LHC First Physics Results Expected

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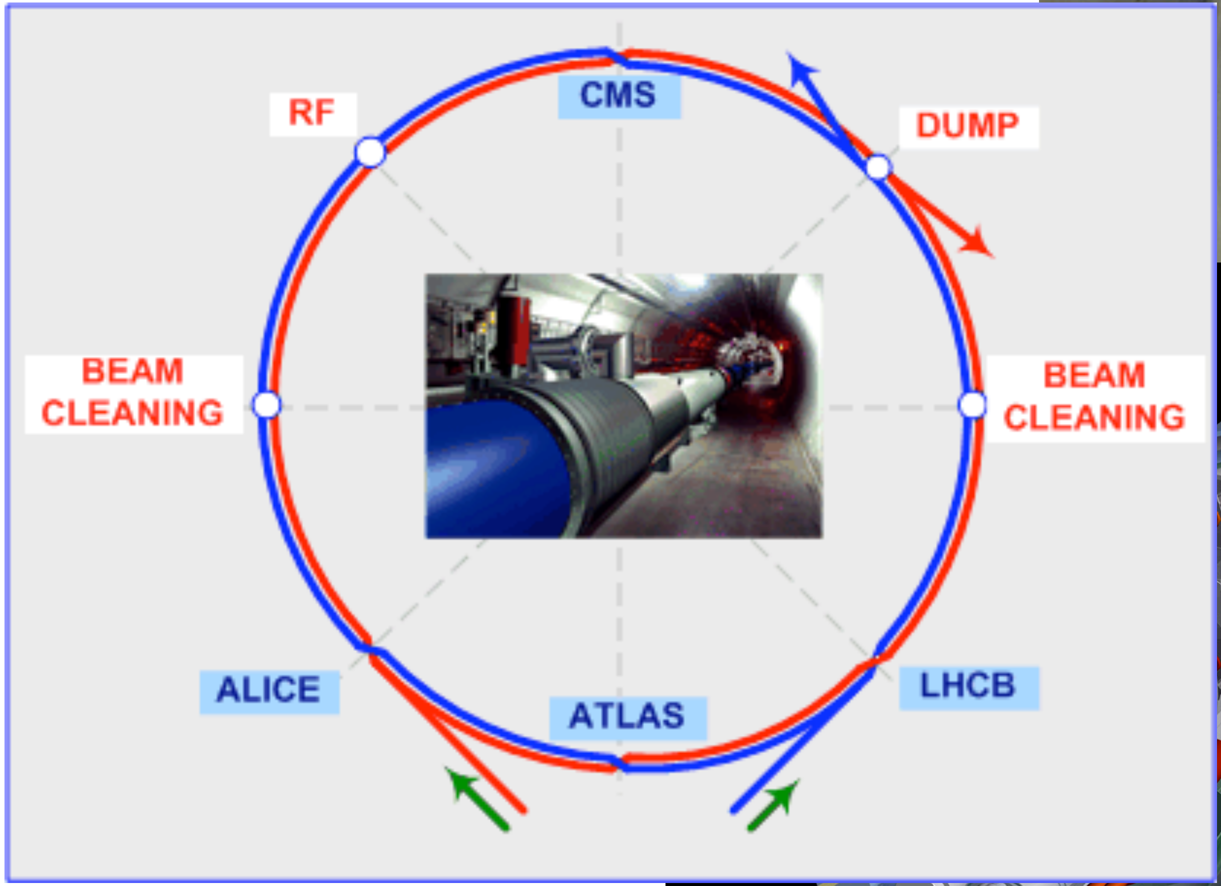
WE-Heraeus-Seminar, Physics at the Terascale

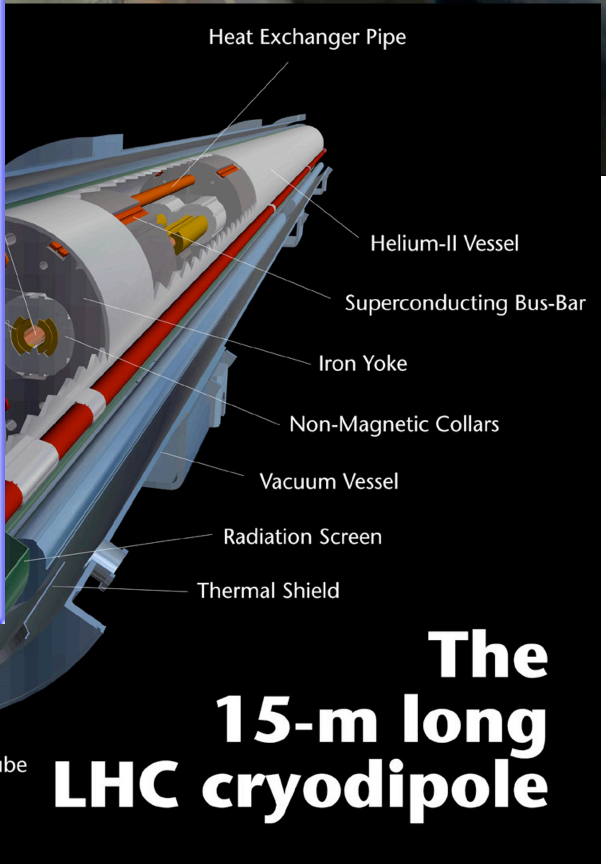
28 April 2008

Outline

- Introduction. The LHC environment.
- What do we expect to do first?
- W/Z production ($L \approx 1\text{-}10\ pb^{-1}$). W/Z + jets, multi-boson production.
- Top production.
- Early discoveries?
- Conclusions.

The LHC

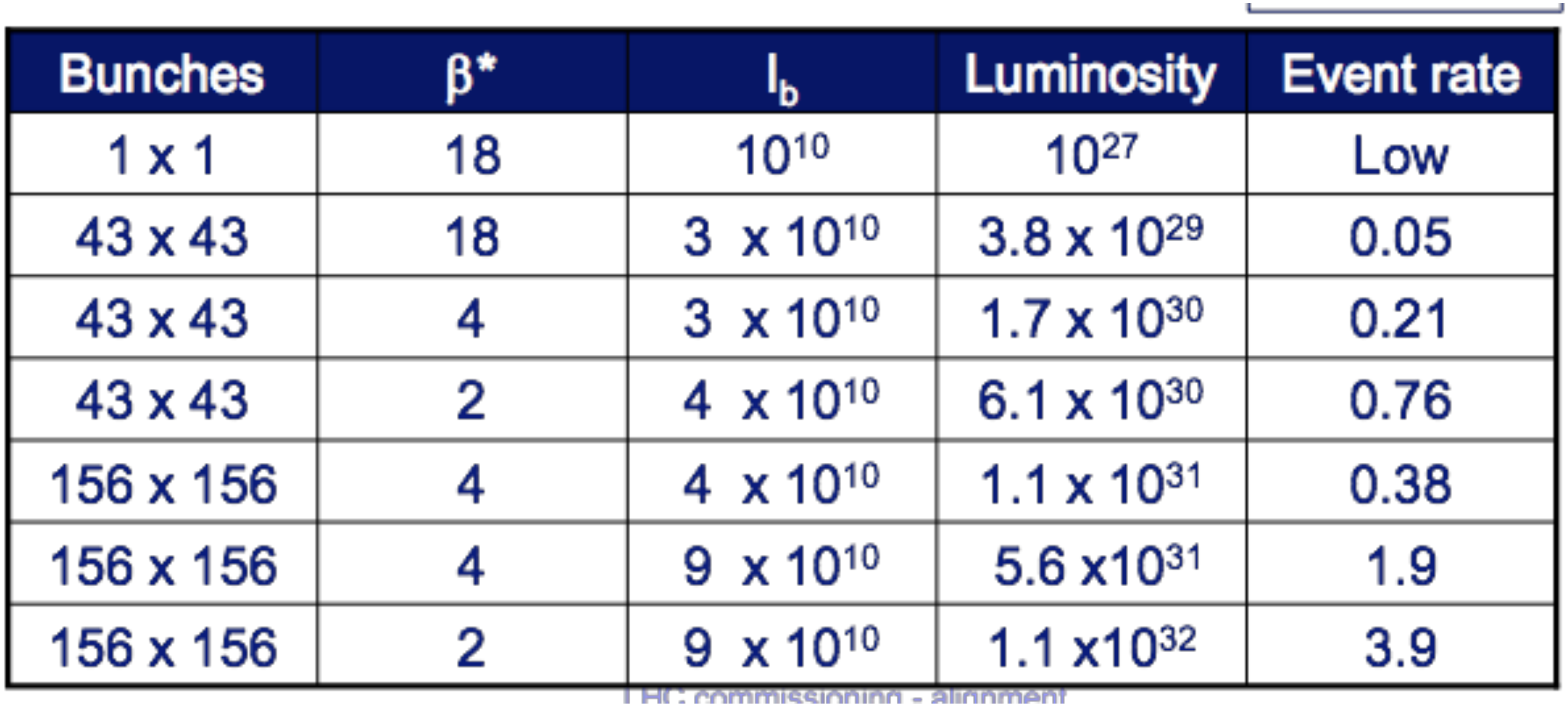




The 15-m long LHC cryodipole

First collisions expected in 2008

LHC luminosities in 2008 (stage A)



Bunches	β*	I_b	Luminosity	Event rate
1 x 1	18	10^{10}	10^{27}	Low
43 x 43	18	3×10^{10}	3.8×10^{29}	0.05
43 x 43	4	3×10^{10}	1.7×10^{30}	0.21
43 x 43	2	4×10^{10}	6.1×10^{30}	0.76
156 x 156	4	4×10^{10}	1.1×10^{31}	0.38
156 x 156	4	9×10^{10}	5.6×10^{31}	1.9
156 x 156	2	9×10^{10}	1.1×10^{32}	3.9

LHC commissioning - alignment

→ 3 pb^{-1}

→ not overnight

Expectations at LHC points 1 (ATLAS) and 5 (CMS)

(Mike Lamont, June 2007)

A realistic schedule in 2008: integrated luminosity ≤ 10 pb^{-1}

What is discussed in this talk

- NOT discussed: initial LHC “engineering” runs at $\sqrt{s}$ = 900 GeV (injection energy), very low luminosities (< 10^{30} cm^{-2} s^{-1}), pre-calibrations, cosmic runs.

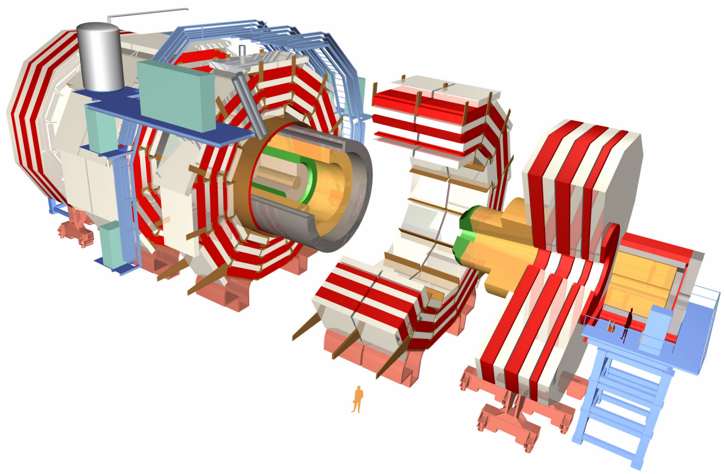
- This talk mainly discusses physics at $\sqrt{s}$ = 14 TeV for instantaneous luminosities in the range10^{30}-10^{32} cm^{-2} s^{-1} . The very first data (2008) will be collected at an energy near $\sqrt{s}$ = 10 TeV. Some comments on the implications of this change at the end of the talk…

- This talk discusses the physics for integrated luminosities << 1 fb^{-1} in the two general purpose detectors ATLAS and CMS.

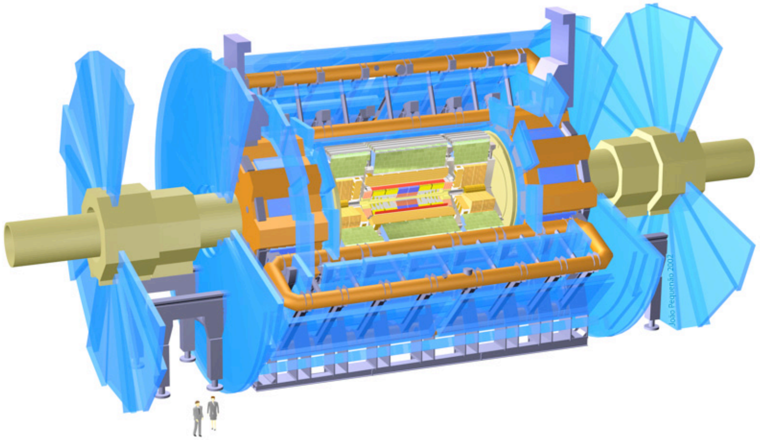
- In summary: we will focus on EARLY MEASURENTS AT THE LHC.

LHC detectors are similar but not equal...

CMS



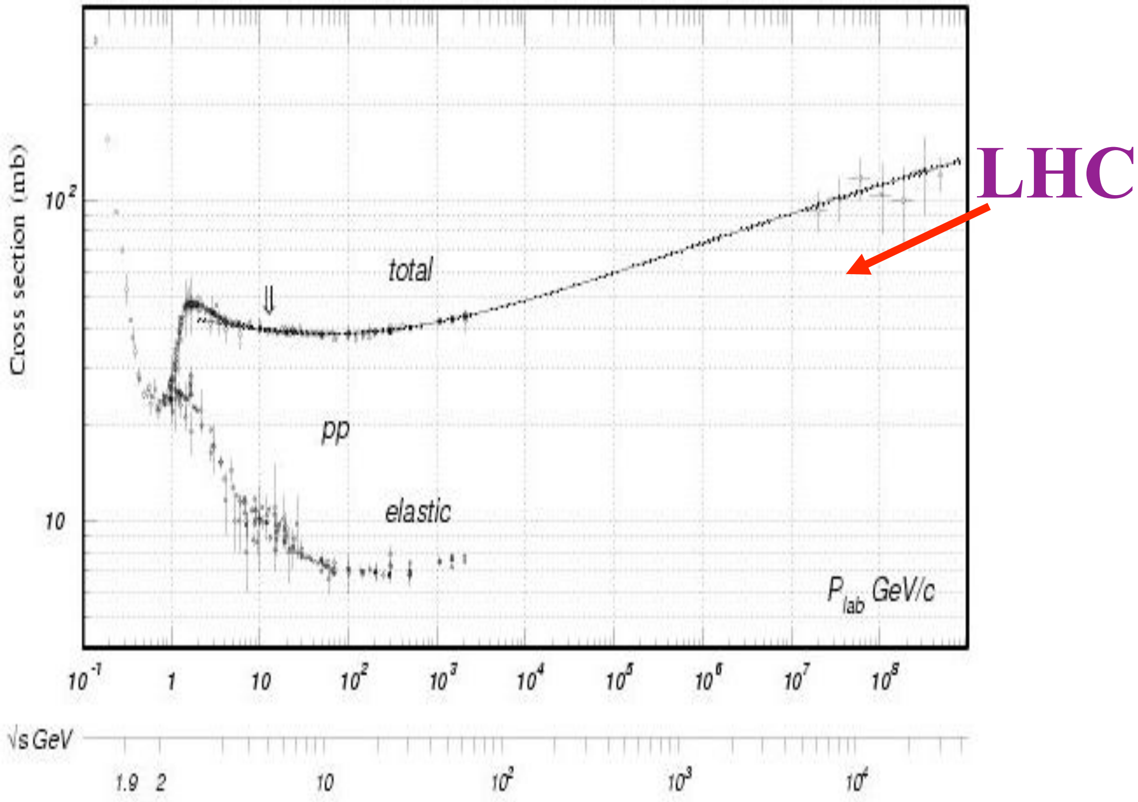
ATLAS

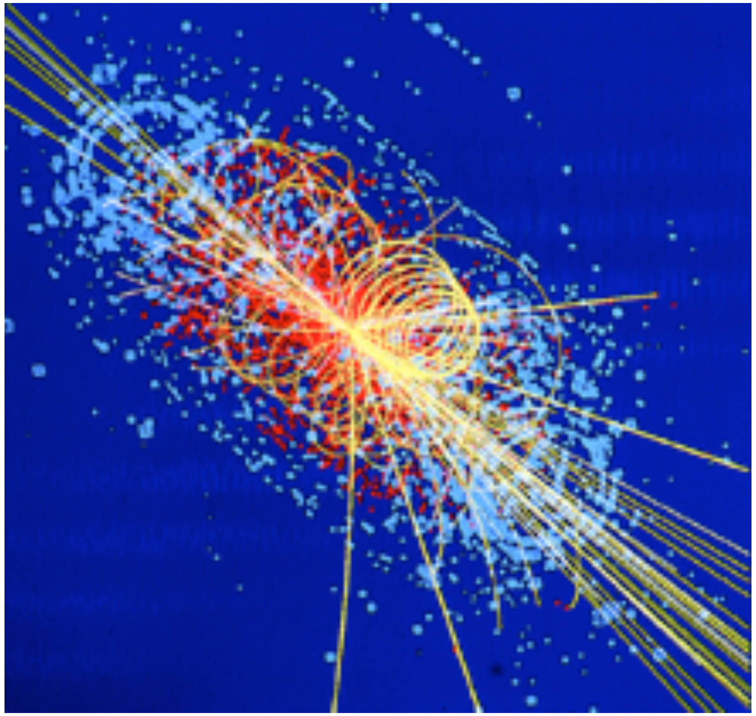


- Weight and size
- Magnetic field: (CMS: big solenoid 4 T; ATLAS: solenoid 2 T + air toroids).
- Inner tracking: (CMS: silicon, 15% at 1 TeV; ATLAS: silicon + transition radiation tracker. 50% at 1 TeV)

- Electromagnetic calorimeter: (CMS: $PbWO_4$ crystals, very good energy resolution, 5% at 1 GeV; ATLAS: liquid argon, 10% at 1 GeV, but very good granularity and uniformity).
- Muon spectrometer: (CMS: very redundant detection/trigger system; ATLAS: very good “stand-alone” momentum resolution, 7% at 1 TeV)

The LHC environment



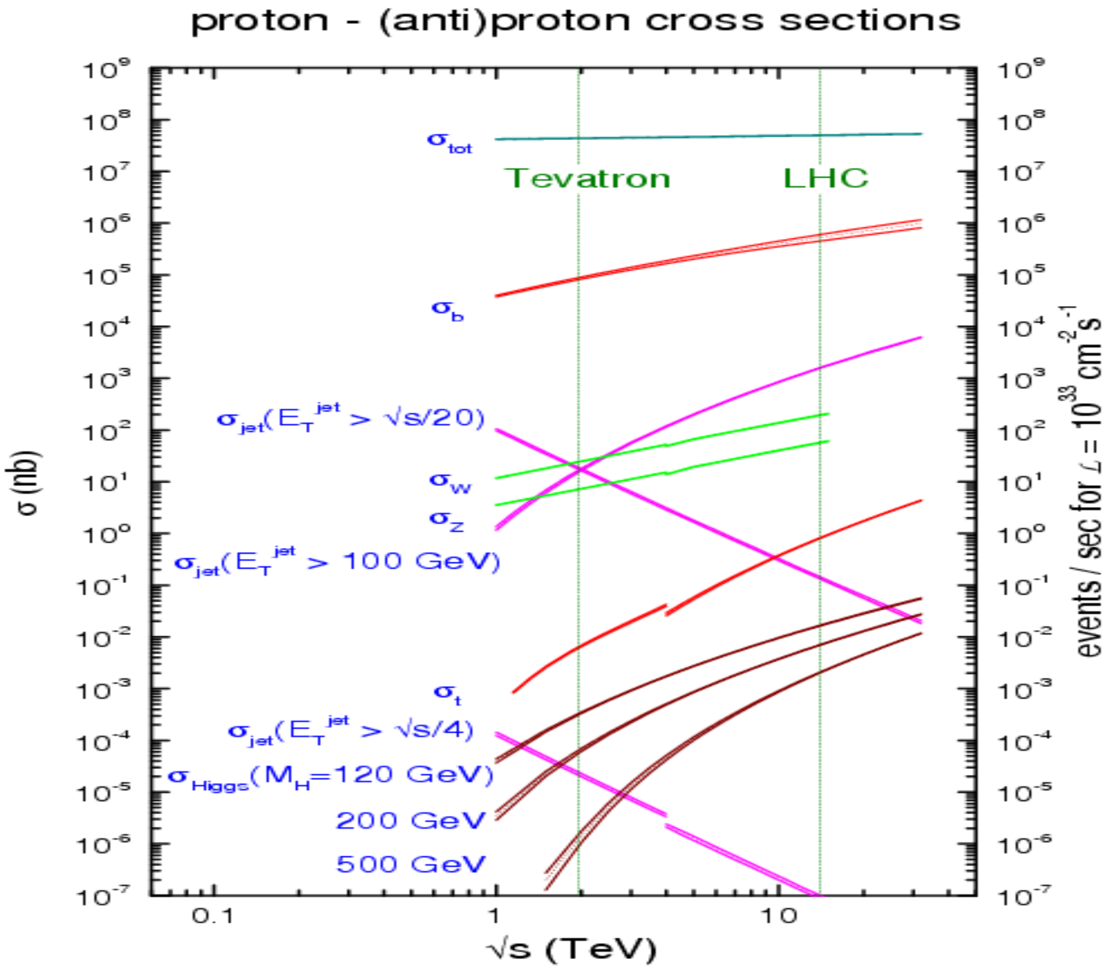


Inelastic cross section ~ 100 mb

10^3-10^6 events/s already at startup (L ~ 10^{28}-10^{31} cm^{-2}s^{-1})

Very 'busy' events: mostly hadronic activity

How does it compared with previous hadron colliders?

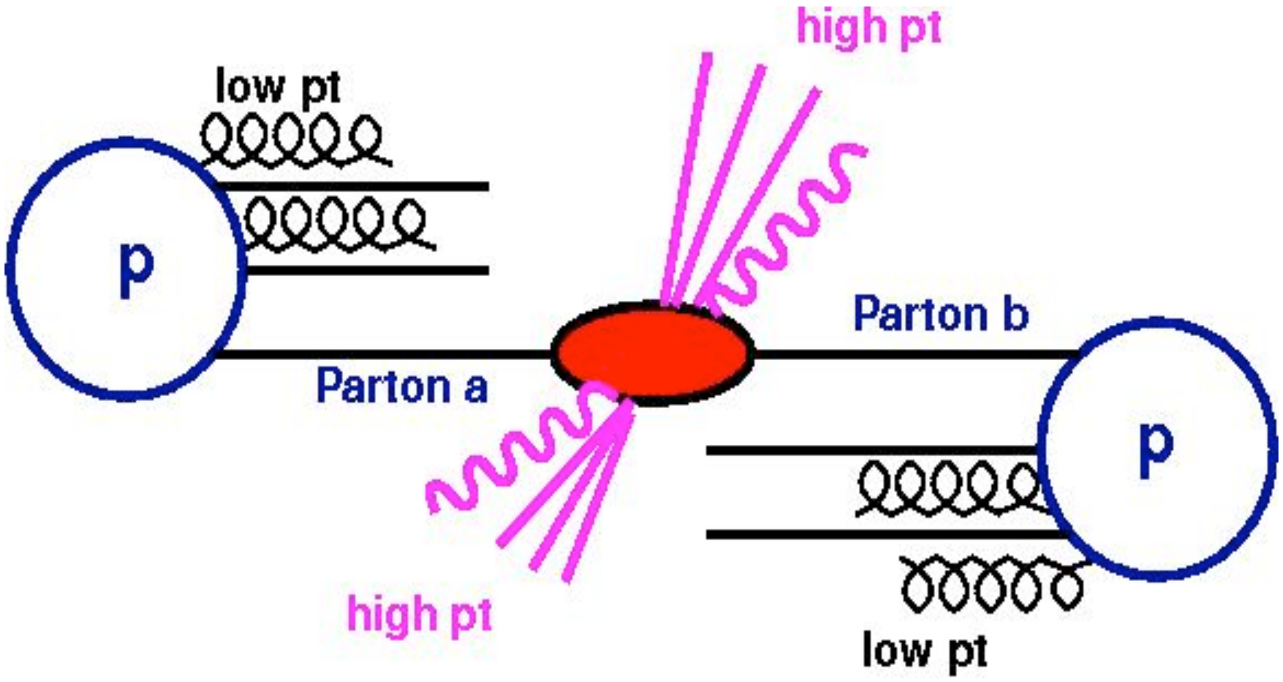


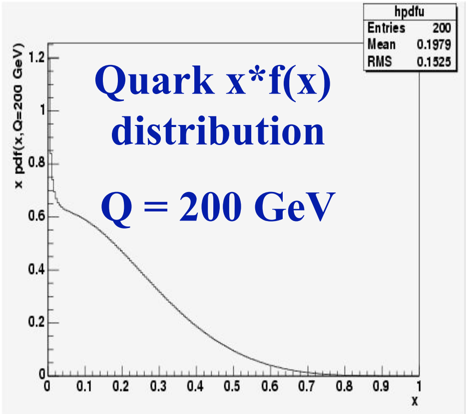
(Campbell, Huston, Stirling, hep-ph/0611148)

(Inelastic) cross sections at the LHC are essentially one order of magnitude larger than at the Tevatron

This increase is even larger for some relevant cross sections, like pp➔Higgs, top-antitop, …

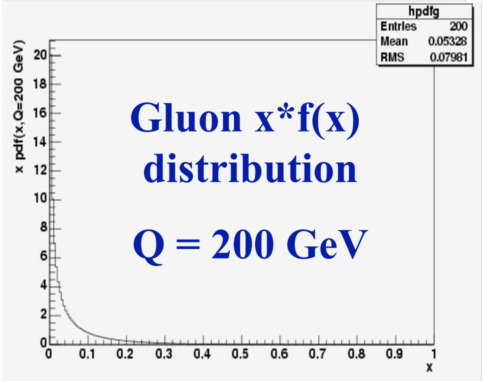
‘Hard’ interactions at the LHC





Quark x*f(x) distribution

Q = 200 GeV



Gluon x*f(x) distribution

Q = 200 GeV

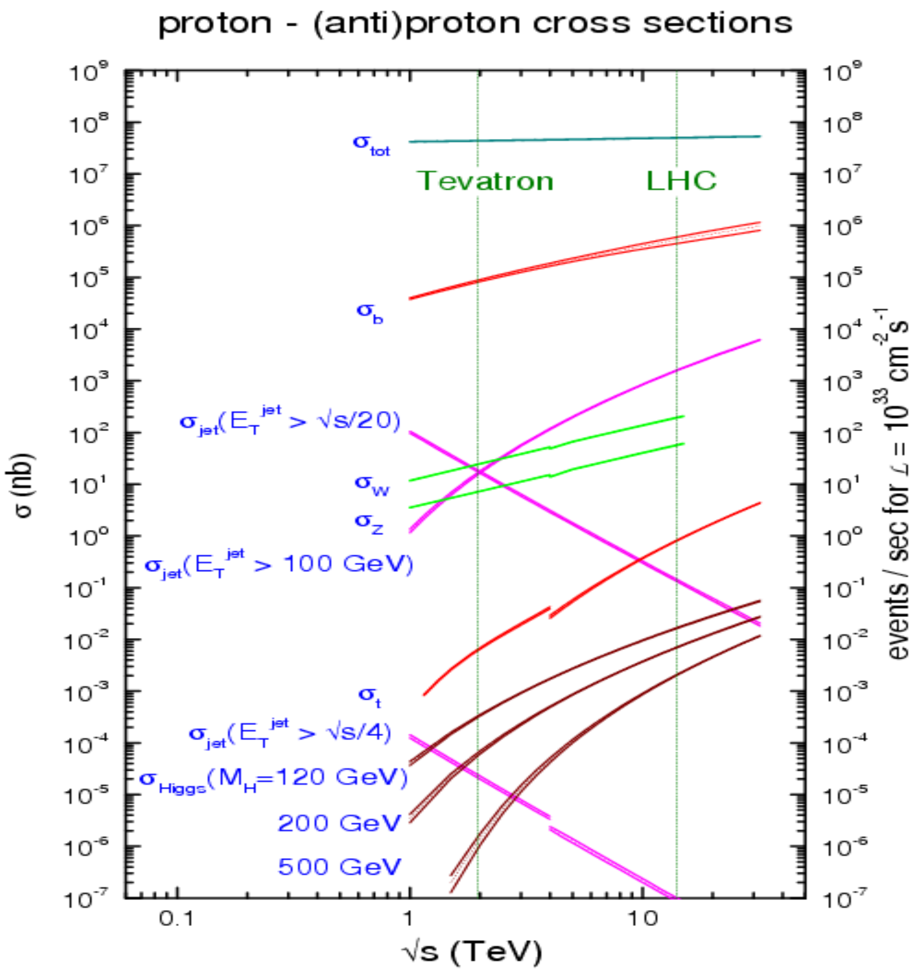
$$\sigma(pp \rightarrow H; x_A, x_B, Q^2) = \int dx_A \int dx_B \, pdf_{p\rightarrow A}(x_1, Q^2) \;\; pdf_{p\rightarrow B}(x_B, Q^2) \;\; \sigma(AB \rightarrow H; Q^2)$$

where x_A et x_B are the 'momentum fractions' from each proton

'taken' by the A and B partons

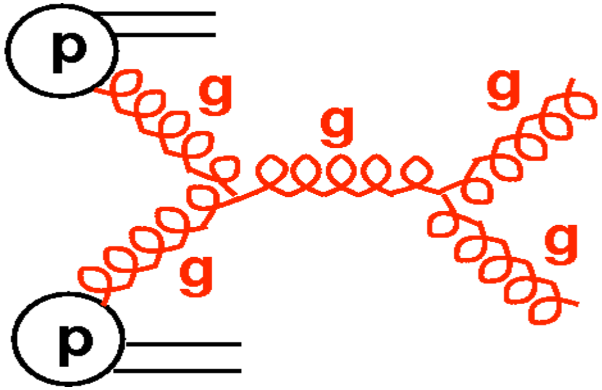
$A, B \in \{\, gluon, quark, antiquark, \dots \}$

Main processes

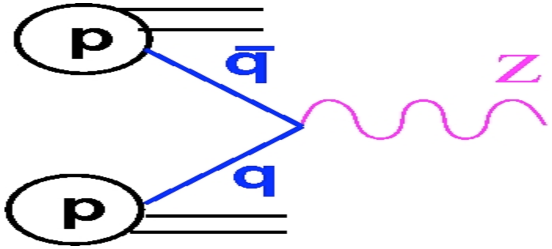


(Campbell, Huston, Stirling, hep-ph/0611148)

QCD interactions of the type gg→gg, qqbar, qg→qg, … dominate the cross section.



W and Z production is sub-dominant. Leptonic decays of these bosons are quite clean.

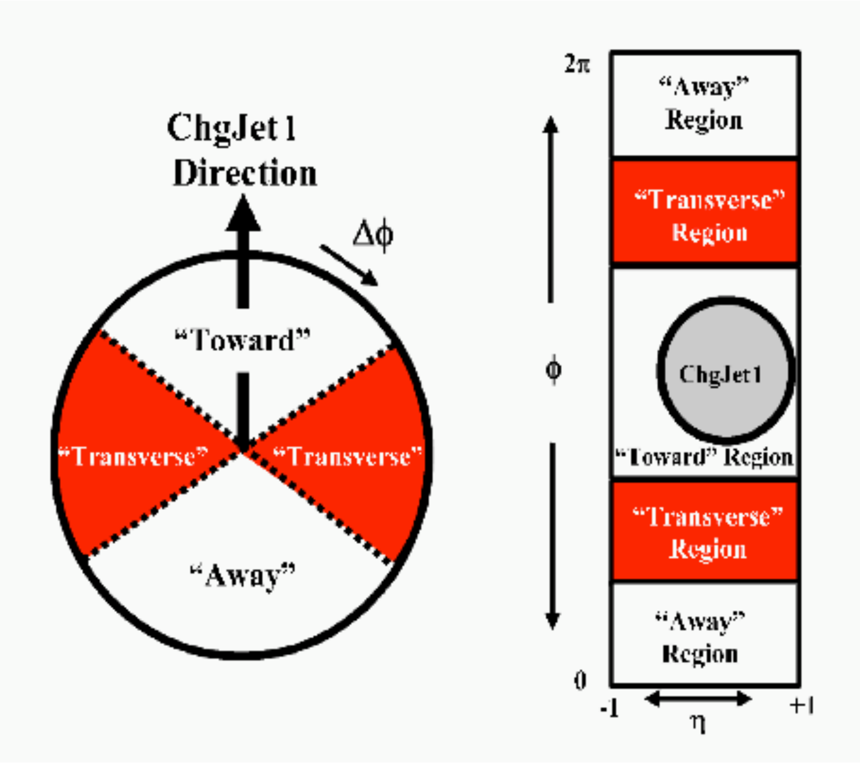


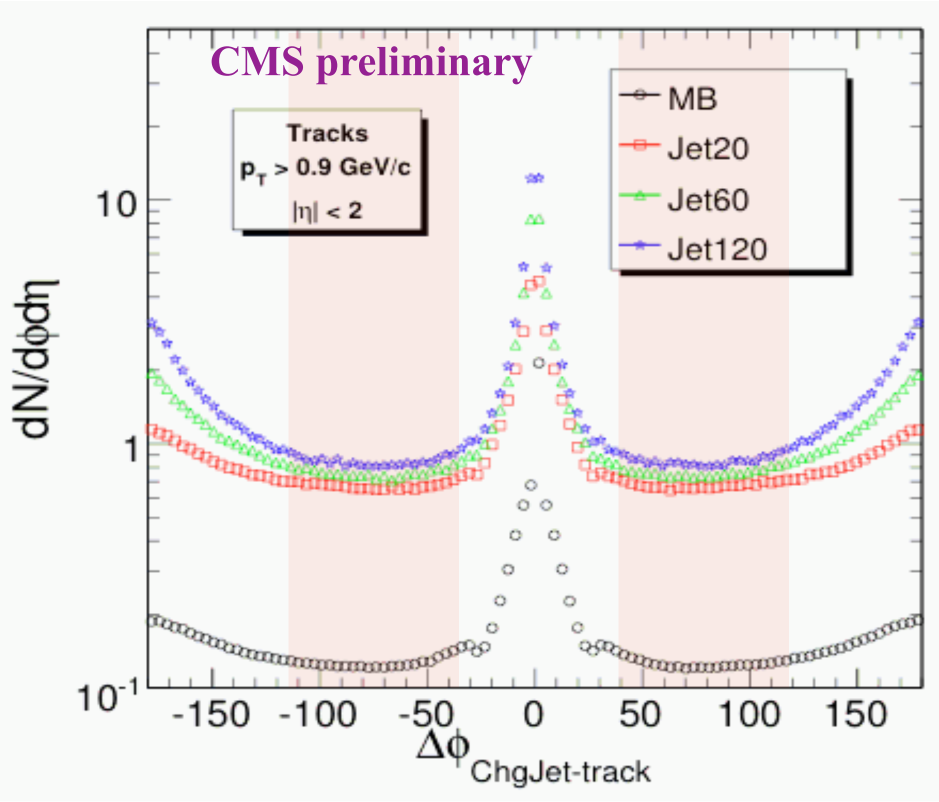
Typical amount of events in 1 pb^{-1}

Process	# events in 1 pb^{-1}
QCD jets with $p_T > 150$ GeV	1000 (10% trigger bandwidth)
$J/\Psi \rightarrow \mu^+\mu^-$	15000
$\Upsilon \rightarrow \mu^+\mu^-$	3000
$W \rightarrow \mu\nu$	6000
$Z \rightarrow \mu^+\mu^-$	600
Top-antitop $\rightarrow \mu\nu$ + jets	20, but distinguishable from background?
Jets with $p_T > 1$ TeV	10

At $\sqrt{s} = 14$ TeV, per experiment, assuming approximate/safe ATLAS / CMS acceptances

What should we do first?





- **Understanding the LHC underlying event environment:**
  - **The underlying activity mainly affects the "transverse" region (in red)**
  - **This is a necessary step to tune our Monte Carlos (multiple interactions, …)**

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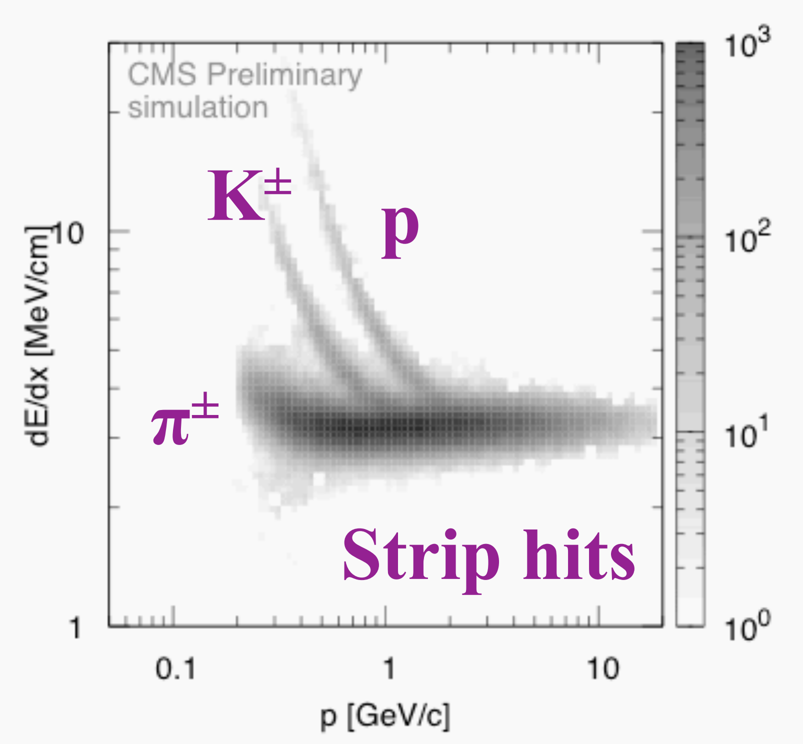
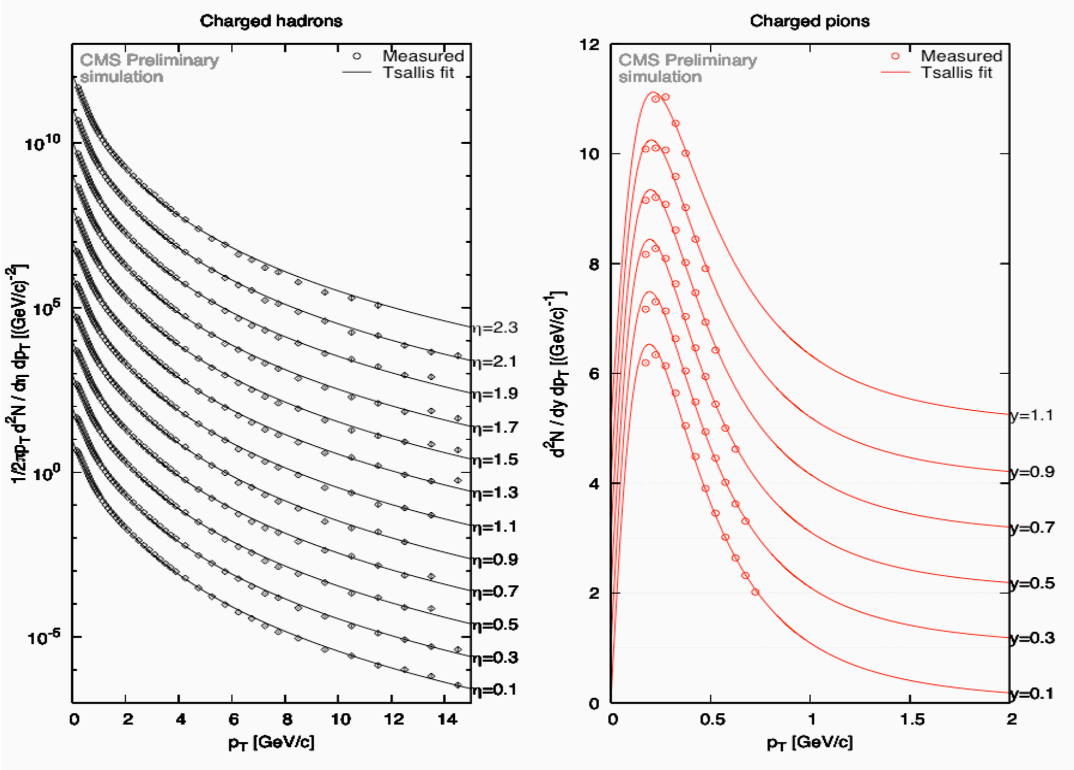
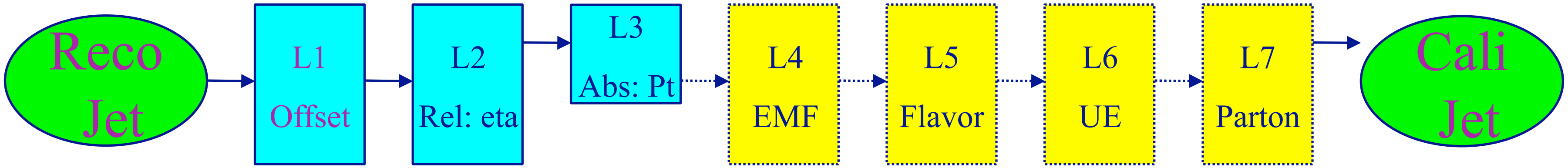
What should we do first?





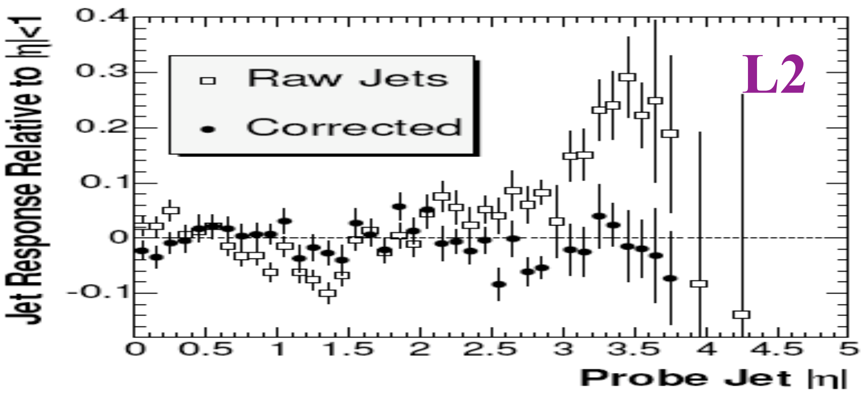
- **Understanding the charged hadron spectrum:**
  - **LHC is a new energy domain**
  - **Studying the tracker performance: low pT, tracking, pattern recognition, dE/dX particle identification, ..**

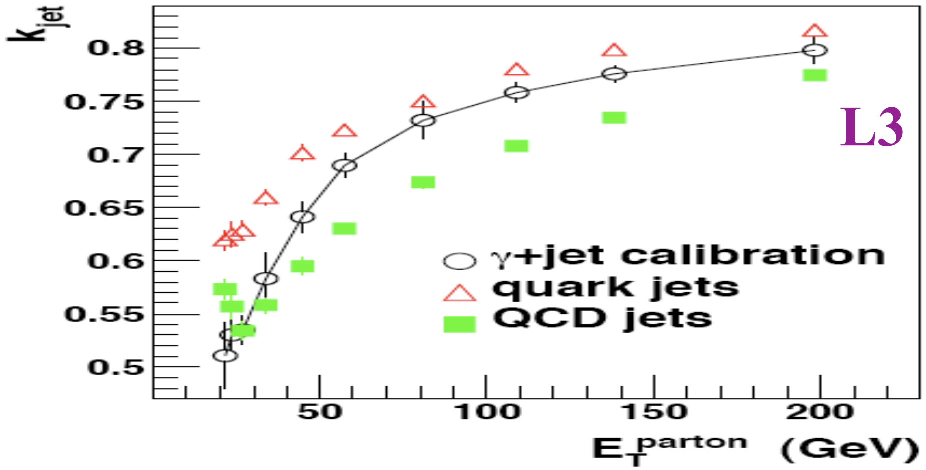
What should we do first?



Reco Jet → L1 Offset → L2 Rel: eta → L3 Abs: Pt → L4 EMF → L5 Flavor → L6 UE → L7 Parton → Cali Jet

- **Understanding jets. First steps (CMS):**
  - **L1: offsets. Basic calibrations, pedestals, noise treatment, …**
  - **L2: equalize response as a function of pseudo-rapidity**
  - **L3: Absolute scale corrections.**





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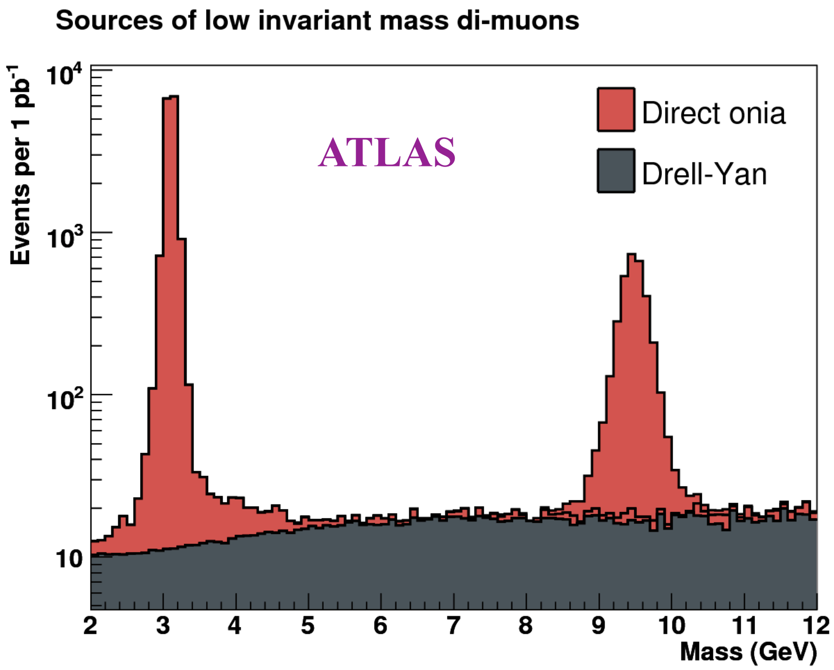
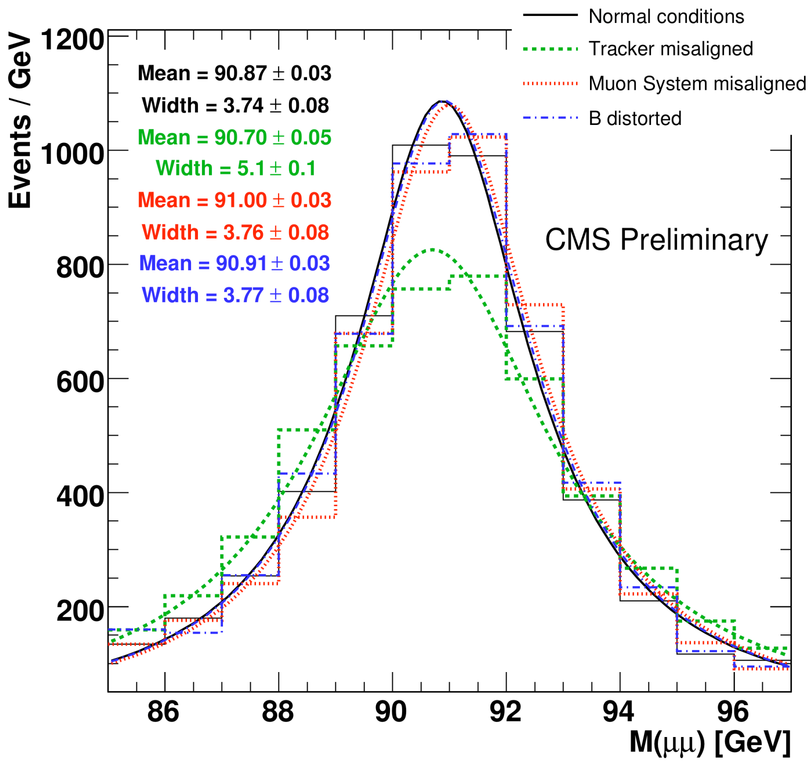

Sources of low invariant mass di-muons



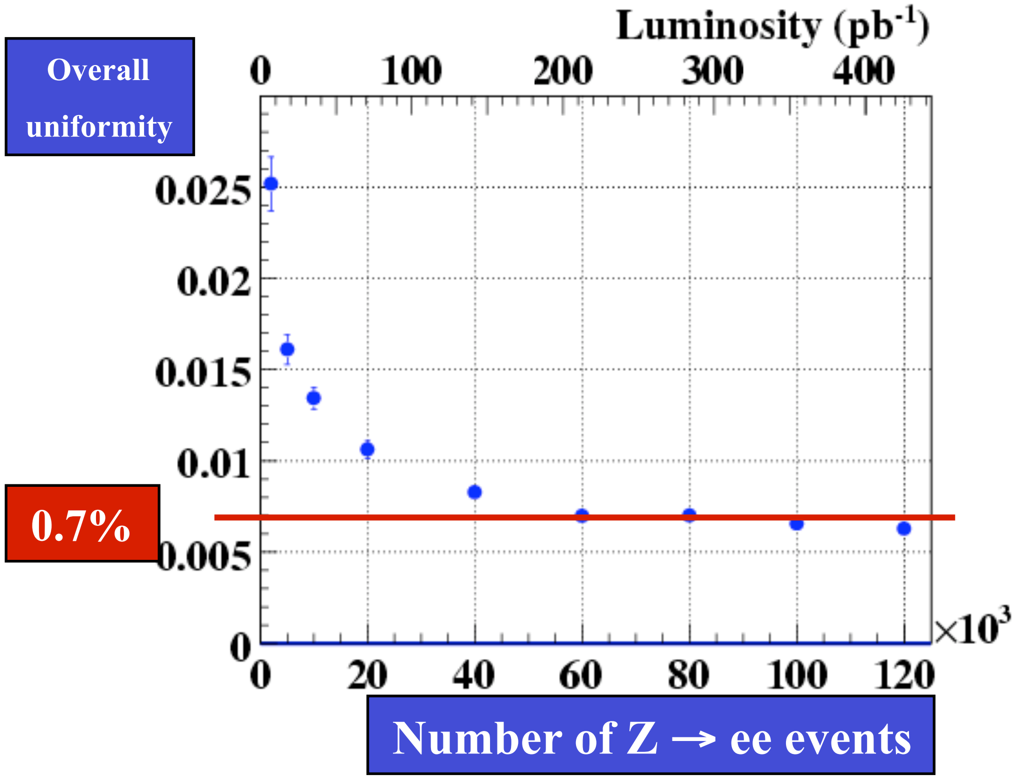
- Understanding the dimuon spectra:
  - Thousands of dimuons from J/Psi and Upsilon for 1 pb^{-1}, hundreds from Z.
  - First opportunity to understand tracking and muon resolutions as a function of p_T (multiple scattering, alignment distortions, magneticc field uncertainties, …)

Why are early EW measurements interesting?

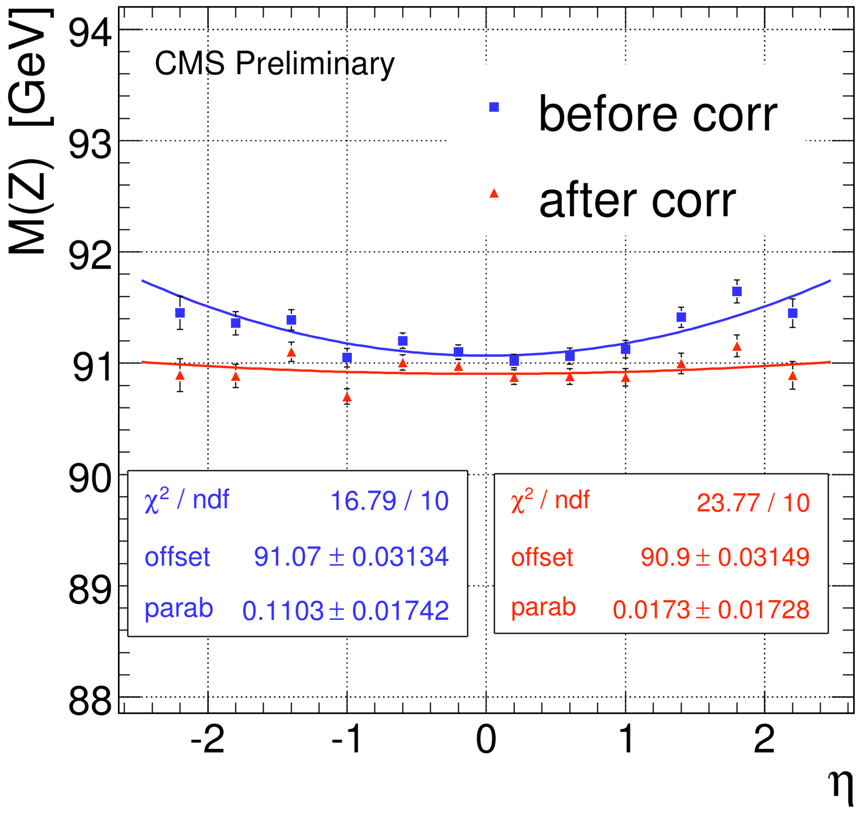
- 1) Because they are related with ‘known’ physics...
  - EW properties precisely studied in previous colliders like LEP, HERA, Tevatron.
  - W/Z/γ^*/top production well understood/studied in previous hadronic colliders (Tevatron)
- ... they become a unique tool to understand:
  - Calibrate our detectors and their response (muons, electrons/photons, jets)
  - Understand backgrounds for new physics signals
  - Understand detector details and develop sophisticated tools (b-tagging, b-jets, measurement of missing transverse energy).

Calibration with EW measurements

ATLAS, ECAL intercalibration



CMS, muon momentum scale



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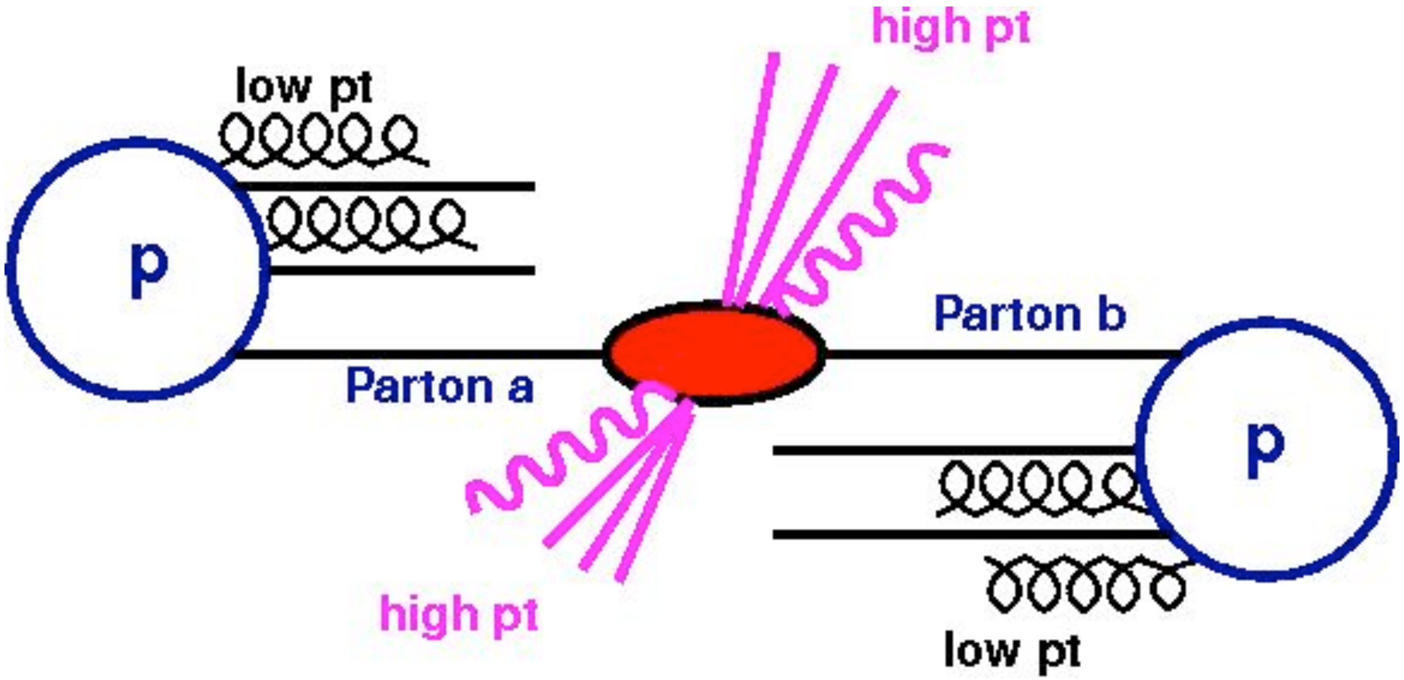

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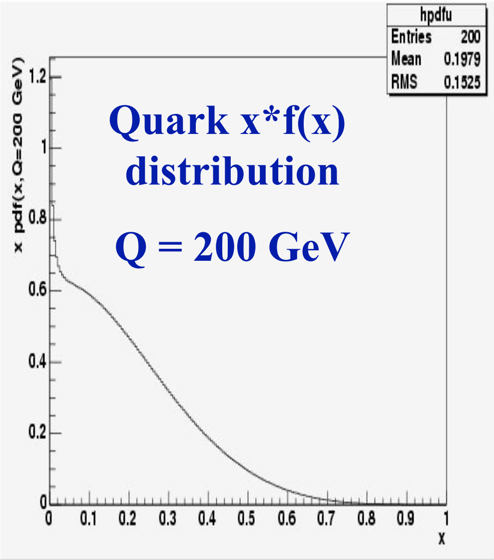
where x_A et x_B are the 'momentum fractions' from each proton

'taken' by the A and B partons

$$A, B \in \{\, gluon, quark, antiquark, \ldots \}$$

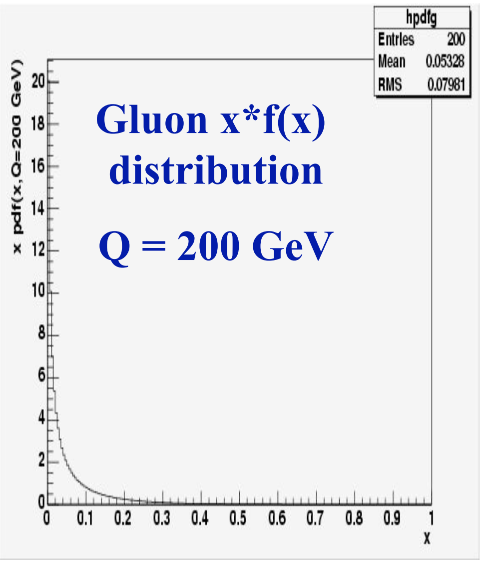
Why are early EW measurements interesting?

- 2) Because they are NOT so well 'known' processes at the LHC:
  - This is a new (x, Q^2) regime... Are parton density functions (PDF) as 'predicted'?
  - Gluons play a more dominant role at higher energies.
  - Top precision physics is in a starting phase.



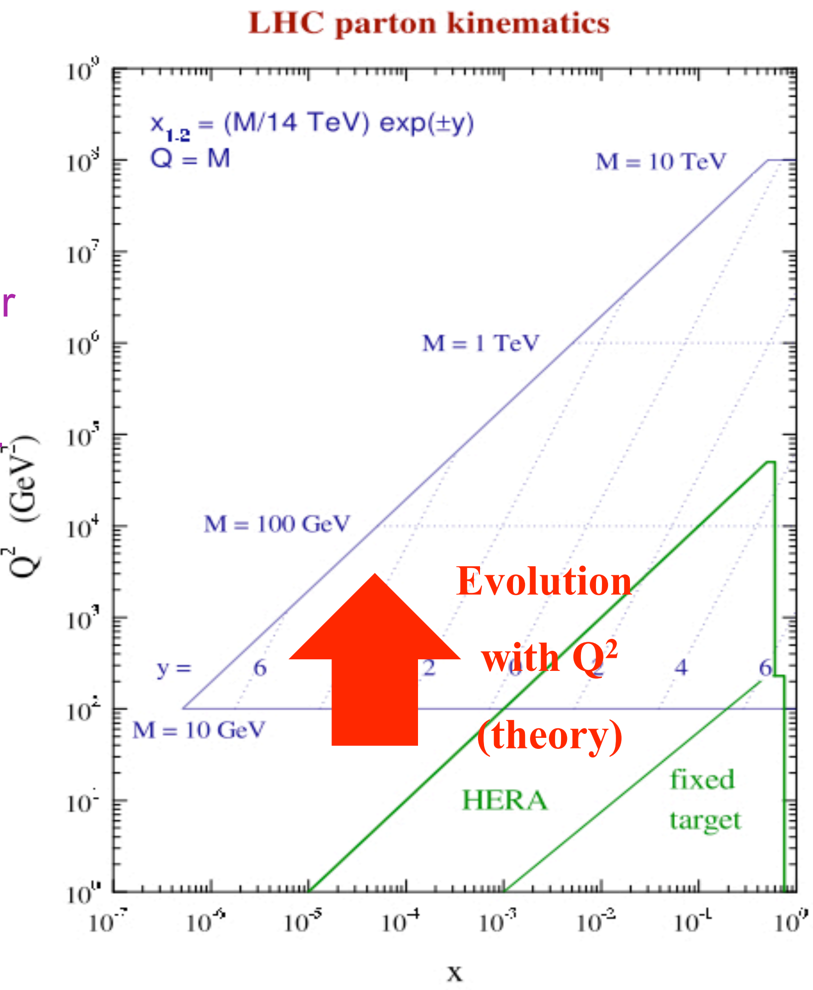
Quark x*f(x) distribution

Q = 200 GeV



Gluon x*f(x) distribution

Q = 200 GeV



LHC parton kinematics

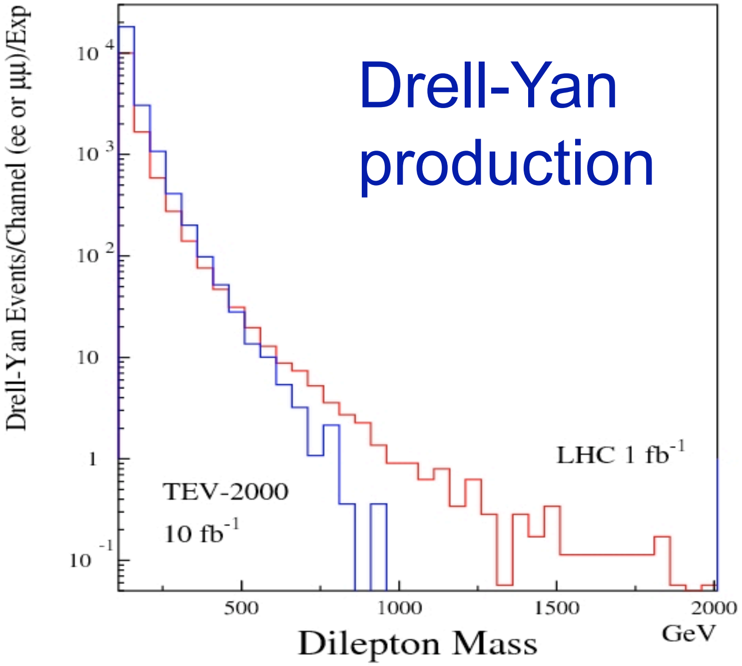
Evolution with Q^2 (theory)

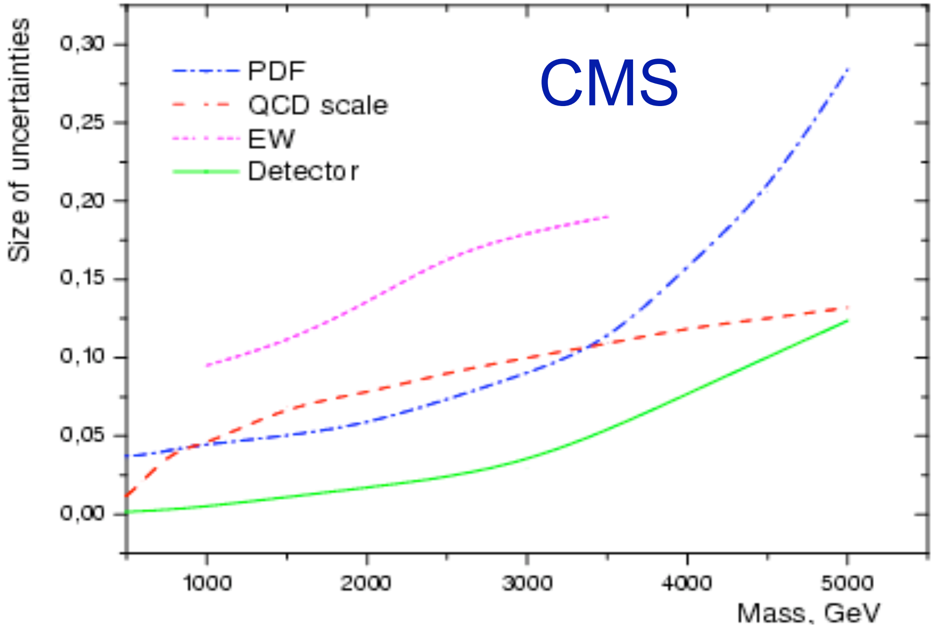
(Campbell, Huston, Stirling, hep-ph/0611148)

Why are early EW measurements interesting?

- 3) Because physics channels involving Z,W,γ^*,top production are easily distorted by almost any new physics sources at the new energy scales opened up by the LHC, even with low luminosity:

$\sqrt{s}$ (LHC) ~ 7-10 $\sqrt{s}$ (Tevatron, LEP) !!





Systematic error ~ 10% ?

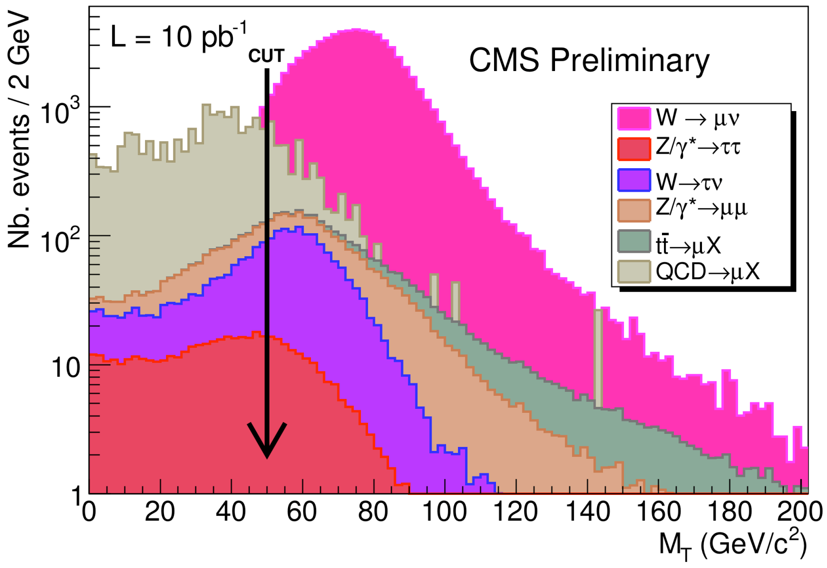
Inclusive W/Z production

- ✔ **First ‘electroweak’ signals to be observed. Already at a luminosity of 1 pb^{-1}, thousands of W/Z leptonic decays will be at our disposal: σ(LHC) ~ several nb ~ 10 σ(Tevatron).**

- ✔ **Main guidelines:**
  - ✔ Selection W and Z samples with decays into leptons of high purity
  - ✔ Simple criteria
  - ✔ Minimally dependent on calibration uncertainties and limited knowledge of the detector response (i.e. start-up oriented).

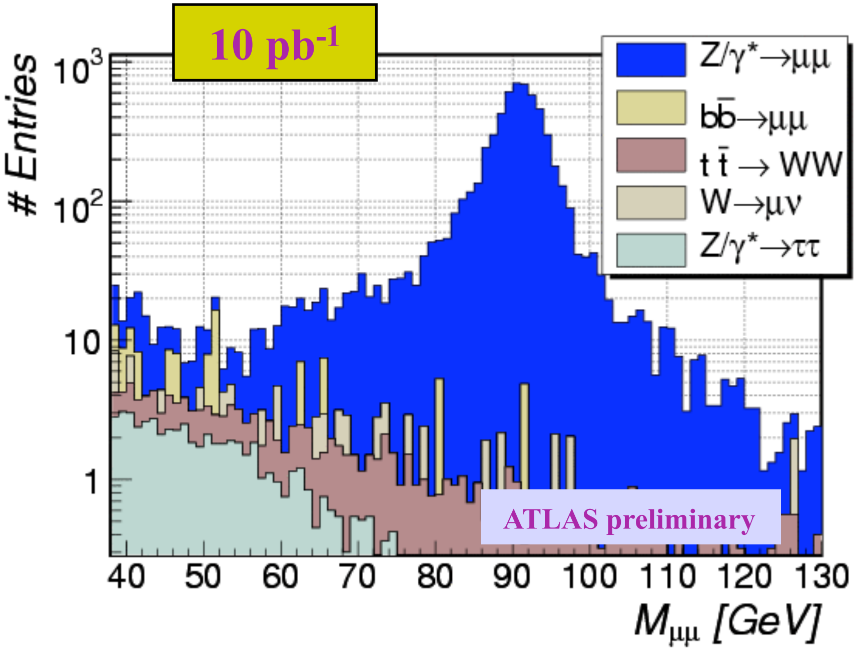
Example: Z/W->leptons

- Safe definitions of ‘hard’ leptons ($L=10^{32}$ $cm^{-2}s^{-1}$):
  - P_t > 20-25 GeV (well above trigger thresholds)
  - Well inside the detector acceptance (good control of trigger and detector efficiencies).
  - Loose isolation criteria.
- Efficiencies and backgrounds determined from data as much as possible.
- Relaxed cuts in general on reconstructed masses for Z, on missing transverse energy/mass for W



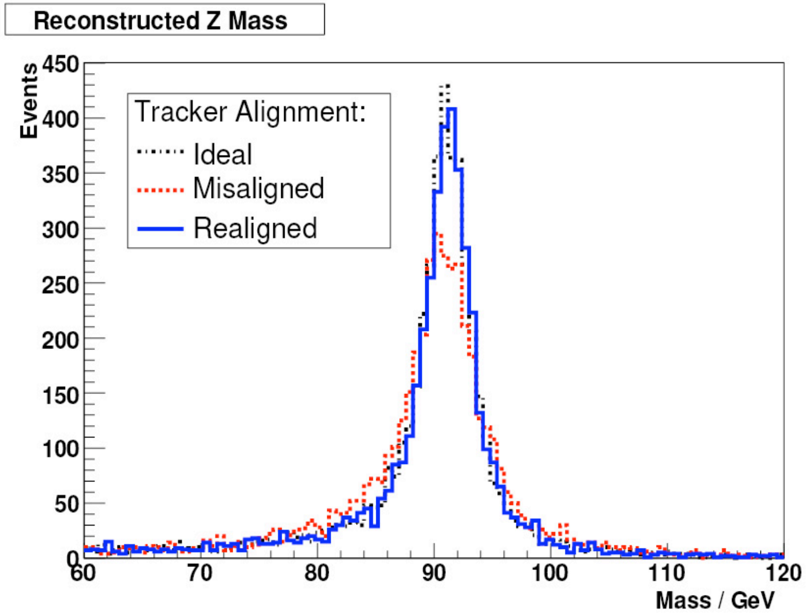
$Z\rightarrow\mu\mu$: invariant mass criteria

ATLAS



No stringent cuts on the invariant mass are required

CMS, tracker alignment exercise



Initial tracker misalignment does not distort the shape dramatically =>
selection criteria OK to get initial samples for alignment and energy scale calibration

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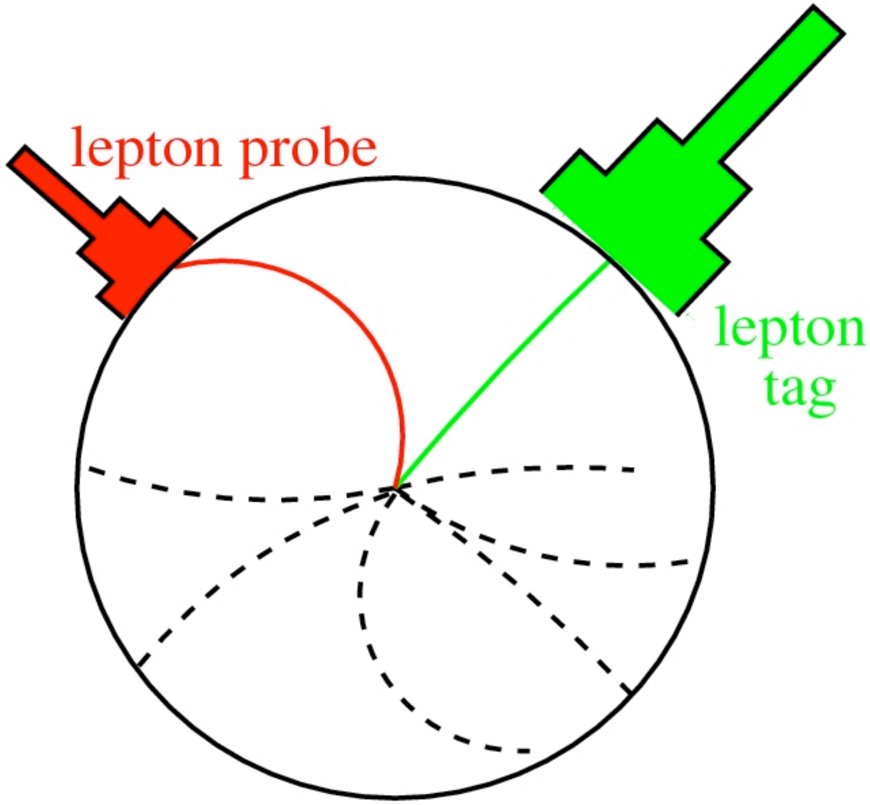
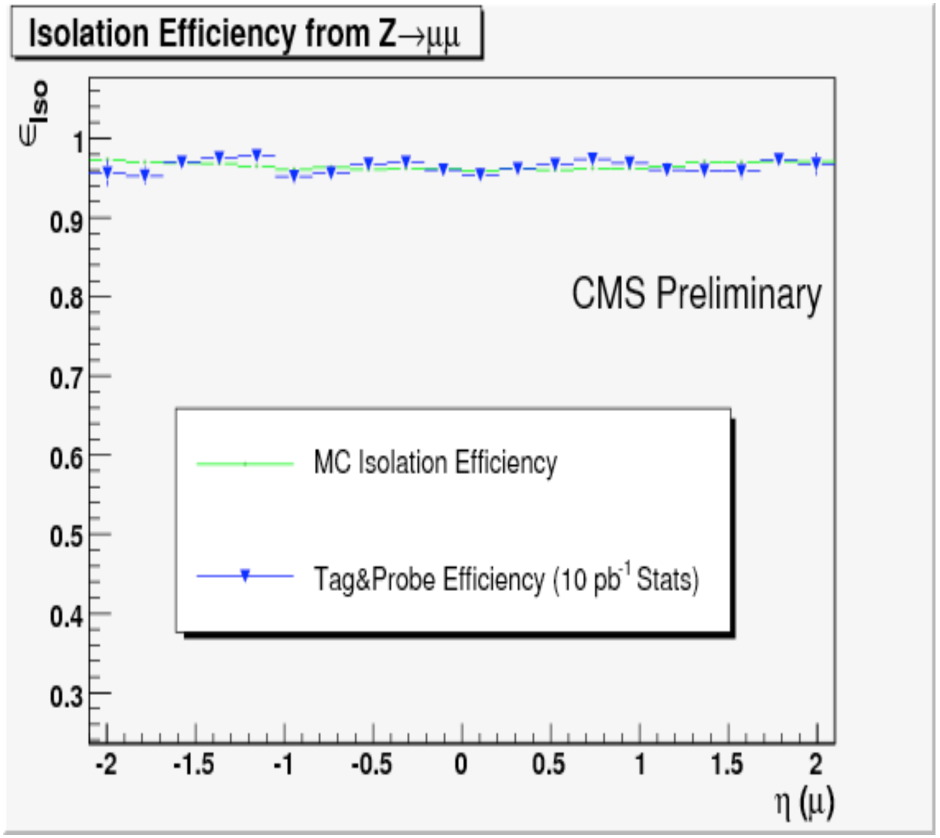
Extracting efficiencies from data



- Extensive use of tag-and-probe methods with L ≥ 10 pb^{-1}:
  - Select pure Z samples by tightening criteria on the ‘tag’ lepton
  - Measure directly the efficiency on the unbiased ‘probe’

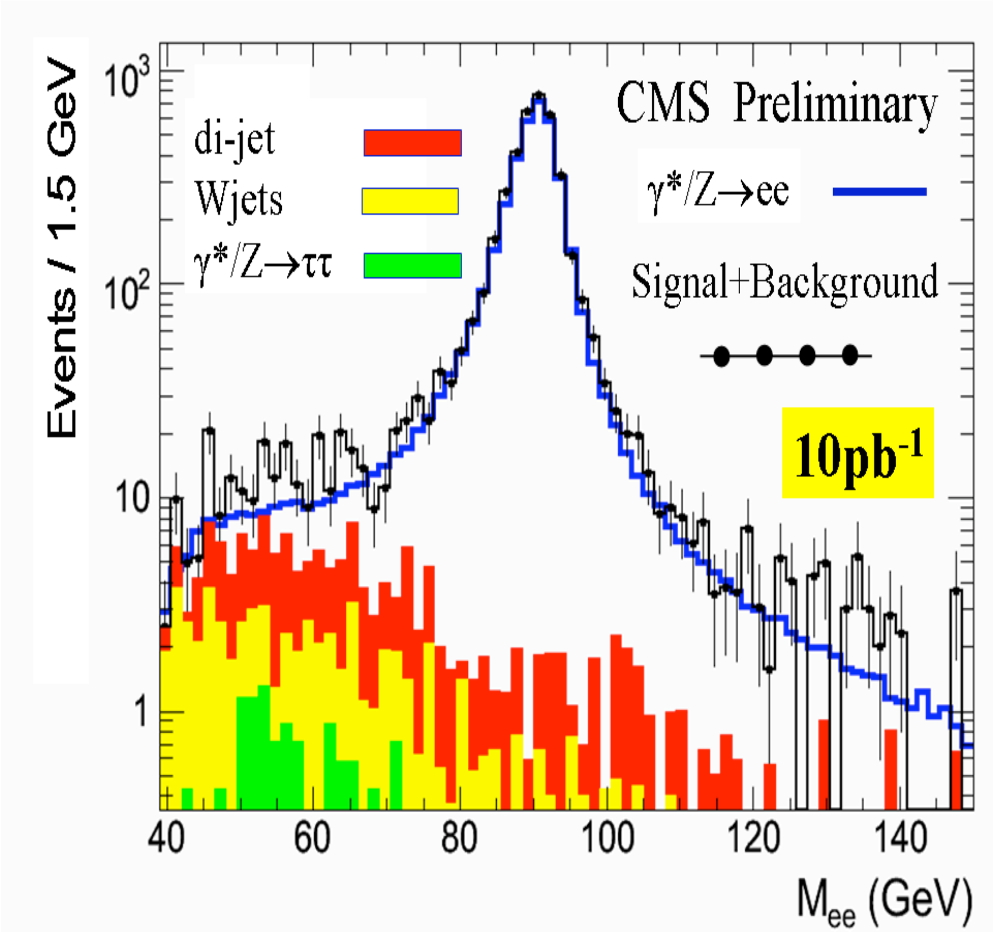
Tag-and-probe method: simple example

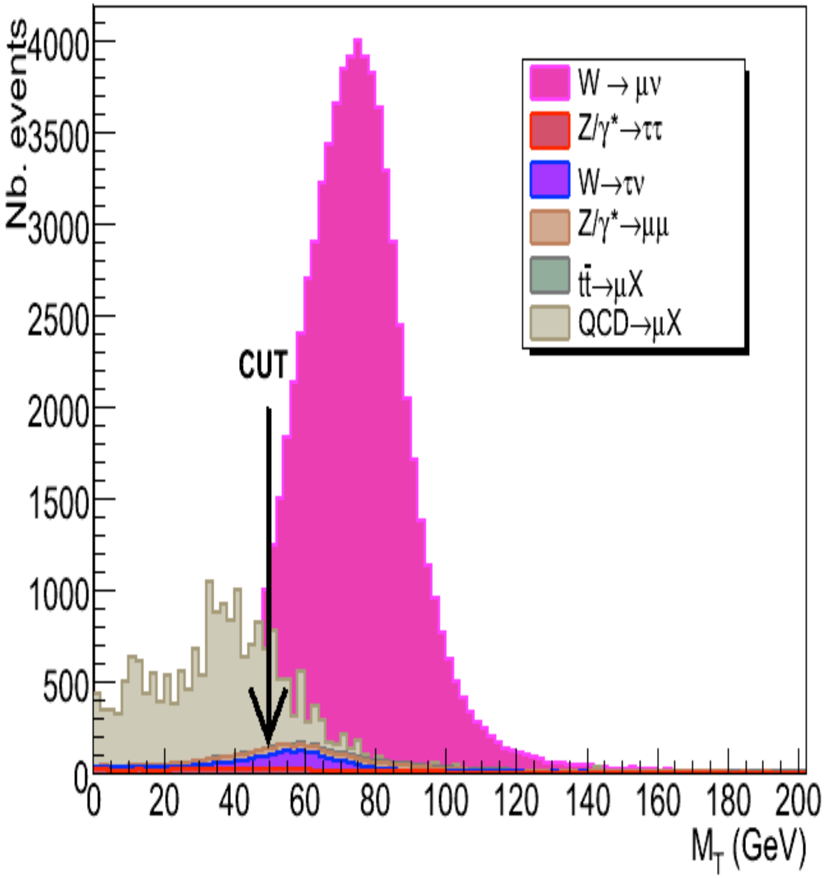
Side	**Definition**
Tag	Isolated global muon with pt>20 GeV
Probe	Global muon with pt>20 GeV
Probe Type	**Description**
Isolated	Probe side is isolated
Non isolated	Probe side is not isolated



- Important comments:
  - The method must be validated on Monte Carlo simulations
  - Some biases may arise due to intrinsic correlations between sides

Determining backgrounds from data

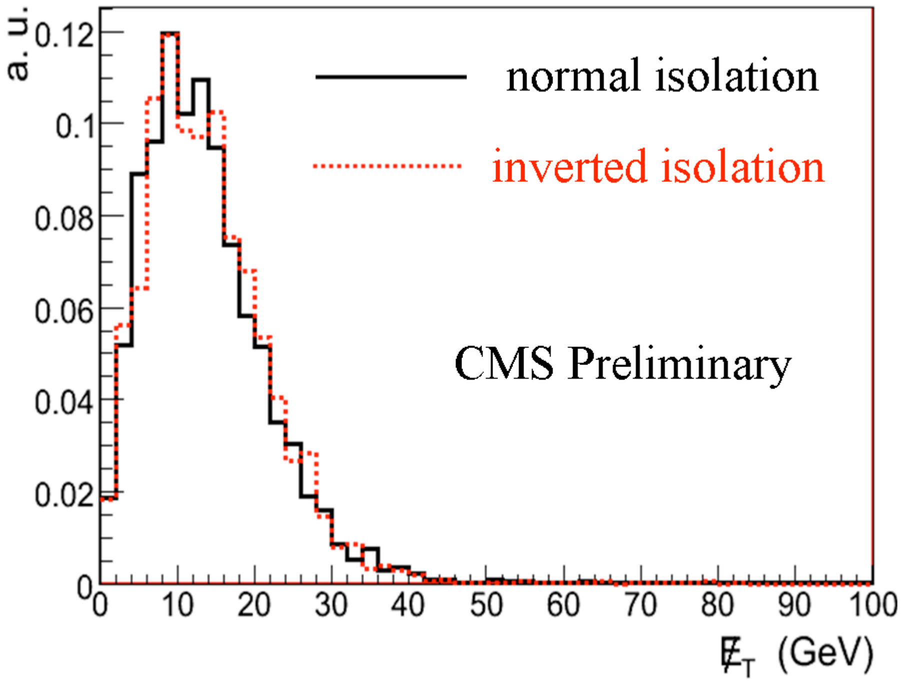




Backgrounds are relatively small after cuts, but there can be disagreements with simulations: estimate them from data too

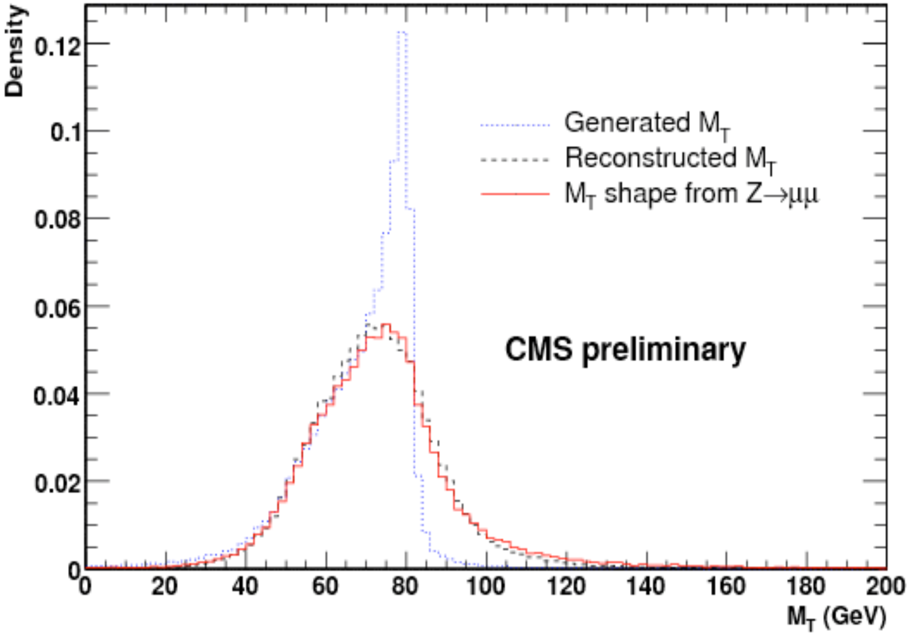
Determining backgrounds from data

Methods to determine QCD backgrounds in W->lν



Missing transverse energy for 'selected' electrons in QCD background for W->eν

Inverting the isolation cut



Missing transverse mass for selected muons in QCD background for W->μν

Use Z->μμ in data to study/describe the calorimetric response

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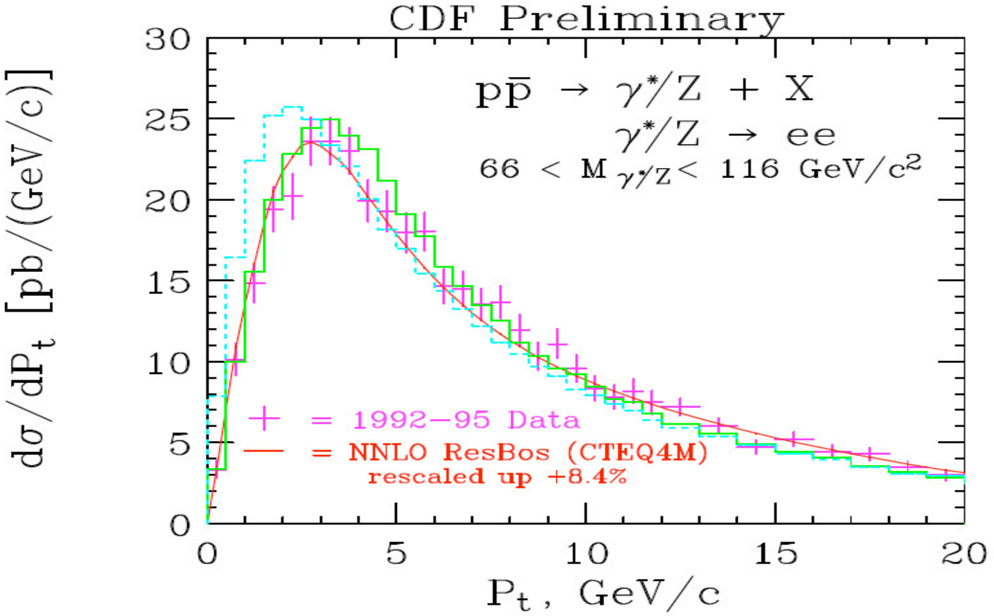
The low-p_T part of the spectrum

- There is some non-trivial tuning of Monte Carlo generators, particularly for non-perturbative / semi-phenomenological parameters:



CDF

Old Z ->ee sample

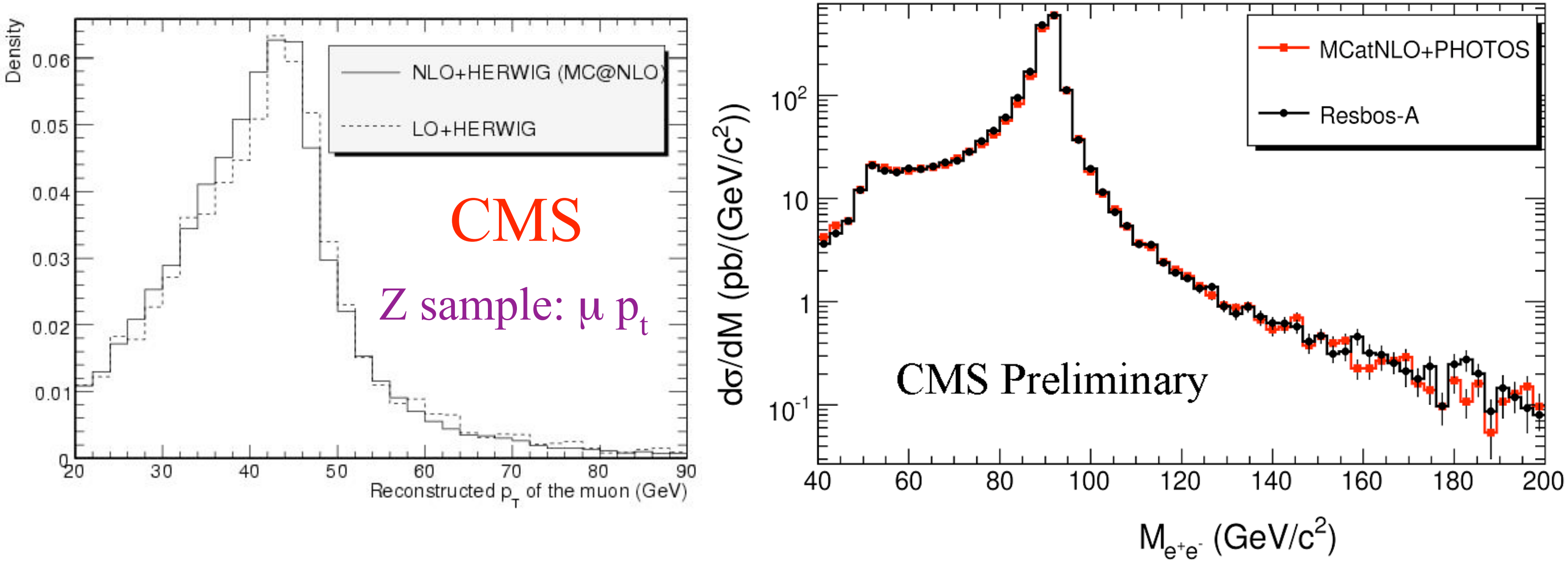
Best agreement with $k_T \sim 2$ GeV (green histogram)

Also agreement with NNLO 'resummed' calculations (RESBOS)

- Example: k_T in PYTHIA, giving ~ the typical size of intrinsic transverse momentum of the parton inside the proton.

NLO and NNLO predictions

- LO -> NLO studies with MC@NLO: used to determine systematic uncertainties on the experimental acceptance (~ 2 %).



- In the long term, once NLO effects are understood, and low pt shapes well reproduced, systematics can be assigned according to NLO vs. NNLO comparisons (present estimate ~ 1%).

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PDF uncertainties

Z sample (CMS TDR)

Test	Rate uncert. (%)	Acceptance uncert. (%)
CTEQ5L→CTEQ5M	18.2	1.1
CTEQ61(0)→CTEQ61(1:40)	$^{+5.8}_{-7.9}$	$^{+0.4}_{-0.7}$
CTEQ61→MRST2001E	1.5	0.1

W sample (CMS TDR)

Test	Rate uncert. (%)	Acceptance uncert. (%)
CTEQ5L→CTEQ5M	15.8	2.0
CTEQ61(0)→CTEQ61(1:40)	$^{+5.6}_{-7.4}$	$^{+0.6}_{-0.9}$
CTEQ61→MRST2001E	0.4	0.1

A. Experimental uncertainties on the PDFs are determined by using different subsets of PDFs and some specific recipes.

B. Uncertainties of the theoretical assumptions to build PDFs can be estimated by comparing the sets proposed by different groups (MRST and CTEQ, for instance).

C. TWO types of PDF uncertainties:

   1. On the estimated acceptance: they are part of the experimental error
   2. On the estimated total rate: they affect theoretical estimates of cross section

D. We are experimentalists: we will study the rapidity distributions in data, confront them to the existing PDF sets and improve these sets if possible.

Cross sections (CMS TDR, 1 fb^{-1})

$$\sigma(pp \to Z+X \to \mu^+\mu^- + X) = 1160 \pm 2(stat.) \pm 28(syst.) \pm \text{lumi uncert.} \,[\text{pb}]$$

i.e.

$$\frac{\Delta\sigma}{\sigma} = 0.13\,\% \pm 2.4\,\% \pm \text{lumi uncert.} \qquad (\text{k-factor}=1.45)$$

$$\sigma(pp \to W+X \to \mu\nu + X) = 14700 \pm 6(stat.) \pm 540(syst.) \pm \text{lumi uncert.} \,[\text{pb}]$$

i.e.

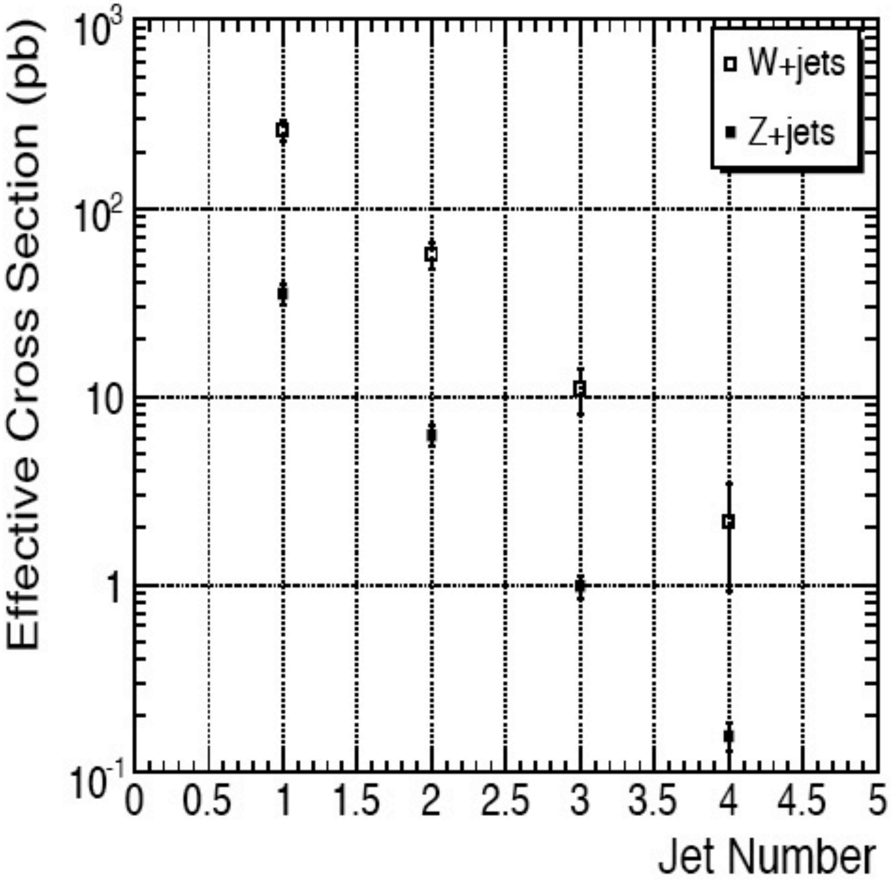
$$\frac{\Delta\sigma}{\sigma} = 0.04\,\% \pm 3.8\,\% \pm \text{lumi uncert.} \qquad (\text{k-factor}=1.36)$$

Conversely, a luminosity measurement with a 6-7% systematic uncertainty is possible, if today's estimates are proven to be correct (to be confronted to the first rapidity distributions obtained at the LHC).

(PDF uncertainties in the theoretical expected rate ~ 6%)

pp->W/Z + jets

CMS: visible cross sections [pb]
(= #events seen / pb)



This channel is relevant for:

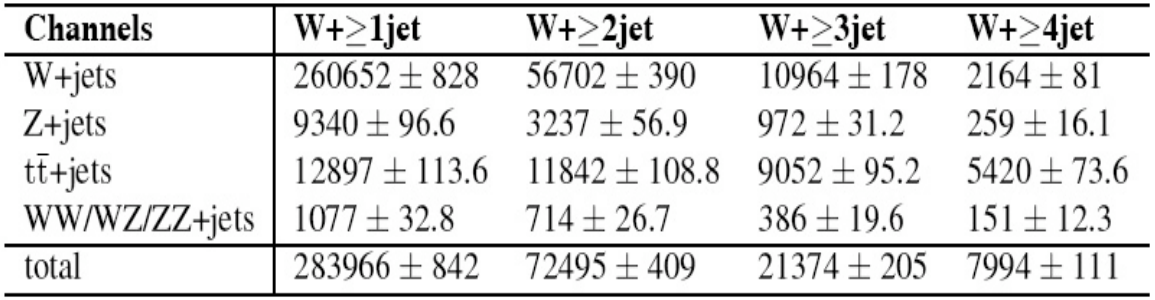
- Physics: QCD studies
- Reduce jet energy scale uncertainties (via Z + jet)
- It is an important background for many new particles searches (looking for leptons and jets)

pp->W/Z + jets

- Not so different from inclusive W/Z production. Jet must be identified and the QCD background must eliminated via very stringent lepton isolation cuts

Analysis from CMS (E_T(jet) > 50 GeV)

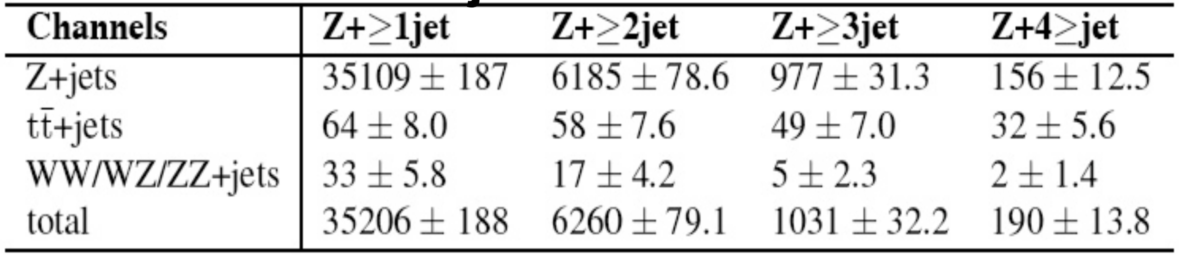
Number of W+jets events for L = 1 fb^{-1}



Channels	W+≥1jet	W+≥2jet	W+≥3jet	W+≥4jet
W+jets	260652 ± 828	56702 ± 390	10964 ± 178	2164 ± 81
Z+jets	9340 ± 96.6	3237 ± 56.9	972 ± 31.2	259 ± 16.1
$t\bar{t}$+jets	12897 ± 113.6	11842 ± 108.8	9052 ± 95.2	5420 ± 73.6
WW/WZ/ZZ+jets	1077 ± 32.8	714 ± 26.7	386 ± 19.6	151 ± 12.3
total	283966 ± 842	72495 ± 409	21374 ± 205	7994 ± 111

sizeable top background in W+jet channels

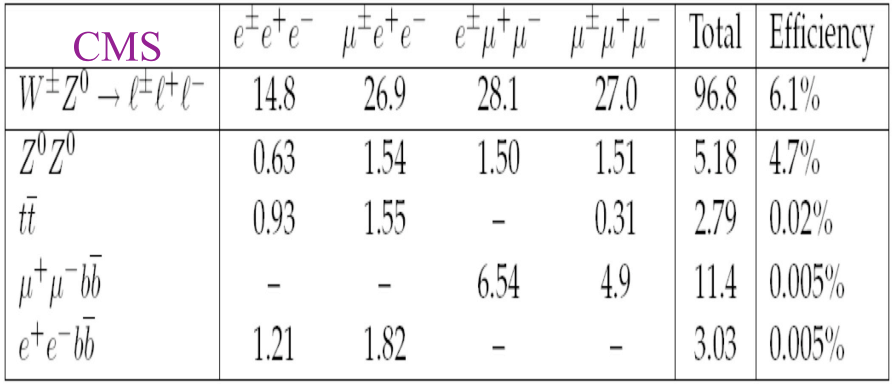
Number of Z+jets events for L = 1 fb^{-1}



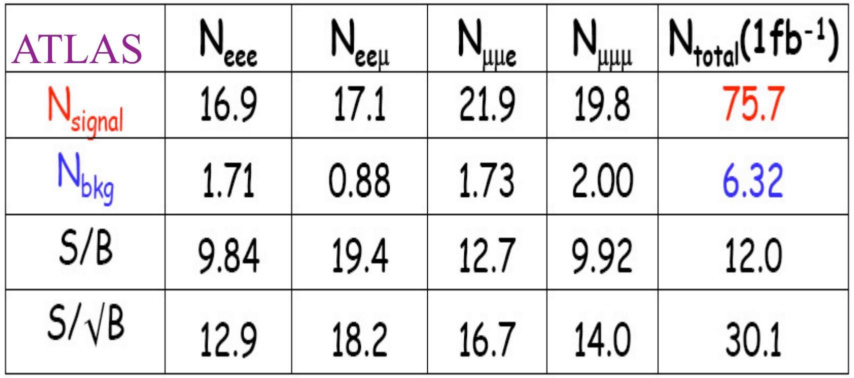
Channels	Z+≥1jet	Z+≥2jet	Z+≥3jet	Z+4≥jet
Z+jets	35109 ± 187	6185 ± 78.6	977 ± 31.3	156 ± 12.5
$t\bar{t}$+jets	64 ± 8.0	58 ± 7.6	49 ± 7.0	32 ± 5.6
WW/WZ/ZZ+jets	33 ± 5.8	17 ± 4.2	5 ± 2.3	2 ± 1.4
total	35206 ± 188	6260 ± 79.1	1031 ± 32.2	190 ± 13.8

Z + 4 jets already observable with L ~ 100 pb^{-1}

Diboson production



CMS	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency
$W^\pm Z^0 \to \ell^\pm \ell^+ \ell^-$	14.8	26.9	28.1	27.0	96.8	6.1%
$Z^0 Z^0$	0.63	1.54	1.50	1.51	5.18	4.7%
$t\bar{t}$	0.93	1.55	-	0.31	2.79	0.02%
$\mu^+ \mu^- b\bar{b}$	-	-	6.54	4.9	11.4	0.005%
$e^+ e^- b\bar{b}$	1.21	1.82	-	-	3.03	0.005%

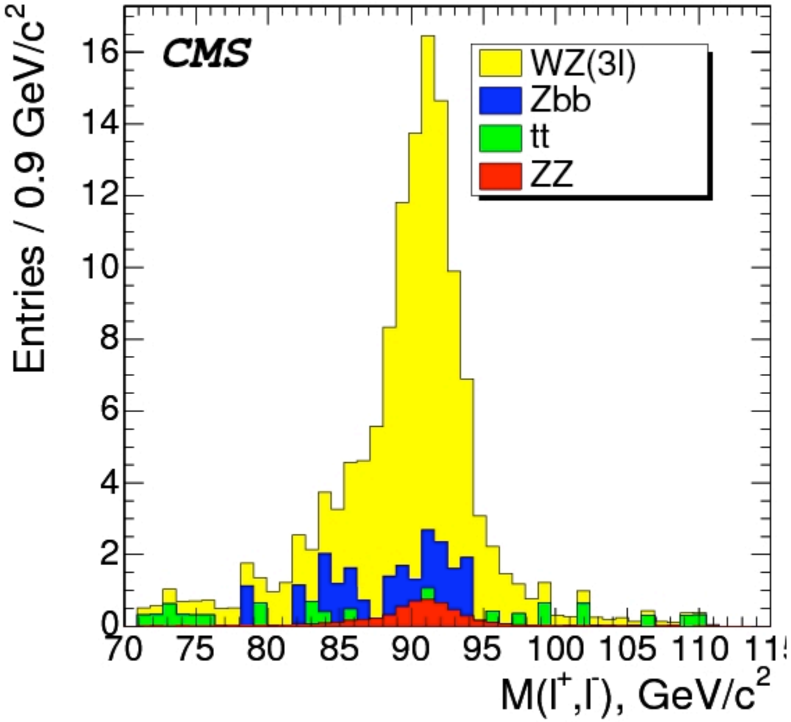


ATLAS	N_{eee}	$N_{ee\mu}$	$N_{\mu\mu e}$	$N_{\mu\mu\mu}$	$N_{total}(1fb^{-1})$
N_{signal}	16.9	17.1	21.9	19.8	75.7
N_{bkg}	1.71	0.88	1.73	2.00	6.32
S/B	9.84	19.4	12.7	9.92	12.0
$S/\sqrt{B}$	12.9	18.2	16.7	14.0	30.1

Diboson production is important for:

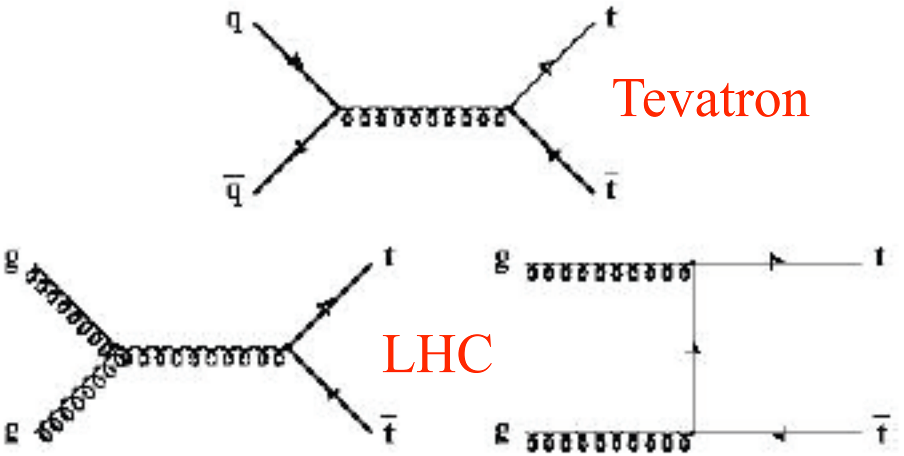
- TGC measurements (but not early)
- Understand background for new physics (H->WW, for instance)

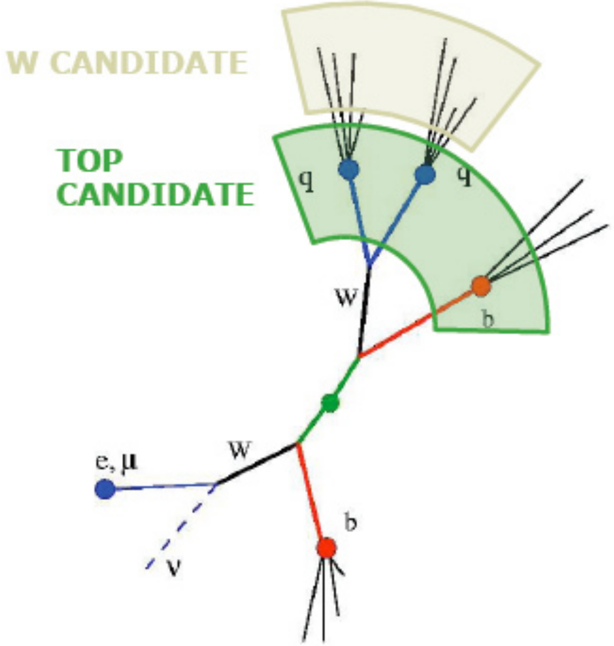
WZ production already observable in CMS (5σ) with L = 150 pb^{-1} !!



Top production

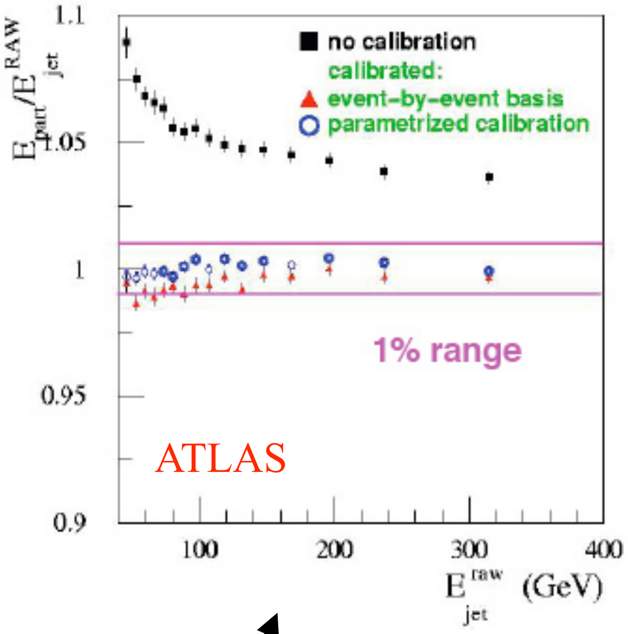
- ✓ Top production is huge at the LHC: σ ~ 800 pb, dominant process is gg->ttbar , rate ~ 100 times Tevatron for the same luminosity.



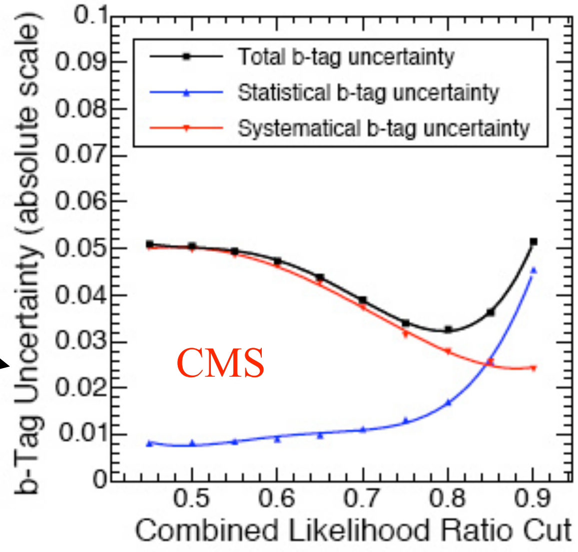


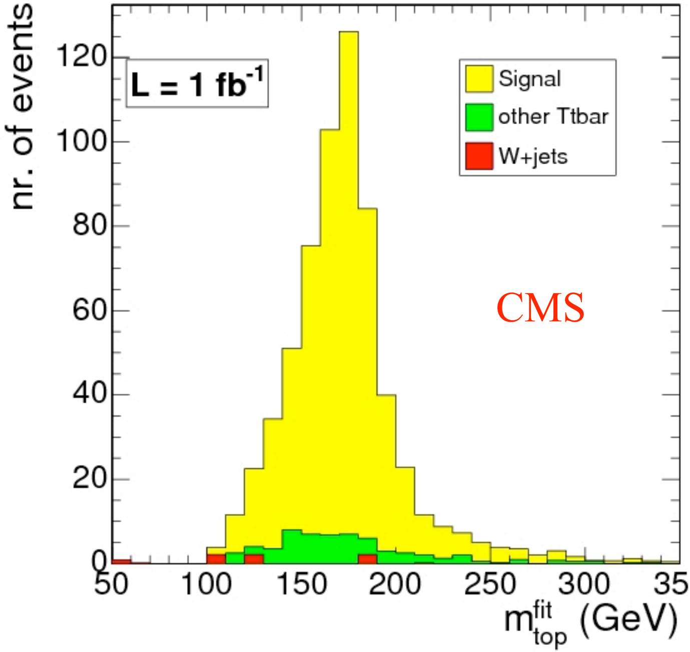
- ✓ Understanding top production => understanding the whole detector: lepton identification, resolutions, isolation, jets, missing energy, b-tagging, ... => spin-offs: jet scale calibration, b-tagging efficiencies,...

Top studies



b-tagging efficiency determination (in ttbar events)





Energy scale calibration (with W bosons in ttbar events)

+ many other inputs (alignment, calibrations, missing ET,...)

Final mass plot

General misconception?

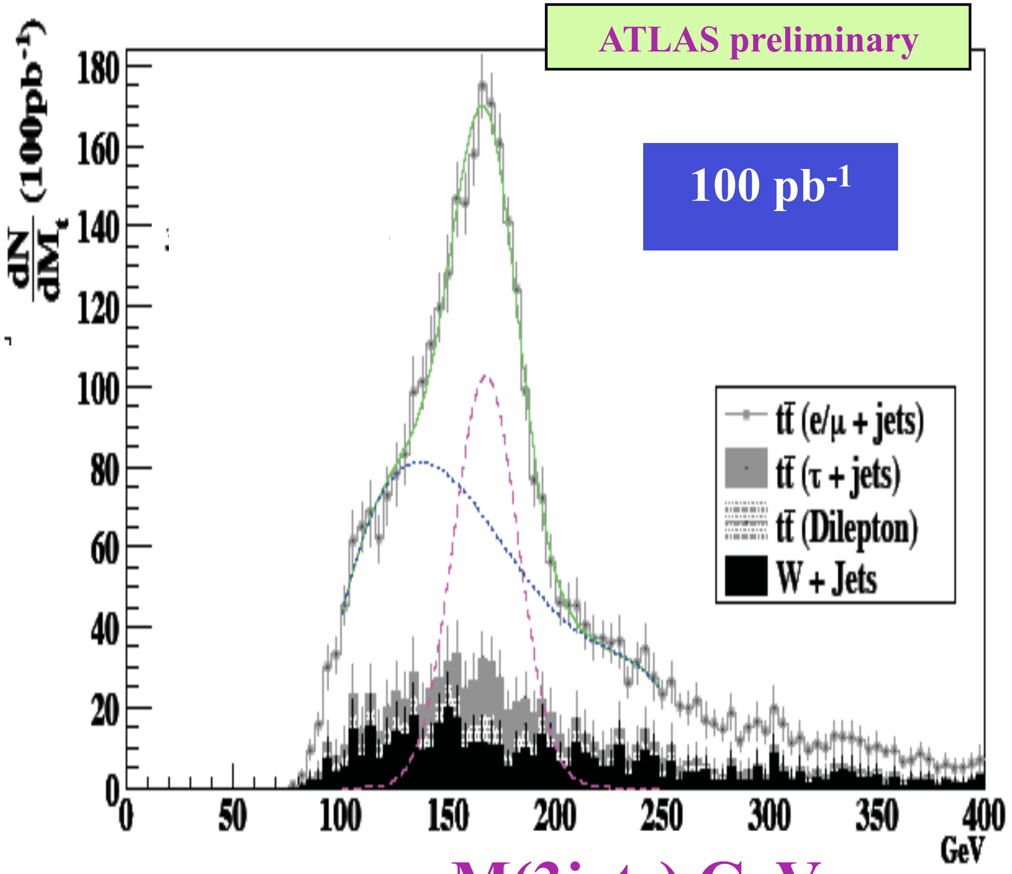
- ✓ There is the general assumption that detectors in hadronic colliders take too much time to calibrate and understand. This might not be the case at the LHC.
  - ✓ Note that at Tevatron top cross sections are small and collecting large EW samples for calibration took some time.
  - ✓ LHC detectors with an integrated luminosity of L ~ 100 pb^{-1} will have an enormous amount of dilepton events at resonances (J/Psi. Y, Z) and ttbar events to understand jet resolutions and b-tagging.
  - ✓ The challenge is rather on the organizational side: we need to process and analyze all these useful data as soon as possible.

Top production

- ✓ Progressive scenarios are considered by both experiments (ATLAS, CMS):
  - ✓ L ~ 10 pb^{-1}: rediscover the top (leptonic W decays, semi-leptonic channels, measure cross sections for the first time)
  - ✓ L ~ 100 pb^{-1}: establish methods, precise measurement of cross sections, first measurements of the top mass, start to understand detector effects in more detail.
  - ✓ L ~ 1 fb^{-1}: detector ‘almost’ understood, exploit full physics potential.

Top studies at $\leq$ 100 pb^{-1} (ATLAS)

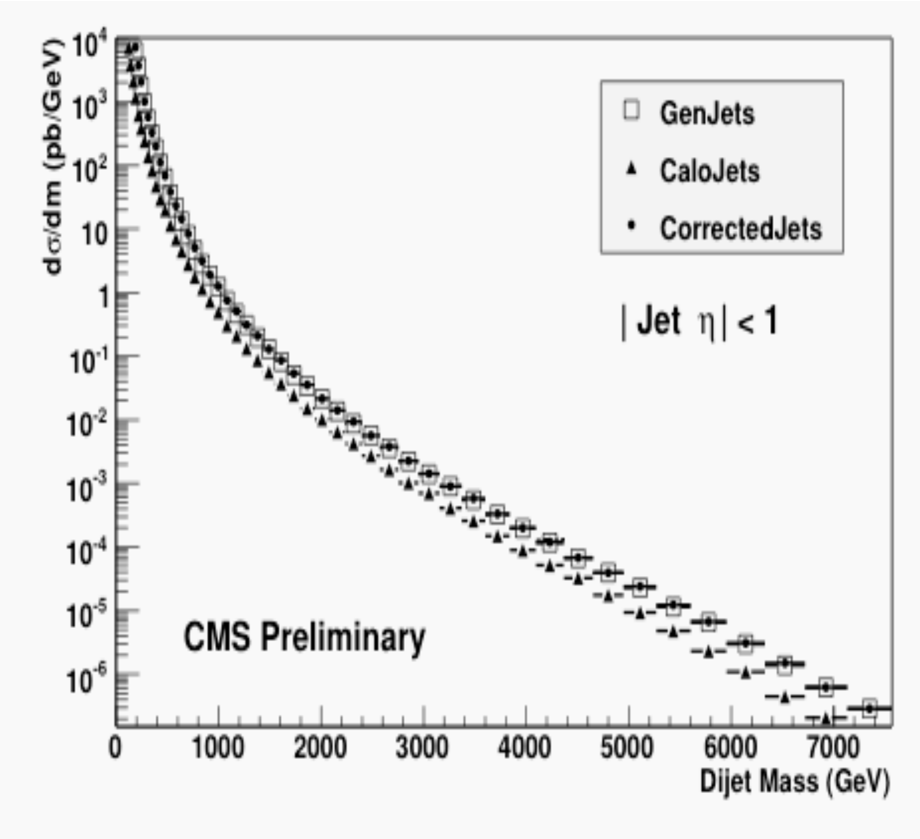
- p_T(lepton) > 20 GeV
- 3 jets with p_T(jet) > 40 GeV
- 1 jet with p_T(jet) > 20 GeV
- Missing E_T>20 GeV
- |η(lepton)|<2.4, |η (jet)|<2.5
- Top is reconstructed as the 3-jet combination with the highest p_T sum

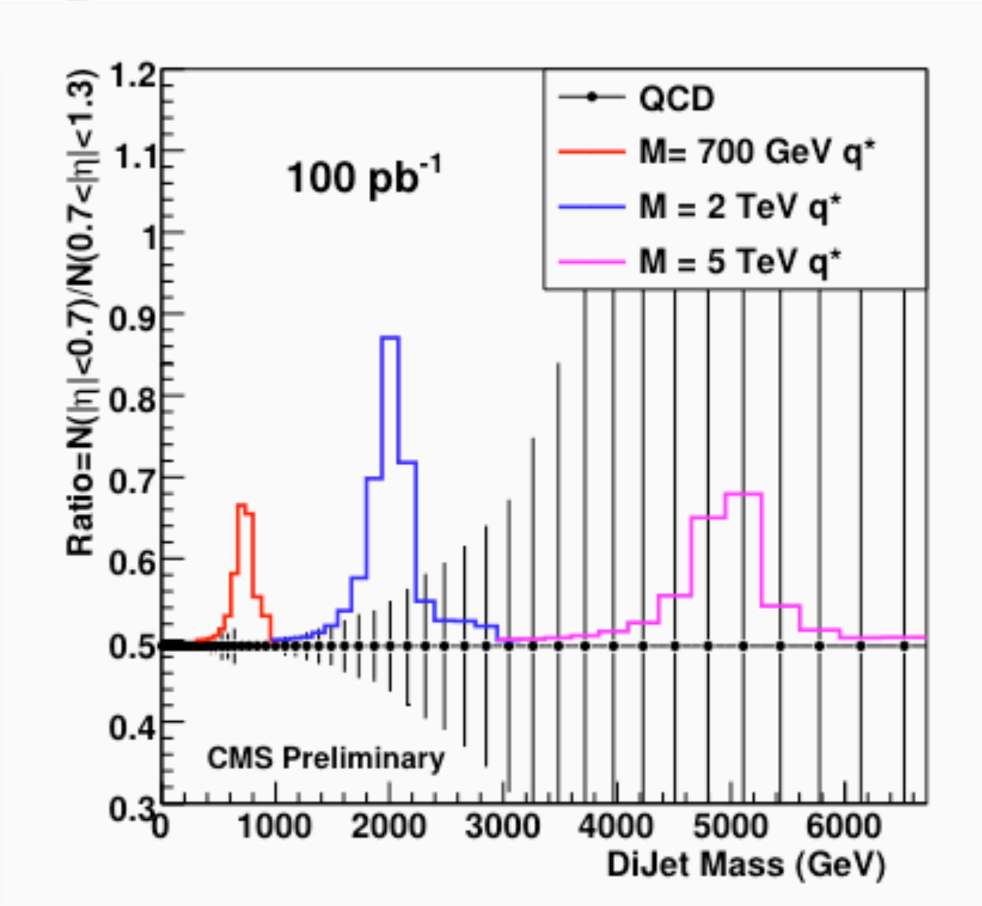


M(3jets) GeV

Loose cuts: no b-tagging, …

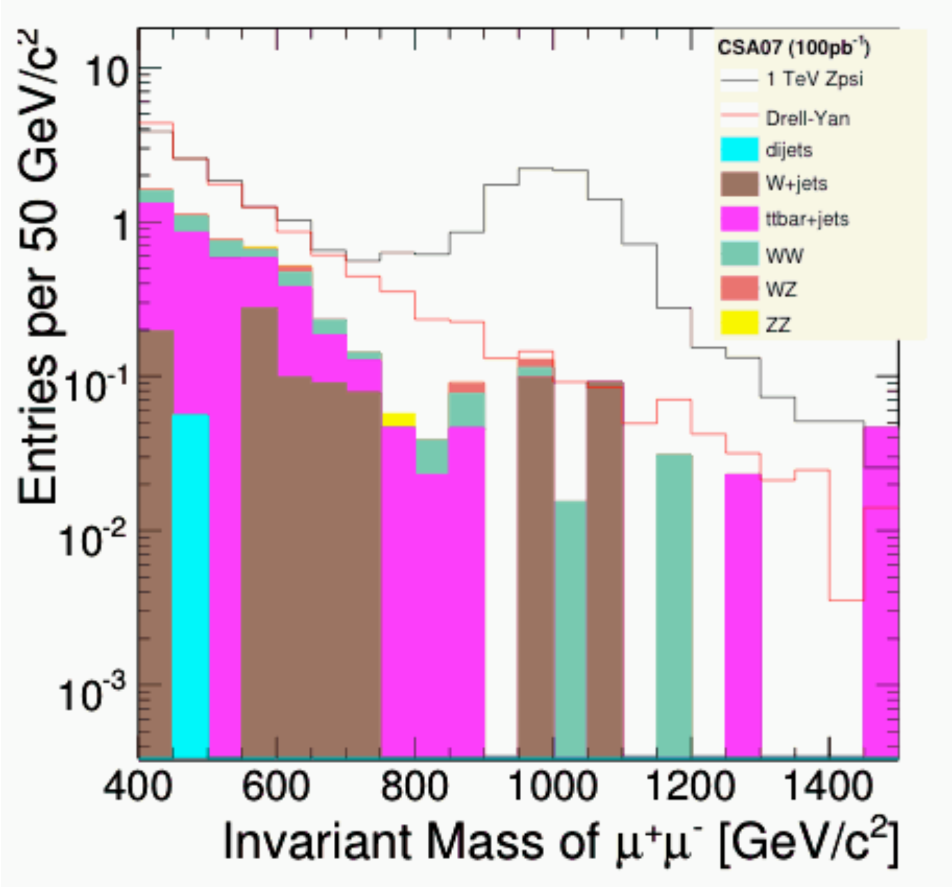
What about early discoveries?

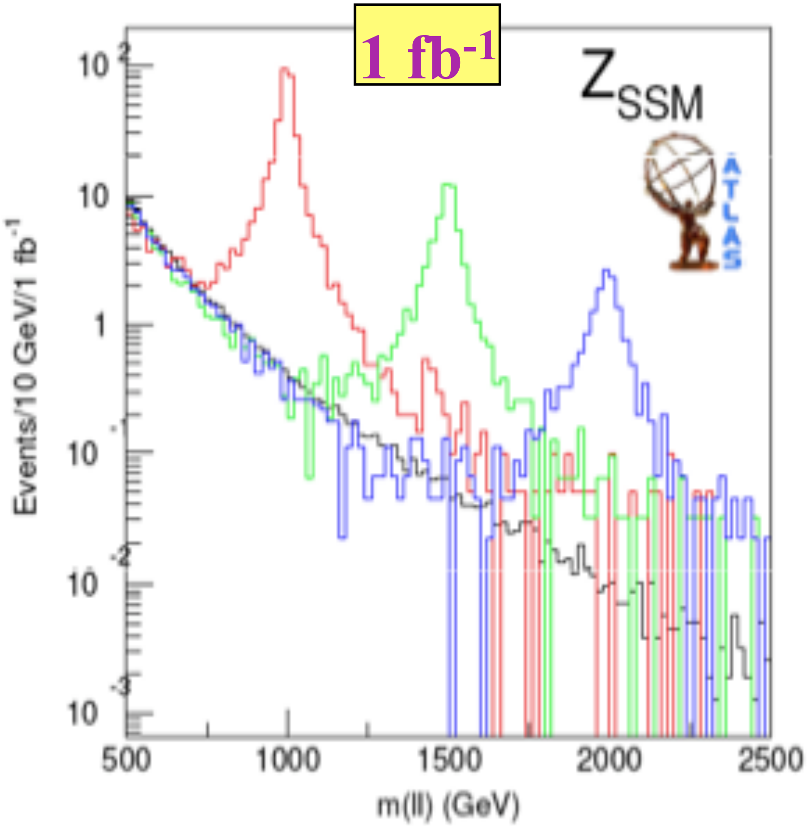




- Using di-jet invariant mass spectrum. CMS: use ratios in different angular regions (new physics manifests at low eta).

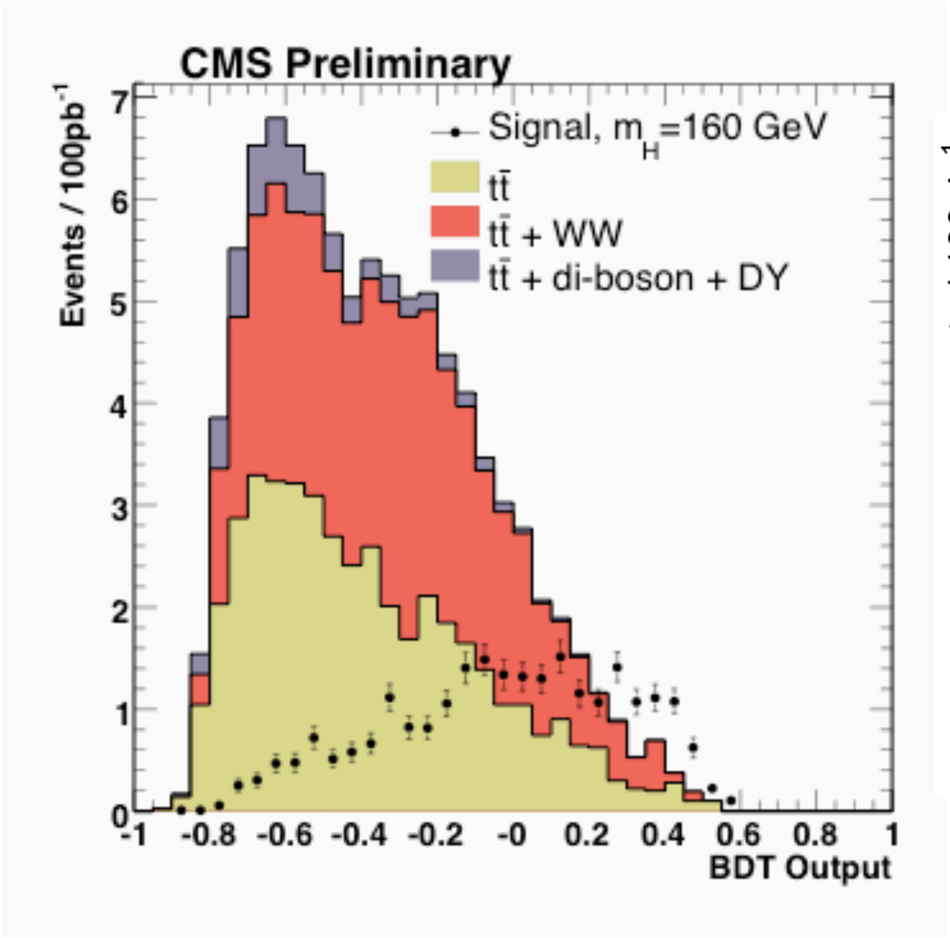
What about early discoveries?

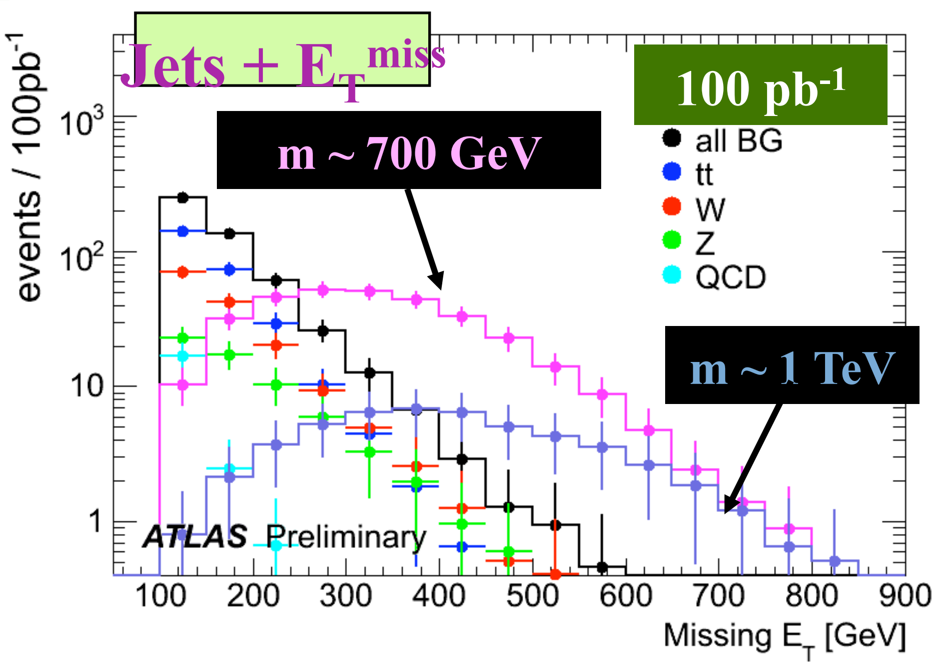




- **100 pb^{-1} are enough to discover di-lepton resonances in the TeV range, as predicted in some extensions of the Standard Model.**

What about early discoveries?





Jets + E_T^{miss}

100 pb^{-1}

m ~ 700 GeV

m ~ 1 TeV

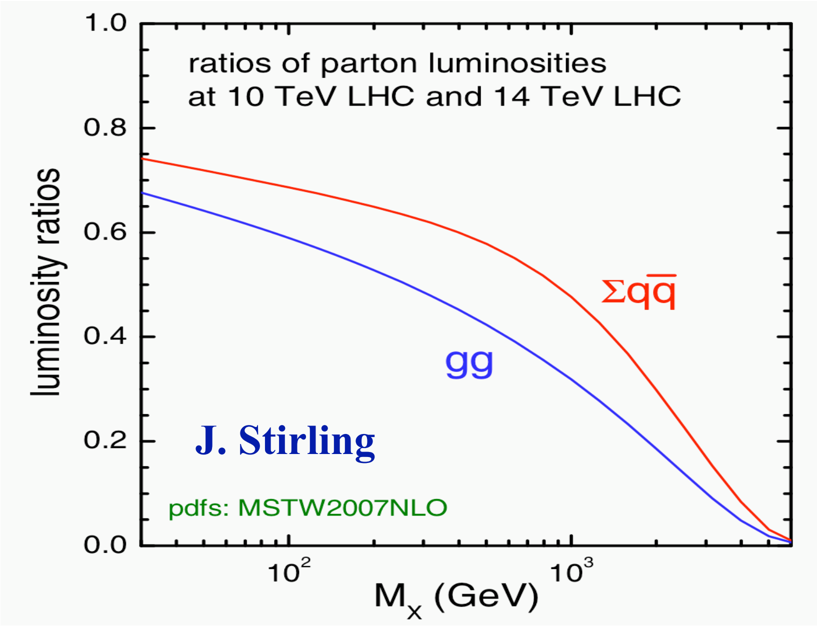
- **Higgs and SUSY discoveries are difficult for L < 1 fb^{-1}**

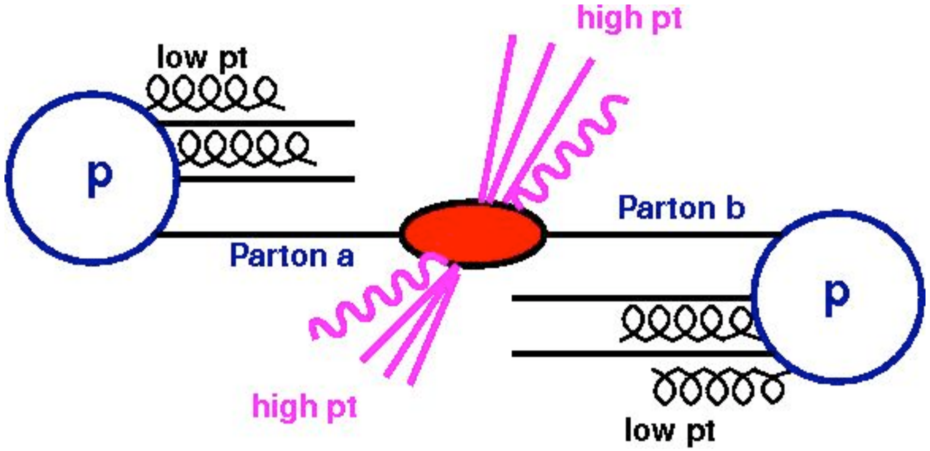
•**One needs to understand backgrounds and tails first…**

Ciemat

Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

The LHC at √s = 10 TeV





- ✓ Major changes with respect to √s = 14 TeV:
  - ✓ Cross sections reduced by a factor of two:
    - ✓ W/Z cross sections ~ 70% (slightly compensated by larger acceptance at lower rapidities)
    - ✓ Ttbar cross section ~ 50%
    - ✓ Higgs (m=200 GeV) ~ 50%

- ✓ Strong reduction of the energy reach for high masses and energy scales
  - ✓ Z' resonance (m=2 TeV) ~ 30%
  - ✓ One order of magnitude less reach for new physics effects at scales of ≥ 4 TeV

- ✓ Subtle effects:
  - ✓ Less gluon-gluon relative to qqbar hard interactions (PDF effect)

Conclusions

- QCD and EW processes at start-up are extremely important in the LHC programme:
  - They are unique tools to understand our detectors and algorithms
  - They are not so well known: PDF uncertainties in a new (x,Q^2) regime.
  - They are the main background for our searches and maybe the first ‘warning flag’ for early new physics.

- These processes will provide sizeable samples already at luminosities as low as 1 pb^{-1} (jets, W/Z). New channels will become visible before reaching 1 fb^{-1}: top (~ 20 pb^{-1}), W/Z + 4 jets (~100 pb^{-1}) ,dibosons (WZ, ~150 pb^{-1}), ...

- LHC experiments are developing strategies and organizing efforts to understand as soon as possible our detectors and the basic QCD/EW processes. This is critical for the success of the LHC programme.