QCD and Electroweak physics at the LHC

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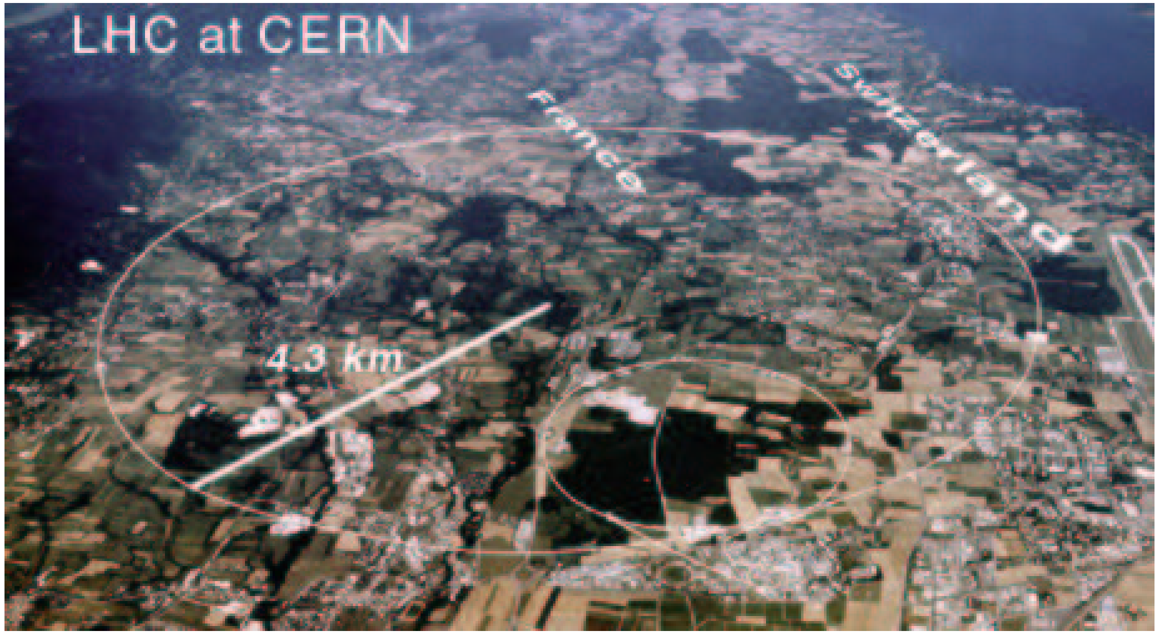
LHC (Large Hadron Collider):

- p-p collisions at $\sqrt{s}$ = 14TeV
- bunch crossing every 25 ns (40 MHz)

Ø low-luminosity: **L ≈ 10^{33}cm^{-2}s^{-1}**
($\mathcal{L}$ ≈ 10 fb^{-1}/year)

Ø high-luminosity: **L ≈ 10^{34}cm^{-2}s^{-1}**
($\mathcal{L}$ ≈ 100 fb^{-1}/year)



Process	**σ (nb)**	**Events/year ($\mathcal{L}$ = 10 fb^{-1})**
$W \to e\nu$	15	~ 10^8
$Z \to e^+ e^-$	1.5	~ 10^7
$t\bar{t}$	0.8	~ 10^7
Inclusive jets **p_T > 200 GeV**	100	~ 10^9

large statistics: **small statistical error!**

Production cross section and dynamics are largely controlled by QCD.

Mass reach up to ~ 5 TeV

Test QCD predictions and perform precision measurements.

ATLAS: A Toroidal LHC ApparatuS

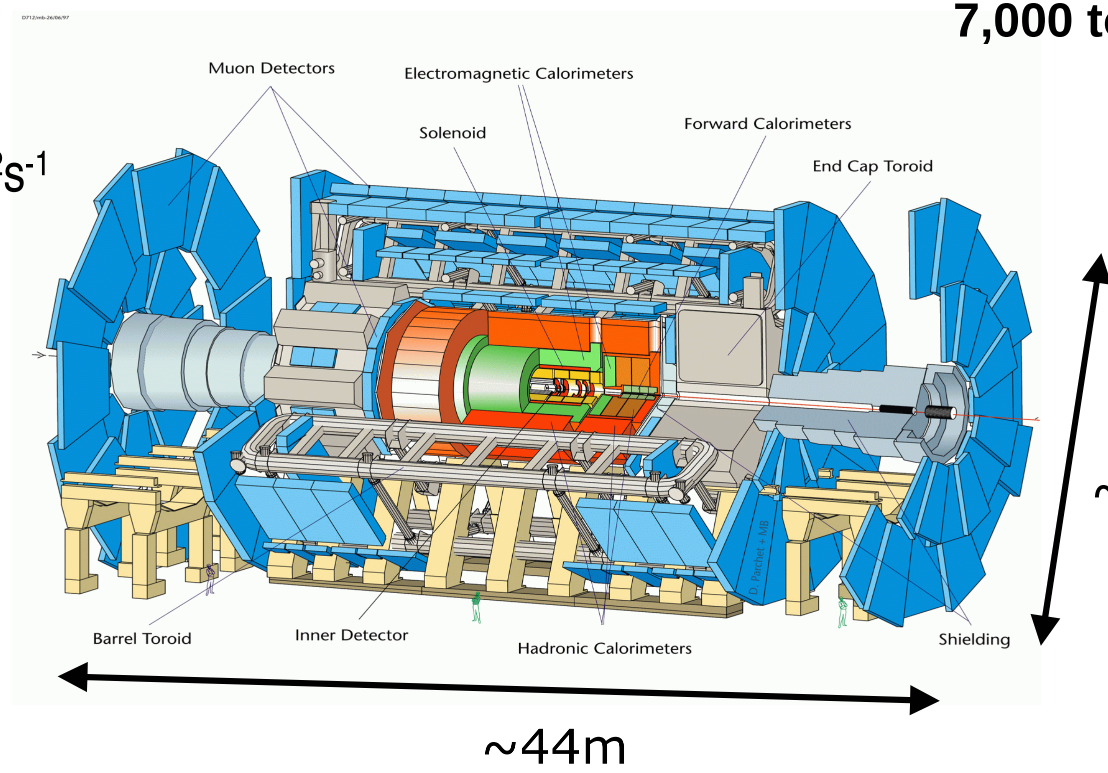
- **Multi-purpose detector**
  coverage up to $|\eta| = 5$;
  design to operate at $L = 10^{34} cm^{-2} s^{-1}$

- **Inner Detector (tracker)**
  Si pixel & strip detectors + TRT;
  2 T magnetic field;
  coverage up to $|\eta| < 2.5$.

- **Calorimetry**
  highly granular LAr EM calorimiter
  ($|\eta| < 3.2$);
  hadron calorimeter – scintillator tile
  ($|\eta| < 4.9$).

- **Muon Spectrometer**
  air-core toroid system.

7,000 tons



Lepton energy scale: precision of 0.02% ($Z \to ll$)

Jet energy scale: precision of 1% ($W \to jj$; $Z \to ll$ + jets)

Absolute luminosity: precision ≤ 5% (machine, optical theorem, rate of known processes)

QCD Physics at the LHC

- Precision tests & measurements in unexplored kinematic region.
- Jet physics.
- Parton luminosities and p.d.f.'s (high-Q^2 processes at LHC: parton-parton collider).
- Direct photon production ($f_g(x)$, background to $H \rightarrow \gamma\gamma$, parton dynamics).
- Measurement of the α_S at very large scales.
- Background processes: multi-parton interaction, minimum-bias and the underlying event.
- Conclusion: QCD studies.

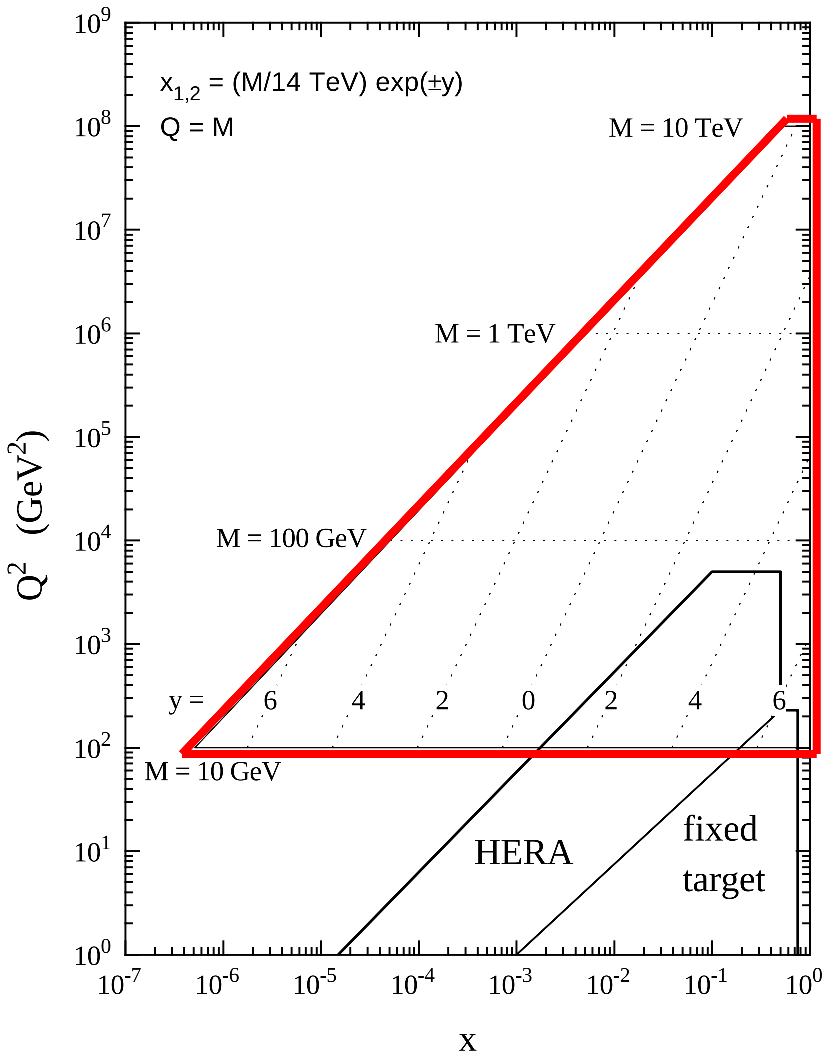
LHC Parton Kinematics

- Essentially all physics at LHC are connected to the interactions of quarks and gluons at large transferred momentum.

- **This requires a solid understanding of QCD.**

- Accurate measurements of SM cross sections at the LHC will further constrain the pdf's.

- The kinematic acceptance of the LHC detectors allows a large range of **x** and $\mathbf{Q^2}$ to be probed.



Jet physics

$\mathcal{L}$ = 30 fb^{-1}

Jet E_T	N_{events}
> 1 TeV	4 x 10^5
> 2 TeV	3 x 10^3
> 3 TeV	40

- Test of pQCD in an energy regime never probed!
- The measurement of di-jets and their properties (E_T and $\eta_{1,2}$) can be used to **constrain p.d.f.'s**.
- Inclusive jet cross section: $\alpha_S(M_Z)$ measurement with **10% accuracy**.
  (can be reduced by using the 3-jet to 2-jet production)
- Multi-jet production is important for several physics studies:
  a) $t\bar{t}$ production with hadronic final states
  b) Higgs production in association with $t\bar{t}$ and $b\bar{b}$
  c) Search for R-parity violating SUSY (8 – 12 jets).
- **Systematic errors**:

Ø jet algorithm,

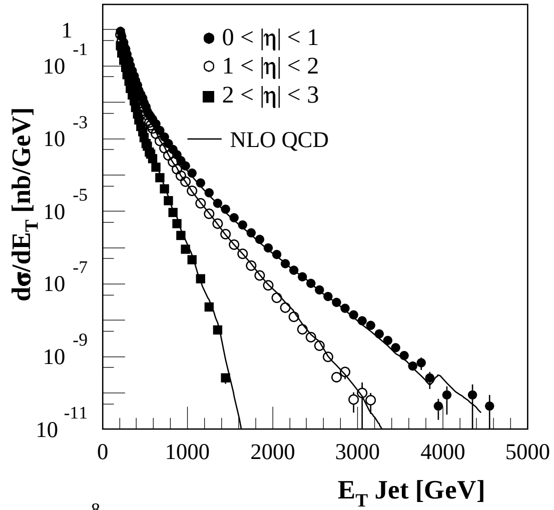
Ø calorimeter response (jet energy scale),

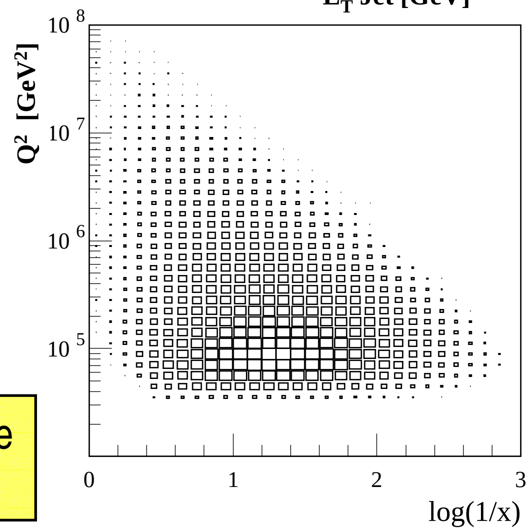
Ø jet trigger efficiency,

LVL1, jet-E_T 180 (290) GeV at low (high) luminosity, $|\eta| < 3.2$

Ø luminosity (dominant uncertainty 5% -10%),

Ø the underlying event.





At the LHC the **statistical** uncertainties on the jet cross-section will be **small**.

Measuring parton luminosities and p.d.f.'s

$$N_{events}(pp \to X) = L_{p-p} \times pdf(x_1, x_2, Q^2) \times \sigma_{theory}(q, \bar{q}, g \to X)$$

Uncertainties in **p-p luminosity (±5%)** and **p.d.f.'s (±5%)** will limit measurement uncertainties to ±5% (at best).

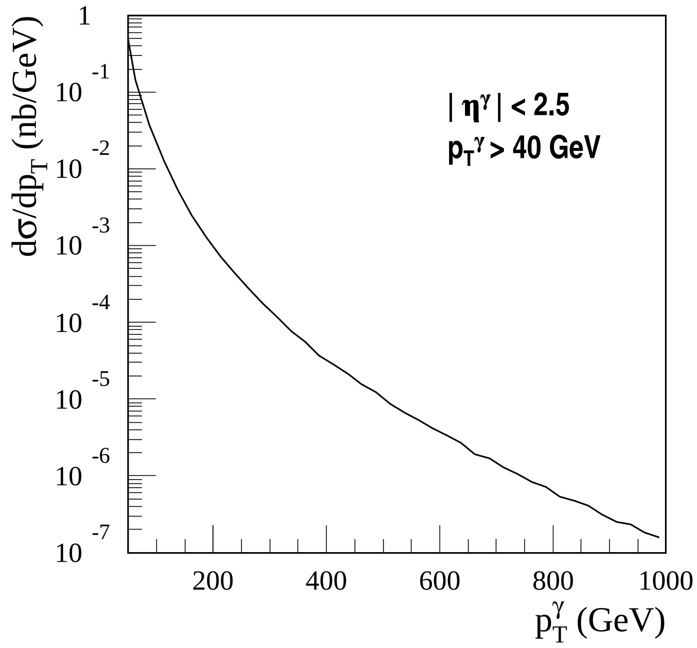
- For **high Q^2** processes LHC should be considered as a **parton-parton collider** instead of a p-p collider.
  - Using only **relative cross section measurements, might lead eventually to accuracies of ±1%**.

$q\bar{q}$ (u,d) (high-mass DY lepton pairs and other processes dominated by $q\bar{q}$)	**W± and Z** leptonic decays	precise measurements of mass and couplings; huge cross-sections (~nb); small background. x-range: 0.0003 – 0.1 ± 1%
g (high-Q^2 reactions involving gluons)	**γ-jet**, Z-jet, W±-jet	γ-jet studies: γ p_T > 40 GeV x-range: 0.0005 – 0.2 γ-jet events: γ p_T ~ 10-20 GeV low-x: ~ 0.0001 ±1%
s, c, b	**γc, γb, sg→Wc**	quark flavour tagged γ-jet final states; use inclusive high-p_T μ and b-jet identification (lifetime tagging) for c and b; use μ to tag c-jets; 5-10% uncertainty for x-range: 0.0005 – 0.2

Direct photon production

Understanding photon production:

- Higgs signals **($H \rightarrow \gamma\gamma$)** & background;
- prompt-photon can be used to study the underlying parton dynamics;
- gluon density in the proton, **$f_g(x)$** (requires good knowledge of α_s)



Production mechanism:

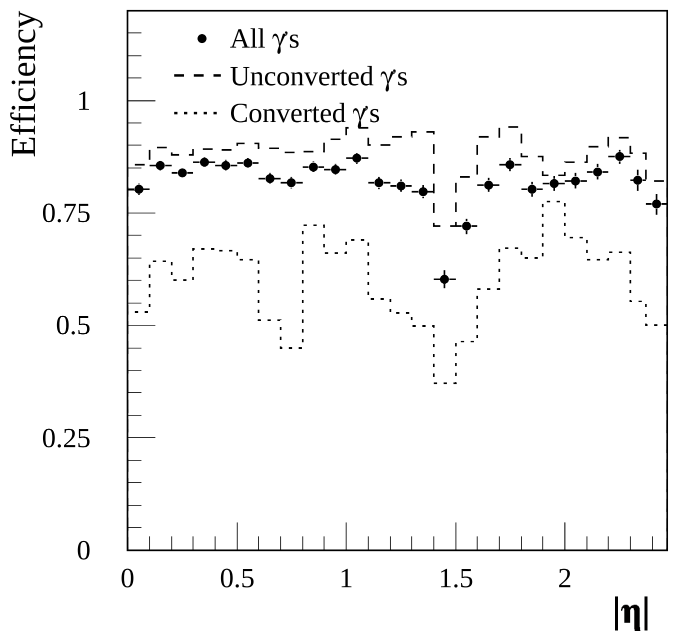
$qg \rightarrow \gamma q$	dominant (QCD Compton scattering)
$q\bar{q} \rightarrow \gamma g$	

Background: mainly related to fragmentation (non-perturbative QCD)

Isolation cut: reduces background from fragmentation (π^0)
(cone isolation)

ATLAS: high granularity calorimeters ($|\eta| < 2.5$) allow good background rejection.

Low luminosity run: the photon efficiency accuracy is more than **80%** (LAr calorimeter).



Determination of α_s: scale dependence

- Verification of the running of α_S : check of QCD at the **smallest distance scales**:
  - Ø α_S= 0.118 at 100 GeV
  - Ø α_S~ 0.082 at 4 TeV

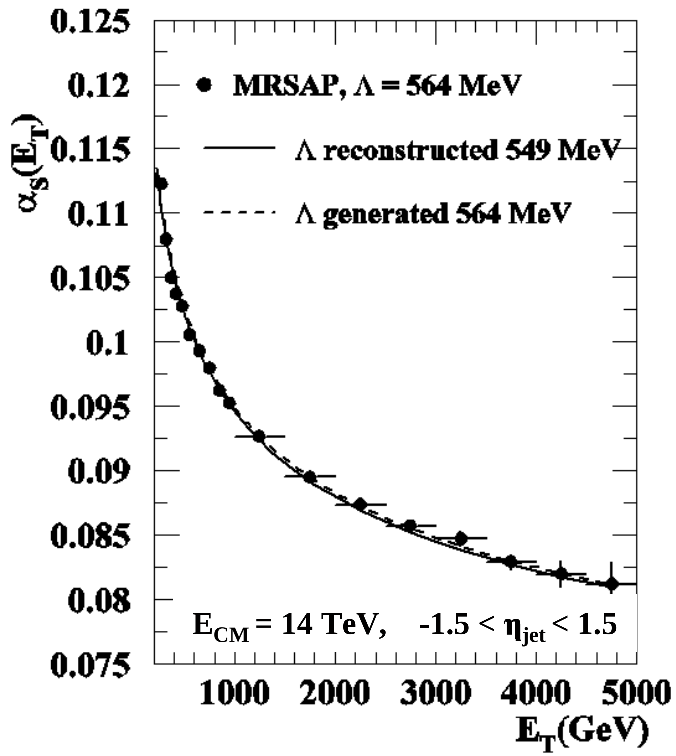
- However, measurements of α_S will not be able to compete with precision measurements from e^+e^- and DIS (gluon distribution).

- Differential cross-section for inclusive jet production (NLO)

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

- A and B are calculated using p.d.f.'s.

- Fitting this expression to the measured inclusive cross-section gives for each E_T bin a value of $\alpha_S(E_T)$.

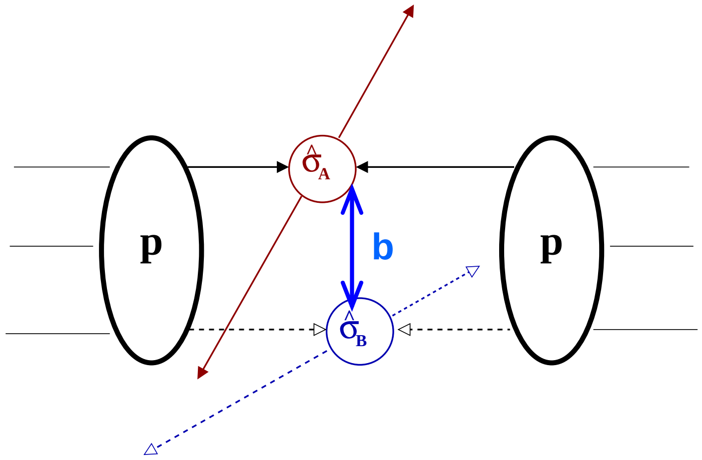


- **Systematic uncertainties:**

Ø p.d.f. set (±3%),
Ø parametrization of A and B,
Ø renormalization and factorization scale (±7%).

Multiple parton interactions

- AFS, UA2 and more recently (and crucially!) CDF, have measured **double parton** interactions.



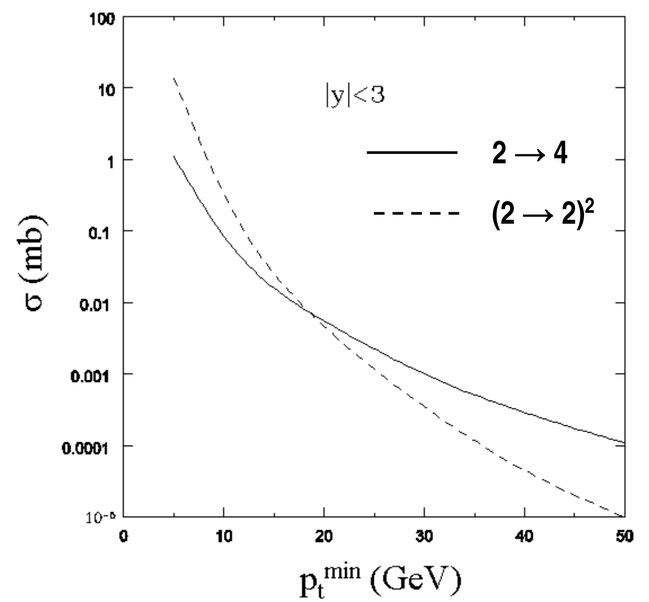
$$\sigma_D\left(p_T^{\,cut}\right) = m\,\frac{\sigma_A \sigma_B}{2\sigma_{eff}} \quad \Longrightarrow \quad \sigma_{eff} = 14.5 \pm 1.7 \text{ mb}$$

- σ_{eff} has a geometrical origin;
- parton correlation on the transverse space;
- it is energy and cut-off independent.

- σ_D decreases as $p_T \to \infty$ and grows as $p_T \to 0$.
- σ_D increases faster with **s** as compared to σ_S.

Multiple parton collisions are **enhanced** at the LHC!

4-jet production: 2 → 4 v (2 → 2)^2



- **Source of background:**

- **WH+X → (lν) $b\bar{b}$+X,**
- **Z$b\bar{b}$ → (lν) $b\bar{b}$+X,**
- **W + jets, Wb + jets and W$b\bar{b}$ + jets,**
- **$t\bar{t}$ → llbb,**
- **final states with many jets p_T^{min} ~ 20 – 30 GeV.**

Minimum-bias and the underlying event

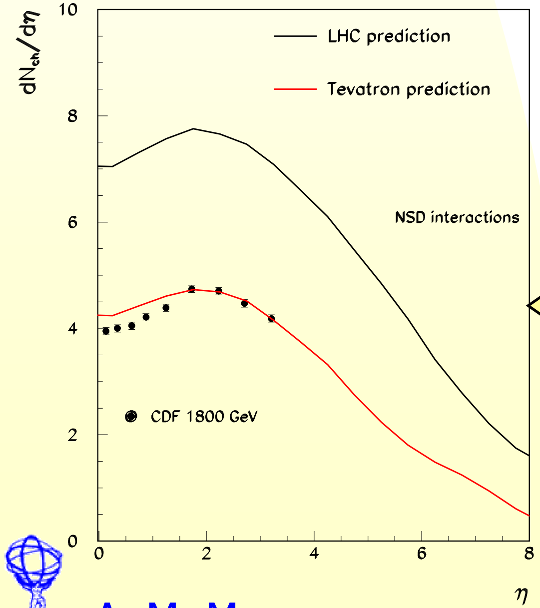
Minimum bias events

Experimental definition: depends on the experiment **trigger**! “Minimum bias” is usually associated to **non-single diffractive events** (NSD), e.g. ISR, UA5, E735, CDF.

$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$

σ_{tot} ~ 102 mb

$\sigma_{n.dif}$ ~ 55 - 65mb



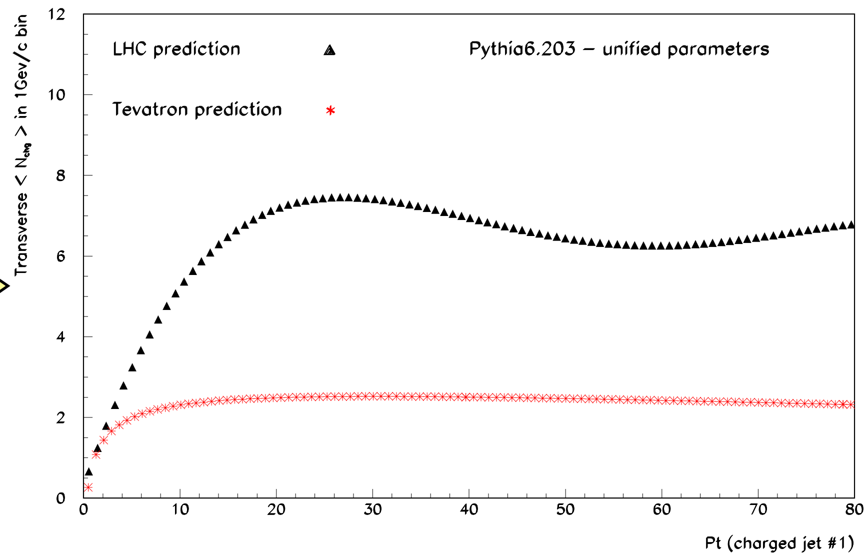
Best described with MPI models!

Underlying event in charged jet evolution (CDF analysis)

$$\Delta\phi = \phi - \phi_{ljet}$$

It is not only minimum bias event!

In a hard scattering process, the underlying event has a **hard component** (initial + final-state radiation and particles from the outgoing hard scattered partons) and a **soft component** (beam-beam remnants).



Conclusions: QCD physics

- LHC will probe QCD to unexplored kinematic limits;
- Jet studies (test of pQCD, constrain p.d.f.'s, physics studies);
- Luminosity uncertainties can be reduced by measurements of relative luminosities: high-Q^2 and wide x-range;
- Prompt-photon production will lead to improved knowledge of background levels ($H \rightarrow \gamma\gamma$), $f_g(x)$ and parton dynamics;
- α_s at high-energy scales (test of the running of α_s);
- Multiple parton scattering: source of background and/or new physics channels;
- Minimum-bias and the underlying event: improved understanding of events dominated by soft processes.

EW Physics at the LHC

- **W mass** measurement
- Improvements in the measurements of the mass of the top quark ($\mathbf{m_t}$).
- A_{FB} asymmetry in dilepton production: $\mathbf{\sin^2\theta_{eff}^{lept}(M_Z^2)}$.
- EW single top quark production: direct measurement of $\mathbf{V_{tb}}$.
- Triple gauge boson couplings (TGC).
- EW physics conclusions.

W mass measurement

• W mass is one of the fundamental parameters of the SM (α_{QED}, G_F, $\sin\theta_W$)

$$M_W = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}}\frac{1}{\sin\theta_W\sqrt{(1-\Delta R)}}$$

• Precise measurements will constrain the mass of the SM Higgs or the h boson of the MSSM;

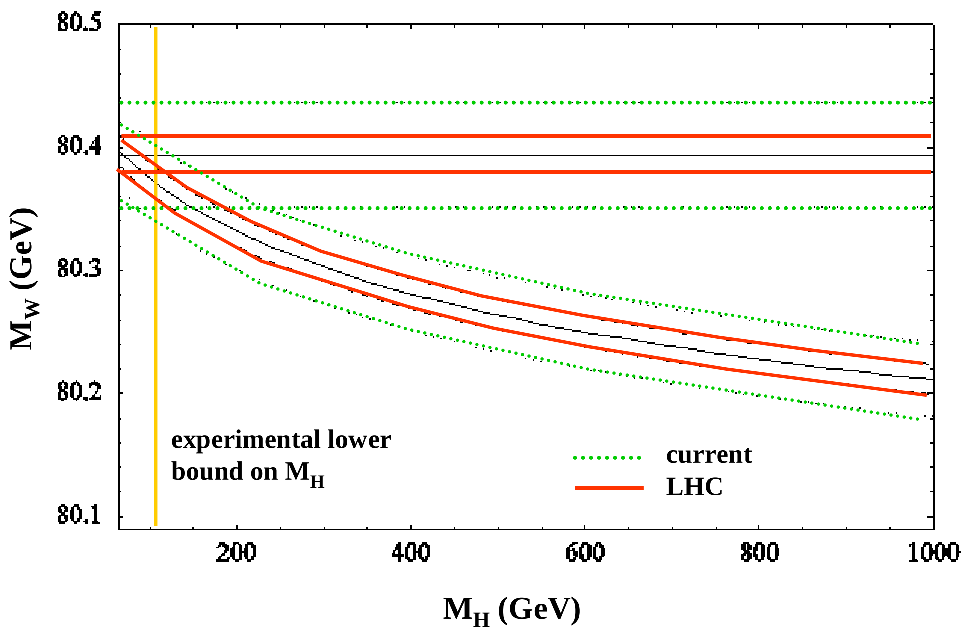
• At the time of the LHC start-up the W mass will be known with a precision of about **30 MeV** (LEP2 + Tevatron)

• Equal weights in a χ^2 test:

$$\Delta M_W \approx 0.7\times10^{-2}\,\Delta m_t$$

At the LHC **Δm_t~ 2 GeV**

M_W = 80.446 ± 0.040 GeV (LEP2 – PDG)



M_W should be known with a precision of about **15 MeV** (combining e/μ and CMS data).

(achievable during the low-luminosity phase at ATLAS)

• **constrains M_H to ~25% .**

W mass measurement

Sources of uncertainty:

- **Statistical uncertainty**: **< 2 MeV** for $\mathcal{L} \approx 10\ fb^{-1}$

$$pp \rightarrow W + X$$
$$W \rightarrow l \nu_l$$

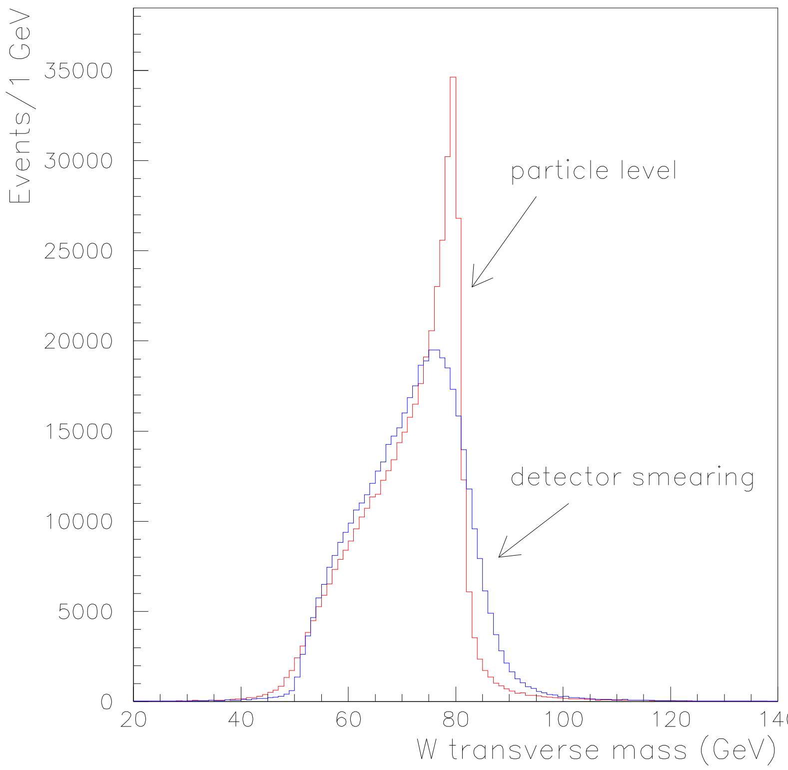
σ = 30 nb (l=e,μ)

3x10⁸ events ($\mathcal{L} \approx 10\ fb^{-1}$)

- **Systematic error** will arise mainly from the MC reliability in reproducing the data
a) physics: W p_t spectrum, structure functions, W width, radiative decays and background.
b) detector performance: lepton scale, energy/momentum resolution and response to recoil.

- Lepton energy and momentum scale:
~0.1% at Tevatron
~0.02% at LHC – ATLAS (tuned to $Z \rightarrow l^+ l^-$, l=e, μ)

- Knowledge of absolute luminosity (uncertainty on cross sections)



Ø **Detector resolution + pile-up** will smear significantly the transverse mass distribution.
(method limited to the low-luminosity phase!)

Top mass

- Together with M_W, $\mathbf{m_t}$ helps to **constrain the SM Higgs mass.**

  $\mathbf{m_t = 175.3 \pm 4.4}$ **GeV** (global fit – PDG)

- $t\bar{t}$ production is expected to be the main background to new physics processes: production and decay of **Higgs bosons** and **SUSY particles**.
- Precision measurements in the top sector are important to get more clues on the origin of the fermion mass hierarchy.
- Top events will be used to **calibrate the calorimeter jet scale** ($W \to jj$ from $t \to bW$).

$$\sigma_{NLO}(pp \to t\bar{t}) = \mathbf{833\ pb} \text{ at LHC}$$

> 8x10⁶ events at ($\mathcal{L} \approx 10$ fb^{-1})

$gg \to t\bar{t}$ (~ 90%) (~7 pb at Tevatron)

$q\bar{q} \to t\bar{t}$ (~ 10%)

SM dominant decay

$t\bar{t}$ leptonic decays ($t \to bW$)	
single lepton: $W \to l\nu$, $W \to jj$	**29.6%** (**2.5 x 10^6 events**)
di-lepton: $W \to l\nu$, $W \to l\nu$	**4.9%** (**400,000 events**)

$\mathcal{L} \approx 10$ fb^{-1}

Best channel for $\mathbf{m_t}$ **measurement** will be $t\bar{t} \to WWb\bar{b} \to (l\nu)(jj)b\bar{b}$ ($m_t = m_{jjb}$)

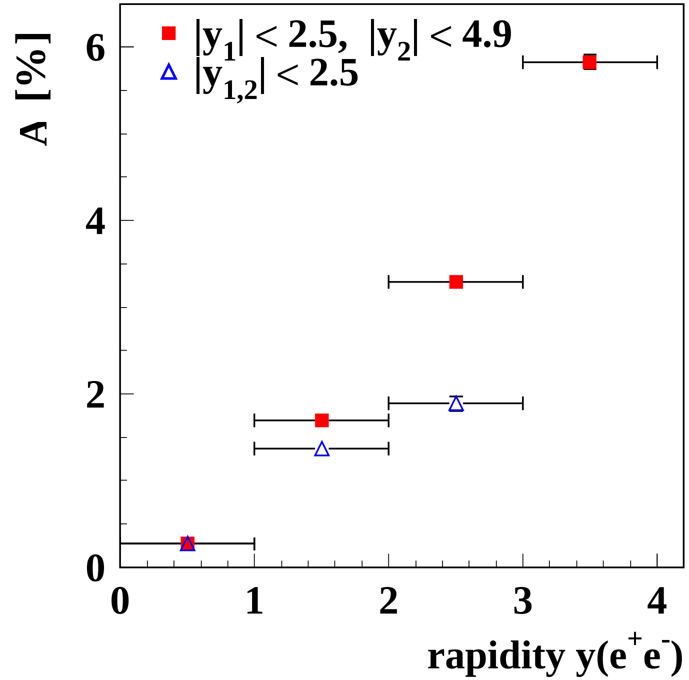
Δm_t ~ 1.5 GeV

Δm_t at LHC will be dominated by systematic errors!

- Jet energy scale:
  ~3% at Tevatron
  ~1% at LHC – ATLAS (including $W \to jj$ from $t \to bW$)
- Final state gluon radiation (~1%)

Determination of $\sin^2\theta_{eff}^{lept}(M_Z^2)$

- $\sin^2\theta_{eff}^{lept}$ is one of the **fundamental parameters of the SM!**
- precise determination will **constrain the Higgs mass** and check **consistency of the SM**.
- $\sin^2\theta_{eff}^{lept}$ will be determined at the LHC by measuring **A_{FB} in dilepton production** near the Z pole.



$$A_{FB} = b\ \{ a - \sin^2\theta_{eff}^{lept}(M_Z^2) \}$$

a and **b** calculated to **NLO** in QED and QCD.

$\sigma (Z \rightarrow l^+ l^-) \sim 1.5$ **nb** (for e or μ)

y cuts – e^+e^- (| y(Z) | > 1)	ΔA_{FB} (statistical)	$\Delta \sin^2\theta_{eff}^{lept}$ (statistical)
$\| y(l_{1,2}) \| < 2.5$	3.03×10^{-4}	4.0×10^{-4}
$\| y(l_1) \| < 2.5$; $\| y(l_2) \| < 4.9$	2.29×10^{-4}	1.41×10^{-4}

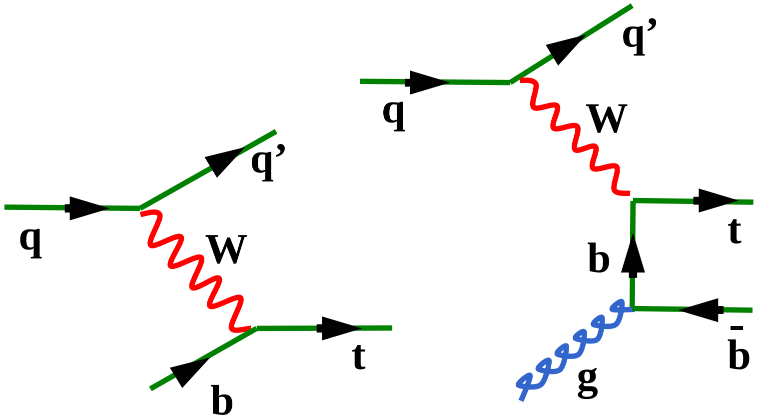
$\mathcal{L} = 100\ fb^{-1}$

- Main systematic effect: **uncertainty on the p.d.f.'s**, lepton acceptance (~0.1%), radiative correction calculations.

$\sin^2\theta_{eff}^{lept}(M_Z^2) = 0.23126 \pm 1.7 \times 10^{-4}$ (global fit PDG)

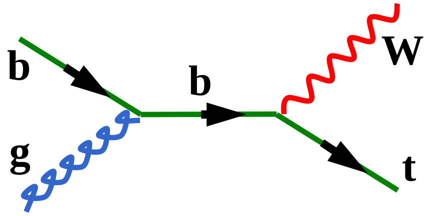
Can be further improved:
combine channels/experiments.

EW single top quark production **(not yet observed!)**



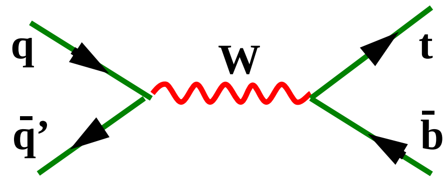
W-gluon fusion

σ_{Wg}~ 250 pb



Wt process

σ_{Wt}~ 60 pb



W* process

σ_{W^*}~ 10 pb

(lower theoretical uncertainties!)

for each process: $\boldsymbol{\sigma} \propto |V_{tb}|^2$

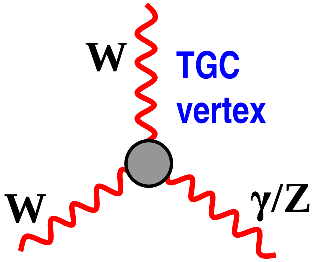
- Probe the **t-W-b vertex**
- **Directly measurement** (only) of the CKM matrix element V_{tb} at ATLAS (assumes **CKM unitarity**)
- **New physics**: heavy vector boson W'
- Source of **high polarized tops!**
- Background: **$t\bar{t}$, $Wb\bar{b}$, Wjj**

Process	S/B	S/√B	$\Delta V_{tb}/V_{tb}$ – statistical	$\Delta V_{tb}/V_{tb}$ – theory
W-gluon	4.9	239	0.51%	7.5%
Wt	0.24	25	2.2%	9.5%
*W**	0.55	22	2.8%	3.8%

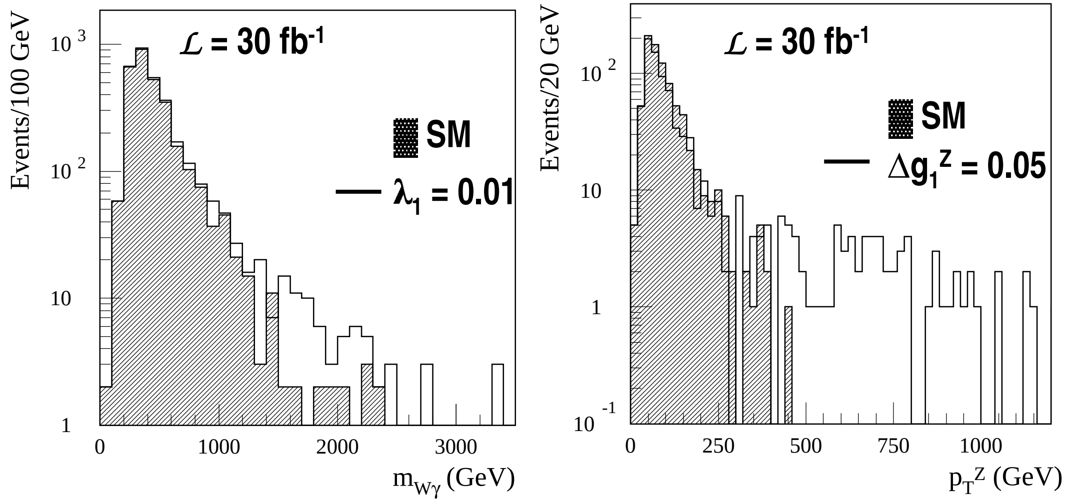
$\mathcal{L}$ = 30 fb^{-1}

Systematic errors: b-jet tagging, luminosity ($\Delta\mathcal{L}$ ~ 5 – 10%), **theoretical (dominate V_{tb} measurements!).**

Triple gauge boson couplings



- TGC of the type **WWγ** or **WWZ** provides a direct test of the non-Abelian structure of the SM (EW symmetry breaking).
- It may also indicate hints of **new physics**: new processes are expected to give anomalous contributions to the TGC.
- New physics could show up as deviations of these parameters from their SM values.



- This sector of the SM is often described by 5 parameters: **g_1^Z, κ_γ, κ_Z, λ_γ** and **λ_γ**, (SM values are equal to $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_\gamma = 0$, at the tree level).

Gauge, C and P invariance

- Anomalous contribution to TGC is **enhanced at high √s** (increase of production cross-section).

• Variables:

Wγ: ($m_{W\gamma}$, $|\eta_\gamma^*|$) and (p_T^γ, θ^*)

WZ: (m_{WZ} , $|\eta_Z^*|$) and (p_T^Z, θ^*)

sensitive to **high-energy behaviour:** m_{WV}, p_T^V

sensitive to **angular information:** $|\eta_V^*|$, θ^*

• SM: vanishing helicity at low $|\eta|$
Non-standard TGC: partially eliminates `zero radiation'

Systematic uncertainties:

• At the LHC, sensitivity to TGC is a combination of the very high energy and high luminosity.

• Uncertainties arising from low p_T background will be quite small: anomalous TGC signature will be found at high p_T.

• Theoretical uncertainties: p.d.f.'s & higher order corrections

Statistical sensitivity at 95% C.L.	
Δg_1^Z	±0.0078
$\Delta\kappa_Z$	±0.069
λ_Z	±0.0058
$\Delta\kappa_\gamma$	±0.035
λ_γ	±0.0025

$\mathcal{L}$ = 30 fb^{-1}

Using max-Likelihood fit to $m_{WV} \otimes |\eta_V^*|$

Conclusions: EW sector

- LHC will allow precision measurements: unexplored kinematic regions, high-statistics (W, Z, b, t factory);
- ATLAS: valuable precision measurements of SM parameters;
- W mass can be measured with a precision of 15 MeV (combinig e/μ and ATLAS + CMS);
- Top mass: ~ 2 GeV (combined with Δm_W~15 MeV, constrains M_H to ~ 25%);
- $\sin^2\theta_{eff}^{lept}(M_Z^2)$ can be determined with statistical precision of 1.4×10^{-4} (competitive to lepton collider measurements!)
- EW single top production: direct measurement of V_{tb}; measurement of top polarization (Wg with statistical precision of ~ 1.6%);
- Sensitivity to anomalous TGC's: indicative of new physics!