Early Physics at the LHC

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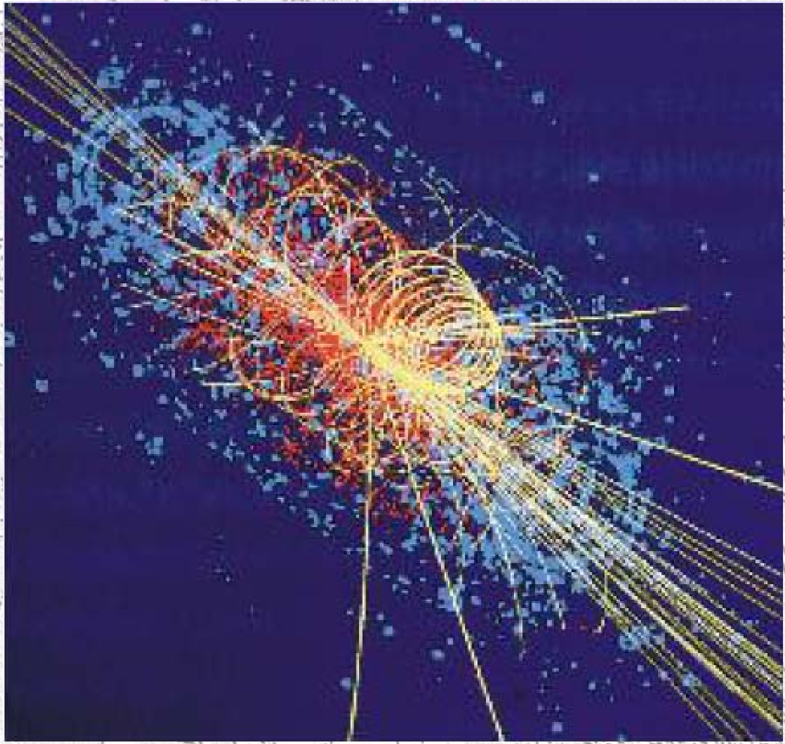
Outline

- Lecture 1:
  Physics at proton colliders
  Status of LHC

- Lecture 2:
  Standard Model physics

- Lecture 3:
  Searches for new particles & phenomena
  e.g. Higgs and SUSY



LHC Startup Scenario

- **Steps from first collisions to full luminosity**

Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156	936	2808	2808
Bunch spacing (ns)	2021-566	75	25	25
N (10^{11} protons)	0.4-0.9	0.4-0.9	0.5	1.15
Crossing angle (μrad)	0	250	280	280
$\sqrt{(\beta^*/\beta^*_{nom})}$	2	$\sqrt{2}$	1	1
σ^* (μm, IR1&5)	32	22	16	16
L ($cm^{-2}s^{-1}$)	$6\times10^{30}-10^{32}$	$10^{32}-10^{33}$	$(1-2)\times10^{33}$	10^{34}

J. Wenninger

LHC Startup Scenario

Approx 30 days of beam time to establish first collisions

1 to N to 43 to 156 bunches per beam

Pushing gradually one or all of:

- **Bunches per beam**
- **Squeeze**
- **Bunch intensity**

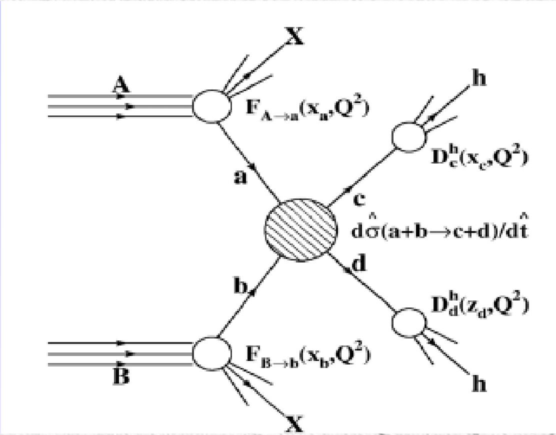
Bunches	β*	I_b	Luminosity	Event rate
1 x 1	18	10^{10}	10^{27}	Low
43 x 43	18	3×10^{10}	3.8×10^{29}	0.05
43 x 43	4	3×10^{10}	1.7×10^{30}	0.21
43 x 43	2	4×10^{10}	6.1×10^{30}	0.76
156 x 156	4	4×10^{10}	1.1×10^{31}	0.38
156 x 156	4	9×10^{10}	5.6×10^{31}	1.9
156 x 156	2	9×10^{10}	1.1×10^{32}	3.9

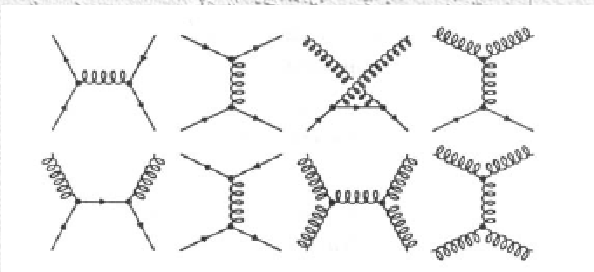
Expected LHC Luminosities

- Disclaimer:
  - my personal, very debatable and probably very wrong guess!
  - just for the sake of our discussion
  - to provide some orientation

- 2008:
  - 0.1 fb^{-1} i.e. ≈ 1 month at $10^{32}/cm^2/s$
- 2009:
  - 1 fb^{-1} 1 year at $10^{32}/cm^2/s$
  - few fb^{-1} if $10^{33}/cm^2/s$ reached
- 2010:
  - ≥ 10 fb^{-1} 1 year at up to $2\cdot10^{33}/cm^2/s$

QCD and Jet Physics

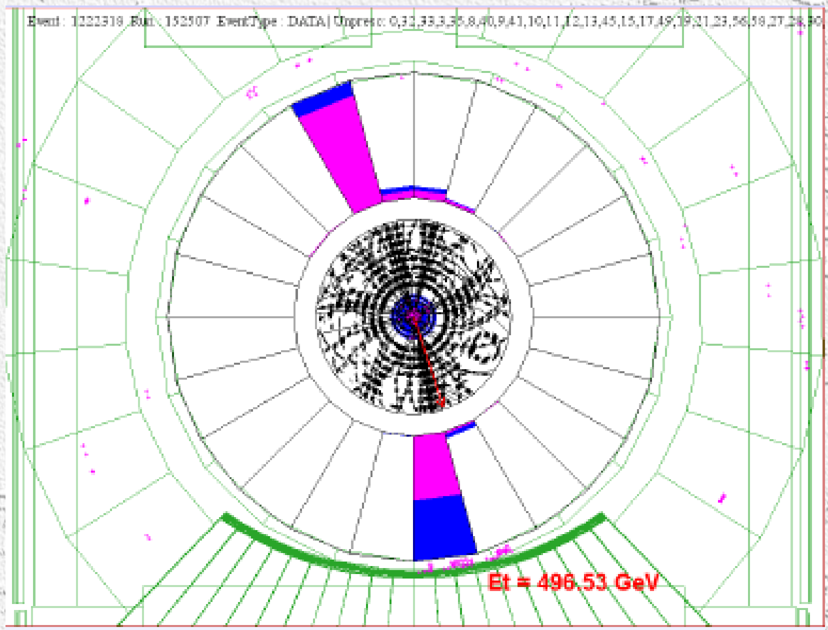




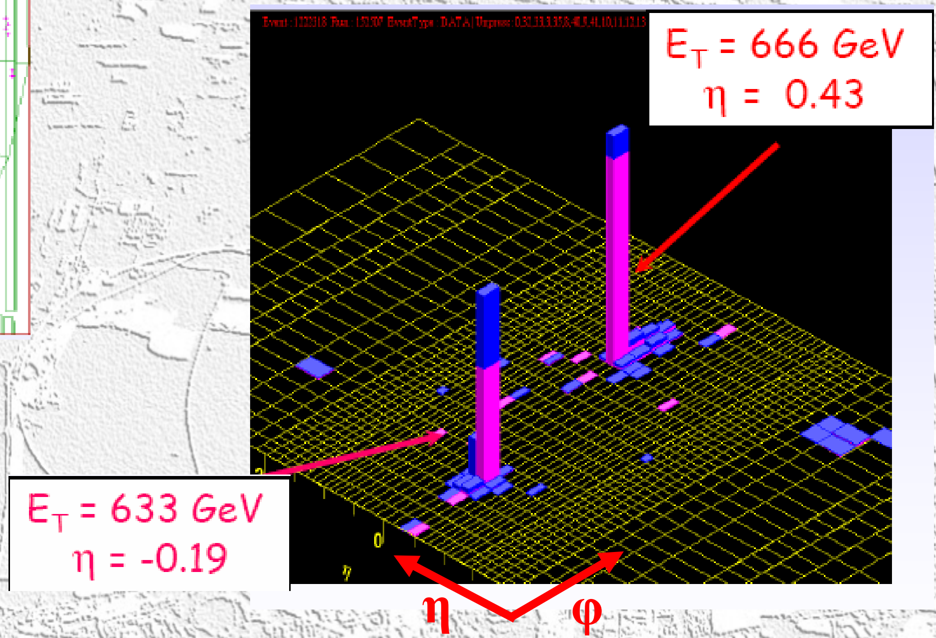
- Hard scattering processes dominated by QCD jet production
- Originating from quark-quark, quark-gluon and gluon-gluon scattering
- colored objects fragment
  → observation of jets with high p_T in the detectors
- Studies of jet production is important
  - test of the experiment
  - test of the theory, down to the smallest distances
  - new physics, e.g. quark substructure?

QCD and Jet Physics

A two-jet event at the Tevatron (CDF)



Lego-plot:
- project objects on ηφ -plane
- height of tower ~ energy

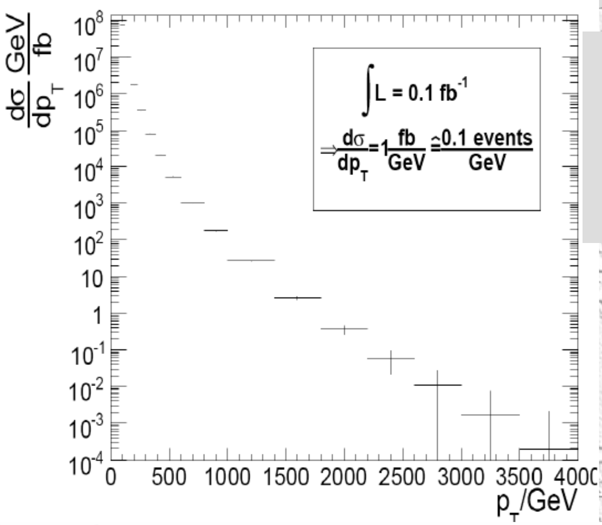


Mass of the di-jet system:

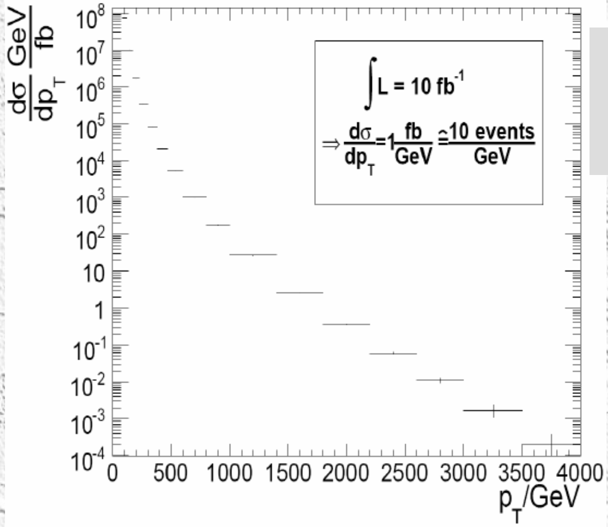
1.364 TeV

LHC Jet Physics

- Jet rates will be one of the first LHC results: statistical precision

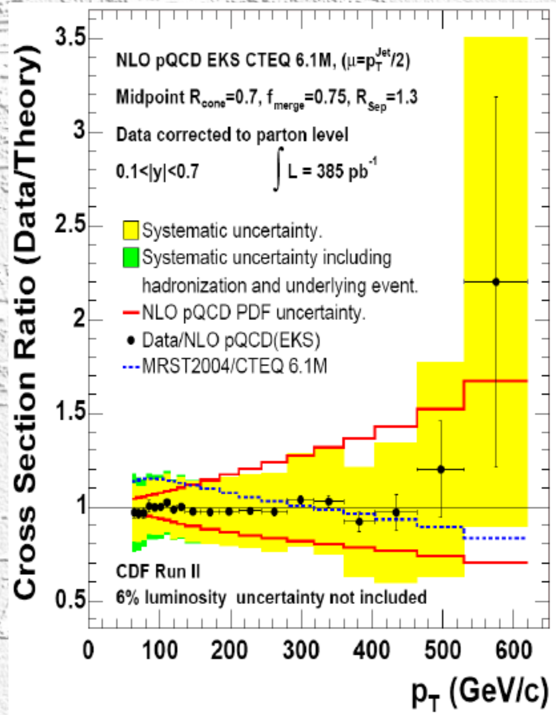


100 pb^{-1} = few weeks at 14 TeV



10 fb^{-1} = 1 year

- compare to CDF result run II

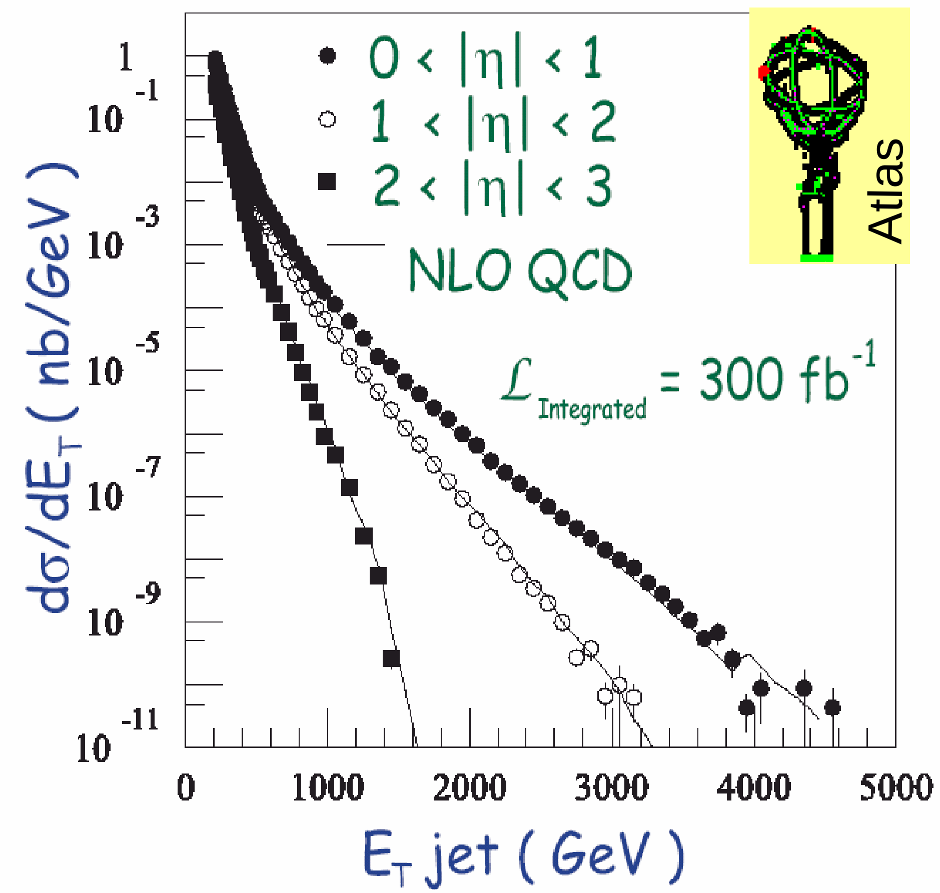


- detector systematic effects expected to be similar to Tevatron
- provides handle on PDF

Jet Physics

Jet physics at the LHC

- E_T spectrum, rate varies over 11 orders of magnitude
- Test QCD at the multi-TeV scale



Inclusive jet rates for 300 fb^{-1}:

E_T of jet	Events
> 1 TeV	$4{\cdot}10^6$
> 2 TeV	$3{\cdot}10^4$
> 3 TeV	400

QCD

Measurement of α_s at LHC limited by

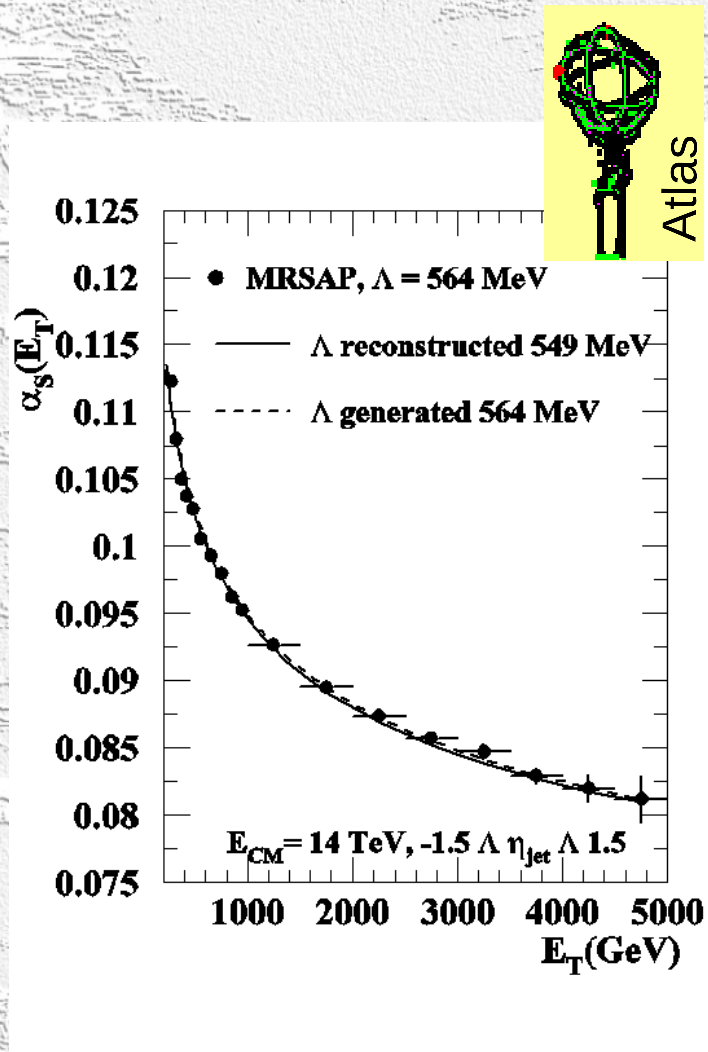
- **PDF (3%)**
- **Renormalisation & factorisation scale (7%)**
- **Parametrisaton (A,B)**

$$\frac{d\sigma}{dE_T} \sim \alpha_S^2(\mu_R)A(E_T) + \alpha_S^3(\mu_R)B(E_T)$$

- **10% accuracy $\alpha_s(m_Z)$ from incl. jets**
- **Improvement from 3-jet to 2-jet rate?**

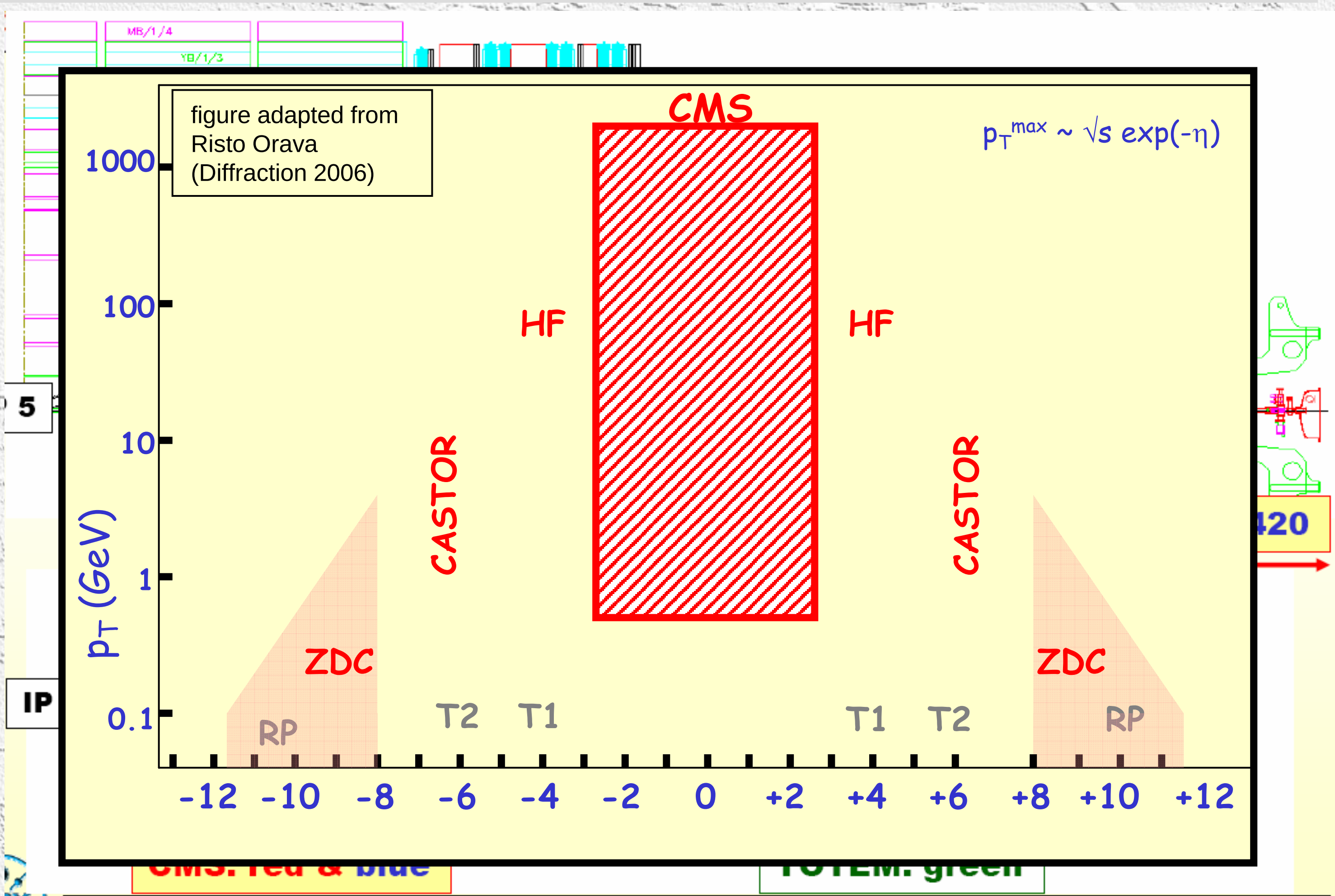
Verification of running of α_s and test of QCD at the smallest distance scale

- **$\alpha_s = 0.118$ at m_Z**
- **$\alpha_s \approx 0.082$ at 4 TeV (QCD expectation)**

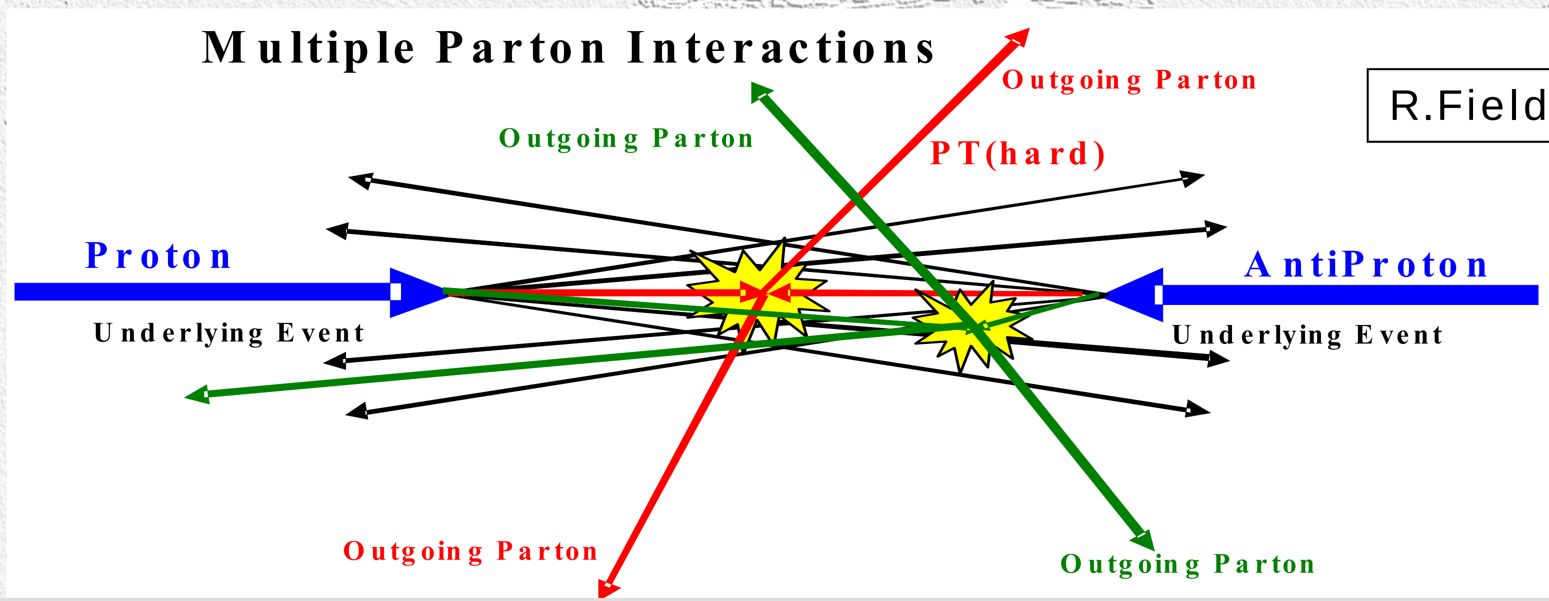


Forward Physics and Diffraction

- CMS + TOTEM share same LHC interaction region
- coverage to large η values (forward region)
- in particuar important for low luminosity phase (i.e. no/low pile-up)



Multiple Interactions & Underlying Event



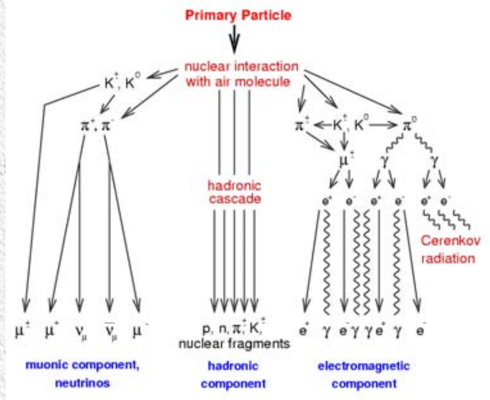
In addition to the single hard interaction with large p_T:

- (soft) interactions with low p_T → Underlying Event
  (remnant-remnant interactions and parton showers ...
  → additional energy offset)
- more hard interactions → Multi – Parton Interactions
  (see evidence from CDF 1997: need > 50% double parton interaction for γ + 3 jet)

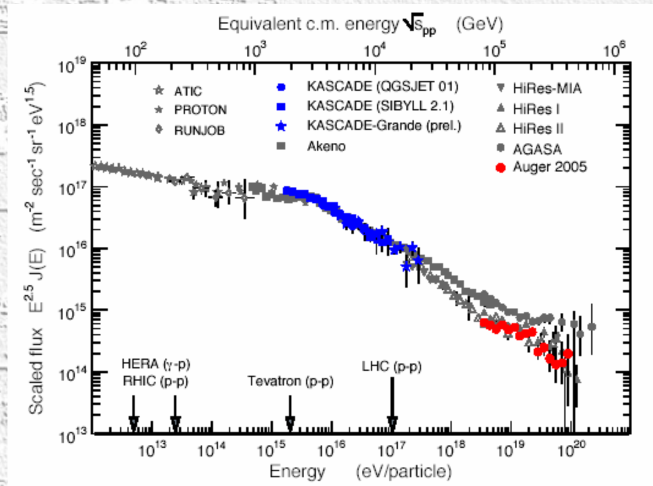
→ important for jet analyses (additional UE energy) or
$p\bar{p} \rightarrow W+H+X$ with $W \rightarrow l+\nu$ and $H \rightarrow b\bar{b}$ (MI: $p\bar{p} \rightarrow W+X_W + b\bar{b}+X_b$ without any Higgs!)

Underlying event and Multi – Parton Interactions crucial for all precision measurements !

Hadronic Shower Models for Cosmic Ray Physics



Dynamics of the high energy particle spectrum is crucial for the understanding of cosmic ray data. But models differ significantly !

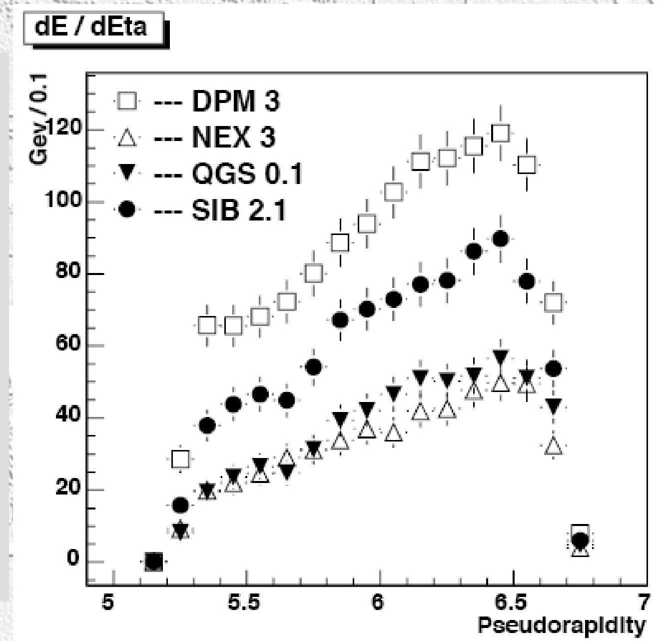


Statistics for 100 PeV in fixed target frame is low

($O(10^{-4})$ particles per m^2 per year).

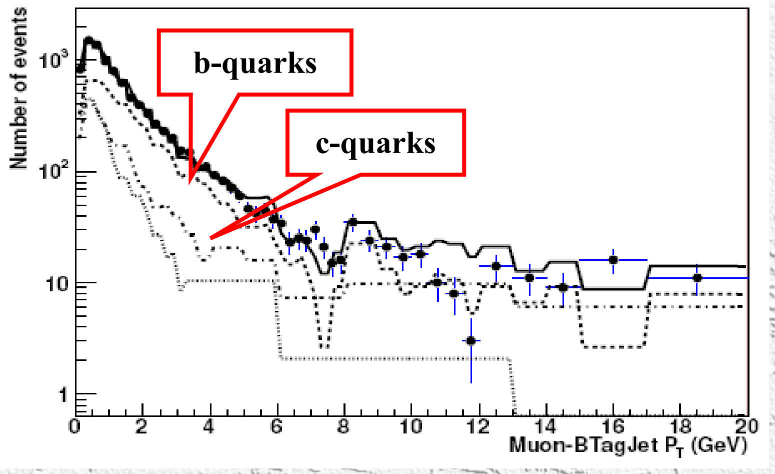
High momenta are needed
→ only available in the forward region

→ measurement of energy (HF, CASTOR, ZDC) and particle flow (T1, T2) in the forward regions will help to tune the models and the generators.



B-physics

- **Inclusive b production**
- cross section error ± 18%
- sensitive up to $p_T \approx 1.5$ TeV

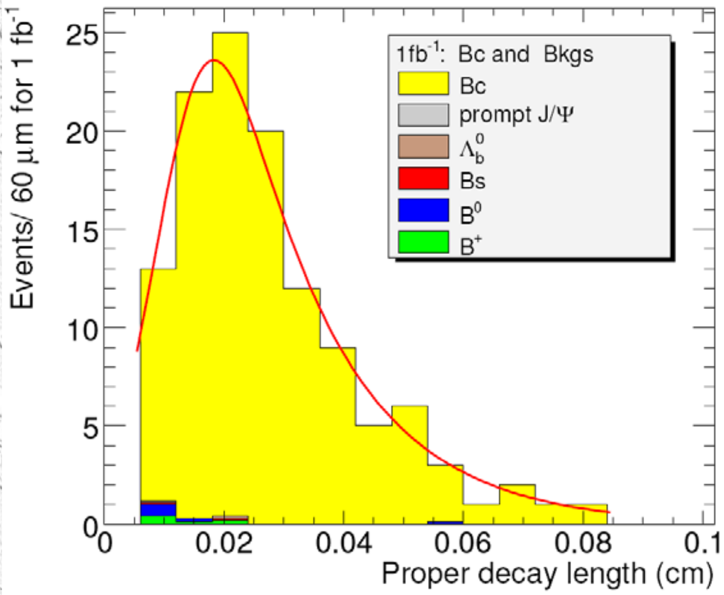


- **B_c hadrons**
- measurement of mass and lifetime
- in 1 fb^{-1} integrated luminosity
  $\approx$ 120 events $B_c \rightarrow J/\Psi\pi$
  with $J/\Psi \rightarrow \mu\mu$

$\Delta m = 22.0 \pm 14.9$ MeV

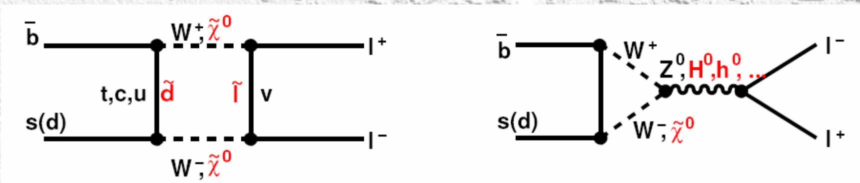
$\Delta\tau = 0.044 \pm 0.010$ ps

Note: need for a J/Ψ trigger



$B_s^0 \to \mu\mu$

- **Rare SM process sensitive to New Physics**



- **CMS AN 2006/097**
  - **1.6% signal effciency $\rightarrow \approx$ 6 events in 10 fb^{-1} (SM)**
  - **2.7·10^{-7} bkgd reduction $\rightarrow \approx$ 48 bkgd events in 10 fb^{-1}**
- **Expected upper limit**

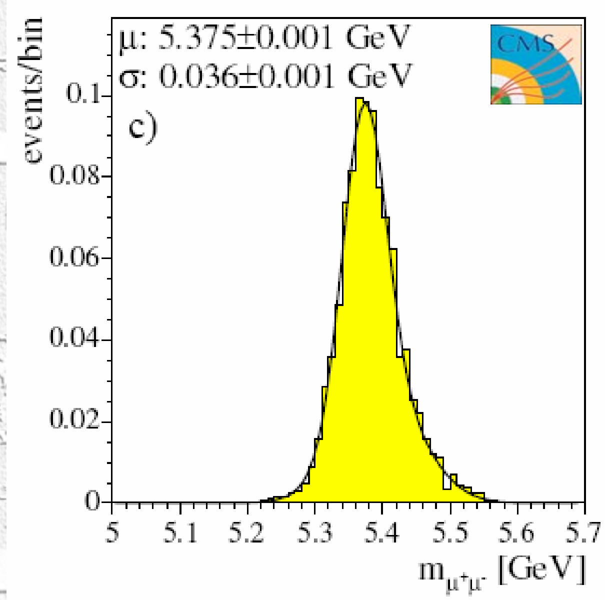
  BR($B_s^0 \rightarrow \mu\mu$) < 1.2·10^{-8}

  $\approx$ 3 times SM expectation

- **better bkgd determination from data (sidebands) will improve sensitivity**

- **SM branching ratio and exp. upper limits**

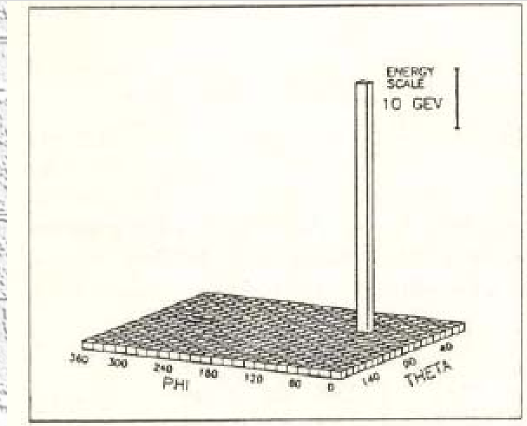
Mode	$B_s^0 \to \mu^+\mu^-$
SM Expect.	$(3.42 \pm 0.54) \times 10^{-9}$
CLEO [2]	-
BELLE [3]	-
CDF [4]	5.8×10^{-7}
D0 [5]	4.1×10^{-7}
BABAR [6]	-
CDF [7]	1.5×10^{-7}

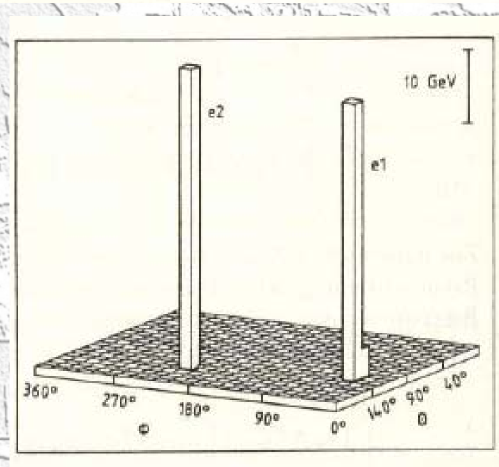


Electroweak Physics (W and Z Bosons)

W and Z bosons were discovered in proton-antiproton collisions
1983: UA1 & UA2 at the SppS collider at CERN

Examples of early W/Z events





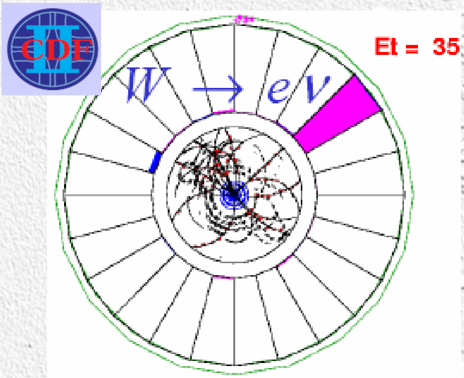
How do W/Z events look like at proton colliders?

Use leptonic decays (electrons & muons)

- **$W \rightarrow l\nu$** — **high p_T lepton + missing E_T**
- **$Z \rightarrow ll$** — **2 oppositely charged, high p_T leptons**

W and Z Bosons

Example from the Tevatron:



Electrons

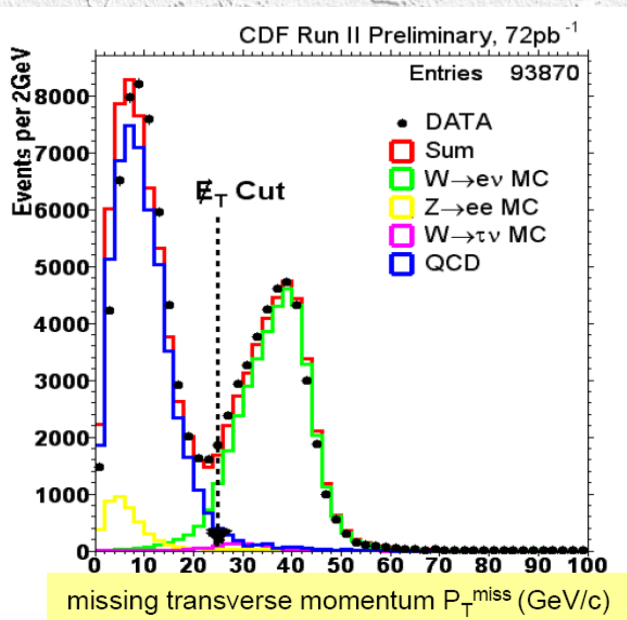
- Isolated el.magn. cluster in the calorimeter
- P_T> 25 GeV/c
- Shower shape consistent with expectation for electrons
- Matched with tracks

Z → ee

- 70 GeV/c^2 < m_{ee} < 110 GeV/c^2

W → eν

- Missing transverse momentum > 25 GeV/c



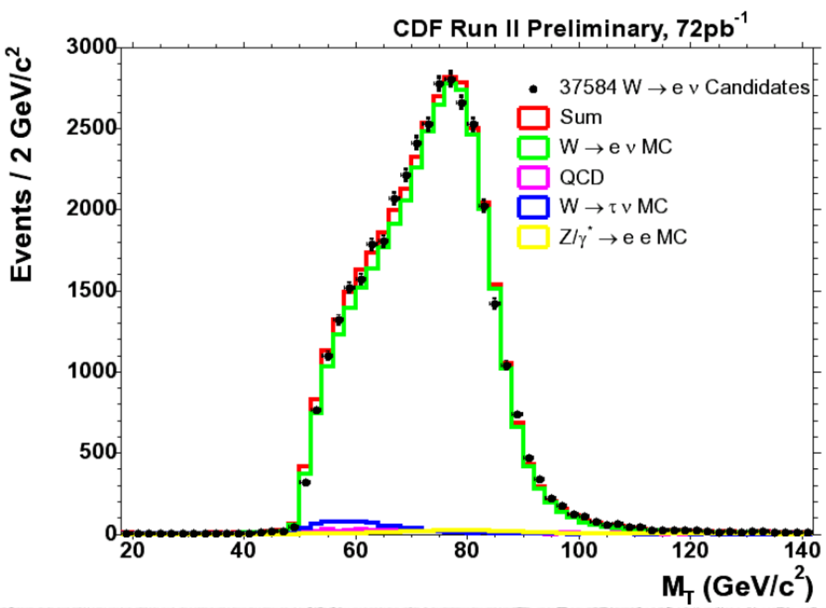
Separation of W →lν events from background

Mass of the W

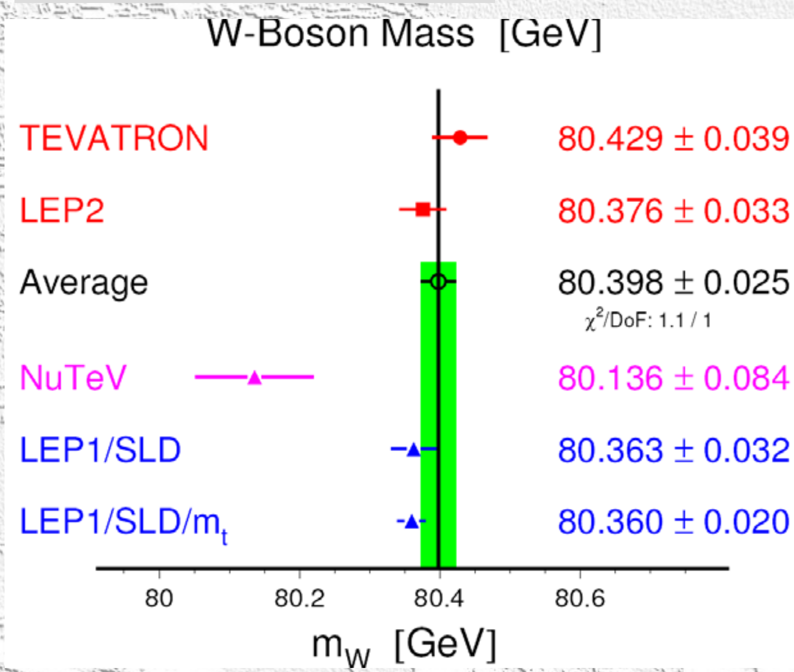
- **precision measurement at proton colliders possible**
- **results competitive to LEP experiments**

- **define transverse mass from missing E_T**

$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos\Delta\phi^{l,\nu}\right)}$$



Latest results on m_W

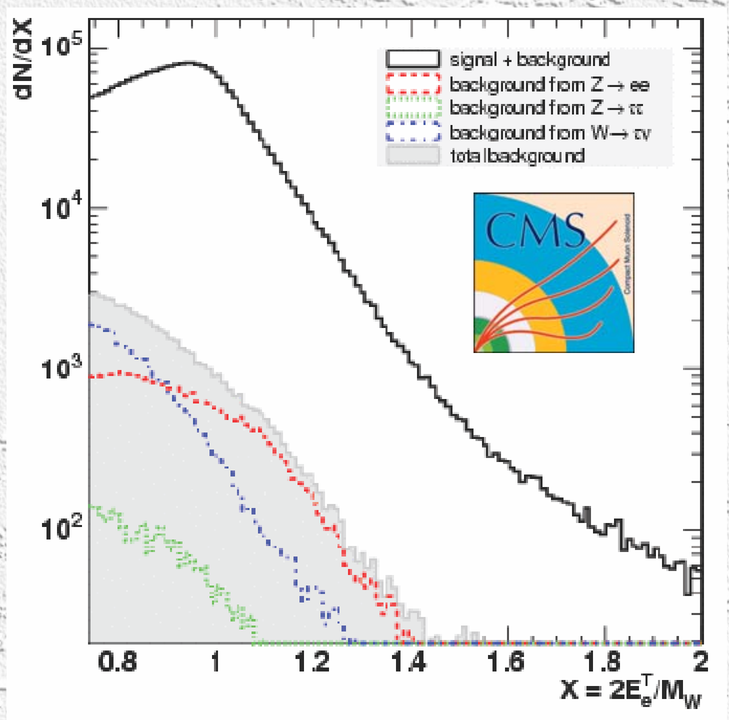


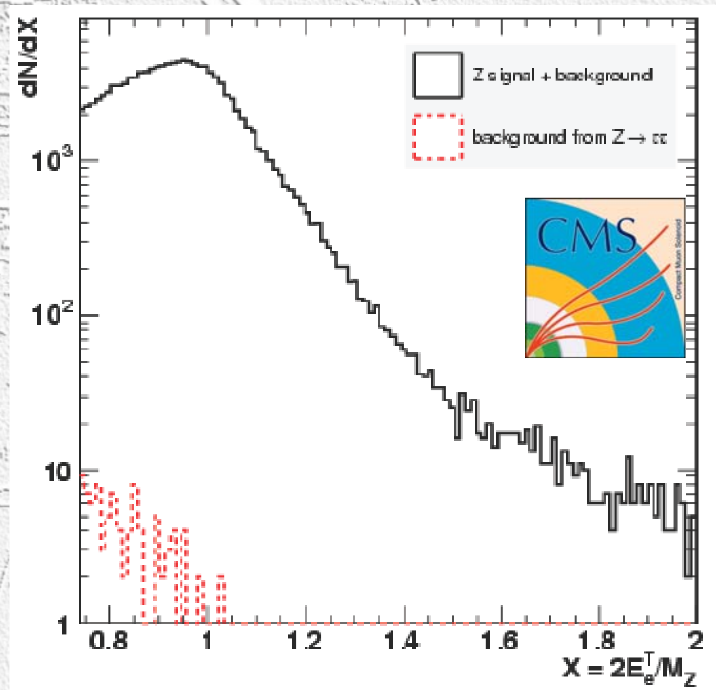
- **$3 \cdot 10^{-4}$ rel. precision on m_W**
- **Tevatron results will improve with increasing Run II statistics**

- **main challenge: electron/muon energy scale**
- **use $Z \rightarrow ee, \mu\mu$ events and precise m_Z from LEP**

W/Z Physics at the LHC

- Very clean selection of W and Z boson possible e.g. CMS study of $W \rightarrow e\nu$ and $Z \rightarrow ee$





- Recall rates (initial phase $10^{33}/cm^2/s$):
  ≈ 200 W/s → ≈ 20 $W \rightarrow e\nu$ /s
  ≈ 50 Z/s → ≈ 1.5 $Z \rightarrow ee$ /s
  plus the same rates for muon decays!

- W and Z events will provide an excellent tool for detector calibration

W Mass at the LHC

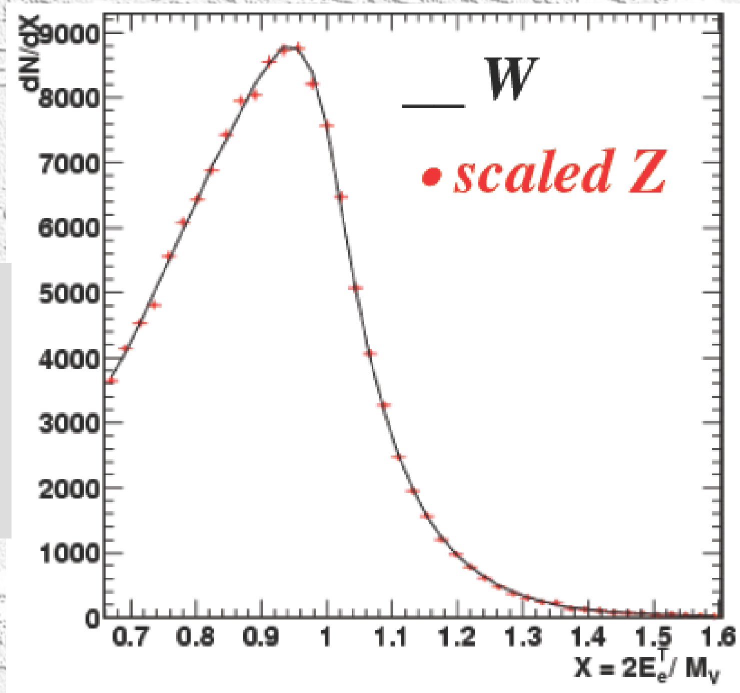
- Any improvement at the LHC requires control of systematic error to 10^{-4} level
  - take advantage from large statistics $Z \rightarrow e^+e^-, \mu^+\mu^-$
  - most experimental and theoretical uncertainties cancel in W/Z ratio
    e.g. Scaled Observable Method

$O_V = E^T, M^T$ distributions are scaled according to

$$\frac{d\sigma^W}{dO_W}(O_W = XM_W) = \frac{M_Z}{M_W} R(X) \frac{d\sigma^Z}{dO_Z}(O_Z = XM_Z)$$

T.Giele, S.Keller, PR D57 (1998)

$$R(X) = \frac{d\sigma^W / dX_W}{d\sigma^Z / dX_Z}$$



- Another method:
  generate $W \rightarrow e(\mu)\nu$ „Monte Carlo“ from data by removing a lepton from $Z \rightarrow e^+e^-, \mu^+\mu^-$ events

- NNLO calculations (p_T spectra) probably needed to achieve the required precision

W Mass at the LHC

CMS: detailed study of statistical and systematic errors

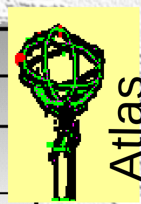
- **1 fb^{-1}: early measurement**
- **10 fb^{-1}: asymptotic reach, best calibrated & understood detector, improved theory etc.**

Source of uncertainty	uncertainty with 1 fb^{-1}	ΔM_W [MeV/c^2] with 1 fb^{-1}	uncertainty with 10 fb^{-1}	ΔM_W [MeV/c^2] with 10 fb^{-1}
scaled lepton-p_T method applied to W→ $e\nu$				
statistics		**40**		15
background	10%	10	2%	2
electron energy scale	0.25%	10	0.05%	2
scale linearity	0.00006/ GeV	30	<0.00002/ GeV	<10
energy resolution	8%	5	3%	2
MET scale	2%	15	<1.5%	<10
MET resolution	5%	9	<2.5%	< 5
recoil system	2%	15	<1.5%	<10
total instrumental		**40**		**<20**
PDF uncertainties		20		<10
Γ_W		15		<15
p_T^W		30		30 (or NNLO)
transformation method applied to W→ $\mu\nu$				
statistics		**40**		15
background	10%	4	2%	negligible
momentum scale	0.1%	14	<0.1%	<10
$1/p^T$ resolution	10%	30	<3%	<10
acceptance definition	η-resol.	19	$< \sigma_\eta$	<10
calorimeter E_T^{miss}, scale	2%	38	≤1%	<20
calorimeter E_T^{miss}, resolution	5%	30	<3%	<18
detector alignment		12	–	negligible
total instrumental		**64**		**<30**
PDF uncertainties		≈20		<10
Γ_W		10		< 10

W Mass at the LHC

ATLAS study:

Source	CDF Run Ib	ATLAS or CMS	$W \rightarrow l\nu$, one lepton species
	30K evts, 84 pb^{-1}	60M evts, 10fb^{-1}	
Statistics	65 MeV	< 2 MeV	
Lepton scale	75 MeV	15 MeV	most serious challenge
Energy resolution	25 MeV	5 MeV	known to 1.5% from Z peak
Recoil model	33 MeV	5 MeV	scales with Z statistics
W width	10 MeV	7 MeV	$\Delta\Gamma_W \approx 30$ MeV (Run II)
PDF	15 MeV	10 MeV	
Radiative decays	20 MeV	<10 MeV	(improved Theory calc)
$P_T(W)$	45 MeV	5 MeV	$P_T(Z)$ from data, $P_T(W)/P_T(Z)$ from theory
Background	5 MeV	5 MeV	
TOTAL	113 MeV	≤ 25MeV	Per expt, per lepton species



- Combine both channels & both experiments

$\Rightarrow \quad \Delta m_W \leq 15$ MeV (LHC)

Compare to

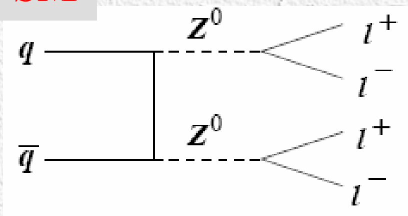
2007: $m_W = 80\,398 \pm 25$ MeV — LEP & Tevatron Run I/II

2009: $m_W \approx 80$ ... ± 20 MeV $(2.5 \cdot 10^{-4})$ — expected after Tevatron Run II

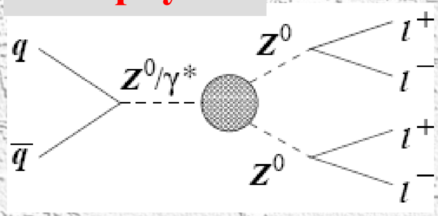
Di-Boson Production at the LHC

- very interesting: WW,ZZ final states not yet observed at the Tevatron
  first WZ events observed early 2007
- test triple gauge boson couplings (TGC)
  - γWW and ZWW precisely fixed in SM
  - γZZ and ZZZ do not exist in SM!

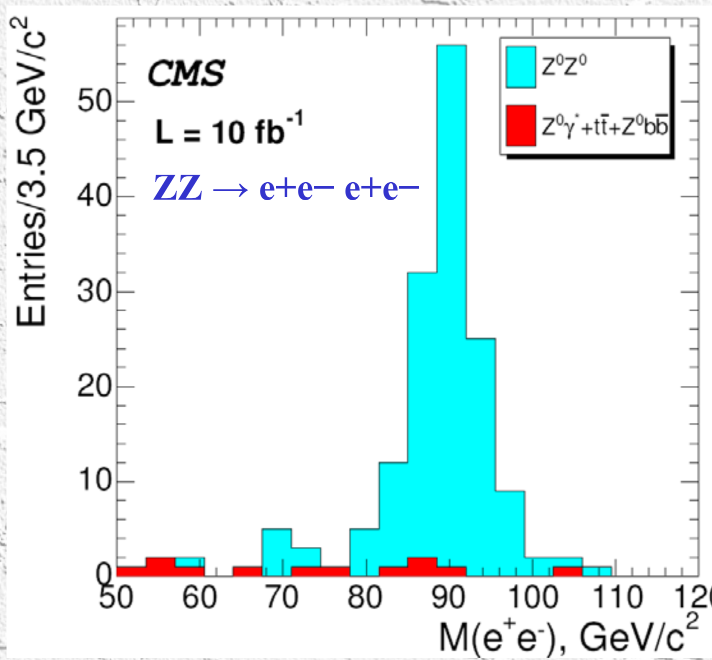
SM

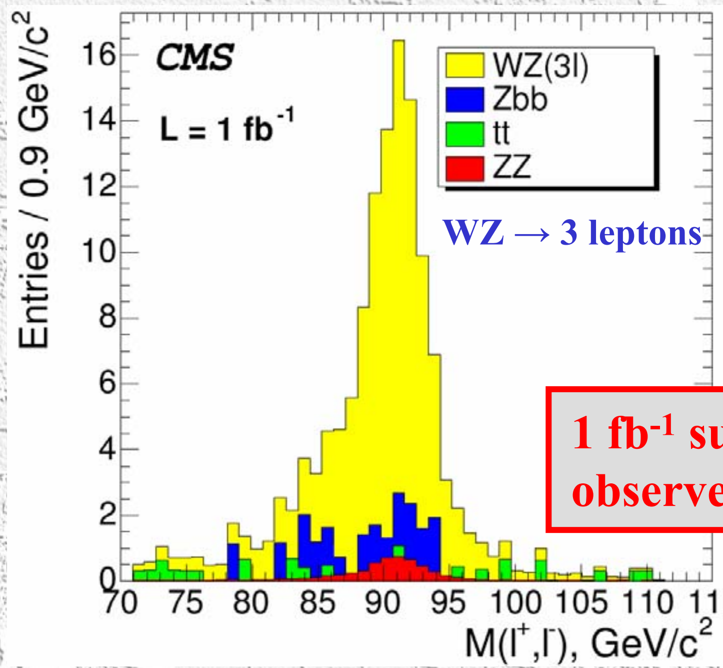


New physics



- deviations from SM are amplified with E
- also Wγ and Zγ final states can be used

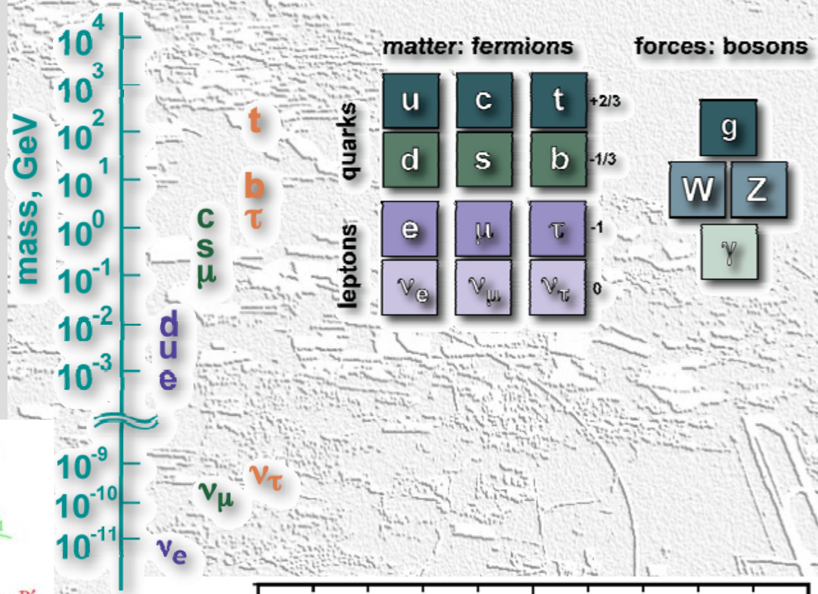




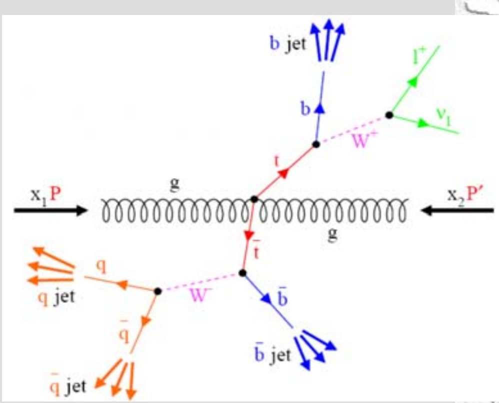
1 fb^{-1} sufficient to observe both processes

Motivation Top Physics

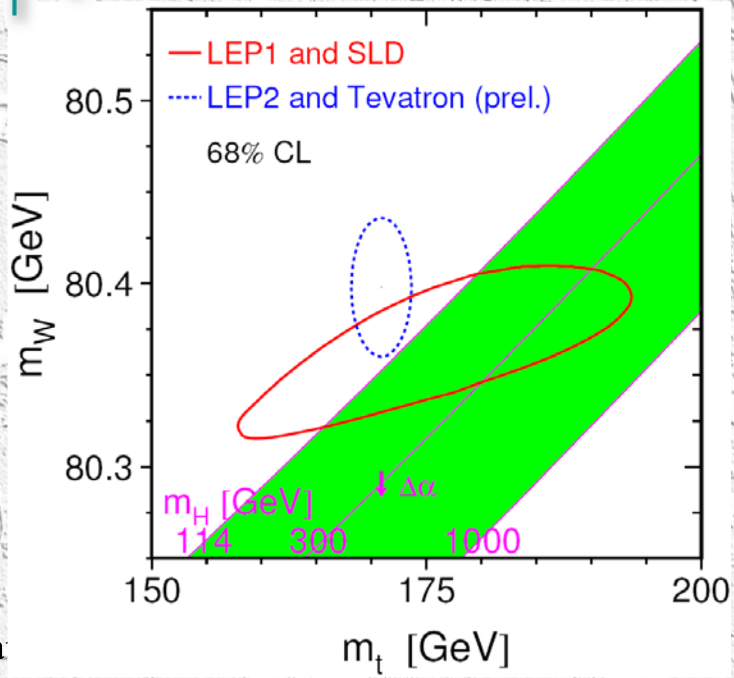
- **The top is by far the heaviest SM fermion**
  - could provide insight to mass generation
  - coupling to Higgs
    - neutral, e.g. loops
    - charged, e.g. $t \rightarrow H^+ b$
  - exotics $X \rightarrow$ ttbar



- **It has very short lifetime**
  - the only quark that does not hadronise!
  - allows spin analysis from decay products (à la tau)



- **Top mass**
  - important parameter in EW precision tests
  - m_t enters quadratically in rad. corrections
  - m_H only logarithmically!

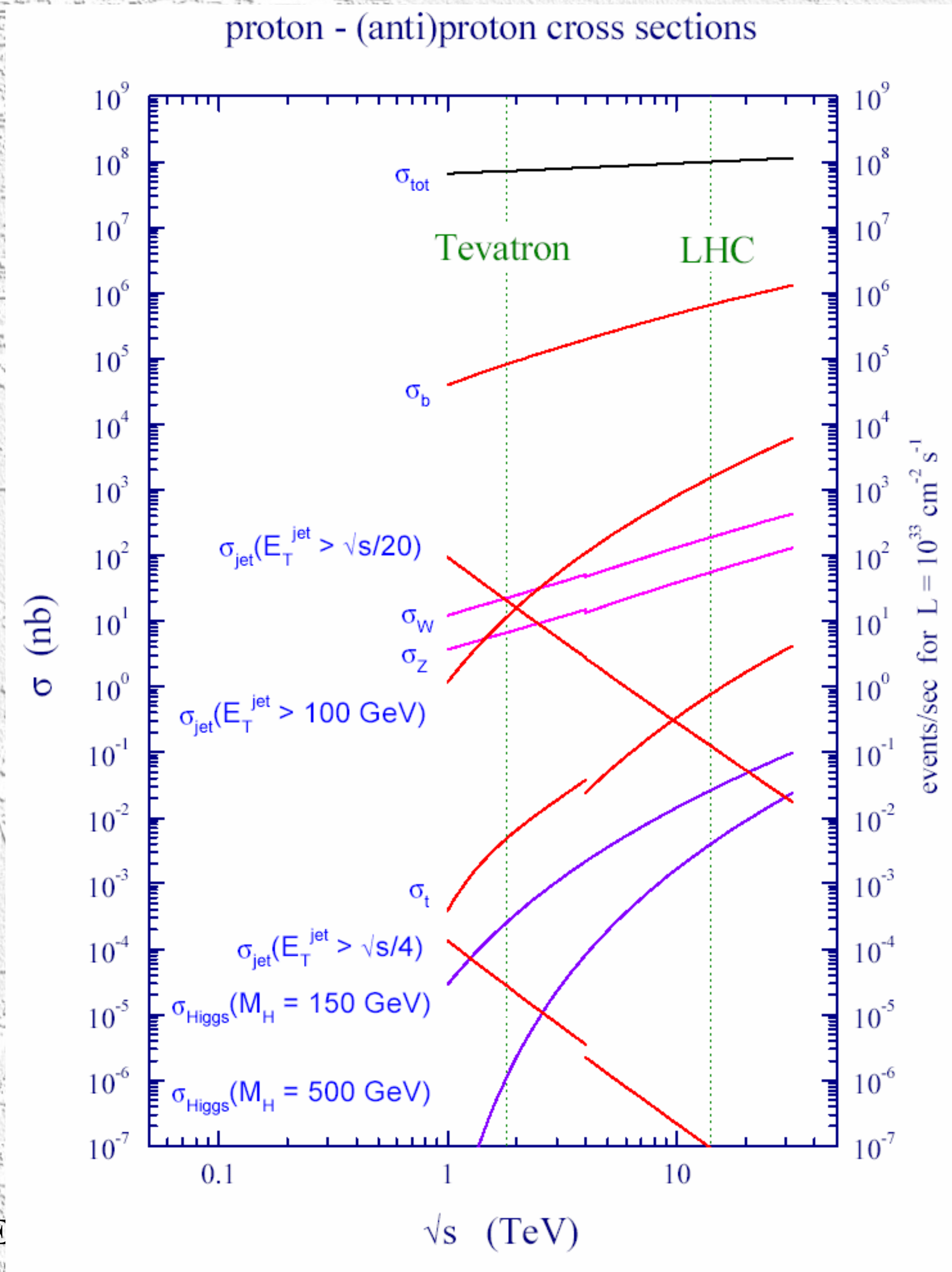


Why Top Physics at the LHC?

- **LHC is a top factory**
  - **at 10^{33}/cm²/s**
    1 ttbar per second or
    10 million per year

- **Cross section ≈ 100 times larger than at the Tevatron**
  7 pb Tevatron
  > 800 pb LHC

- **LHC will eclipse existing knowledge on the top**
  despite problems like
  - **pile-up**
  - **less striking signatures**

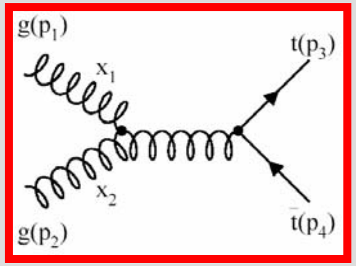


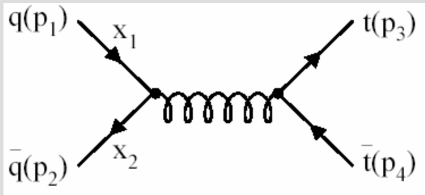
Why Top Physics at the LHC?

- ttbar production is standard candle at high Q^2
  - relatively precisely measureable and calculable
  - cross checks impact of pdf, underlying event, pile-up, …

- ttbar production

≈ 90% gluon fusion ≈ 10% quark annihilation

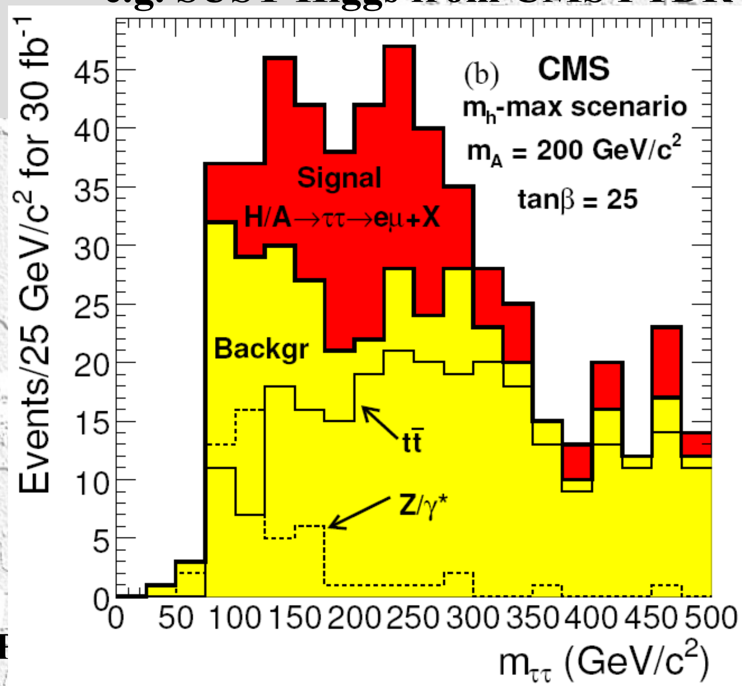




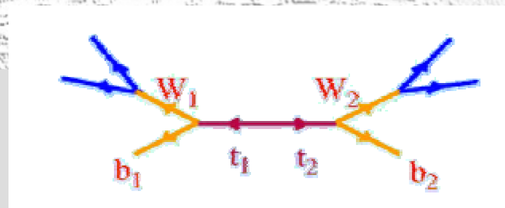
i.e. similar to e.g. Higgs production

- Important background reaction for many New Physics channels
  - high cross section
  - presence of high p_T lepton(s)
  - multi-jet final states

e.g. SUSY Higgs from CMS PTDR

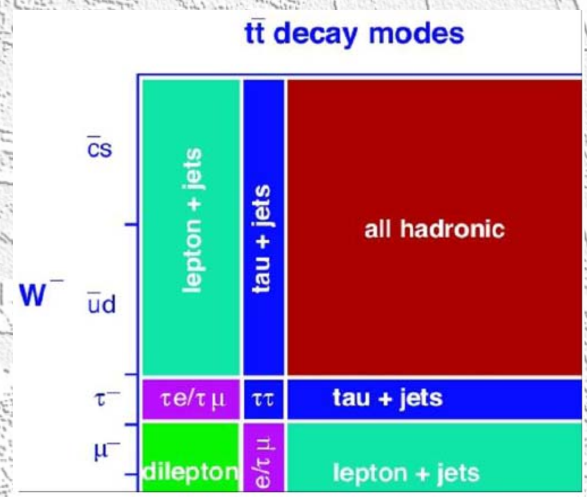


Top Quark Decay



- **Top decay: ≈ 100% t → bW**
- **Other rare SM decays:**
  - **CKM suppressed t → sW, dW: 10^{-3} –10^{-4} level**
- **& non-SM decays, e.g. t → bH^+**

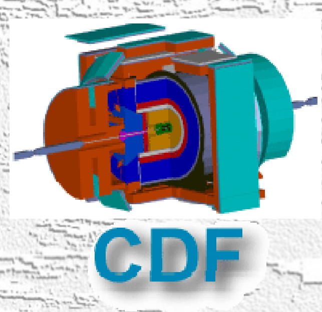
In SM topologies and branching ratios are fixed:
- **expect two b-quark jets**
- **plus W^+W^- decay products:**
  - **2 charged leptons + 2 neutrinos**
  - **1 charged lepton + 1 neutrino + 2 jets**
  - **4 jets (no b-quark!)**

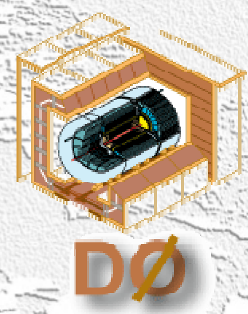


$t\bar{t} \rightarrow l\nu l\nu bb$	5%	$(e+\mu)$
$t\bar{t} \rightarrow l\nu qqbb$	30%	$(e+\mu)$
$t\bar{t} \rightarrow qqqqbb$	46%	

What do we know about the Top?

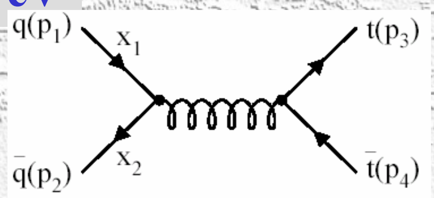
- Discovered and so far exclusively produced at the Tevatron
- New results from Run II
  Luminosity O(1/fb) >> Run I





- ttbar cross section at 1.96 TeV

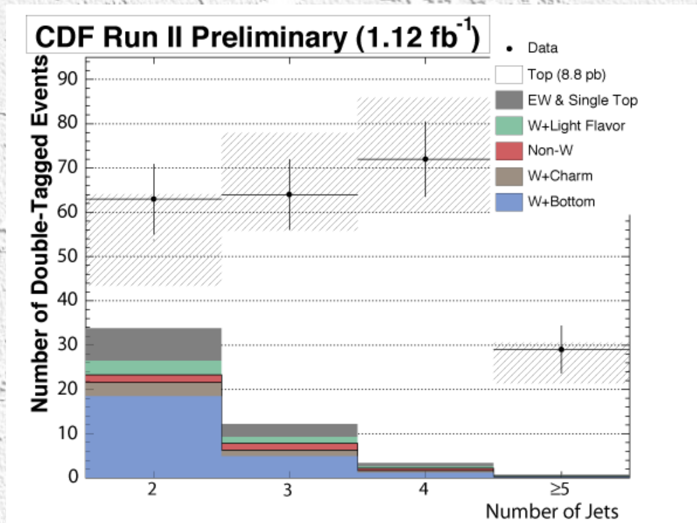
$$\sigma_{th}(\bar{p}p \to t\bar{t}) \approx 6.7 \text{ pb}$$

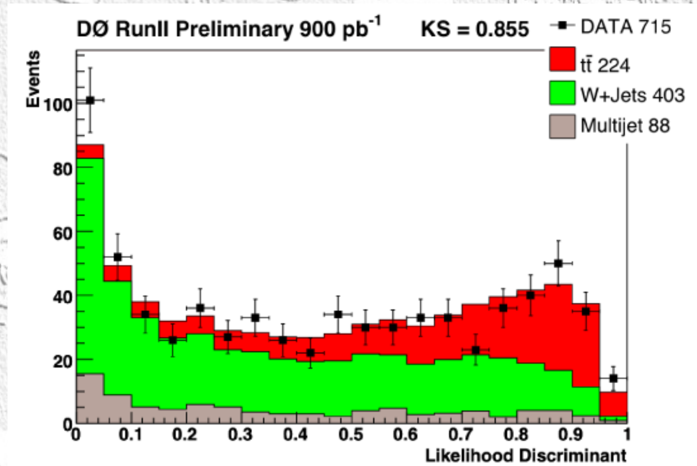


- **Using single-lepton channel**

σ_{tt}=8.2 ± 0.5(stat)± 0.9(sys) pb

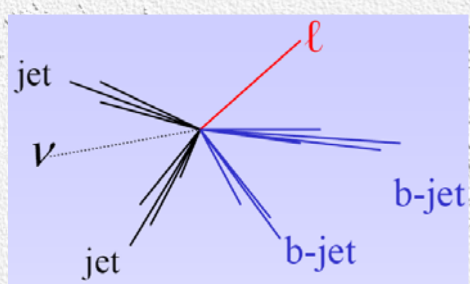
σ_{tt}=8.1 ± 0.9(stat)± 0.5(sys) pb



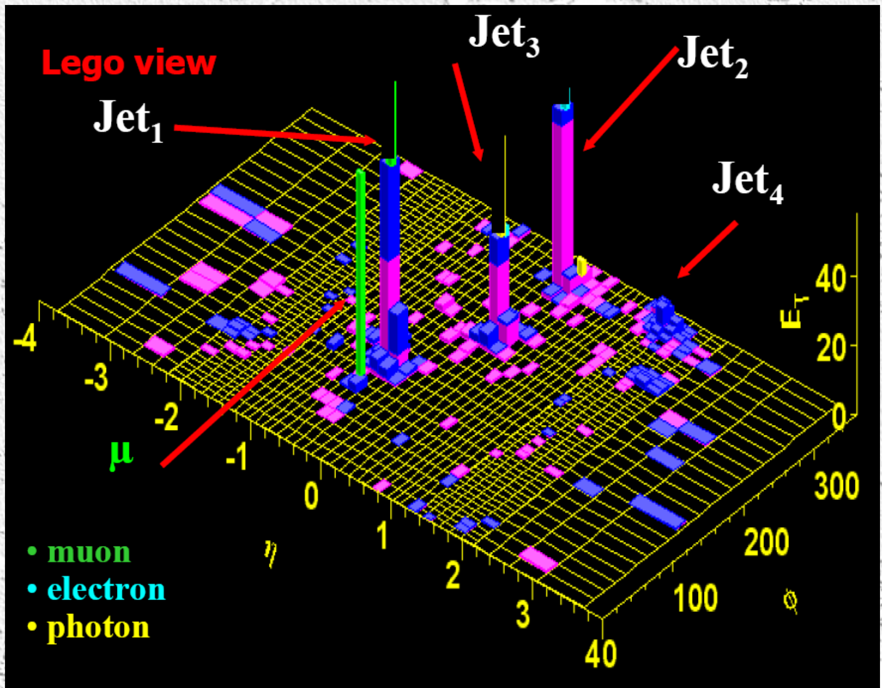


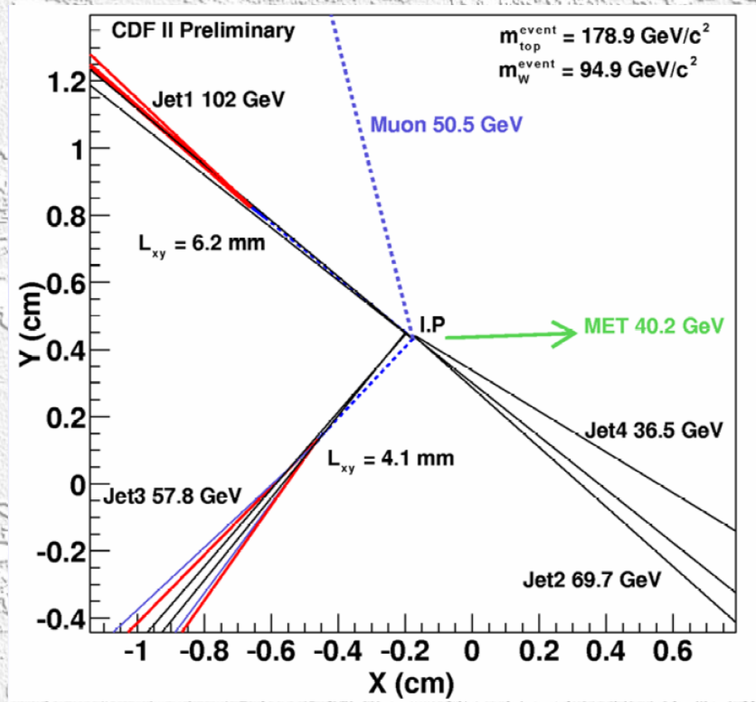
A Top-Pair Event at CDF

- semi-leptonic channel

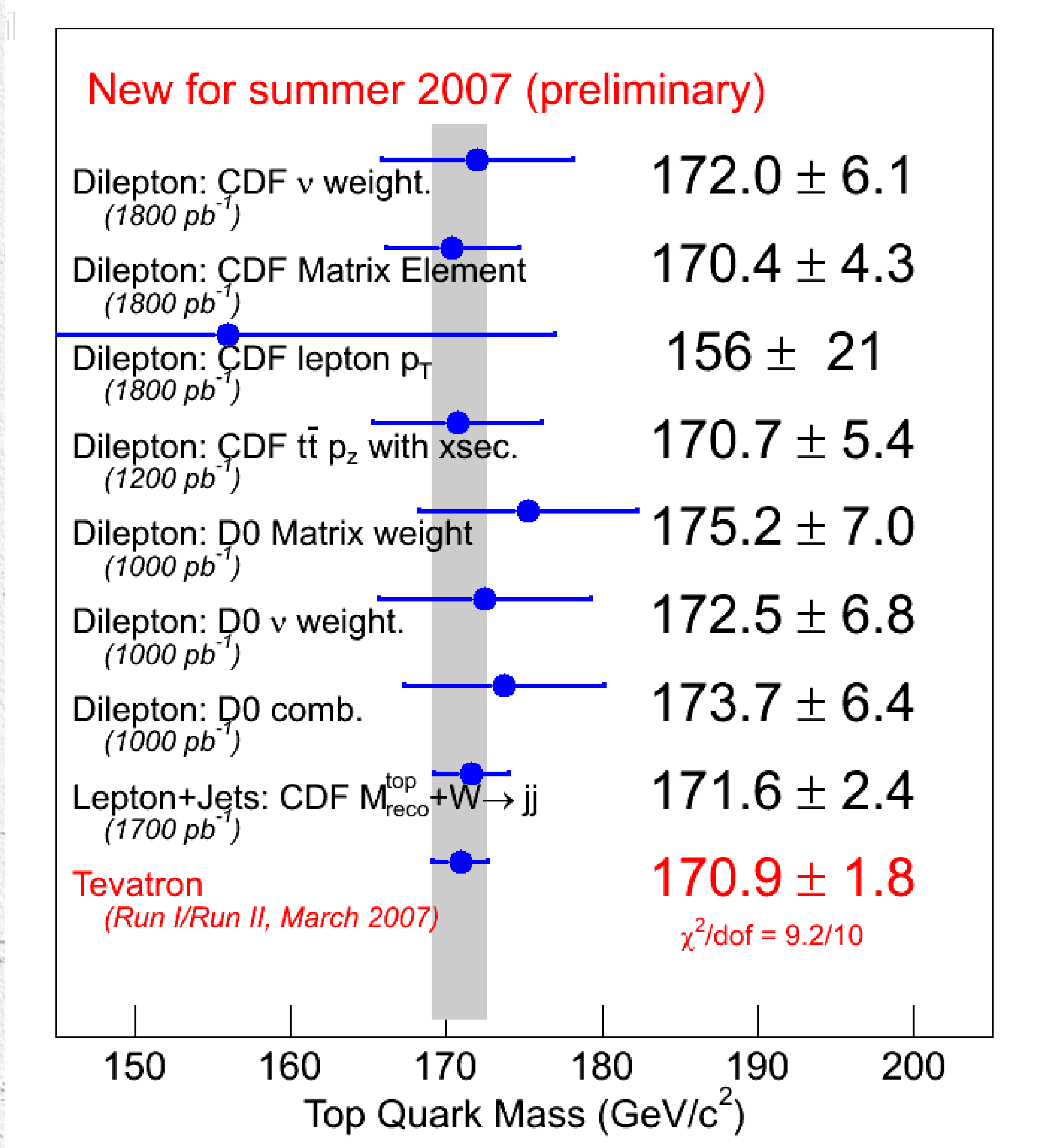


- 1 muon
- 1 neutrino (missing E_T)
- 2 light quark jets
- 2 b-quark jets
  tagged by displaced vertices



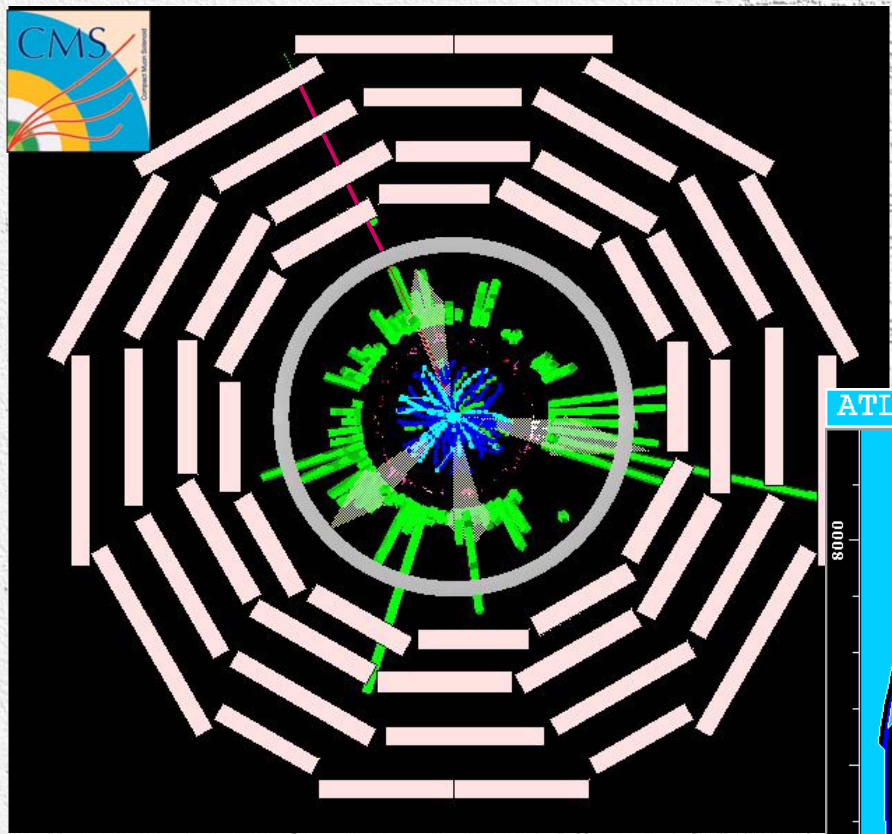


Top Mass Measurement

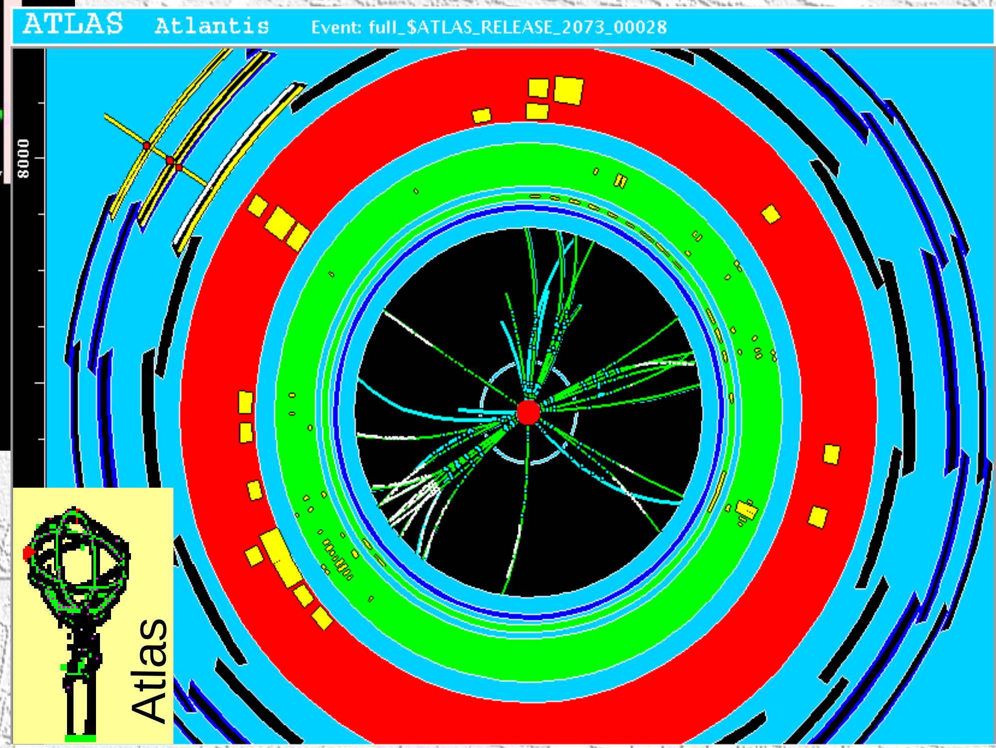


≈ 1% precision!

Top Quarks at the LHC

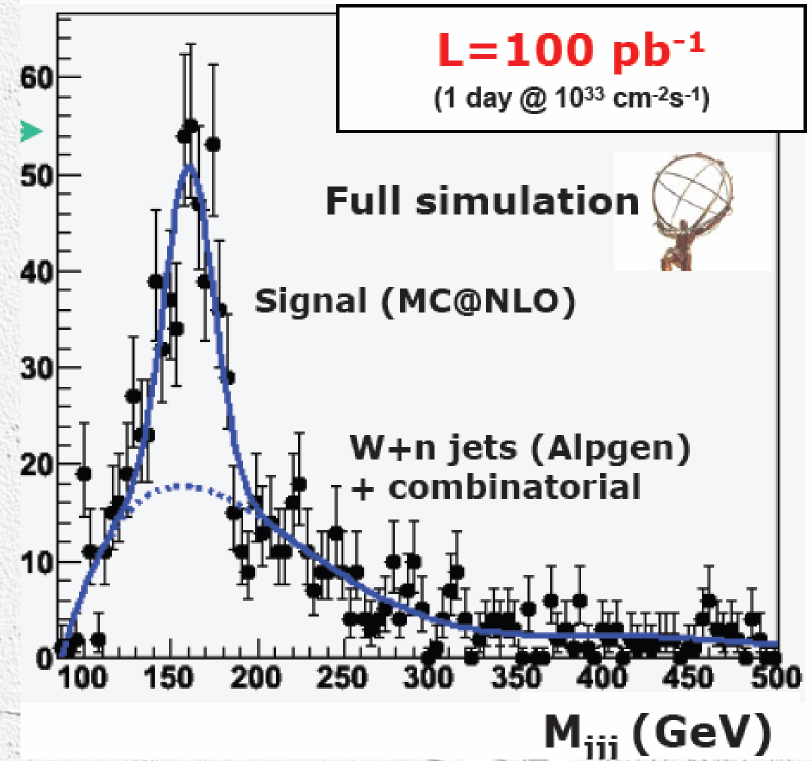


Examples of simulated
tt → bb qq μν events
from CMS & ATLAS

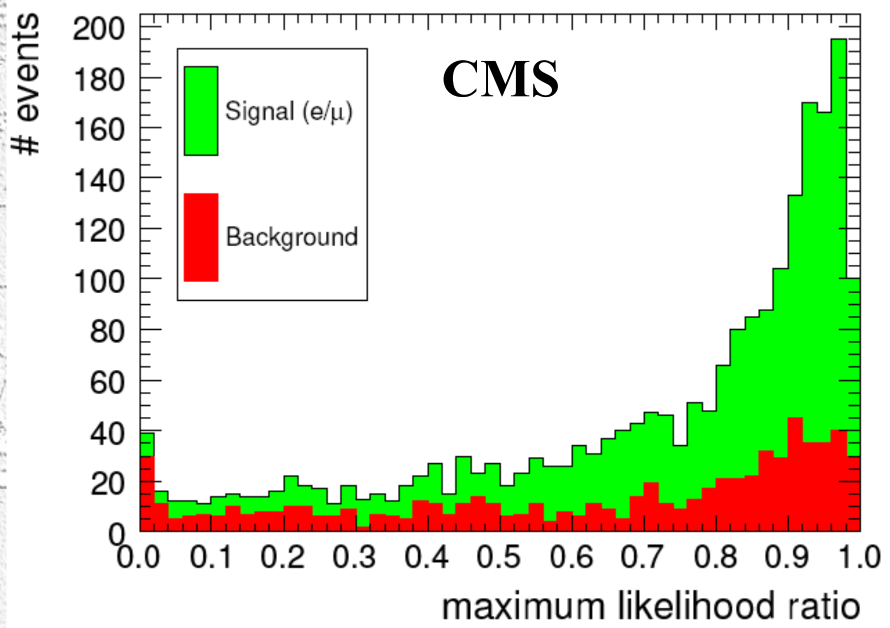


Top Pairs at the LHC

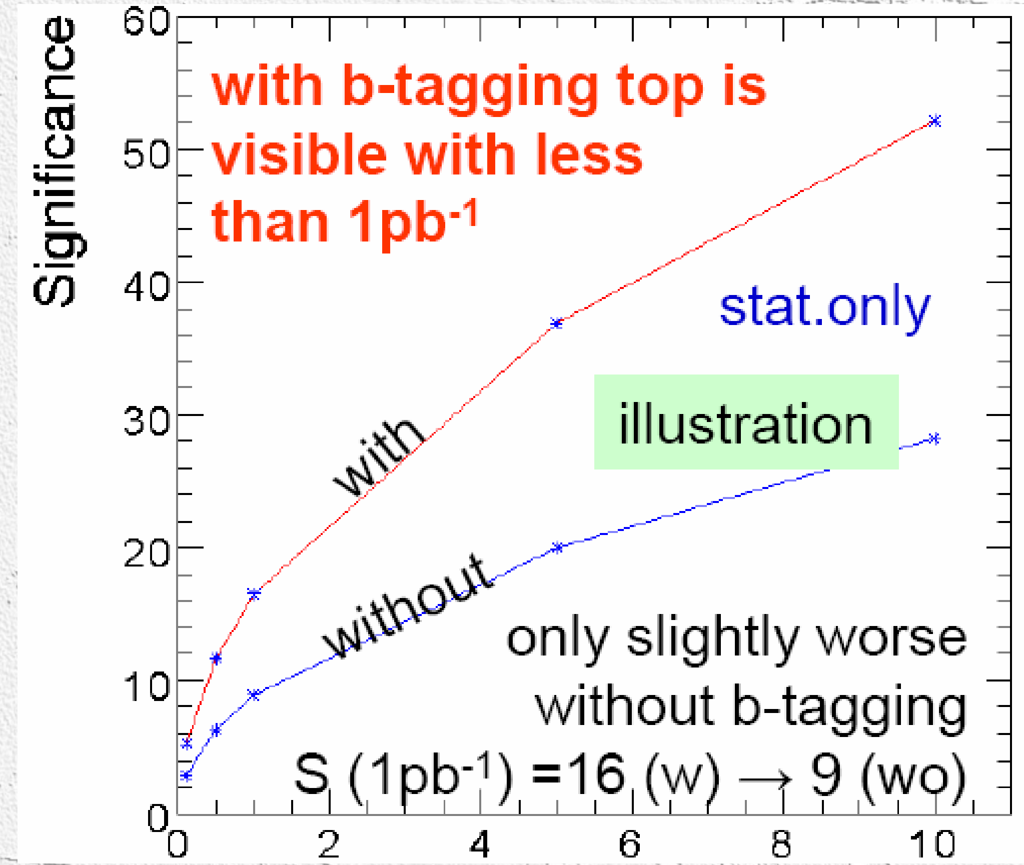
- Re-discovery of top possible with low luminosity (< 100 pb^{-1})
- Semi-leptonic events



S. Kasselmann, Ph.D. thesis



Re-discovery of Top at the LHC

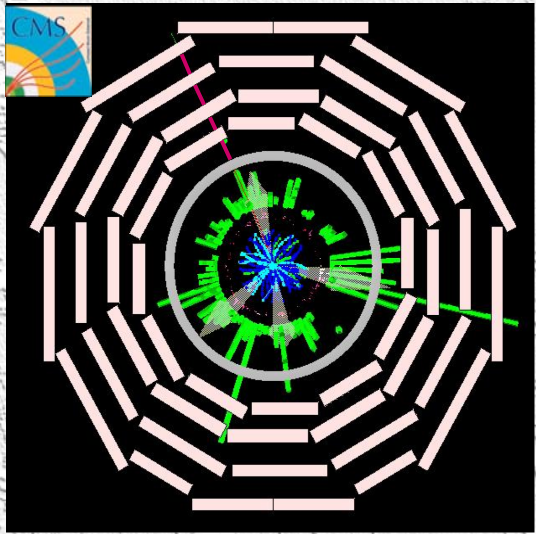


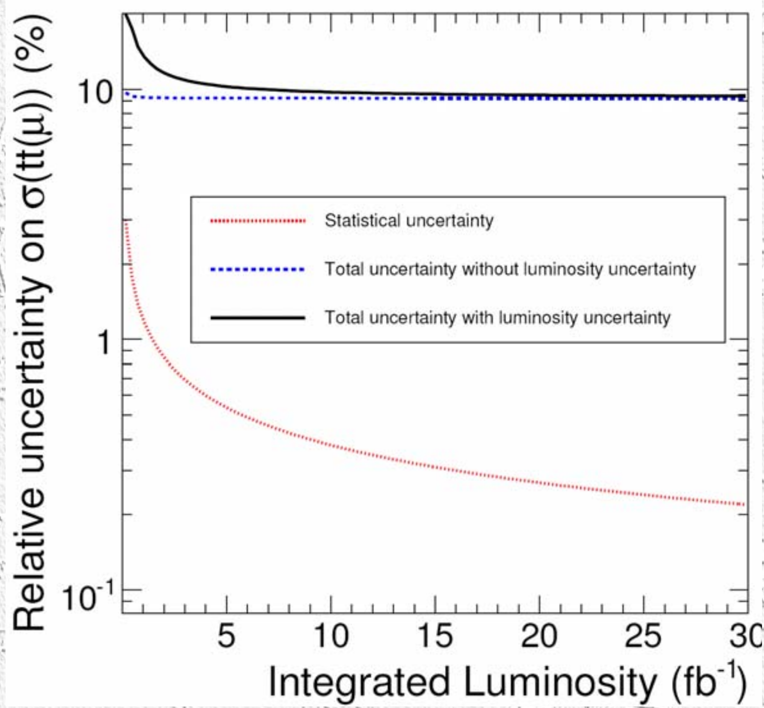
Observation of the top quark:
- demonstrates that the full detector works
  - electrons/ muons
  - jets
  - missing ET
  - b-tag

Single-Lepton Channel

- golden channel
- clean signature and large branching ratio < 4% non-ttbar bkgd

μ channel
tt→bbqqμν





	$\Delta\hat{\sigma}_{t\bar{t}(\mu)}/\hat{\sigma}_{t\bar{t}(\mu)}$		
	1 fb^{-1}	5 fb^{-1}	10 fb^{-1}
Simulation samples (ϵ_{sim})		0.6%	
Simulation samples (F_{sim})		0.2%	
Pile-Up (30% On-Off)		3.2%	
Underlying Event		0.8%	
Jet Energy Scale (light quarks) (2%)		1.6%	
Jet Energy Scale (heavy quarks) (2%)		1.6%	
Radiation (Λ_{QCD}, Q_0^2)		2.6%	
Fragmentation (Lund b, σ_q)		1.0%	
b-tagging (5%)		7.0%	
Parton Density Functions		3.4%	
Background level		0.9%	
Integrated luminosity	10%	5%	3%
Statistical Uncertainty	1.2%	0.6%	0.4%
Total Systematic Uncertainty	13.6%	10.5%	9.7%
Total Uncertainty	13.7%	10.5%	9.7%

- **Cross section error ≈ 10%**

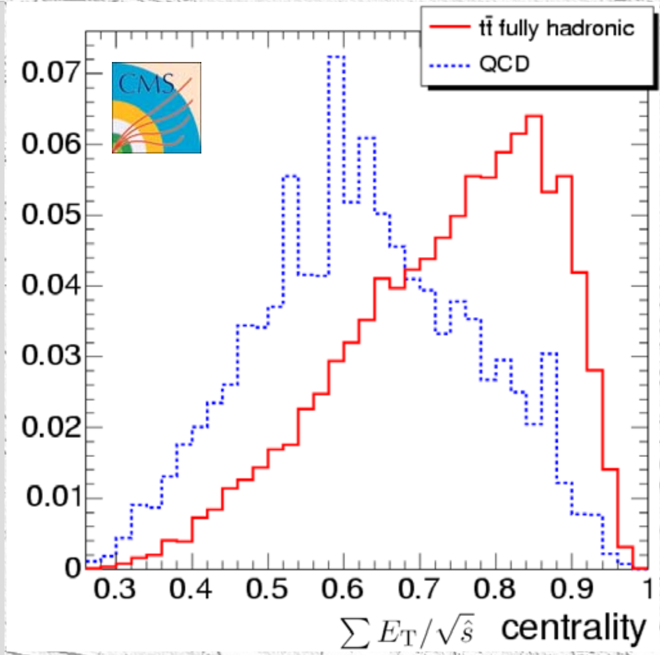
Fully Hadronic Channel

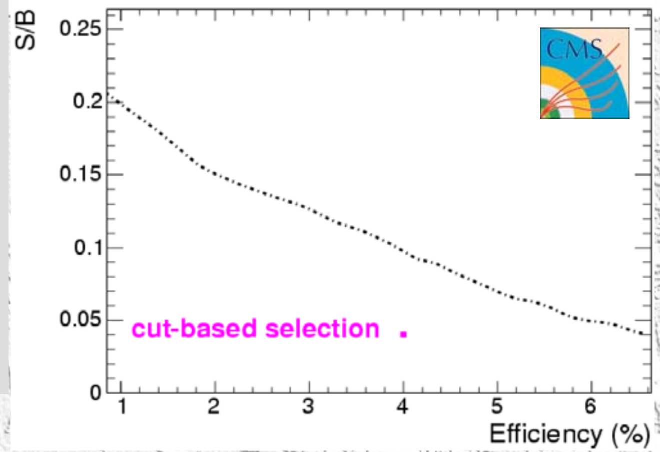
- tt → bb qqqq
- well defined final state with ≥ 6 jets
- enormous QCD background

- Need special trigger scheme, e.g. CMS
  - optimised E_T thresholds
  - pixel b/tag
  - 17% signal efficiency
  - S/B ≈ 1/300

- selection based on kinematic variables e.g. centrality
  - simple cut-based
  - and NN selection

- Cross section measurement to ≈ 20%





Top Mass at the LHC

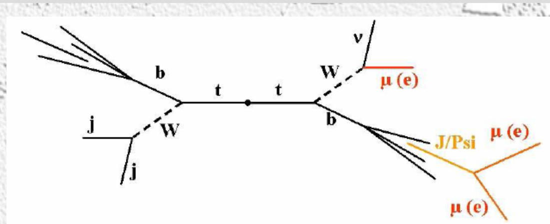
All decay topologies can be used:

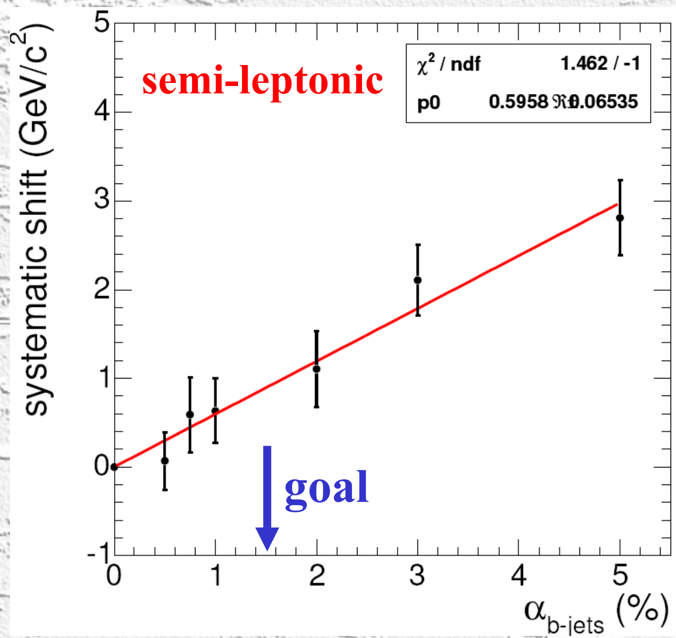
- **di-lepton events**
  kinematics underconstraint
  but sensitive to m_t

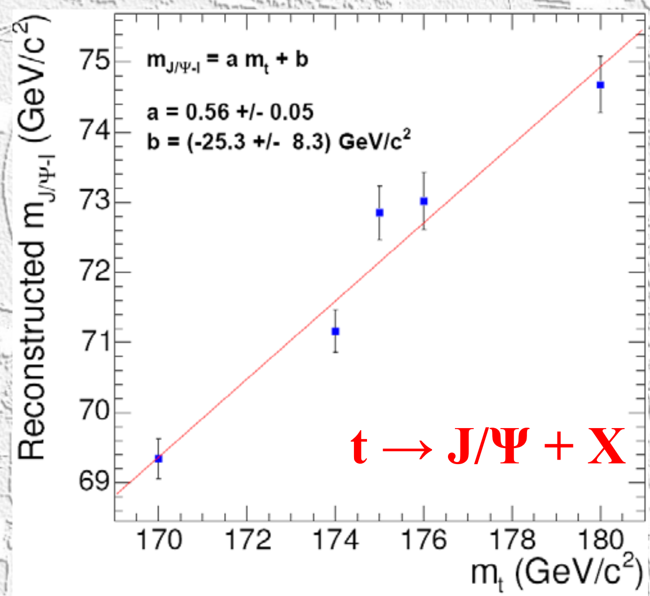
- **semi-leptonic events**
  golden channel, ideogramm method
  limited by b-jet E-scale

- **fully hadronic top pairs**
  suffers from QCD and combinatorial background

- **exclusive $t \rightarrow J/\Psi + X$ decays**
  low stat., but different systematic
  partial reconstruction J/Ψ + lepton from W





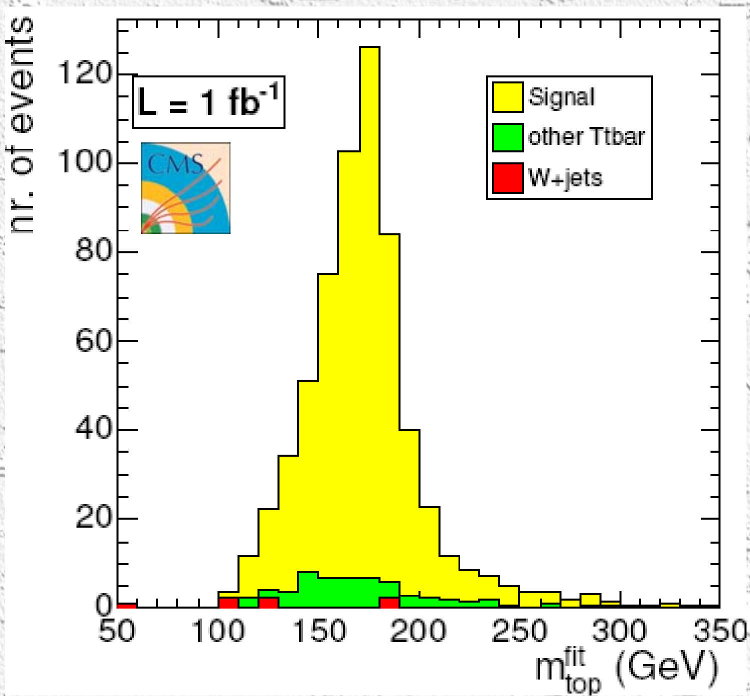


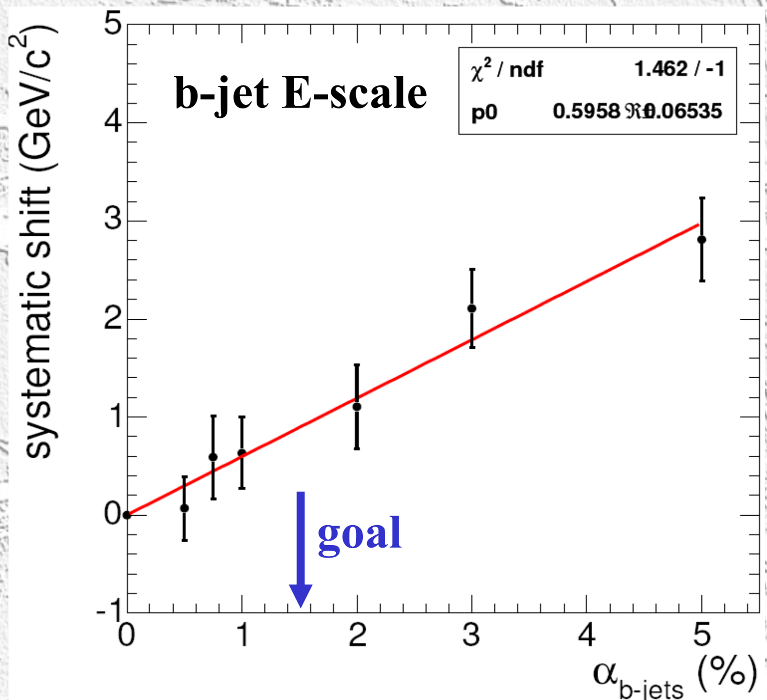
Measurement of the Top Mass

- **single-lepton channel**
  - **sophisticated ideogramm method developed**
  - **self-calibrating using m_W constraint**
  - **reduced bias and sys error**

- **study of systematic errors:**

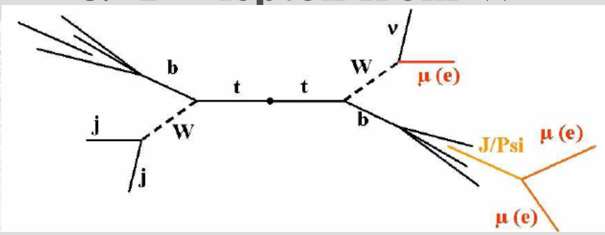
	Standard Selection		
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up (5%)	0.32	0.23	0.21
Underlying Event	0.50	0.35	0.25
Jet Energy Scale (1.5%)	2.90	1.05	0.96
Radiation (Λ_{QCD}, Q_0^2)	0.80	0.27	0.22
Fragmentation (Lund b, σ_q)	0.40	0.40	0.30
b-tagging (2%)	0.80	0.20	0.18
Background	0.30	0.25	0.25
Parton Density Functions	0.12	0.10	0.08
Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty (10 fb^{-1})	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15

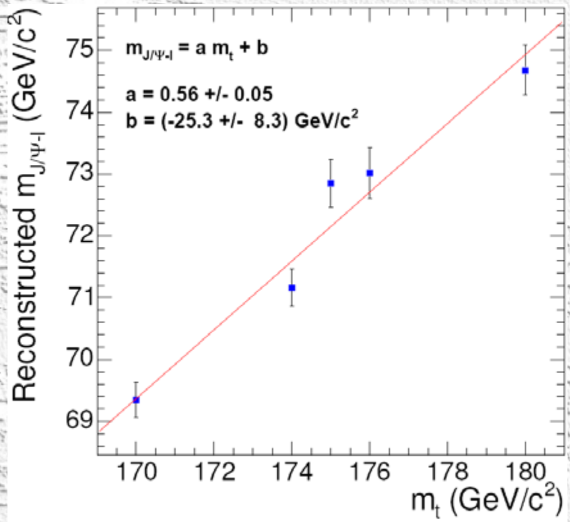




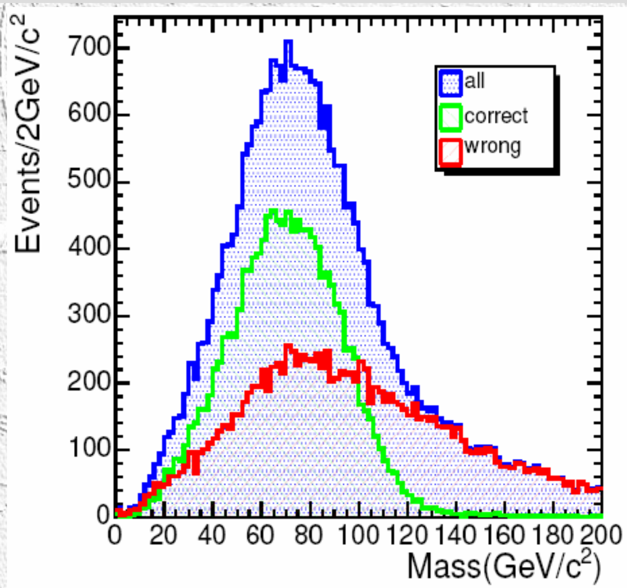
Measurement of the Top Mass

- exclusive t → J/Ψ + X decays
  - partial reconstruction of J/ Ψ + lepton from W





- low statistics, but different systematics
  - only leptons, no jets
  - theory is important



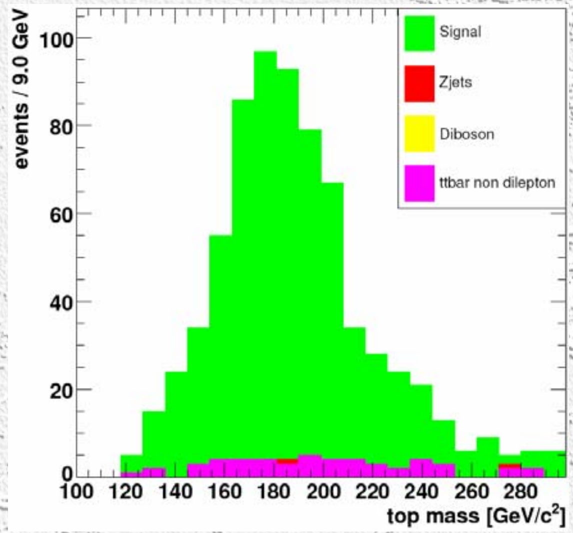
Source	δm_t(GeV/c²)
Λ_{QCD}	0.31
Q^2	0.56
Scale definition	0.71
b-quark fragmentation	0.51
Light jet fragmentation	0.46
Minimum bias/Underlying event	0.64
Proton PDF	0.28
Total theoretical	1.37
Electron E scale	0.21
Muon p scale	0.38
Electron E resolution	0.19
Muon p resolution	0.12
Jet E scale	0.05
Jet E resolution	0.05
Background knowledge	0.21
Total experimental	0.54
Total systematic	1.47

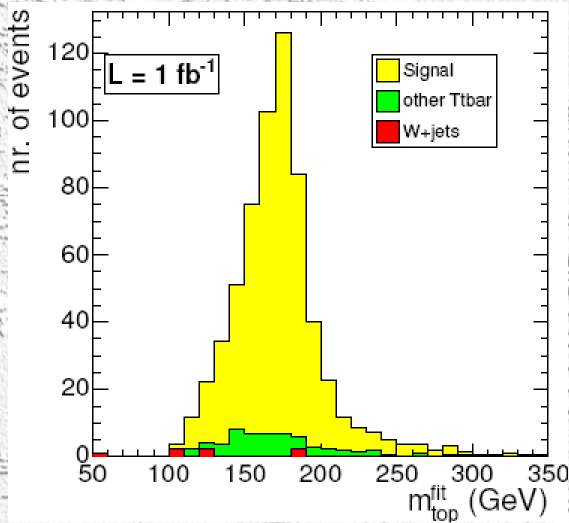
- ± 0.8 GeV (stat) ± 1.5 GeV with 20 fb^{-1} achievable

Top Mass at the LHC

Recent detailed studies by CMS:

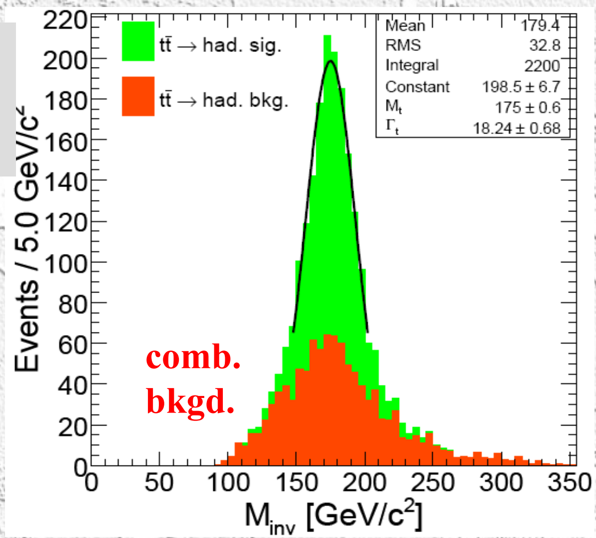
di-leptonic
± 1.2 GeV

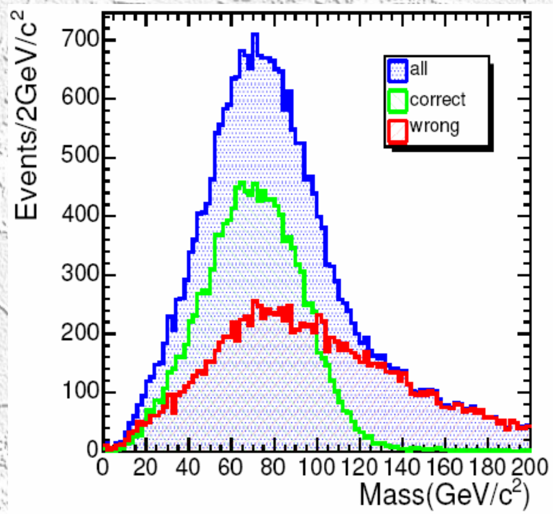




semi-leptonic
± 1.2 GeV

fully hadronic
± 2 GeV



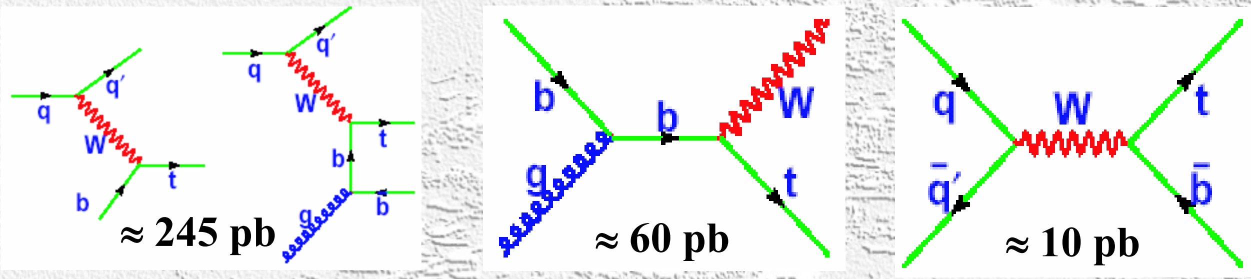


$t \to J/\Psi + l + X$
± 1.5 GeV

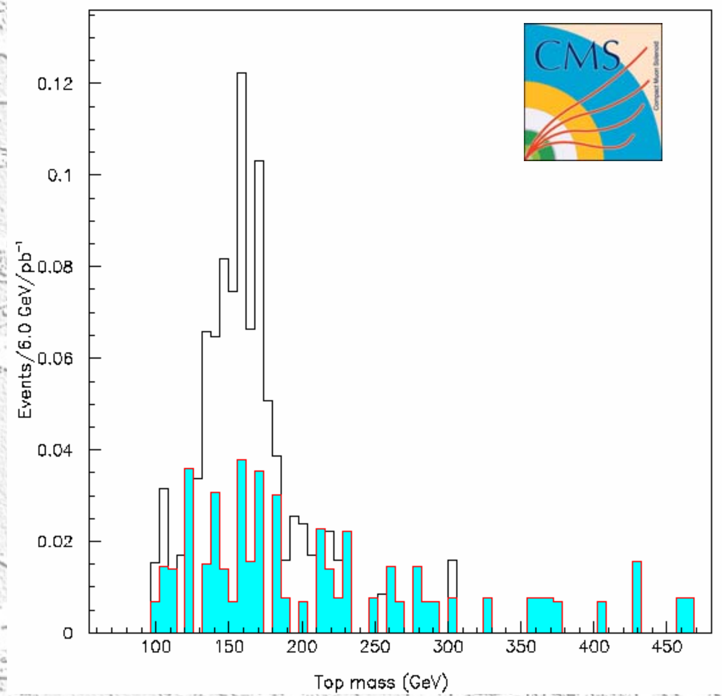
→ total top mass error ≤ 1 GeV possible with O(10 fb^{-1}) of well understood data

Single Top Production

Production mechanisms and cross sections:



- **direct measurement of V_{tb}**
- **observable by Tevatron in Run II**
- **LHC $\sigma_t \approx 1.5\ \sigma_{\bar{t}}$**



- **Selection:**

  $t \rightarrow bW \rightarrow b\ e\nu\ (\mu\nu)$

  b-jet + high p_T lepton

  reconstruction of top mass
- **Background from $t\bar{t}$**

  signal to bkgd. 3.5 : 1

experimental determination of V_{tb} to percent level (with 30 fb^{-1})