Standard Model Physics

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TECHNISCHE UNIVERSITÄT DRESDEN

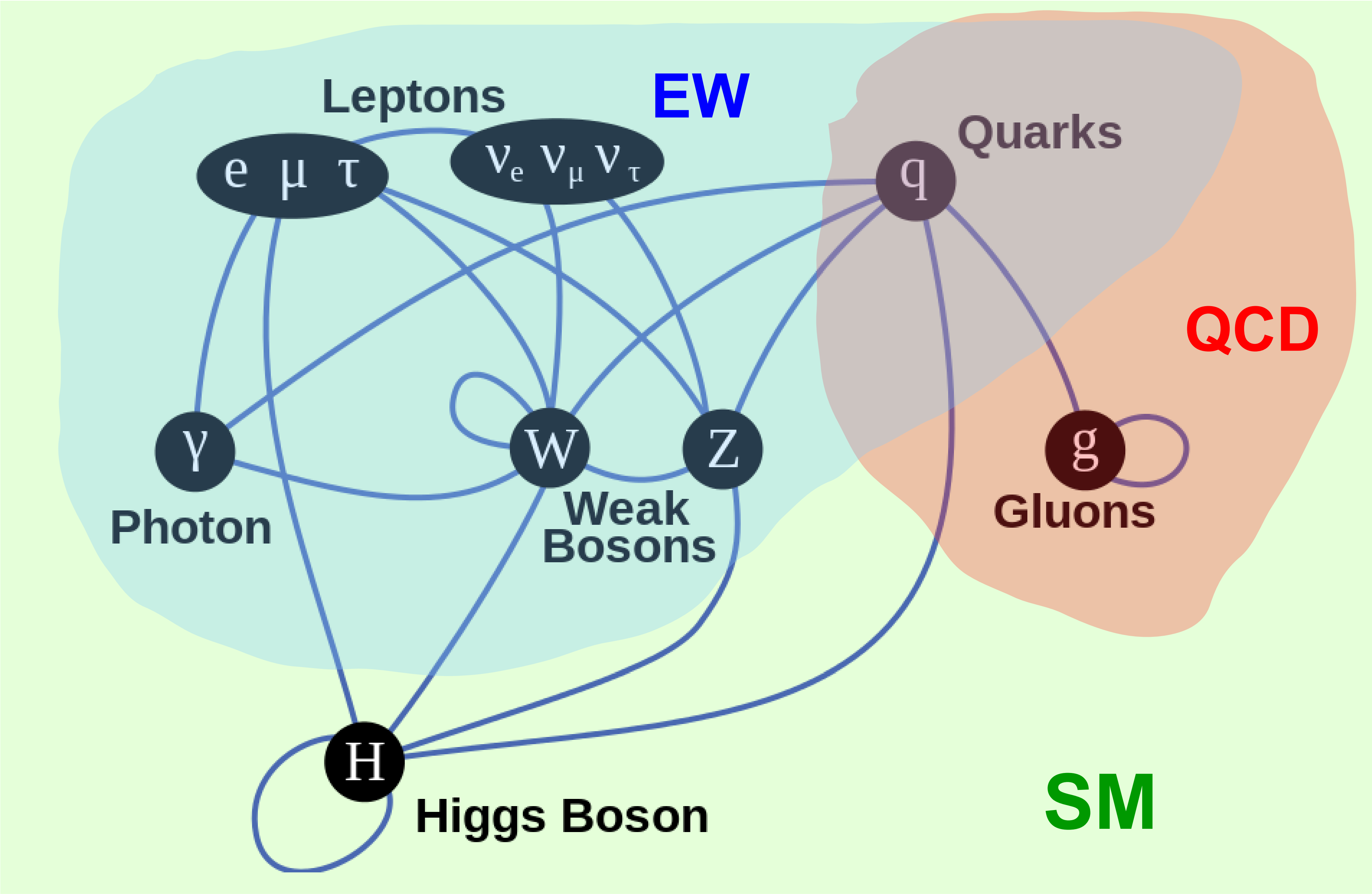
Outline

1. Electroweak physics
   - W and Z boson production
   - W mass measurement
   - determination of weak mixing angle
   - diboson production at the LHC
   - gauge boson couplings

2. QCD physics
   - reminder of QCD basics
   - hadronic jets
   - perturbative QCD measurements
   - soft QCD effects

Electroweak Physics
Introduction

Particle content of the Standard Model



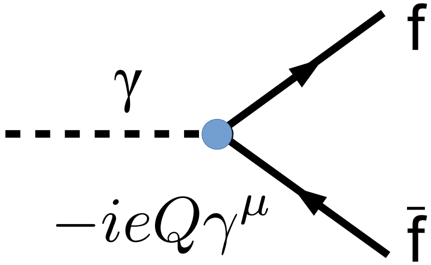
Snapshot of the electroweak SM

- local gauge theory:
  Lagrangian remains invariant under gauge transformations

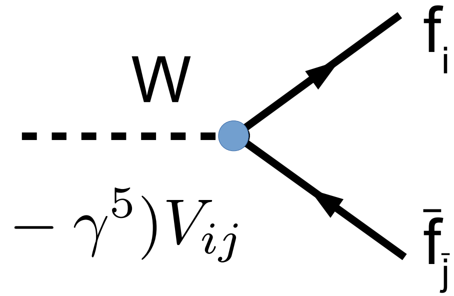
$$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$$

- 3 + 1 gauge fields W_1, W_2, W_3, B
- physical states:
  - 2 charged W bosons $$W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp iW_2)$$
  - photon, Z boson $$\begin{pmatrix} A \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$
- important Standard Model parameter: weak mixing angle θ_W

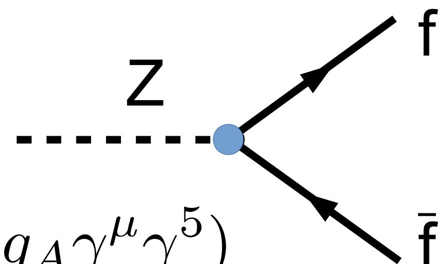
Fermion–boson vertices



$$-ieQ\gamma^\mu$$



$$-ig_W|T_3|\frac{1}{\sqrt{2}}\gamma^\mu(1-\gamma^5)V_{ij}$$



$$-i\frac{g_W}{\cos\theta_W}\frac{1}{2}(g_V\gamma^\mu - g_A\gamma^\mu\gamma^5)$$

$$g_A^f = T_3 = \pm\frac{1}{2}$$

$$g_V^f = T_3 - 2Q\sin^2\theta_W$$

- Unified electroweak theory: $g_W = \dfrac{e}{\sin\theta_W}$
- Two coupling parameters: $e = \sqrt{4\pi\alpha} \approx 0.3$ $\quad \sin^2\theta_W \approx 0.23$

$$\rightarrow g_W \approx 0.6$$

→ LHC measurements of W and Z boson processes to test the predictions

Standard Model relationships

- Photon is massless, but W and Z gauge bosons are massive: $M_W\,,\ M_Z$
- Gauge boson masses related to gauge couplings:

$$M_W = g_W \frac{v}{2} \ \text{and}\ M_Z = \sqrt{g_W^2 + g_Y^2}\,\frac{v}{2}$$

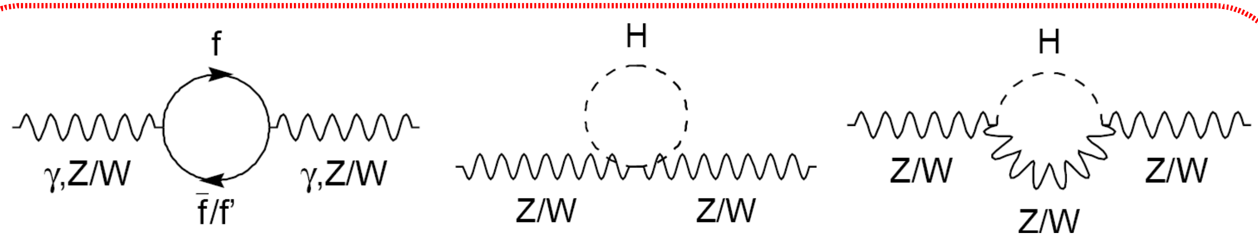
- Parameter $v \approx 246$ GeV: Higgs vacuum expectation value

- Important prediction of the Standard Model: $\dfrac{M_W}{M_Z} = \cos\theta_W$

(LEP measurement of M_z cannot be improved at LHC)

- Measure M_W and $\sin^2\theta_W$ precisely at the LHC → radiative corrections need to be included

$$M_W = \left(\frac{\pi\alpha}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_w\sqrt{1-\Delta r}}$$



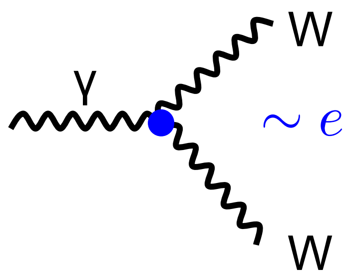
top/bottom loop in W-propagator $\sim m_{top}^2$

Higgs-loops in propagator $\sim \log(m_H/m_W)$

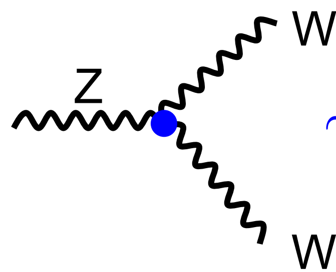
Gauge boson couplings

Standard Model gauge group is non-Abelian
→ gauge bosons couple to each other

- Triple gauge boson (TGC) vertices:

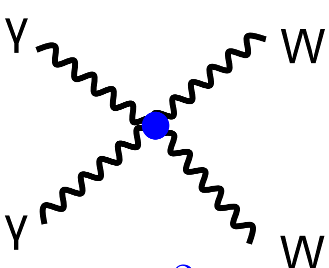


$\sim e$

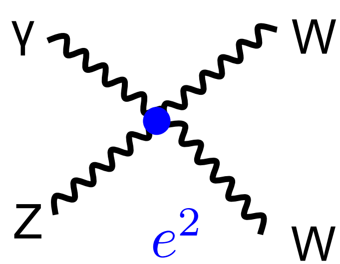


$\sim \frac{e}{\tan\theta_W}$

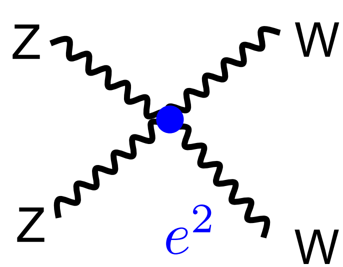
- Quartic gauge boson (QGC) vertices:



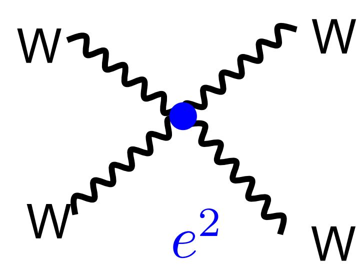
$\sim e^2$



$\sim \frac{e^2}{\tan\theta_W}$



$\sim \frac{e^2}{\tan\theta_W^2}$



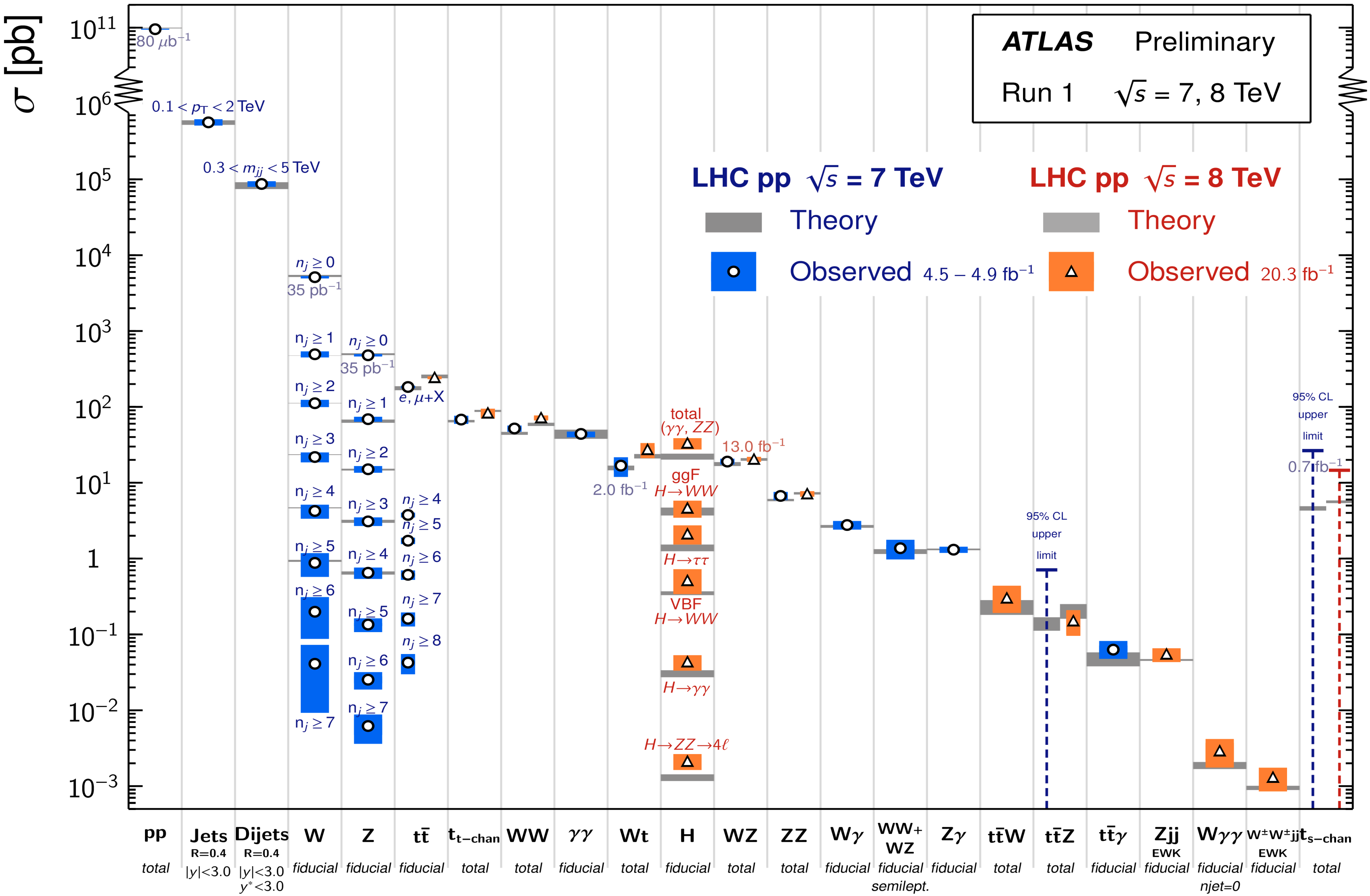
$\sim \frac{e^2}{\sin\theta_W^2}$

- → measure TGCs and QGCs in WW, WZ, ZZ, γW, γZ final states at the LHC
- ***new physics may appear in gauge boson interactions***

Electroweak Physics at the LHC

Standard Model Production Cross Section Measurements

Status: March 2015



Standard Model Production Cross Section Measurements

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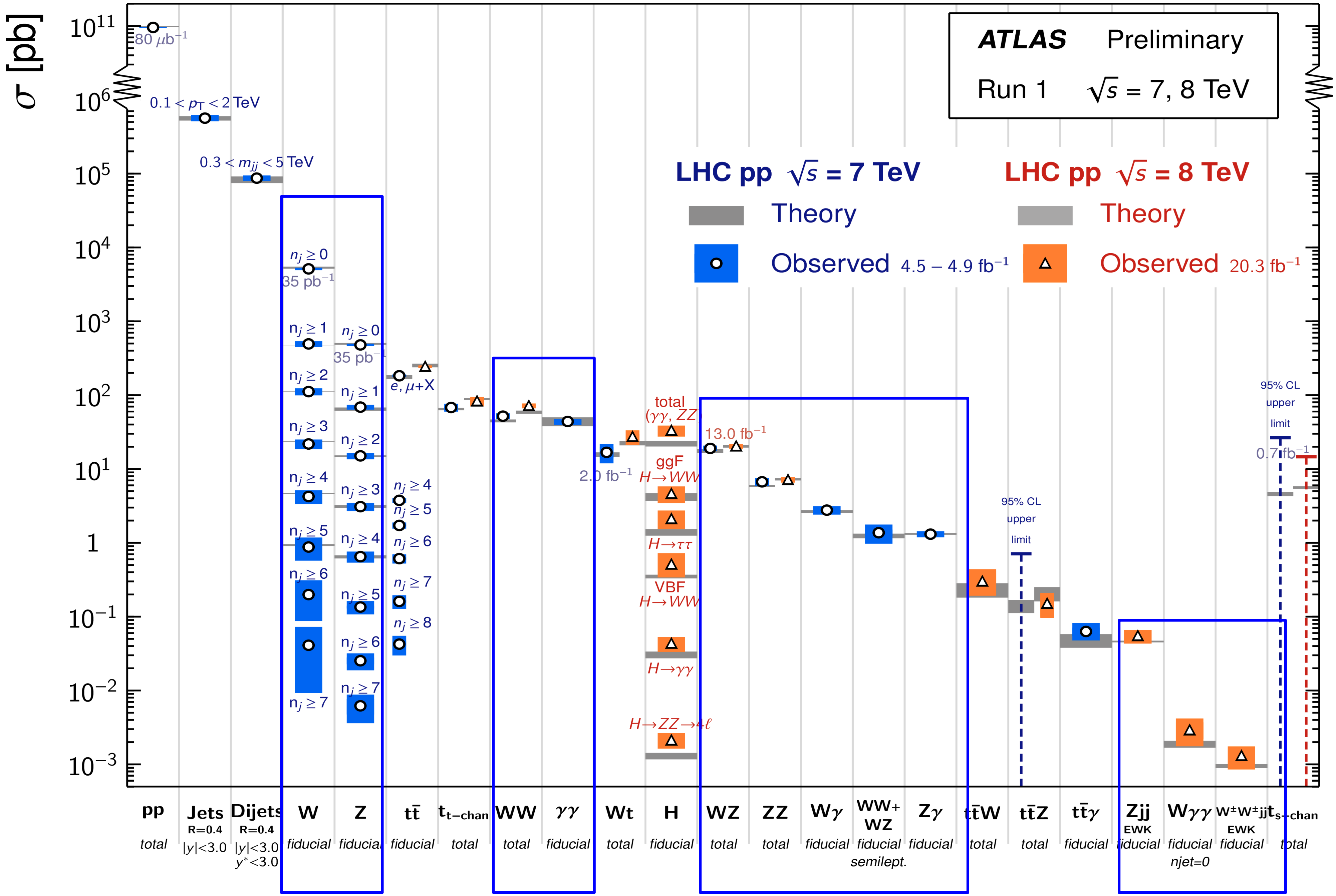
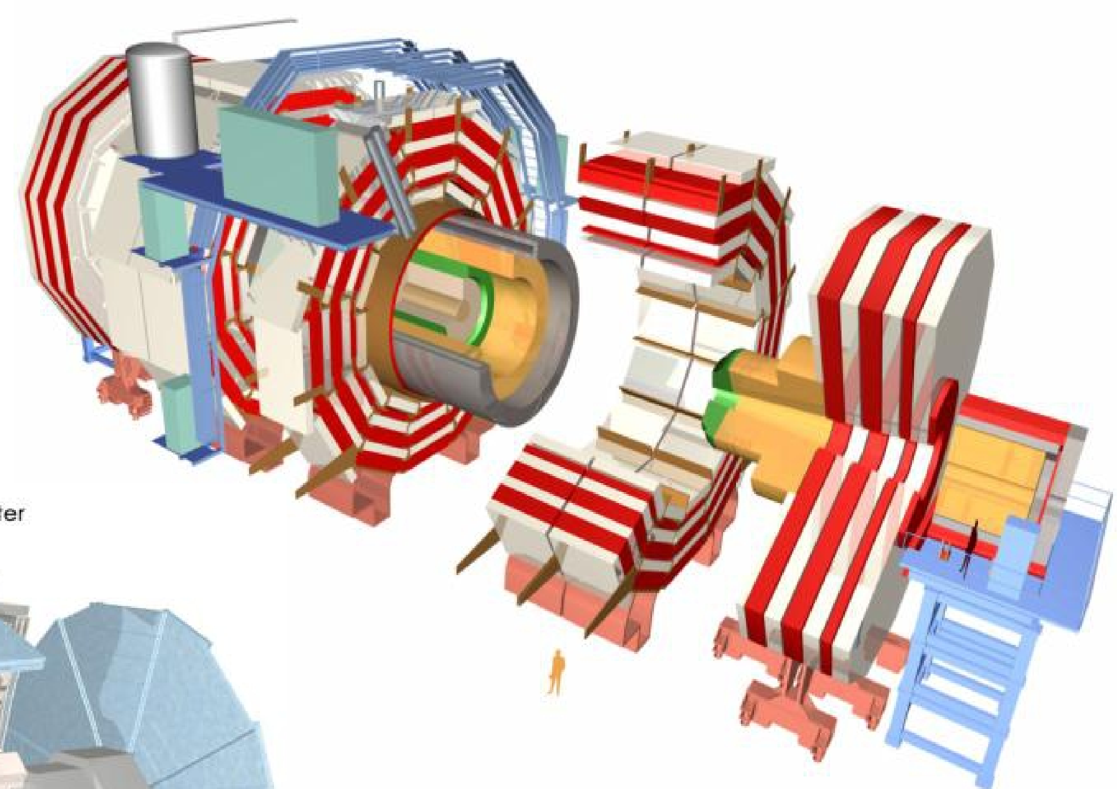
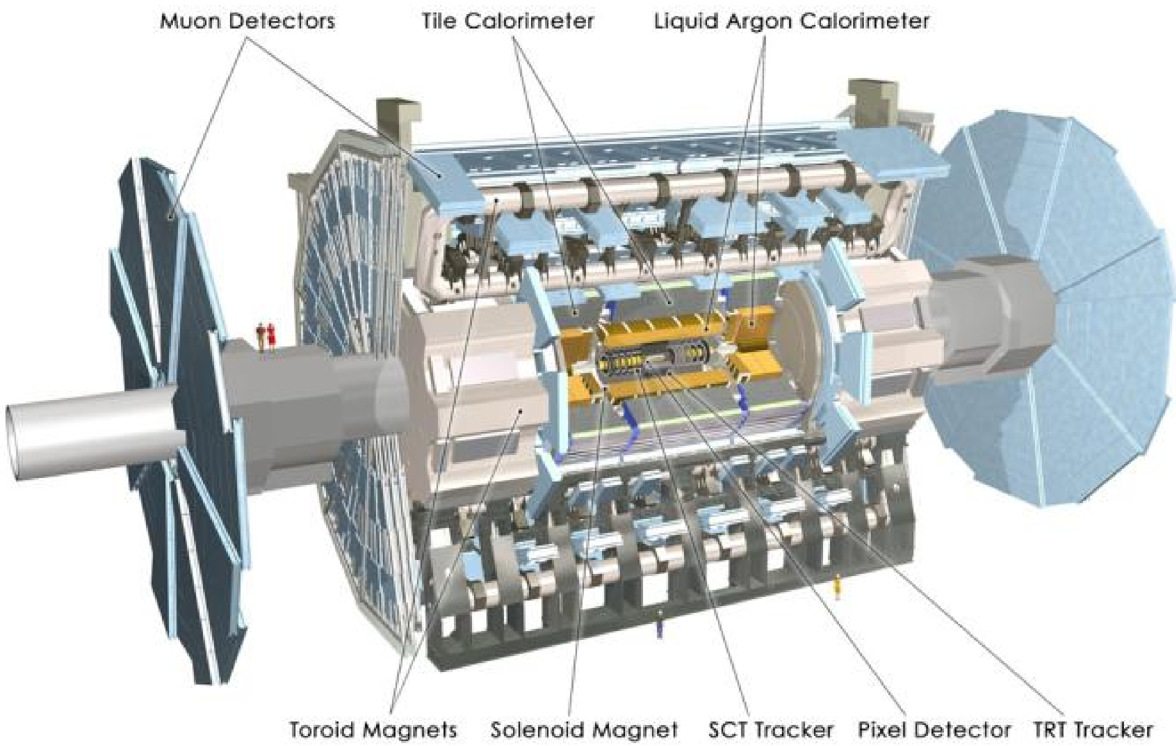


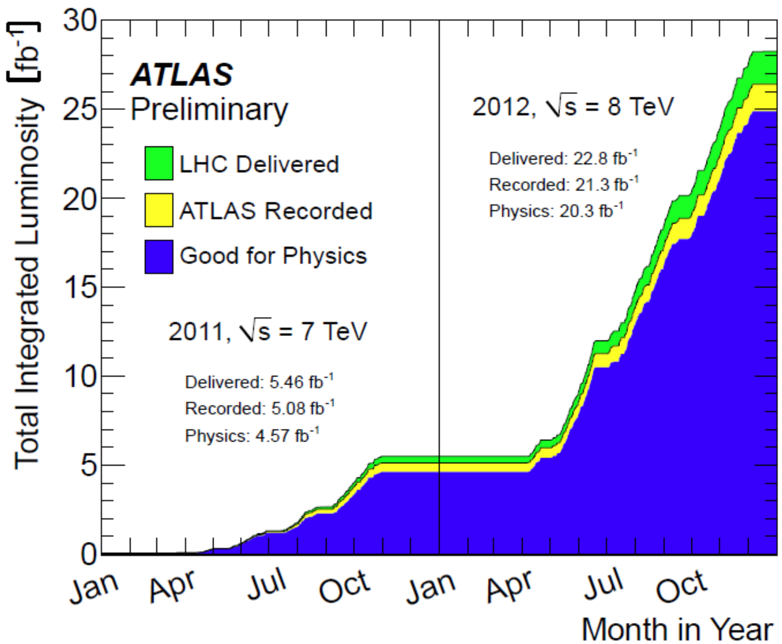
ATLAS and CMS detectors at the LHC

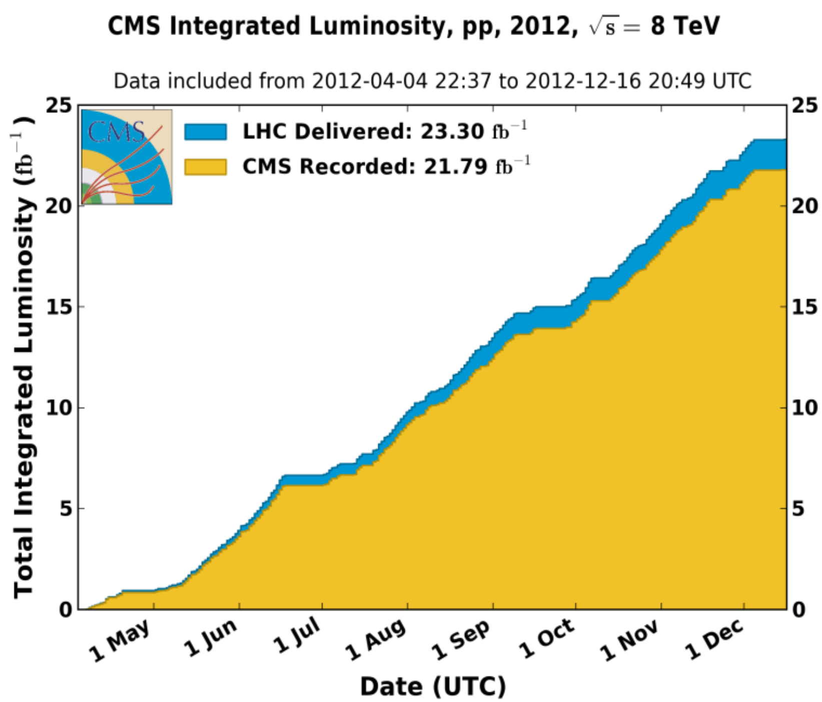




ATLAS and CMS detectors at the LHC

- ATLAS and CMS performed extremely well in 2011/12:
  - 97% – 100% of detector channels operational
  - 91% – 93% data taking efficiency
- Luminosity recorded: ~5 fb^{-1} at 7 TeV and 21 fb^{-1} at 8 TeV per experiment

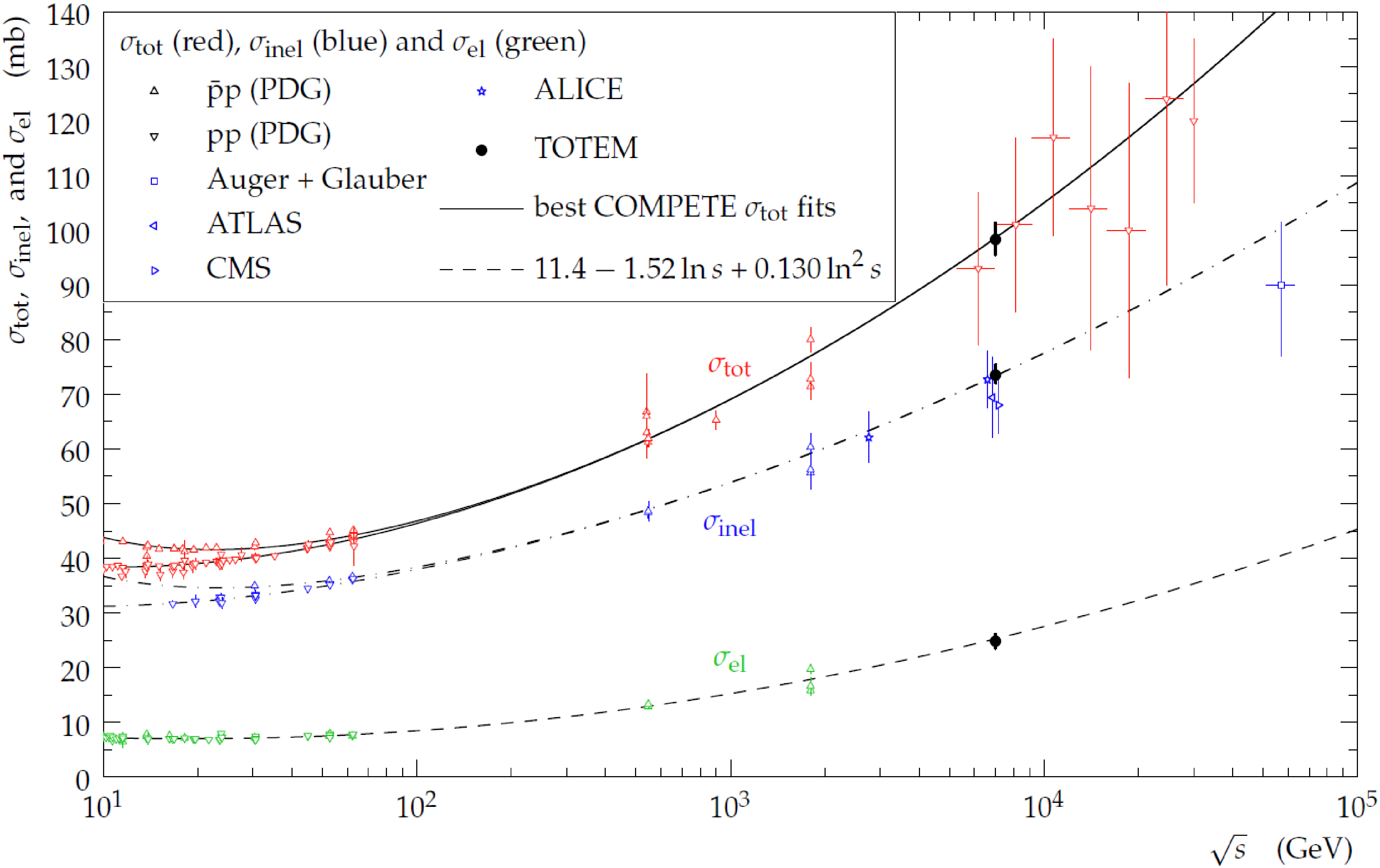




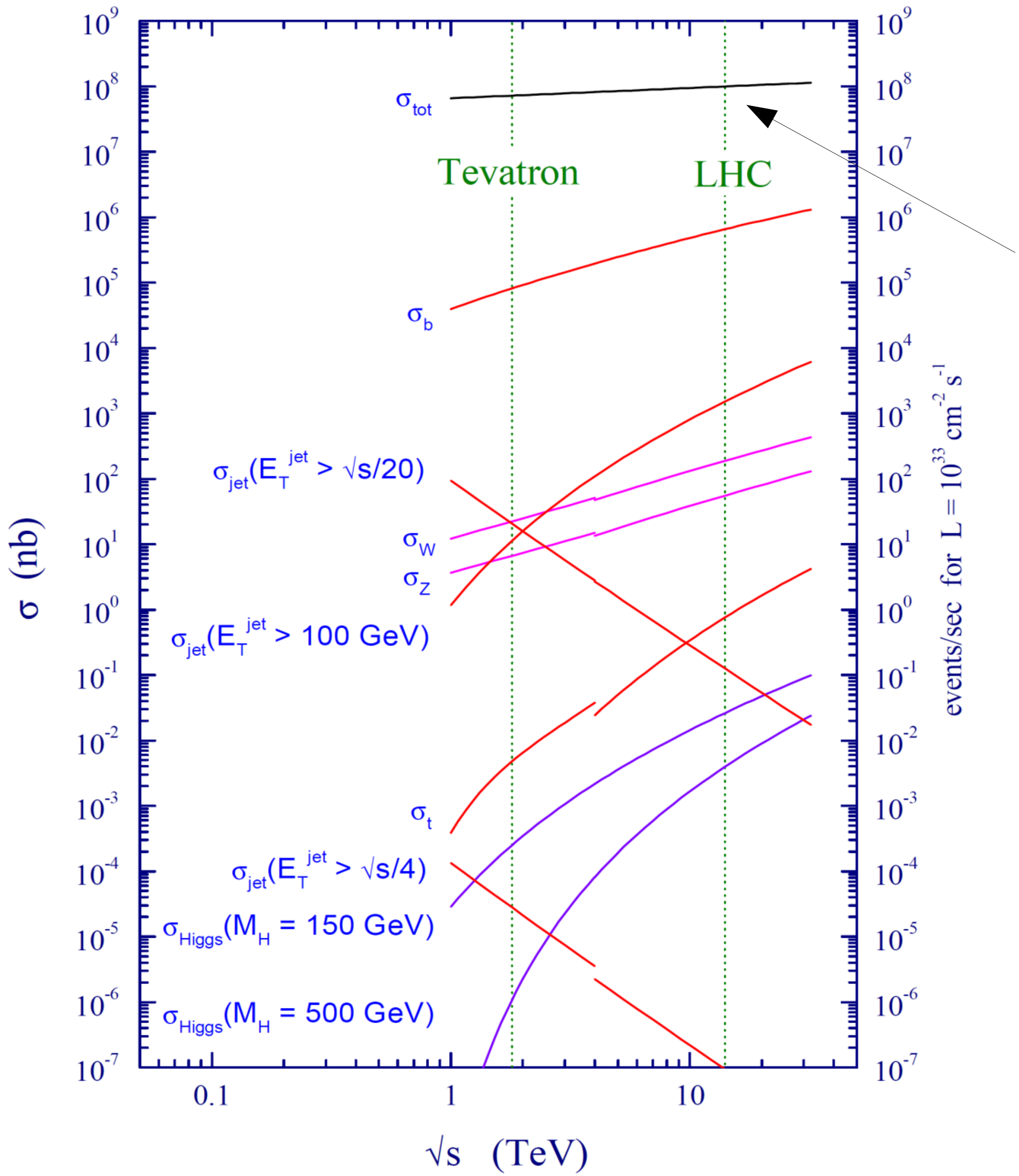
Number of events: $N = L \cdot \sigma \cdot \epsilon \cdot A$

L = luminosity
σ = cross section
ε = detection efficiency
A = detector acceptance

pp cross section measurements



Overview of production rates at LHC



Typical production cross sections at Tevatron and LHC:

$\sigma_{tot} \approx 100$ mb

$\sigma_{W\to l\nu} \approx 10$ nb

$\sigma_{Z\to ll} \approx 1/10\ \sigma_{W\to l\nu}$

$\sigma_{tt} \approx 1/60\ \sigma_{W\to l\nu}$

$\sigma_{WW} \approx 1/200\ \sigma_{W\to l\nu}$

$\sigma_{WZ} \approx 1/500\ \sigma_{W\to l\nu}$

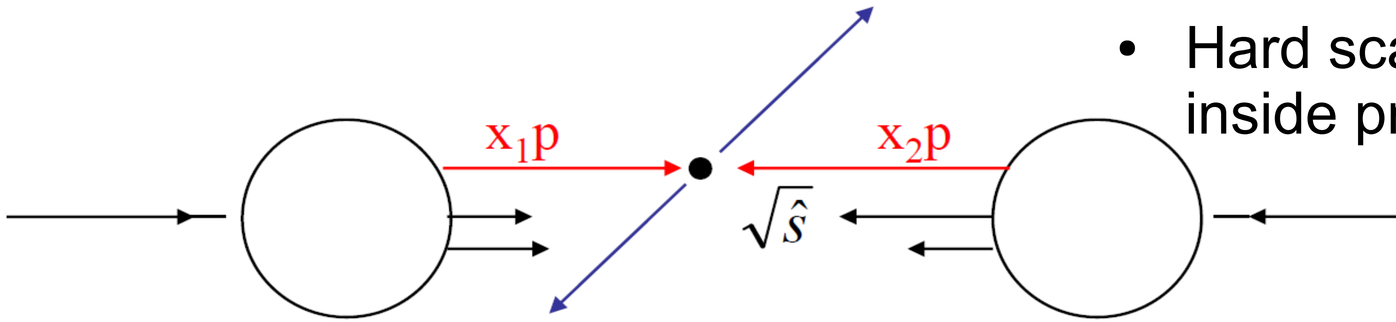
$\sigma_{ZZ} \approx 1/2000\ \sigma_{W\to l\nu}$

$\sigma_{2jet} \approx 10^6\ \sigma_{W\to l\nu}$

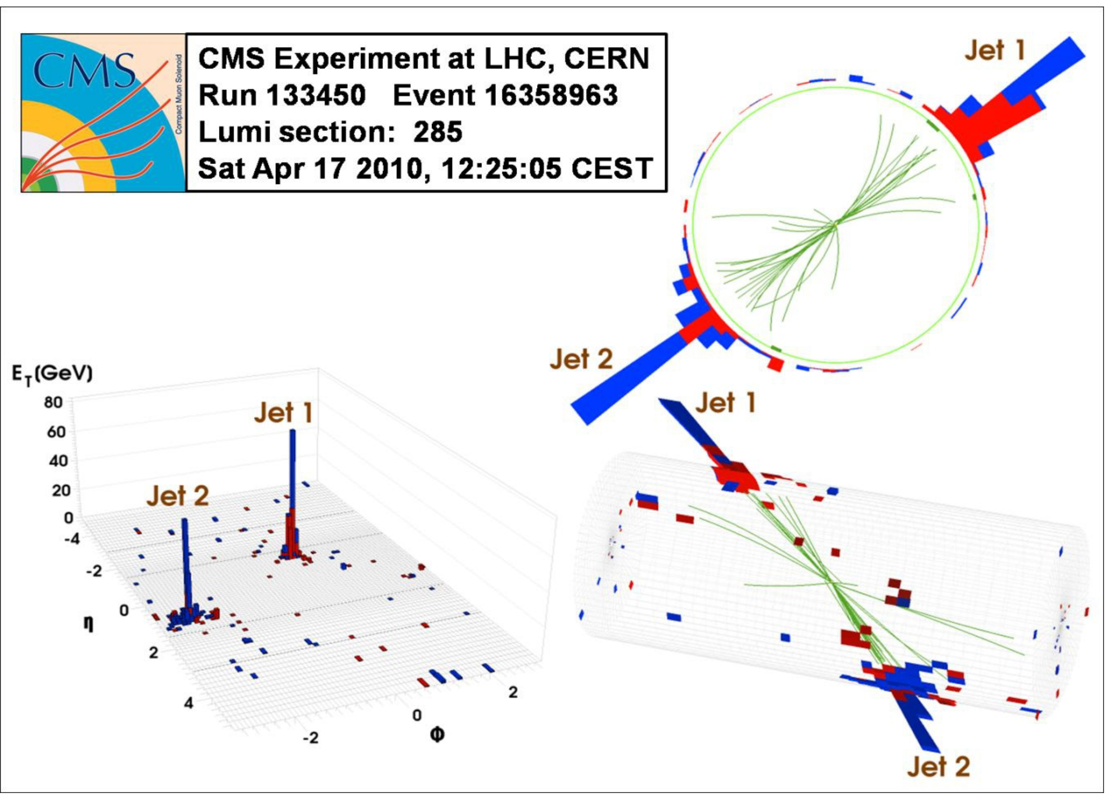
Cross section range:
100 mb to 10 fb

→ 13 orders of magnitude!

Properties of 'interesting' pp-collision events



- Hard scattering of partons inside proton
- Gluons and quarks carry momentum fractions x_1, x_2
- QCD events are far more frequent than EW events
- Many hadrons produced from proton remnants: 'underlying event'
- Strategy: identify the interesting physics with high-p_T leptons, photons and jets or missing transverse energy E_T^{miss}



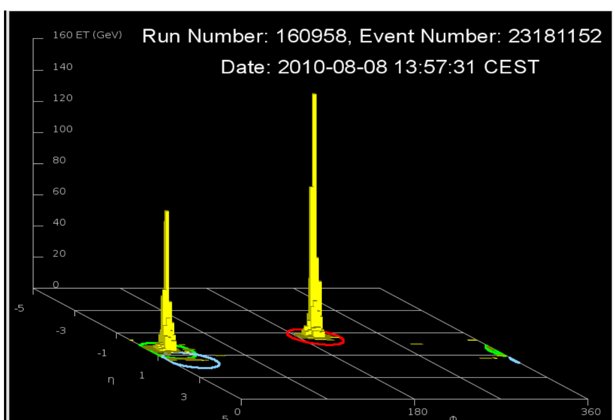
Dijet event at 7 TeV in the CMS detector

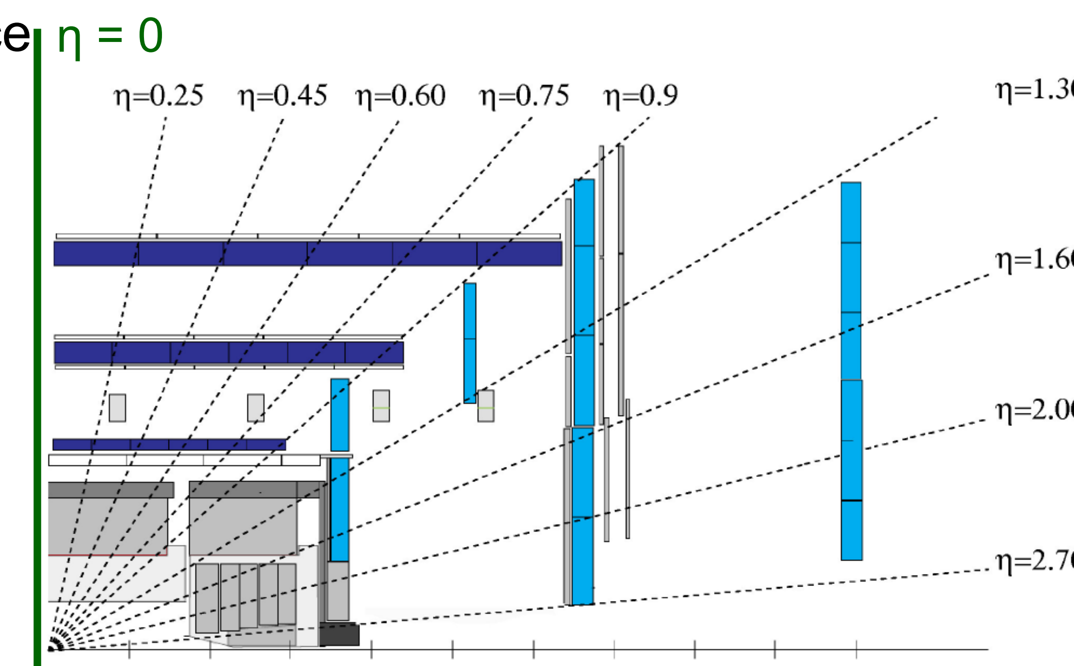
Event kinematics: pseudorapidity

- longitudinal momentum of partons basically unknown
  → measure transverse energy and momentum, E_T, p_T
- rapidity y: equal to velocity at slow velocities (v/c << 1), can be simply added
  - rapidity differences (Δy) are invariant under Lorentz boosts along beam axis
  - usually approximated by pseudorapidity η

$$y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L} \approx \eta = \frac{1}{2}\ln\frac{|\vec{p}|+p_L}{|\vec{p}|-p_L} = -\ln\tan\left(\frac{\theta}{2}\right)$$

- detector is mapped onto η-φ space





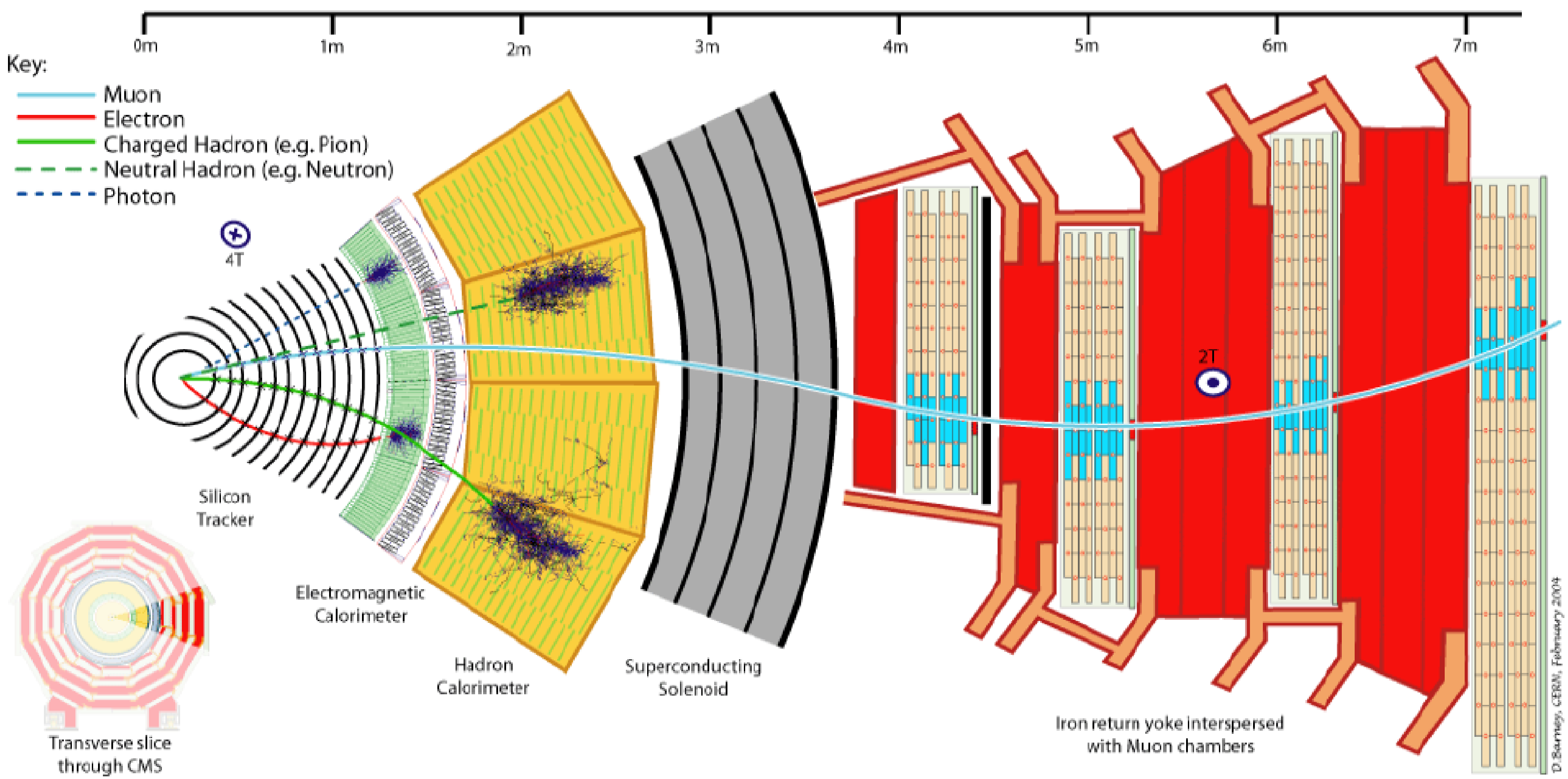
- radius of 'cone' in η-φ space:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

The basic ingredients: physics objects

The decay products of W, Z, Higgs, SUSY, ... are reconstructed in the detector, e.g.

Electrons, Photons, Muons, Tau leptons, QCD jets from quarks and gluons,
'Invisible' particles, like neutrinos, as missing transverse energy, E_T^{miss}



Charged Particles	Electrons Photons	Hadrons	3.8 Tesla Solenoid	Iron yoke (return flux) Muons

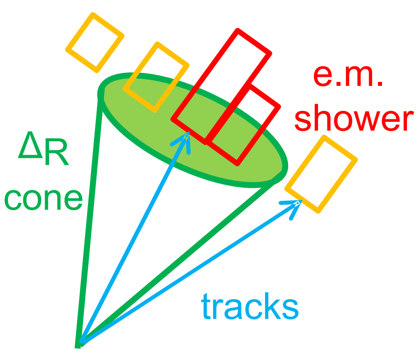
Isolation of physics objects – example

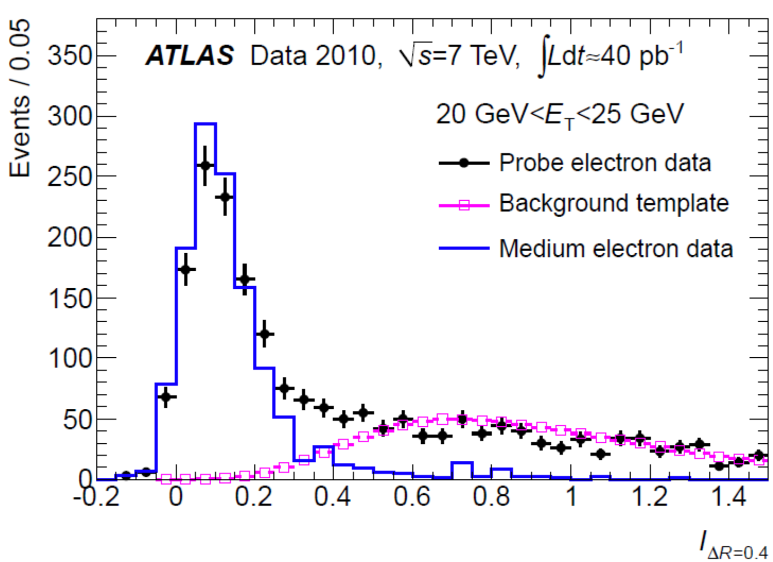
- QCD jets may look like photons, electrons, taus or induce signals in the muon spectrometers
- heavy flavour jets contain leptons from heavy meson decays

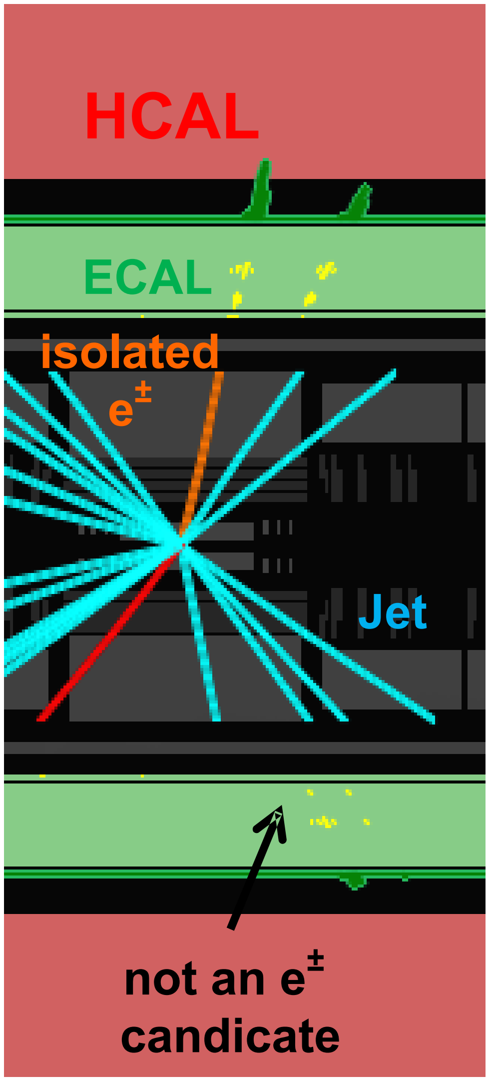
  → need 'isolation' variables

- Example: energy in cone around EM cluster excluding central cluster and normalised to cluster energy

$$I_{\text{calo,iso}} = \frac{\sum\limits_{\Delta R<a} E_T^{\text{calo}}}{E_T^{\text{cluster,central}}}$$





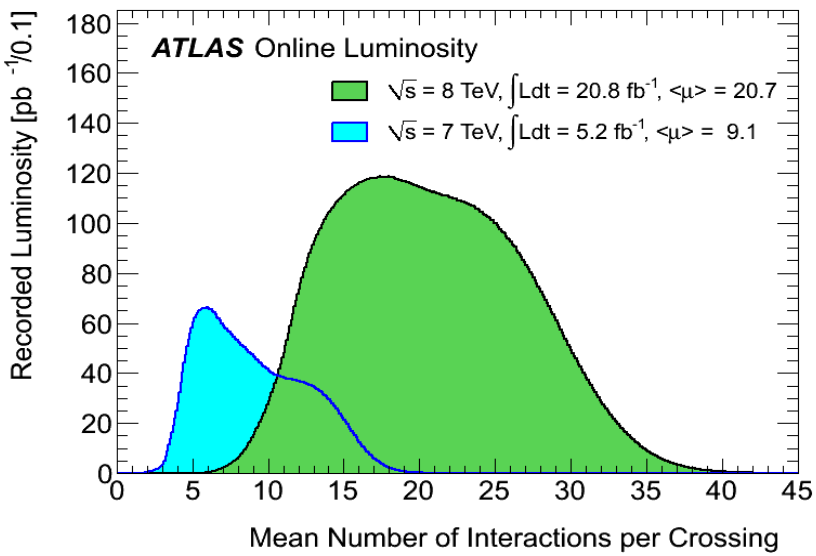


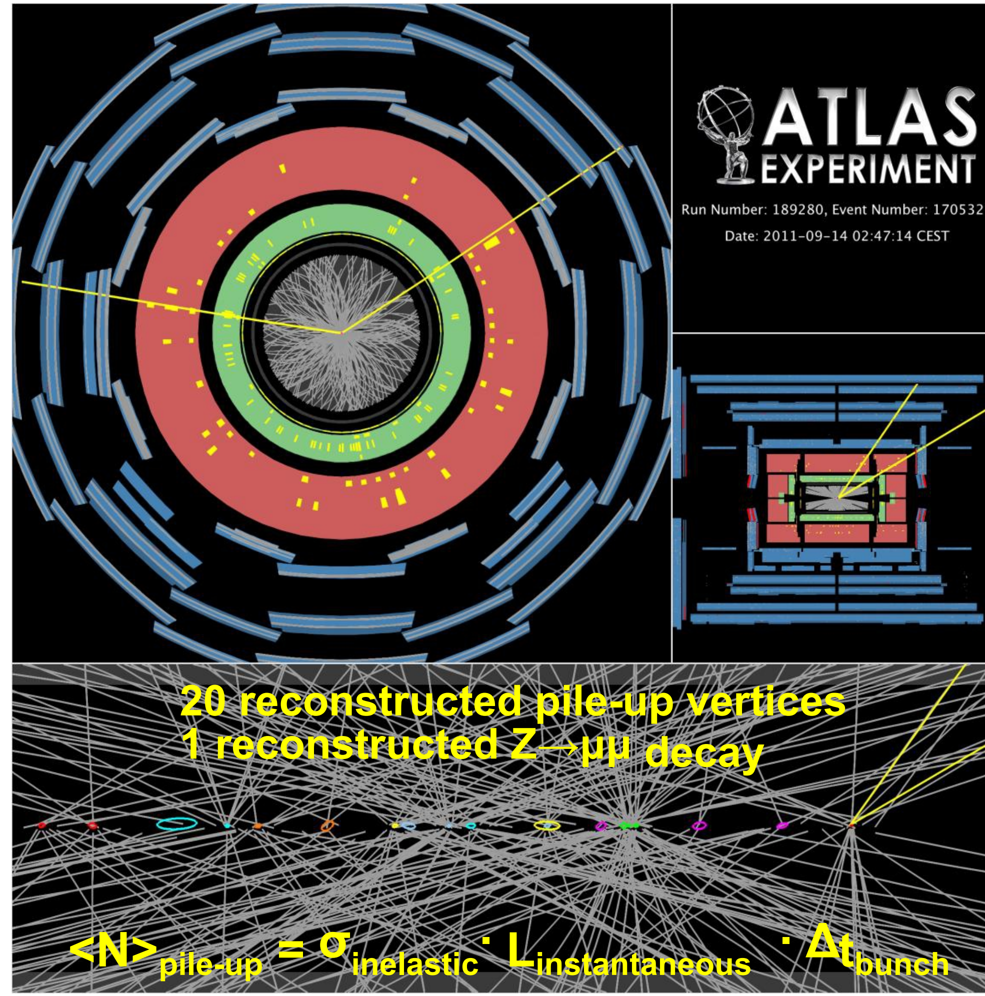
- typically more robust against pileup : track based isolation variables, e.g.

$$I_{\text{track,iso}} = \frac{\sum\limits_{\Delta R<b} p_T^{\text{tracks}} - p_T^{\text{track,lepton}}}{p_T^{\text{lepton}}}$$

LHC luminosity and event pileup

- at higher luminosities, more than one pp pair collides inelastically: up to 40 pileup events in 2012



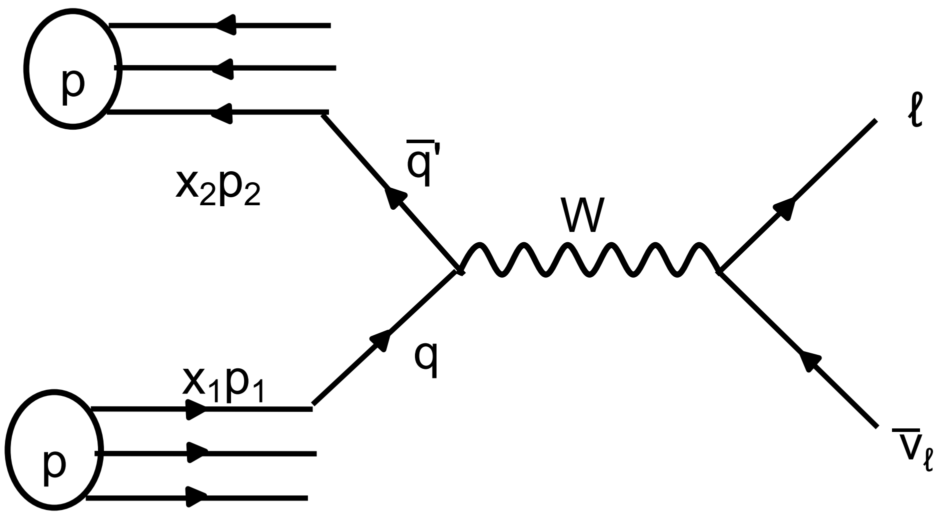


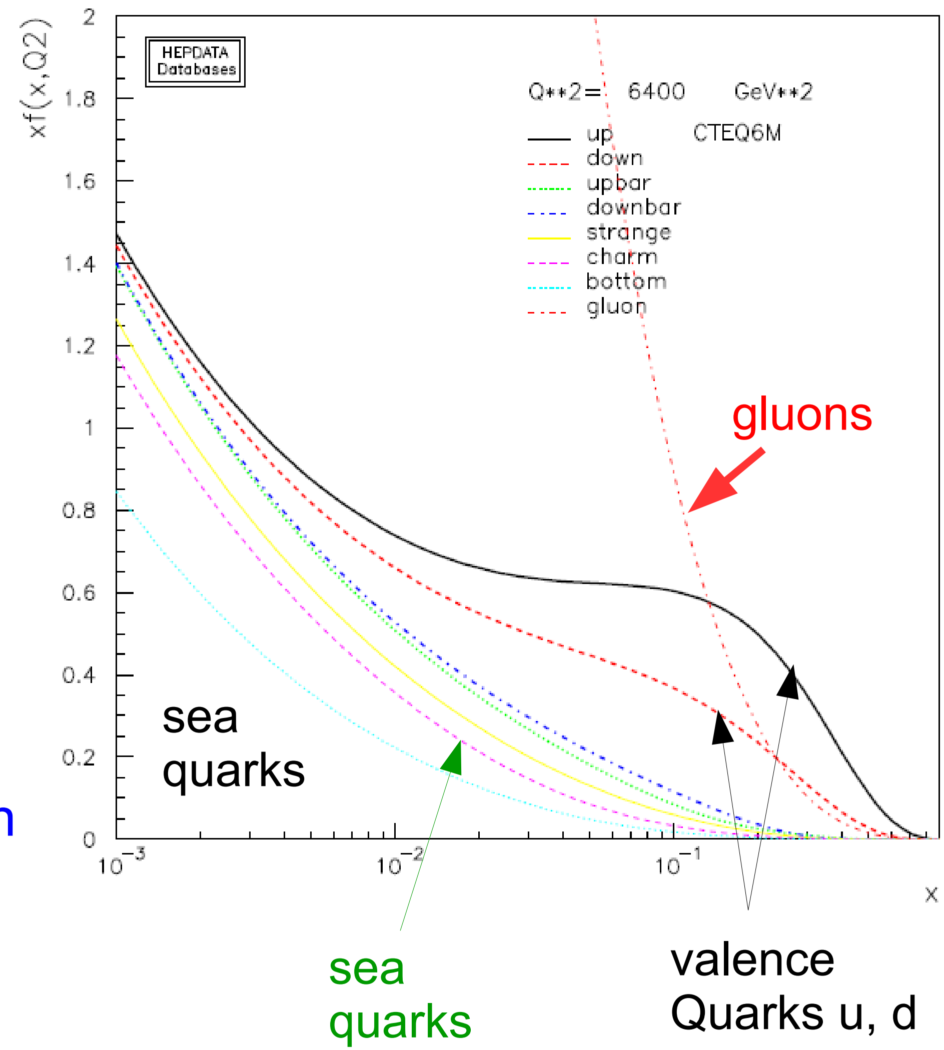
- instantaneous luminosity in 2012 up to 8 x 10^{33} cm^{-2}s^{-1}

- plans after long shutdown (2015+):
  - protons will collide every 25 ns (used to be 50 ns) would bring 2x more pileup
  - instantaneous luminosity (0.9-1.6) x 10^{34} cm^{-2}s^{-1}
  - average number of pileup events: ~ 43
  - centre-of-mass energy: 13 TeV

Electroweak Physics Measurements

A closer look at W-boson production



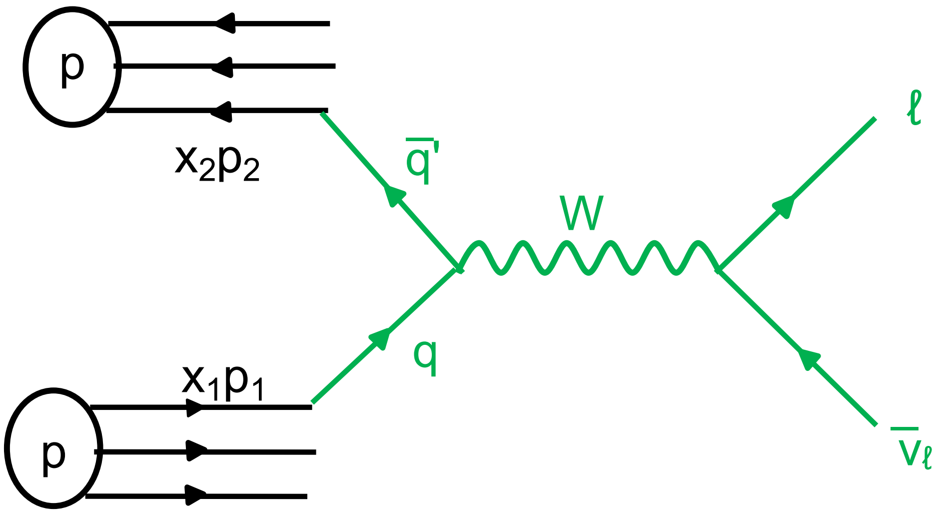


- W boson production at lowest order
- Quarks carry momentum fractions x_1, x_2
- Probability density to find a parton i with a given energy fraction x in a proton is given by the parton distribution function (PDF):

$$f_i(x,Q^2)$$

  - Q^2 = energy scale of the process, here $\approx M_W^2$
  - Which x_i values do we need to use?

Production cross section at lowest order



Cross section of parton–parton reaction: $\sigma_{ij} = \sigma(i + j \rightarrow W \rightarrow l\nu)$

Multiplied with parton density functions

Multiplied with 4-momentum conservation term

$$\sigma = \sum_{i,j} \int \sigma_{ij}(\hat{s}) \int_0^1 \int_0^1 f_i(x_1) f_j(x_2) \delta(\hat{s} - x_1 x_2 s)\, dx_1\, dx_2 d\hat{s}$$

Integrated over all possible reduced center-of-mass energies and summed over all possible initial states

W⁺ and W⁻ differential cross section

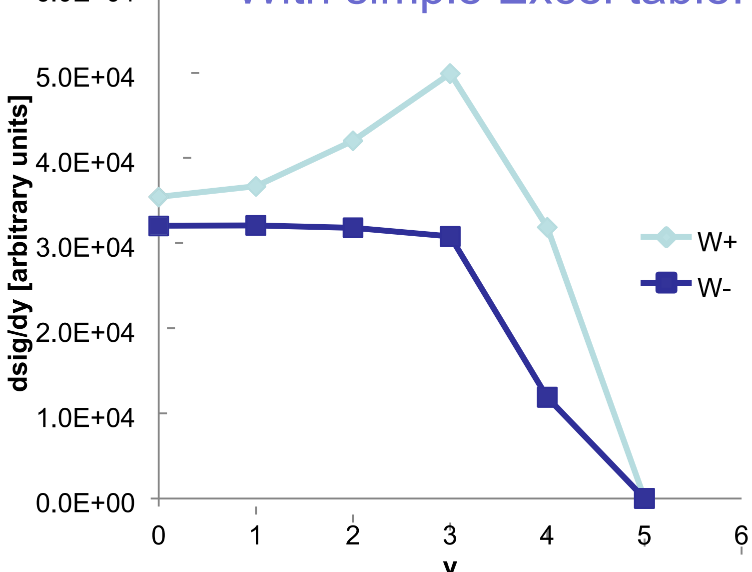
$$\frac{d\sigma}{dy}(pp \to X) \approx \sum_{i,j} \sigma_{ij} \frac{M^2}{s} f_i(x_1) f_j(x_2) \qquad \text{with } x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

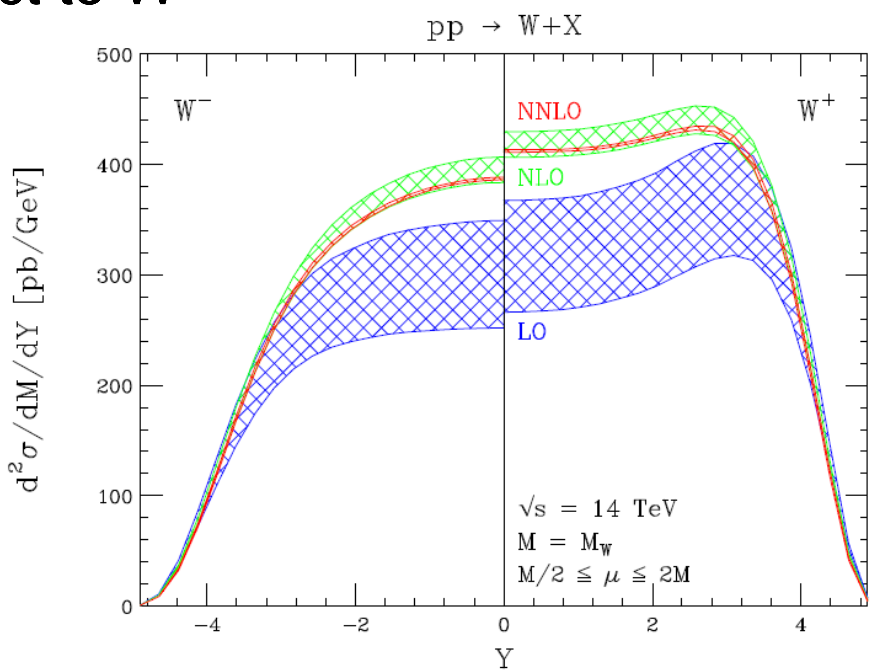
Example: $u + \bar{d} \to W^+$, $\bar{u} + d \to W^-$ $\Big\}$ $\sigma(u + \bar{d} \to W^+) = \sigma(\bar{u} + d \to W^-) \equiv \sigma_W$

- $\bar{u}$ and $\bar{d}$ PDFs are about the same (sea quarks)
- At y = 3.0 ($x_1 \approx 0.20$, $x_2 \approx 0.0005$) → the u and d PDFs differ by a factor of ~2

→ W^+ production is enhanced with respect to W^-

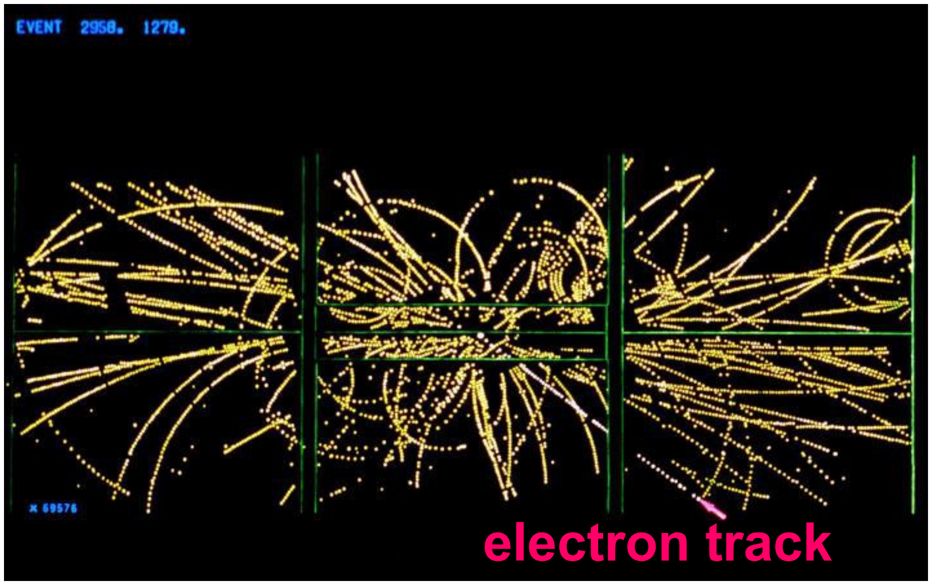
With simple Excel table:

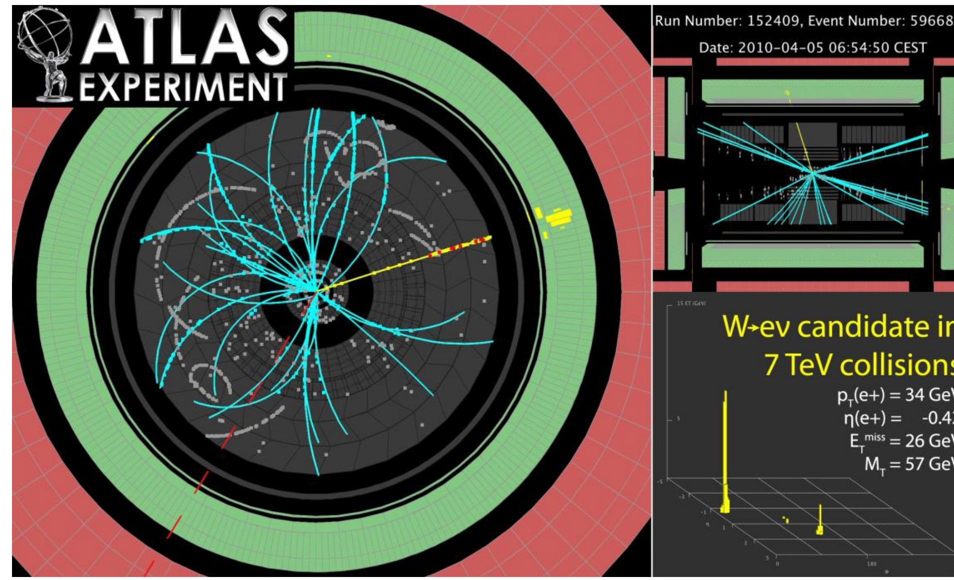


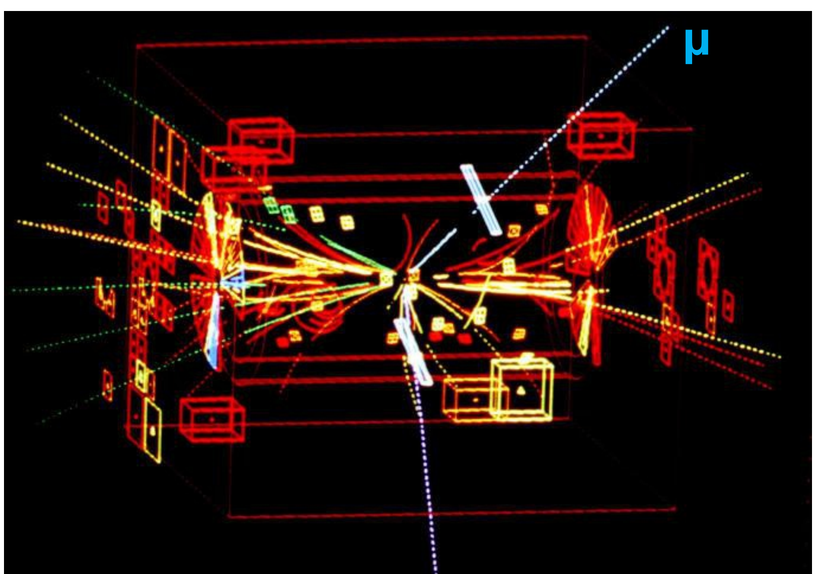


Measurement of W and Z Bosons

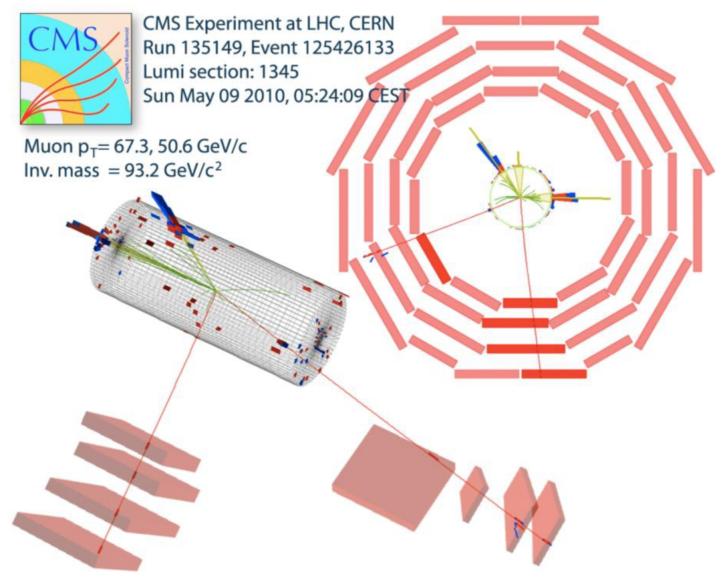
First W and Z bosons (C. Rubbia, 1983) look very similar to LHC measurement



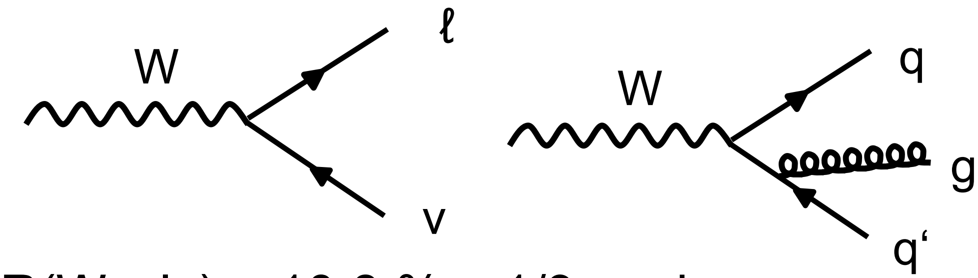


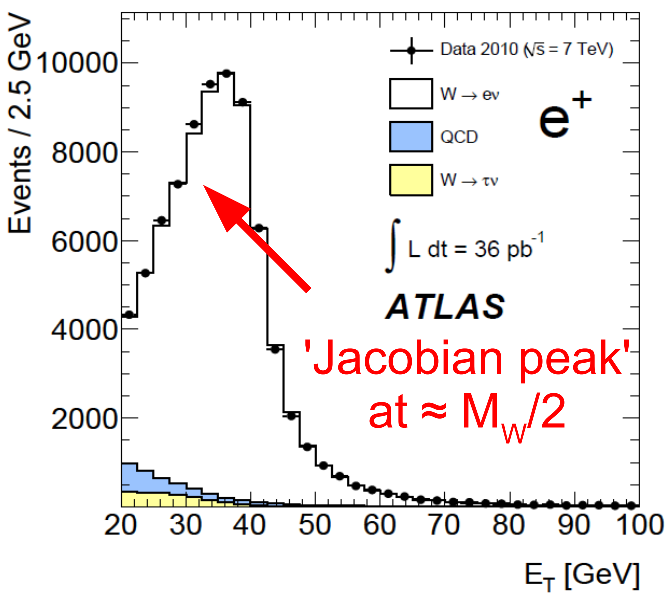


μ



Measurement of W-boson cross sections



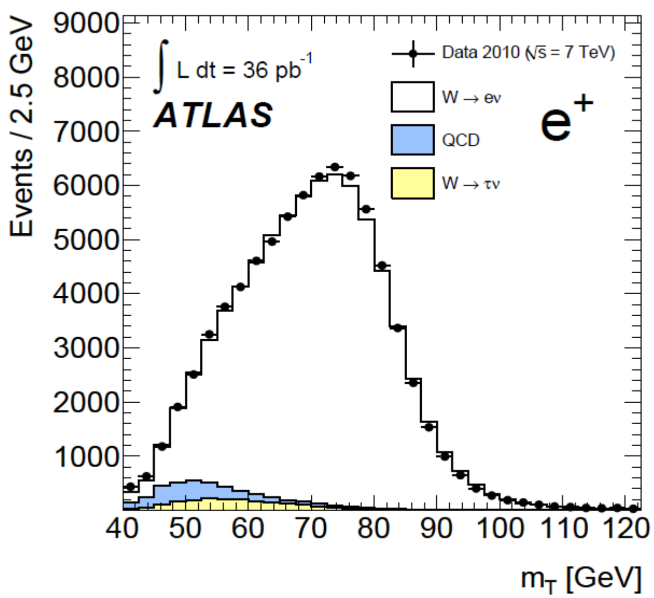


- BR(W→lν) = 10.8 % ≈ 1/9 each
- BR(W→qq') = 67.5 % ≈ 6/9 together
- important background from QCD multijet events in dijet channel → use lν decay channel
- Event selection:
  - lepton p_T > 20 GeV
  - E_T^{miss} > 25 GeV → neutrino
  - *W* mass would be

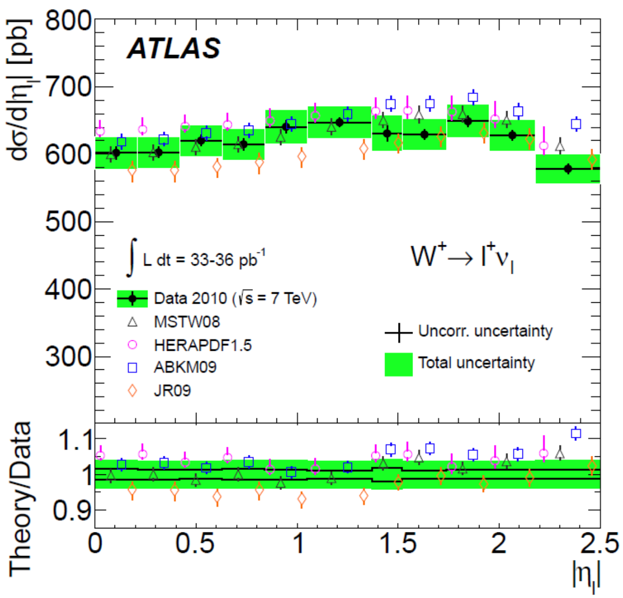
$$M_W \approx \sqrt{2E^\ell E^\nu (1 - \cos\alpha(\ell,\nu))}$$

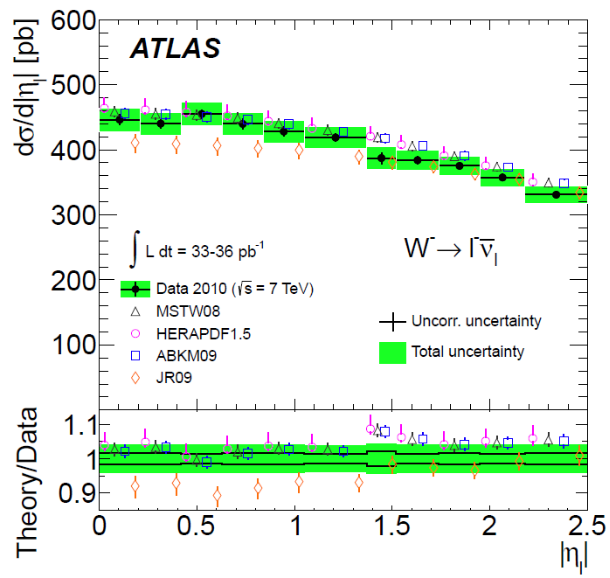
  - but E^ν and angle cannot be measured → transverse mass: M_T > 40 GeV

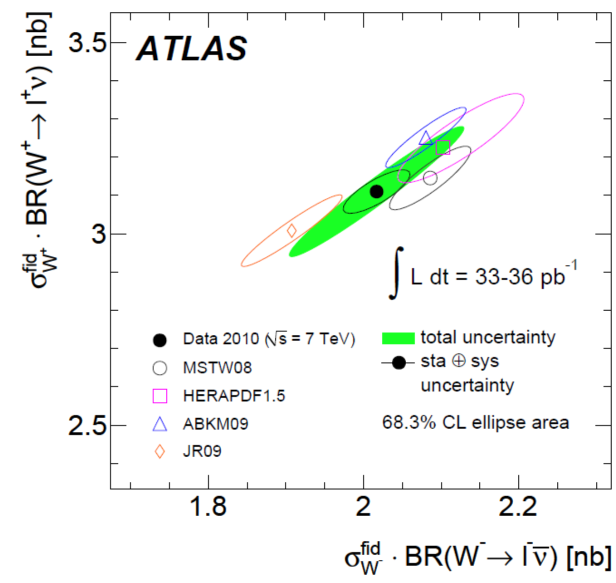
$$M_T = \sqrt{2p_T^\ell p_T^{miss}(1 - \cos\Delta\phi(p_T^\ell, p_T^{miss}))}$$



Measured W^+ and W^- cross sections



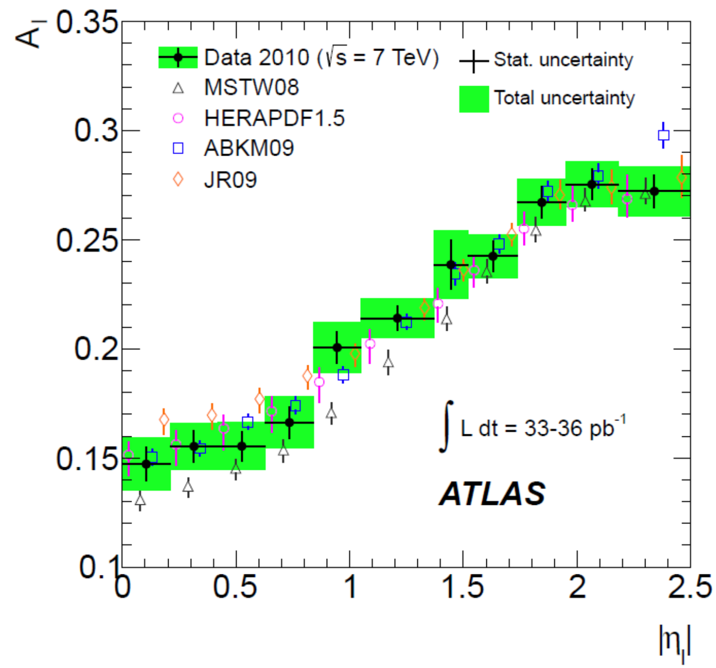




W-charge asymmetry:

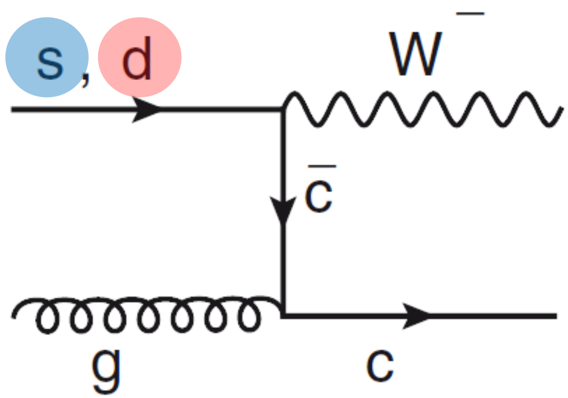
$$A_\ell(\eta_\ell) = \frac{d\sigma_{W+}/d\eta_\ell - d\sigma_{W-}/d\eta_\ell}{d\sigma_{W+}/d\eta_\ell + d\sigma_{W-}/d\eta_\ell}$$

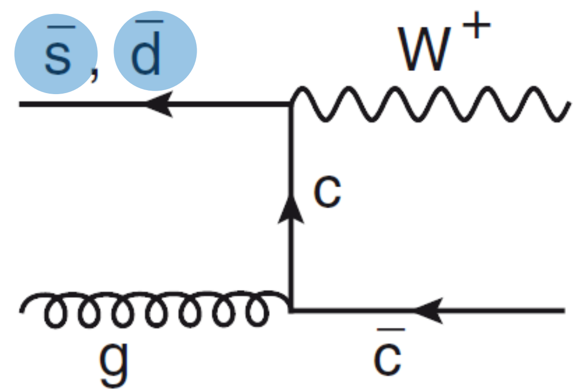
very sensitive to correct description of parton densities inside proton



arxiv: 1109.5141

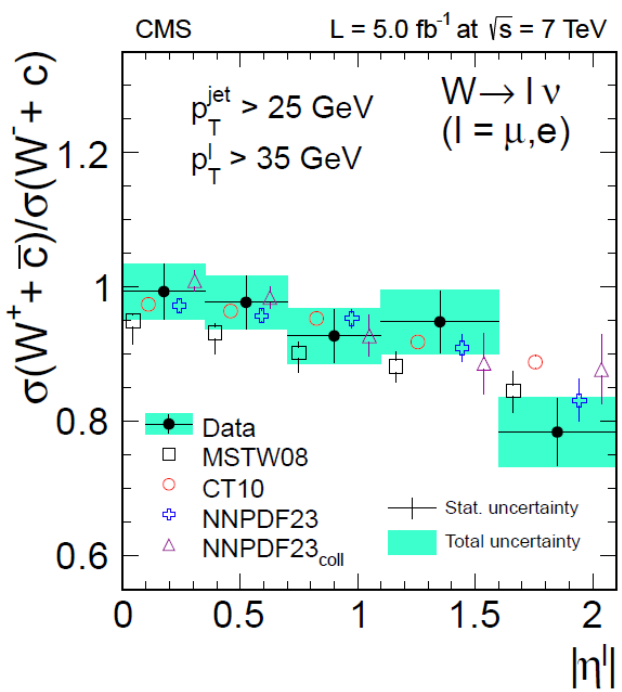
Measured W^+ and W^- + charm cross sections

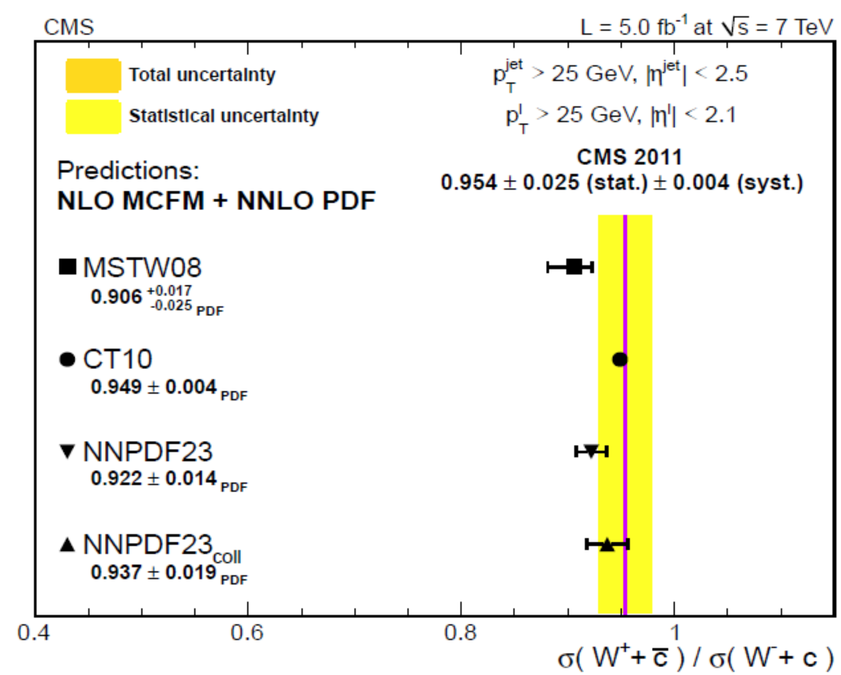




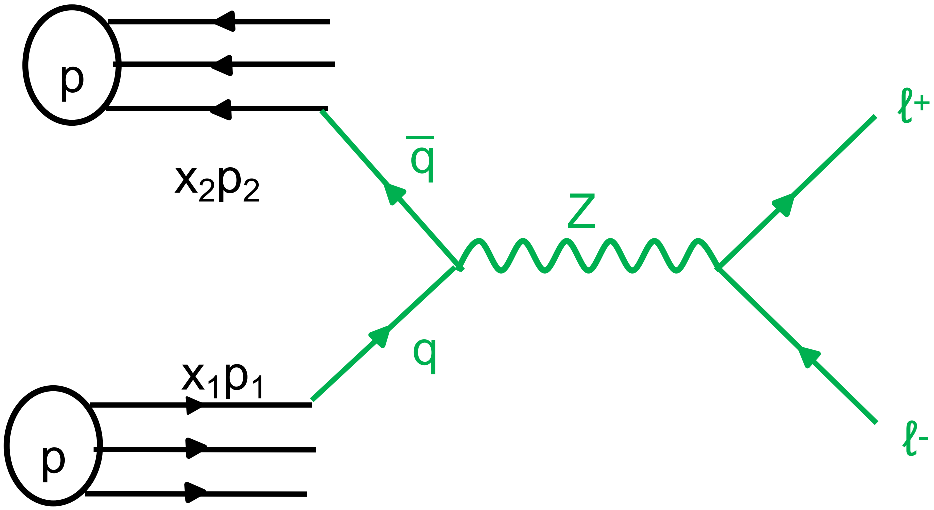
x_f(valence quark) >
x_f(sea quarks)

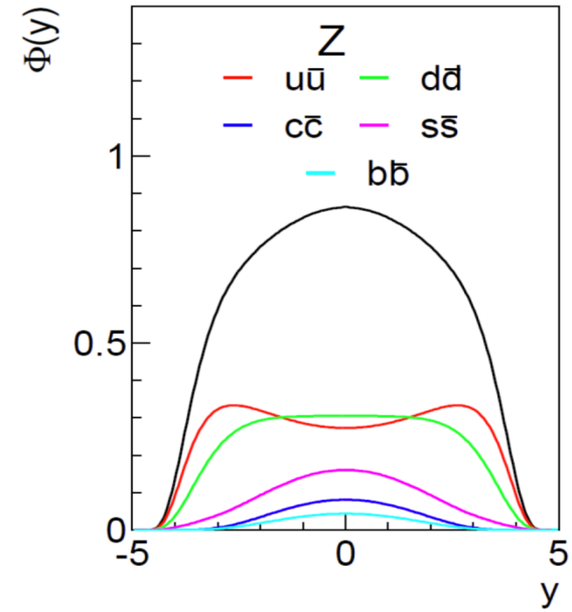
$\sigma(W^- + c) > \sigma(W^+ + \bar{c})$



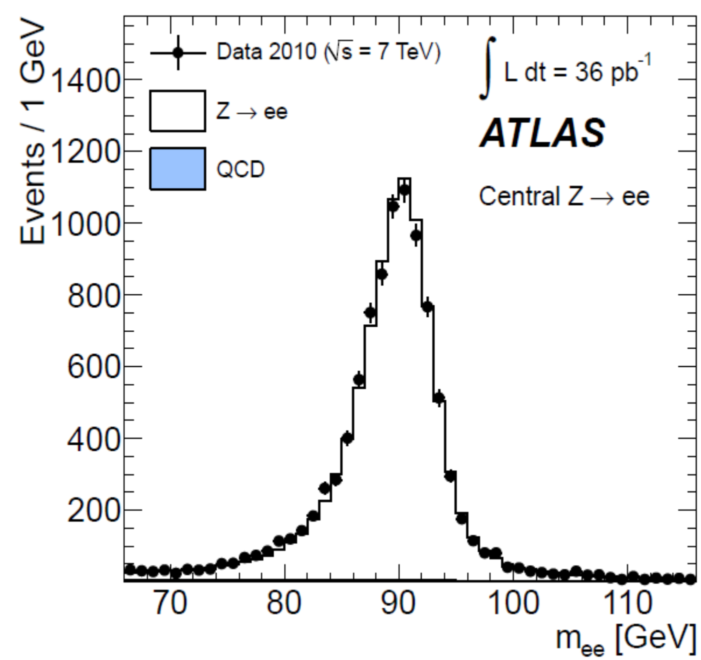


Measurement of Z production





- Lowest order: initial partons are quark + antiquark
- Hadronic Z decays have large QCD multijet background
  → measure $Z \to l^+l^-$ decays
- Event selection:
  - 2 opposite-sign leptons p_T >20 GeV
  - invariant mass m_{ll} around nominal Z mass 66 GeV < m_{ll} < 116 GeV

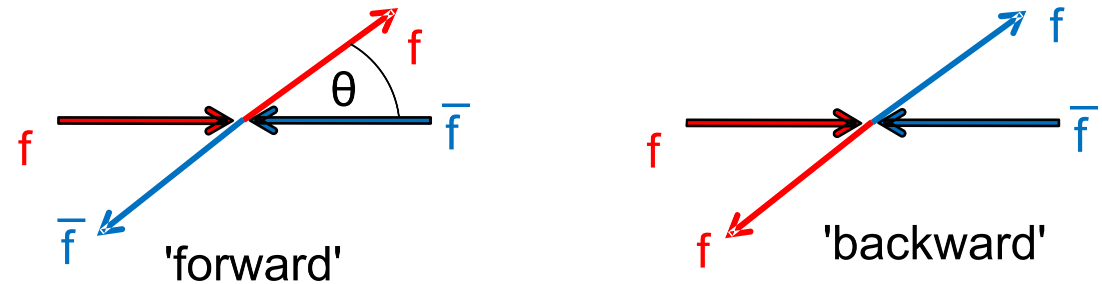


Weak mixing angle at the LHC

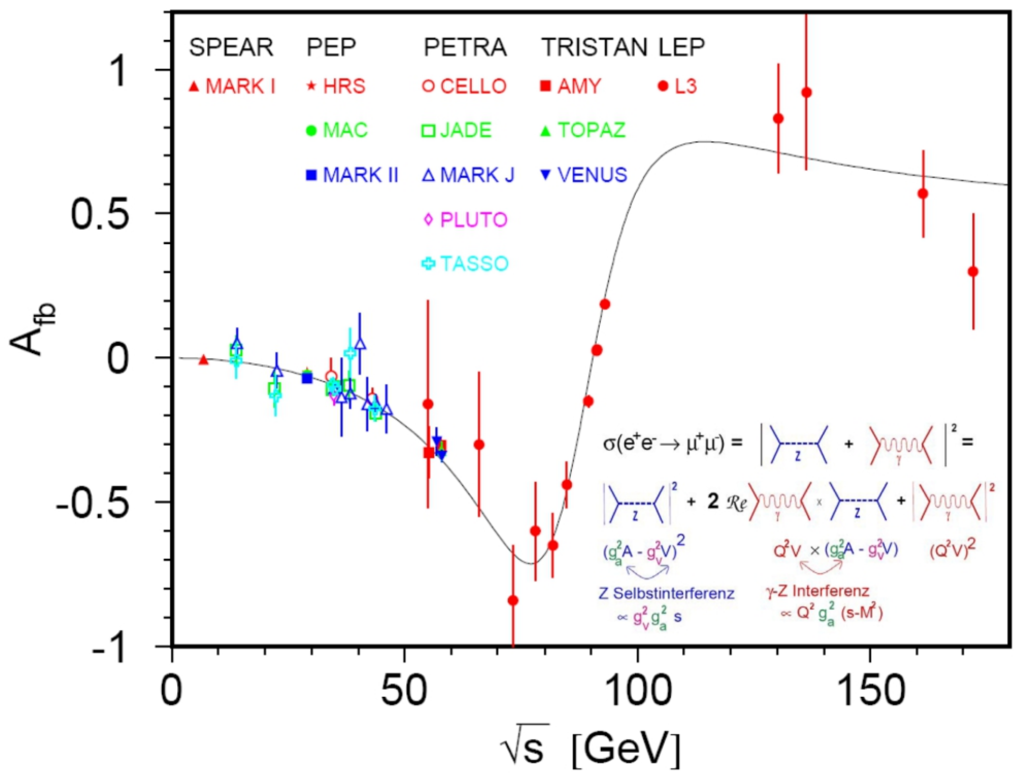
- Z boson production at LHC is the 'inverse' of the LEP process

LHC: $q\bar{q} \to Z/\gamma^* \to e^+e^-$ LEP: $e^+e^- \to Z/\gamma^* \to q\bar{q}$

- in the Z rest frame: measurement of forward–backward asymmetry



$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

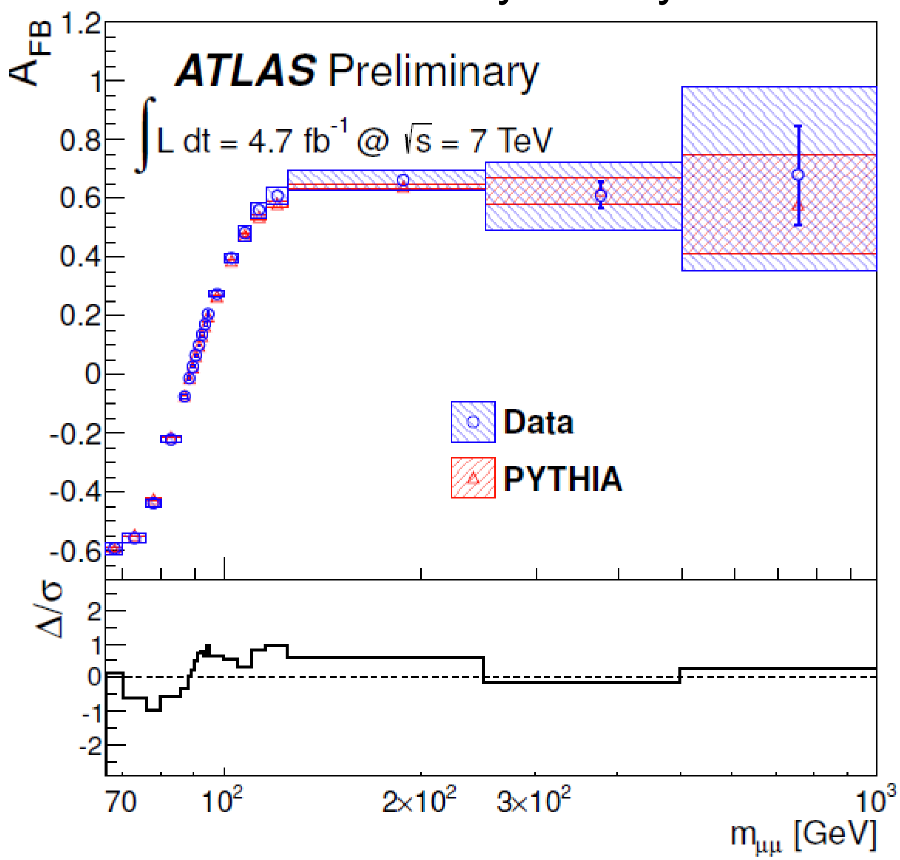


- A_{FB} depends on Z-to-fermion couplings

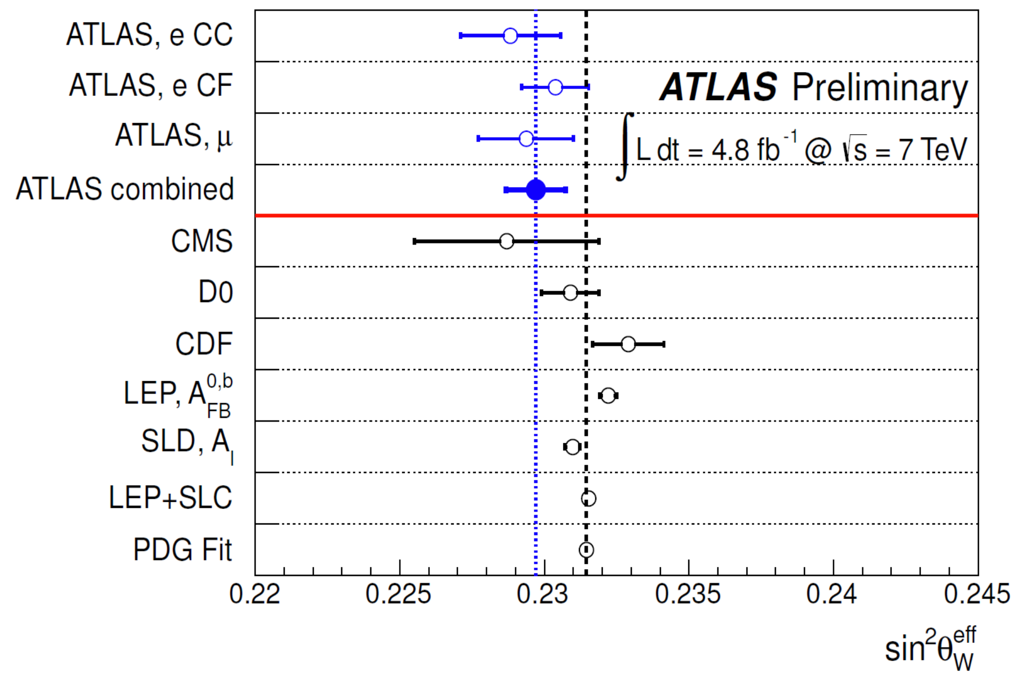
$$A_{FB}(g_V, g_A) = A_{FB}(\sin^2\theta_w)$$

Weak mixing angle measurement

unfolded asymmetry:



ATLAS-CONF-2013-043
arXiv:1110.2682

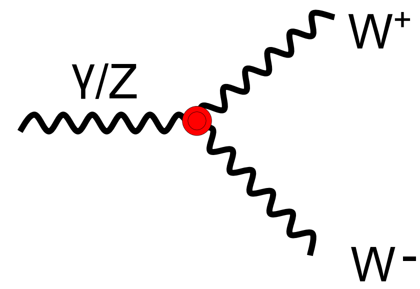


ATLAS result:

$$\sin^2\theta_W^{\mathrm{eff}} = 0.2297 \pm 0.0004(\mathrm{stat.}) \pm 0.0009(\mathrm{syst.})$$

- LHC expects a precision of $\delta\sin^2\theta_W = 3 \cdot 10^{-4}$ with 100 fb^{-1}
- compare to LEP: $\delta\sin^2\theta_W = 1.6 \cdot 10^{-4}$

Couplings between gauge bosons



- Non-Abelian nature of SM predicts triple gauge boson couplings (TGC)
- Coupling strength in the SM:

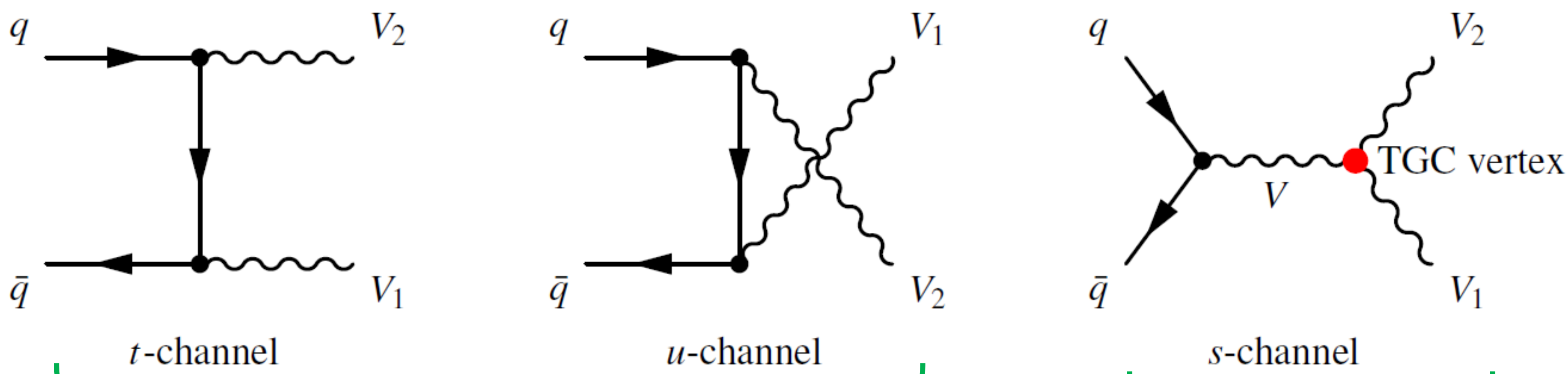
  $g_{WW\gamma} = e \qquad g_{WWZ} = e / \tan\theta_W$

- measure these couplings and test for anomalous contributions
- effective Lagrangian is used to model these (V = γ or Z):

$$\frac{\mathcal{L}_{WWV}}{ig_{WWV}} = g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu V^{\nu\rho}$$

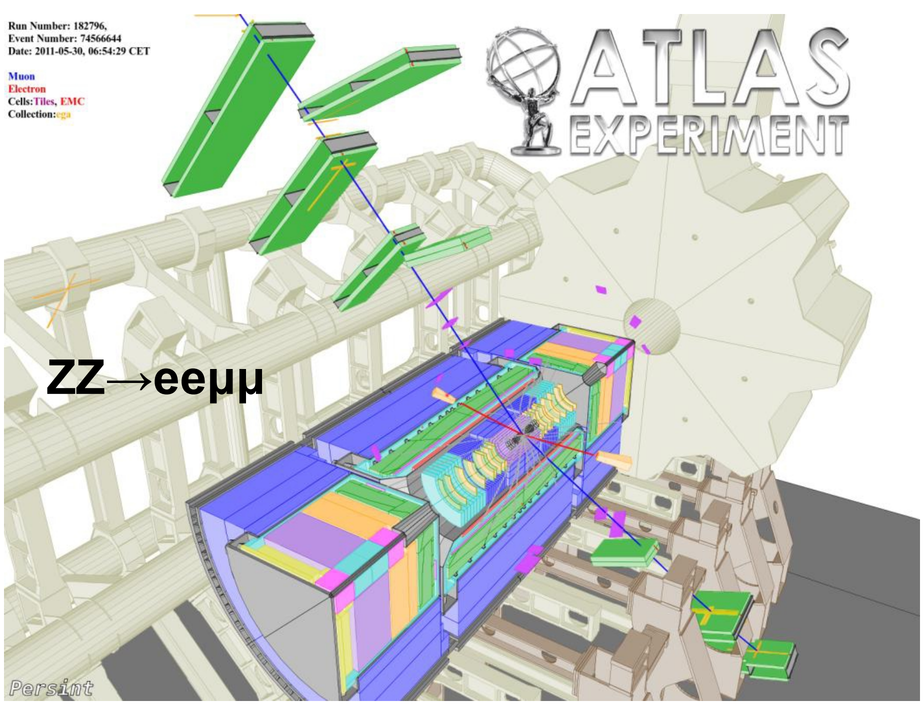
- In the SM: $g_1^\gamma = g_1^Z = 1 \qquad \kappa^\gamma = \kappa^Z = 1 \qquad \lambda^\gamma = \lambda^Z = 0$

Diboson production



WW, WZ, Wγ, ZZ, Zγ

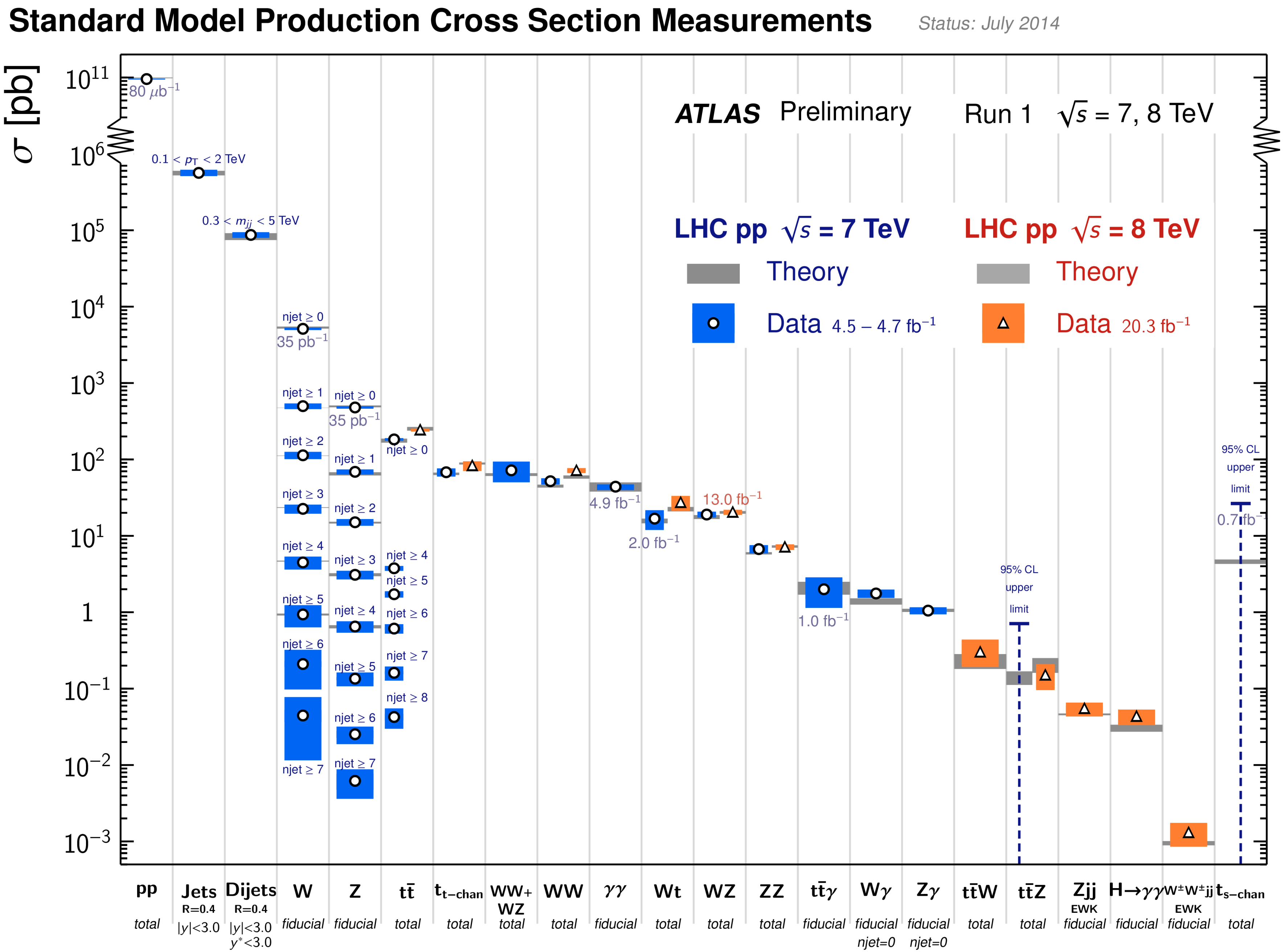
Z/γ → WW
W → WZ, Wγ
~~Z/γ → ZZ, Zγ~~ forbidden



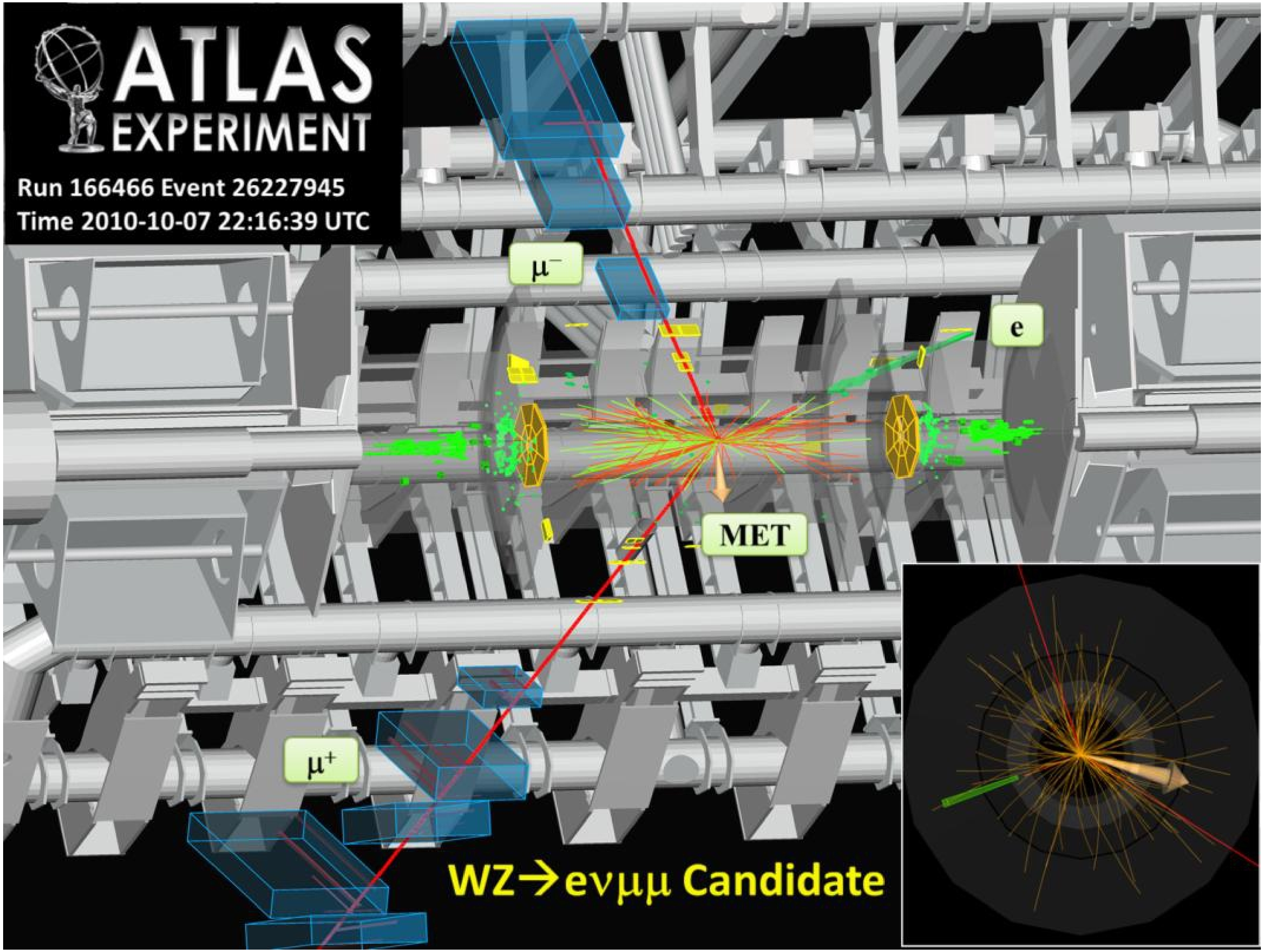
At LHC, diboson decays to electrons and muons are measured:

pp → ZW → ll lν
pp → WW → lν lν
pp → ZZ → ll ll, ll νν
pp → Zγ → ll γ
pp → Wγ → lν γ

Overview: Standard Model cross sections



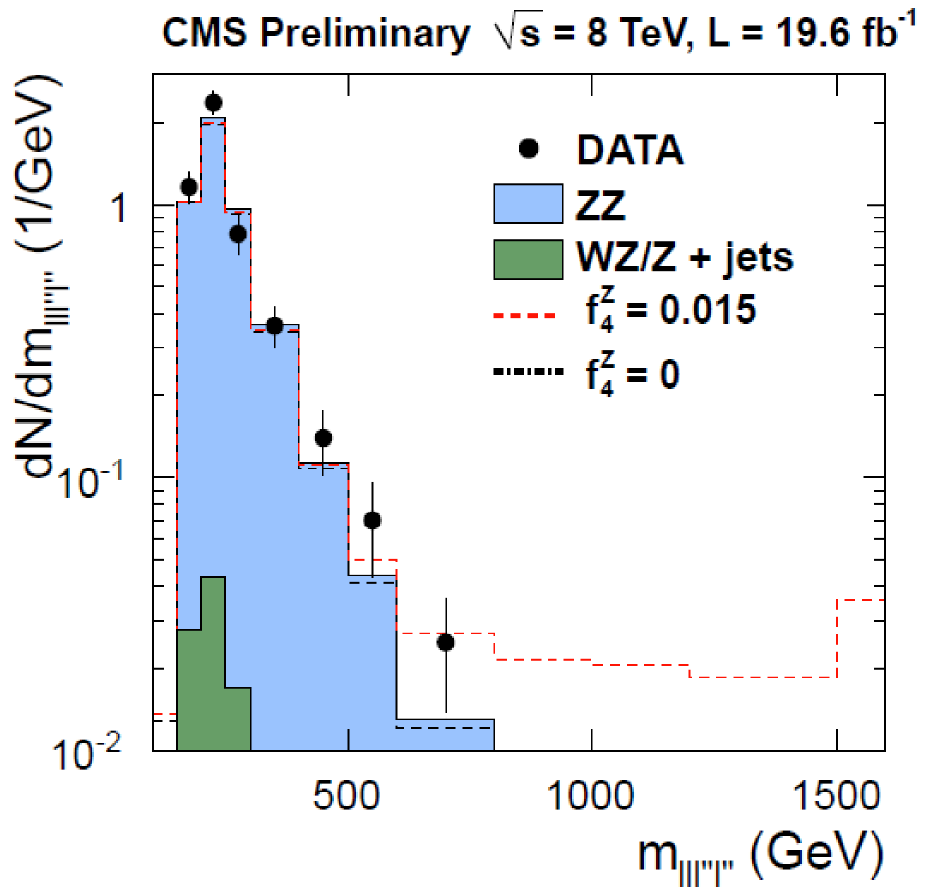
Diboson production



Gauge boson couplings

- Anomalous contributions are derived from diboson cross-sections

  → anomalous contributions ~ (Δcoupling)^2
- Example: anomalous ZZγ/ZZZ coupling

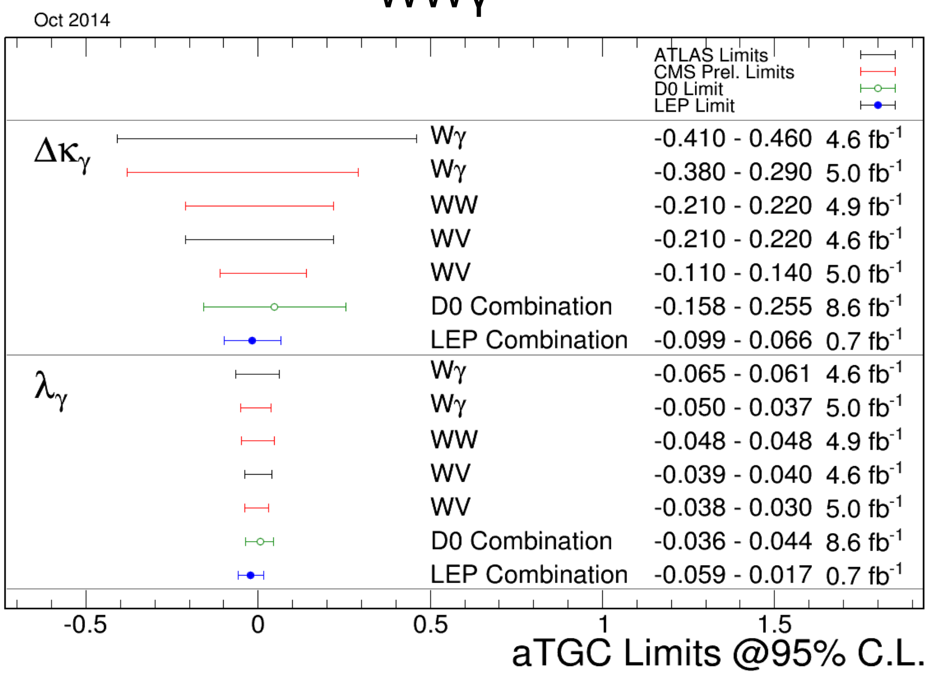


(anomalous) TGC

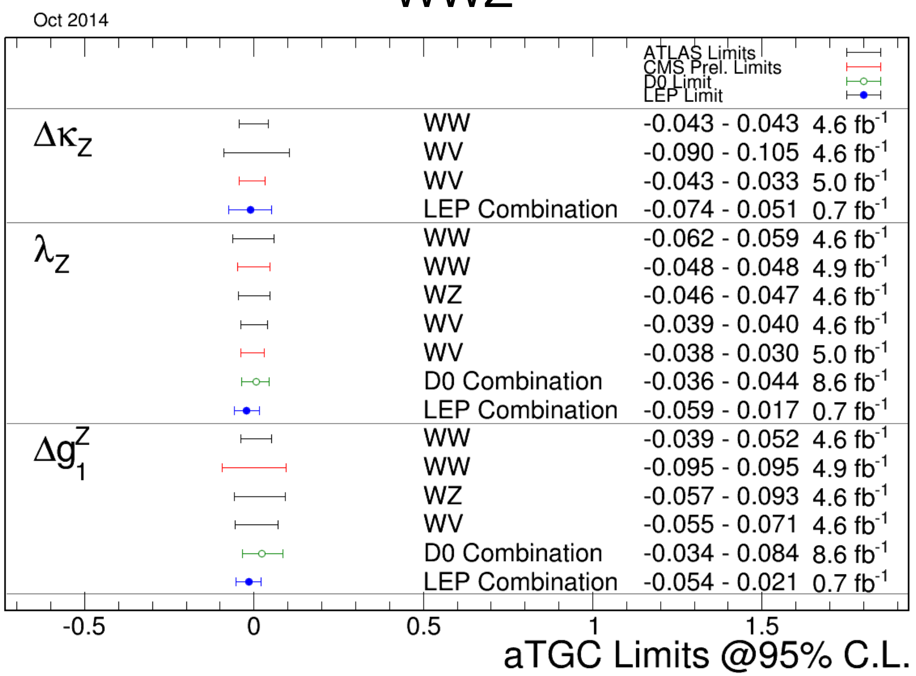
95% CL upper limits on contributions due to anomalous couplings

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

WWγ



WWZ



In the SM:

- $g_1^{\gamma} = g_1^{Z} = 1$; $\Delta g = g - 1$
- $\kappa_{\gamma} = \kappa_{Z} = 1$; $\Delta\kappa = \kappa - 1$
- $\lambda_{\gamma} = \lambda_{Z} = 0$

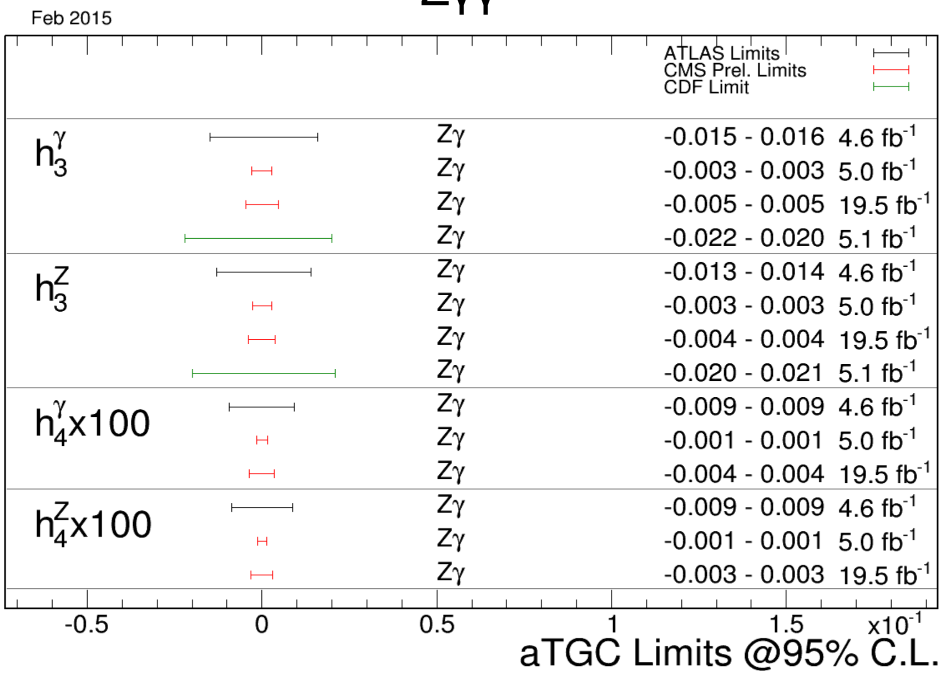
No deviations from SM values observed!

(anomalous) TGC

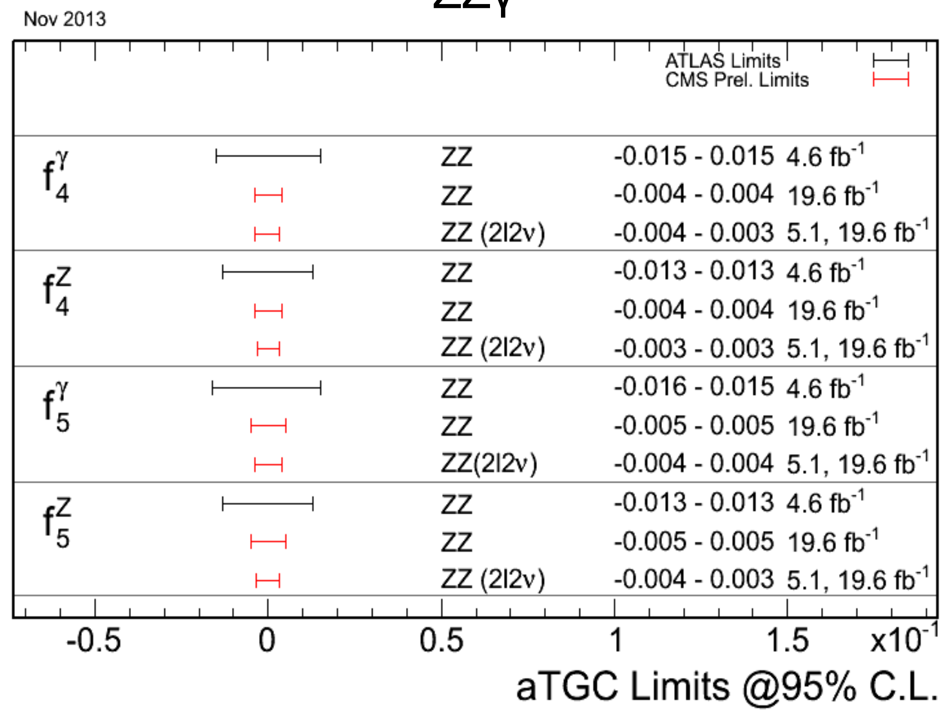
95% CL upper limits on contributions due to anomalous couplings

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Zγγ



ZZγ



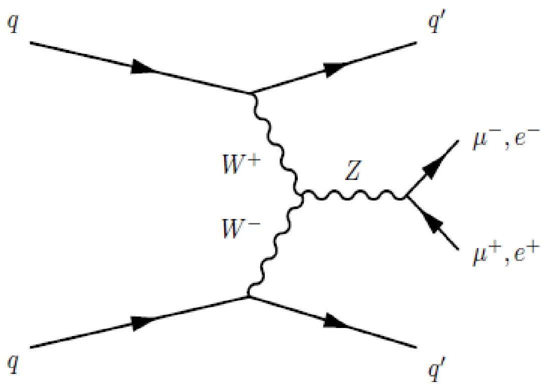
In the SM:

- $h_3 = h_4 = f_4 = f_5 = 0$

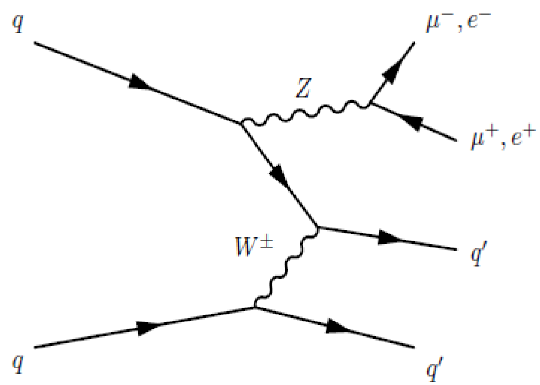
No deviations from SM values observed!

Vector boson fusion: Zjj

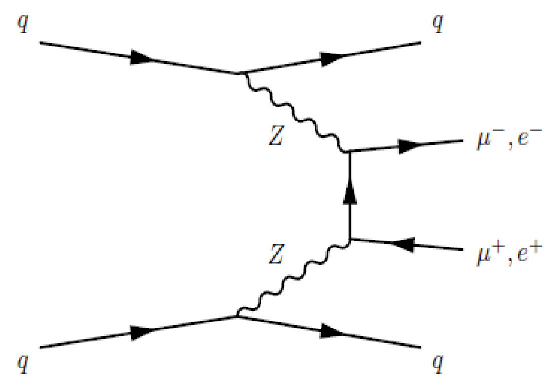
Electroweak Zjj production: rare, ~ 1% of inclusive Zjj cross section



(a) vector boson fusion

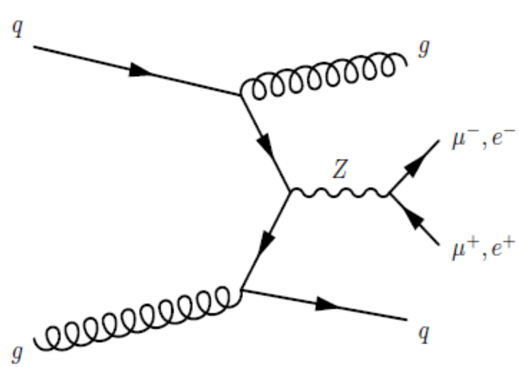


(b) Z-boson bremsstrahlung

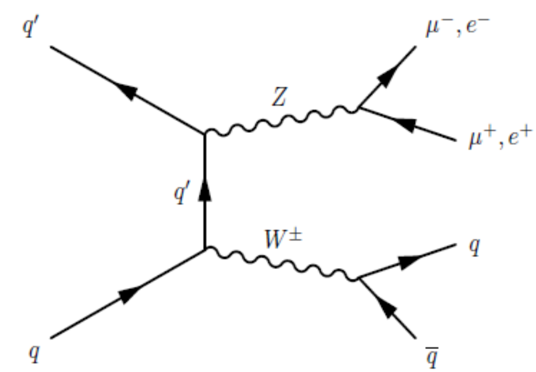


(c) non-resonant $\ell^+\ell^- jj$

VBF: 'tagging' jets well separated in rapidity (y) with large dijet mass (m_{jj})



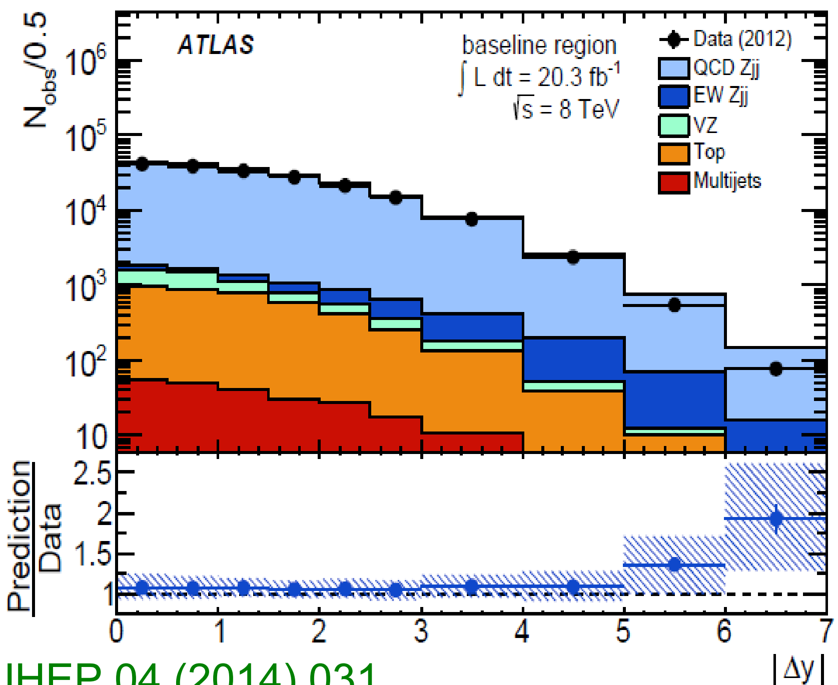
(a) strong Zjj production



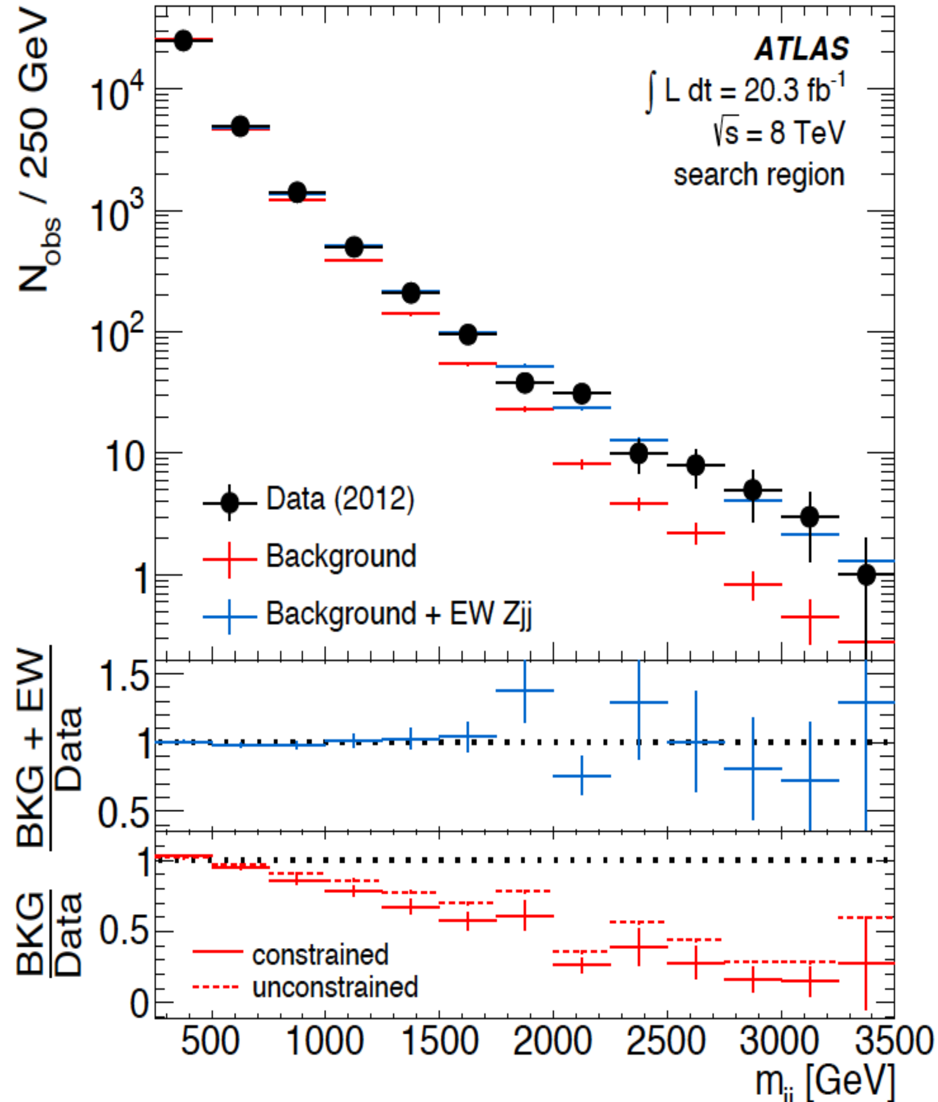
(b) diboson-initiated

Vector boson fusion: Zjj

- high mass and large rapidity difference of tagging jets:



JHEP 04 (2014) 031



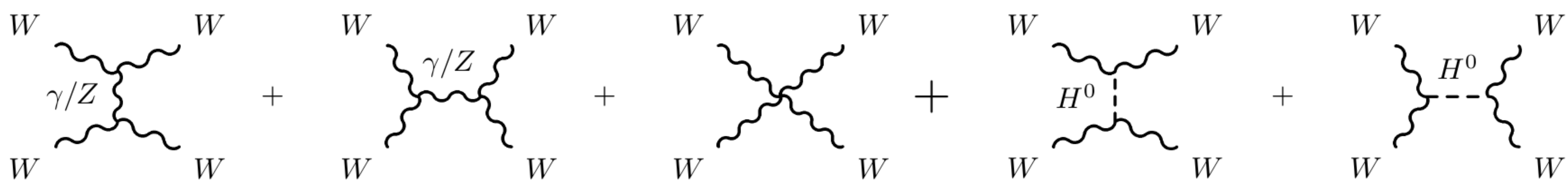
- Measurement (!) in fiducial volume:

$$\sigma_{\rm EW} = 54.7 \pm 4.6\,({\rm stat})\,^{+9.8}_{-10.4}\,({\rm syst}) \pm 1.5\,({\rm lumi})\,{\rm fb}.$$

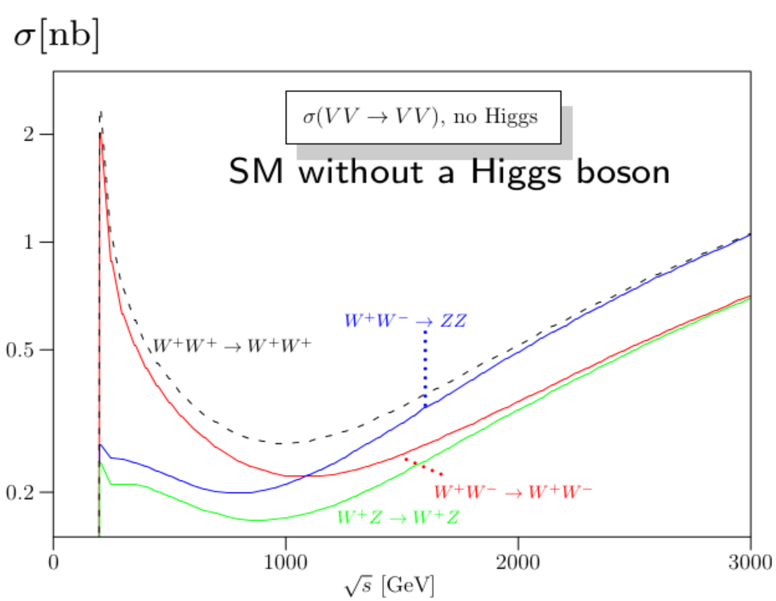
  - SM prediction (POWHEG) σ = $46.1 \pm 0.2\,({\rm stat})\,^{+0.3}_{-0.2}\,({\rm scale}) \pm 0.8\,({\rm PDF}) \pm 0.5\,({\rm model})$ fb

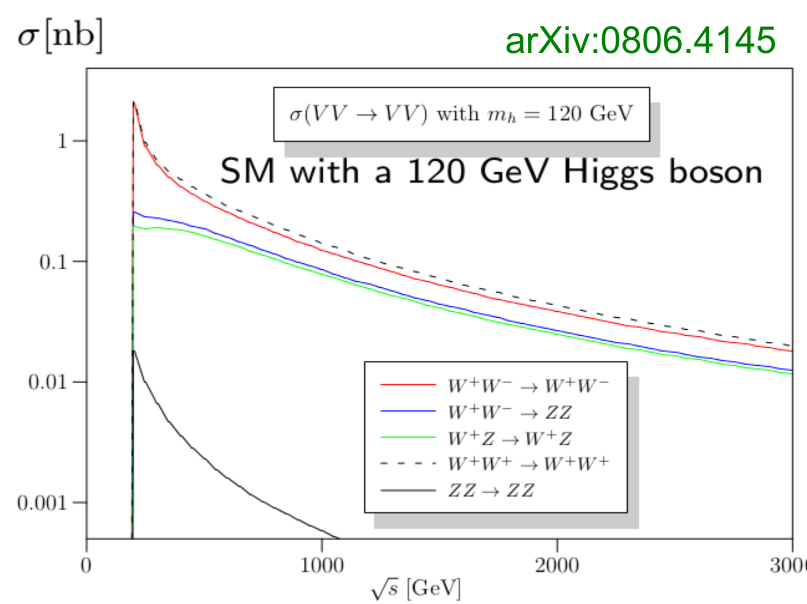
VV scattering and the role of the Higgs boson

- The mechanism responsible for EWSB must regulate the cross section $\sigma(VV \to VV)$ to restore unitarity above ~ 1 – 2 TeV
- A light SM Higgs boson cancels increase for large energies (exact cancellation for HWW coupling)



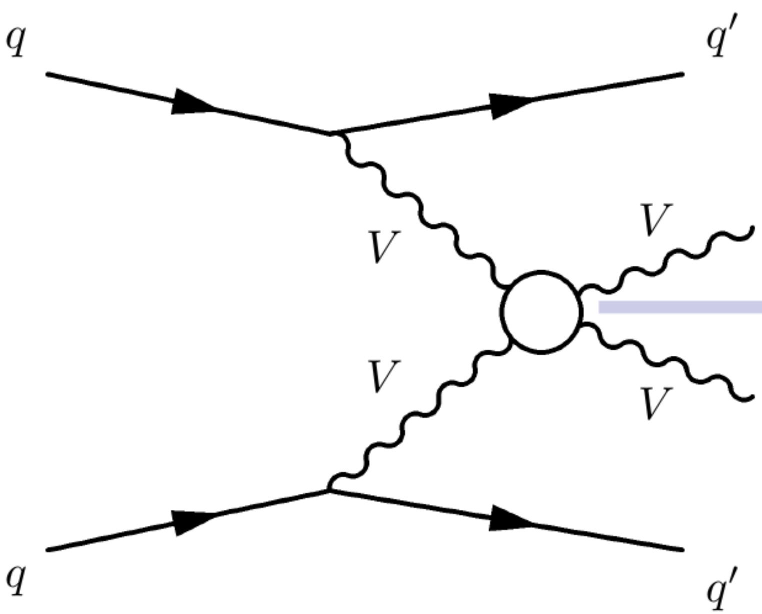
Total cross sections as a function of the m_{VV} center-of-mass energy:

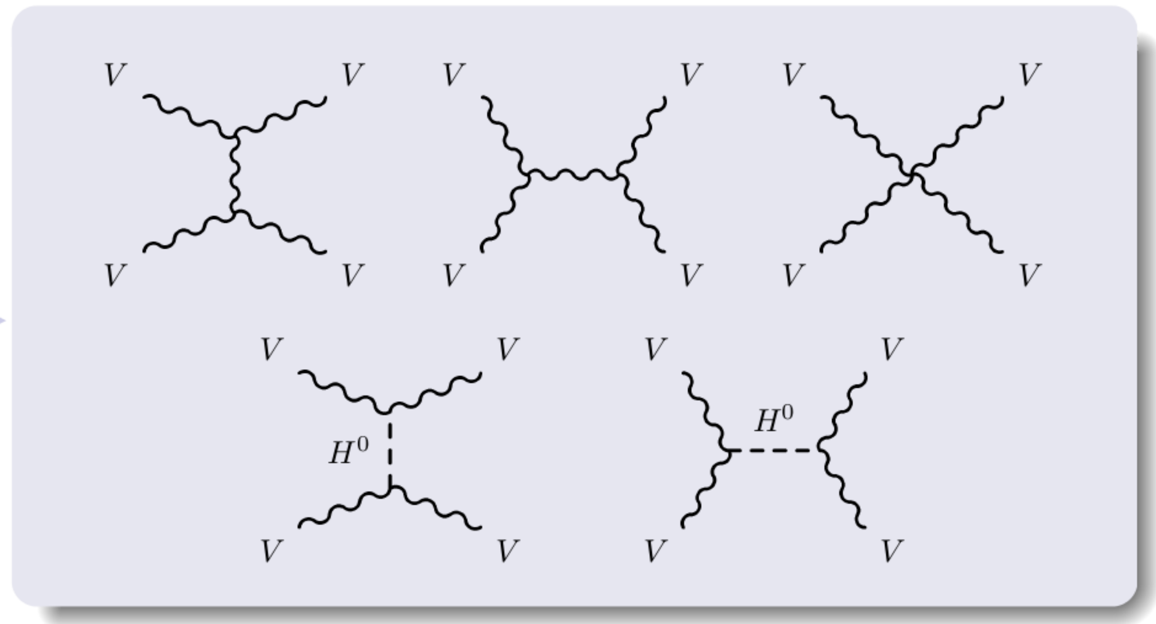




Vector boson scattering

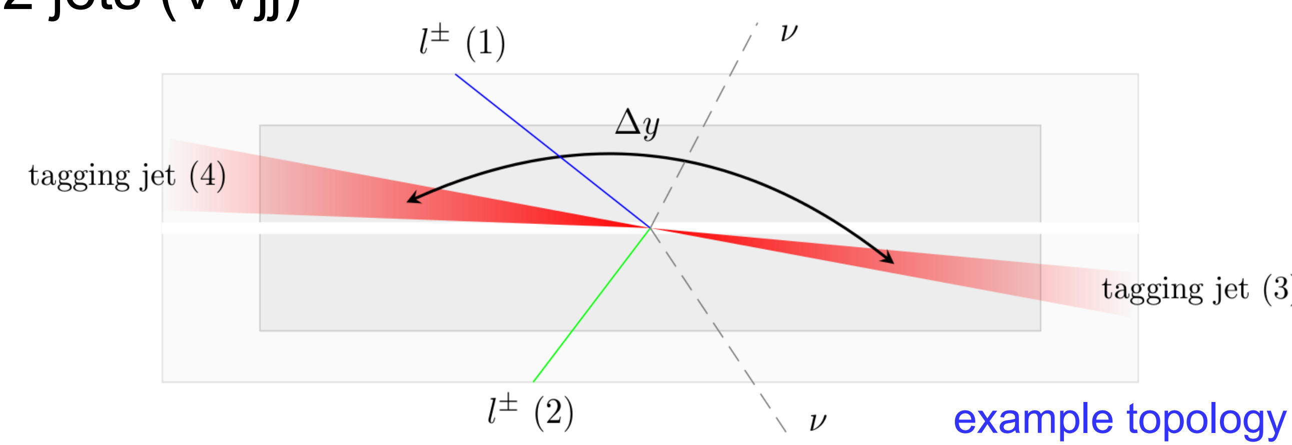
- Protons in LHC serve as source of vector boson beams





- Signature: diboson + 2 jets (VVjj)

  'tagging' jets typically with large m_{jj} and well separated in y



VBS processes (heavy vector bosons only)

- Leading order cross sections (Sherpa) at √s = 8 TeV:

final state	sensitive to $VV \to$	σ^{EW} [fb]	σ^{strong} [fb]	$\sigma^{\mathrm{EW}}/\sigma^{\mathrm{strong}}$
$\ell^\pm \ell^\pm \nu\nu' jj$	$W^\pm W^\pm$	19.5	18.8	$\sim$ **1:1**
$\ell^+ \ell^- \nu\nu' jj$	$W^\pm W^\mp$, ZZ	93.7	3192	$\sim$ 1:35
$\ell^+ \ell^- \ell'^\pm \nu' jj$	$W^\pm Z$	30.2	687	$\sim$ 1:20
$\ell^+ \ell^- \ell'^+ \ell'^- jj$	ZZ	1.5	106	$\sim$ 1:70*

numbers by P. Anger

* includes γ^*, would be also 1:20 – 1:30 with higher m_{ll} cut

(generator cuts: $m_{\ell\ell} > 4$ GeV, $p_T^l > 5$ GeV, $p_T^j > 15$ GeV)

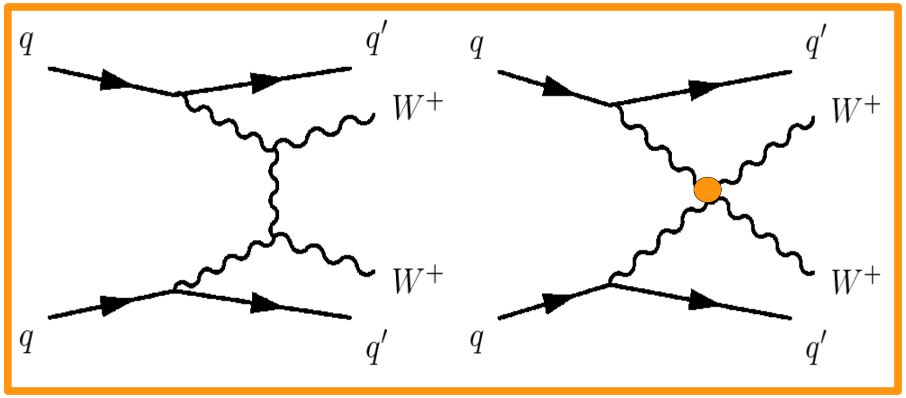
- most promising measureable VVjj final states in terms of VBS:
  - same electric charge-sign ('same-sign') $W^\pm W^\pm jj$

    → no gg or gq initial state at leading order

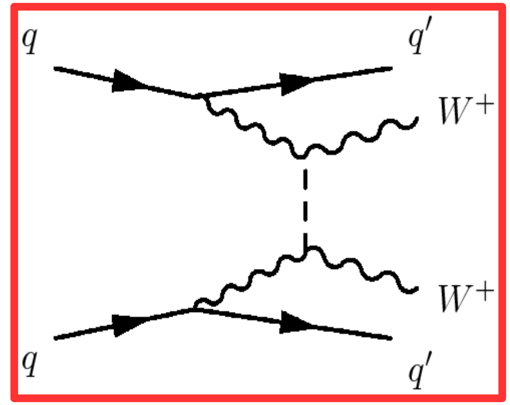
    □ strong $W^\pm W^\pm jj$ contributions very small
  - $W^\pm Zjj$ → clean channel due to 3-lepton final state

W±W±jj production at the LHC

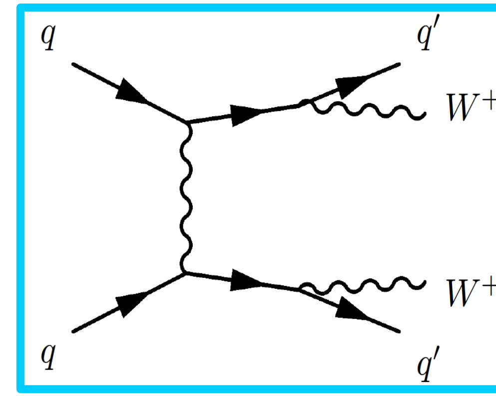
Signal: electroweak W±W±jj



self interactions,
including quartic gauge vertex

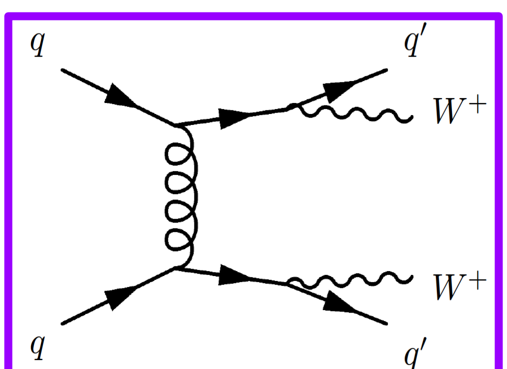


Higgs contribution



non-resonant

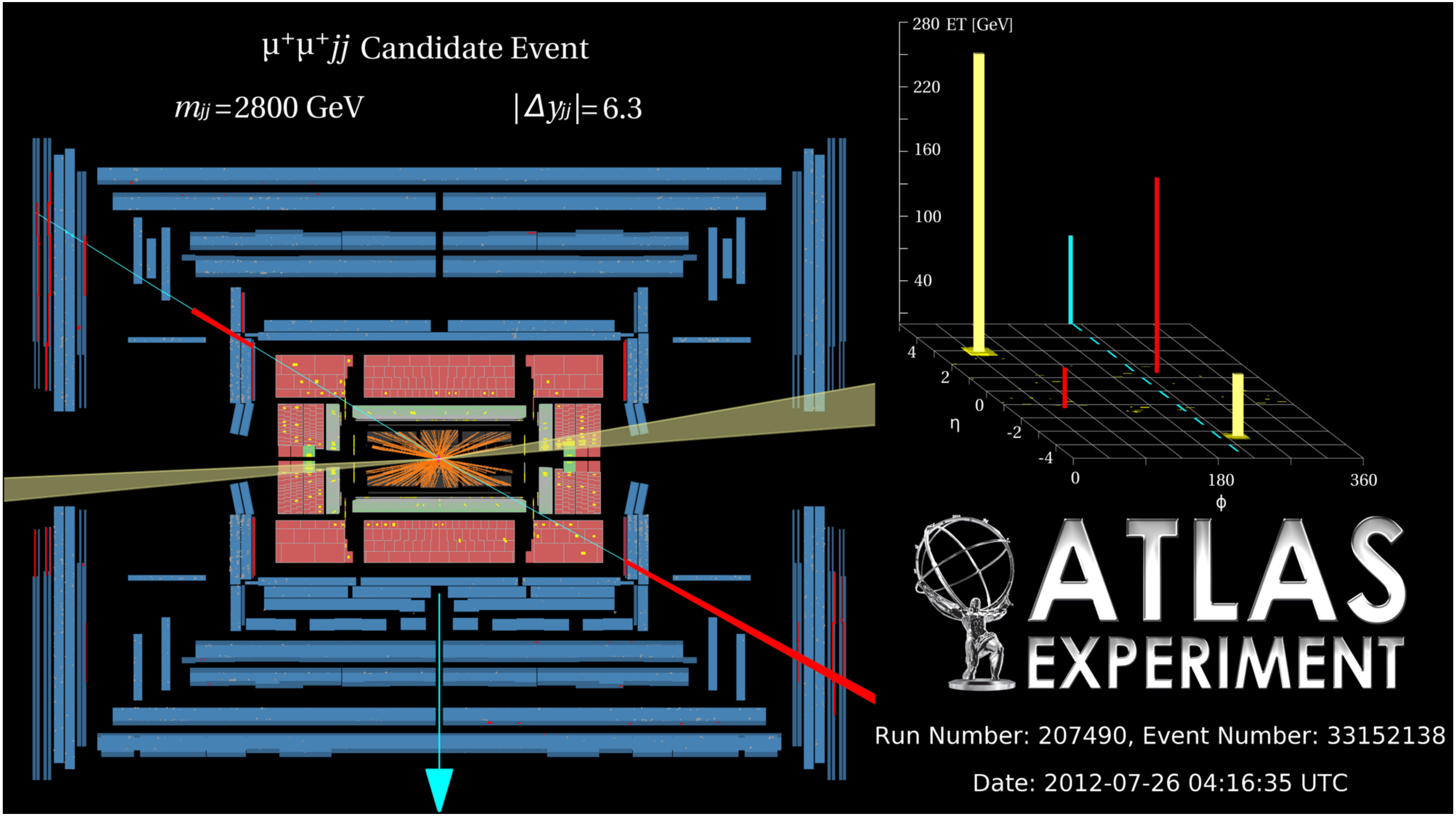
Strong W±W±jj



can be separated from electroweak signal
using topological cuts

$W^{\pm}W^{\pm}jj$ candidate event

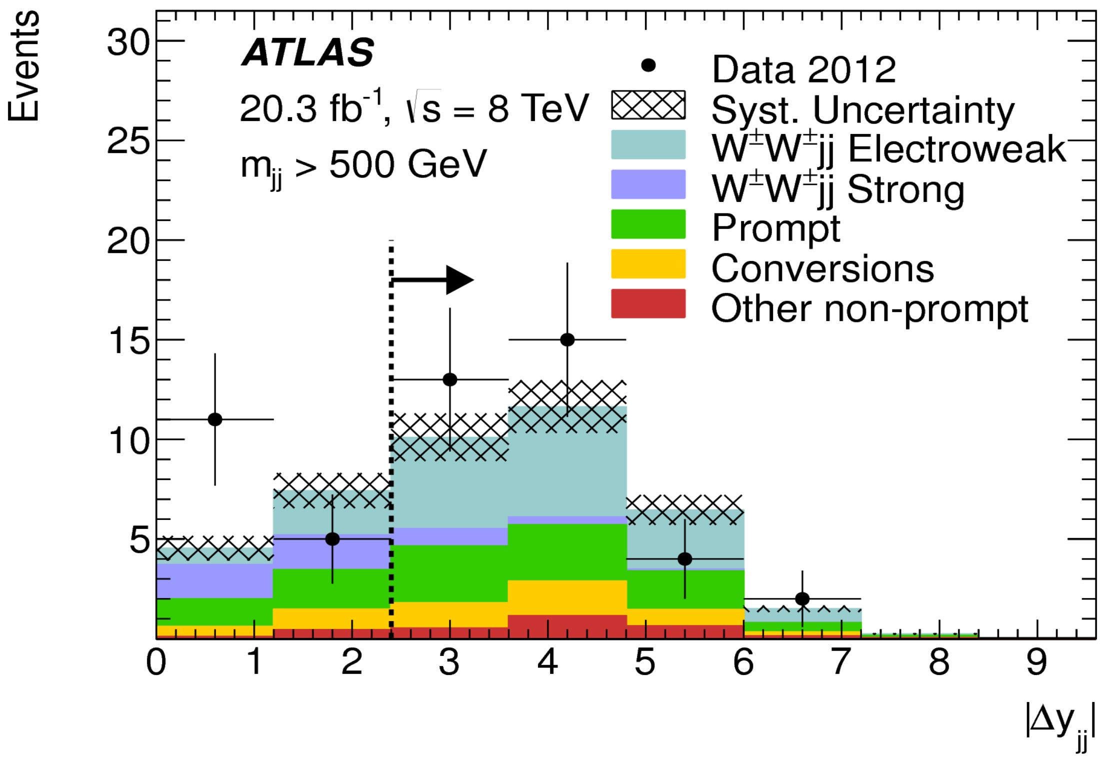
Phys. Rev. Lett. 113, 141803



$W^\pm W^\pm jj$ production measurement at ATLAS

Phys. Rev. Lett. 113, 141803

Rapidity difference $|\Delta y_{jj}|$ between the 'tagging' jets:

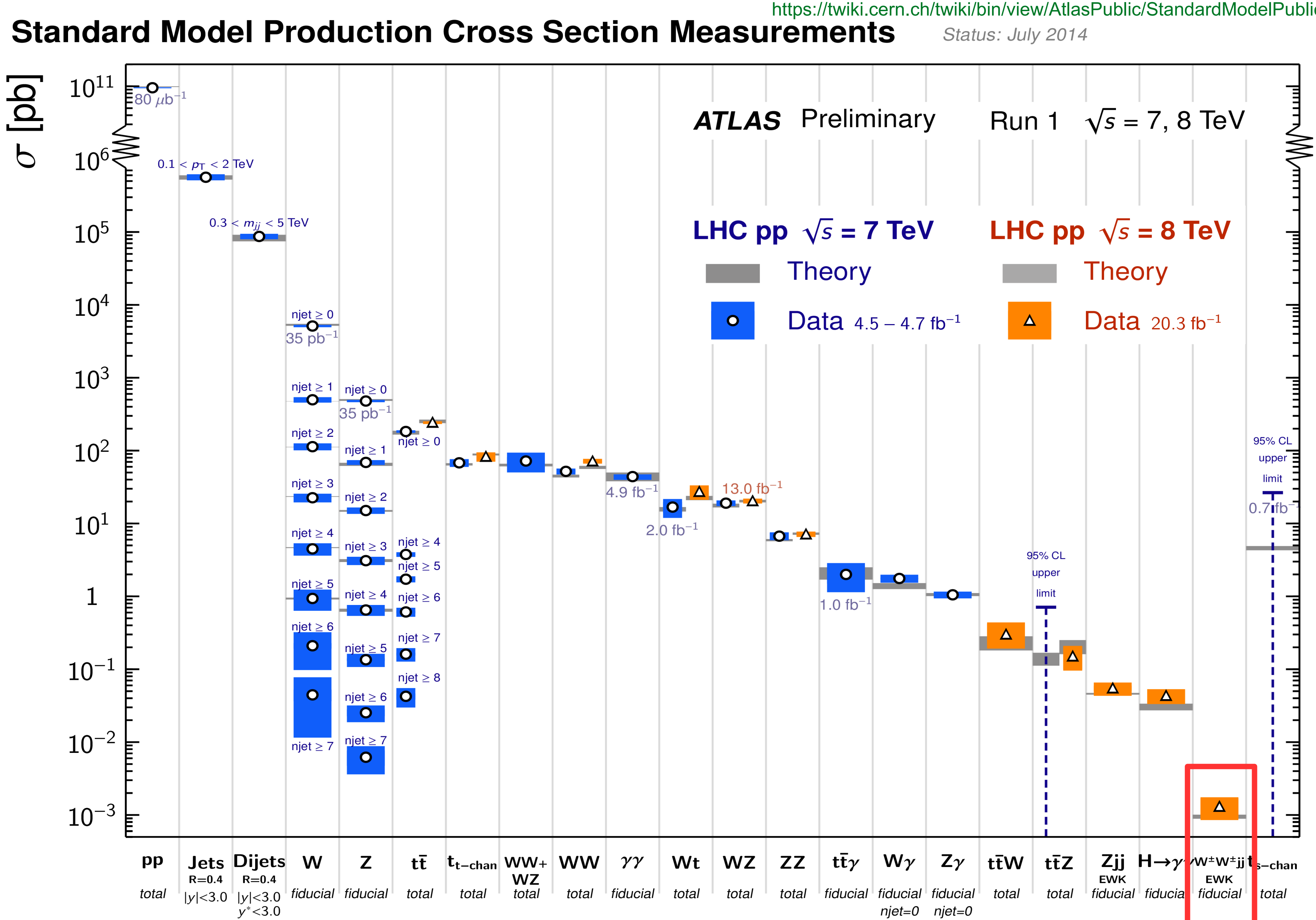


In order to extract the electroweak $W^\pm W^\pm jj$ component, require that the tagging jets have a large rapidity difference ($|y| > 2.4$)

Measured fiducial cross section:
$\sigma = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ fb (predicted: 0.95 ± 0.06 fb)
significance: 3.6 standard deviations (expected: 2.8 s.d.)

Overview of SM cross sections

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults



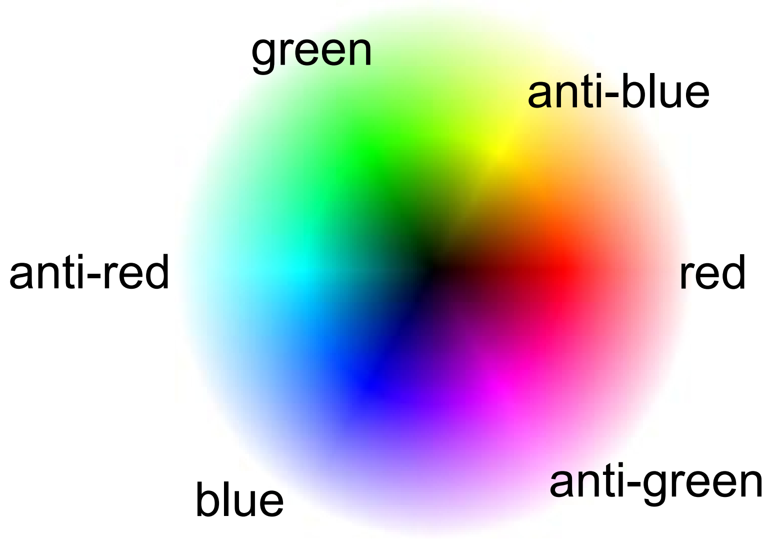
Summary of LHC electroweak measurements

- LHC machine performs well and delivered good data
  - 5.6 fb^{-1} at 7 TeV and 21.7 fb^{-1} at 8 TeV
  - starting up again in this year at 13 TeV
- production cross sections of W and Z boson
  - W mass with 10 MeV ultimate precision per experiment
- diboson production WW, WZ, ZZ, Wγ, Zγ,
  - TGC will be measured to precision beyond $\Delta\kappa/\Delta\lambda/\Delta g_1 = 0.01$
  - QGC measured for the first time in vector boson scattering
- perform a new measurement of the weak mixing angle
  - $\delta\sin^2\theta_W = 3 \cdot 10^{-4}$ and maybe better

We know that the Standard Model is just an effective theory which will need extensions at very high energies

- keep your eyes open when looking at invariant mass spectra, angular distributions, coupling measurements, etc.

QCD Physics



Snapshot of QCD

Quantum chromodynamics: theory of strong interactions

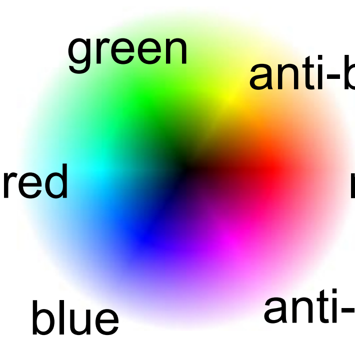
developed by Fritzsch, Gross, Politzer, Wilczek, Gell-Mann, Leutwyler, Weinberg in the 1970s

- gauge theory with gauge group $SU(3)_C$

NP 2004

- interaction between colour-charged particles: quarks and gluons
- 3 coulour charges of quarks:

- gluons carry colour and anticolour:



$$R\bar{G}, R\bar{B}, G\bar{R}, G\bar{B}, B\bar{R}, B\bar{G}$$

$$\frac{1}{\sqrt{2}}(R\bar{R} - B\bar{B})$$

$$\frac{1}{\sqrt{6}}(R\bar{R} + G\bar{G} - 2B\bar{B})$$

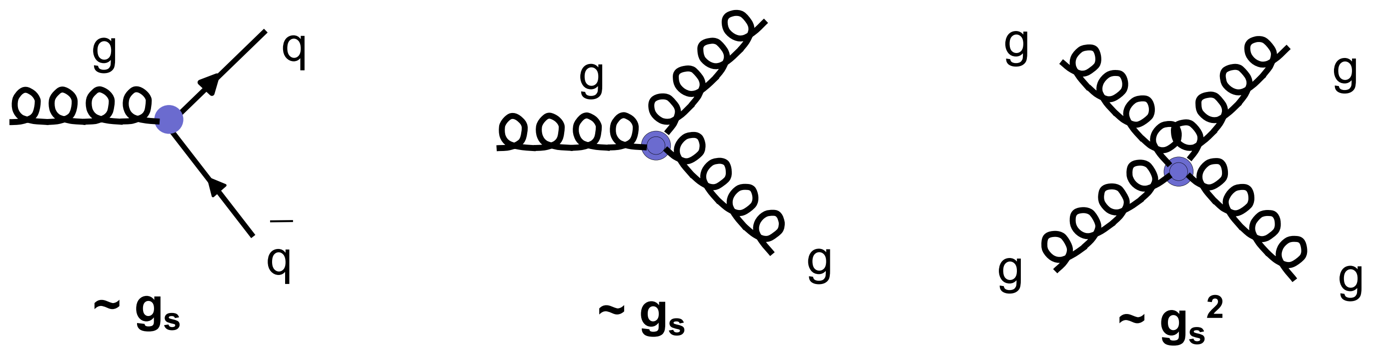
 g

8 gluons (colour octet)

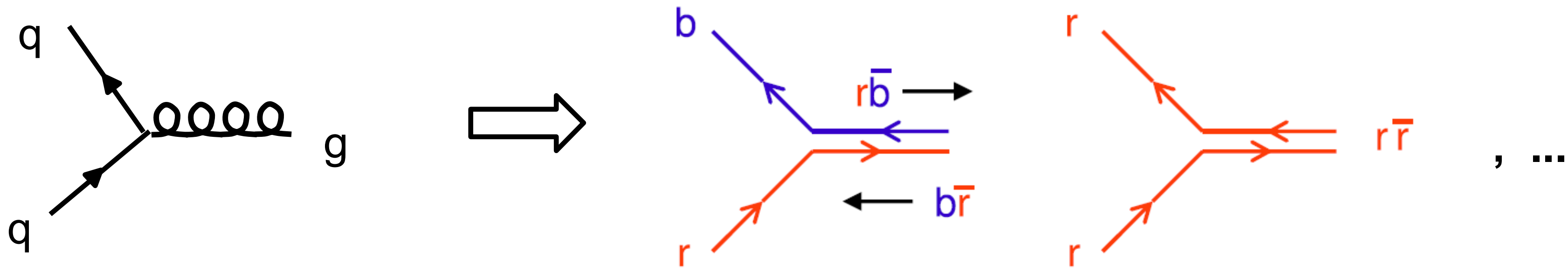
- the colour singlet state is not observed: $\frac{1}{\sqrt{3}}(R\bar{R} + G\bar{G} + B\bar{B})$
- non-Abelian theory: → gluons can couple to each other

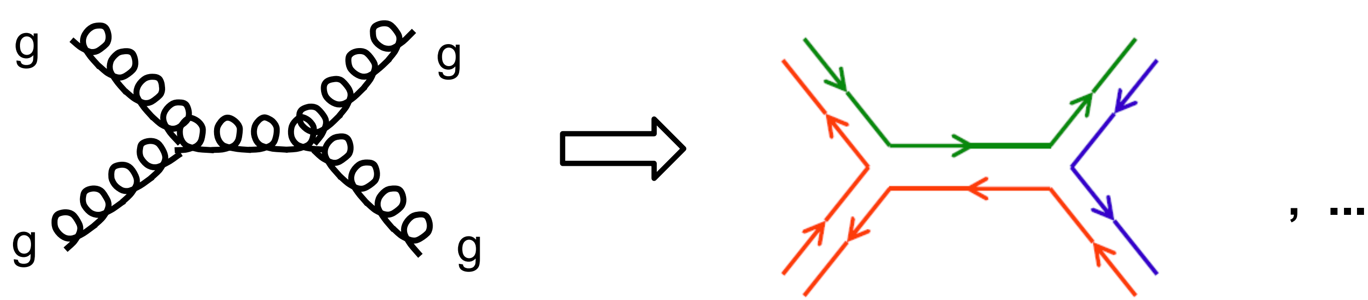
→ infinite-range strong interaction

QCD vertices



- strong coupling constant: $\alpha_s = \frac{g_s^2}{4\pi}$
- colour charge is conserved at each vertex



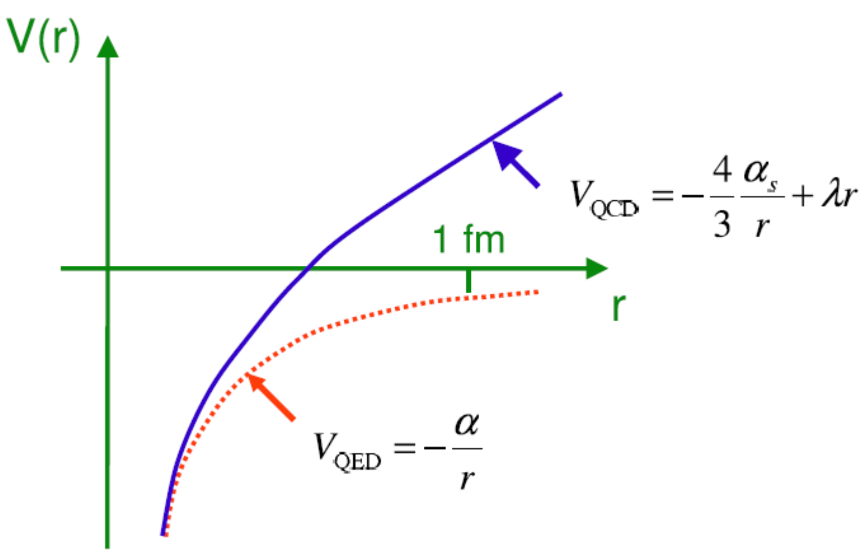


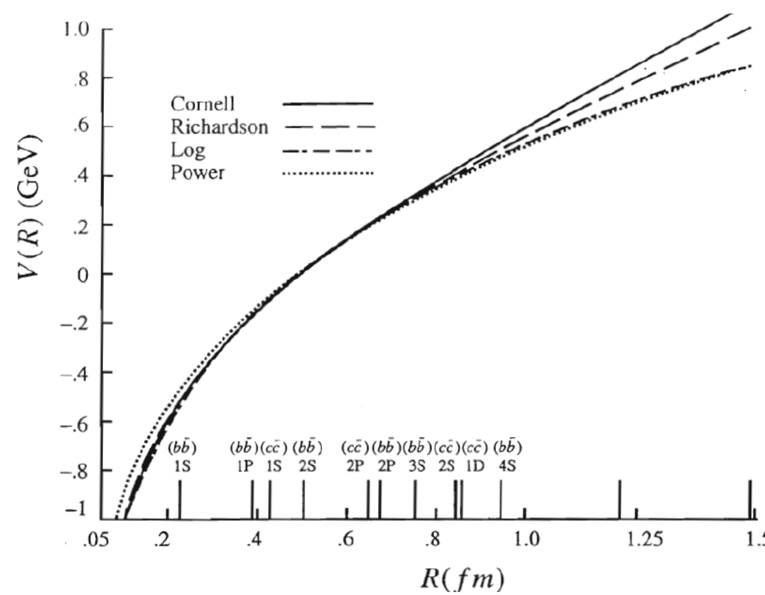
QCD potential

Potential between two quarks and quark + antiquark
→ binding depends on sign of C

$$V(r) = +C\frac{\alpha_s}{r} \qquad V(r) = -C\frac{\alpha_s}{r}$$

Result: only quark and antiquarks can form bound states → mesons





Would need infinite energy to separate quarks since V(r) ~ r at large distances
→ formation of new $q\bar{q}$ pairs → hadronisation and fragmentation → jets of particles

QCD potential

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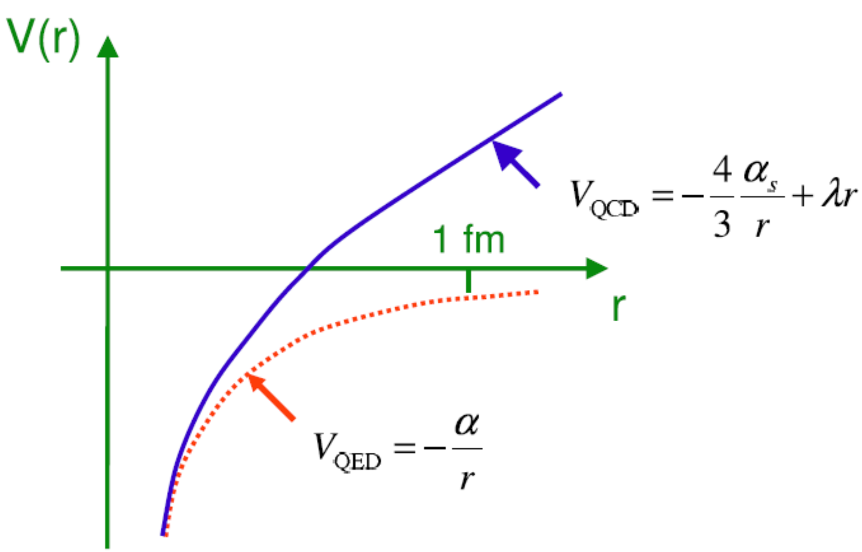
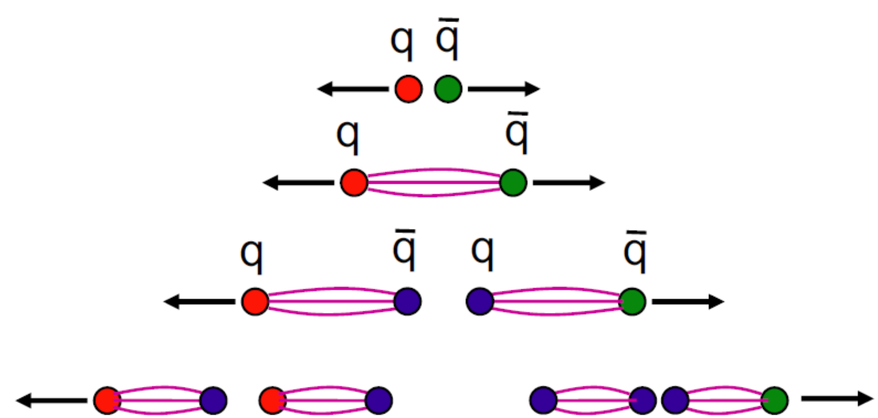
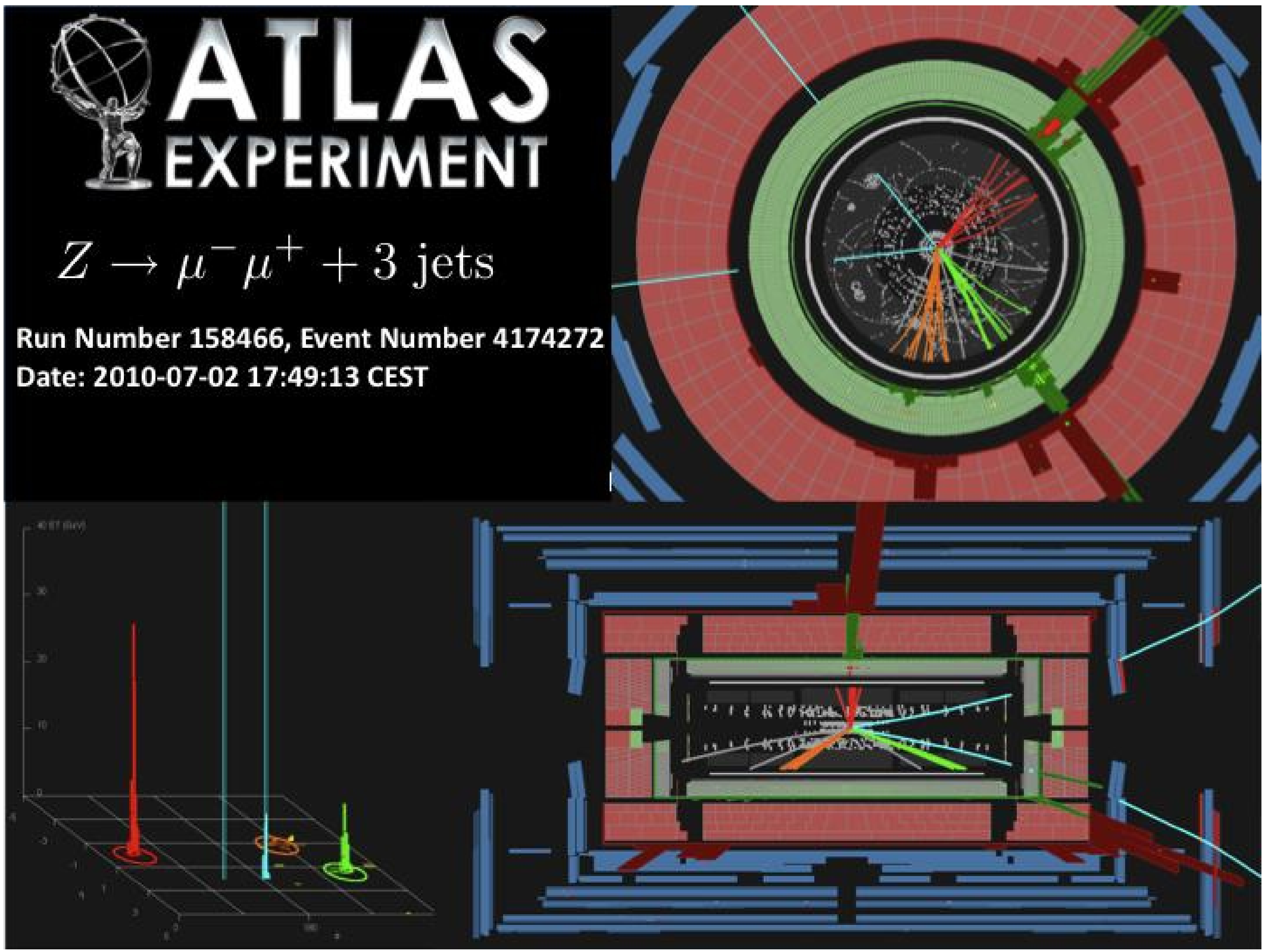




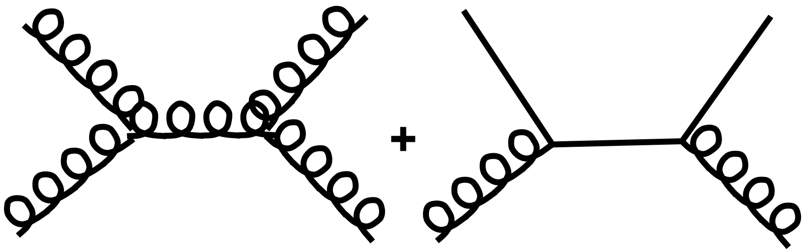
Would need infinite energy to separate quarks since V(r) ~ r at large distances
→ formation of new $q\bar{q}$ pairs → hadronisation and fragmentation → jets of particles

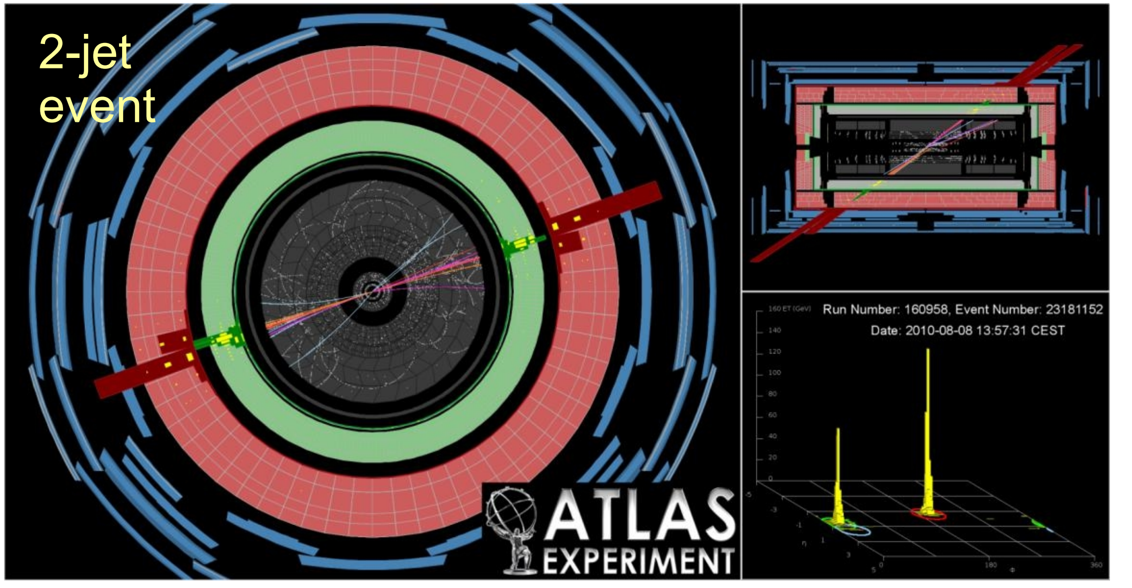
Jets from quarks and gluons

- quarks and gluons cannot exist as free particles → hadronisation
- collimated stream of charged and neutral hadrons → QCD jets

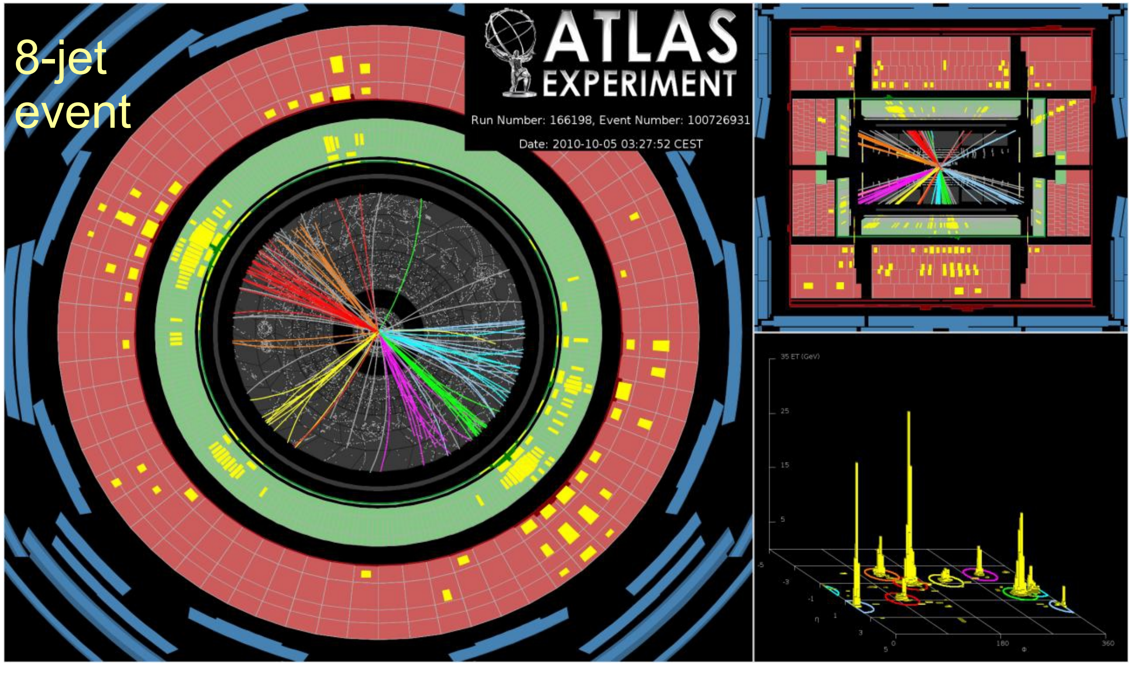


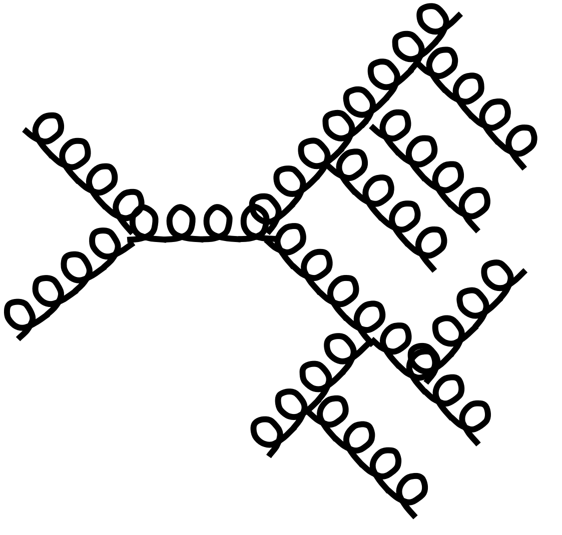
Multijet events at the LHC





+ ....

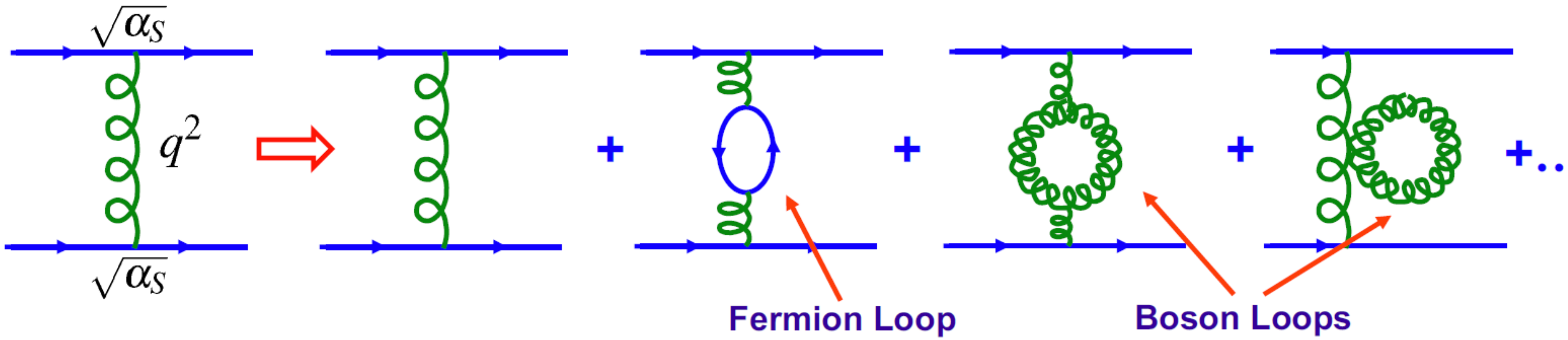




+ ....

Running coupling

Gluon exchange receives contributions from additional loop digrams:

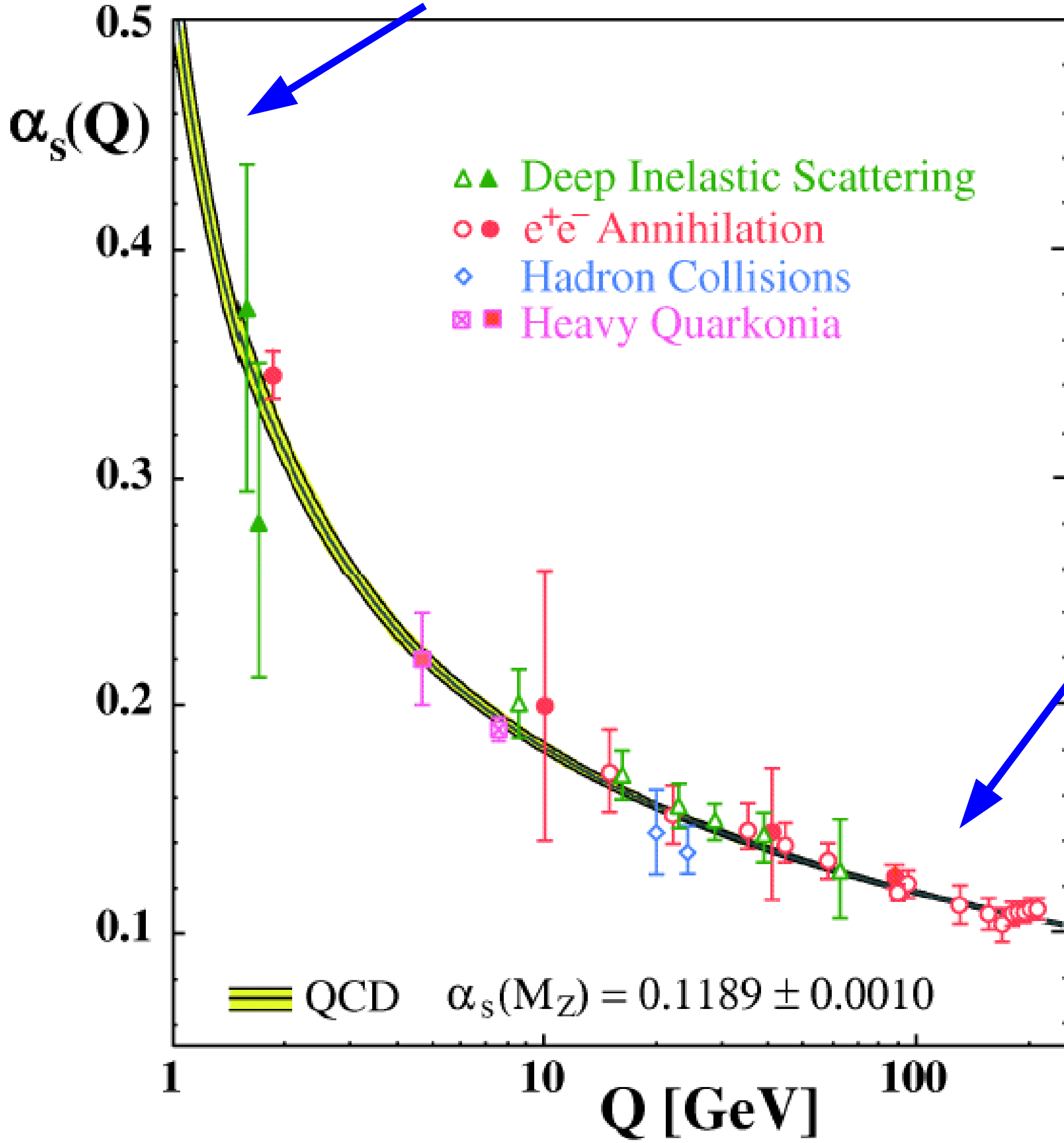


Renormalisation: absorb these contributions into a redefined coupling constant $\alpha_s(Q^2)$

$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + b_0\,\alpha_s(Q_0^2)\,\log\frac{Q^2}{Q_0^2}} \quad \text{with} \quad b_0 = \frac{11N_c - 2N_f}{12\pi} > 0 \quad \text{for} \quad N_c = 3 \quad \text{and} \quad N_f = 5, 6$$

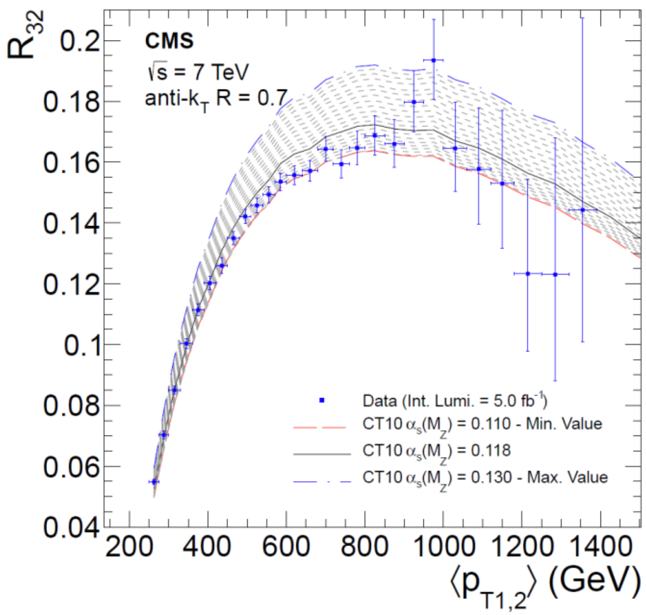
Running of the strong coupling

confinement → non-perturbative regime ('soft')

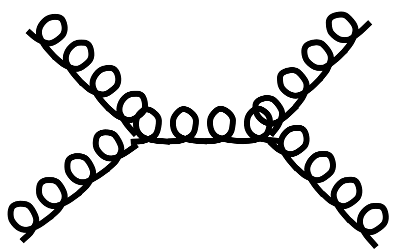


asymptotic freedom
→ perturbative regime
('hard')

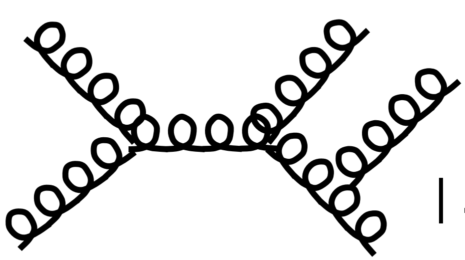
Running of the strong coupling



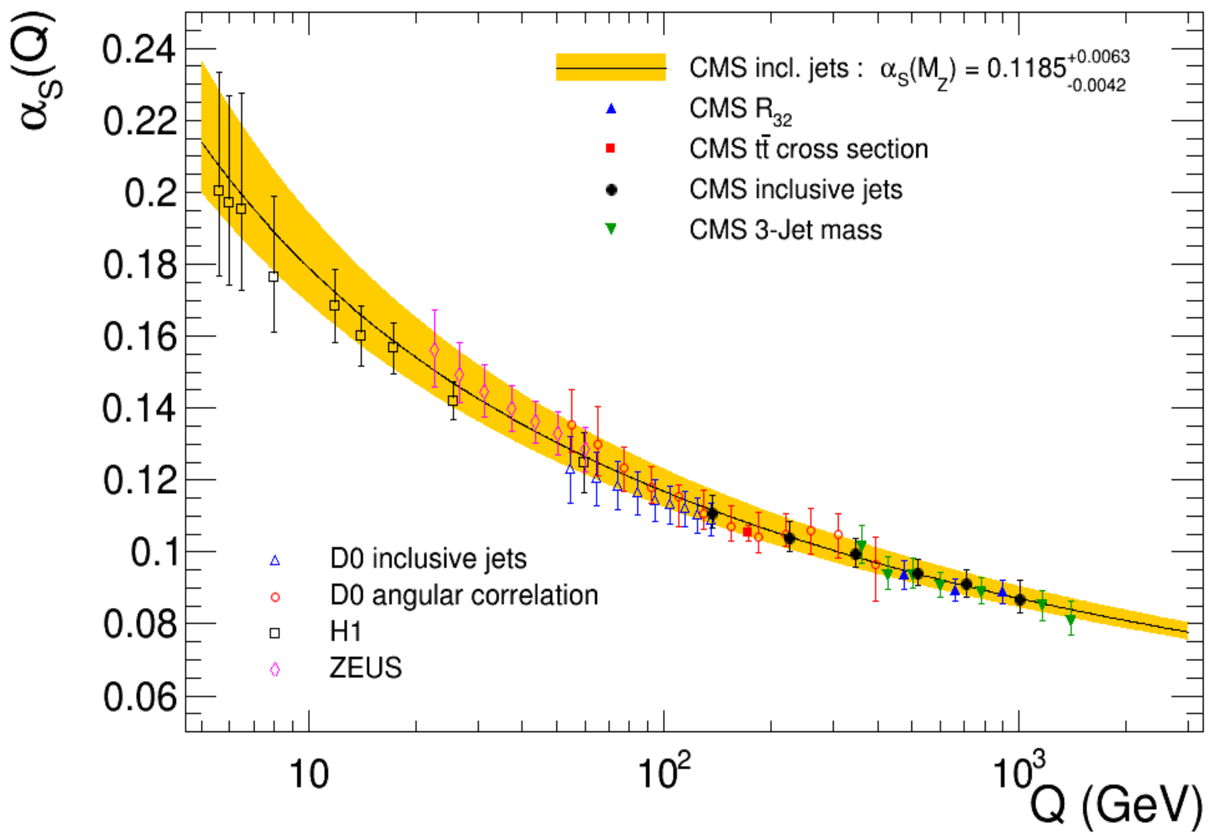
Measurement of the ratio of the inclusive 3-jet cross section to the inclusive 2-jet cross section in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ and first determination of the strong coupling constant in the TeV range



$|\ldots|^2 \sim \alpha_s^2$



$|\ldots|^2 \sim \alpha_s^3$



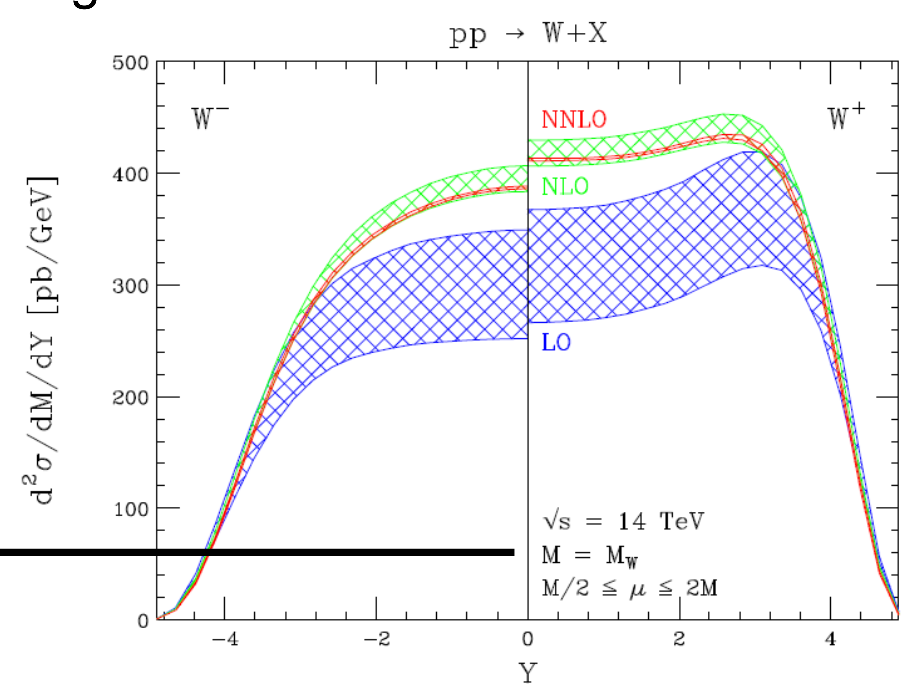
Approach to QCD calculations

- Expand the cross section in a perturbative series in α_s (where possible):

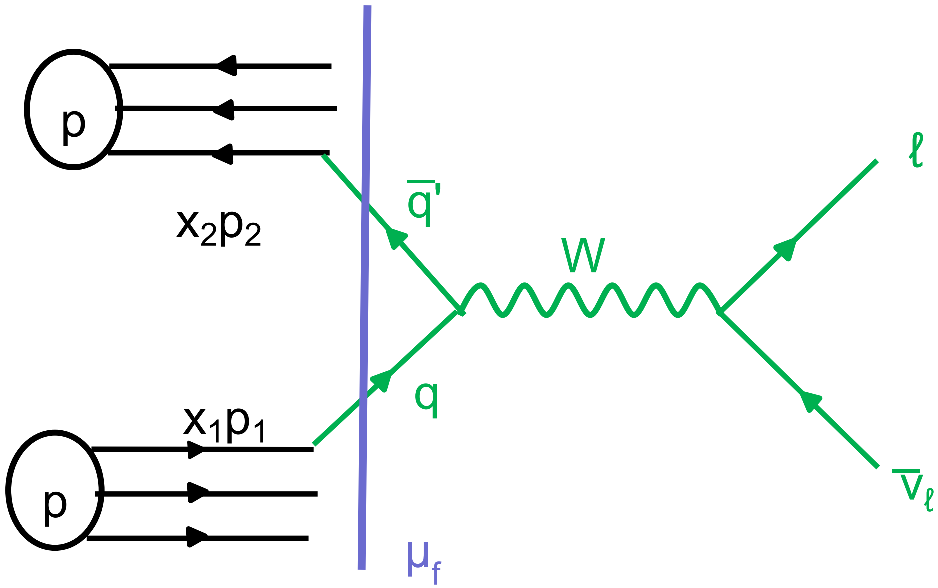
$$\sigma = C_0 + \alpha_s(Q^2)C_1 + (\alpha_s(Q^2))^2 C_2 + \ldots = \sum_{n=0}^{\infty} C_n (\alpha_s(Q^2))^n$$

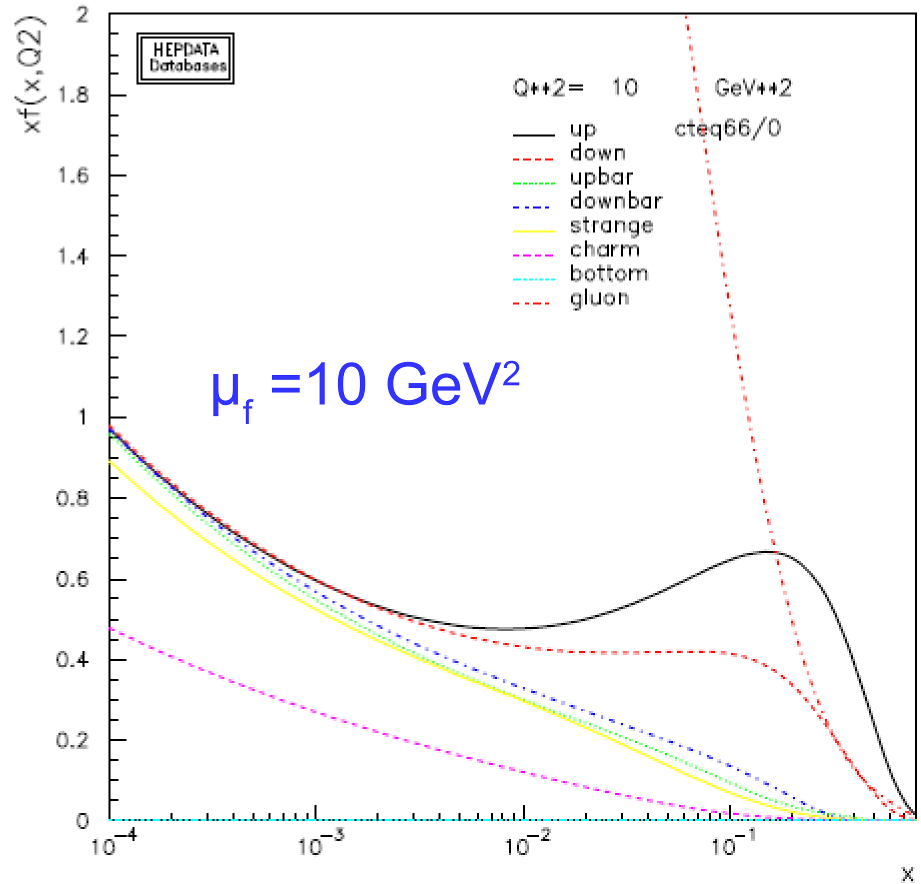
- usually only the first terms of the series are calculated: LO, NLO, NNLO, ...
- large logarithmic contributions are typically also summed up: leading-log, ...
- The renormalisation process absorbs divergences in the calculation by introducing a renormalisation scale parameter μ_r
  → logarithms become $\log(\mu_r^2/Q^2)$
  and α_s becomes $\alpha_s(\mu_r^2)$
- 'simple' stability test of your theoretical prediction by variation of the scale μ_r

$$M = M_W$$
$$M/2 \leq \mu \leq 2M$$

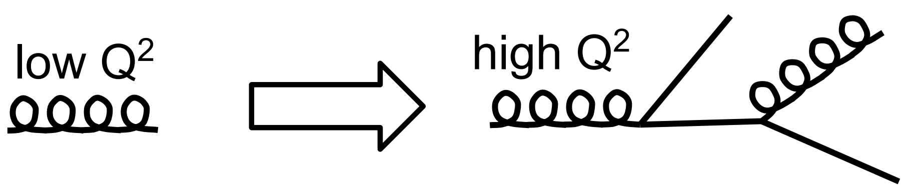


Factorisation with PDFs





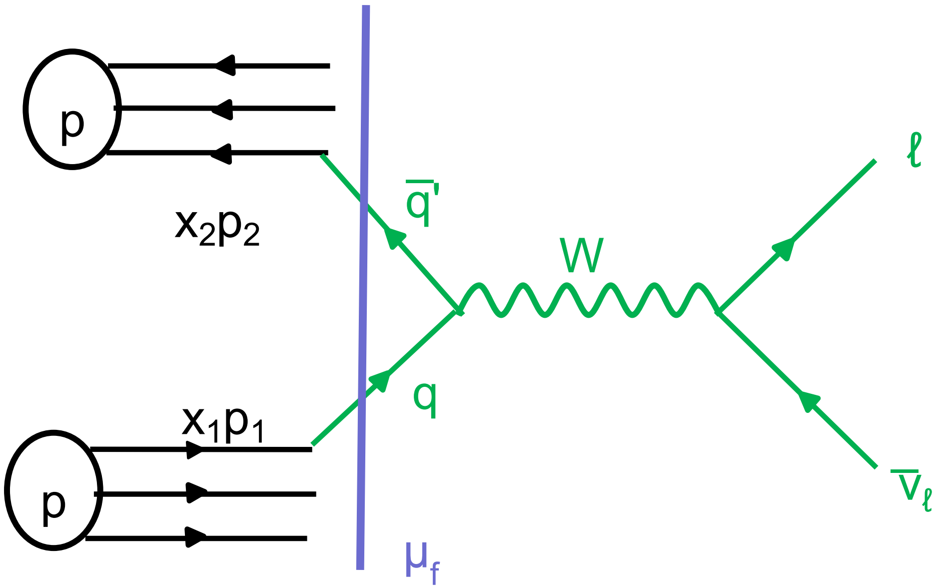
- factorisation energy scale μ_f
- PDFs are energy-scale dependent:

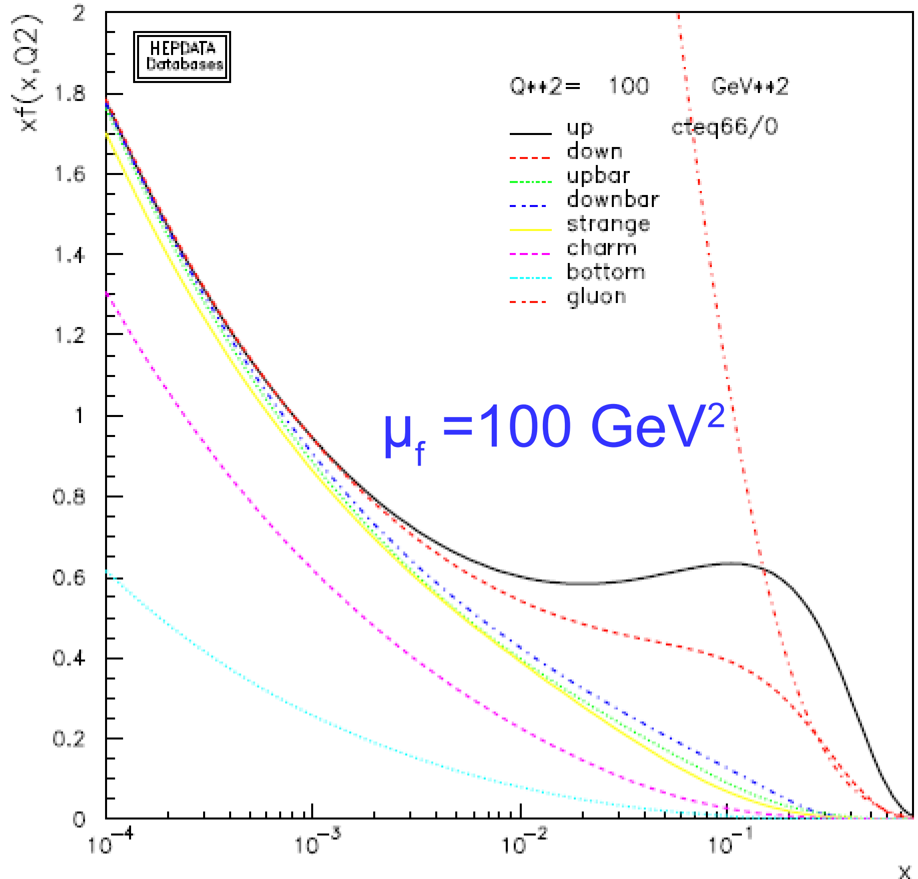


$$\sigma = \sum_{i,j} \int \sigma_{ij}(\hat{s}, \mu_f, \mu_r) \int_0^1 \int_0^1 f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \delta(\hat{s} - x_1 x_2 s)\, dx_1\, dx_2 d\hat{s}$$

partonic cross section and PDFs must be matched properly

Factorisation with PDFs





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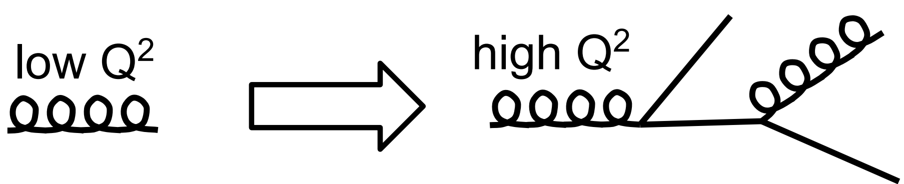

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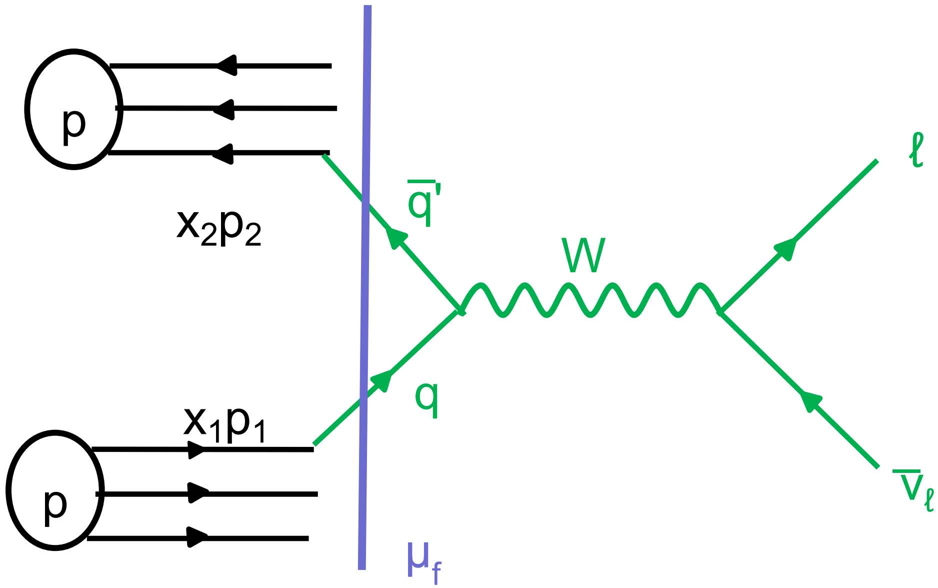
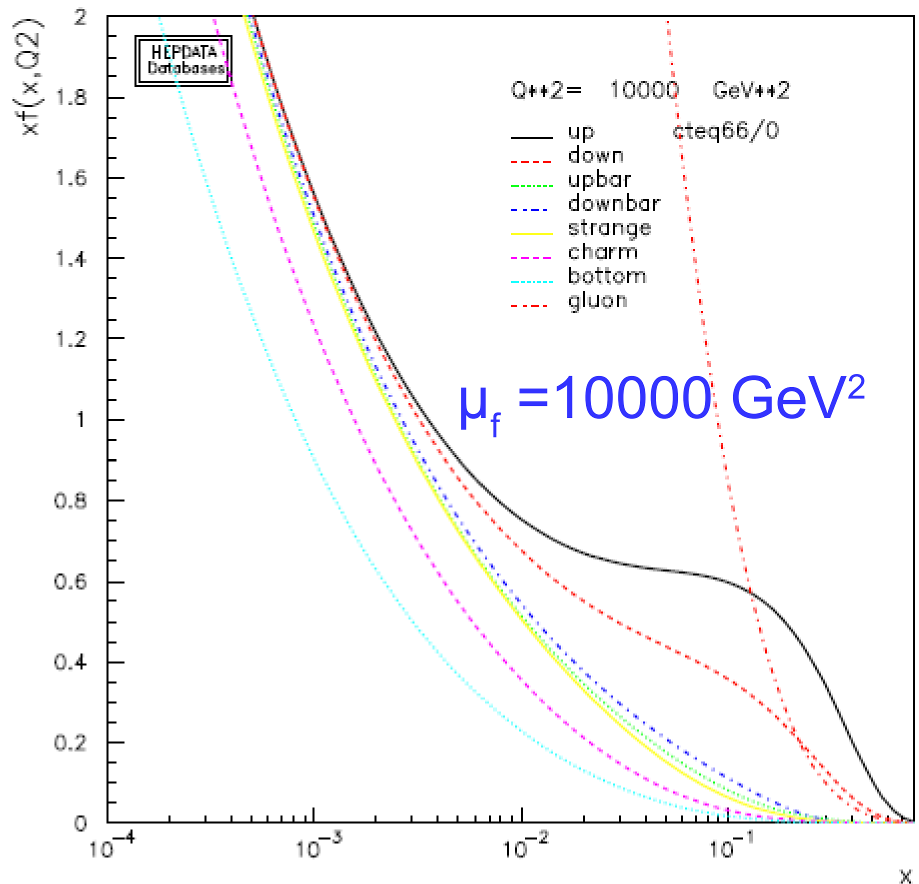
partonic cross section and PDFs must be matched properly

Factorisation with PDFs





- factorisation energy scale μ_f
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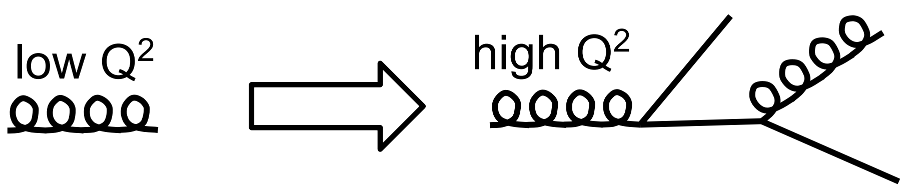


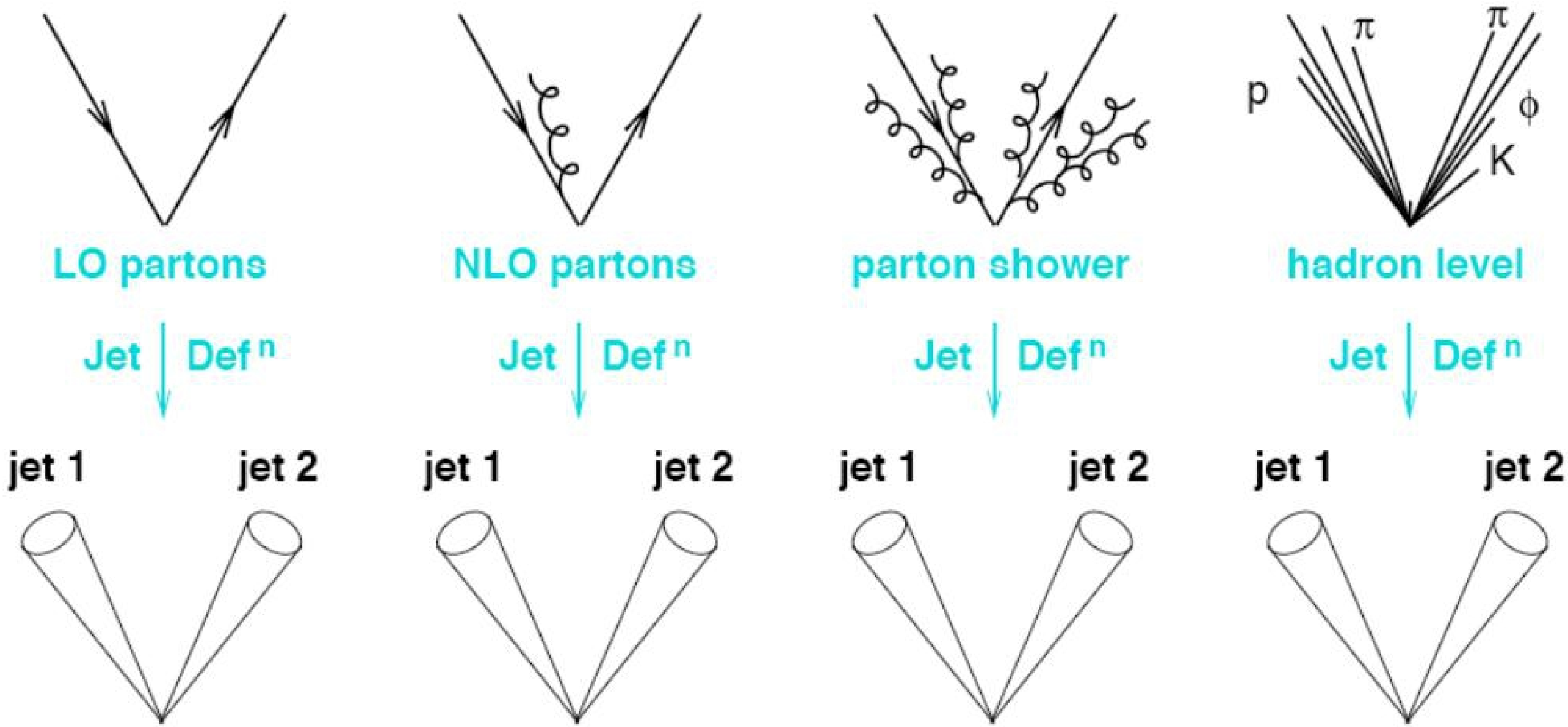
$$\sigma = \sum_{i,j} \int \sigma_{ij}(\hat{s}, \mu_f, \mu_r) \int_0^1 \int_0^1 f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \delta(\hat{s} - x_1 x_2 s)\, dx_1\, dx_2 d\hat{s}$$

partonic cross section and PDFs must be matched properly

How to Identify Jets?

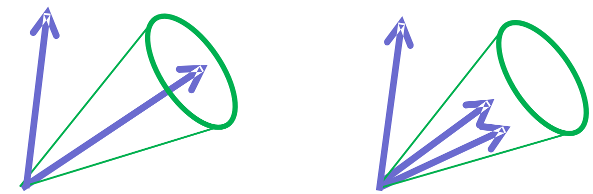
Jet algorithm should collect all particles in the same way for

- leading order partons
- partons + gluon emission
- parton shower (soft)
- hadrons → detector

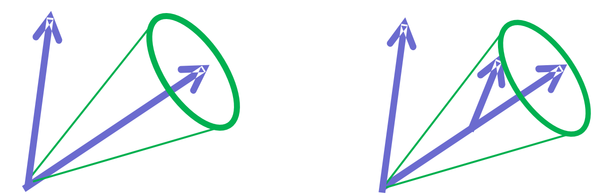


Jet Algorithms

- criteria:
  - collinear safe: finds the same jets given one particle or two collinear particles with same total energy:



  - infrared safe: finds the same jets even in the presence of soft radiation in the event:



- cone algorithms:
  - combine particles in cones of fixed size in $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
  - jet-reconstruction algorithm can be seeded from energy clusters
  - overlapping jet cones can be split or merged
  - not collinear safe, not infrared safe
- clustering algorithms:
  - define distance of particles in angular and p_T space
  - particles which are close to each other are combined to jets
  - can be constructed in a collinearly and infrared safe fashion

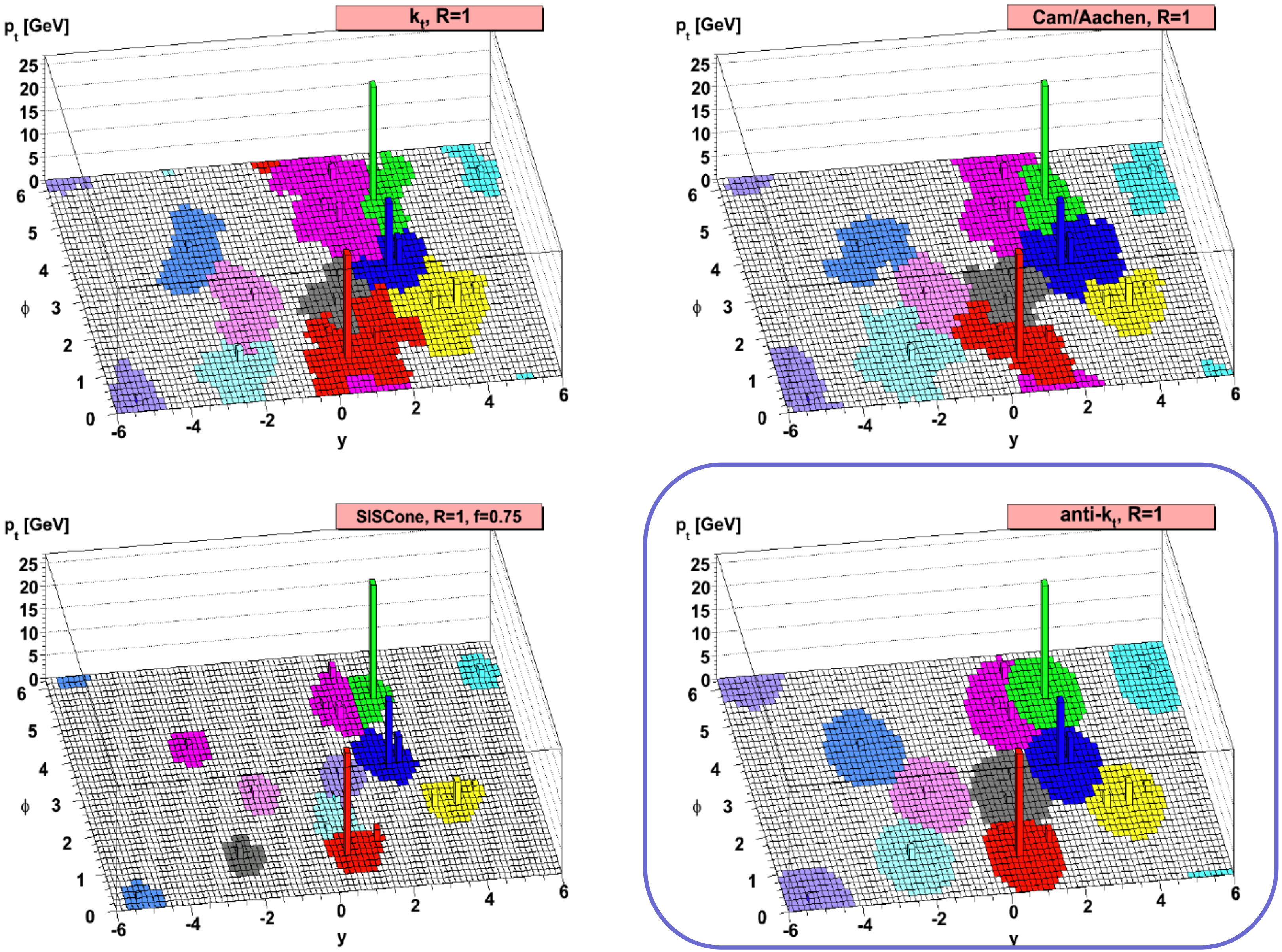
k_t-type jet algorithms

- a new name for a known quantity: $k_t = p_T$
- distance measure between two particles i and j: $d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$
- distance measure between object i and beam: $d_{iB} = k_{ti}^{2p}$,

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

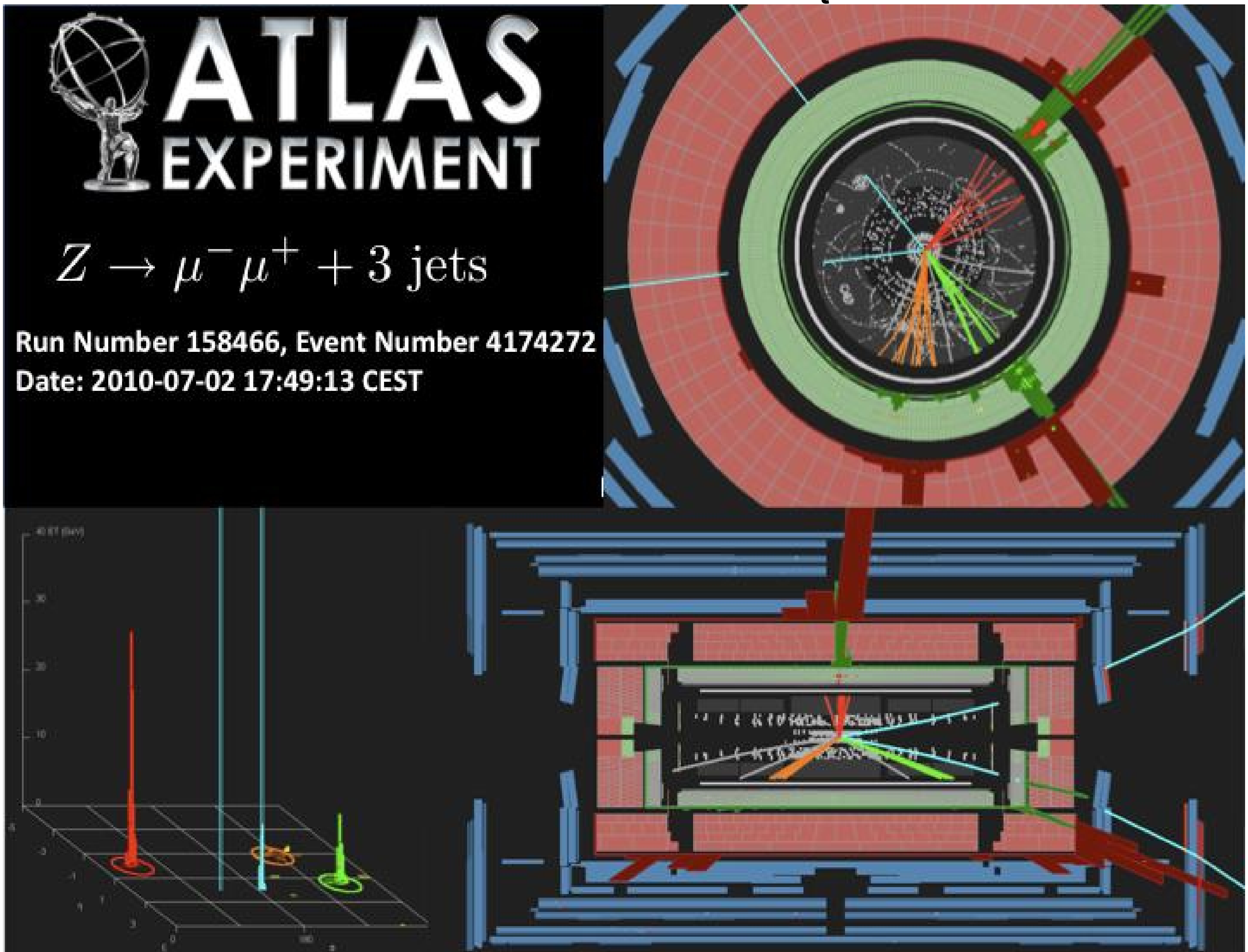
- iteratively combine all particles/objects for which d_{ij} gives the smallest value
- call it a jet and remove from the list if d_{iB} is smaller than the smallest d_{ij}
- R is a free parameter ≈ cone size
- p is a free parameter and fixes the exponent of the transverse momentum:
  - p = 0 ('Cambridge/Aachen algorithm')
  - p = +1 ('k_t algorithm')
  - p = -1 ('anti-k_t algorithm')

Jet algorithms



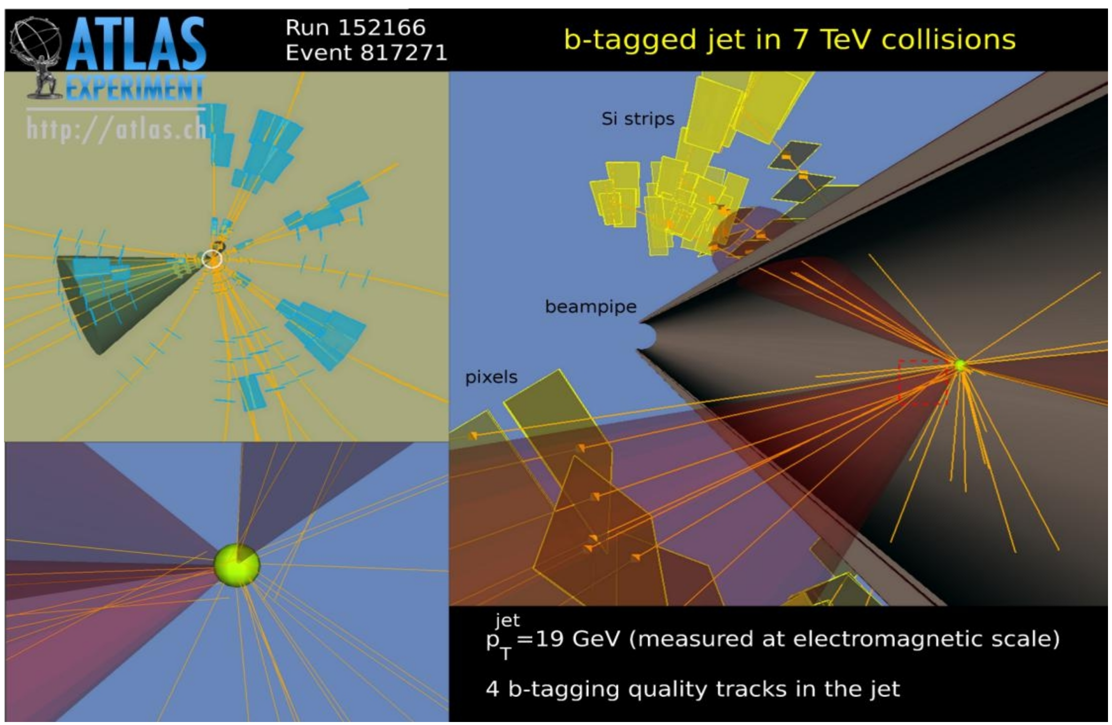
soft particles are merged to hard objects
before merged among themselves

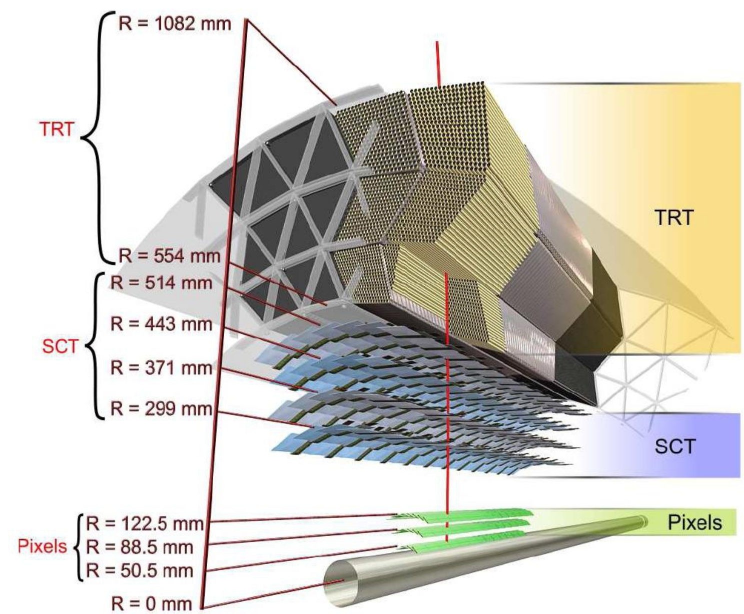
Event with anti-k_t jets



Detection of b-quark jets: 'b tagging'

- lifetime τ of B mesons 1.5-1.6 ps → $c\tau \approx 500$ μm, e.g. $|B^-\rangle=|b\bar{u}\rangle$
- weak decay into D meson + leptons/hadrons 88%, e.g. $|D^0\rangle=|c\bar{u}\rangle$
- detection of B decays and b-quark-jets by secondary vertex
- extrapolation of tracks to primary vertex and to secondary vertices



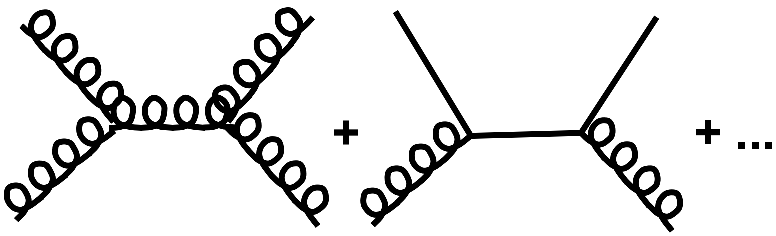


Example: distance between primary and seconday vertex is about 6 mm in the plane transverse to the beam axis

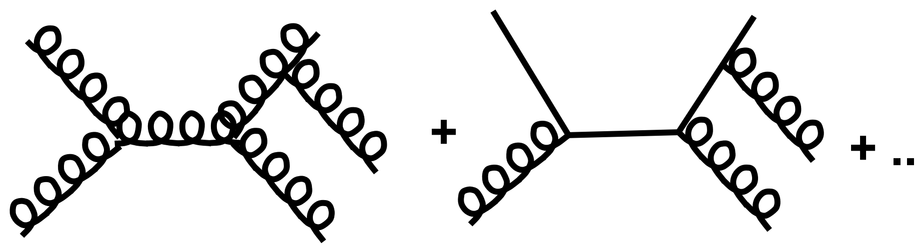
Monte Carlo for processes with jets

Two ways to introduce jet production in QCD calculation:

- matrix element at some fixed order in α_s,
  e.g. 2-jet at $O(\alpha_s^2)$



  3-jet at $O(\alpha_s^3)$



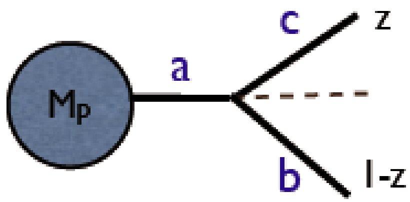
- there are methods to calculate n-gluon graphs, W/Z+ n-jet matrix elements, ...
- limited to energy range where perturbative calculation makes sense

  → soft gluon emission or collinear emission are treated by parton shower methods

  → the two approaches are then combined ('matching')

Parton shower

Matrix element for gluon emission q → q + g (or g → g + g) is strongly enhanced when particles are close to each other in phase space:



$$\frac{1}{(p_q+p_g)^2} \simeq \frac{1}{2E_qE_g(1-\cos\theta)} = \frac{1}{t}$$

soft and collinear divergence

- z = momentum fraction of emitted parton
- matrix element can be factorised:

splitting function

$$|M_{p+1}|^2 d\Phi_{p+1} \simeq |M_p|^2 d\Phi_p \frac{dt}{t}\frac{\alpha_S}{2\pi} P(z)dzd\phi$$

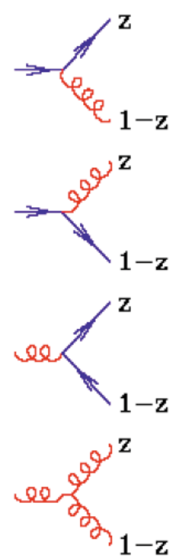
$$\hat{P}_{qq}(z) = C_F\left[\frac{1+z^2}{(1-z)}\right],$$

$$\hat{P}_{gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right],$$

$$\hat{P}_{qg}(z) = T_R\left[z^2+(1-z)^2\right],$$

$$\hat{P}_{gg}(z) = C_A\left[\frac{z}{(1-z)}+\frac{1-z}{z}+z(1-z)\right]$$

$$C_F = \frac{4}{3}, C_A = 3, T_R = \frac{1}{2}.$$



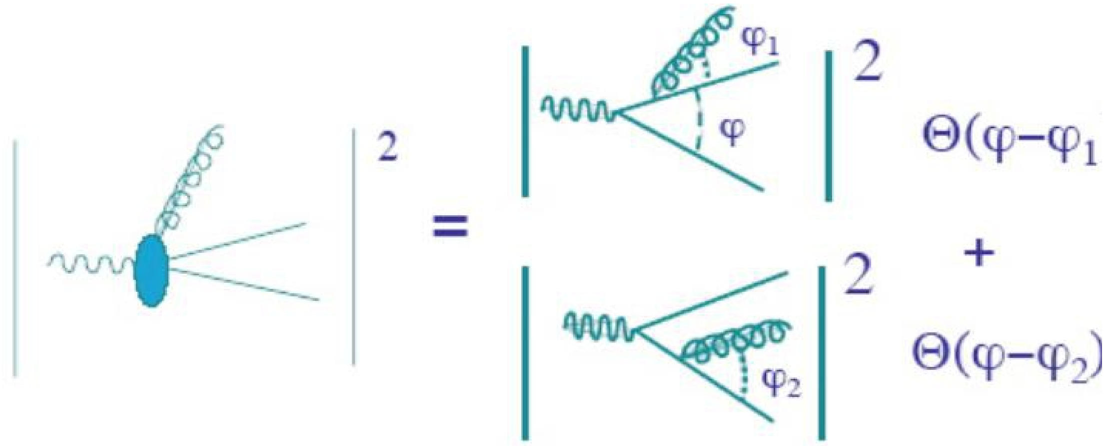
- gluons radiate most
- emission process can be iterated
- non-branching probability can be calculated (Sudakov factor)

Parton shower

- Radiation happens only for angles smaller than the opening angle of the colour-connected partons

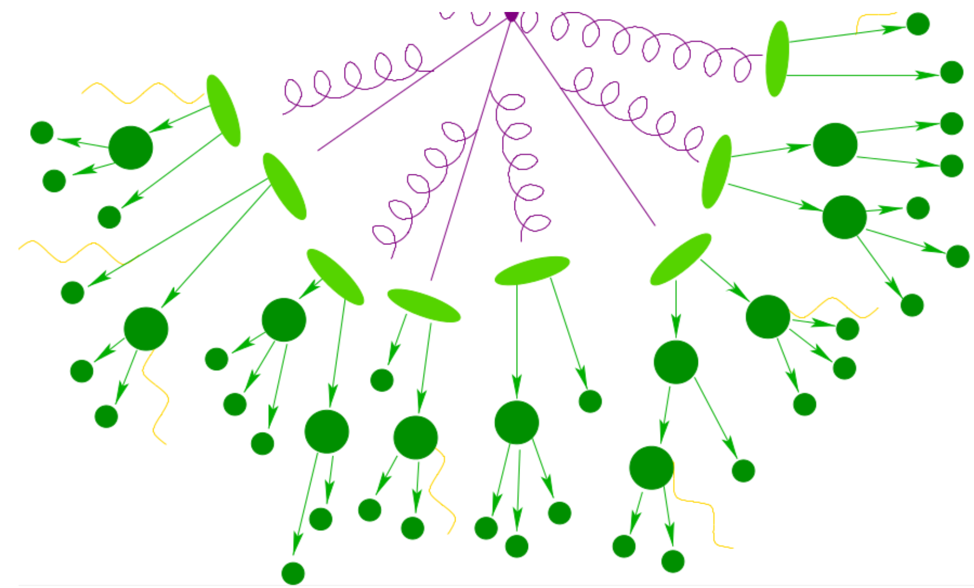
  → angular ordering

  → collimated jets

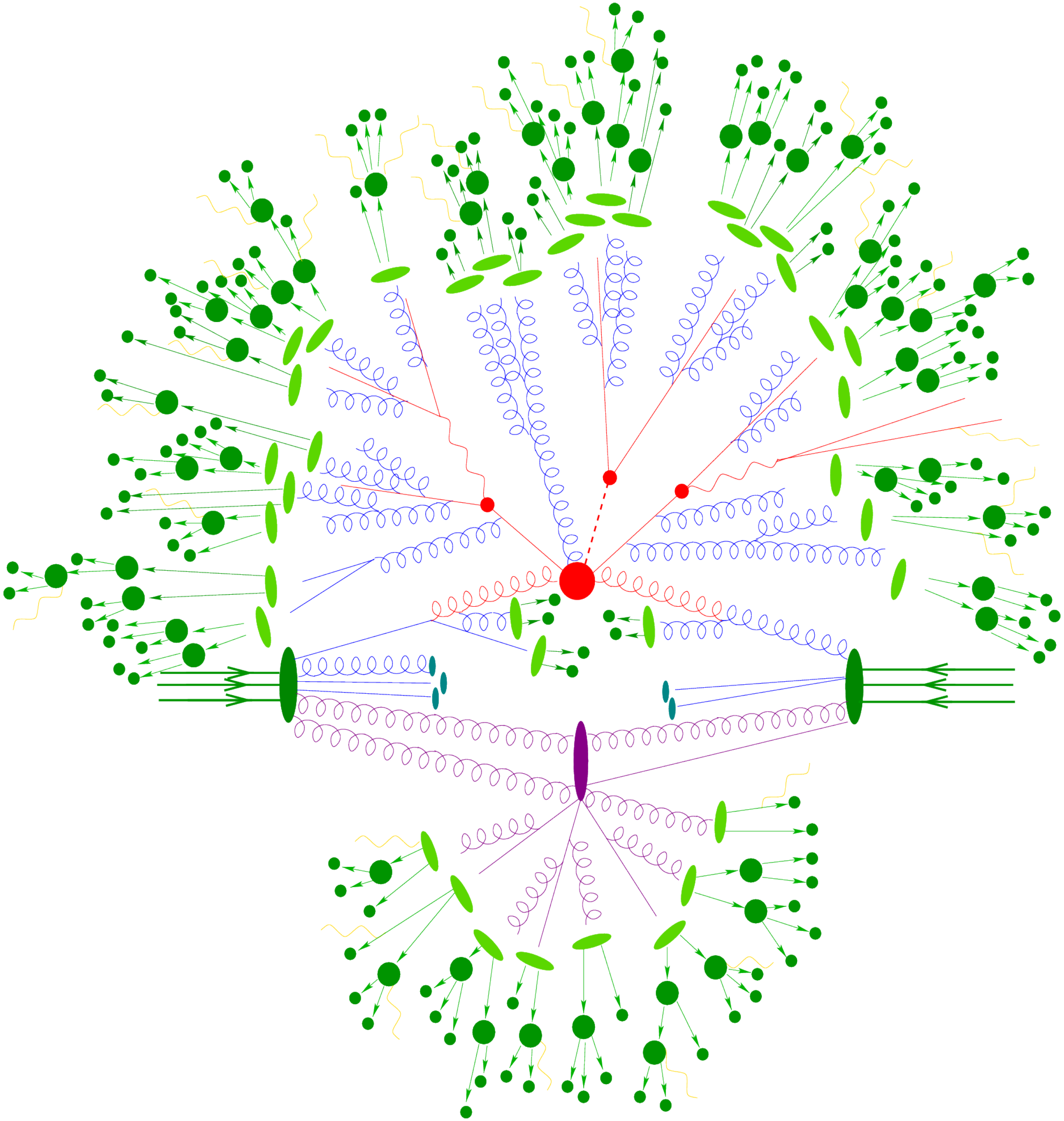


- emission stops at cut-off energy
- it is a free parameter (to be tuned)
- bound states can be formed

  → hadronisation

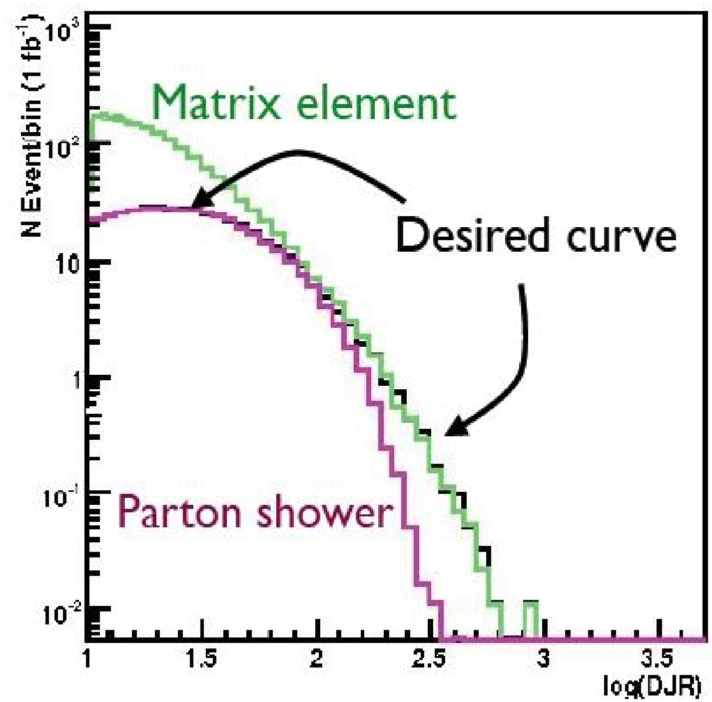


The full picture



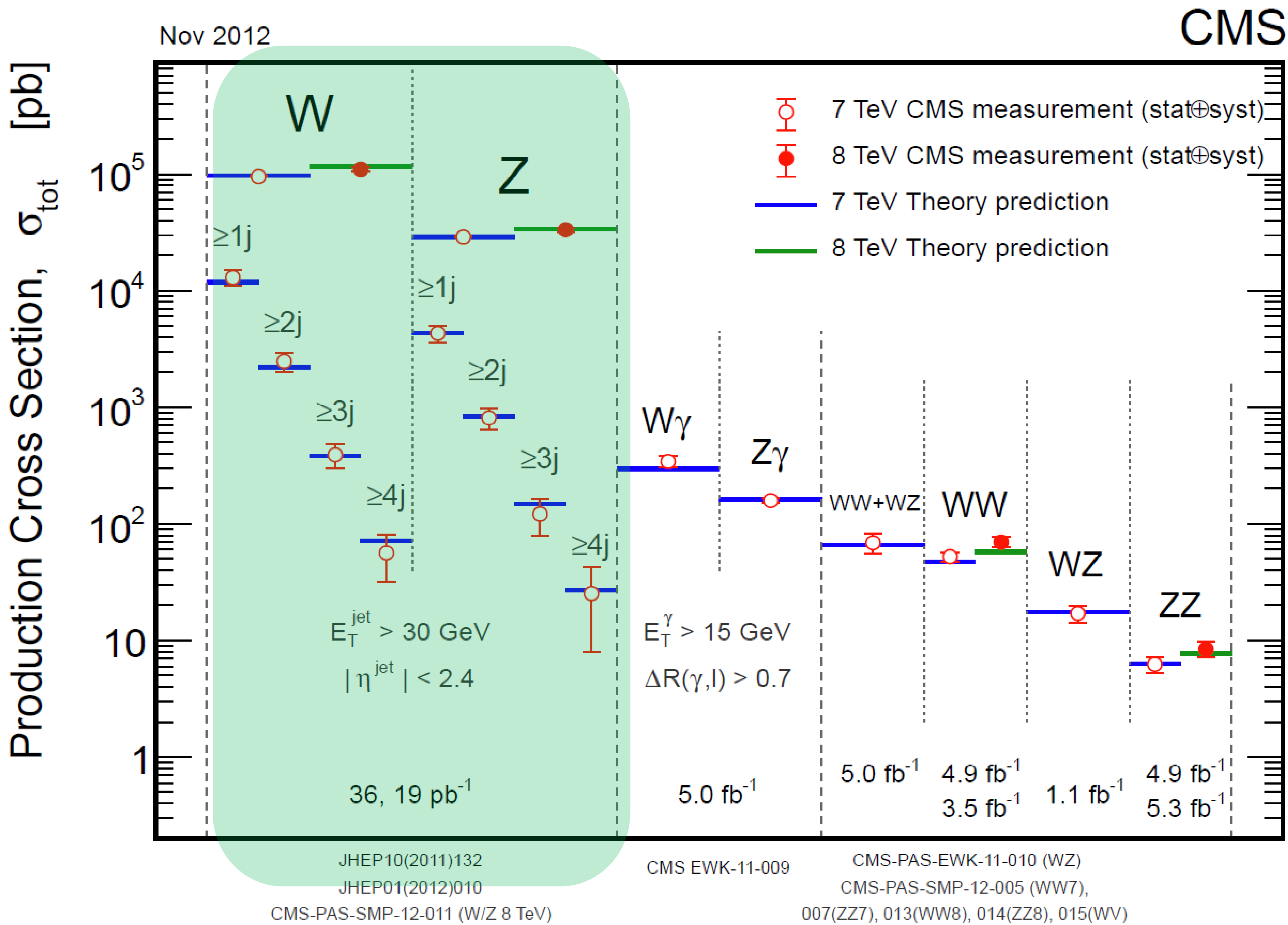
Proper matching/merging of parton shower and matrix element done by:

- Sherpa
- MC@NLO
- POWHEG
- ....

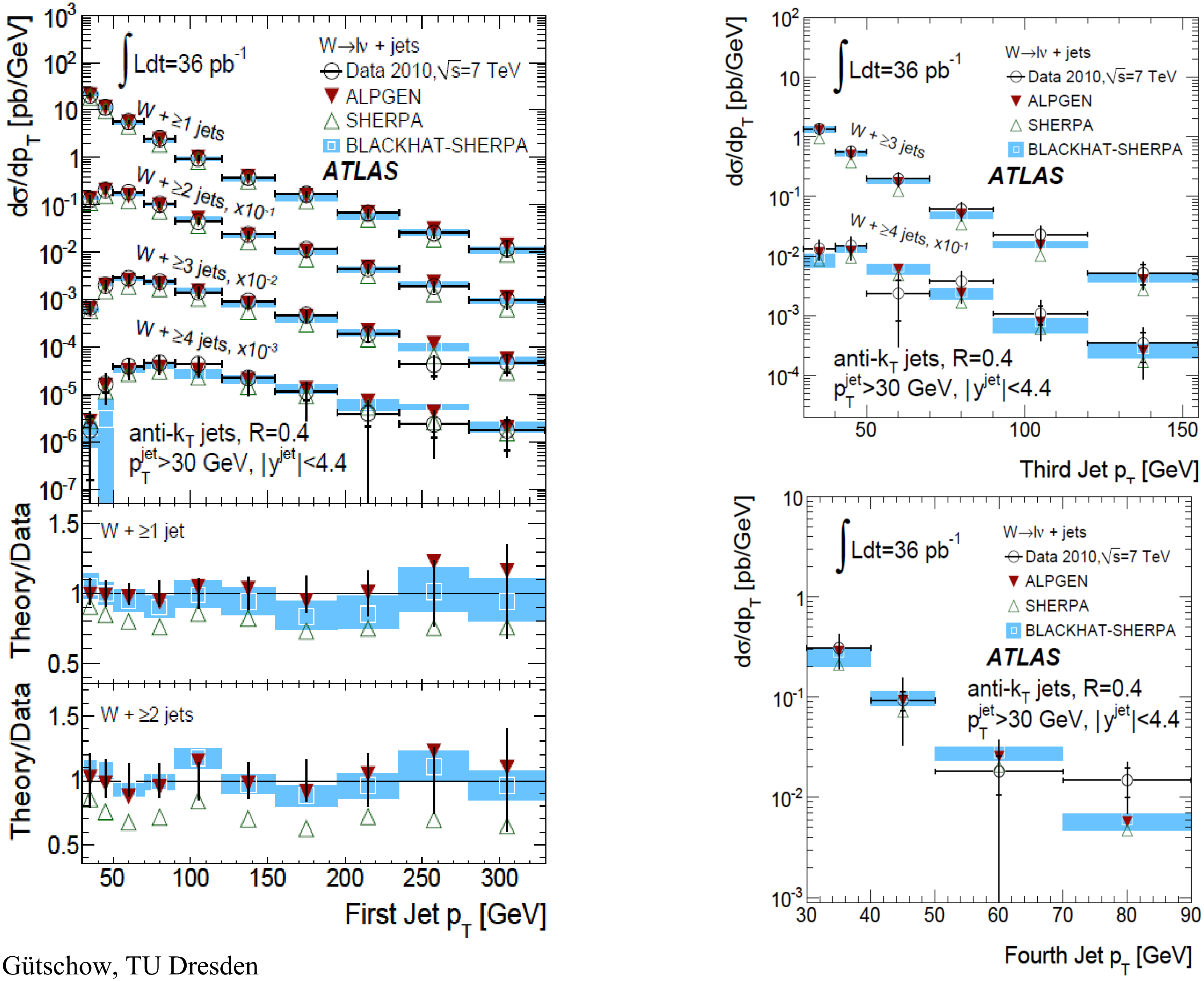


double counting of emissions is avoided/corrected for

Overview: W/Z + n jets production



Jet p_T spectra in W + n jet channels

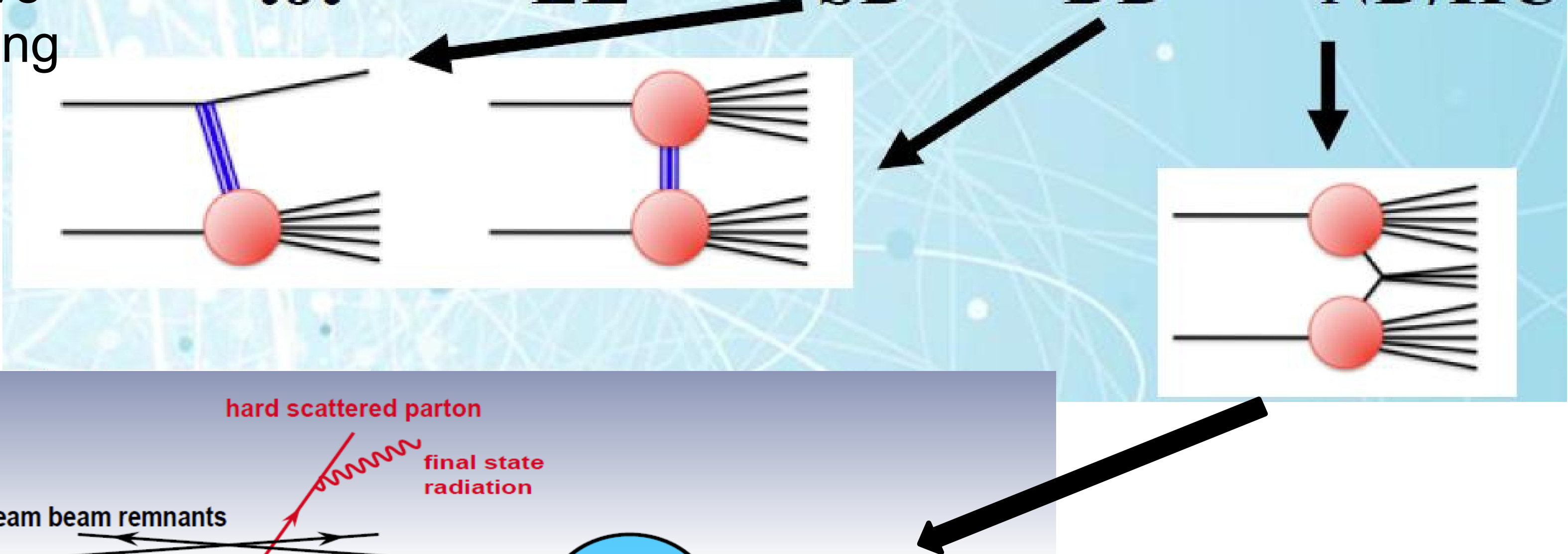


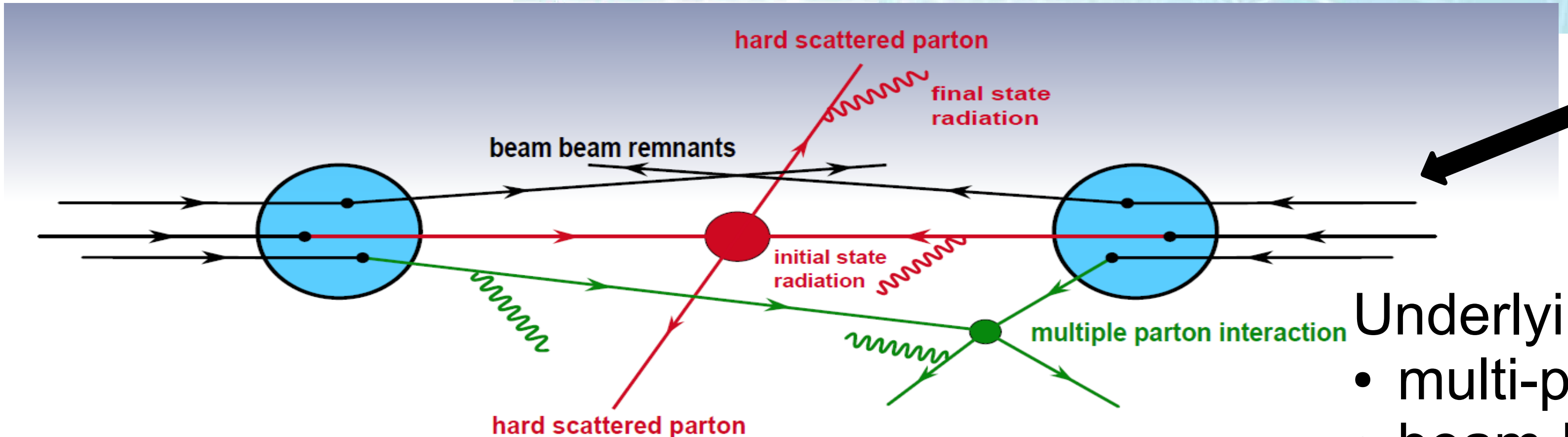
Soft QCD

- Categories of pp cross section:
  - EL = elastic
  - SD = single diffractive
  - DD = double diffractive
  - ND = non-diffractive
  - HC = hard scattering component

- minimum bias trigger accepts large fraction of inelastic cross section

$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND/HC}$$

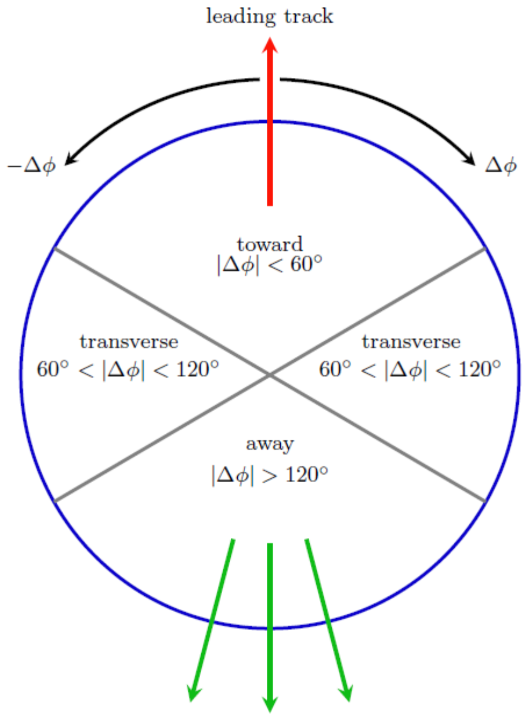


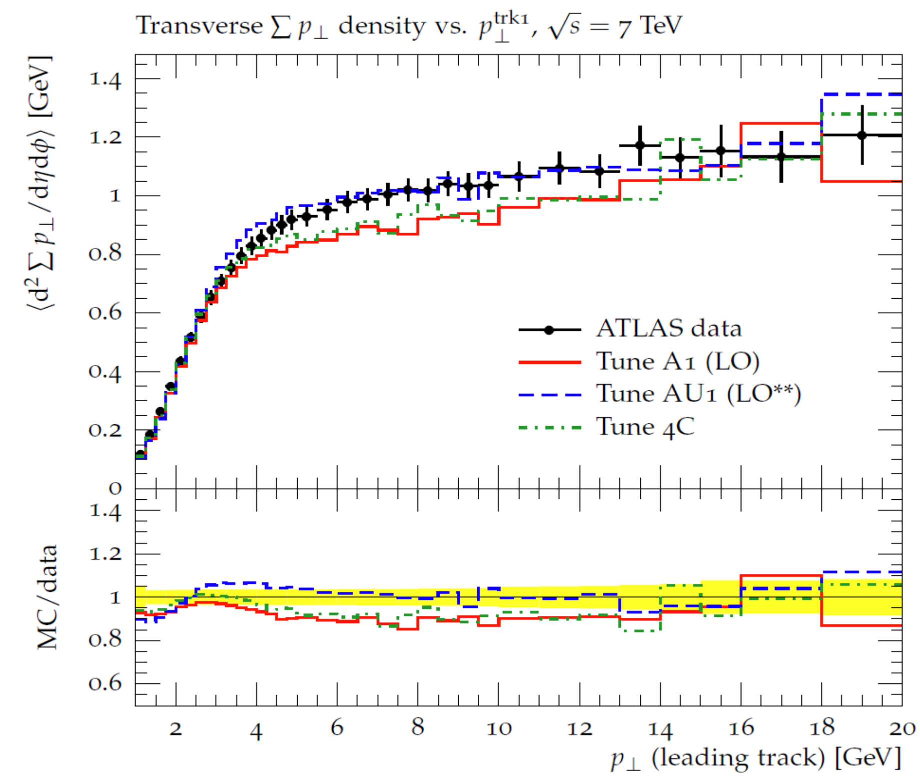


Underlying event
- multi-parton interaction
- beam-beam remnants
- initial/final state radiation

Underlying event measurement

- tagging of the hard scattering process, e.g. leading track with highest p_T
- divide azimuthal plane into 'toward', 'away', 'transverse' region (with respect to highest p_T track)
- transverse region particularly sensitive to underlying event activity

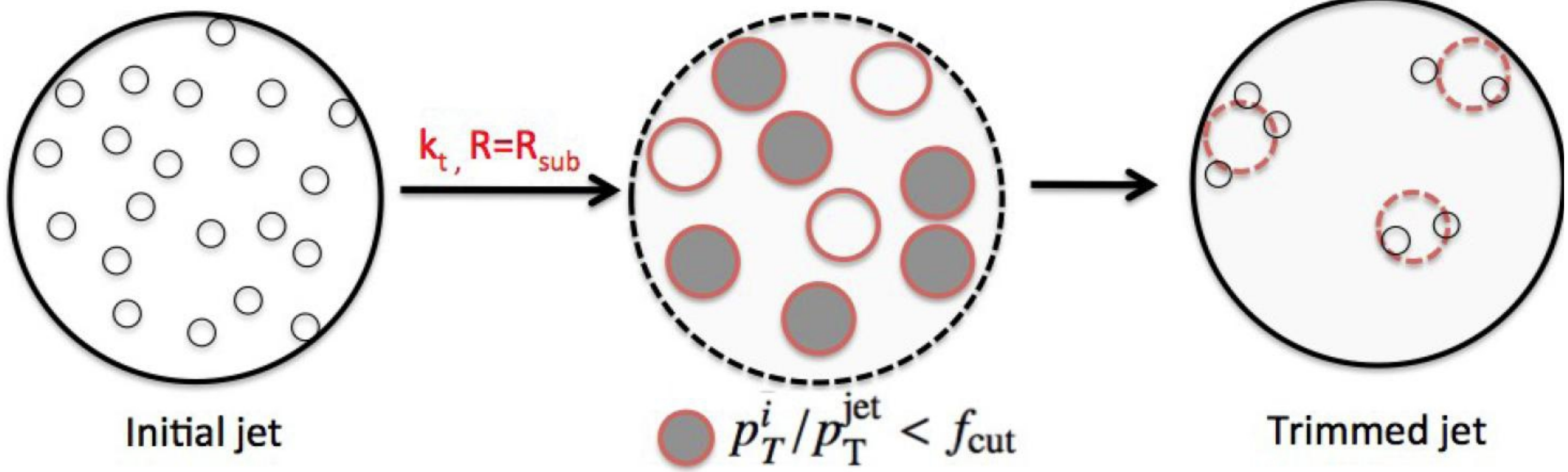




- use data to tune Monte Carlo predictions
- important ingredient for other measurements (recall: jet rapidity gaps,...)

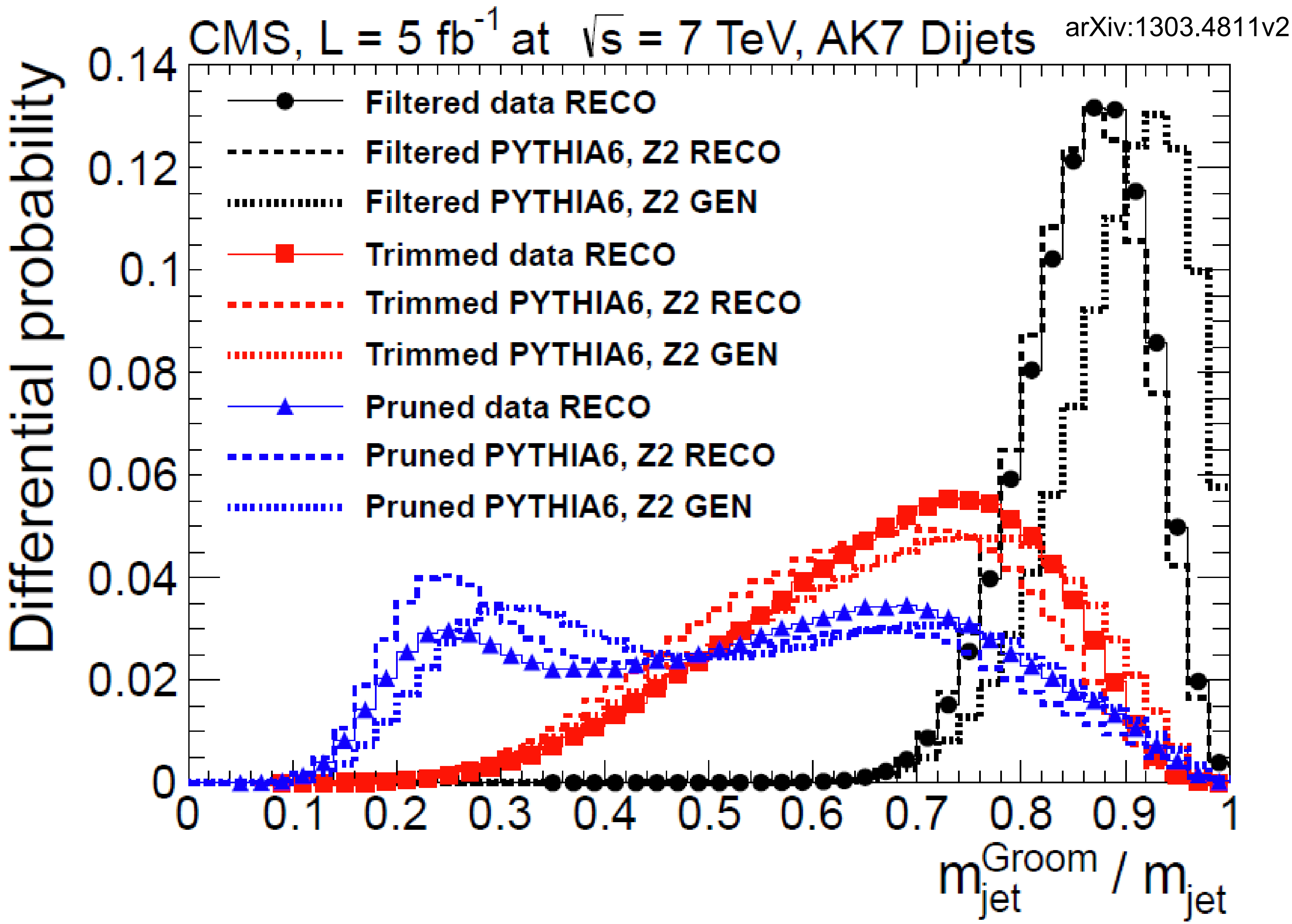
Jet substructure

- particles from underlying event and pileup are overlaid to hadronic jets
- How to remove these particles from interesting physics, e.g. heavy particle decays like $H \rightarrow b\bar{b}$?
- Example: trimming
  - create jet substructures with resolution parameter R_{sub}
  - remove substructures with relative p_T cut
  - remaining subjets are the trimmed jets

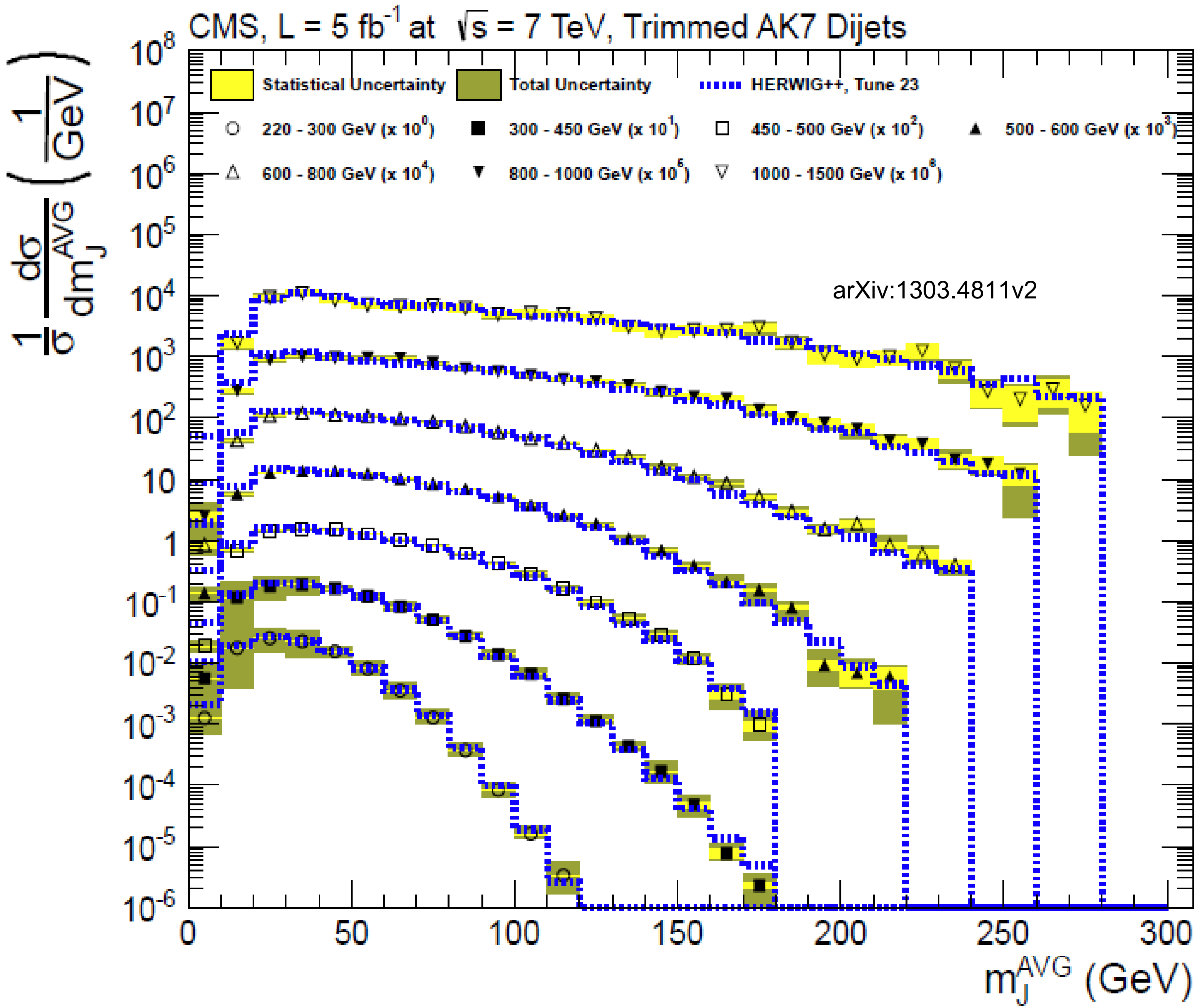


- other methods: pruning, filtering, mass drop, ...

Jet grooming/trimming/pruning



Jet grooming/trimming/pruning



Summary of QCD at LHC

- QCD is involved in all process at the LHC
  - protons and their partons are strongly interacting particles
- understanding hard and soft QCD effects is important for precise measurements (M_W) or searches for rare processes
- remember the basic picture: