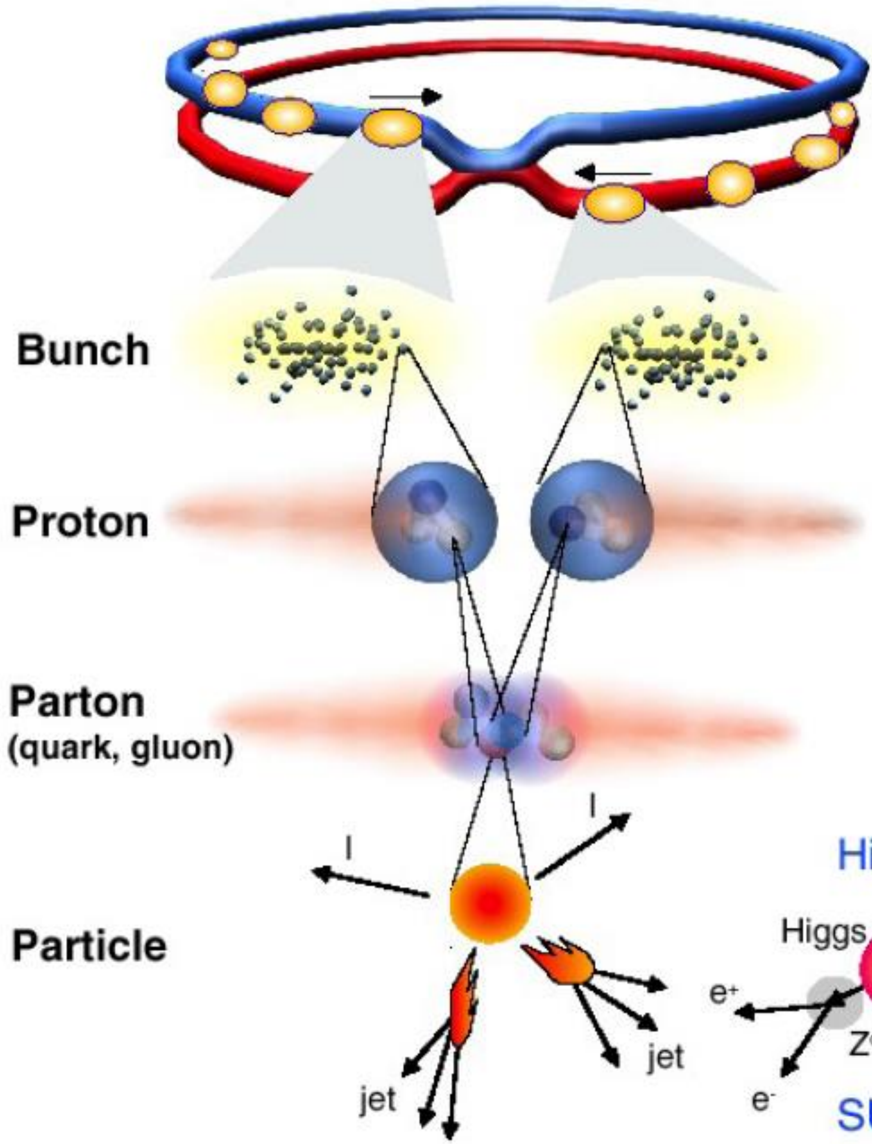
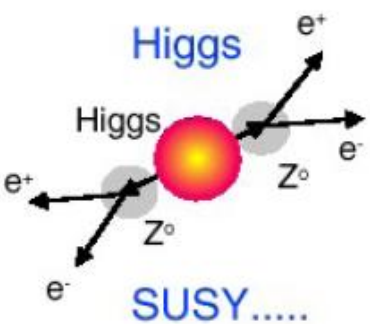
Collisions at LHC

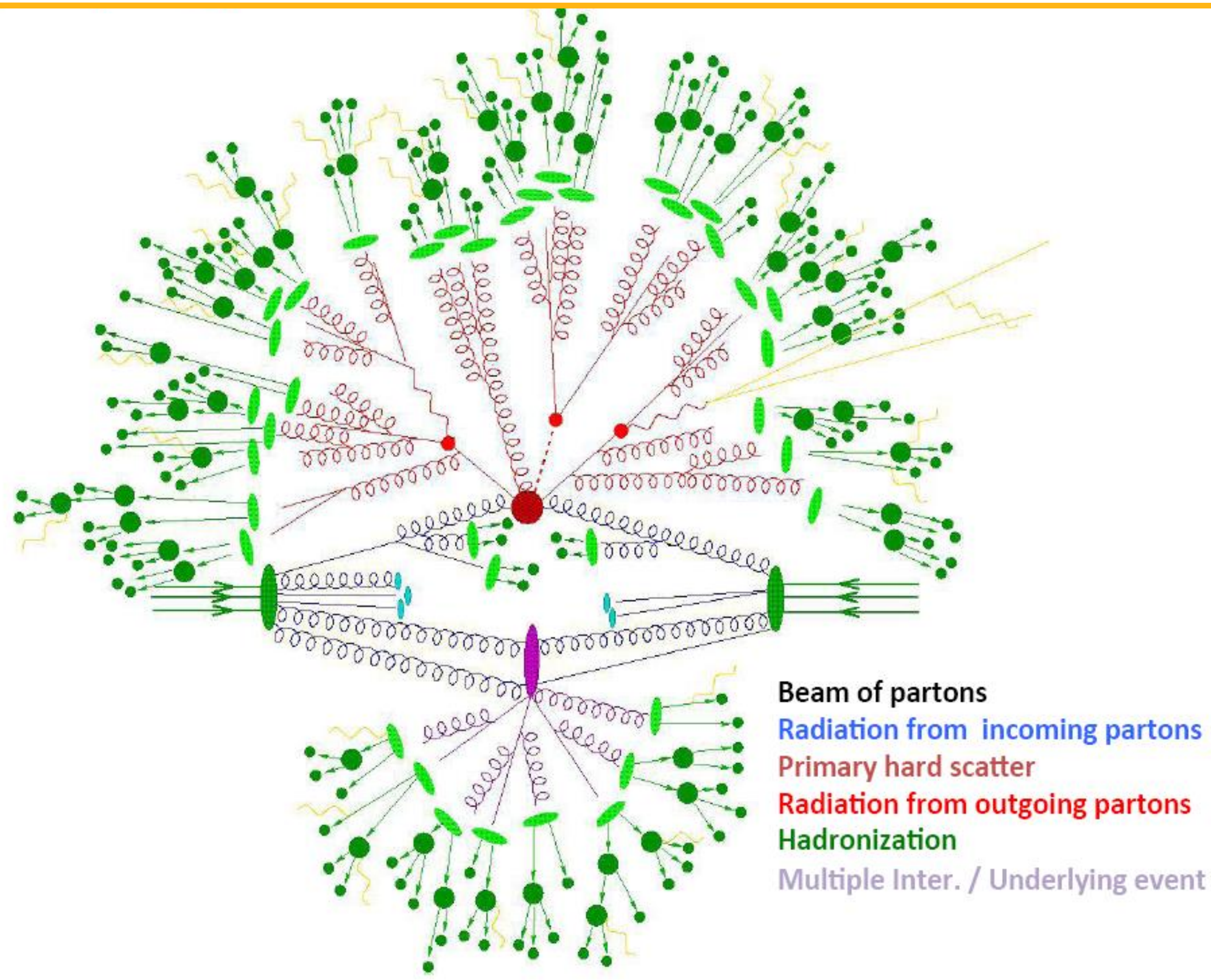


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz



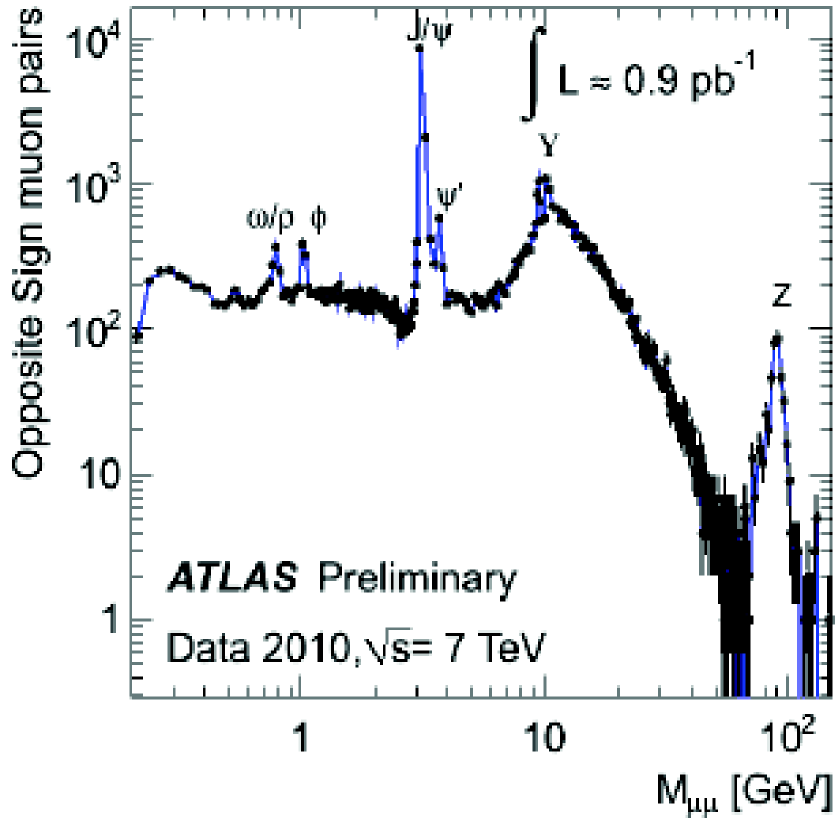
Selection of 1 in 10,000,000,000,000

Typical pp collision



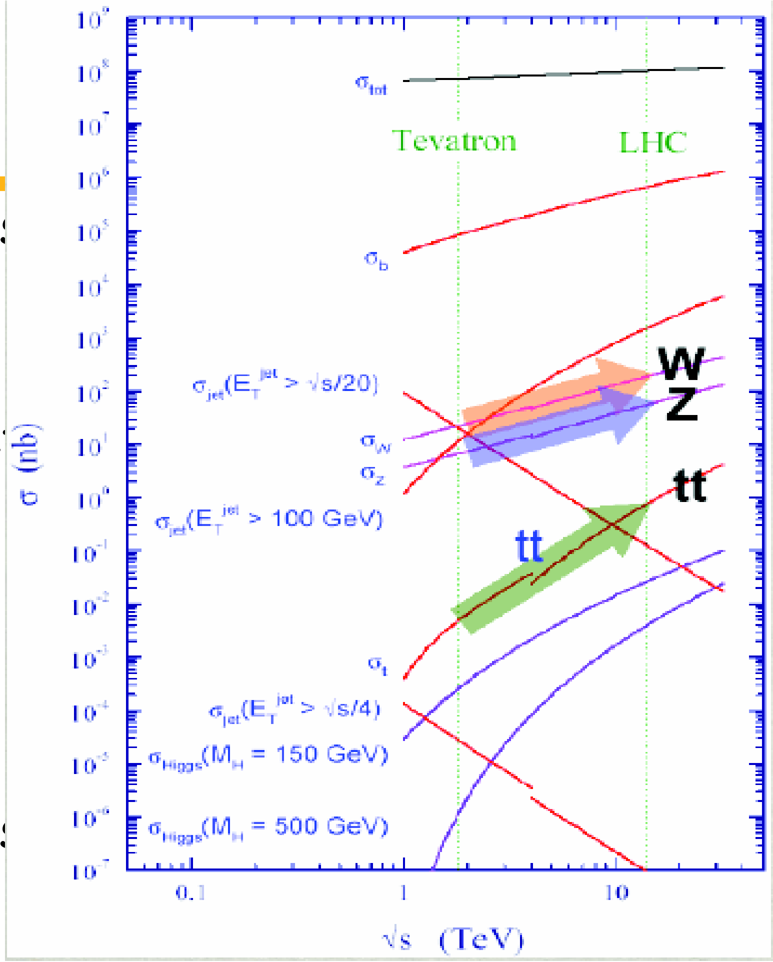
Retracing history of particle physics

- With up to 1pb^{-1} (public results) we made it up to 80's
- Results at sumer conferences 2010
- Onia(J/Psi, ✡📭 Y,...) + first hundreds of W,Z in the leptonic channels



Bosons at LHC

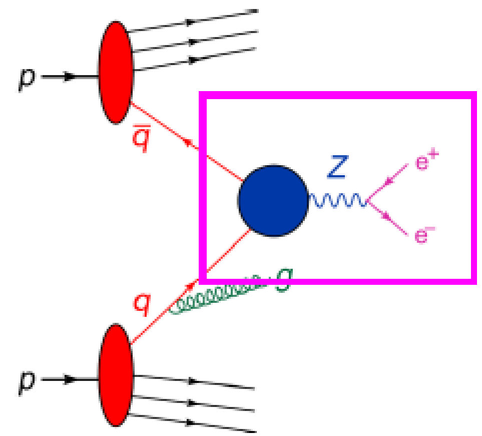
- Well measured by previous experiments
  - Inclusive cross sections, $R(W^+/W^-)$, $R(W/Z)$
  - Differential distributions, associated jet multiplicity, A_{FB}, etc.
- Yet still educational at the LHC
  - Cross sections at $\sqrt{s} = 7 TeV$
  - New pdf constraints possible
- "Standard candles" for high-p_T analyses
  - Calibration, alignment
  - Independent luminosity measurements



Just departure point for high-p_T Beyond Standard Model analyses

QCD factorisation and parton model

- Asymptotic freedom guarantees that as short distances (large transverse momenta) partons in the proton are almost free
- Sampled ”one at a time” in hard collisions
  - QCD improved parton shower model



“suitable” final state

Parton distribution function: prob. of finding parton a in proton 1, carrying fraction x_1 of its momentum

factorization scale (“arbitrary”)

$$\sigma^{pp\to X}(s;\alpha_s,\mu_R,\mu_F) = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2\, f_a(x_1,\alpha_s,\mu_F)\, f_b(x_2,\alpha_s,\mu_F) \times \hat{\sigma}^{ab\to X}(sx_1x_2;\alpha_s,\mu_R,\mu_F)$$

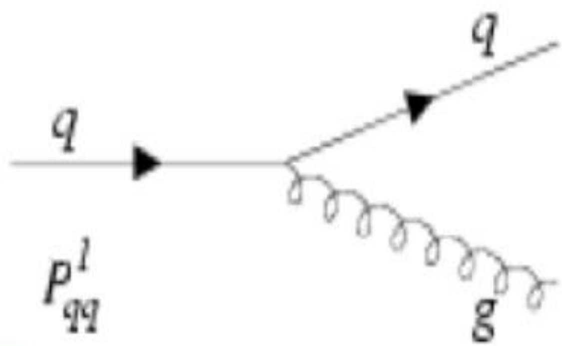
Partonic cross section, computable in perturbative QCD

partonic CM energy^2

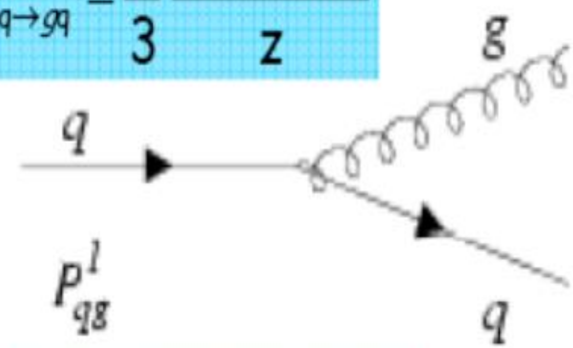
renormalization scale (“arbitrary”)

Altarelli-Parisi splitting functions

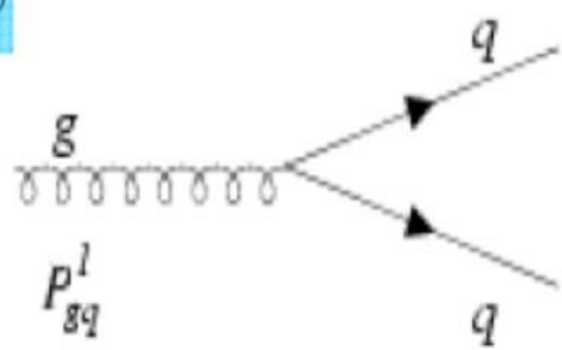
$$P_{q\to qg} = \frac{4}{3}\left(\frac{1+z^2}{1-z}\right)$$



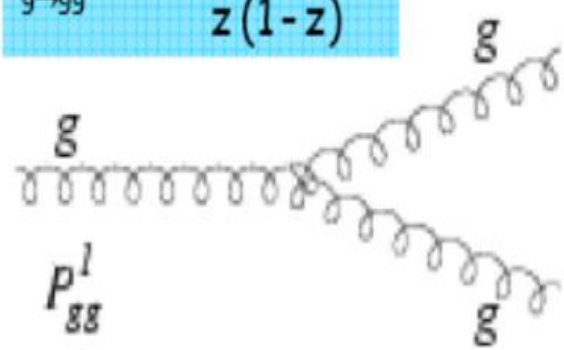
$$P_{q\to gq} = \frac{4}{3}\frac{1+(1-z)^2}{z}$$



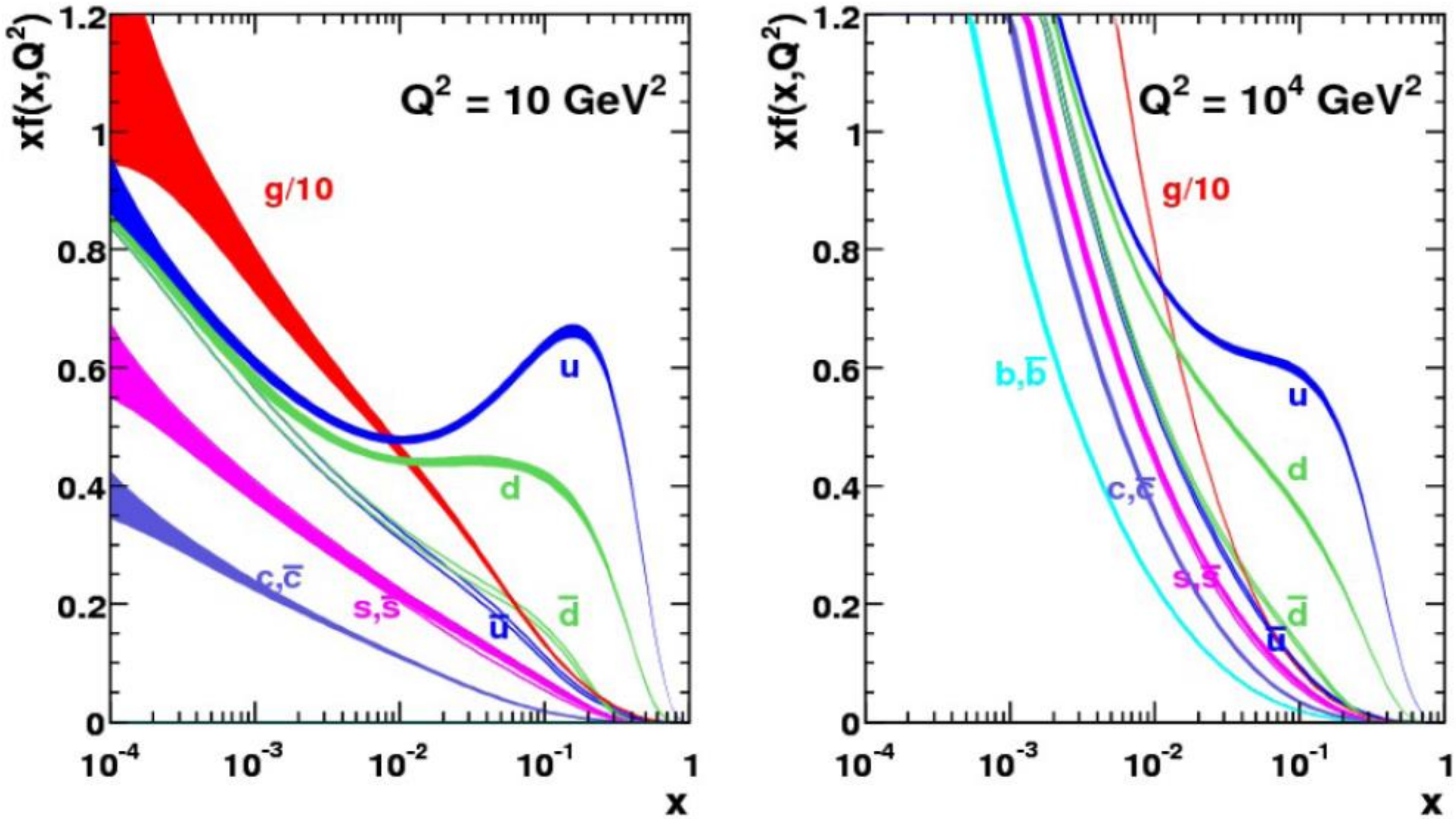
$$P_{g\to q\bar{q}} = \frac{n_f^2}{2}\left(z^2+(1-z)^2\right)$$



$$P_{g\to gg} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$



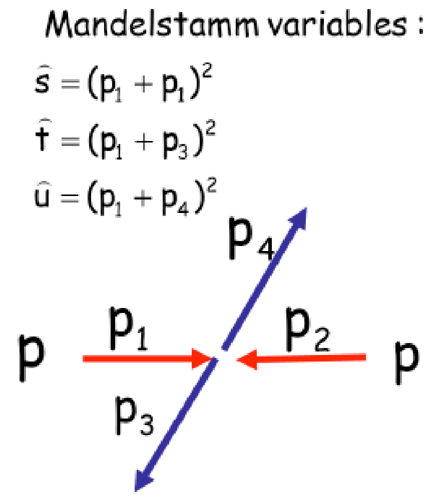
MSTW 2008 NLO PDFs (68% C.L.)



W and Z production

- Cross sections for on-shell W and Z production (in narrow width limit) given by

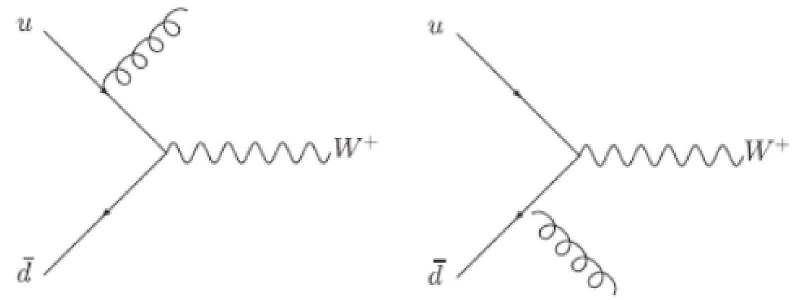
$$\hat{\sigma}^{q\bar{q}'\to W} = \frac{\pi}{3}\sqrt{2}G_F M_W^2 |V_{qq'}|^2 \delta(\hat{s} - M_W^2),$$
$$\hat{\sigma}^{q\bar{q}\to Z} = \frac{\pi}{3}\sqrt{2}G_F M_Z^2 (v_q^2 + a_q^2)\delta(\hat{s} - M_Z^2),$$



- Where $V_{qq'}$ is appropriate CKM matrix element and v_q and a_q are the vector and axial couplings of the Z to quarks
- At LO there is no ♋$_s$ dependence; EW vertex only
- NLO contribution to the cross section is proportional to ♋$_s$; NNLO to ♋$_s^2$; ...

W and Z p_T distributions

- Most of W/Z produced at low p_T but can be produced at non-zero p_T due to the diagrams with emitted gluon



$$\sum |\mathcal{M}^{q\bar{q}' \to Wg}|^2 = \pi \alpha_S \sqrt{2} G_F M_W^2 |V_{qq'}|^2 \, \frac{8}{9} \, \frac{\hat{t}^2 + \hat{u}^2 + 2M_W^2 \hat{s}}{\hat{t}\hat{u}} \,,$$

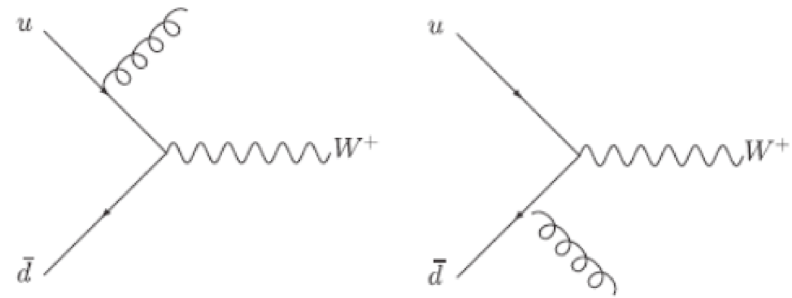
$$\sum |\mathcal{M}^{gq \to Wq'}|^2 = \pi \alpha_S \sqrt{2} G_F M_W^2 |V_{qq'}|^2 \, \frac{1}{3} \, \frac{\hat{s}^2 + \hat{u}^2 + 2\hat{t} M_W^2}{-\hat{s}\hat{u}} \,,$$

- Sum over colors and spins in initial states and average over same in final states
- Transverse momentum distribution obtained by convoluting these matrix elements with pdf's in usual way

W and Z p_T distributions

- Back to 2->2 subprocess, where Q^2 is virtuality of the W

$$|\mathcal{M}^{u\bar{d}\to W+g}|^2 \sim \left(\frac{\hat{t}^2+\hat{u}^2+2Q^2\,\hat{s}}{\hat{t}\,\hat{u}}\right)$$



- Convolute with pdf's

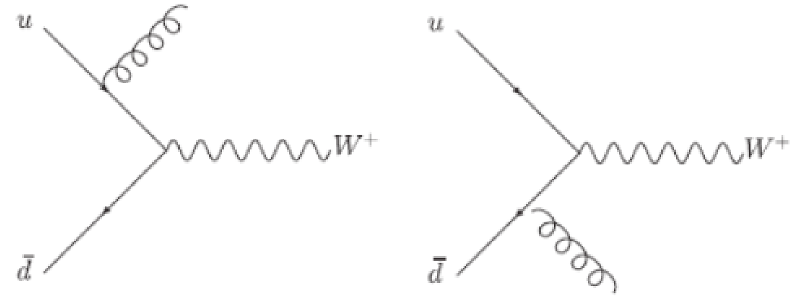
$$\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2\, f_u(x_1, Q^2)\, f_{\bar{d}}(x_2, Q^2)\, \frac{|\mathcal{M}|^2}{32\pi^2\hat{s}}\, \frac{\mathrm{d}^3 p_W}{E_W}\, \frac{\mathrm{d}^3 p_g}{E_g}\, \delta(p_u + p_{\bar{\mathrm{d}}} - p_g - p_W)$$

- Transform into differential cross-section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2 \mathrm{d}y\, \mathrm{d}p_T^2} \sim \frac{1}{s} \int \mathrm{d}y_g\, f_u(x_1, Q^2)\, f_{\bar{\mathrm{d}}}(x_2, Q^2)\, \frac{|\mathcal{M}|^2}{\hat{s}}$$

W and Z p_T distributions

- In the limit of leading divergence we can write



$$\frac{d\sigma}{dQ^2 dy\, dp_T^2} \sim \frac{2}{s}\frac{1}{p_T^2}\int dy_g\, f_u(x_1, Q^2) f_{\bar{d}}(x_2, Q^2) + (\text{sub-leading in } p_T^2)$$

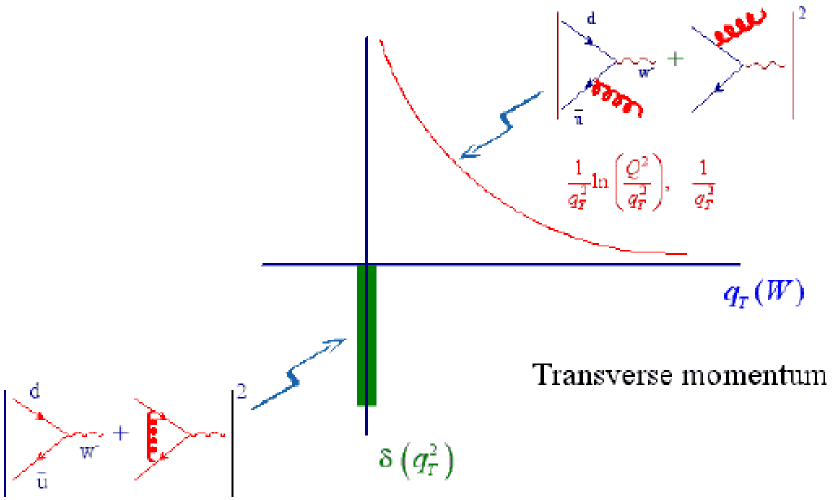
- As p_T of W becomes small, limits on y_g integration are given by +- $\log(s^{1/2}/p_T)$
- The results is then

$$\frac{d\sigma}{dQ^2 dy\, dp_T^2} \sim \frac{\log(s/p_T^2)}{p_T^2}$$

- It diverges unless we apply a p_T^{min} cut; final distribution depends on α_s times log

Shortcomings of fixed order calculations

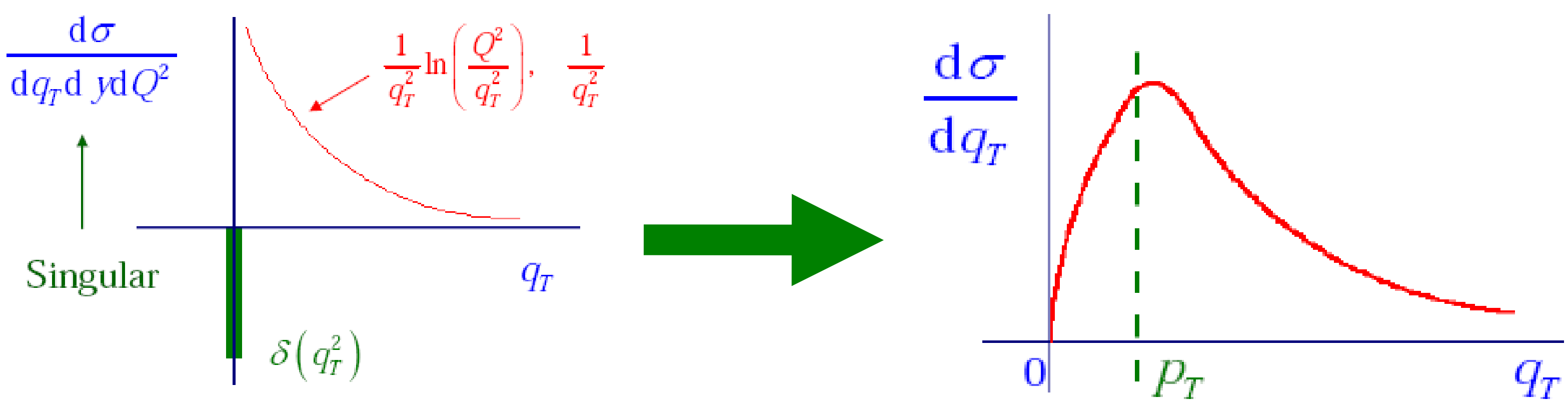
- Divergent, without cut on p_T^{min}, cannot describe the data



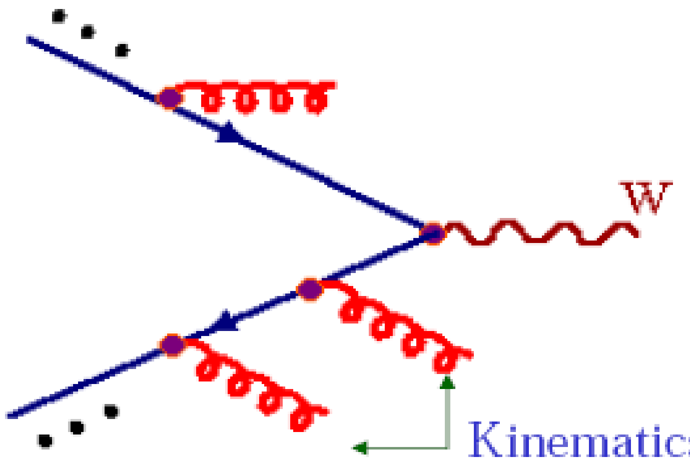
(at NLO)

QCD resummation

- Resummation: reorganise calculations in terms of large Logs $L(Q^2/p_T^2)$; regularised at low p_T range;
- Different schemes: CSS which includes also non-perturbative effects; Sudakov form factors; exponentation;



Monte Carlo approach example: Parton Shower



Backward Radiation
(Initial State Radiation)

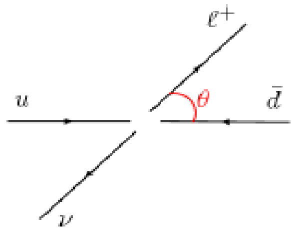
Kinematics of the radiated gluon, controlled by Sudakov form factor with some arbitrary cut-off. (In contrast to perform integration in impact parameter space, i.e., b space.)

The shape of q_T (w) is generated. But, the integrated rate remains the same as at Born level (finite virtual correction is not included).

Recently, there are efforts to include part of higher order effect in the event generator.

Transverse momenta of charged lepton

- In (ud) c.m. system,

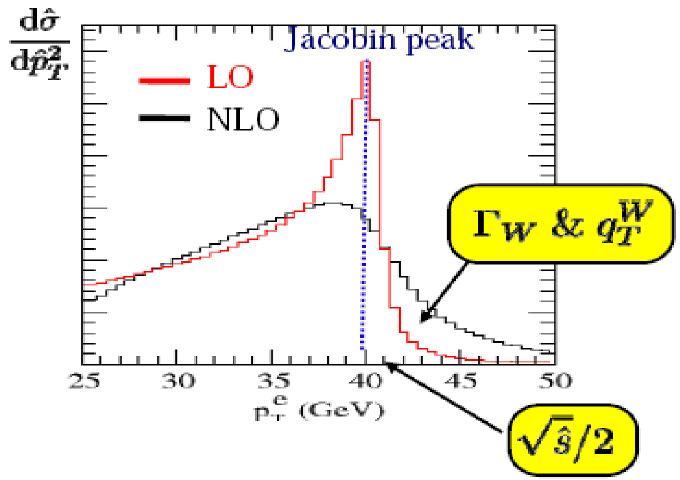


$$\hat{p}_T^2 = \frac{1}{4}\hat{s}\sin^2\theta$$

Jacobin factor

$$\frac{d\cos\theta}{d\hat{p}_T^2} = -\frac{2}{\hat{s}}\frac{1}{\sqrt{1-\frac{4\hat{p}_T^2}{\hat{s}}}}$$

$$\Longrightarrow \frac{d\hat{\sigma}}{d\hat{p}_T^2} \sim \frac{d\hat{\sigma}}{d\cos\theta} \times \frac{1}{\sqrt{1-4\hat{p}_T^2/\hat{s}}}$$

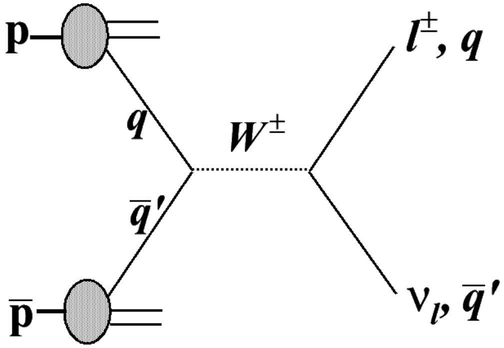


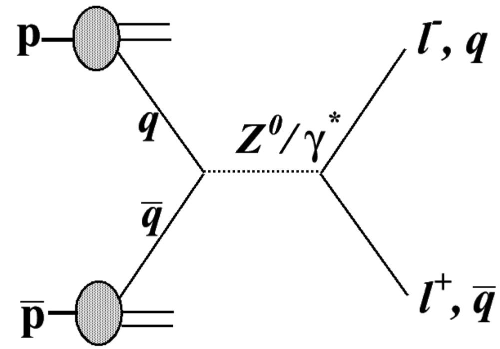
sensitive region for measuring

M_W : $p_T^e \sim 30 - 45$ GeV

Γ_W : not a good observable

Cross-section at LHC (7TeV)





$$\sigma^{NNLO}_{W^+\to\ell\nu} = 6.15\,\mathrm{nb}$$

$$\sigma^{NNLO}_{W^-\to\ell\nu} = 4.3\,\mathrm{nb}$$

$$\sigma^{NNLO}_{W\to\ell\nu} = 10.45\,\mathrm{nb}$$

$$\sigma^{NNLO}_{Z/\gamma*\to\ell\ell} = 0.989\,\mathrm{nb}$$

$$\sigma(W^+) \neq \sigma(W^-)$$

W^+ production: $u\bar{d} + c\bar{s}$

W^- production: $d\bar{u} + s\bar{c}$

Z production: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$

Test QCD (up to NNLO) in production

Hard and soft gluon emission

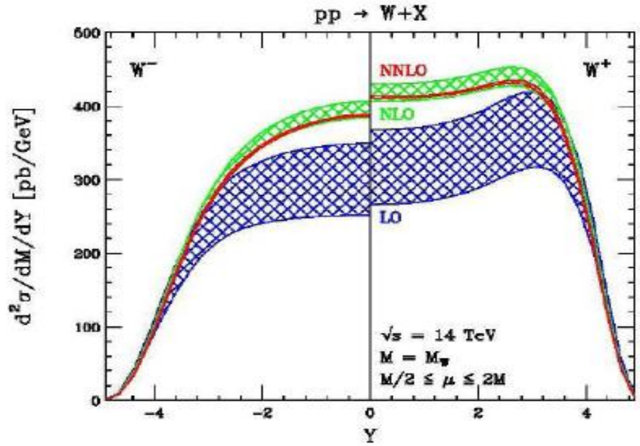
Sensitive to parton distribution functions

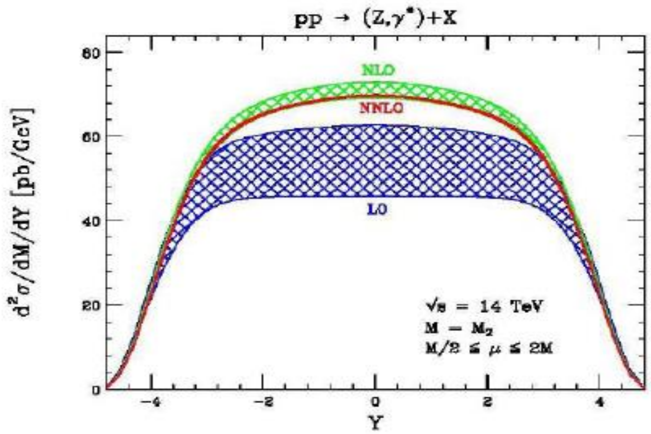
Extract electroweak parameters

$\sin\theta_W$, m_W, quark-boson couplings

Monte Carlo simulations

- Base-line generators:
  - Pythia, Herwig (LO),
  - MCatNLO (NLO)
  - POWHEG (NLO)
- Used as components of for cross-checks
  - FEWZ: complete NLO, NNLL
  - ResBos: NNLL resumation
  - Horace: full 1-loop electroweak
  - PHOTOS:final state QED (exponentiated)





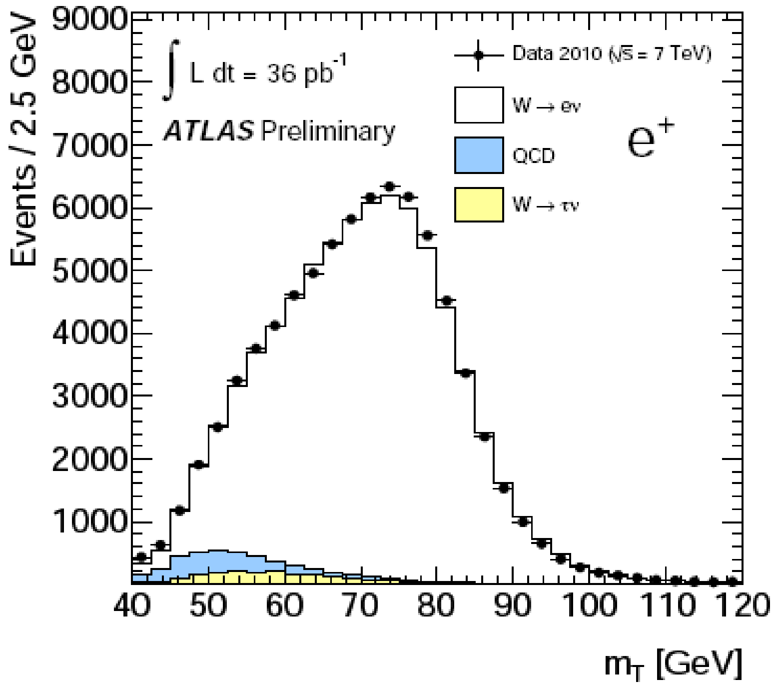
Event selection

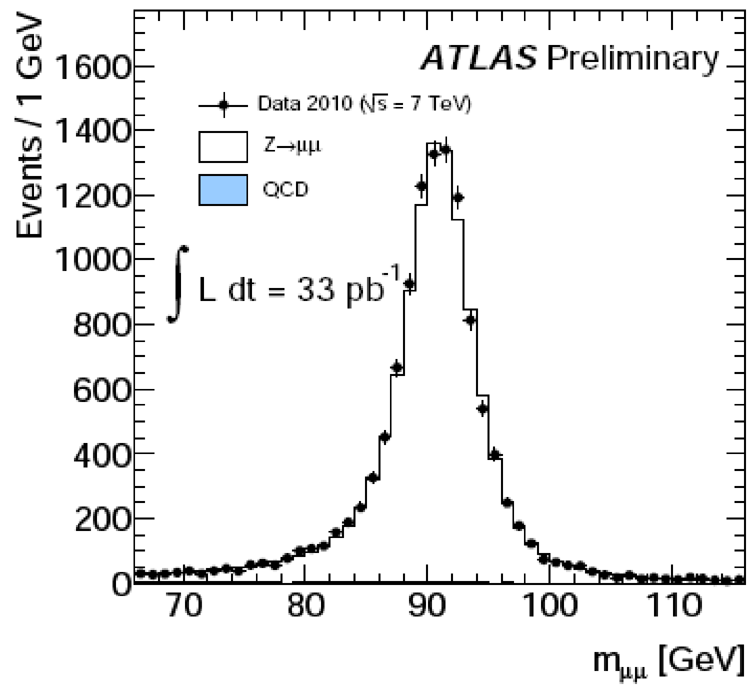
$W \to \ell\nu$

- One e/μ with $p_T > 20$ GeV
- $E_T^{miss} > 25$ GeV
- $m_T(\ell, E_T^{miss}) > 40$ GeV

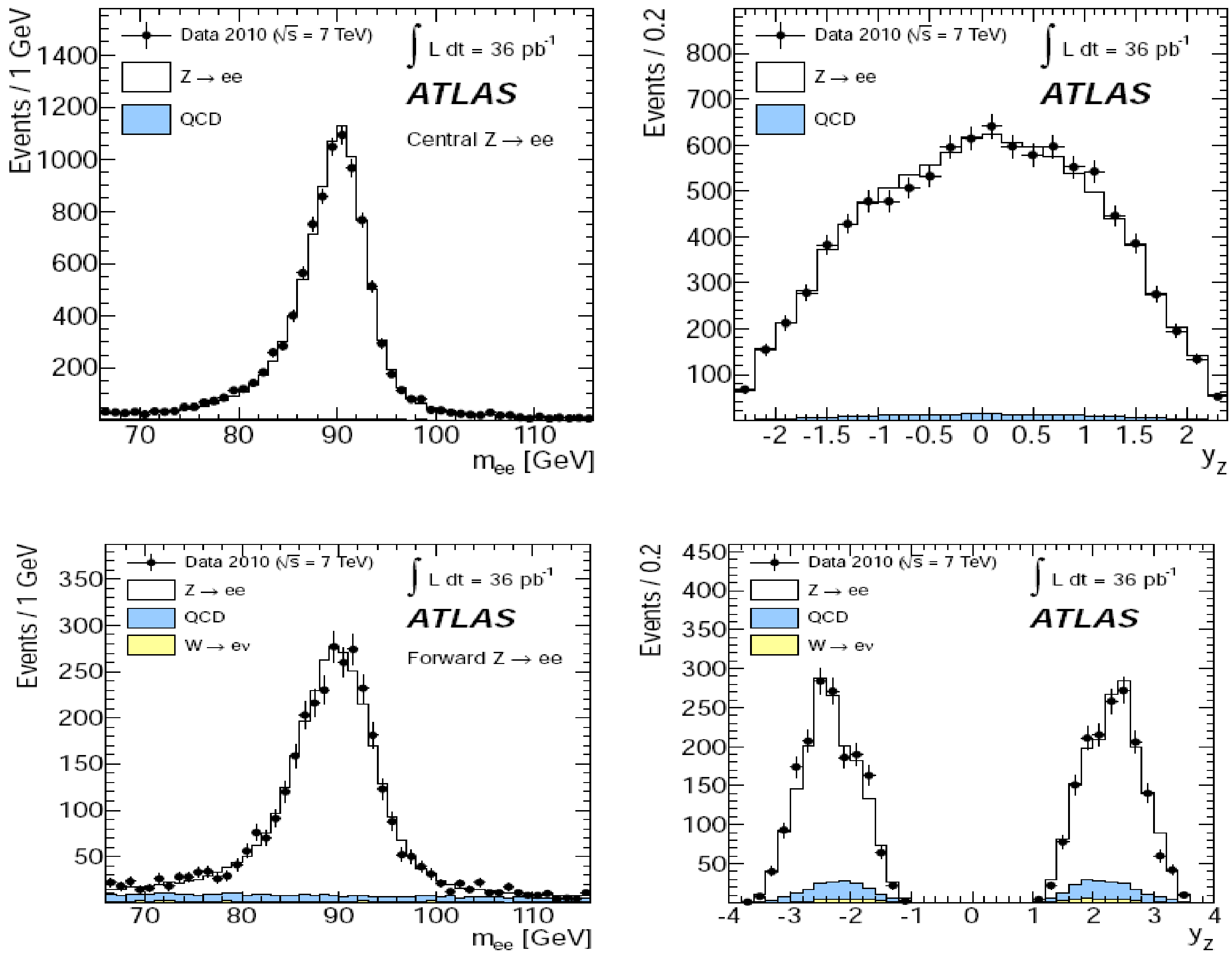
$Z \to \ell\ell$

- Two e/μ with $p_T > 20$ GeV
- $m_{\ell\ell} = 66$–116 GeV



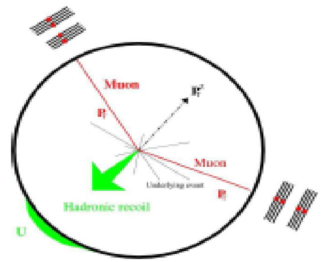


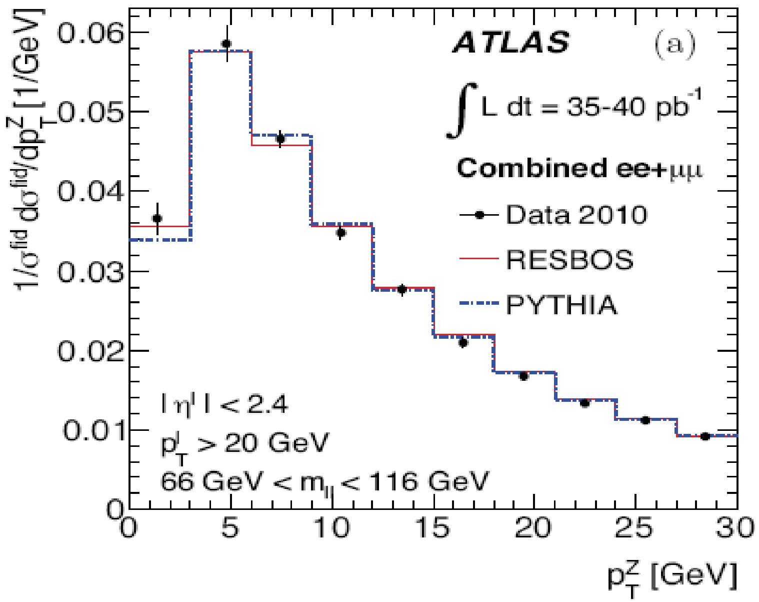
Event selection



Z boson p_T measurement

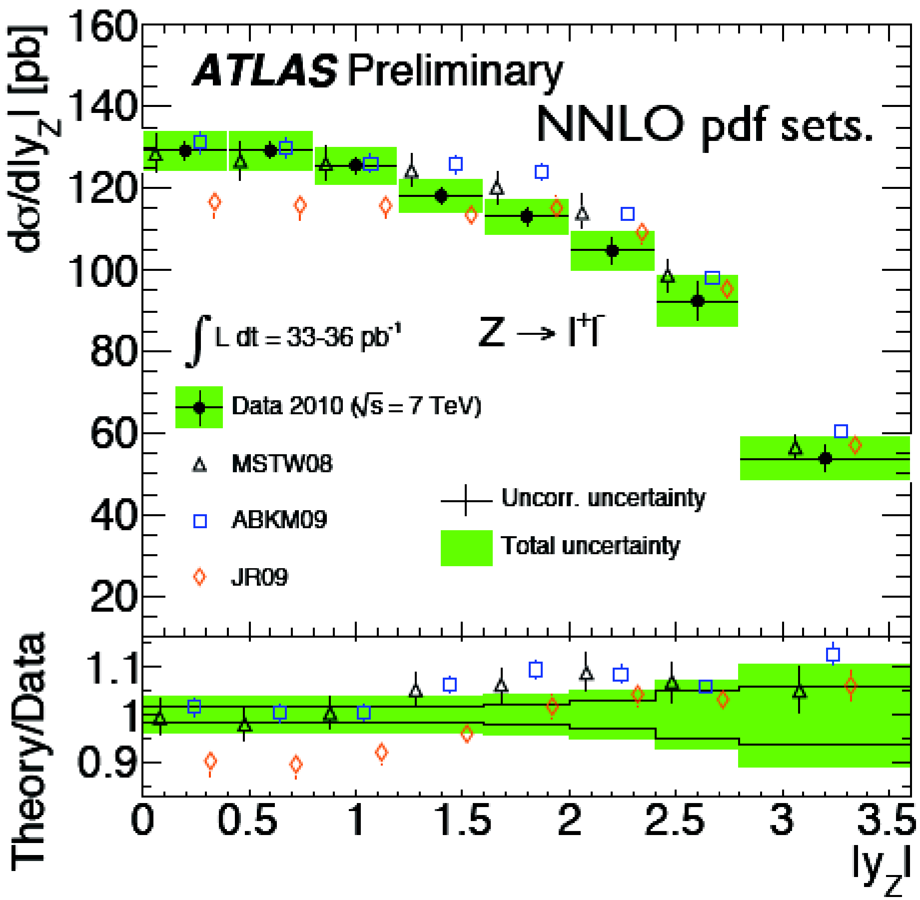
- Important for modeling high-p_T lepton kinematics.
- At leading order, $p_T^{W/Z} = 0$
- Non-zero $p_T^{W/Z}$ is generated through the hadronic recoil of ISR, p_T^R.
- p_T^Z reconstructed directly from $p_T(\mu_1) + p_T(\mu_2)$, while p_T^W reconstructs p_T^R.
- Detector and FSR effects removed with a bin-by-bin unfolding.
- 3-4% precision per bin.



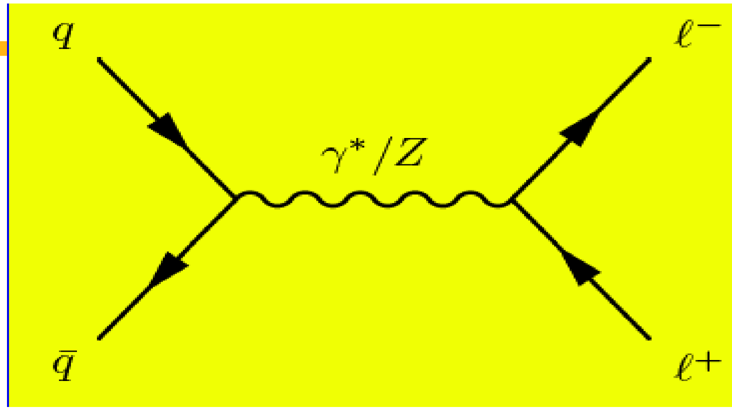


Z differential

- Inclusive production as a function of the Z pseudorapidity
- Lepton flavours combined together taking into account all correlations.
- Z rapidity reaches |y|<3.5 with special electron reconstruction outside tracking volume (|y|<2.5)



DY forward-backward asymmetry



- Direct access to vector and axial couplings

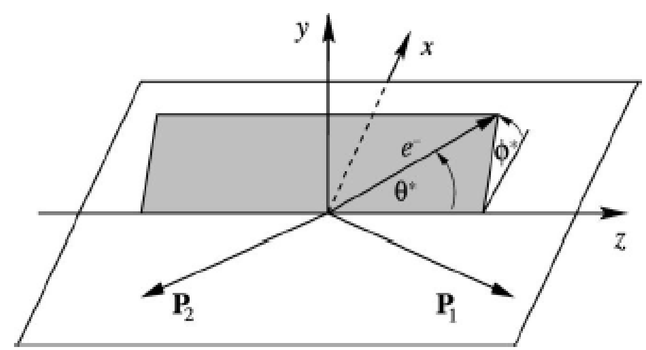
$g_v^f = I_3^f - 2q_f \sin^2\theta_W$ both γ^*-f and Z-f couplings

$g_a^f = I_3^f$ Z-f only coupling

$$\frac{d\sigma}{d\cos\theta^*} \sim \frac{3}{8}(1 + \cos^2\theta^*) + A_{FB}\cos\theta^*$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- **cos**θ^* **> (<) 0** → **forward** (backward) events
- θ^* is the angle of the negative lepton relative the quark momentum in the dilepton centre-of-mass frame
- Minimize the effect of unknown p_T of incoming quark by measuring θ^* in the **Collins-Soper** frame



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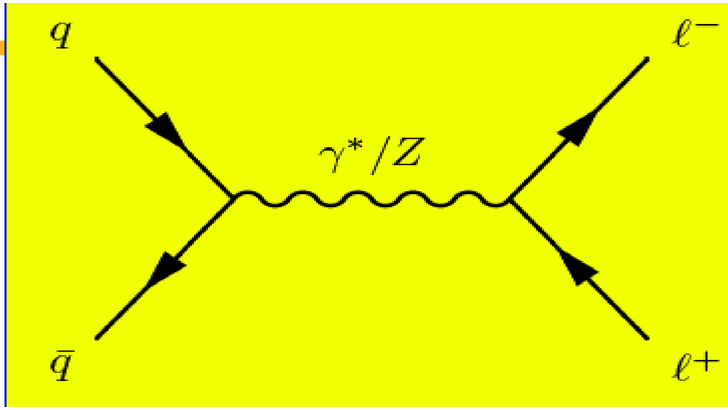


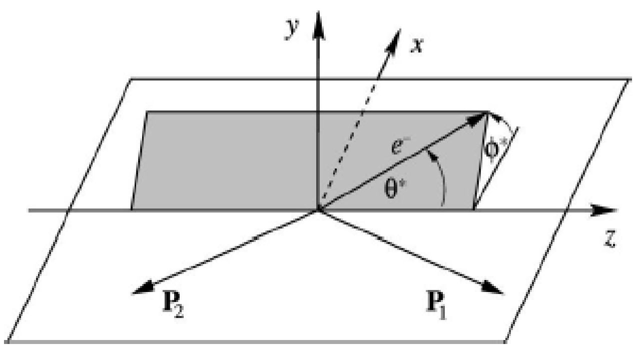
- Direct access to vector and axial couplings

$g_v^f = I_3^f - 2q_f \sin^2\theta_W$ both γ^*-f and Z-f couplings

$g_a^f = I_3^f$ Z-f only coupling

$$\frac{d\sigma}{d\cos\theta^*} \sim \frac{3}{8}(1 + \cos^2\theta^*) + A_{FB}\cos\theta^* \;\Rightarrow\; A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

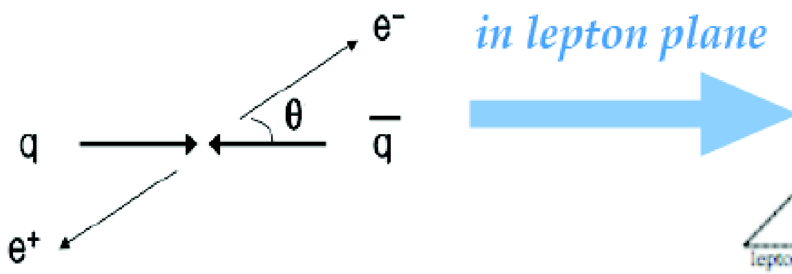
- **cosθ* > (<) 0 → forward (backward)** events
- θ* is the angle of the negative lepton relative the quark momentum in the dilepton centre-of-mass frame
- Minimize the effect of unknown p_T of incoming quark by measuring θ* in the **Collins-Soper** frame



Collins-Soper frame

- Collins-Soper frame : the center of mass frame of dilepton

$$q\bar{q} \rightarrow Z/\gamma* \rightarrow \ell^+\ell^-$$



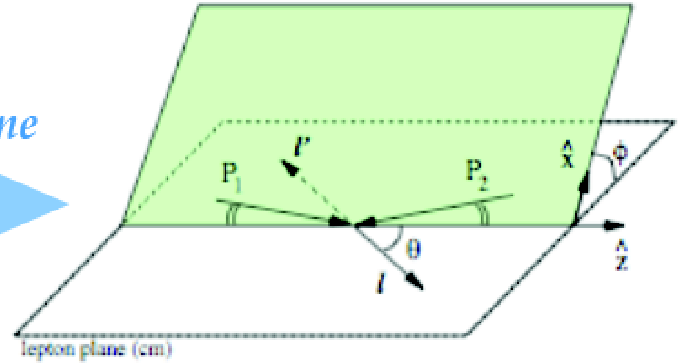


FIG. 1: The Collins-Soper frame.

- Differential cross section of cosθ and φ

$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta)$$ → *LO term*

$$+ \frac{1}{2}A_0(1-3\cos^2\theta)$$ → *$\cos^2\theta$: higher order term*

$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi$$ → *(θ, φ) terms*

$$+ A_4 \cos\theta$$ → *LO term : determine A_{fb}*

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$ → *very small terms*

****All higher order terms are zero at Pt=0***

Z/g* Angular Coefficients

- First measurement of the $p\bar{p} \rightarrow Z/\gamma^* + X \rightarrow e^+e^- + X$ angular distributions with 2.1 fb^{-1}
- Angular distributions of the lepton decay in the Collins-Soper frame are:

$$\frac{d\sigma}{d\cos\theta} \propto (1 + cos^2\theta) + \frac{1}{2}A_0(1 - 3cos^2\theta) + A_4 \cos\theta$$

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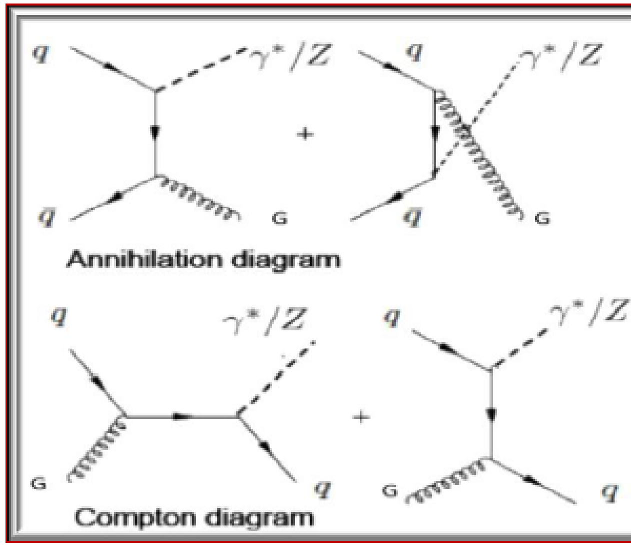
$$\frac{d\sigma}{d\varphi} \propto 1 + \frac{3\pi}{16}A_3 \cos\varphi + \frac{1}{4}A_2 \cos 2\varphi$$

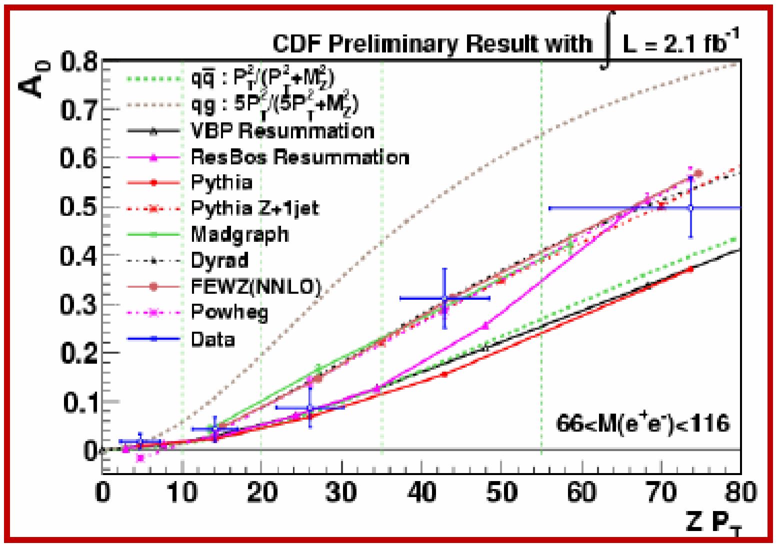
- **Perturbative QCD makes definite predictions on $A_{0,2,3,4}$ depending on the dilepton p_T**
- **At order α_s the Z/γ^* boson can be produced via annihilation or Compton scattering**
- **Probe the contribution of different productions mechanisms contributions**



Z/γ^* Angular Coefficients ($A_{0,2}$)

- At order α_s, both A_0 and A_2 should be the same for Z and γ^*, but they have distinct Z p_T dependencies for annihilation or Compton scattering
- The $A_{0,2}$ trends as a function of Z p_T reveals the two Z production processes contributions, e.g. in Z +1 Jet PYTHIA simulation a significant Compton scattering contribution is expected (~30%)

- **Lam-Tung** relation predicts **A_0=A_2 at LO** and nearly the same at all orders
- Lam-Tung relation is **valid for spin-1 gluons**, but it is broken for scalar gluons
- First measurement of the Lam-Tung relation at large dilepton mass and high transverse dilepton p_T
- **Fundamental test of the vector nature of gluons**



A_0-A_2 = 0.02 ± 0.02