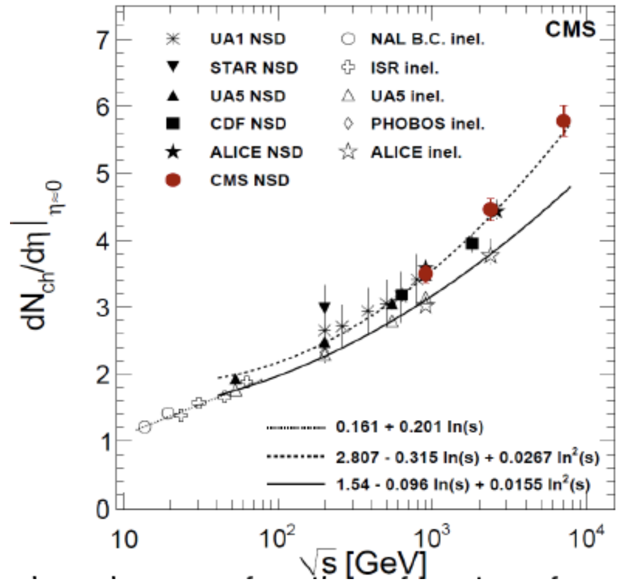


Not well described by models!
Shape is sort of OK
Normalisation is off

Minimum bias and soft QCD





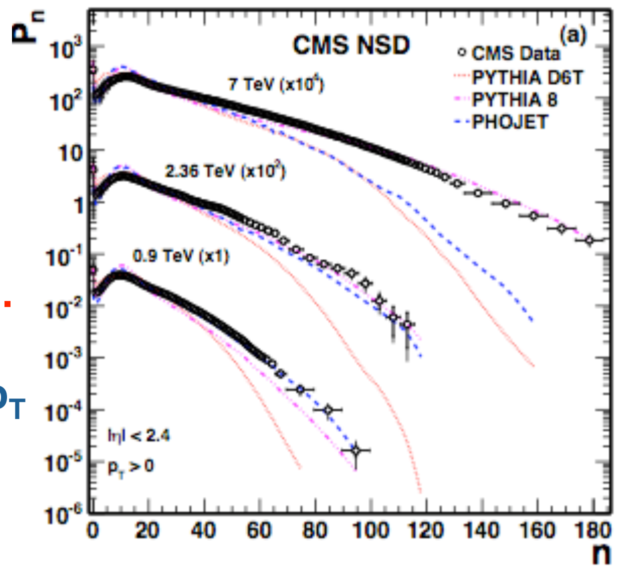


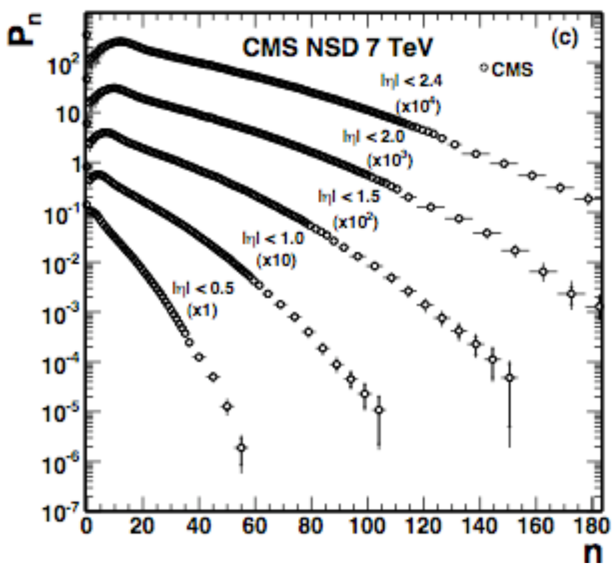
Measurements at 0.9, 2.36 and 7TeV.
Careful check of the scaling of particle multiplicity and <p_T> vs energy.

Rise of the particle density in data stronger than extrapolations from lower energies and model predictions.

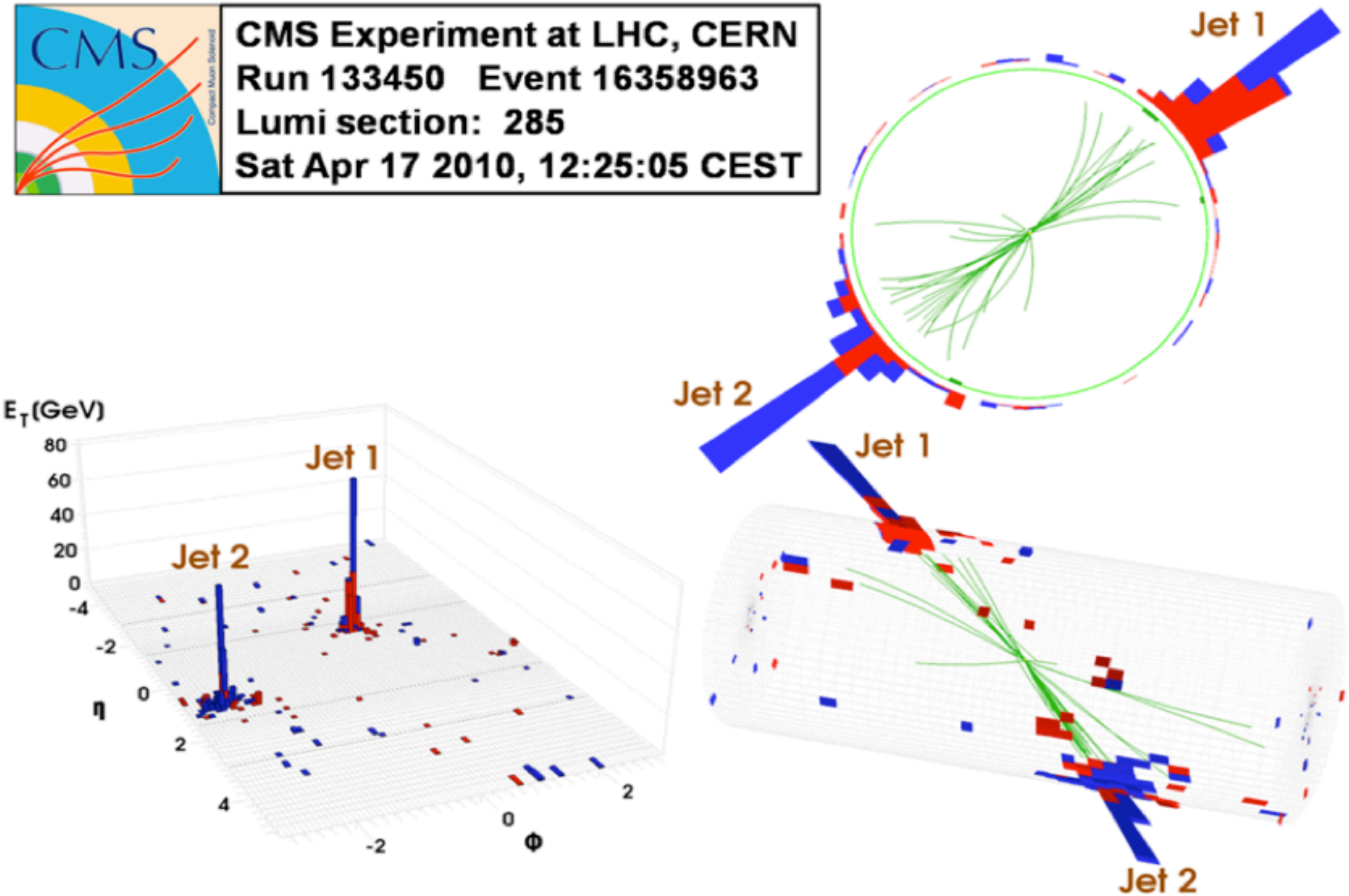
Careful tuning effort of the MC generators. Marginal impact on high p_T physics.

Phys. Rev. Lett. 105 (2010) 032001;
arXiv:1005.329; arXiv:1011.5531;





Jets

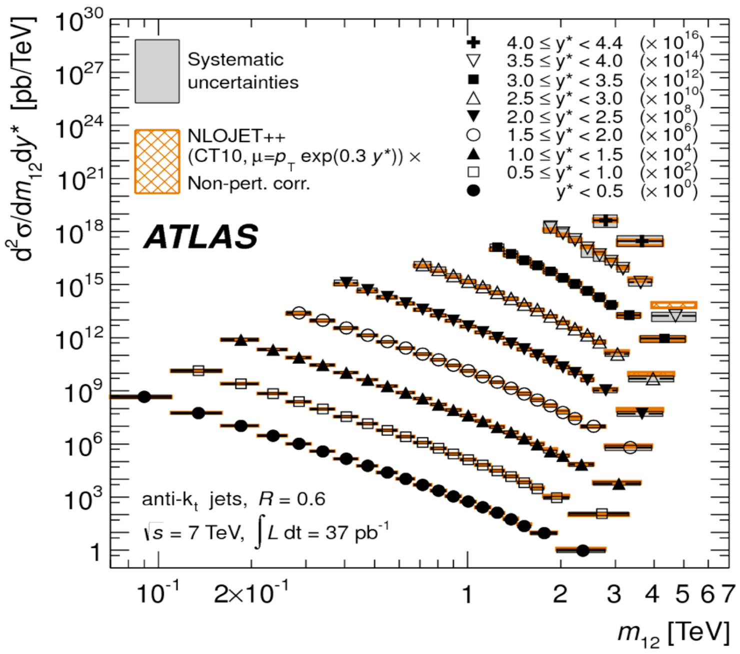

CMS
CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST
Jet 1
Jet 2
E_T(GeV)
80
60
40
20
0
-4
-2
0
2
4
η
-2
0
2
Φ
Jet 2
Jet 1
Jet 1
Jet 2
Jet 1
Jet 2

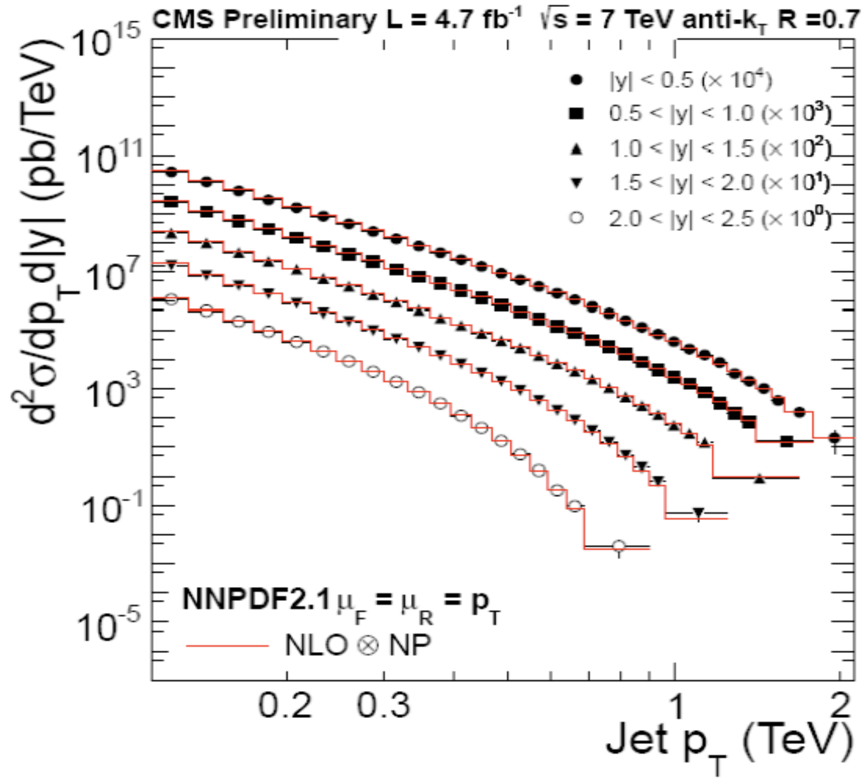
Issues for Jet Observables

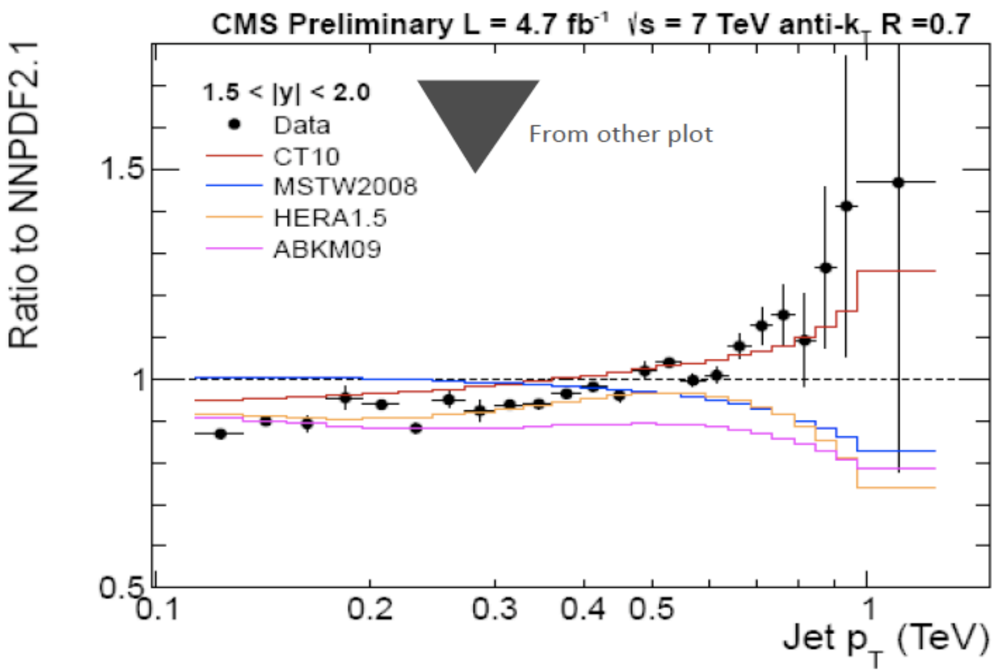
- Jet Triggers and Jet selection
  - turn-on curves, lower p_T-thresholds, matching of samples from different triggers
- Choice of Jet algorithm and jet size
  - use of modern, IR- and collinear safe algorithms
  - standard in CMS: anti-KT, R=0.5, 0.7; standard in ATLAS: anti-KT, R=0.4, 0.7.
- Jet Energy Scale
  - absolute and relative (as function of rapidity)
  - jet cross section falls like power law, power =5 - 6
  - fantastic progress made so far, already better than 3%, hoping to achieve 1%
- Jet Energy resolution
  - smearing of distributions
- Comparison with theory at the “hadron (or particle) level” : correction of pQCD prediction for non-pert. effects
- Often “ratio” observables used to reduce dependence on jet energy scale: di-jet ratio, angular (de-)correlations, event shapes, n-jet ratios, jet shapes, ...

Jet production

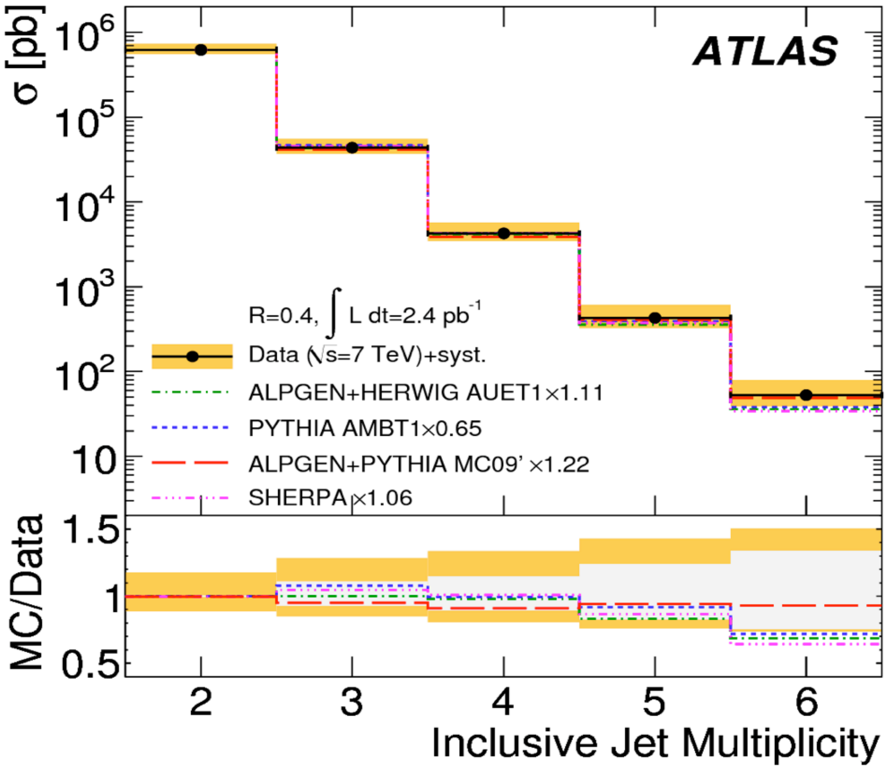
- NLO QCD works over ~9 orders of magnitude!
- Excellent exp. progress: jet energy scale uncertainties at the 1-2% level
- For central rapidities: similar exp. and theo. uncertainties, 5 - 10%
- Inclusive jet data : starts to be important tool for constraining PDFs, eg.also by using ratios at different c.o.m. energies

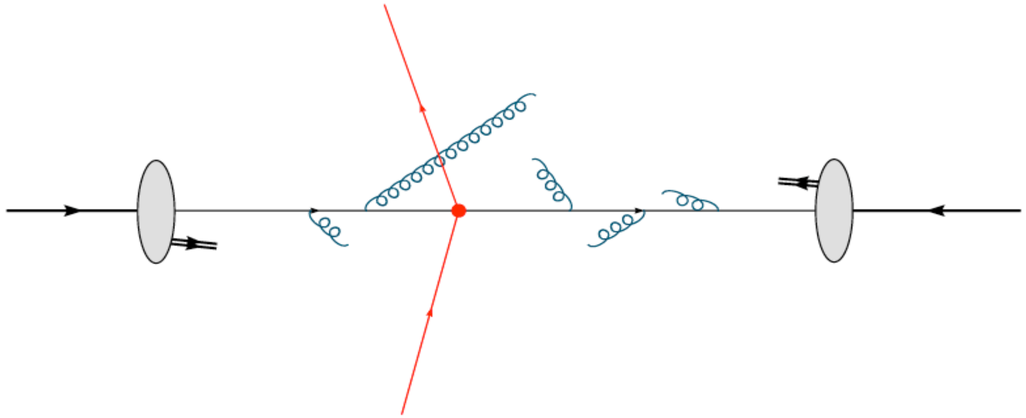






Jet multiplicity



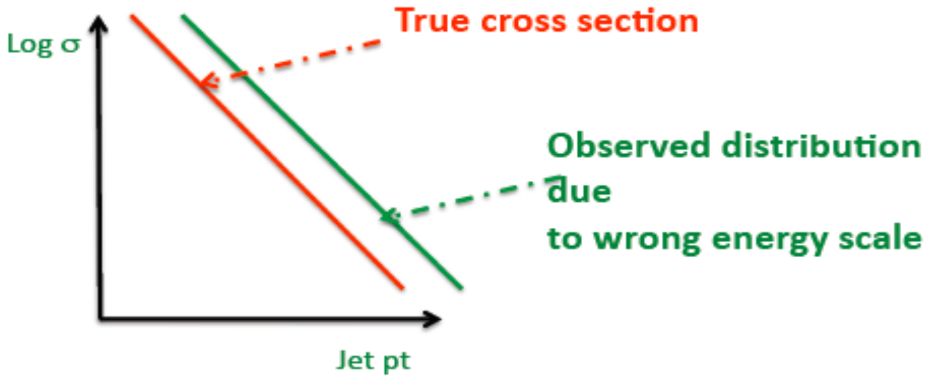


- Another possible test of QCD is obtained by checking the jet multiplicity
- Tests also the modelling of the radiation

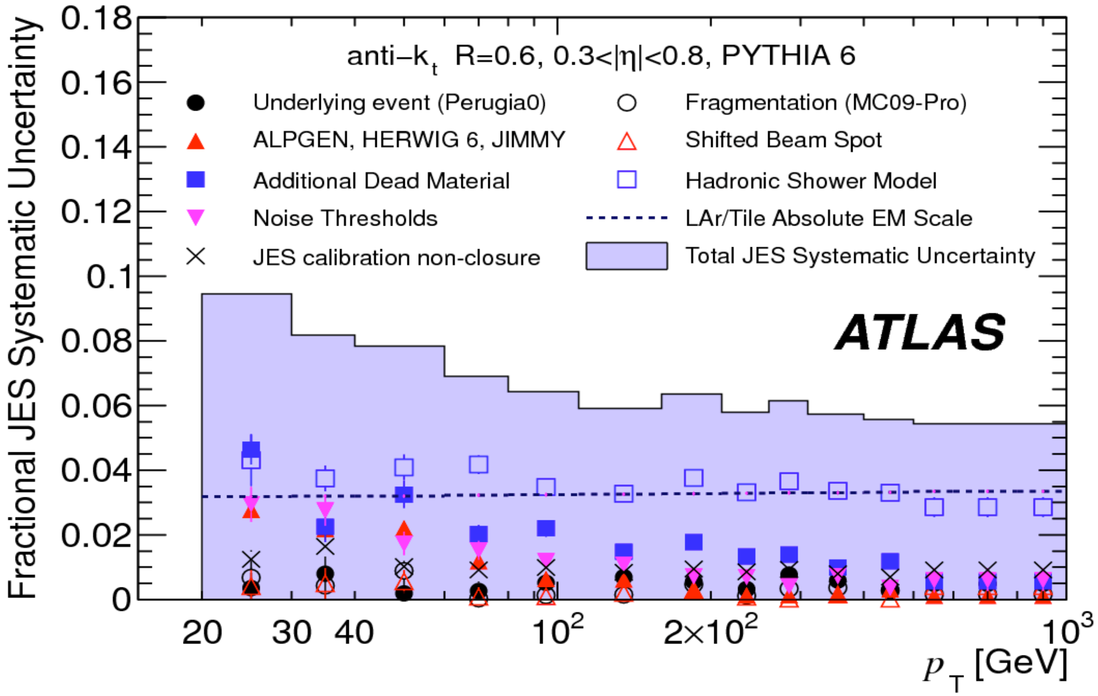
Jet physics: jet energy scale

- Before looking at jet physics be aware!

first of all when we have steeply falling cross sections-> we have a sensitivity of its measurement from the energy scale

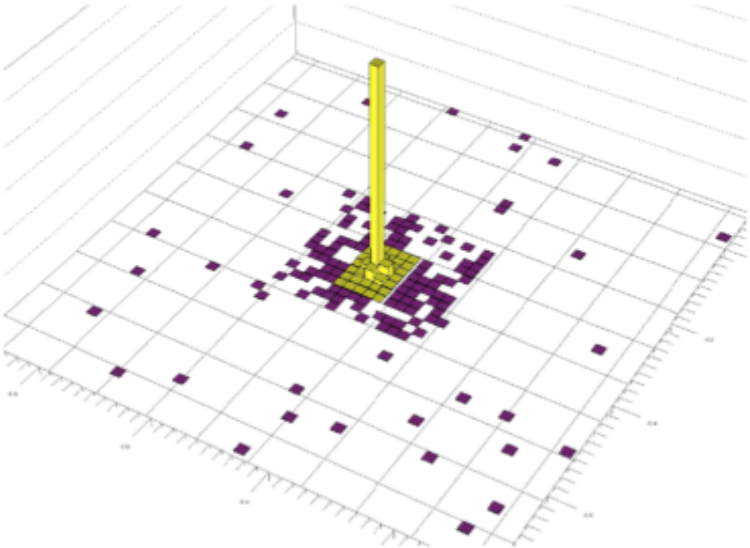


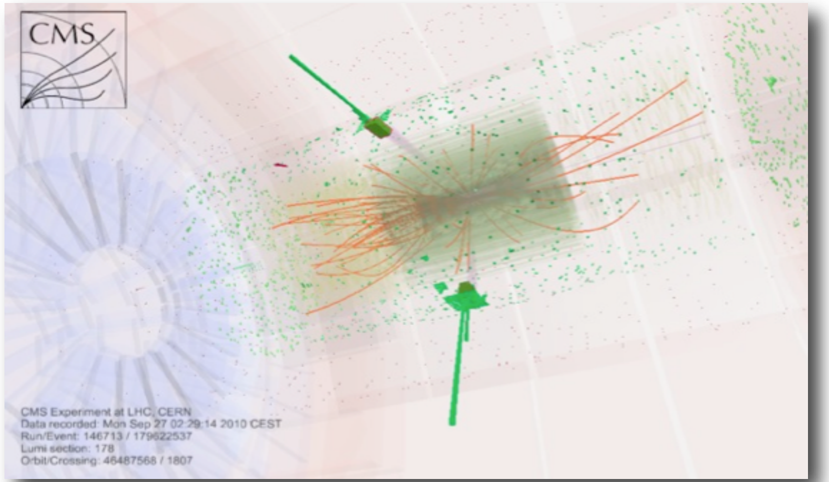
- Jet energy determined from calorimeter (+tracking information)
- Sophisticated calibration procedure



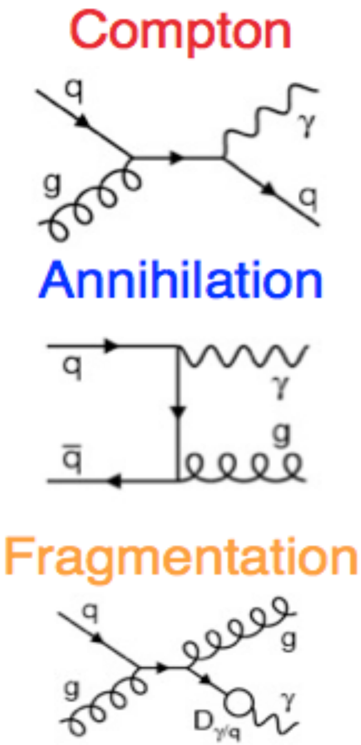
Different contributions to JES error. (jets reconstructed with the Anti-kT algorithm cone 0.6 that is used in ATLAS)

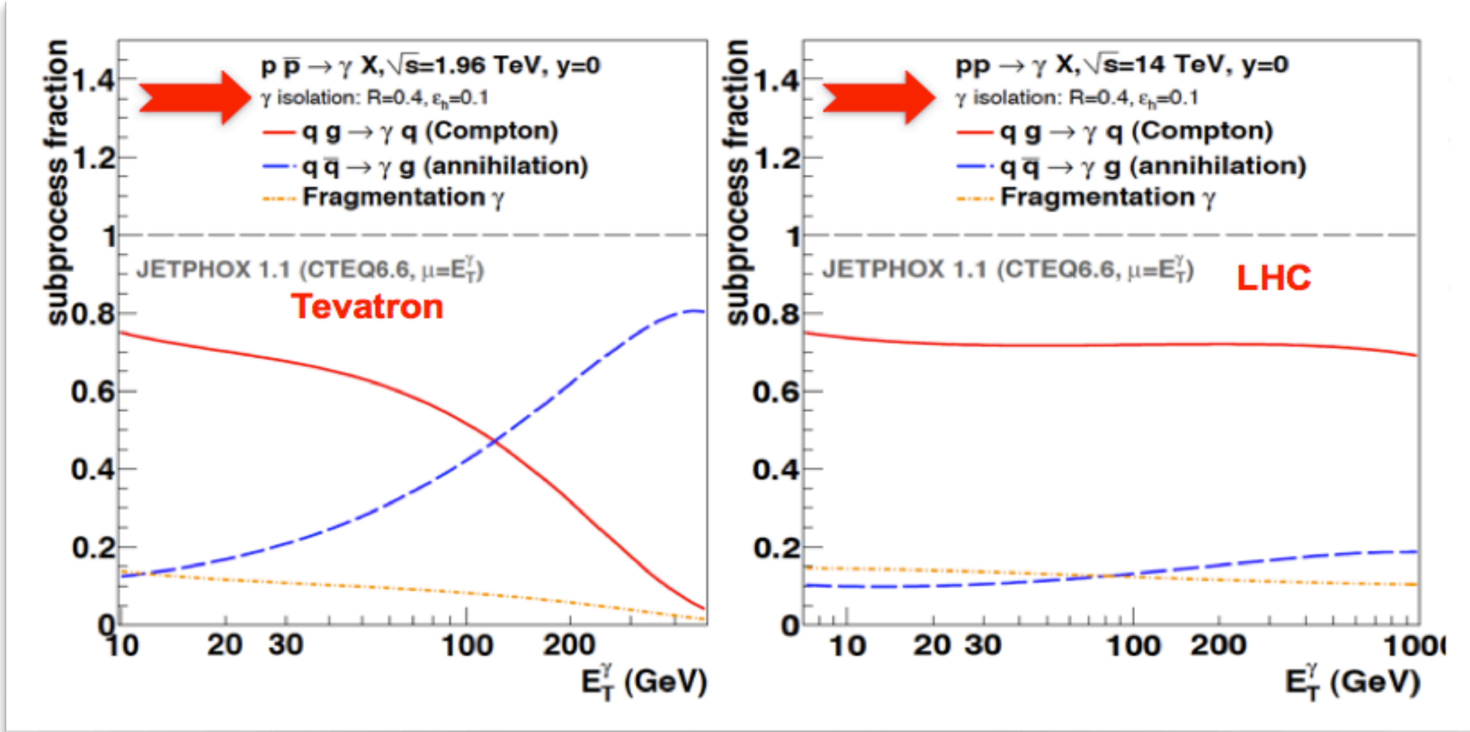
Production of Photons





Direct Photon Production

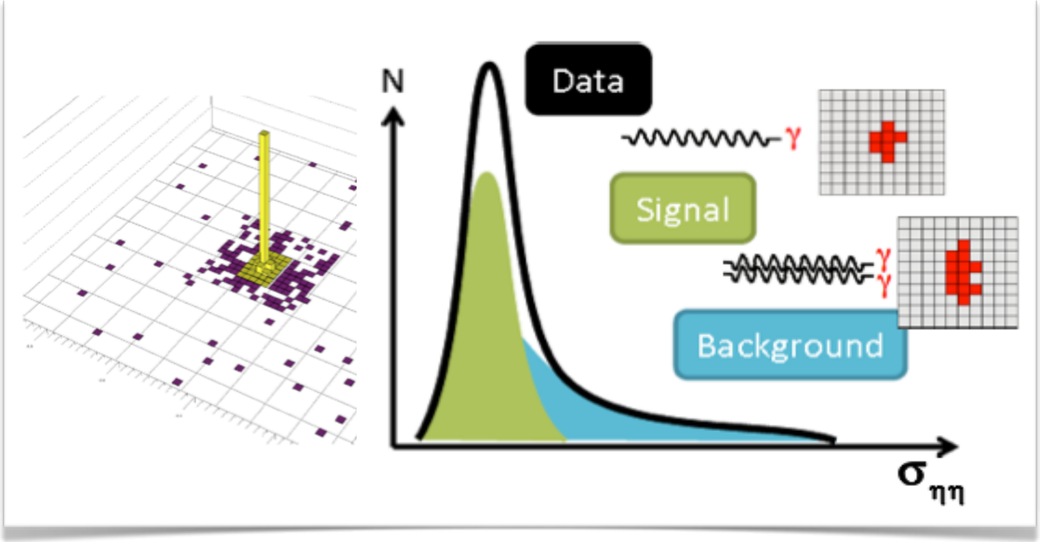




- Important issue
  - fragmentation contribution
  - can be strongly suppressed by isolation requirements
  - theoretically most interesting: Frixione isolation, but not exactly implementable in exp. analyses... many studies ongoing

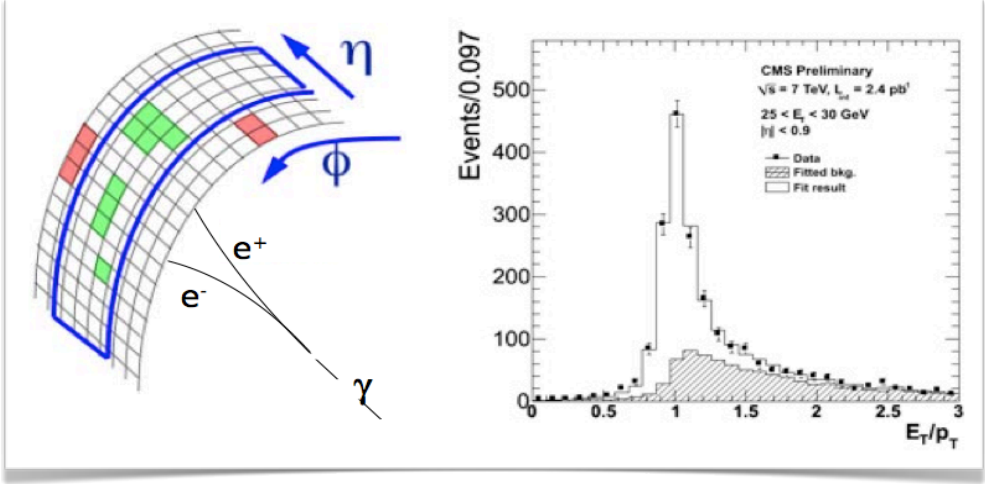
Photon Identification

templates, on isolation or cluster shape variables



powerful at high E_T

Conversions

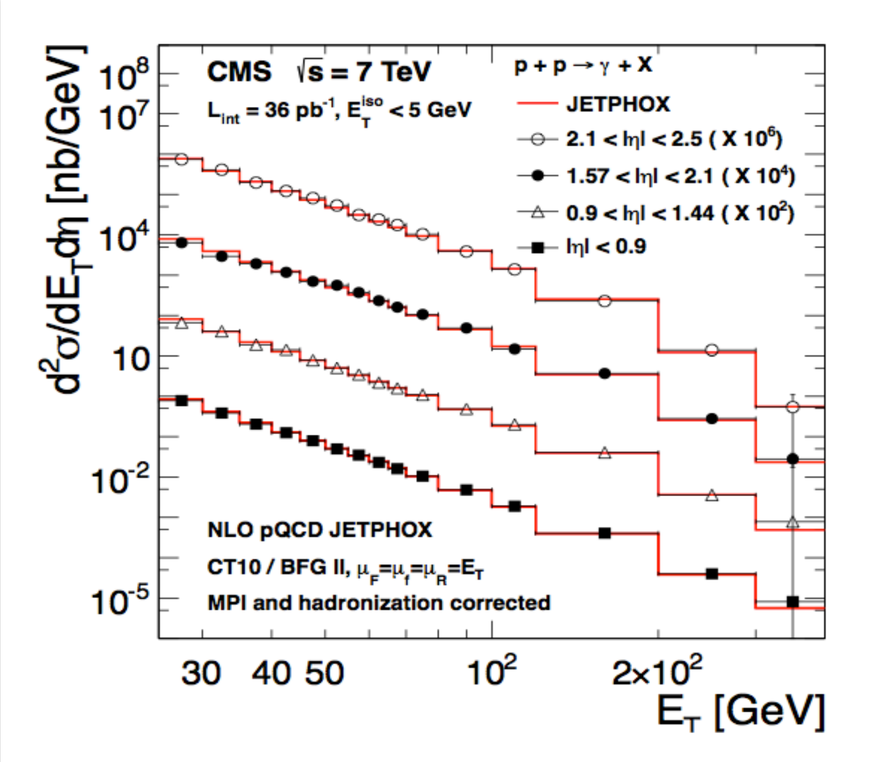


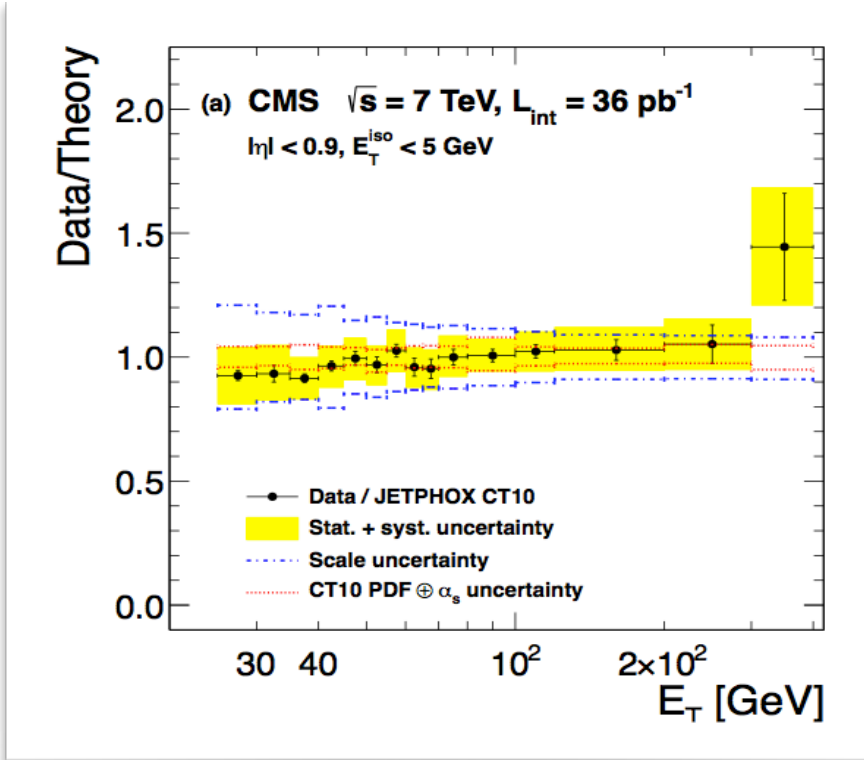
powerful at low E_T

- **Typical efficiencies**: ~100% (trigger), ~85% (reco barrel), ~75% (reco endcap), ~60 – 90% (identification & isolation), Unfolding (bin migrations): ~95%
- **Systematic uncertainties** on the order of 15% or below

Inclusive Production: Results

PRD 84 (2011) 052011

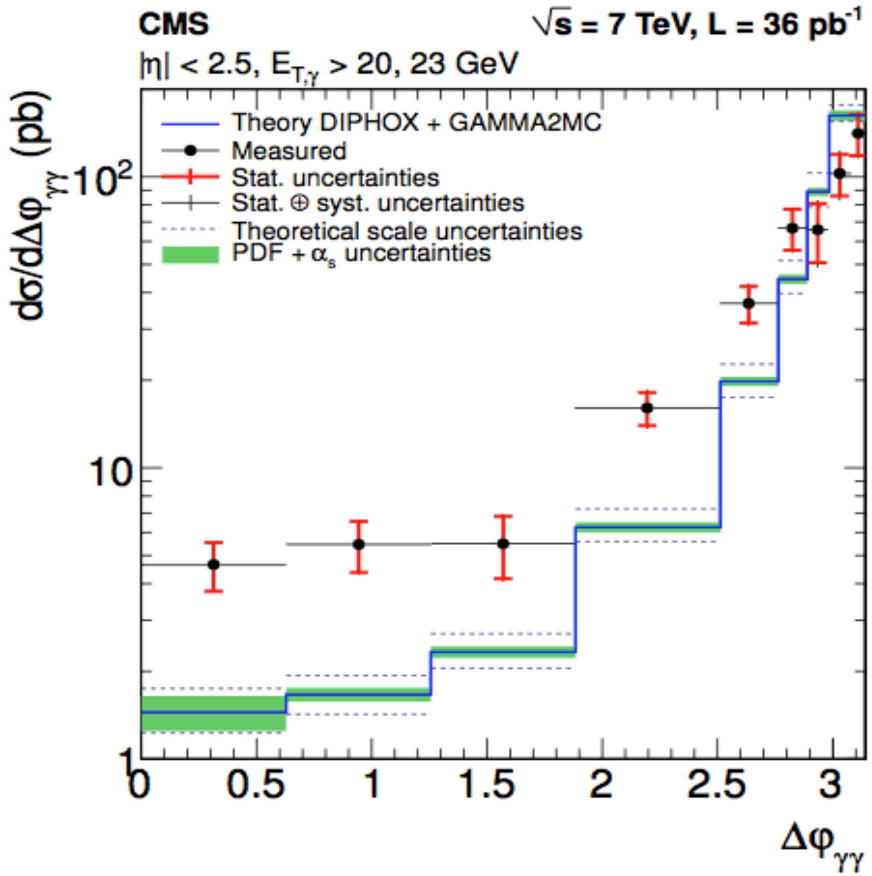




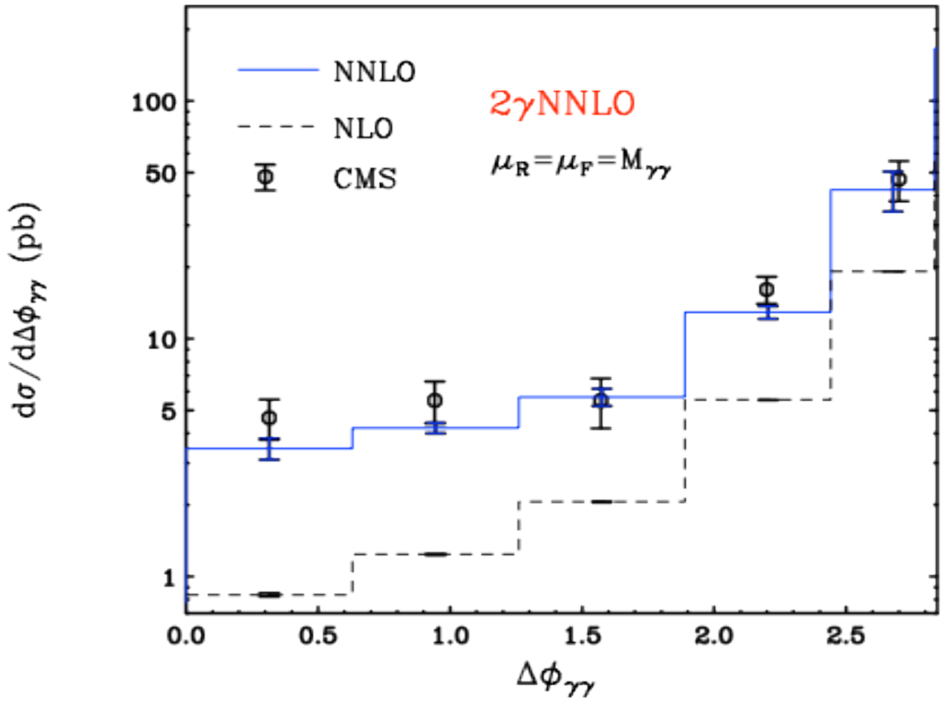
Overall, pretty good agreement with NLO QCD
Slight overprediction at E_T < 50 GeV ?

Di-Photon Production: Results

JHEP 01 (2012) 083



from D. de Florian, M. Grazzini, et al



- **Big discrepancy at small angles???**
  - But note: at very small angles, the NLO calculation is actually a "LO" calculation
  - confirmed by very recent NNLO calculation (see plot on the right)

Conclusion

- Having tuned the basic physics objects and having reached a good understanding of minimum bias and soft QCD events we are ready for the electroweak-physics: W, Z and top.

- Tomorrow's lecture#2.