Introduction to particle physics: experimental part

Making predictions for hadron colliders

- From Feynman diagrams to cross-sections
- From cross-sections to events

First data at LHC

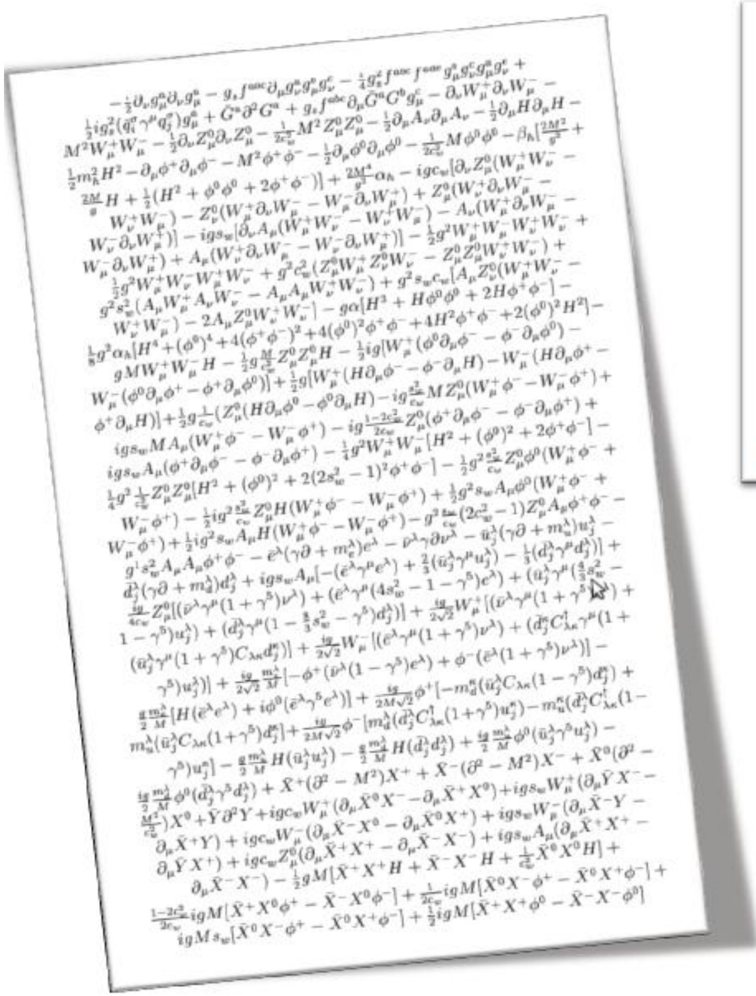
Standard Model measurements

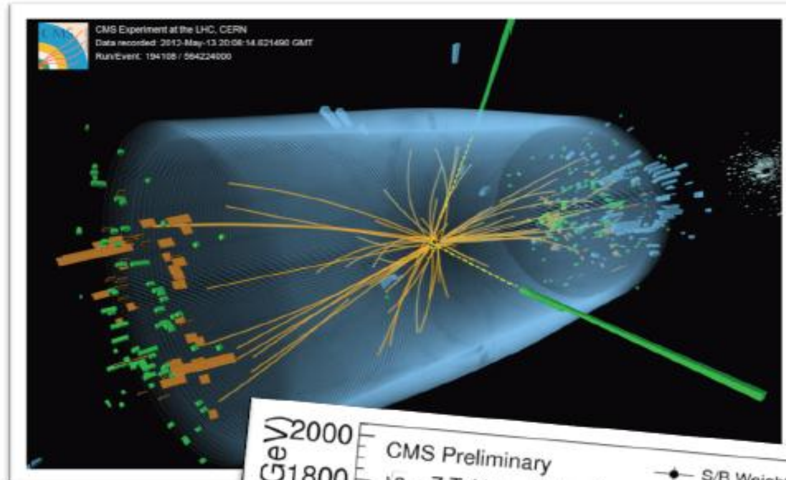
- Soft and hard QCD
- W and Z bosons
- Prompt photons
- b-jets
- Top quarks

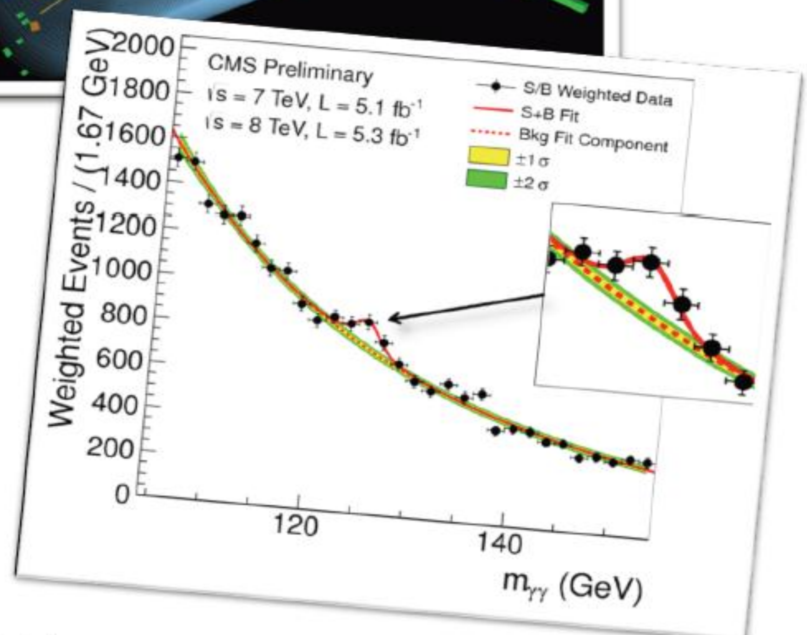
Parts based in part on M. Seymour lecture at CERN Summer School, 2018

Prof. dr hab. Elżbieta Richter-Wąs

Experiment = probing theories with data

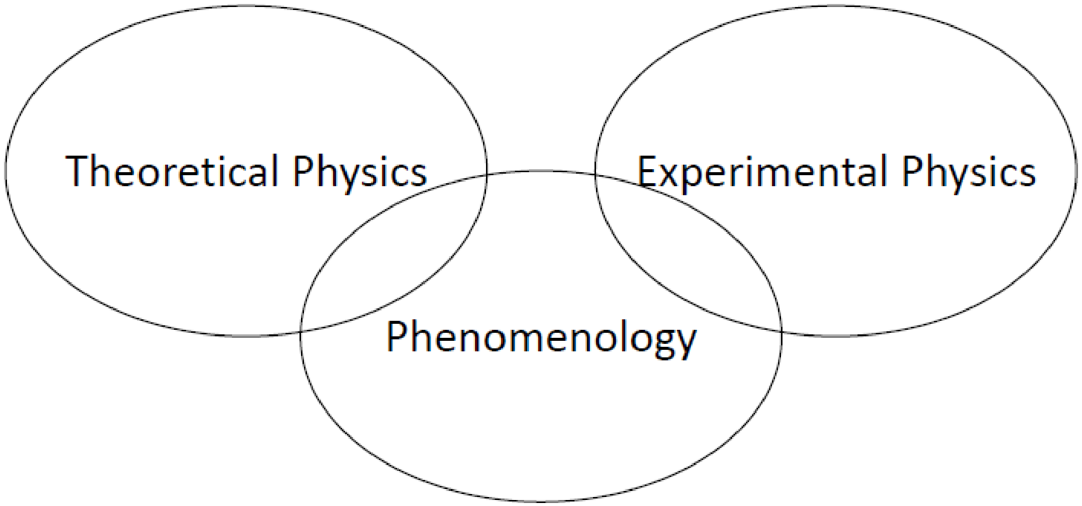






Making predictions for hadron colliders

Phenomenology



Making predictions for hadron colliders

Calculating Event Rates

$$N = \mathcal{L}\,\sigma$$

- N: Number of events
- $\mathcal{L}$: Integrated Luminosity
- σ: Cross section

Making predictions for hadron colliders

Calculating Cross Sections

$$\mathrm{d}\sigma = \frac{1}{F}\,|\mathcal{M}|^2\,\mathrm{d}LIPS$$

Flux factor

$= 2s = 4E_1E_2$

(Quantum mechanical) amplitude squared

Lorentz Invariant Phase Space

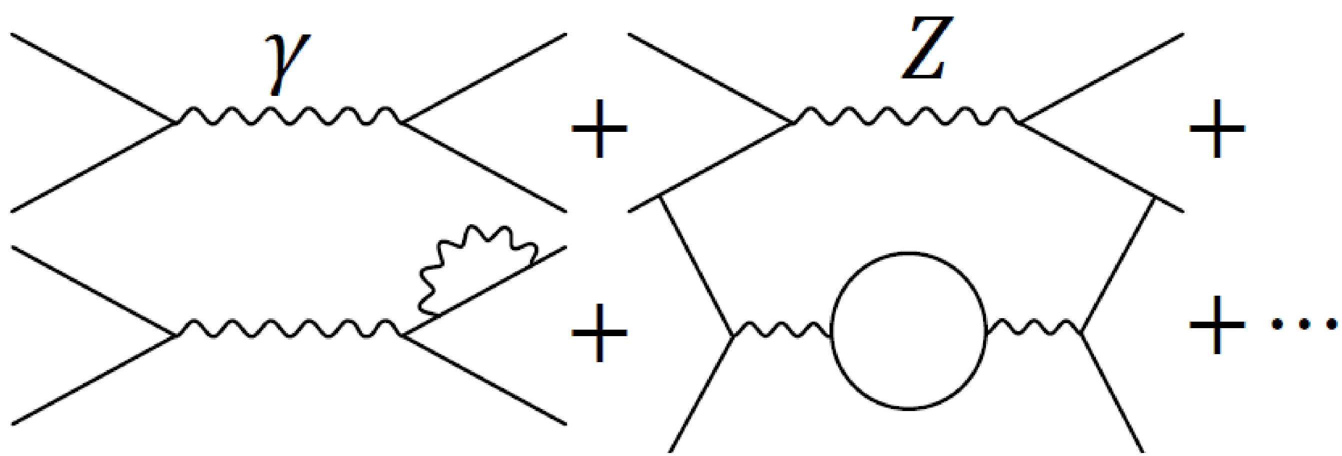
$$= \frac{\mathrm{d}^4 p_i}{(2\pi)^4}(2\pi)\delta\left(p_i^2 - m_i^2\right)\frac{\mathrm{d}^4 p_j}{(2\pi)^4}(2\pi)\delta\left(p_j^2 - m_j^2\right)\ldots\,(2\pi)^4\delta(p_1 + p_2 - p_i - p_j - \ldots$$

Making predictions for hadron colliders

Calculating Cross Sections

$$\mathrm{d}\sigma = \frac{1}{F}\,|\mathcal{M}|^2\,\mathrm{d}LIPS$$

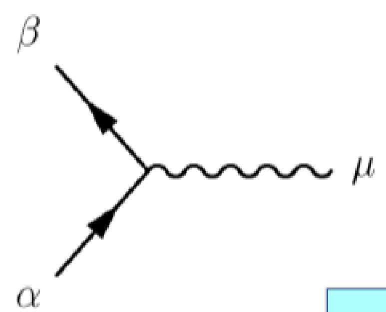
$\mathcal{M} =$



Feynman Rules

$$\rightarrow \left(\frac{i}{\not{p} - m + i\varepsilon}\right)_{\beta\alpha}$$

$$\rightarrow \frac{-i\eta_{\mu\nu}}{p^2 + i\varepsilon}$$



$$\rightarrow -ie\gamma^{\mu}_{\beta\alpha}(2\pi)^4\delta^{(4)}(p_1 + p_2 + p_3).$$

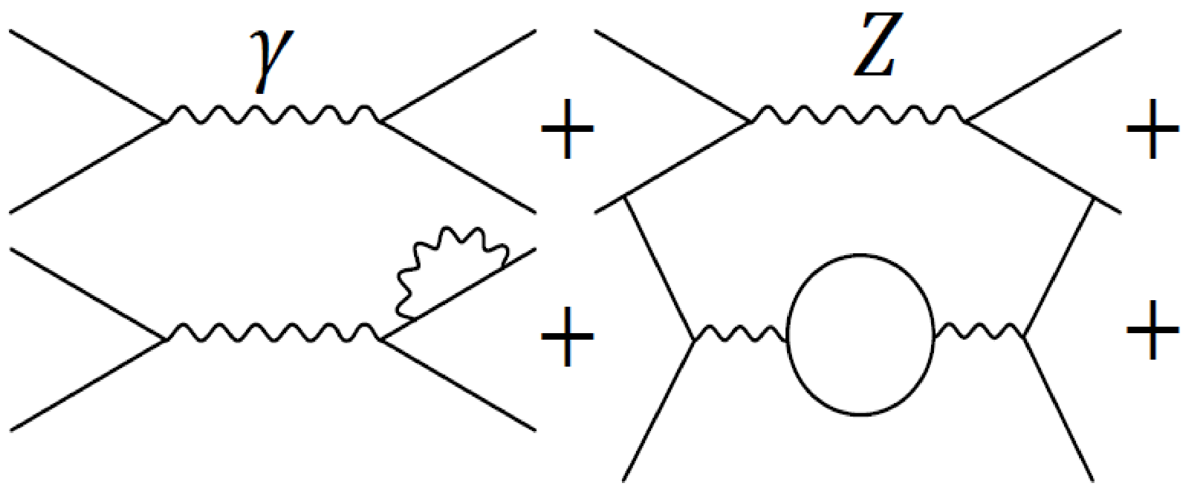
Elementary charge

$$e = \sqrt{4\pi\alpha} \quad \alpha \approx {}^{1}\!/_{137}$$

Making predictions for hadron colliders

Tree Diagrams as Leading Order of Expansion in α

$\mathcal{M} =$



$\mathcal{O}(\alpha)$

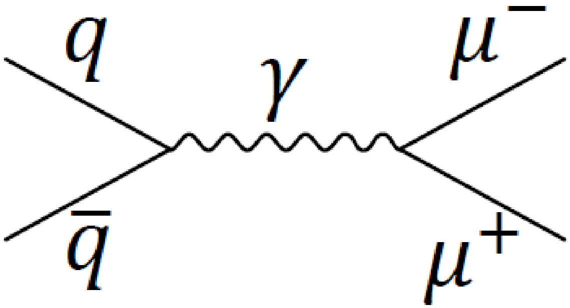
$\mathcal{O}(\alpha^2)$

$\alpha \approx {}^{1}/_{137}$ but $\alpha_s \approx 0.1$

$\Rightarrow$ QCD corrections important

Making predictions for hadron colliders

Example: The Drell-Yan process ($pp \rightarrow \mu^+\mu^-$)

$\mathcal{M} =$ 

$$\Rightarrow |\mathcal{M}|^2 \propto e_q^2 \alpha^2 \frac{t^2 + u^2}{s^2} \propto e_q^2 \alpha^2 (1 + \cos^2\theta)$$

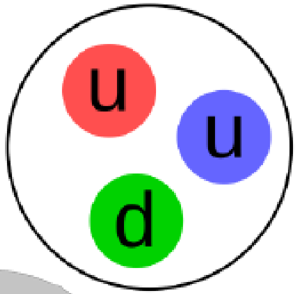
$$\Rightarrow \sigma = \frac{4\pi\alpha^2}{9Q^2} e_q^2$$

$\left(s = Q^2 = (p_q + p_{\bar{q}})^2\right)$

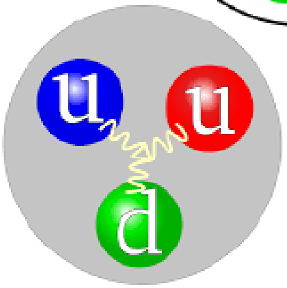
Making predictions for hadron colliders

Proton structure

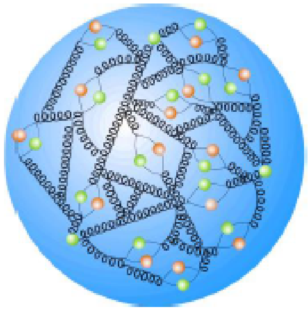
- Proton = uud ?



- Held together by gluons?



- Quantum Field Theory: gluons can create $q\bar{q}$ pairs



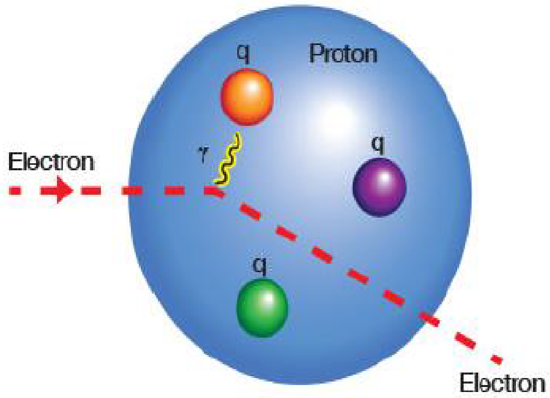
- Proton can interact through any of its partons

Making predictions for hadron colliders

Proton structure: parton distribution functions

- How is the proton's energy shared between its parton constituents?
- Measure in deep inelastic electron scattering
- Quantify by *parton distribution function*

  $f_i(x)\mathrm{d}x$ = probability that parton of type i is found with fraction of proton's momentum between x and $x + \mathrm{d}x$

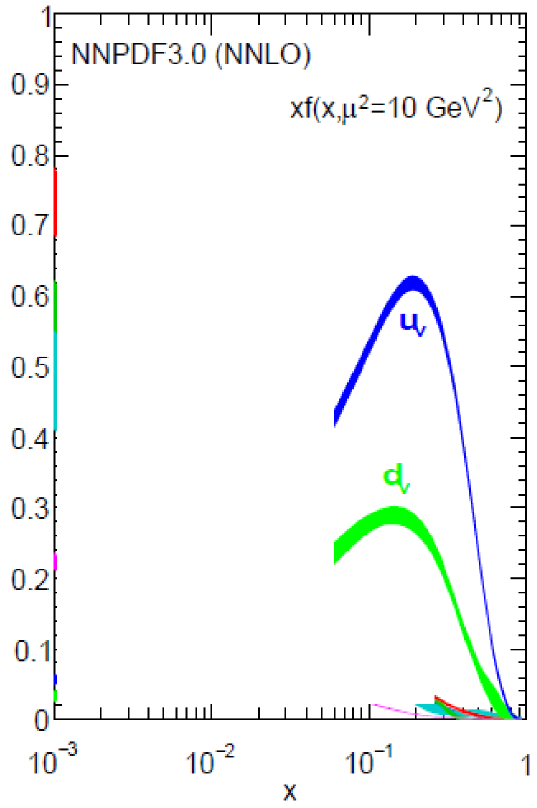


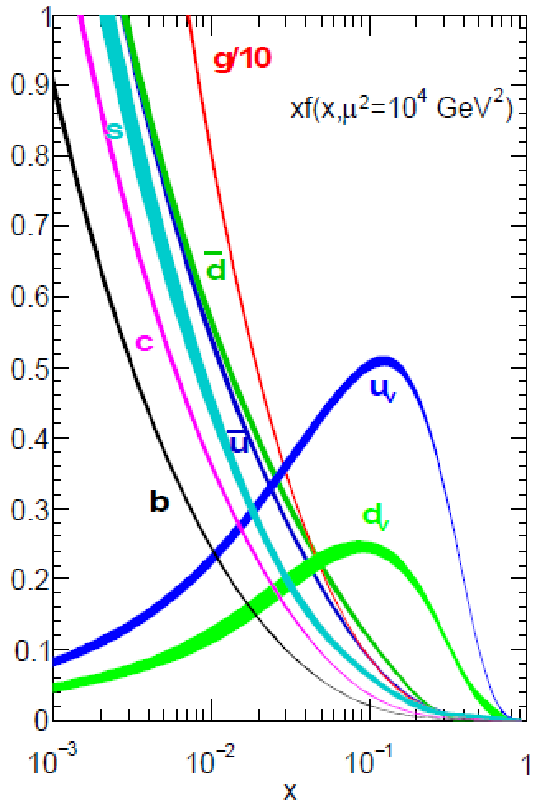
- But how long do those quantum fluctuations live?

⇒ PDFs depend on the momentum scale of the probe $f_i(x, Q^2)\mathrm{d}x$

Making predictions for hadron colliders

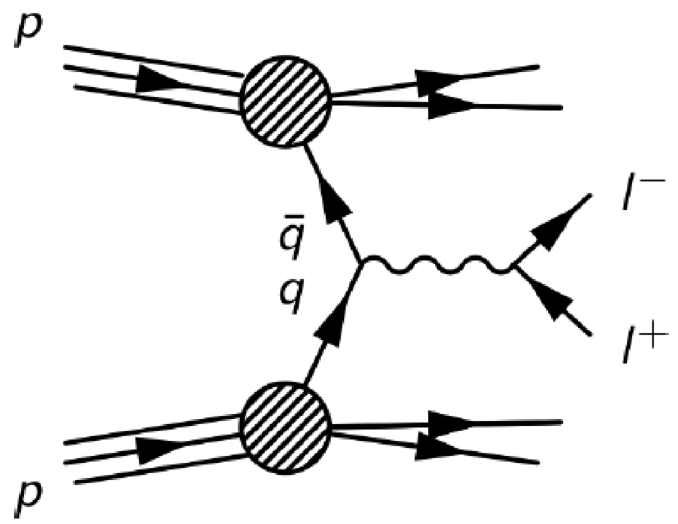
Proton structure: parton distribution functions





Making predictions for hadron colliders

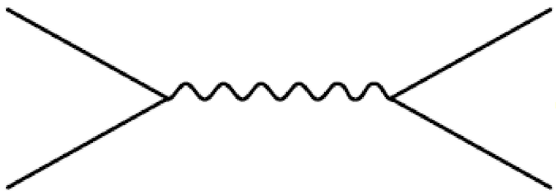
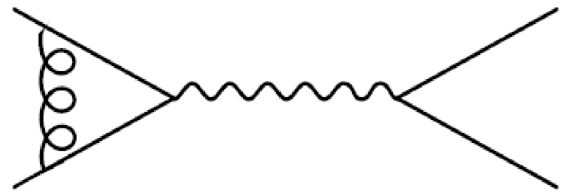
The Drell-Yan process ($pp \to \mu^+\mu^-$)



$$\frac{d\sigma}{dQ^2} = \sum_q \int dx_1\, f_q(x_1, Q^2)\, dx_2\, f_{\bar{q}}(x_2, Q^2) \frac{4\pi\alpha^2}{9Q^2} e_q^2\, \delta(x_1 x_2 s - Q^2)$$

Making predictions for hadron colliders

Loop Diagrams as Higher Order Corrections

$\mathcal{M} =$  $+$  $+ \cdots$

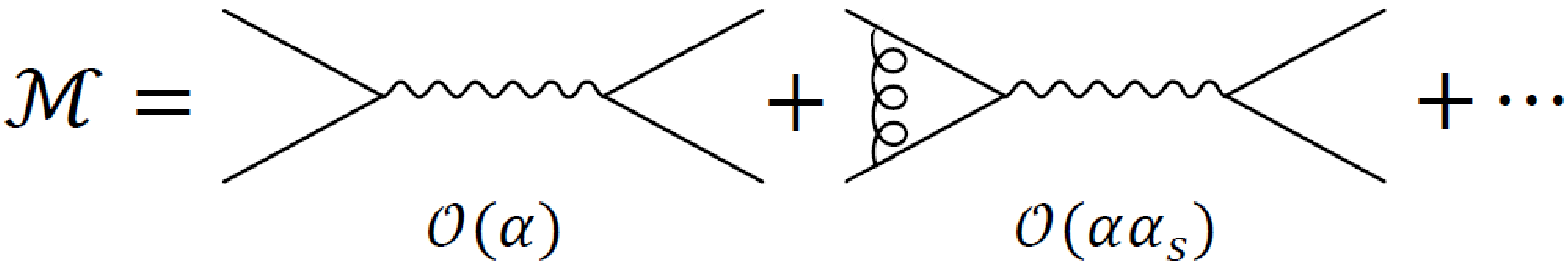
$\mathcal{O}(\alpha)$ $\quad\quad$ $\mathcal{O}(\alpha\alpha_s)$

$$|\mathcal{M}|^2 = |\mathcal{M}_0|^2 + 2\Re(\mathcal{M}_0^*\mathcal{M}_1) + |\mathcal{M}_1|^2 + \cdots$$

$\mathcal{O}(\alpha^2)$ $\quad\quad$ $\mathcal{O}(\alpha^2\alpha_s)$

- Quantum mechanics: sum over unobserved quantum numbers
  = integrate over gluon momenta

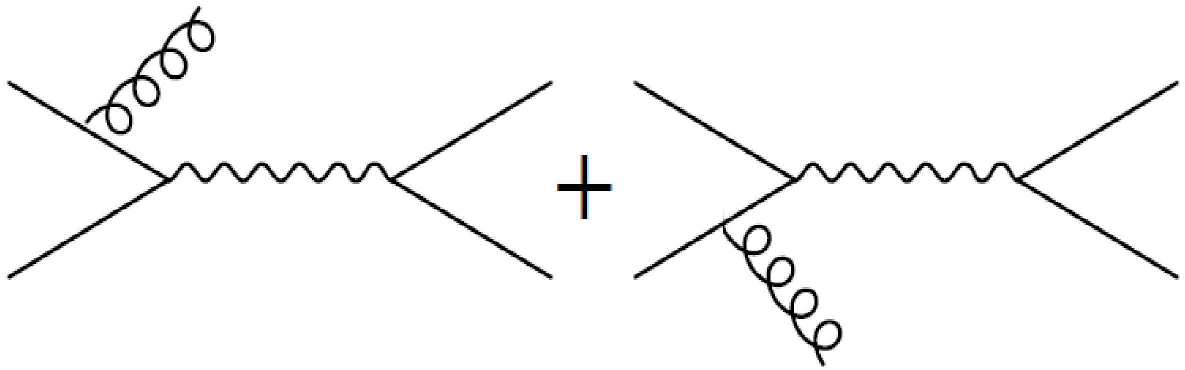
Loop Diagrams as Higher Order Corrections



- Gluon momentum integral is divergent! (= *minus* infinity)
- Divergence comes from:
    - Momentum = 0
    - Momentum = parallel to quark or antiquark

Gluon Emission as Higher Order Correction

$\mathcal{M} =$



$\mathcal{O}(\alpha\sqrt{\alpha_s})$

- Gluon emission describes a different process $(q\bar{q} \rightarrow \mu^+\mu^- g)$
- But if we are only interested in the total cross section for Drell-Yan pairs, must integrate over gluon momenta
- Divergent from momentum = 0 or parallel to quark or antiquark
- Cancels loop divergence

Next-to-Leading Order (NLO) cross section

- $\sigma_{NLO} = \sigma_{tree} + \sigma_{loop} + \sigma_{emission}$
- σ_{loop} and $\sigma_{emission}$ each divergent
  - must regularize and expose singularities of each
  - *Subtraction algorithms*
- Fully automated,
  - e.g. in Madgraph/aMC@NLO, MCFM, Sherpa, Herwig ...

Making predictions for hadron colliders

From Feynman Diagrams to Cross Sections

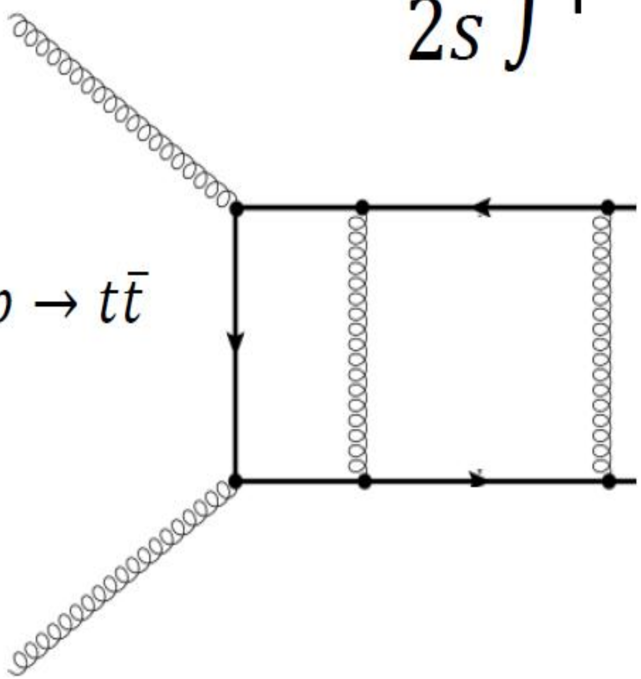
- Major part of phenomenology = calculating cross sections
- LO = write down all tree diagrams, integrate phase space numerically
- Convolute with parton distribution functions (fitted to data)
- NLO = one-loop diagrams, one-emission processes
  - Extract singularities from integrals, integrate analytically
  - Integrate remainders numerically
- NNLO = two-loop diagrams, one-emission at one-loop, and two emissions
- But LHC events contain *hundreds* of additional particles…

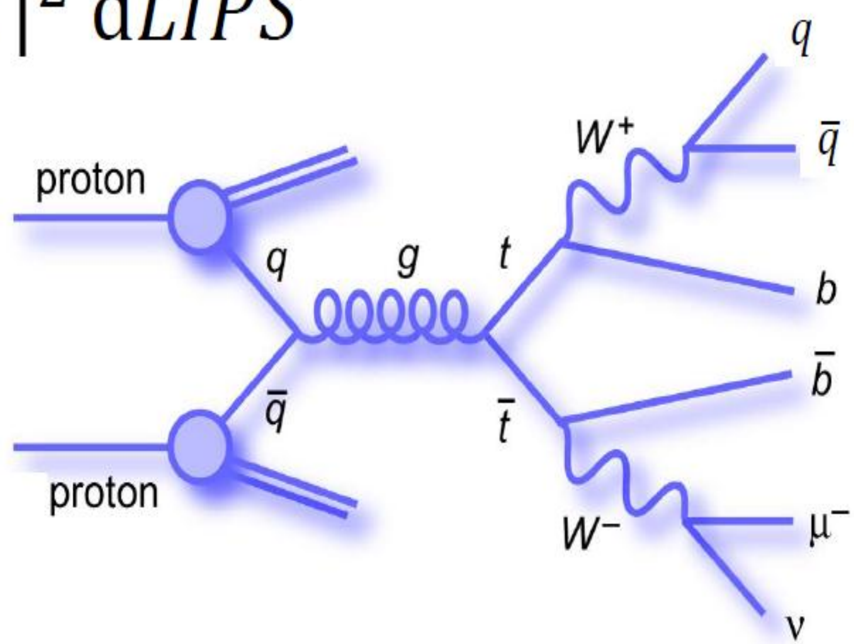
Making predictions for hadron colliders

Cross Sections

$$\sigma = \frac{1}{2s}\int |\mathcal{M}|^2 \, \mathrm{d}LIPS$$

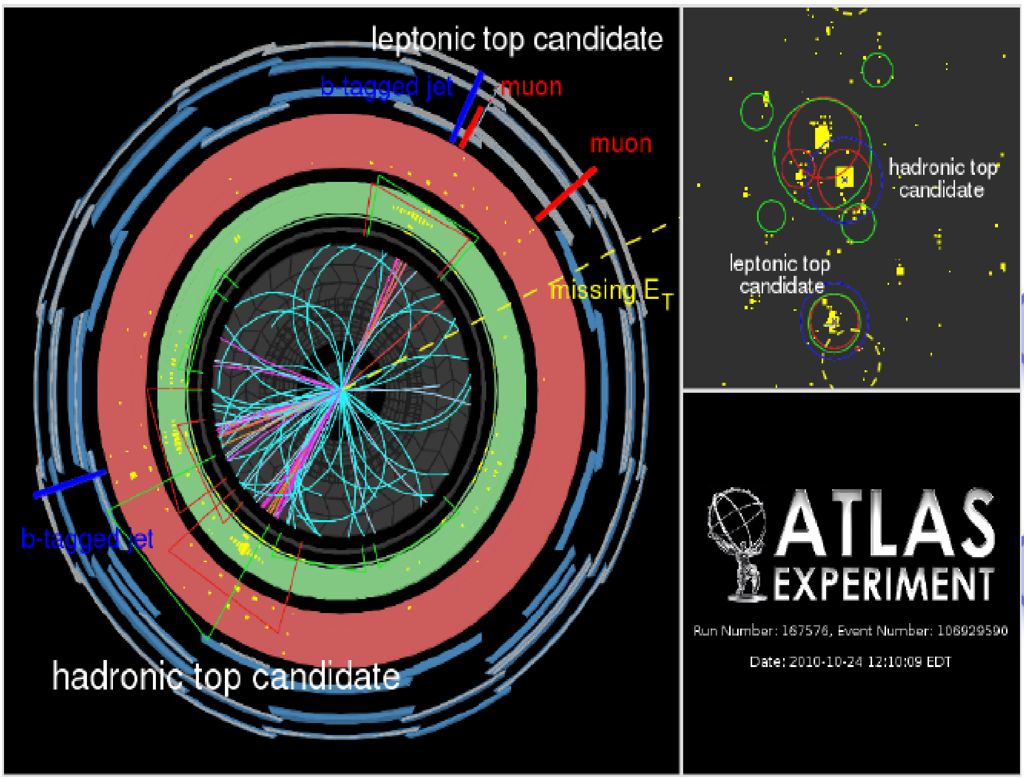
e.g. $pp \rightarrow t\bar{t}$
NNLO

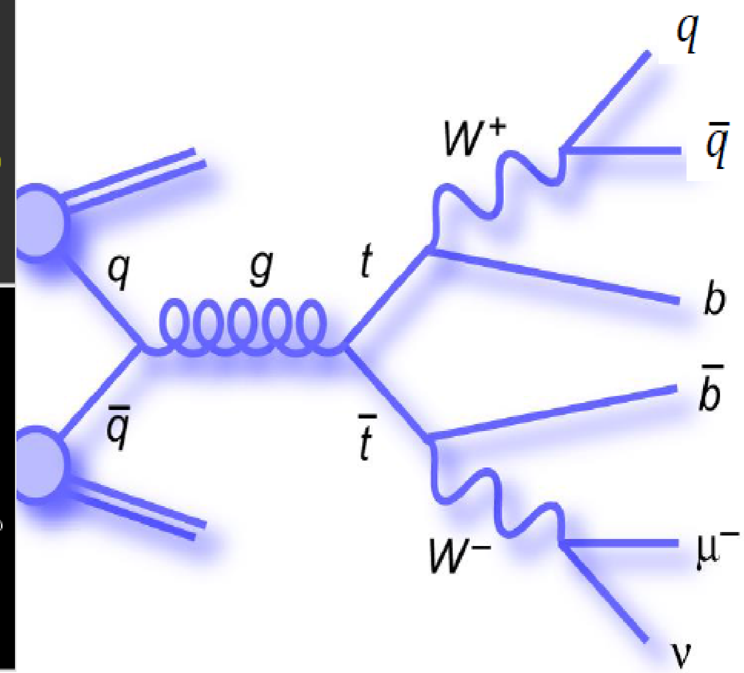




Making predictions for hadron colliders

Cross Sections are not enough

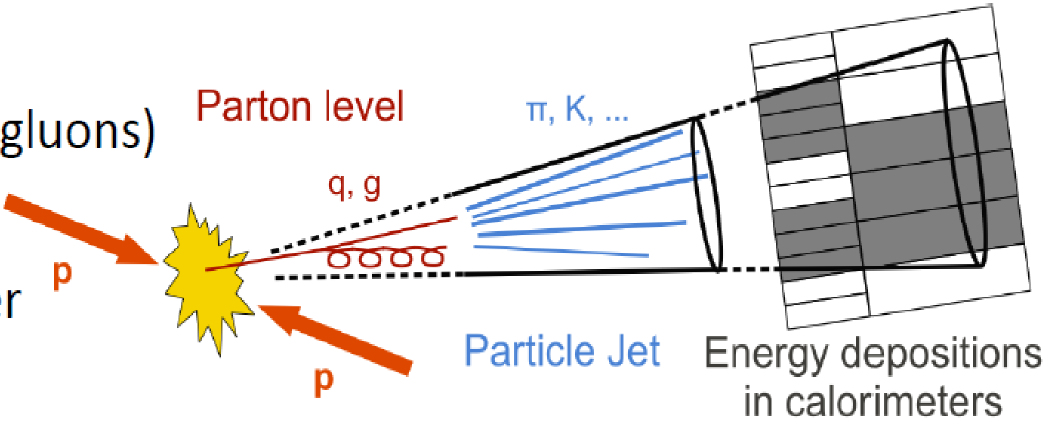




Monte Carlo event structure

Need to describe *event structure*

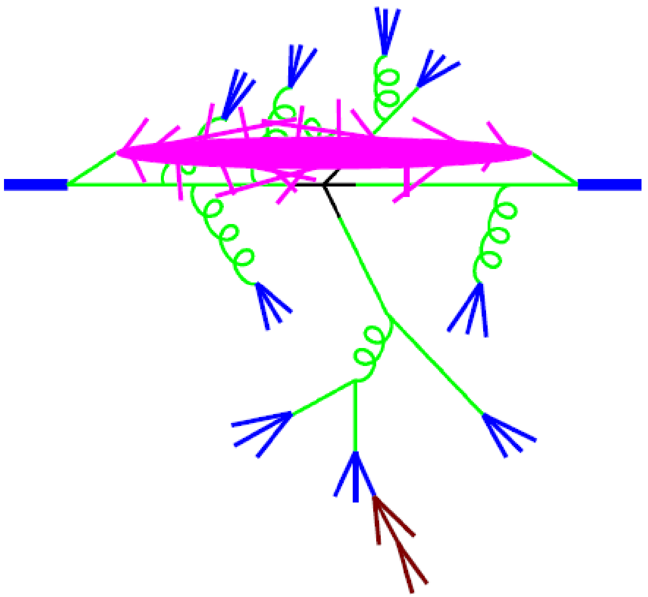
- Hadrons (not quarks and gluons)
- Jets of hadrons
- Remnants of protons after parton extracted
- Unstable particle decays



Monte Carlo event structure

Need Event Generators

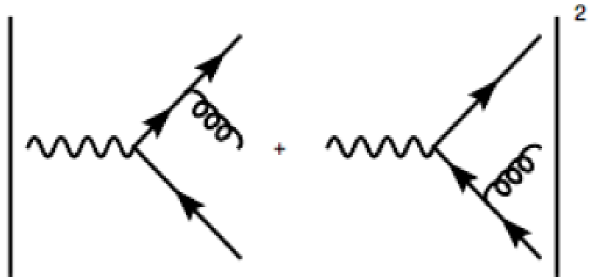
1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Parton showers

Gluon emission is universal

e.g. $e^+e^- \to 3$ partons:



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}z_g} \sim \sigma_0\, C_F\, \frac{\alpha_s}{2\pi}\, \frac{2}{\sin^2\theta}\, \frac{1+(1-z_g)^2}{z_g}$$

$E_g/E_{g,max}$

$e^+e^- \to 2$ partons

"quark charge squared"

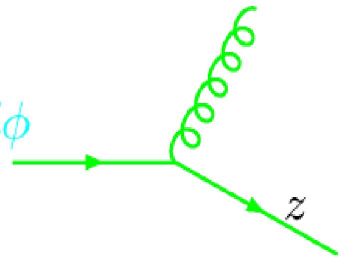
QCD running coupling ~ 0.1

Divergent in collinear limit $\theta \to 0,\pi$ (for massless quarks)
and soft limit $z_g \to 0$

$$d\sigma = \sigma_0 \sum_{\text{jets}} C_F \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2}\, dz \frac{1+(1-z)^2}{z}$$

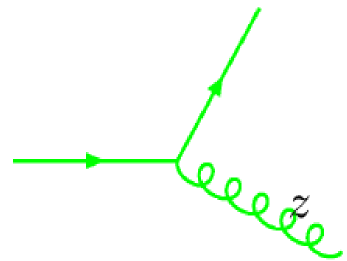
Parton branching is universal

$$d\sigma = \sigma_0 \, \frac{\alpha_s}{2\pi} \, \frac{d\theta^2}{\theta^2} \, dz \, P(z, \phi) d\phi$$



$q \to qg$

$C_F \frac{1+z^2}{1-z}$



$q \to gq$

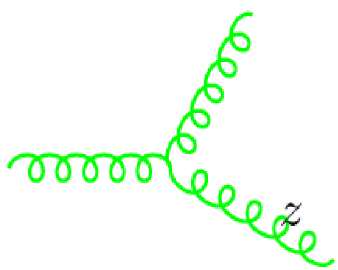
$C_F \frac{1+(1-z)^2}{z}$

$P(z, \phi) =$

"Splitting function":
dependent on flavour and spin but not on how parton was produced

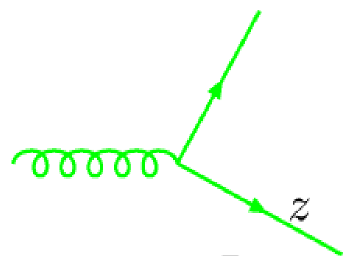
→Probability distribution for parton branching

→Simulation



$g \to gg$

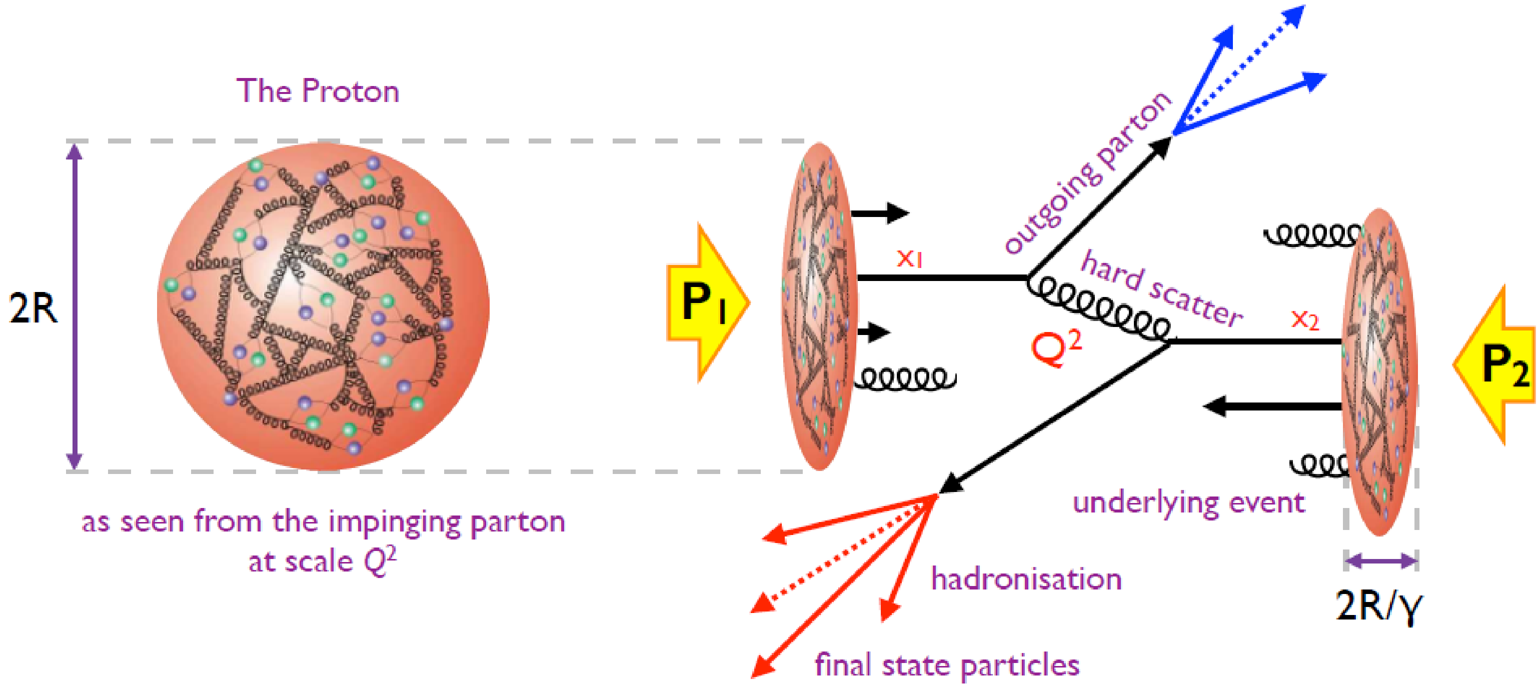
$C_A \frac{z^4+1+(1-z)^4}{z(1-z)}$



$g \to q\bar{q}$

$T_R \left(z^2 + (1-z)^2\right)$

Proton-(anti)proton collisions



Underlying event

- proton remnants from collective interaction of partons not involved in hard scatter
- description necessitate "tuning" of non-perturbative MC parameters based on data

Parton shower and hadronisation

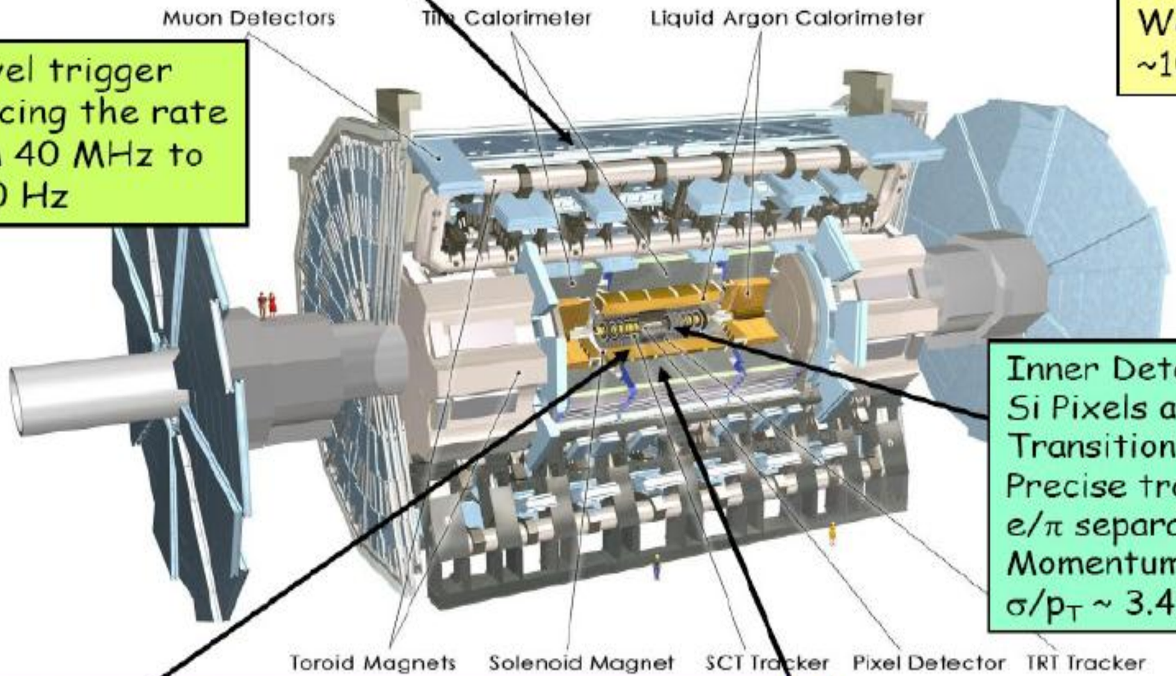
- ISR/FSR emission of gluons
- production of final states hadrons scale < Λ_{QCD} (non-perturbative)
- MC models tuned on data

The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels and strips (SCT) +
Transition Radiation straws
Precise tracking and vertexing,
e/π separation (TRT).
Momentum resolution:
$\sigma/p_T \sim 3.4\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: ~ 1% at 100 GeV, 0.5% at 1 TeV

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Tilecal Fe/scintillator (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$


Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
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Serbia
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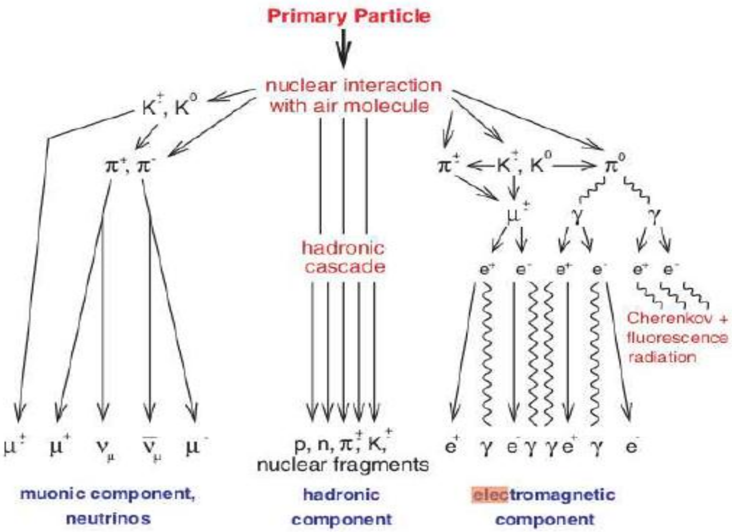
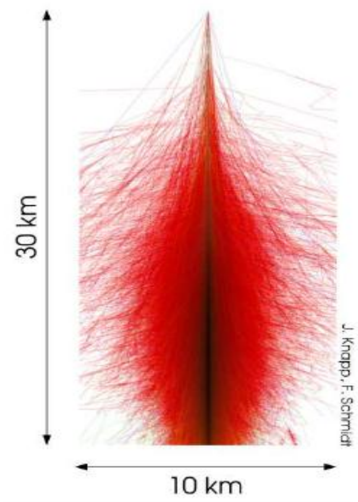
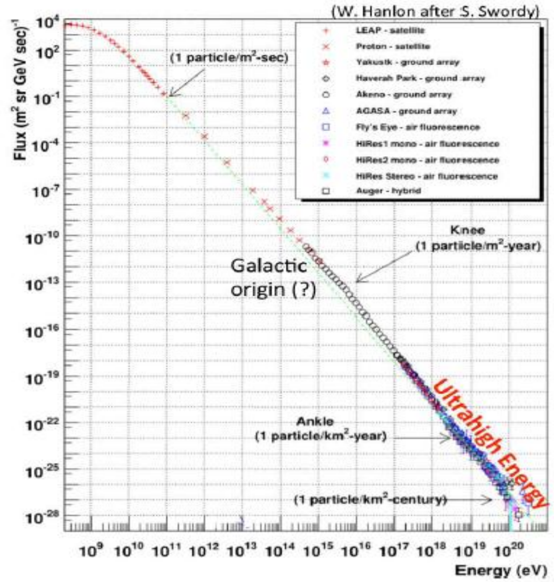
UK
USA
CERN
JINR
ATLAS
Collaboration

Cosmic rays





Simulation proton 10^{14} eV

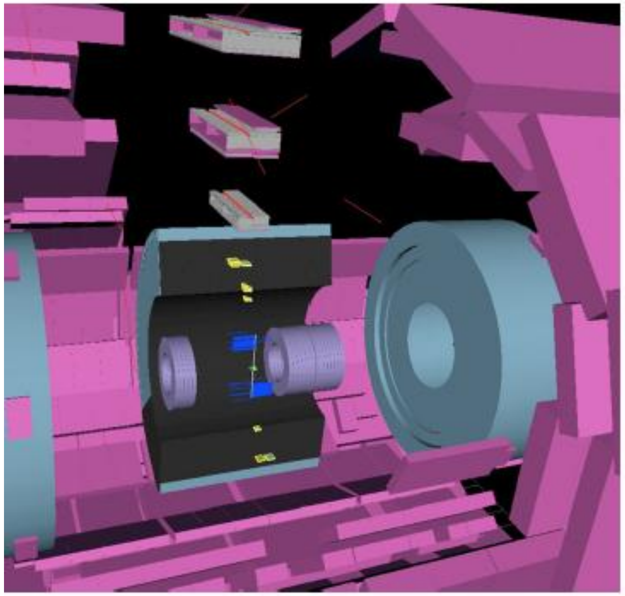


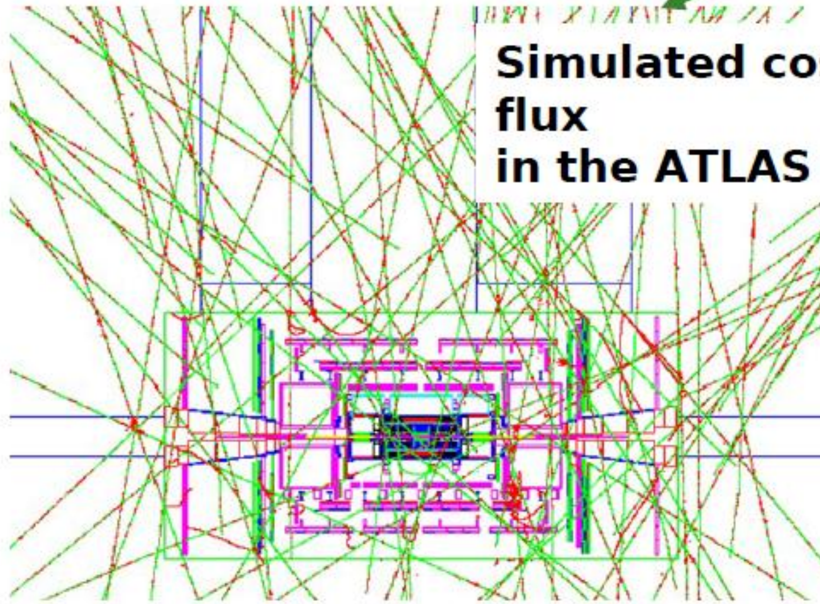
- The most penetrating component of atmospheric showers: the muon component
- At sea level muons represent about 80% of the cosmic ray flux
    - averaged over all energies
    - above E ≈ 1 GeV they contribute almost 100%
- Below 1 GeV the energy spectrum of muons is almost flat
- Above 100 GeV falls exponentially
- It extends to extremely high energies
- The average cosmic ray muon energy is 4 GeV

Cosmic Muons in ATLAS

2008

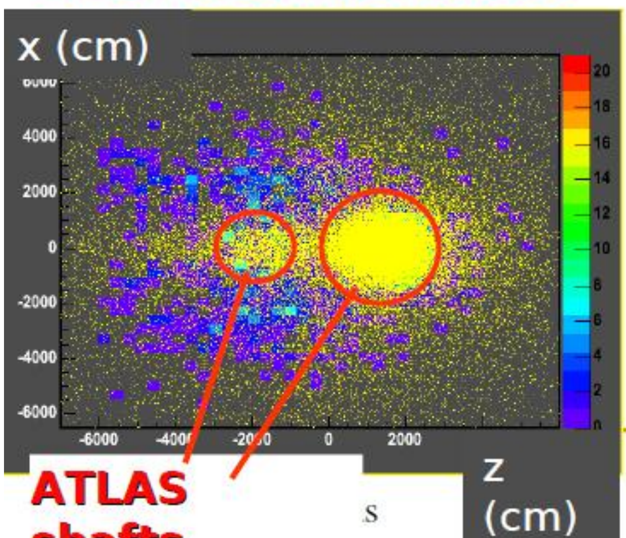
10 ms





Simulated cosmics flux
in the ATLAS cavern

Real Cosmic Event



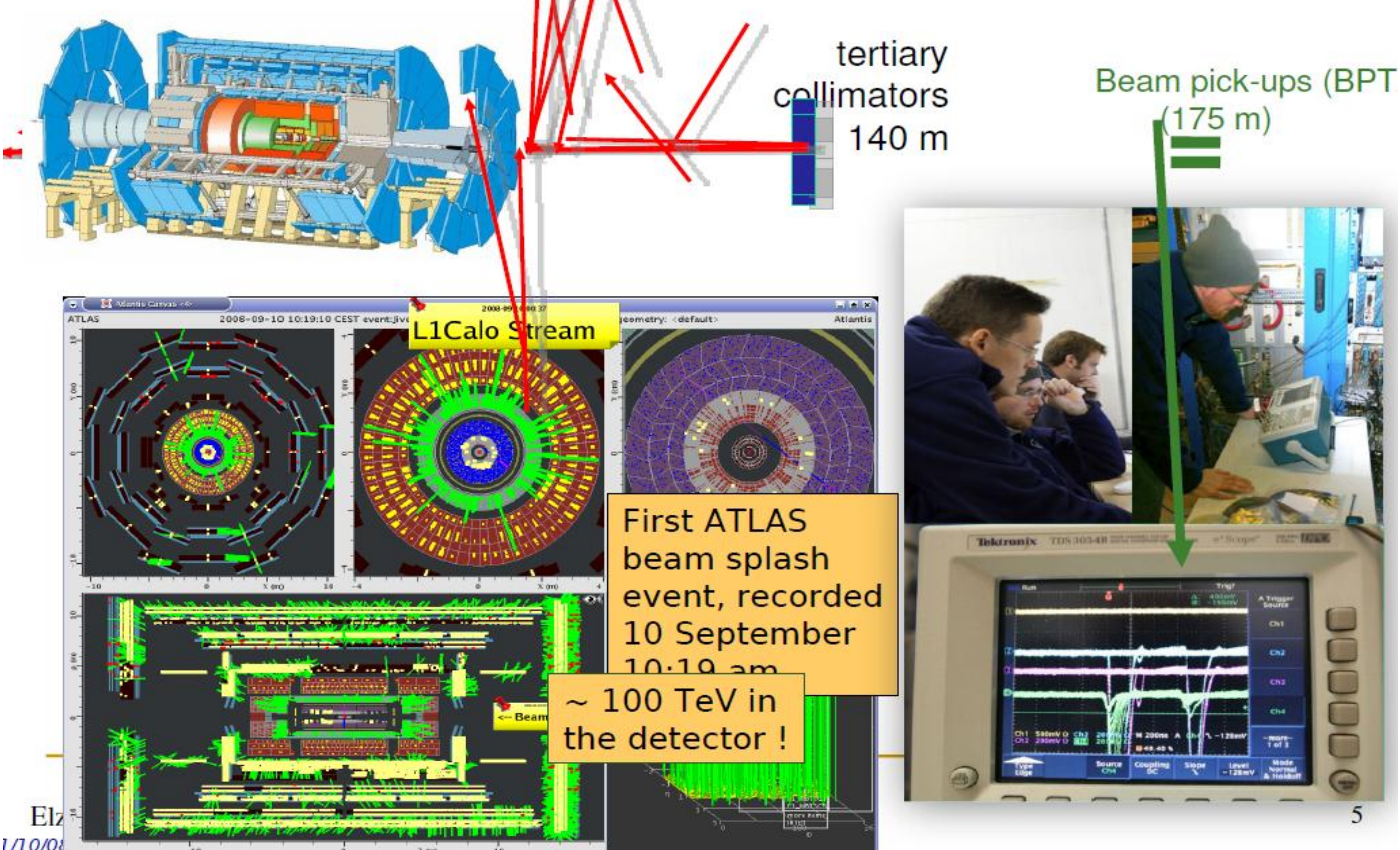
ATLAS shafts

Muon impact points extrapolated to surface as measured by Muon Trigger chambers (RPC)

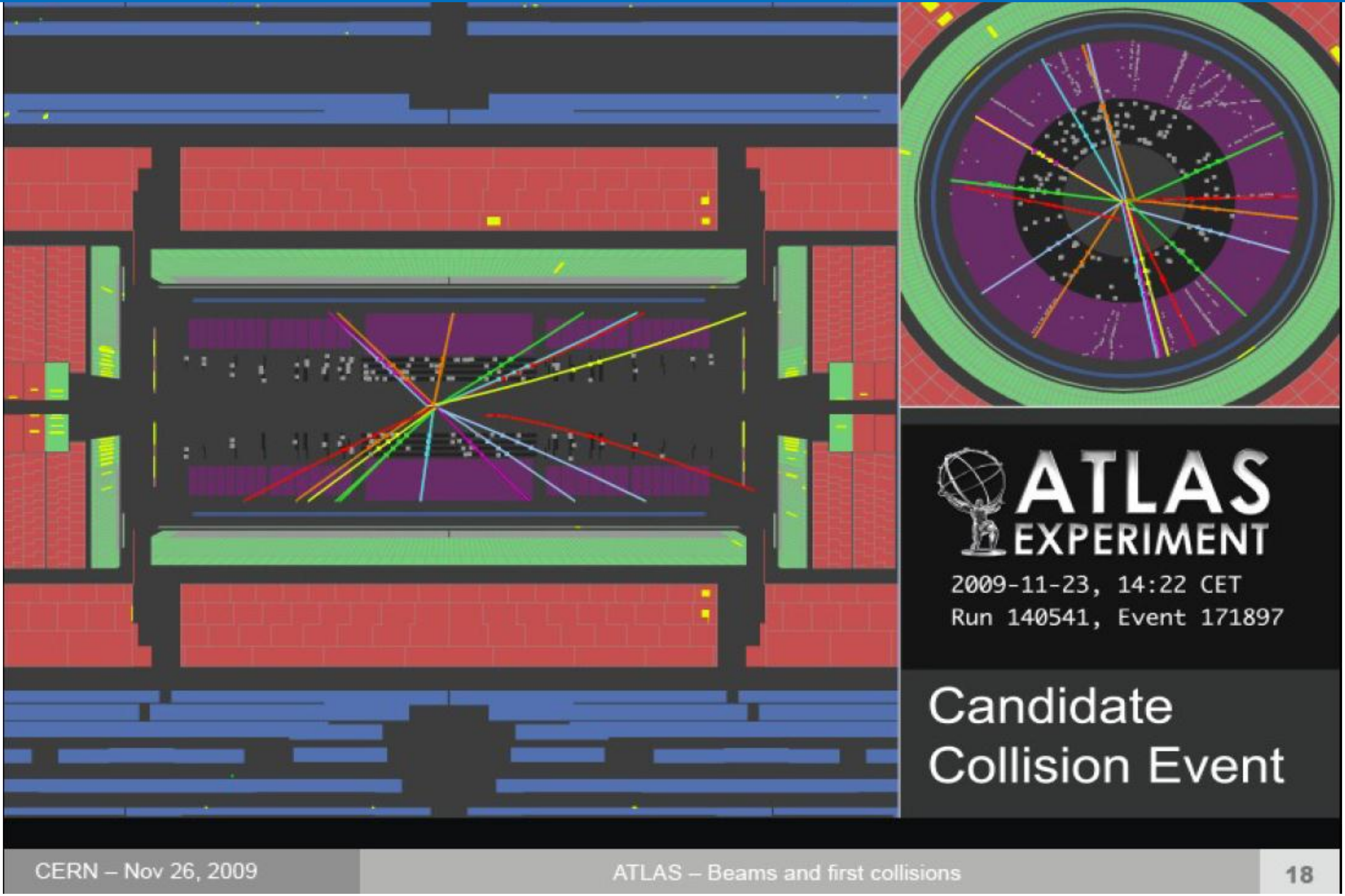
(Calorimeter trigger also

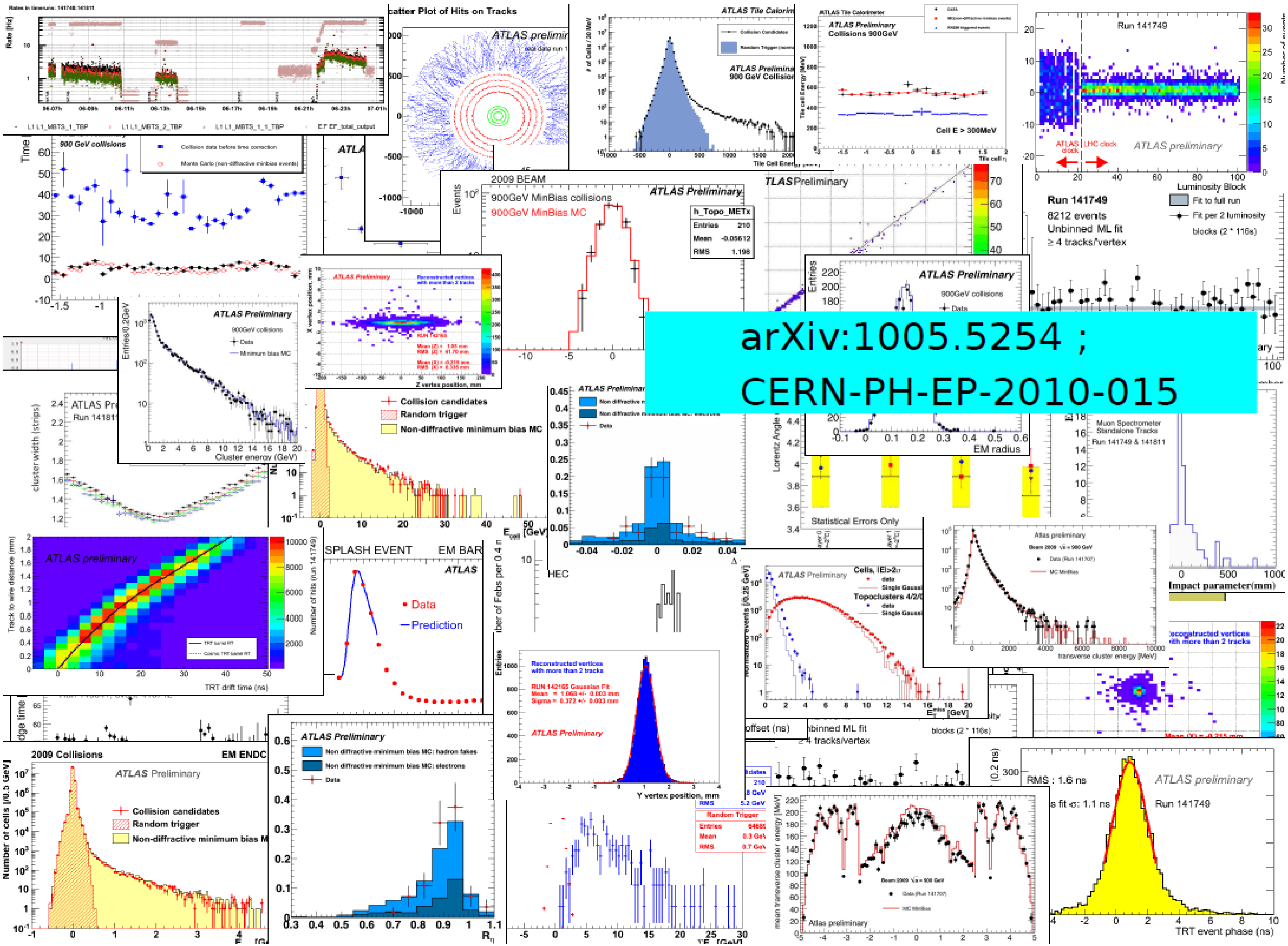
Rate ~100 m below ground:
~ O(15 Hz) crossing Inner Detector

Beam bunches ($2x10^9$ protons at 450 GeV) stopped by (closed) collimators upstream of experiments →
"splash" events in the detectors (debris are mainly muons)



First collisions in ATLAS (2009)

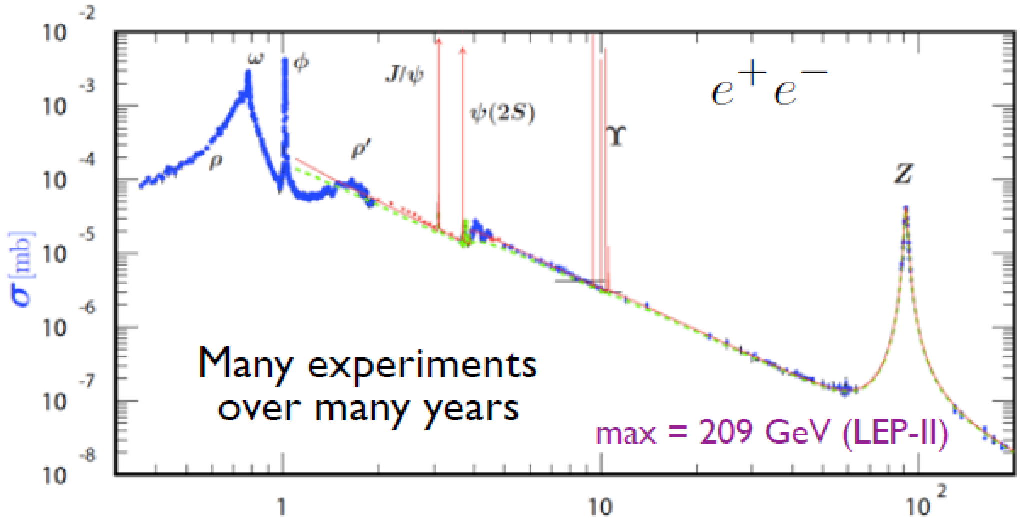




arXiv:1005.5254 ;

CERN-PH-EP-2010-015

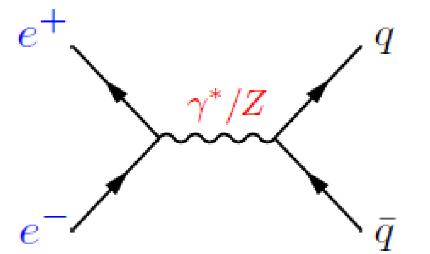
Why Hadron Colliders?



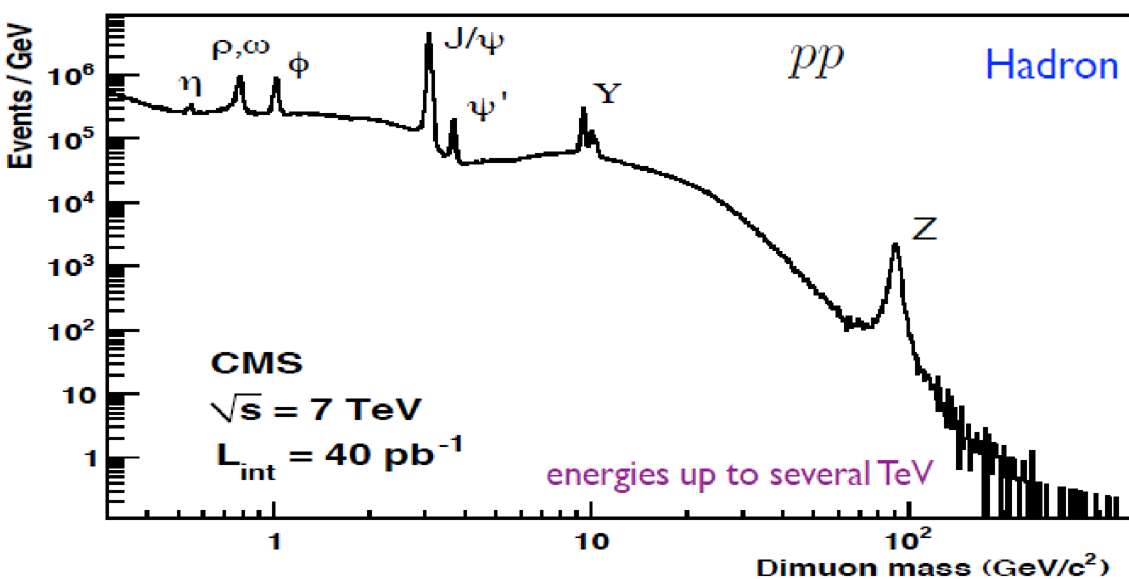
Energy loss and radiated power

$$\frac{\Delta E(e)}{\Delta E(p)} = \frac{P(e)}{P(p)} = \left(\frac{m_p}{m_e}\right)^4 \simeq 10^{13} \quad !!!$$

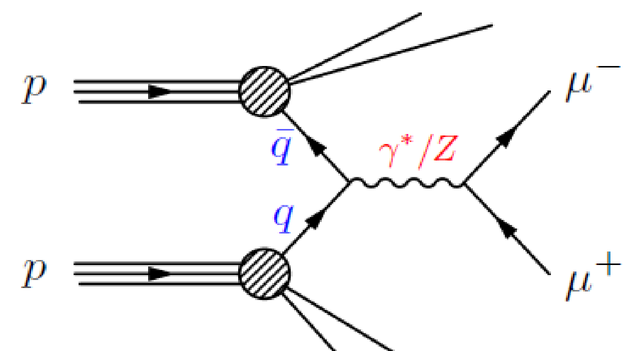
Lepton collider: a fixed CoM energy



$$\sigma(e^+e^- \to q\bar{q}) = N_c e_q^2 \sigma_0$$

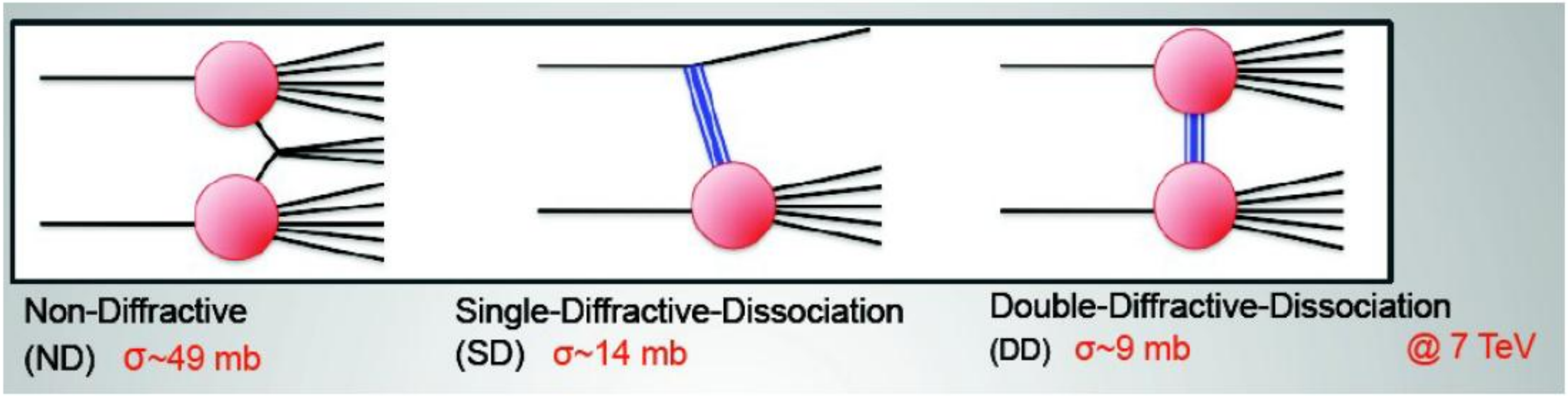


Hadron collider: a continuum of CoM energies

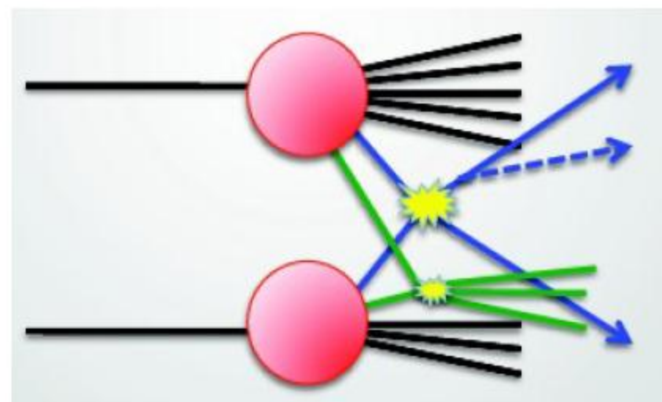


$$\sigma(q\bar{q} \to \mu^+\mu^-) = \frac{e_q^2}{N_C}\sigma_0$$

Dominant QCD processes



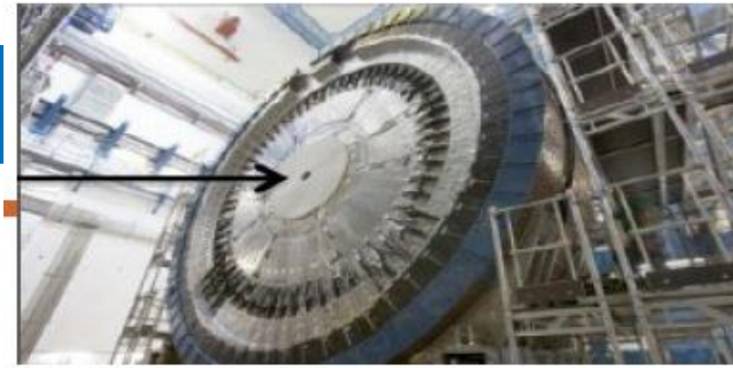
- Multi-parton interactions (**Underlying Event**)

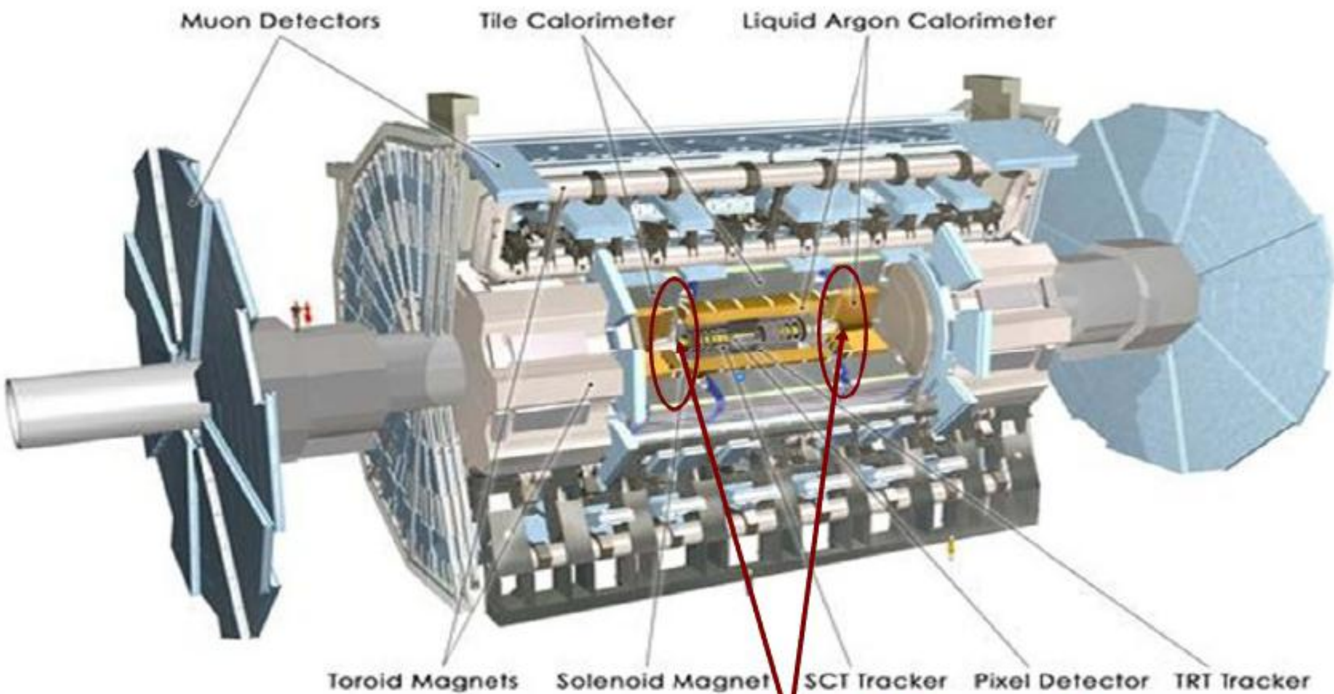


Inelastic cross-sections

- Use only few runs: 7 TeV data (190 μb^{-1}) + 900 GeV data (7μb^{-1}) and 2.36TeV data (0.1μb^{-1})
  - We want to study **all** inelastic pp interactions
  - Instantaneous luminosity very low for these runs: on average ~0.007 interactions per bunch crossing → **99.3% of crossings are empty**.
  - Need to **"trigger"** on inelastic interactions: **Minimum Bias Scintillator Trigger (MBTS)**
    - → sensitive to any charged particle $2.09<|\eta| < 3.84$
    - → 16 counters on each side of ATLAS
- Correct for detector inefficiencies and resolution, eg. present **spectrum of charge particles** not tracks
- **No extrapolation** to regions not seen by ATLAS

MBST Trigger





Trackers: |η|<2.5

Calorimeters: |η|<4.9

Minimum **B**ias
Trigger **S**cintillator
2.1< |η|<3.8

How well we understood detector?

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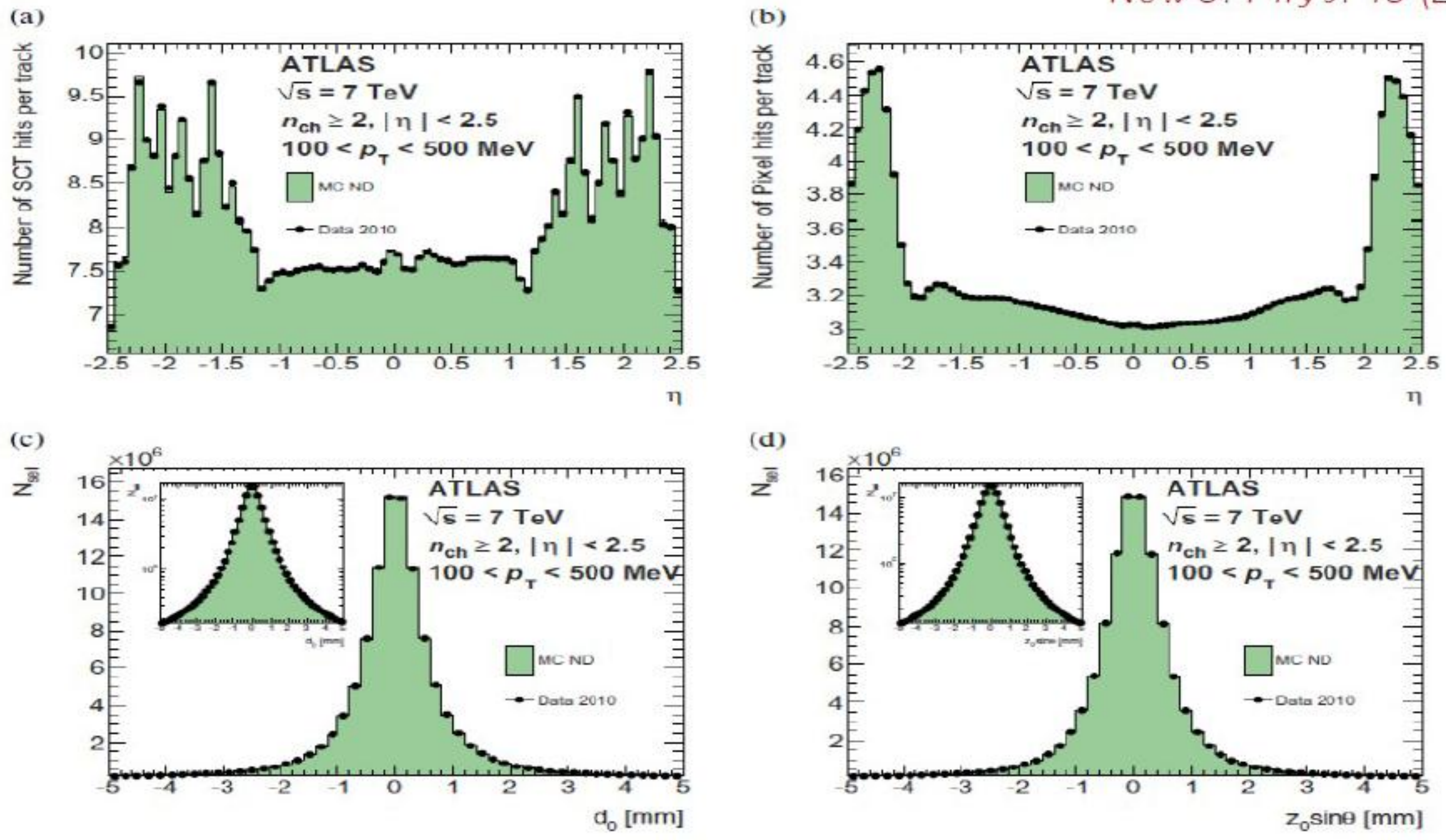
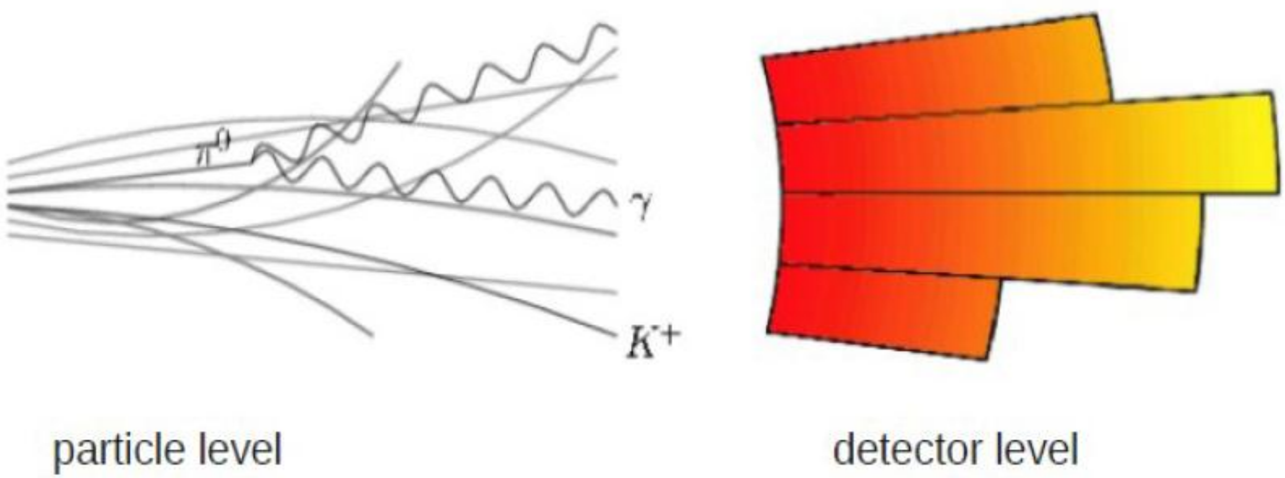


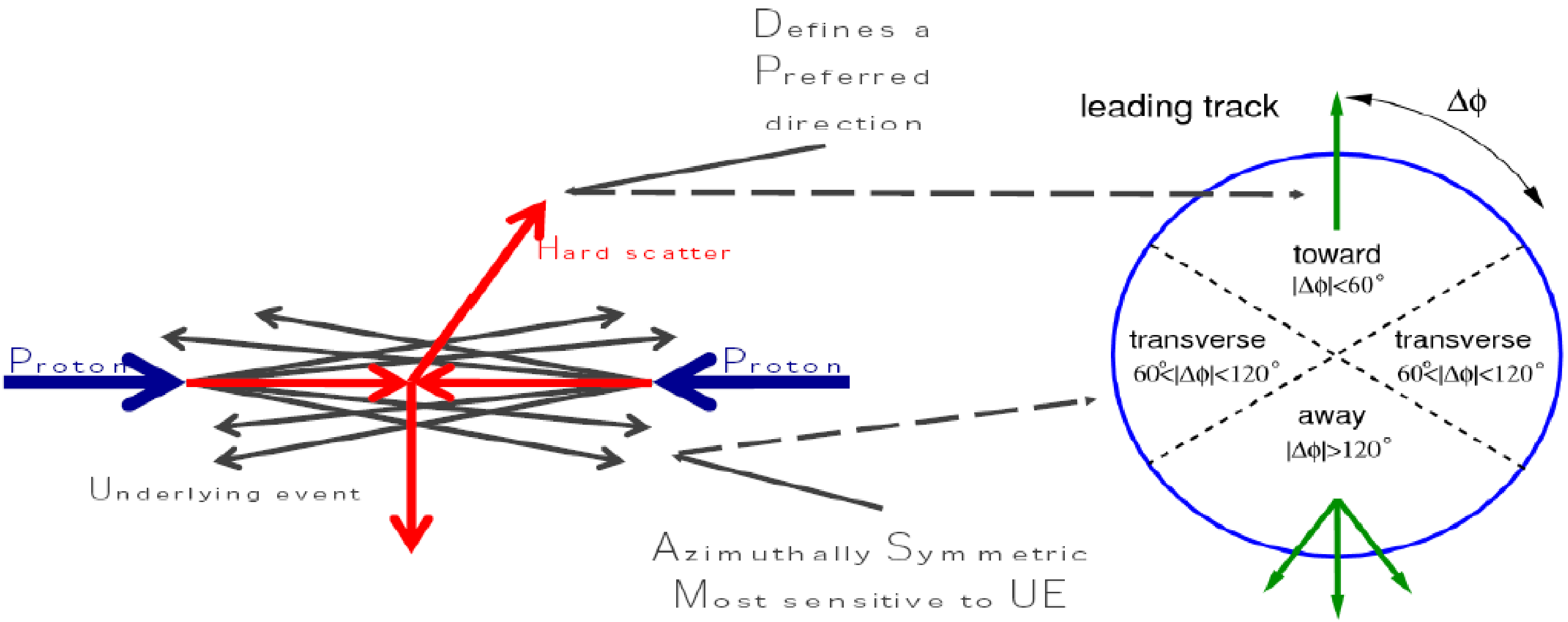
- Excellent agreement between data and MC: Pixel and Silicon hits per track

Unfolding to particle level

- Bayesian iterative unfolding used to correct tracks and clusters back to particle level.
  - Use mapping of truth particles on reconstructed objects (use Monte Carlo)

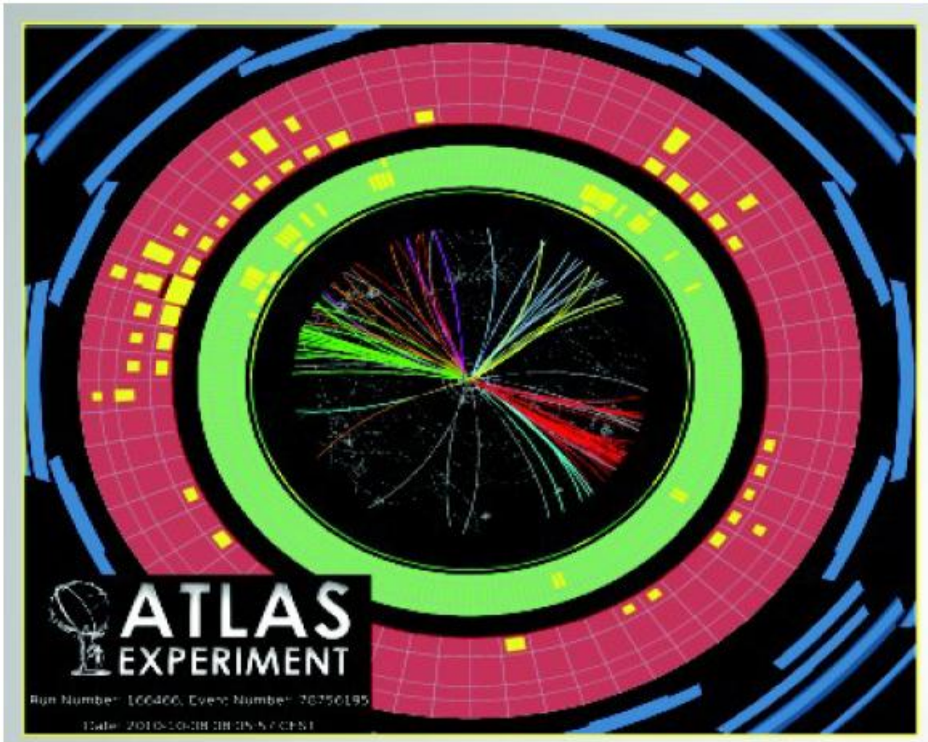


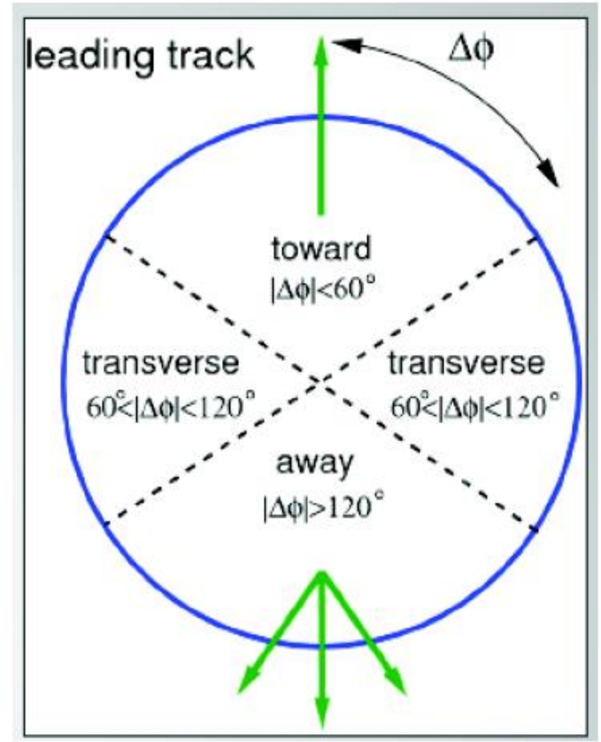
Underlying event



- UE = "everything" - "hard scatter" = beam-beam remnants, MPI, ISR
- Study: charged particle density, transverse momentum, average p_T. Transverse region considered most sensitive to UE

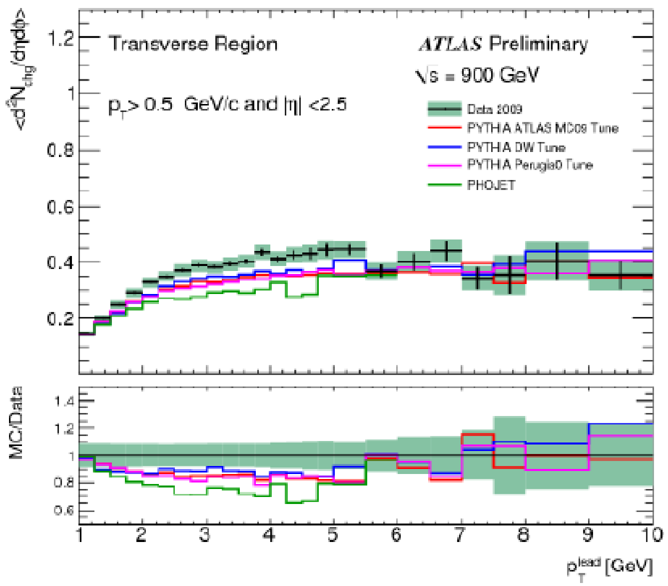
Underlying event

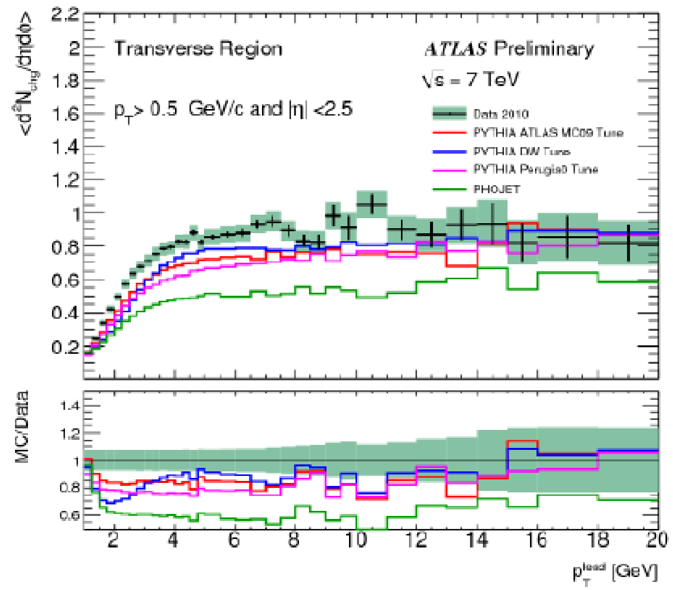




- Define the direction of "hard scatter" as the highest p_T particle
- Study the activity (#of particles) in the region "transverse" to the hard scatter.

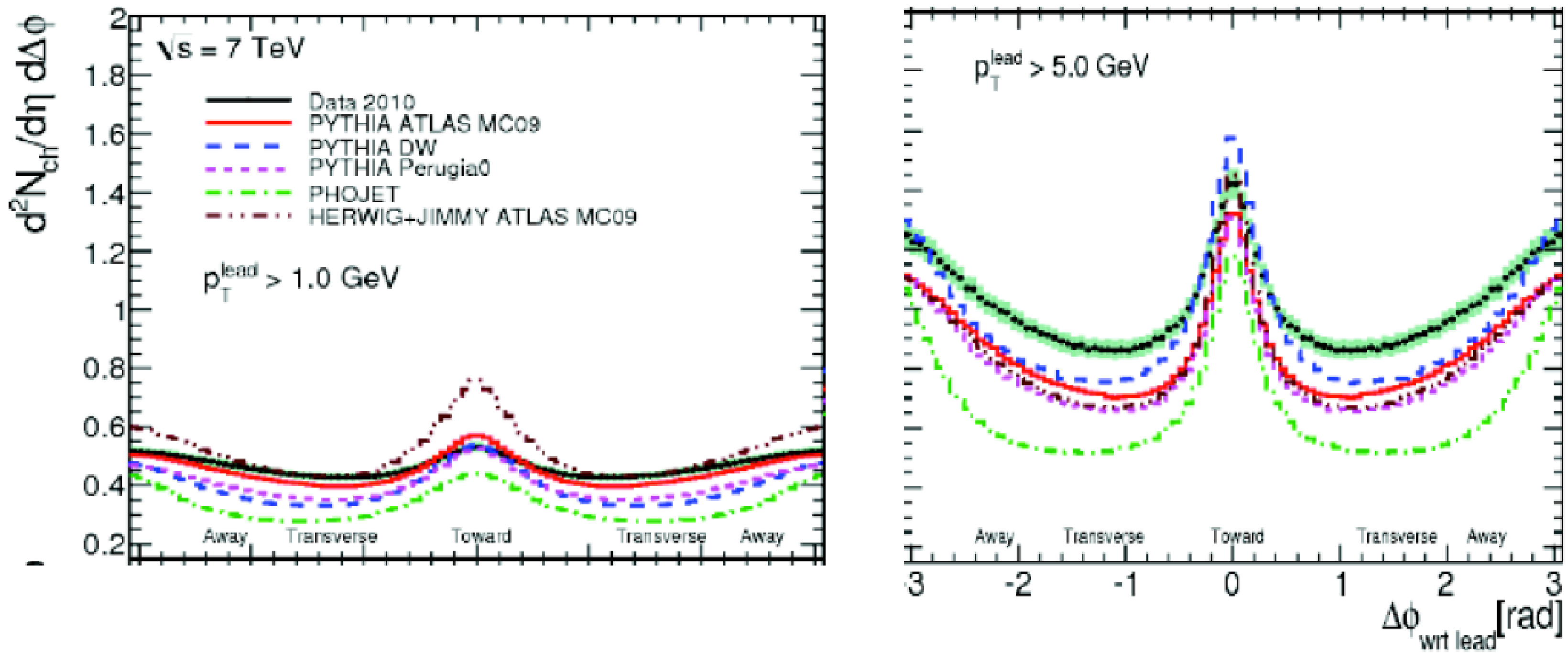
Transverse region particle density





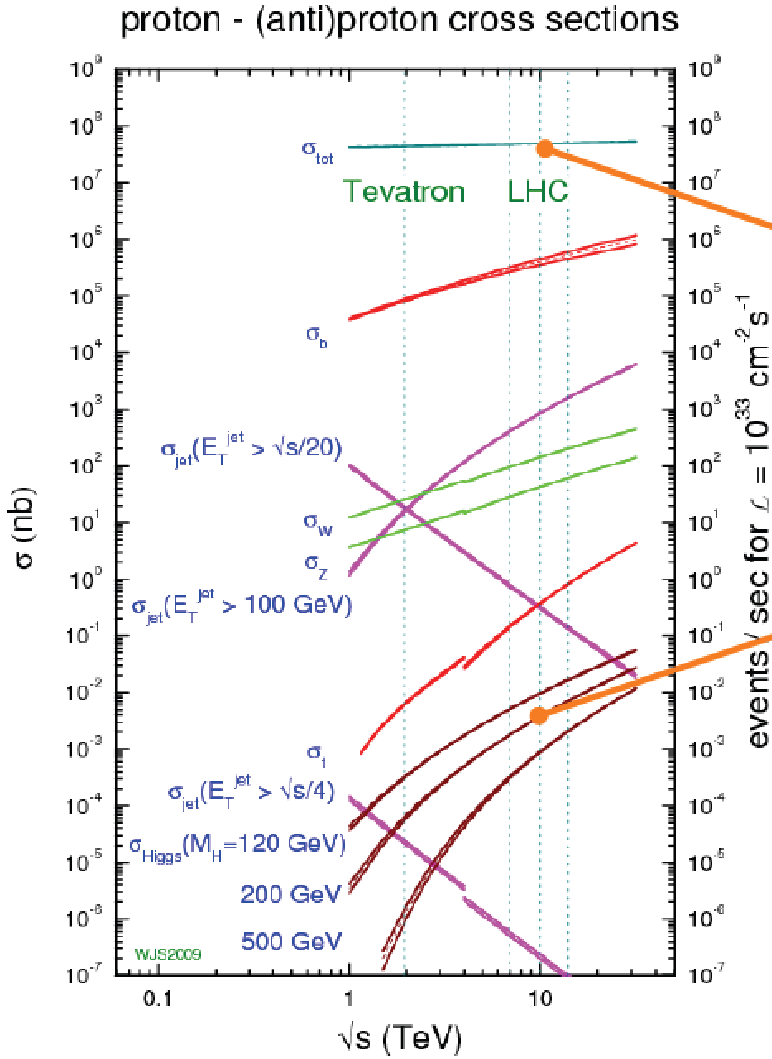
- All tunes underestimate particle density by 10%-15% in the plateau region
- There is factor of ~2 increase in activities between 900 GeV and 7 TeV
- In the plateau region the measured density corrsponds to ~ 2.5 per unit η at 900 GeV and 5 particle at 7 TeV

Particle density angular correlations



- Define the event orientation by the azimuthal angle on the track with the highest p_T.
- MC tunes only reproduce the general features, disagreement in rates both in the transverse region (UE) and in the away region (MPI/Hard Core)

Cross-sections at LHC



10^8 events/s

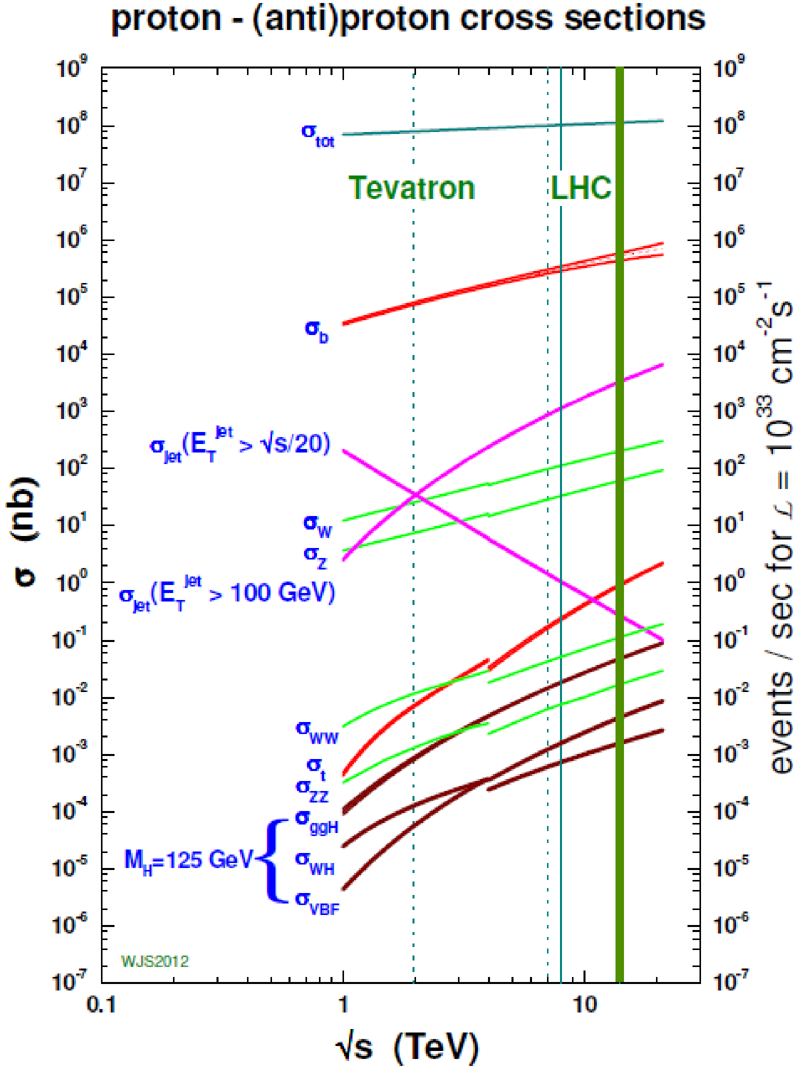
~10^{10}

10^{-2} events/s ~ 10 events/min

[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

Cross-sections at LHC



- Cross sections in pp collisions at 13 TeV
  - total ≃ 100 mb
  - inelastic ≃ 80 mb (diffractive ≃25 mb)
- b-quark pair production ≃ 400 μb
- jet with E_T > 100 GeV ≃ 3 μb
- W and Z bosons : 200 and 60 nb
- top quark pair ≃ 1.0 nb
- WW ≃ 100 pb
- H(125 GeV) ≃ 60 pb
- ZZ ≃ 20 pb

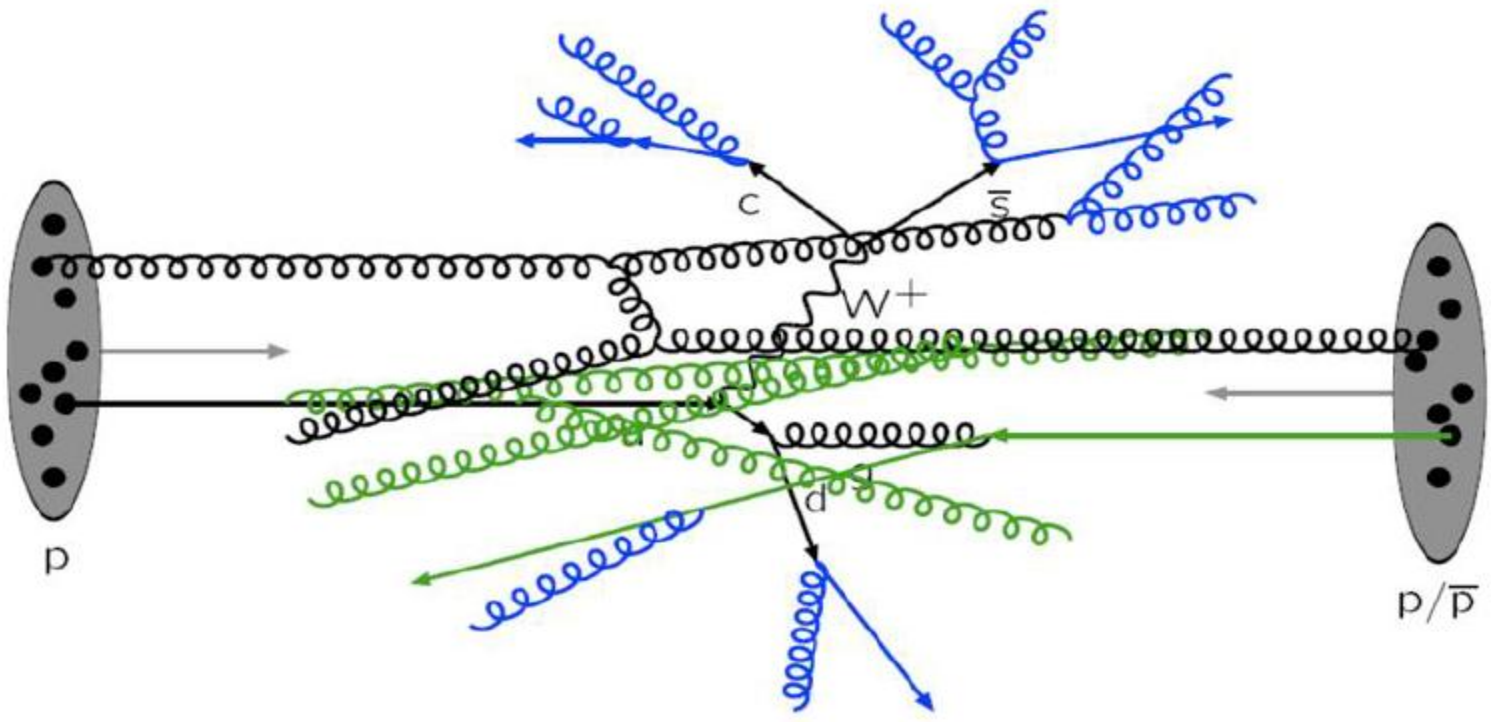
W & Z in leptonic modes

$\sigma(pp \rightarrow W) \times (W \rightarrow \ell\nu) = 20$ nb

$\sigma(pp \rightarrow Z) \times (Z \rightarrow \ell\ell) = 2$ nb

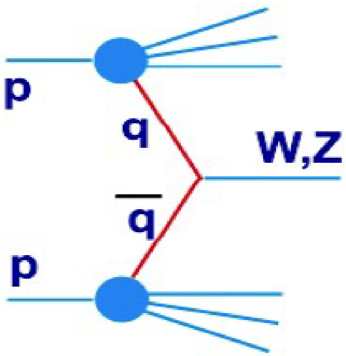
Proton-proton scattering at LHC

- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction ["underlying event"]

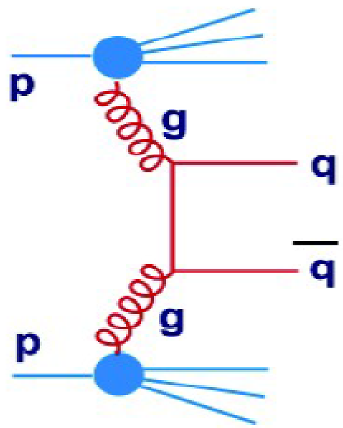


QCD hard scattering processes

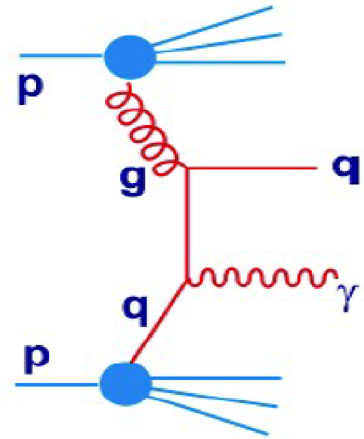
- EW gauge bosons



Di-jets



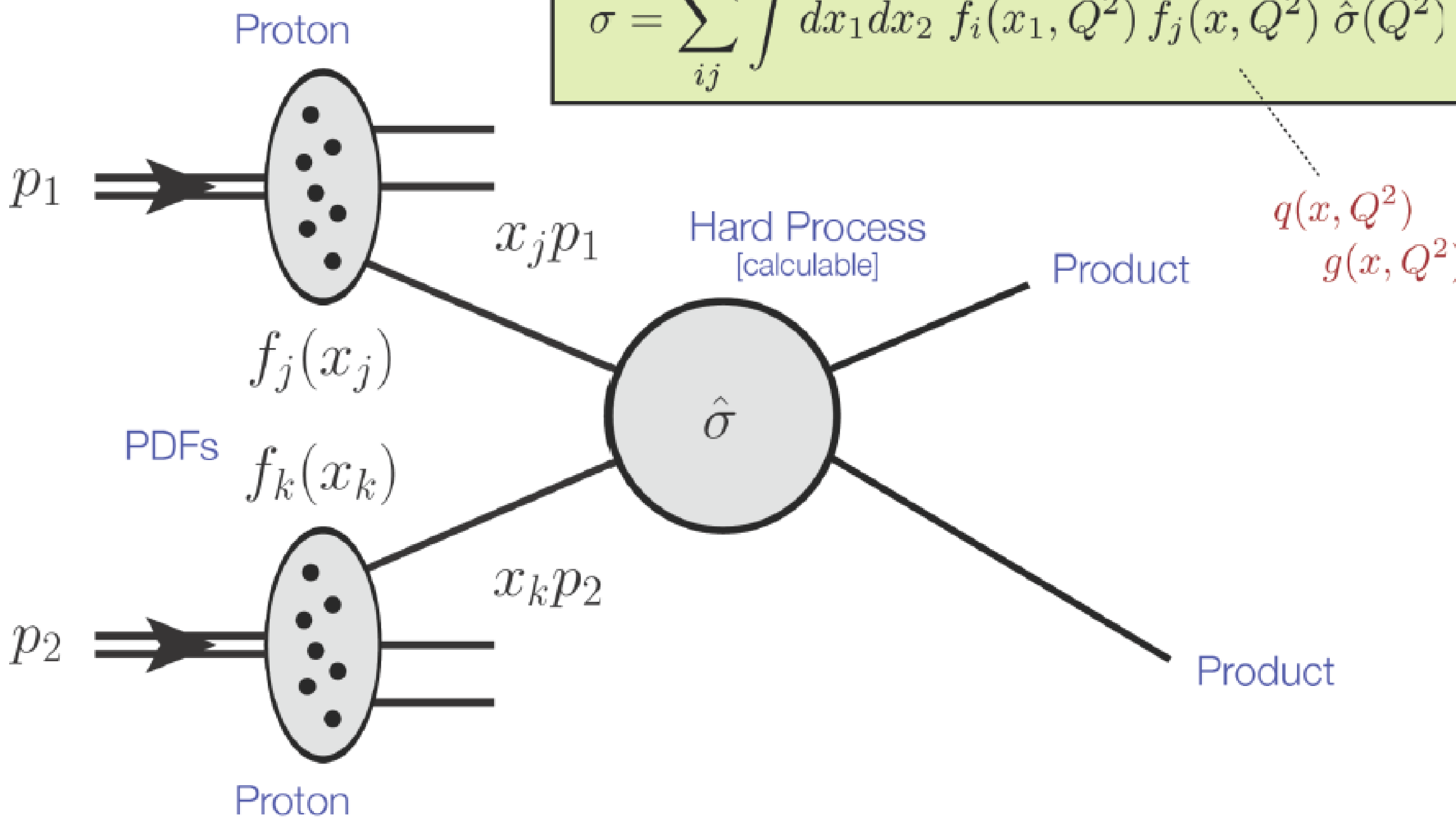
Direct photons



- Measuring those processes test our understanding of:
  - Partonic structure of protons
  - QCD scattering via calculations of N(NLO)
  - Hadronisation/underlying event
  - What makes a good jet algorithm
  - Data driven background estimates for rare processes

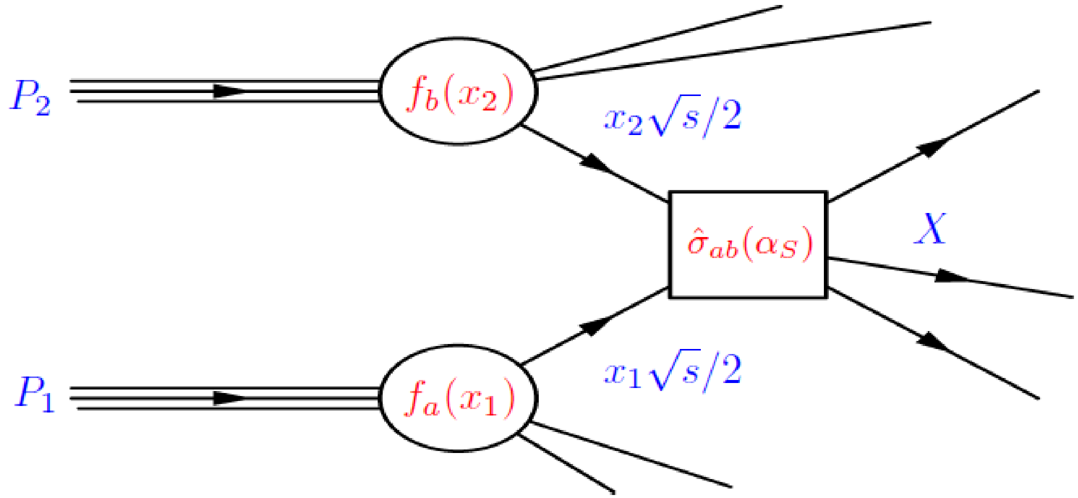
Proton-proton scattering at LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \, f_j(x, Q^2) \, \hat{\sigma}(Q^2)$$



QCD improved Parton Model

Distinguish between soft and hard QCD interactions



Hard interactions controlled through the **factorisation theorem**

Initial collinear singularities are absorbed in PDFs

$$\sigma_{pp\to X} = \sum_{a,b=q,\bar{q},g} \int \mathrm{d}x_1 \mathrm{d}x_2\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}\left(Q^2 = x_1 x_2 s, \alpha_S(\mu_R), \mu_F, \mu_R\right)$$

$$\hat{\sigma}_{ab} = \alpha_S^k \left[\hat{\sigma}^{(0)} + \frac{\alpha_S}{2\pi}\hat{\sigma}^{(1)} + \left(\frac{\alpha_S}{2\pi}\right)^2 \hat{\sigma}^{(2)} + \dots \right]$$

k=2 for dijet production
k=0 for vector boson production

LO — leading order
NLO — next-to-leading order
NNLO — next-to-next-to-leading order

Parton level cross section computed pertubatively

Parton kinematics

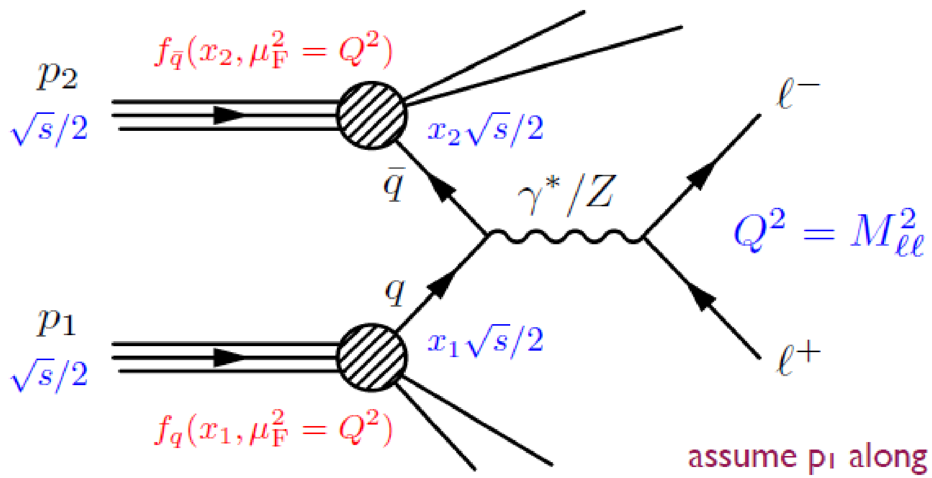
Example of the Drell-Yan process

- lepton pair production via quark-antiquark annihilation

4-momentum of lepton pair (LO)

$$q(x_1) + \bar{q}(x_2) \to \gamma^*/Z \to \ell^+\ell^-$$

$$\begin{cases} E = (x_1 + x_2)\sqrt{s}/2 \\ p_z = (x_1 - x_2)\sqrt{s}/2 \end{cases}$$



$$Q^2 = E^2 - p_z^2 = x_1 x_2 s$$

Define "rapidity" y such that

$$\frac{x_1}{x_2} = \frac{E + p_z}{E - p_z} \equiv e^{2y}$$

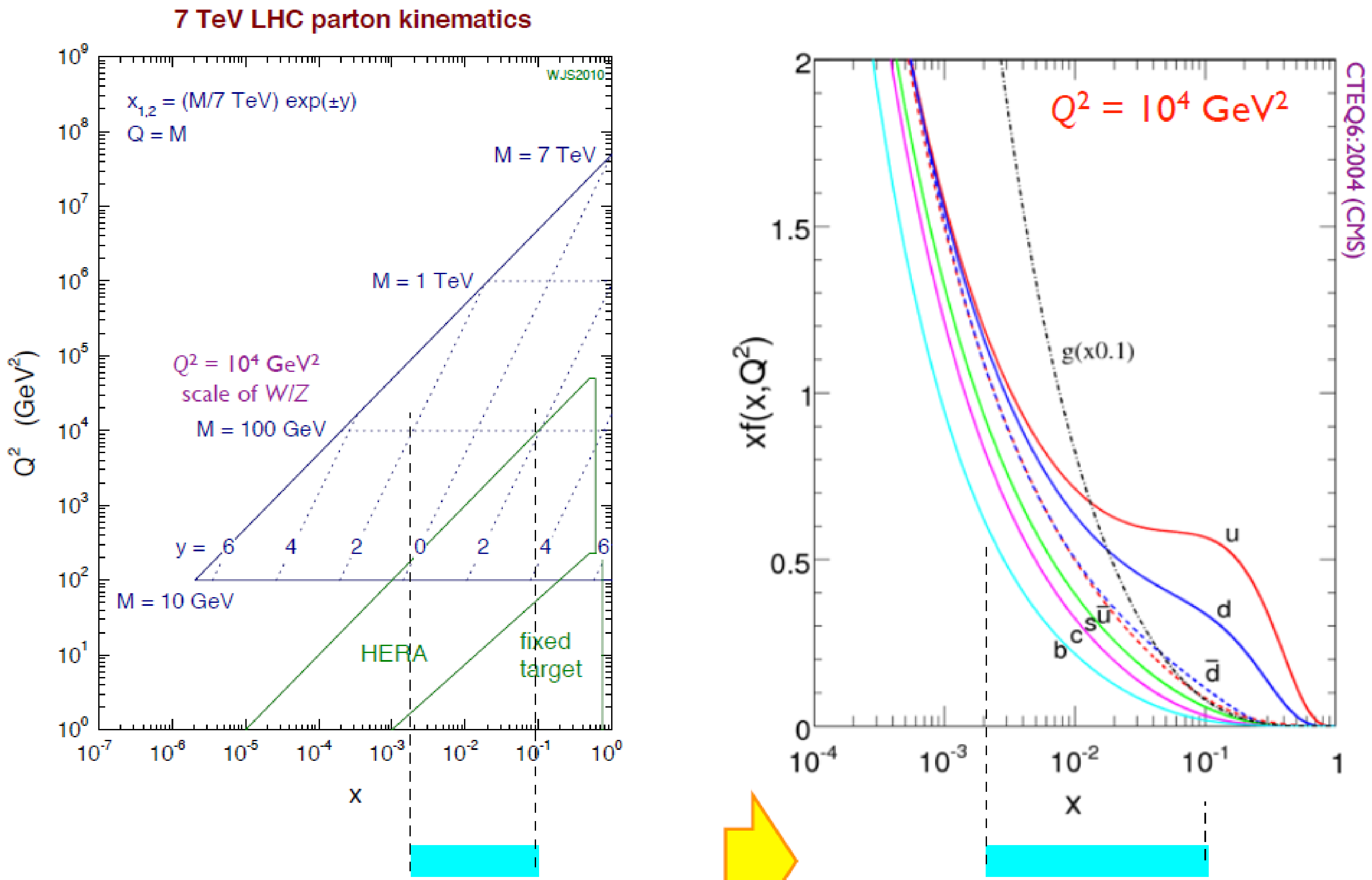
assume p1 along positive beam axis

$$x_1\, x_2 = Q^2/s$$
$$x_1/x_2 = e^{2y}$$

$$x_{1,2} = \frac{Q}{\sqrt{s}}\, e^{\pm y}$$

for a given Q^2,
the rapidity y relates
the x_1 and x_2 of the two partons

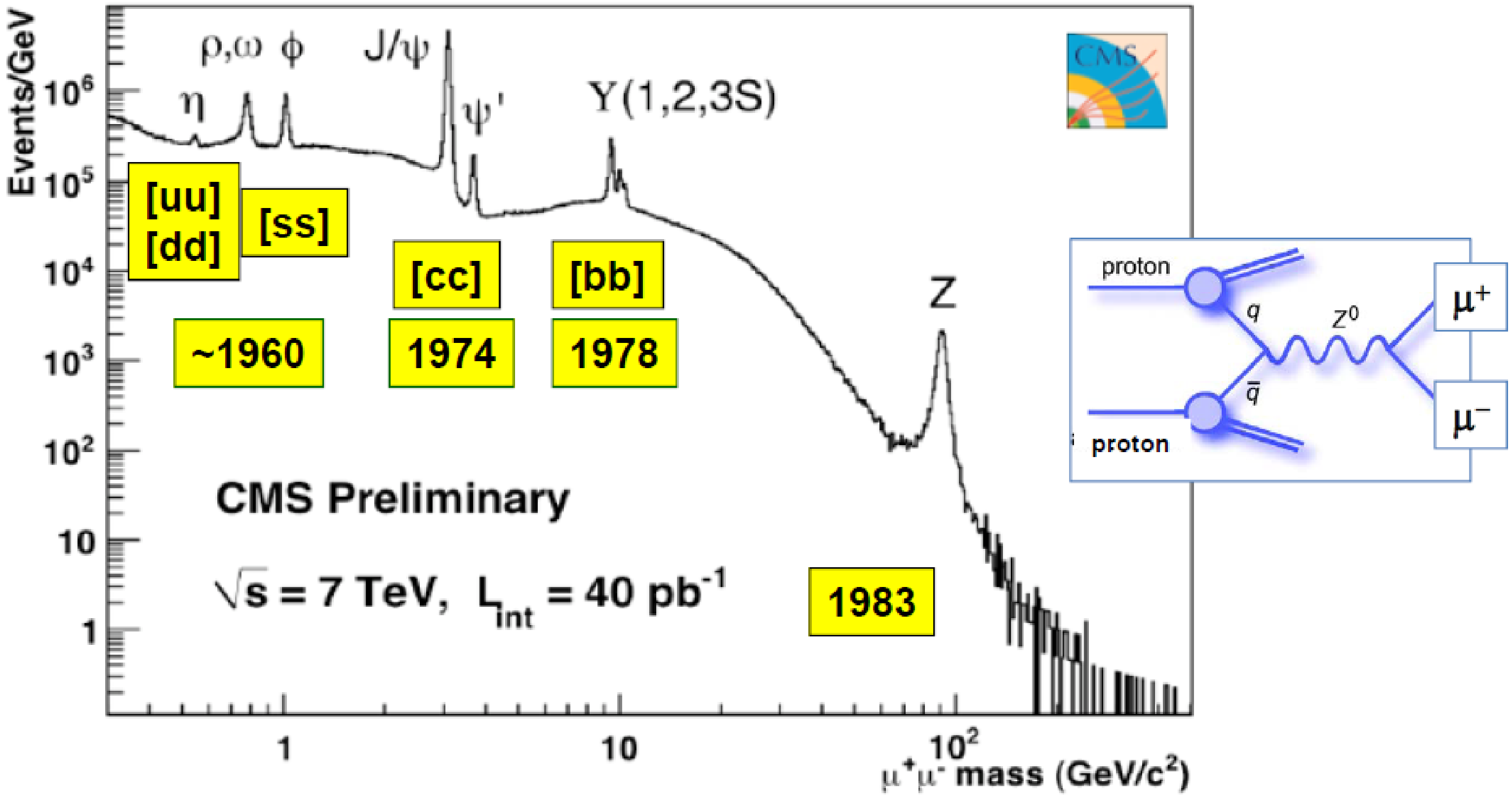
Parton kinematics



range in *x* for
the central production (|*y*|<2)
of *W*/*Z* boson

Year 2010: Retracing history of particle physics

2010 Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model



The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

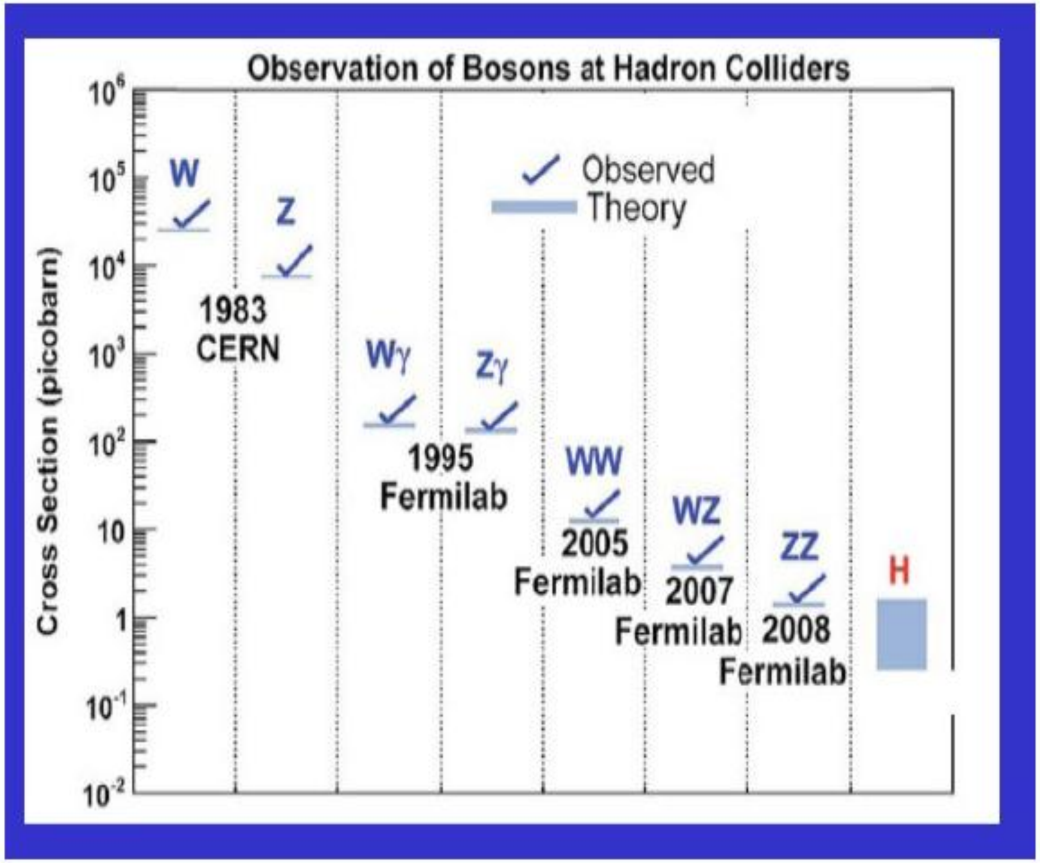
Bosons at hadron colliders

The primary decay chanel is through leptonic decays:

- BR(W→e ν) ~ 10%
- BR(Z→ ee) ~ 3%

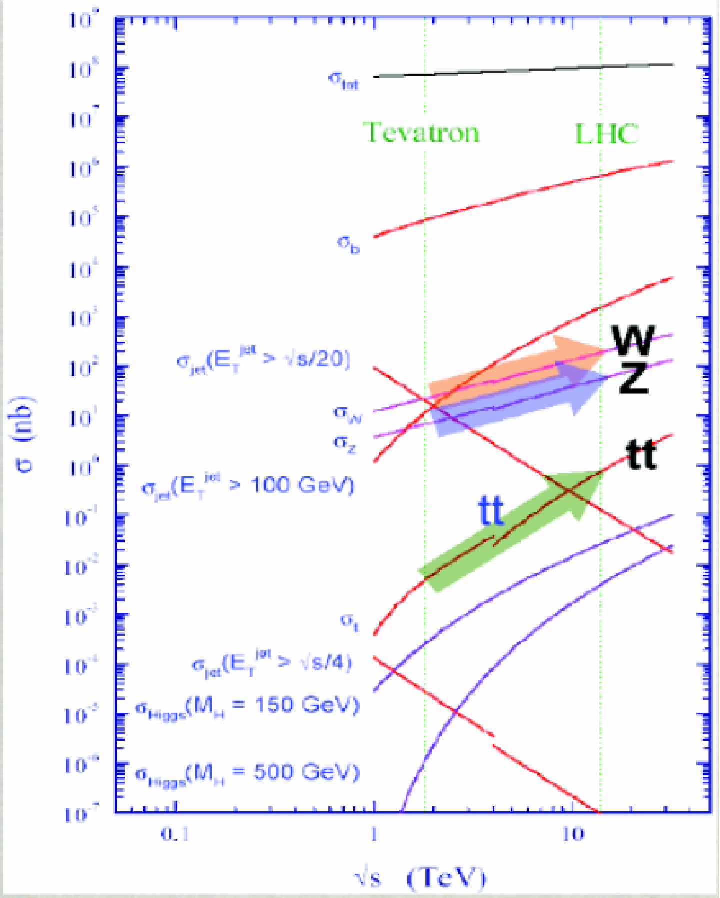
- It means that we are probing σ x BR values orders of magnitude smaller
- At LHC cross-section 5-10 x higher than at Tevatron at Fermilab.

2010

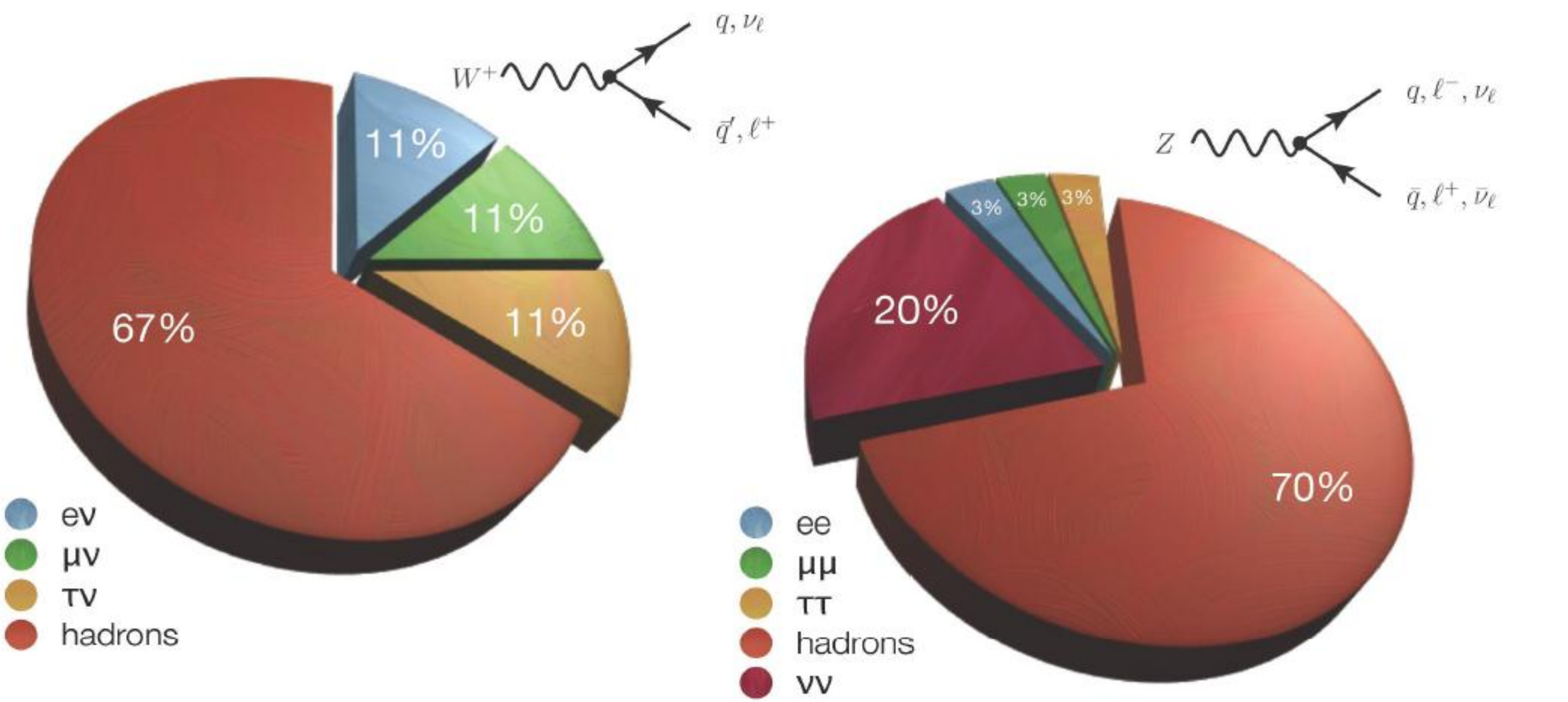


Bosons and top quark at LHC

- **Well measured by previous experiments**
- **Still educational at LHC**
  - Cross-sections
  - New PDF constraints
- **„Standard candles" for high p_T analyses**
  - Calibration, alignment
  - Independent luminosity measurements

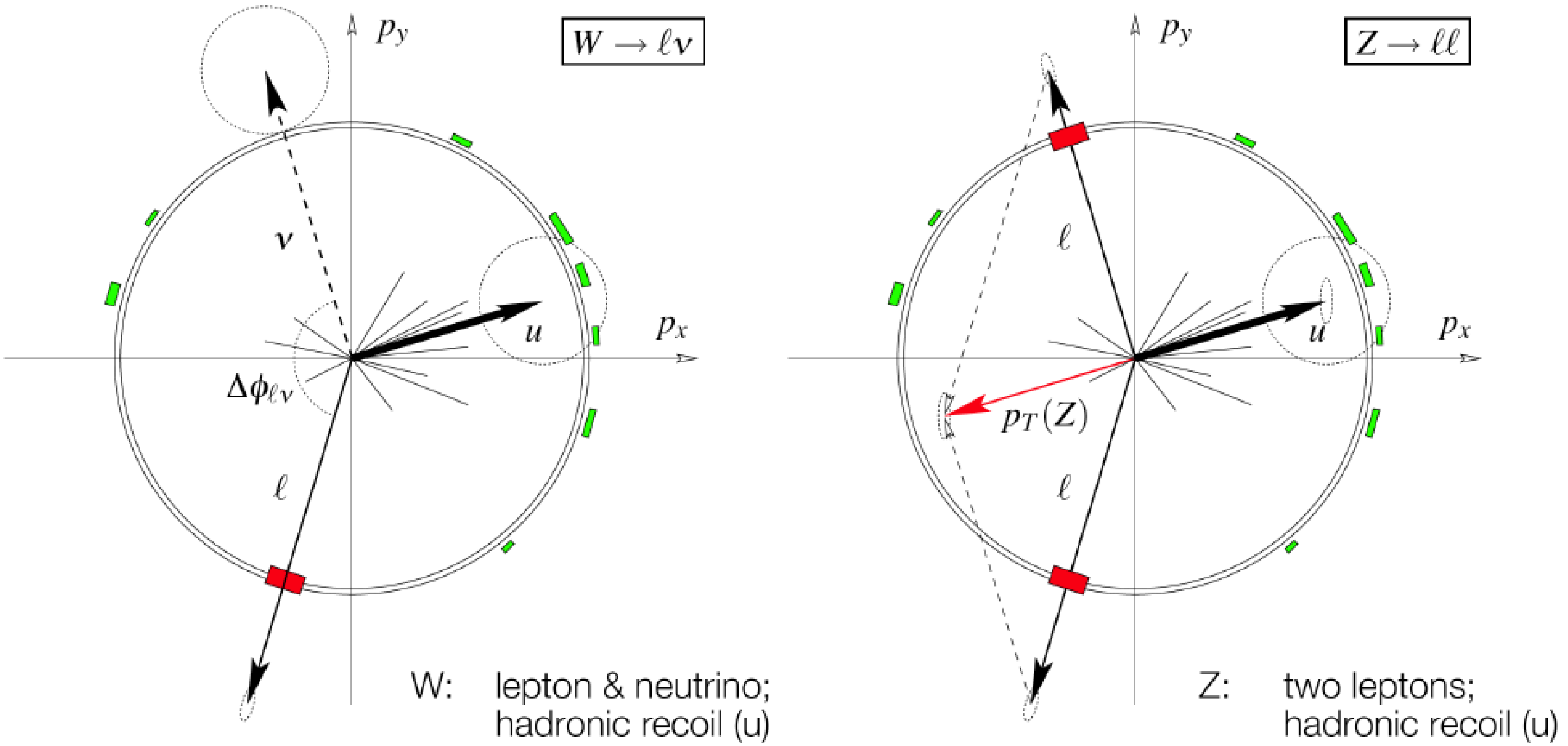


W and Z boson decays



Leptonic decays (e/μ): very clean, but small(ish) branching fractions
Hadronic decays: two-jet final states; large QCD dijet background
Tau decays: somewhere in between…

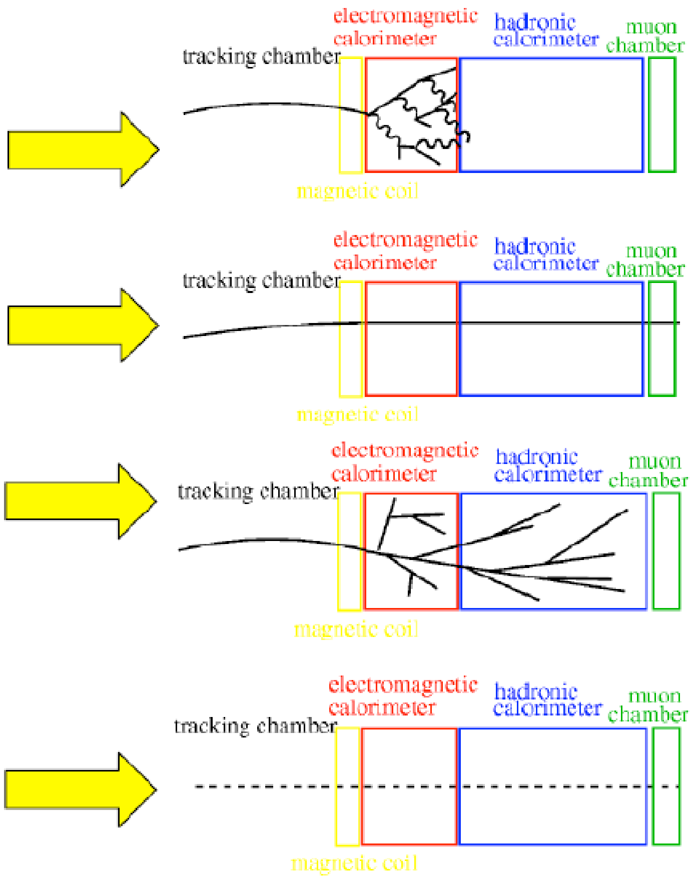
W and Z boson signatures



Additional hadronic activity ➛ recoil, not as clean as e^+e^-
Precision measurements: only leptonic decays

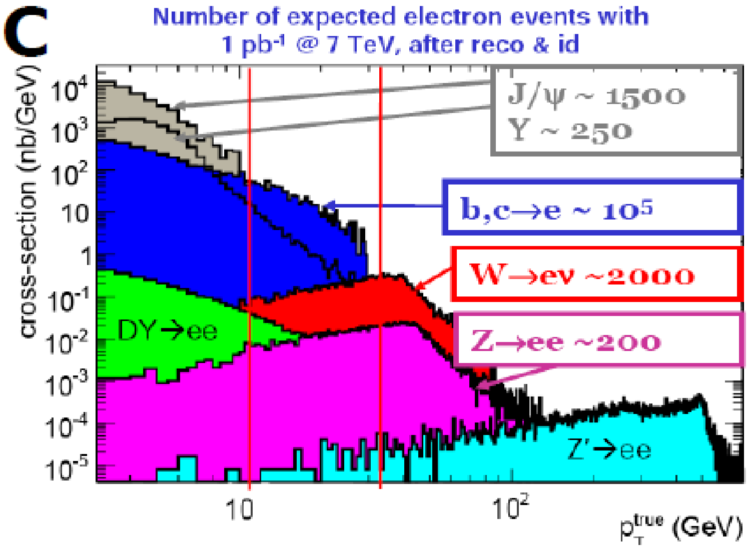
Lepton identification

- Electron:
  - Compact electromagnetic cluster in calorimeter
  - Matched to track
- Muons:
  - Track in the muon chambers
  - Matched to track
- Taus:
  - Narrow jet
  - Matched to one or three tracks
- Neutrinos
  - Imbalanse in transverse momentum
  - Inferred from total transverse energy in detector



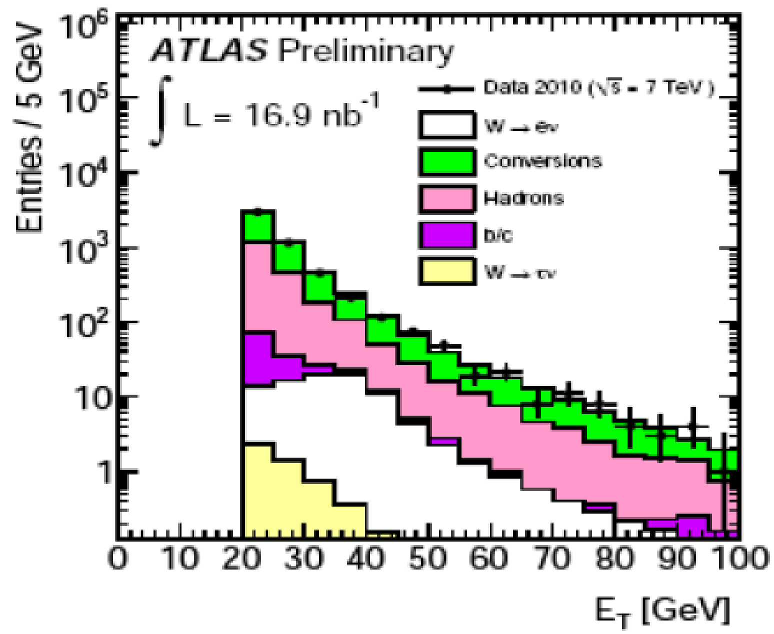
Electrons and jets

MC



- There is also lot of true electrons from semileptonic decays inside jets

DATA: loose electron ID



- Jets can look like electrons
  - Photon conversion from π^0's
  - Early showering charged pions
- And there is lot of jets
- Difficult to model in Monte Carlo
  - Detailed simulation in tracking and calorimeter volume

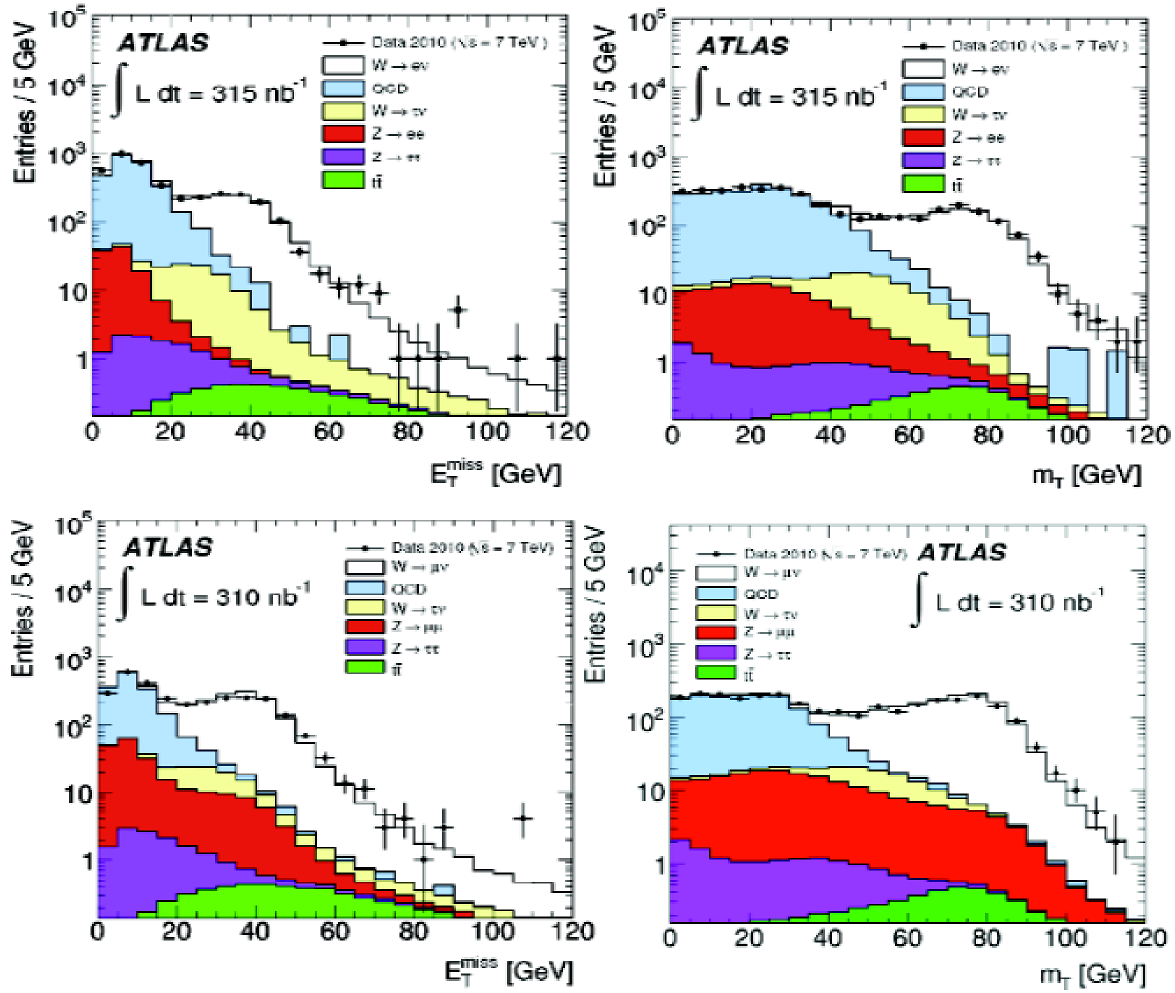
W selection (2010)

Electrons:

- $E_T > 20$ GeV
- *Tight ID*
- *Missing* $E_T > 25$ GeV
- $m_T > 40$ GeV
- ➢ *1069 Candidates*

Muons:

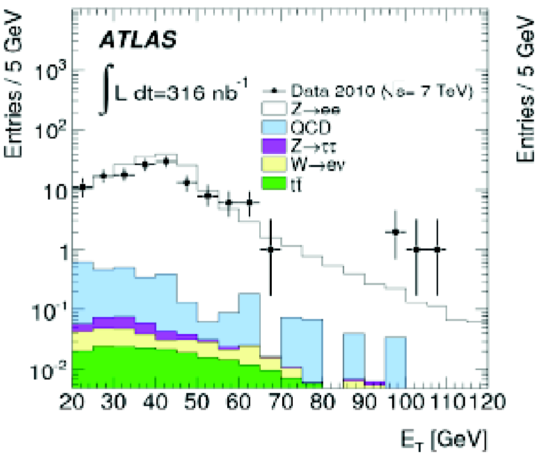
- $p_T > 20$ GeV
- *Track isolation*
- *Missing* $E_T > 25$ GeV
- $m_T > 40$ GeV
- ➢ *1181 Candidates*

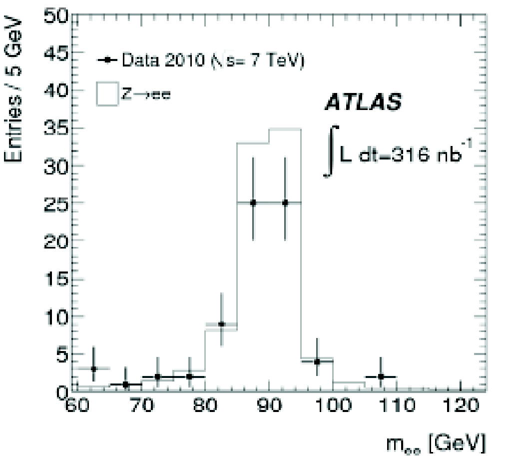


Z selection (2010)

2 Electrons :

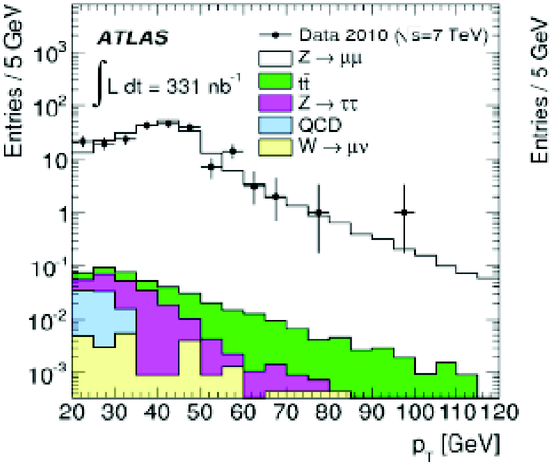
- $E_T > 20$ GeV
- Opposite charge
- Medium ID
- $66 < m_{ee} < 116$ GeV
- ➢ 70 Candidates

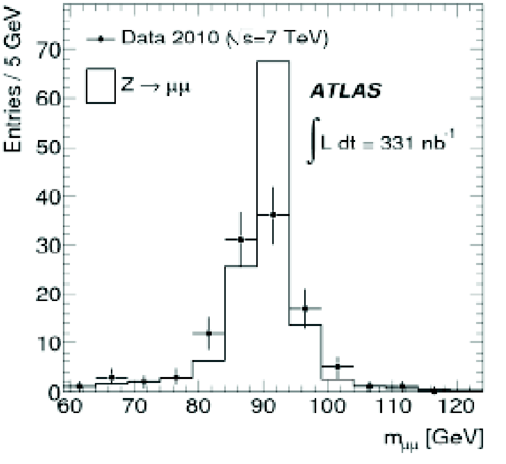




2 Muons :

- $p_T > 20$ GeV
- Track isolation
- Opposite charge
- $66 < m_{\mu\mu} < 116$ GeV
- ➢ 109 Candidates





W backgrounds

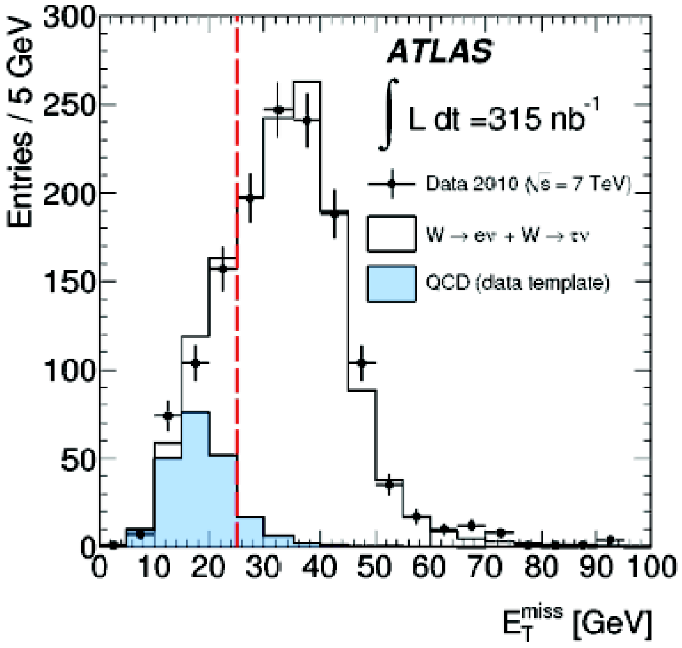
Electrons:

- EW + top background: W→ $\tau\ \nu$ + Z →e^+e^- + $t\bar{t}$

  N_{EW+TOP} = 33.5 ± 0.2(stat) ± 3.0(syst)

- QCD background is estimated with the template method using the missing energy distribution.

  N_{QCD} = 28.0 ± 3.0(stat) ± 10.0(syst)



Muons:

- EW + top background: Z → $\mu^+\mu^-$ + W→ $\tau\ \nu^-$ + $t\bar{t}$

  N_{EW+TOP} = 77.6 ± 0.3(stat) ± 5.4(syst)

- QCD background estimated from comparison of events seen in data after the full selection to number of events observed if the isolation is not applied.

  N_{QCD} = 22.8 ± 4.6(stat) ± 8.7(syst)

$$N_{loose} = N_{nonQCD} + N_{QCD}$$
$$N_{iso} = \epsilon^{iso}_{nonQCD} N_{nonQCD} + \epsilon^{iso}_{QCD} N_{QCD}$$

Cross-section & Luminosity

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\int \mathcal{L}\,\mathrm{d}t \cdot \varepsilon}$$

Luminosity

determined by accelerator, triggers, …

Efficiency

many factors, optimized by experimentalist

W cross-section measurement

The total cross section for each lepton channel can be obtained by:

$$\sigma_W \times BR(W \rightarrow l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

A_W is the geometrical acceptance calculated at generator level:

$$A_W = \left(\frac{N^{acc}}{N^{all}}\right)_{gen}$$

MC	A_W $W^+ \rightarrow e^+\nu$	A_W $W^- \rightarrow e^-\nu$	A_W $W \rightarrow e\nu$	A_W $W^+ \rightarrow \mu^+\nu$	A_W $W^- \rightarrow \mu^-\nu$	A_W $W \rightarrow \mu\nu$
PYTHIA MRST LO*	0.466	0.457	0.462	0.484	0.475	0.480
PYTHIA CTEQ6.6	0.479	0.458	0.471	0.499	0.477	0.490
PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.496	0.479	0.489
MC@NLO HERAPDF1.0	0.475	0.454	0.465	0.494	0.472	0.483
MC@NLO CTEQ6.6	0.478	0.452	0.465	0.496	0.470	0.483

W cross-section measurement

The total cross section for each lepton channel can be obtained by:

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

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MC	A_W $W^+ \to e^+\nu$	A_W $W^- \to e^-\nu$	A_W $W \to e\nu$	A_W $W^+ \to \mu^+\nu$	A_W $W^- \to \mu^-\nu$	A_W $W \to \mu\nu$
PYTHIA MRST LO*	0.466	0.457	0.462	0.484	0.475	0.480
PYTHIA CTEQ6.6	0.479	0.458	0.471	0.499	0.477	0.490
PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.496	0.479	0.489
MC@NLO HERAPDF1.0	0.475	0.454	0.465	0.494	0.472	0.483
MC@NLO CTEQ6.6	0.478	0.452	0.465	0.496	0.470	0.483

C_W correction factor and uncertainties

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

- C_W is a factor correcting for reconstruction, identification and trigger efficiencies of the lepton.

	$W \to e\nu$	$W \to \mu\nu$
C_W	0.66	0.76

- Components to systematic uncertainties, are summarized below:

Parameter	$\delta C_W/C_W(\%)$
Trigger efficiency	<0.2
Material effects, reconstruction and identification	5.6
Energy scale and resolution	3.3
E_T^{miss} scale and resolution	2.0
Problematic regions in the calorimeter	1.4
Pile-up	0.5
Charge misidentification	0.5
FSR modelling	0.3
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	7.0

Electrons

Parameter	$\delta C_W/C_W(\%)$
Trigger efficiency	1.9
Reconstruction efficiency	2.5
Momentum scale	1.2
Momentum resolution	0.2
E_T^{miss} scale and resolution	2.0
Isolation efficiency	1.0
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	4.0

Muons

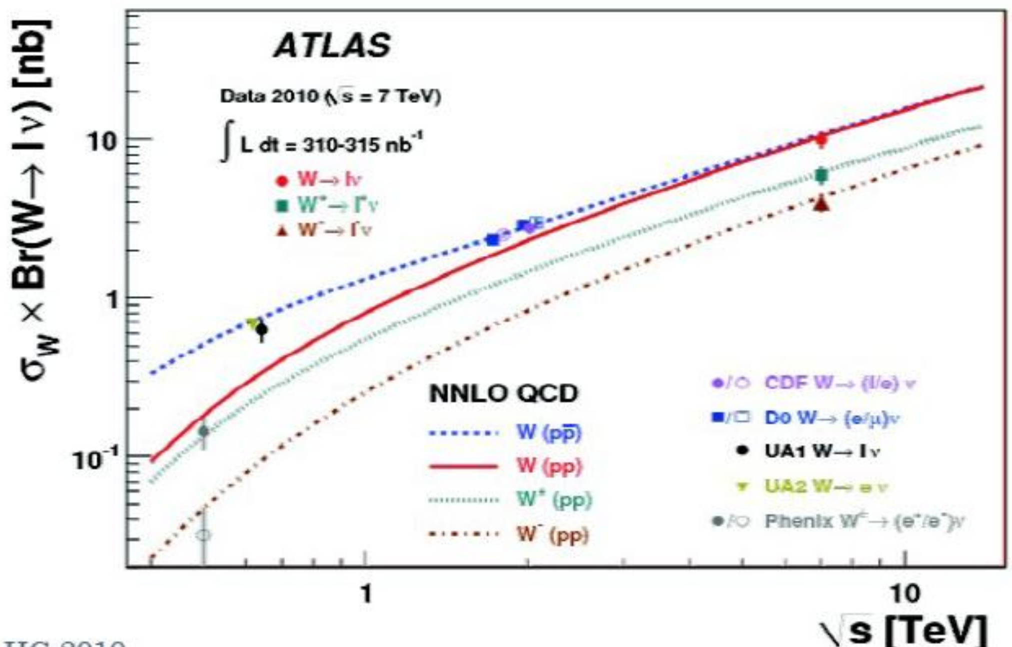
W cross-section measurement

$L \approx 310 - 315\ nb^{-1}$

Theory prediction : 10.46 ± 0.42 nb

$\sigma_W \times BR(W \to e\nu) = [10.51 \pm 0.34(stat) \pm 0.81(sys) \pm 1.16(lumi)]\, nb$

$\sigma_W \times BR(W \to \mu\nu) = [9.58 \pm 0.30(stat) \pm 0.50(sys) \pm 1.05(lumi)]\, nb$



Jose E. Garcia - HEP-LHC-2010

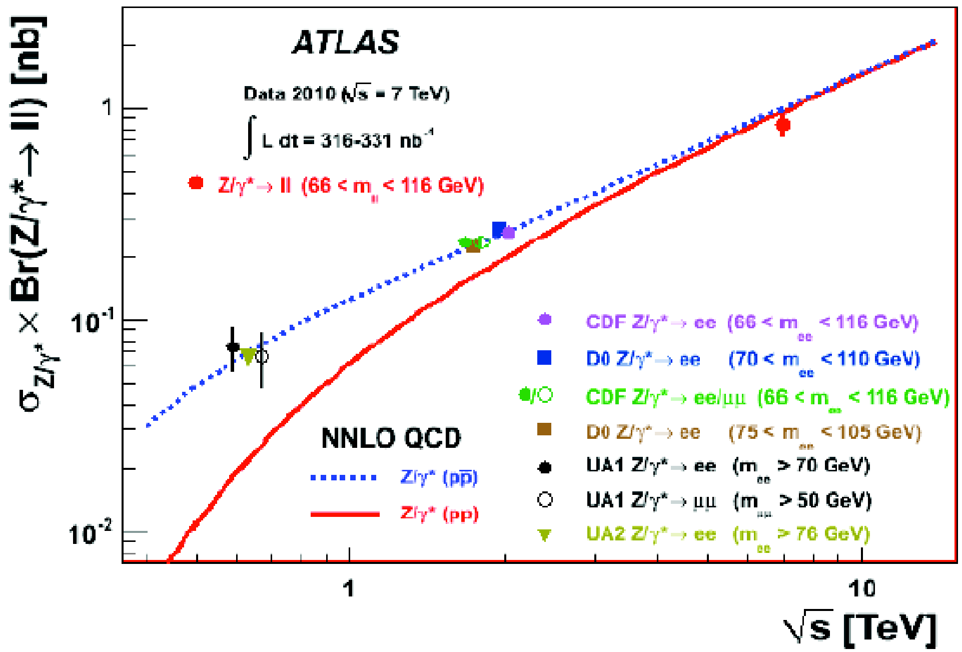
Z cross-section measurement

$L \approx 310 - 315\ nb^{-1}$

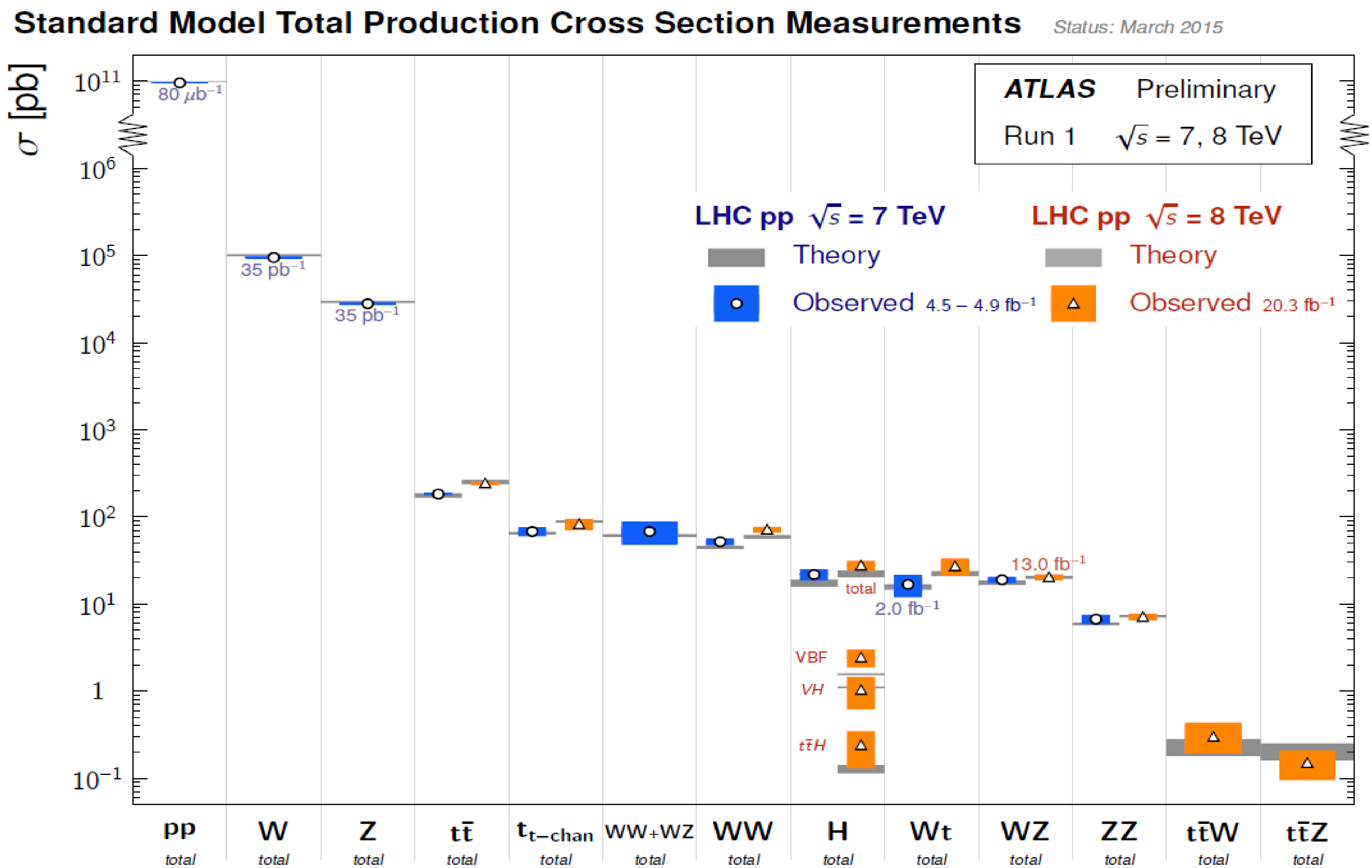
Theory prediction : 0.96 ± 0.04 nb for [66 – 116] GeV mass window

$$\sigma_Z \times BR(Z \rightarrow e^+e^-) = [0.75 \pm 0.09(stat) \pm 0.08(sys) \pm 0.08(lumi)]\, nb$$

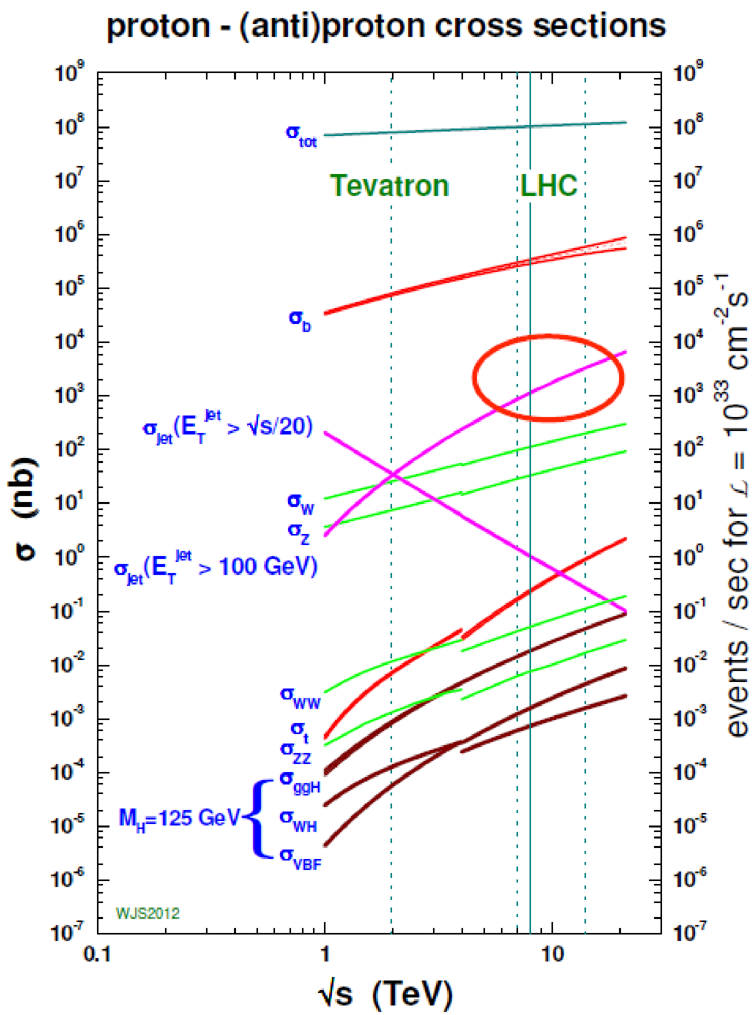
$$\sigma_Z \times BR(Z \rightarrow \mu^+\mu^-) = [0.87 \pm 0.08(stat) \pm 0.06(sys) \pm 0.10(lumi)]\, nb$$



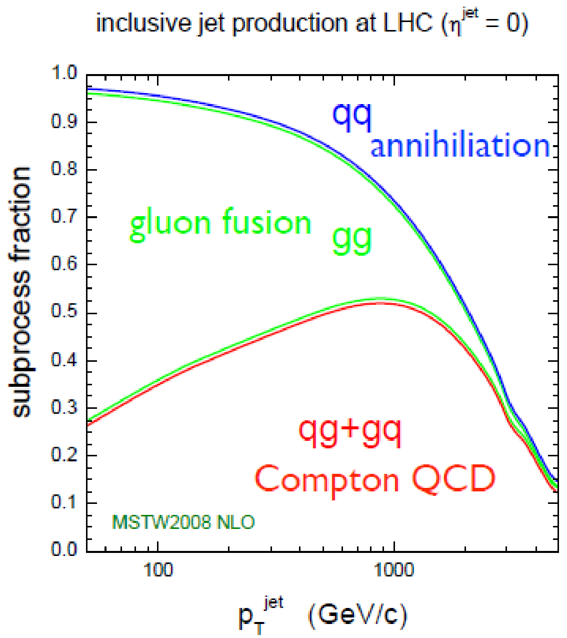
Production cross-sections



Jet physics

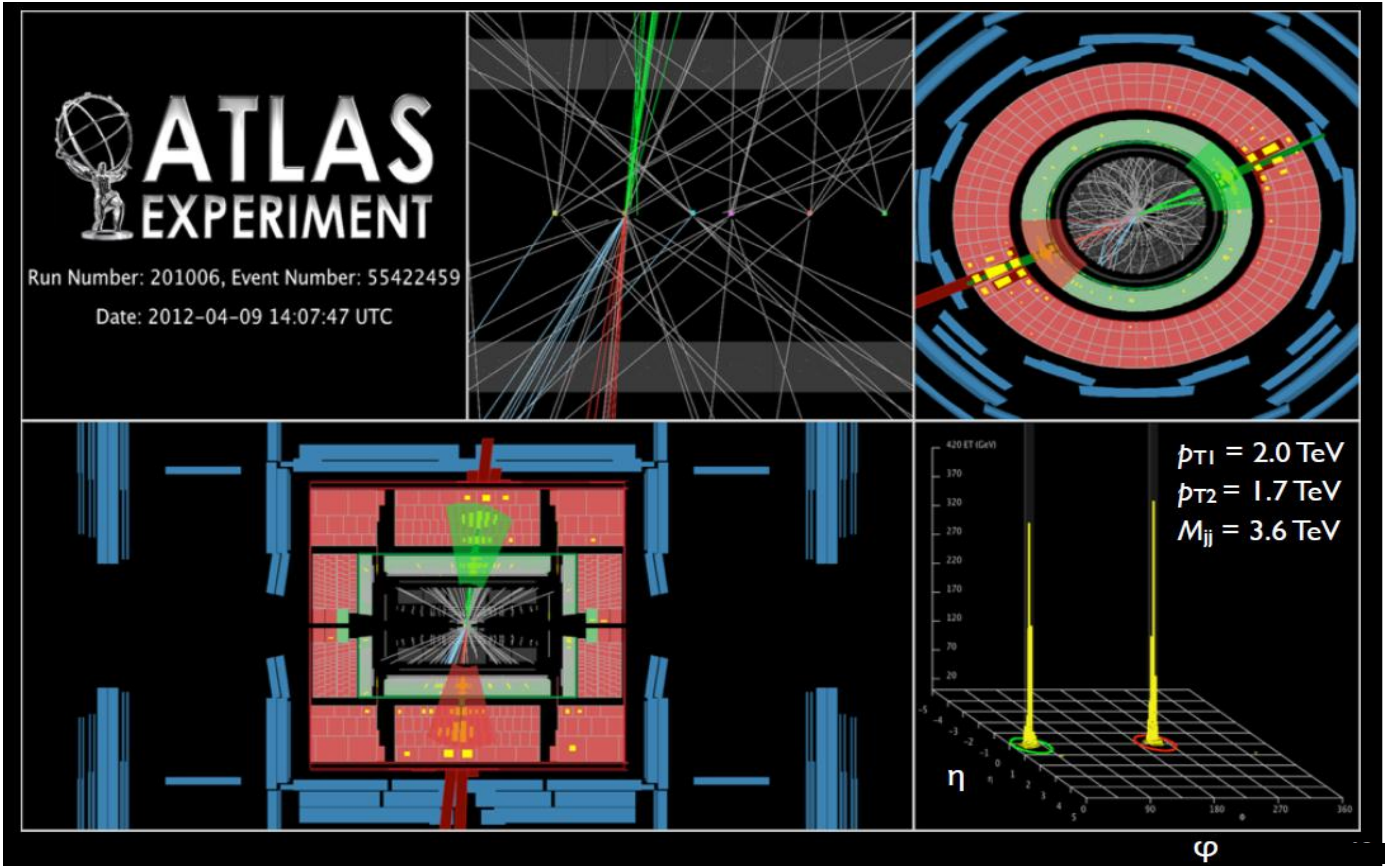


99% of events at the LHC contain at least one jet with $E_T^{jet} > 20$ GeV

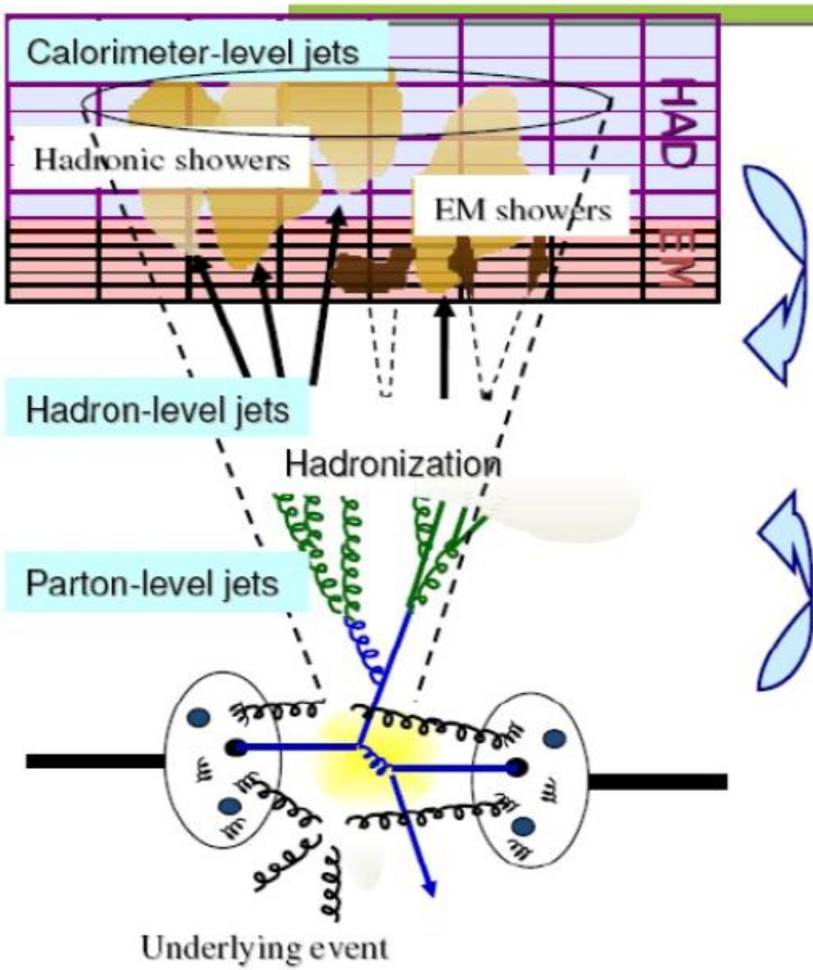


- Understand quark-gluon content of proton up to highest energies
- Perform Rutherford analysis at quark level and constrain quark compositeness

Confinement, hadronisation, jets….



Inclusive jet production



Unfold measurements to the hadron (particle) level

Correct parton-level theory for non-perturbative effects (hadronization & underlying event)

Jets are collimated spray of particles originating from parton fragmentation.
→ To be defined by an algorithm

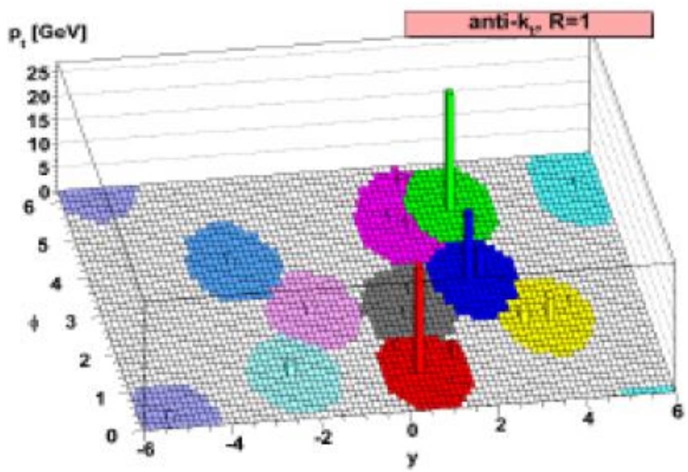
Jet reconstruction

- Jet finding: from partons/particles/energy deposits to jet

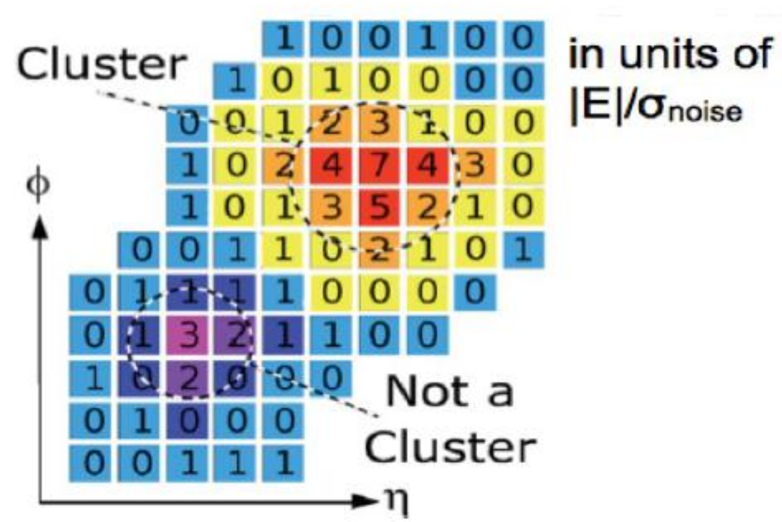
Energy deposits → noise-suppressed 3D clusters:
exploit transverse and longitudinal calorimeter segmentation

Jet inputs clustered with anti-k_T algorithm:

- Infrared safe, collinear safe (⇒ NLO comparisons)
- Regular, cone-like jets in calorimeters
- Distance parameter 0.4, 0.6

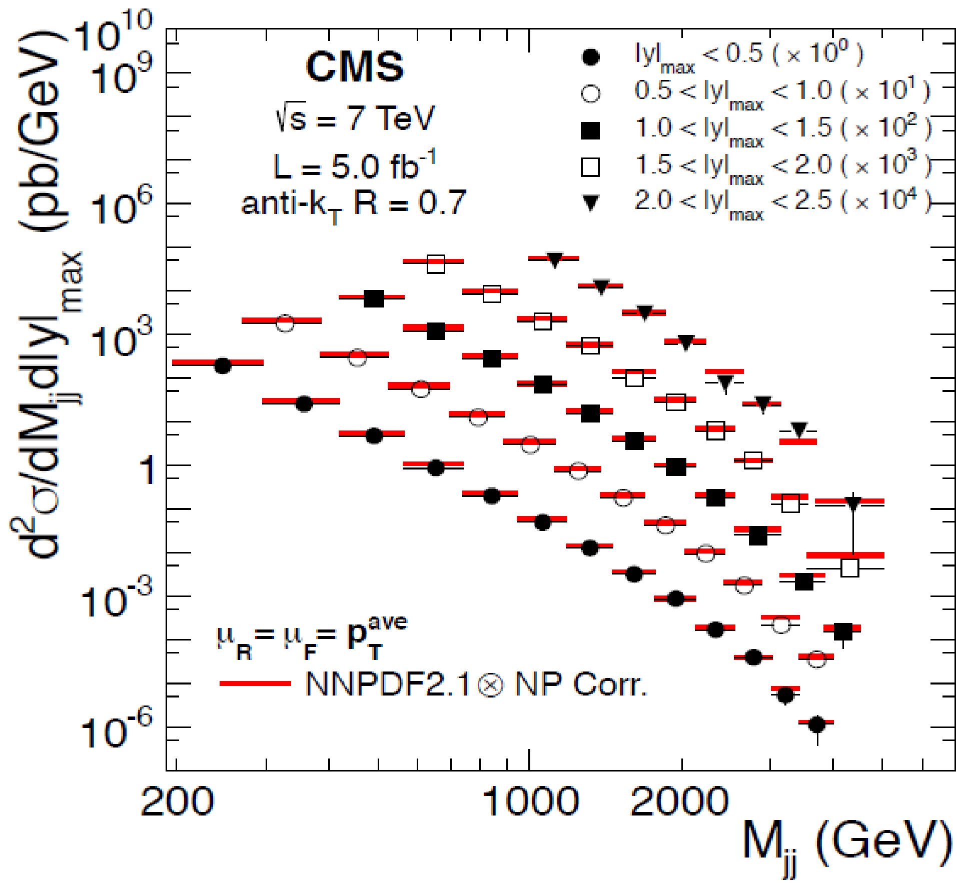


[Cacciari, Salam, Soyez
JHEP 0804:063,2008]



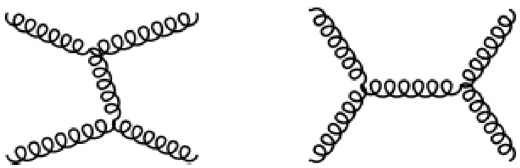
Di-jet cross-section

As a function of di-jet invariant mass in bins of rapidity (up to y_{max} = 2.5)

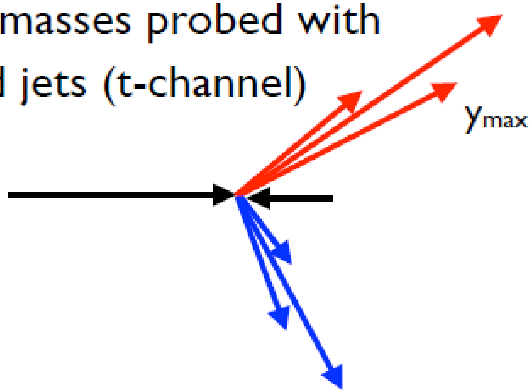


Excellent agreement between NLO theory prediction and data over eight orders of magnitude

Probing di-jet masses up to 4 TeV



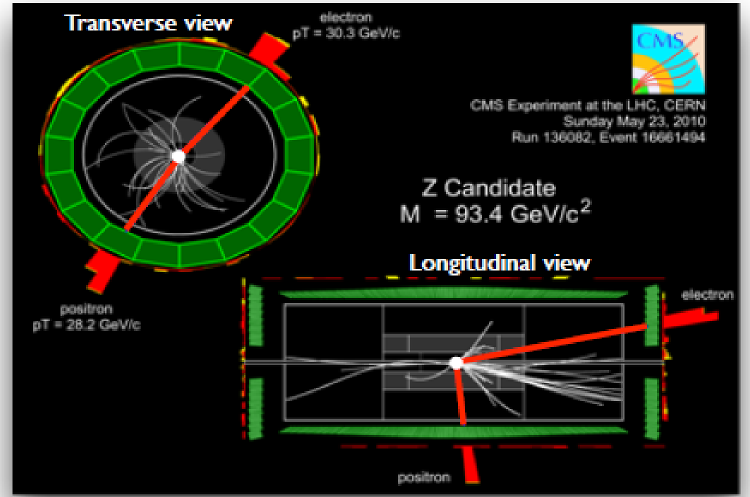
Higher masses probed with forward jets (t-channel)



$2 \rightarrow 2$ process

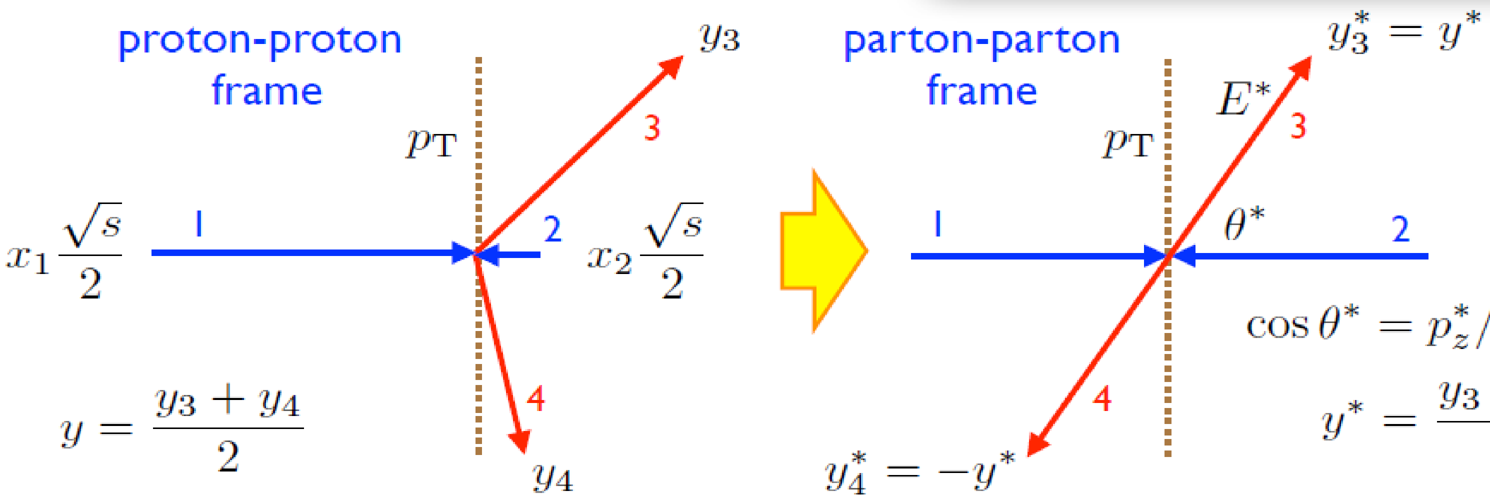
$$p_1 + p_2 \rightarrow p_3 + p_4$$

incoming partons (along beam axis) — outgoing particles (assumed massless)



From p_T, y_3 and y_4 extract:

- mass and rapidity of the 3+4 pair
- (hence x_1 and x_2)
- CoM scattering angle



$$y = \frac{y_3 + y_4}{2}$$

$$\cos\theta^* = p_z^*/E^* = \tanh y^*$$

$$y^* = \frac{y_3 - y_4}{2}$$

$$M = 2p_T \cosh \frac{y_3 - y_4}{2}$$

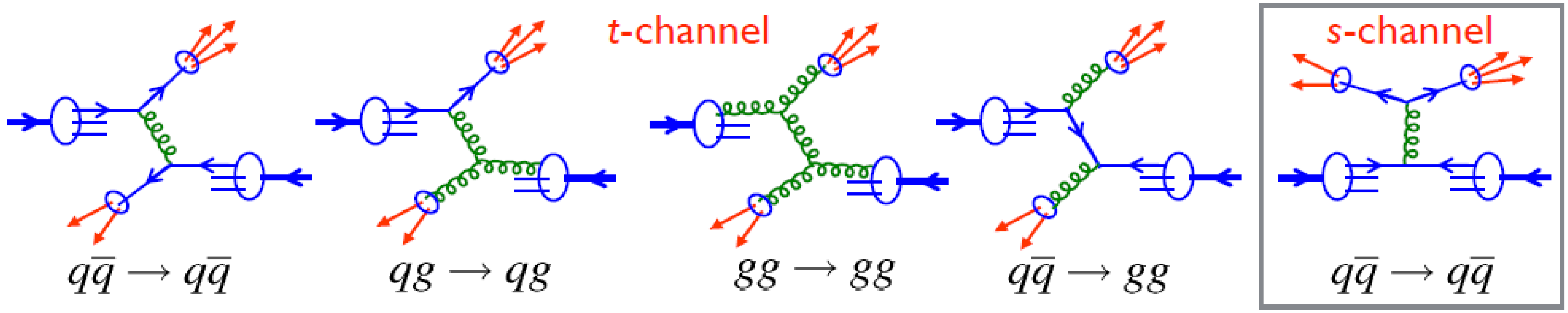
$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

$$\cos\theta^* = \tanh \frac{y_3 - y_4}{2}$$

The difference in rapidity determines the centre of mass scattering angle

Quark Compositeness?

Most important subprocesses via exchange of a massless vector boson in the *t*-channel

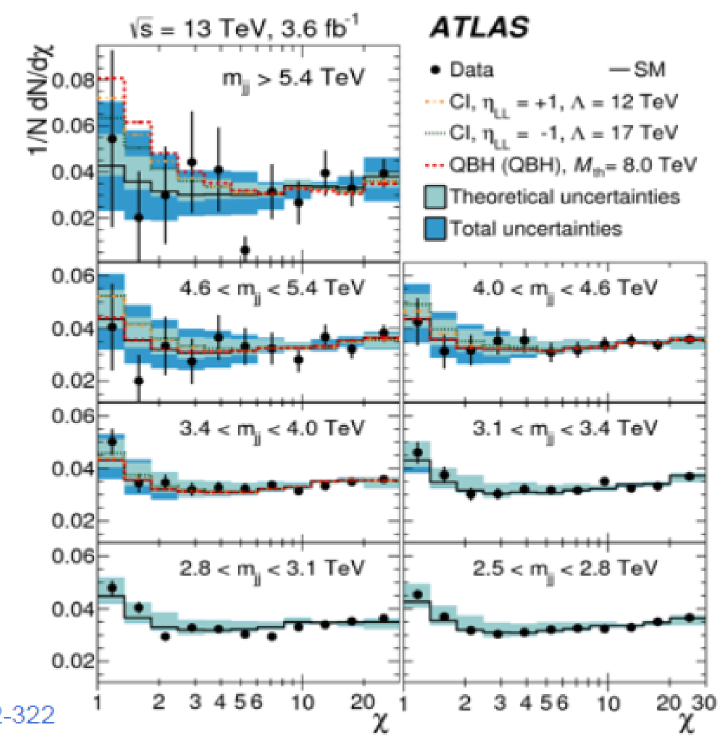


Rutherford at quark level
$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim \frac{1}{\sin^4(\theta^*/2)}$$

Variable
$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*} = e^{|y_3-y_4|}$$

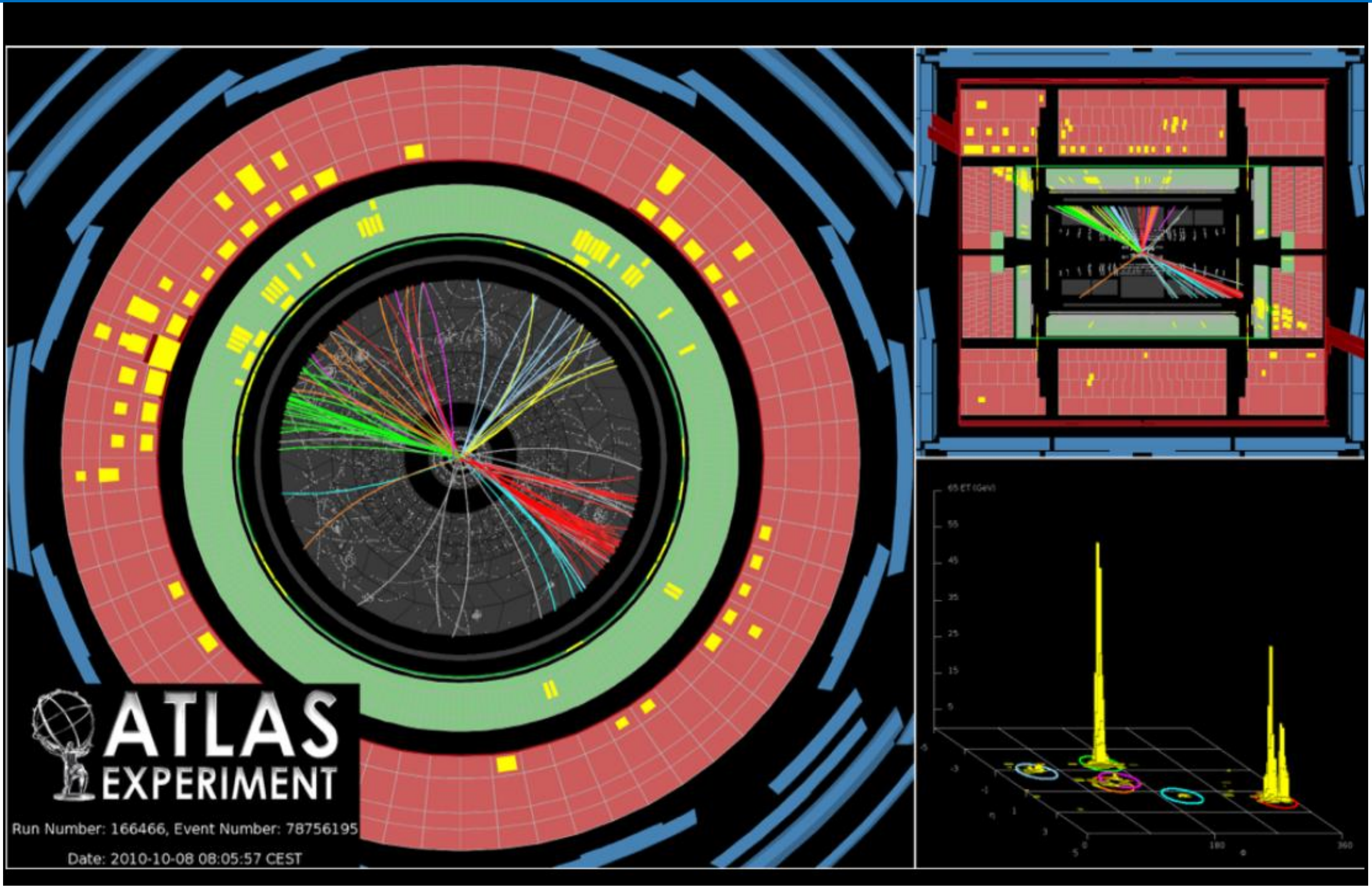
For pointlike quark: $\frac{d\hat{\sigma}}{d\chi} \sim \text{cst}$ at small angle

No evidence for quark/gluon compositeness from angular distributions



PLB 754 (2016) 302-322

Three jets


ATLAS
EXPERIMENT
Run Number: 166466, Event Number: 78756195
Date: 2010-10-08 08:05:57 CEST

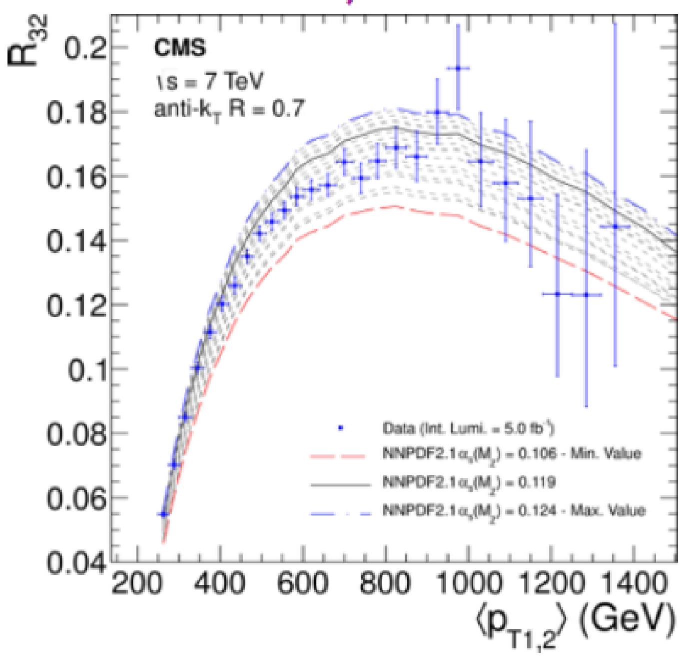
Constraints on Strong Coupling

Constraints on α_S from several jet analyses

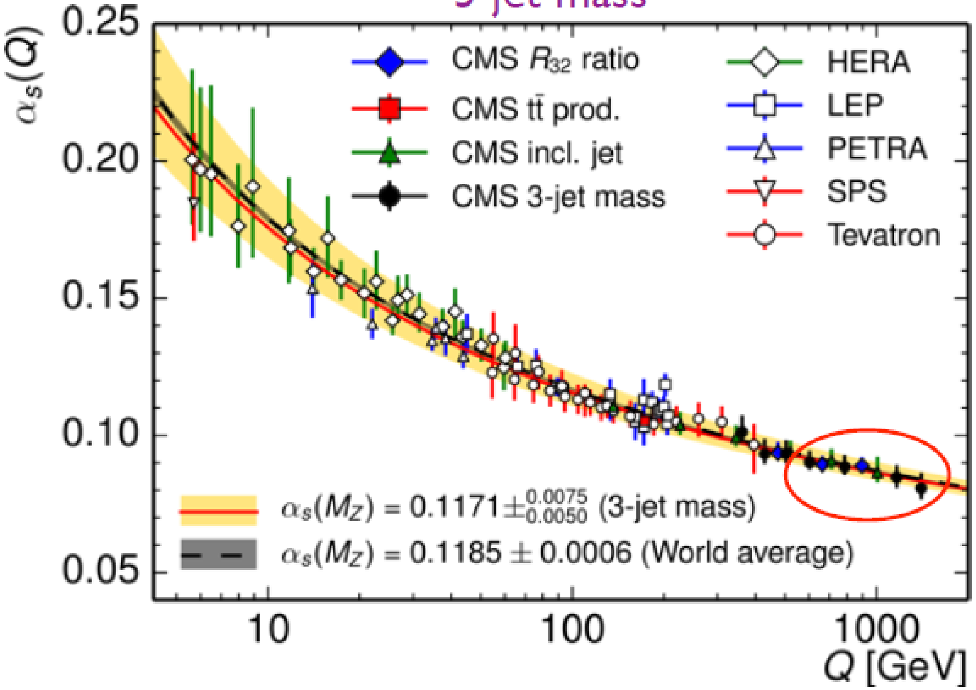
- inclusive jet production
- ratio 3-jets to 2-jets
- 3-jet mass spectrum

Uncertainties usually dominated by theory (PDFs and scales)

3 to 2 jet ratio



3-jet mass

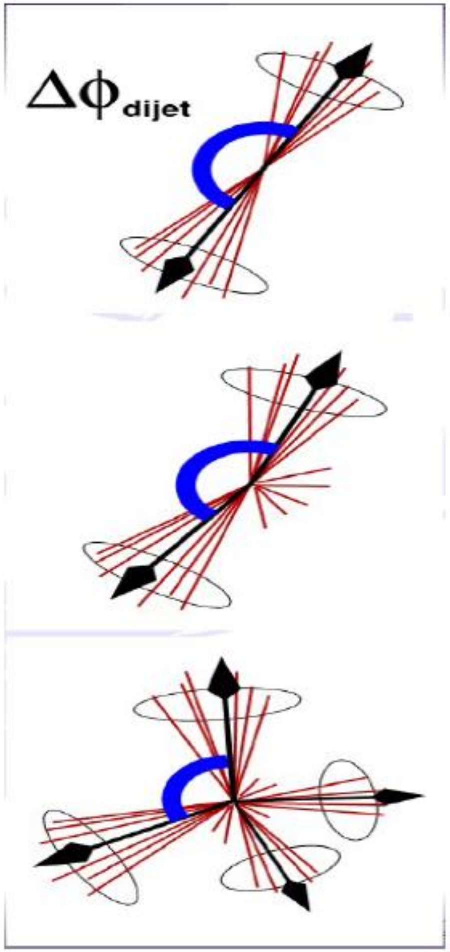


Not competitive with most precise measurements at the Z boson

- but in unprecedented range in energy (two orders of magnitude in Q!)

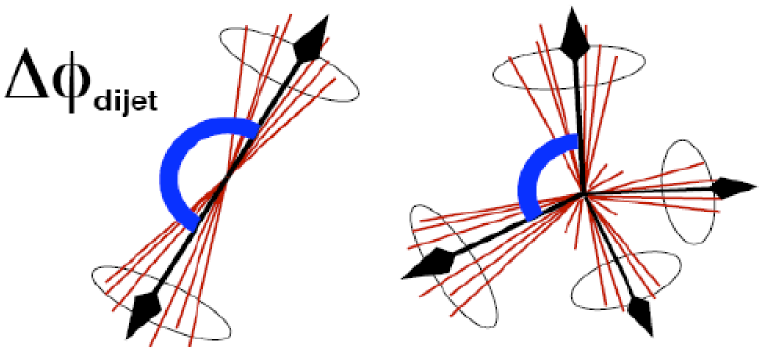
Multi-jet events

- Azimuthal decorrelations in dijet events and distribution of energy within jets sensitive to QCD radiation structures
  - Probing higher order QCD radiation
  - Main systematics: cluster energy scale (separate from JES) and unfolding

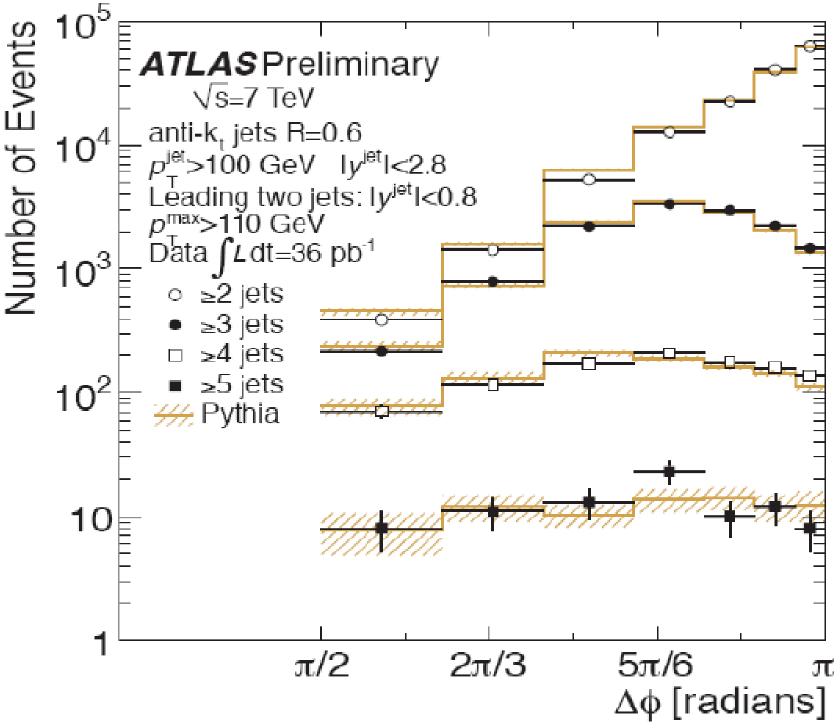


Azimuthal decorrelations

- Complementary to multi-jet cross section measurement.
- Pure di-jets have azimutal angle Φ between jets equal to π.
- With additional hard radiation, i.e. extra jets, phi becomes smaller.



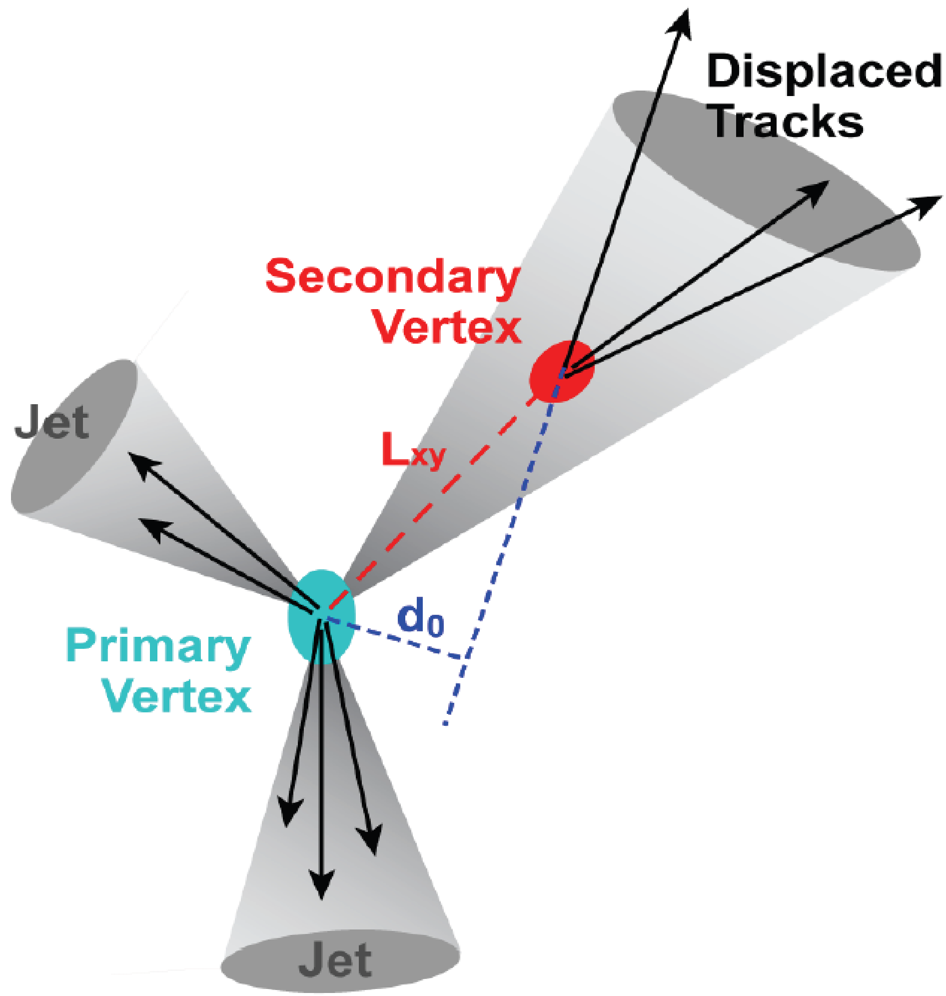
- Requiring additional jets flattens distribution.



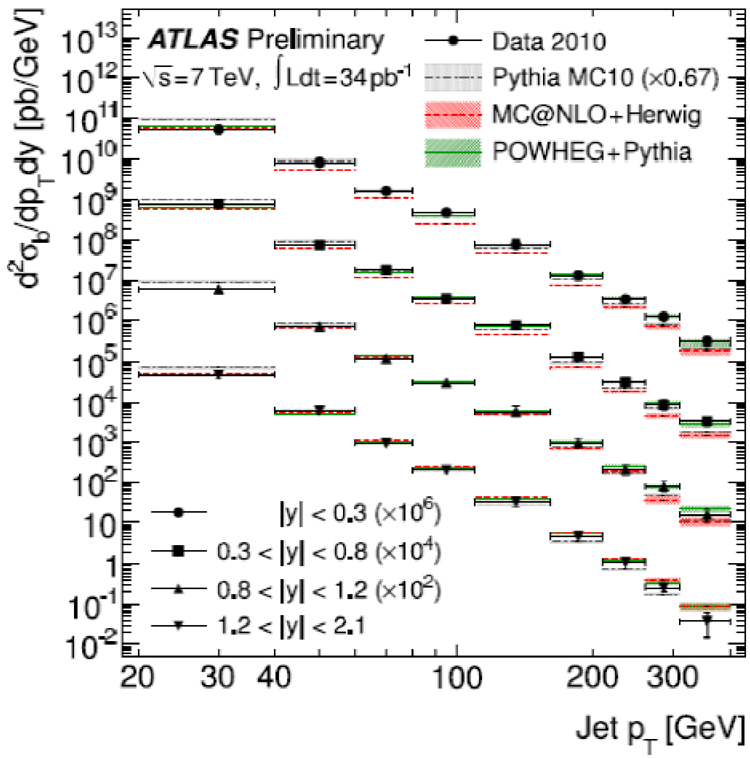
Confinement, hadronisation, jets....

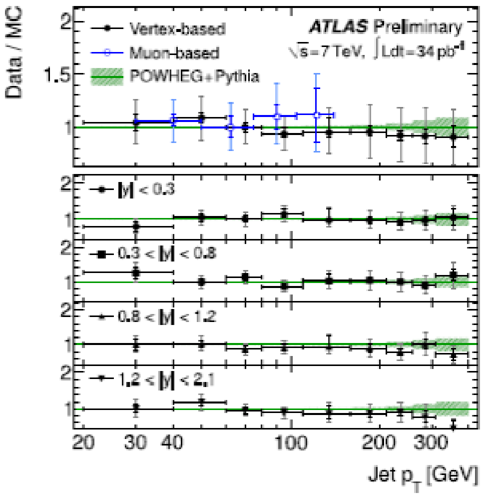
B-tagging

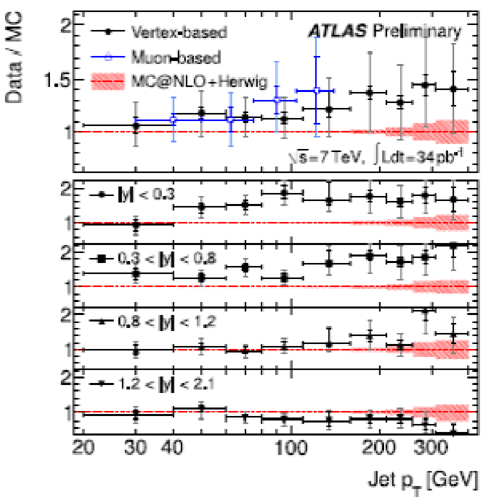
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark content
- Similar procedure for c quark…



b-jet cross-sections

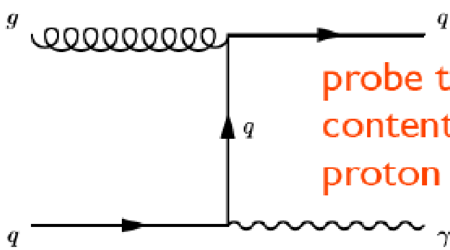




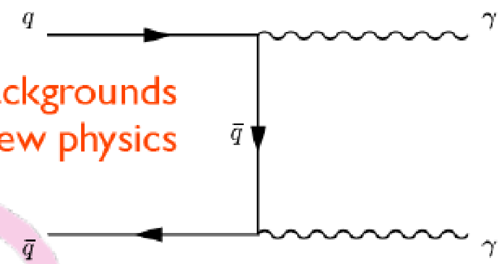


- Good agreement with Powheg+PYTHIA
- MC@NLO+Herwig predicts too few central jets, too many forward jets

Why measure prompt photons

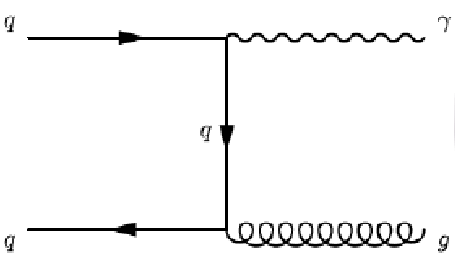


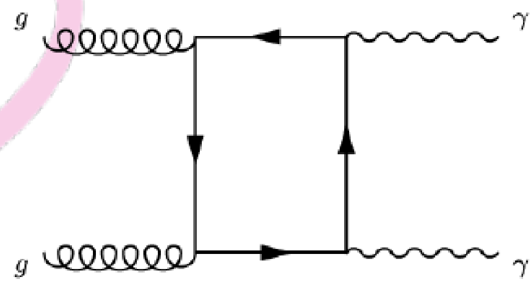
probe the gluon content of the proton



QCD backgrounds to new physics

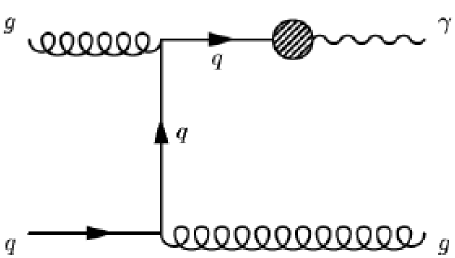
test NLO *p*QCD predictions using a measurement without jets



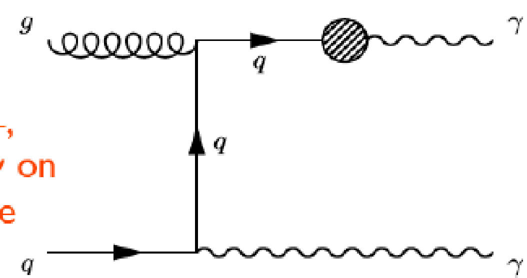


resummation

k_T factorisation

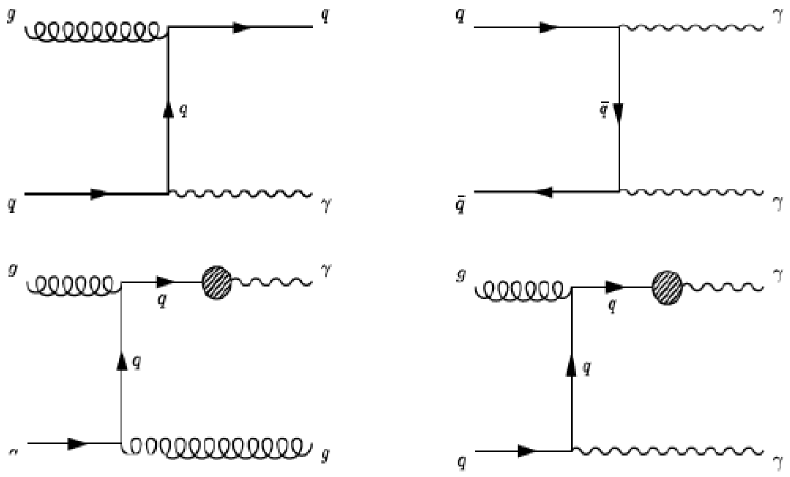


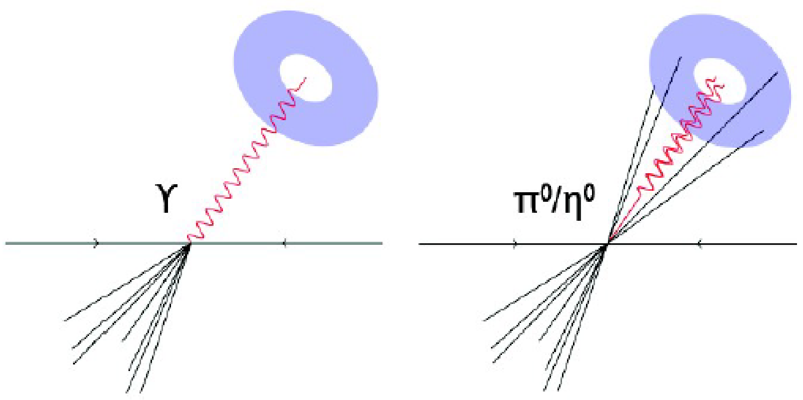
fragmentation important at low E_T, suppressed by isolation cut. MCs rely on fragmentation function to compute



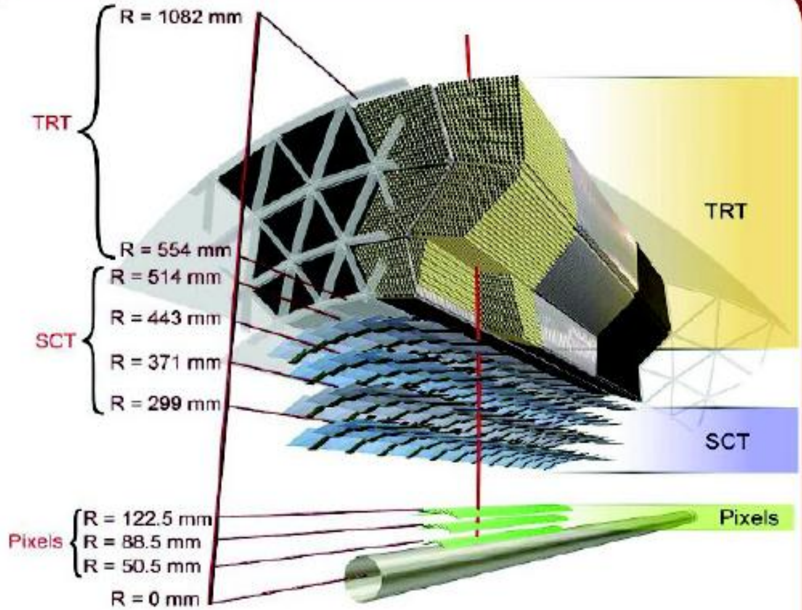
Prompt and isolated photons

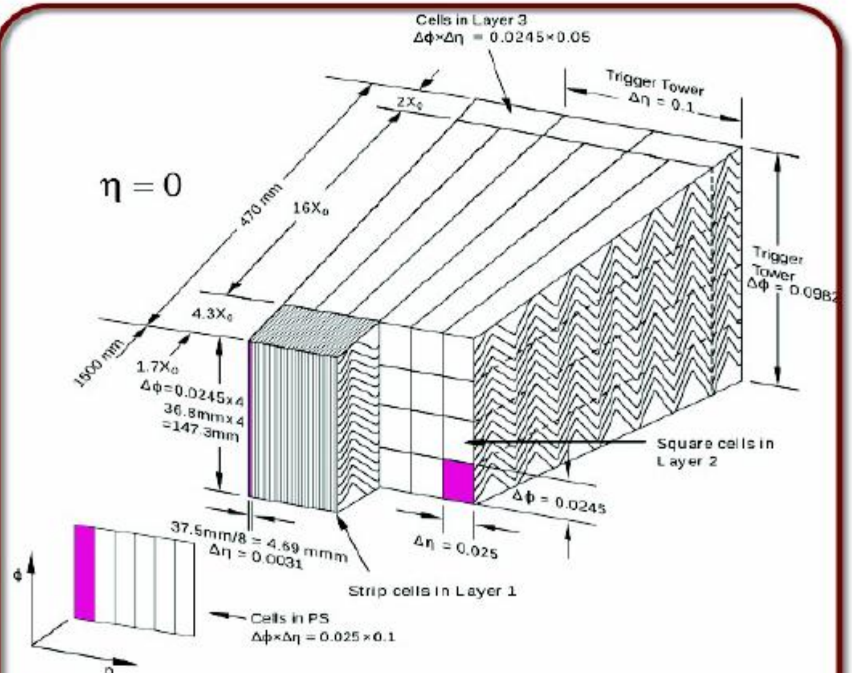
- Prompt:
  - Direct from the hard scattering
  - Parton fragmentation more important at low E_T
- Isolated:
  - Isolation criteria to reduce bgd from QCD jets
    - Photons from neutral meson decay in jets
  - Reduced fragmentation component:
    - ~30% reduction at 15 GeV
    - <10% above 35 GeV





Measuring photons with ATLAS

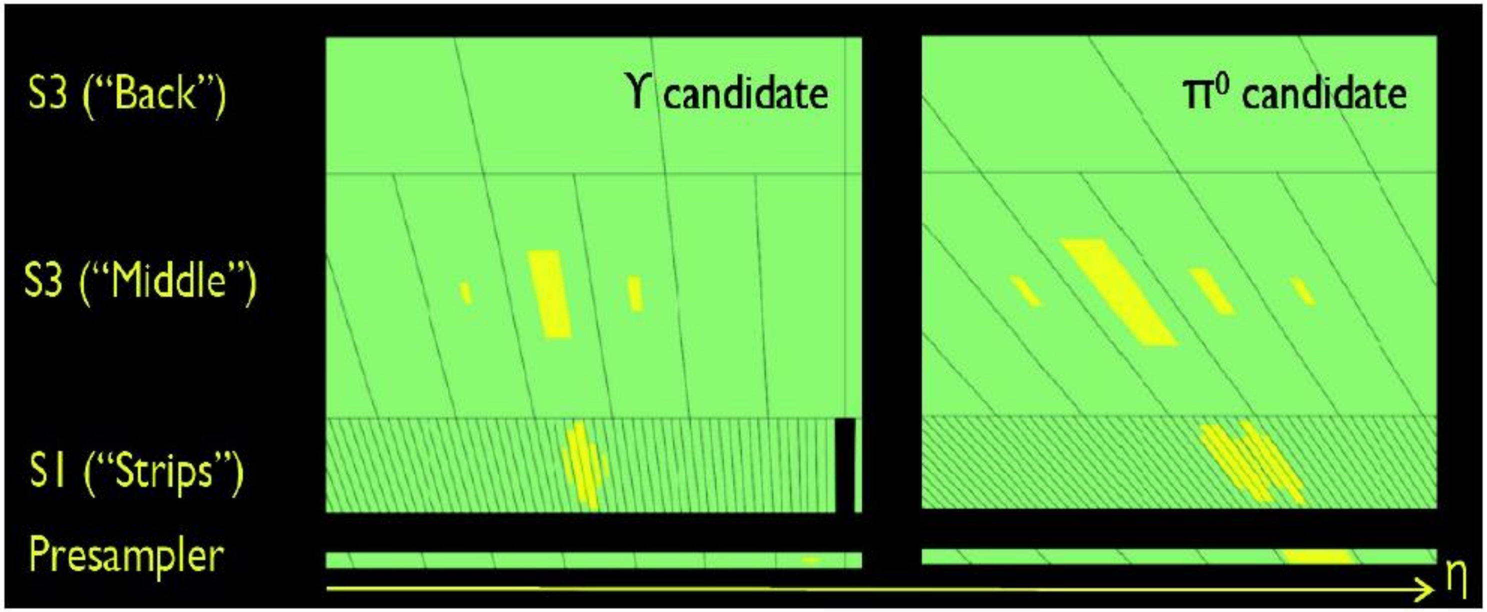


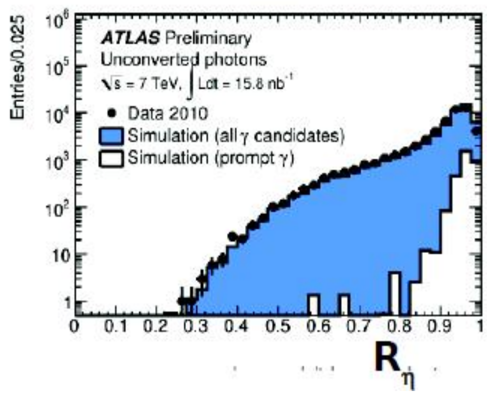


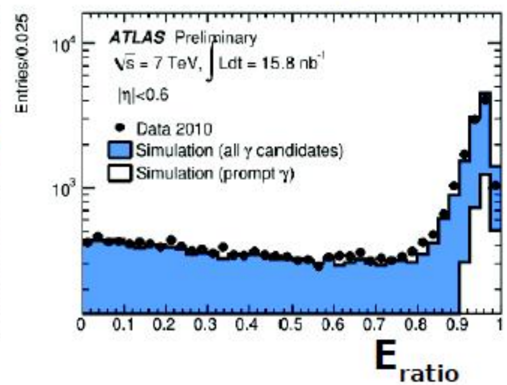
- Inner detector
  - ✓ track charged particles
  - ✓ measure transition radiation
  - ✓ e/γ discrimination
  - ✓ γ conversion reconstruction

- Pb-LAr EM calorimeter
  - ✓ η/φ/longitudinal segmentation
  - ✓ fine granularity in 1st layer up to η<2.37
  - ✓ γ energy and direction
  - ✓ γ/π⁰ separation (EM shower moments)

Photon identification



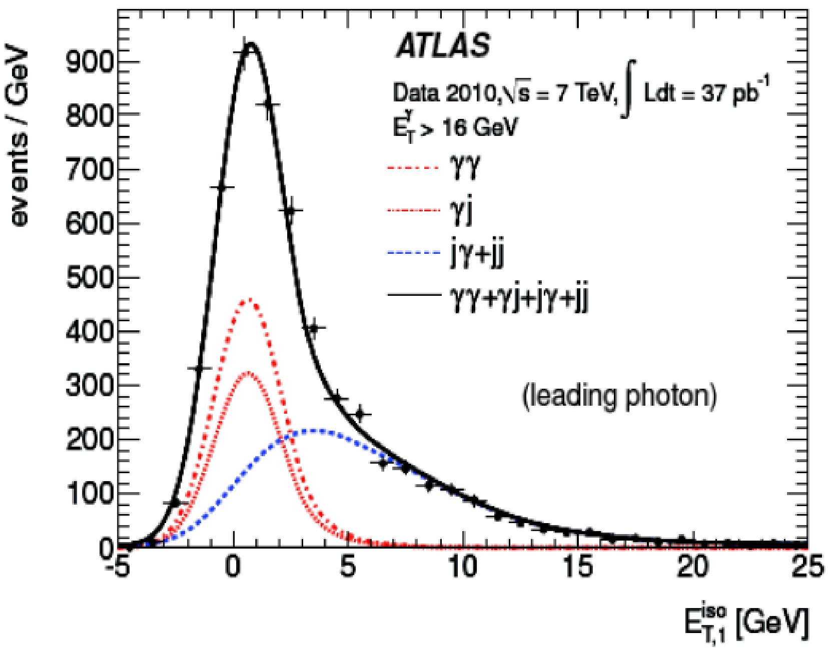


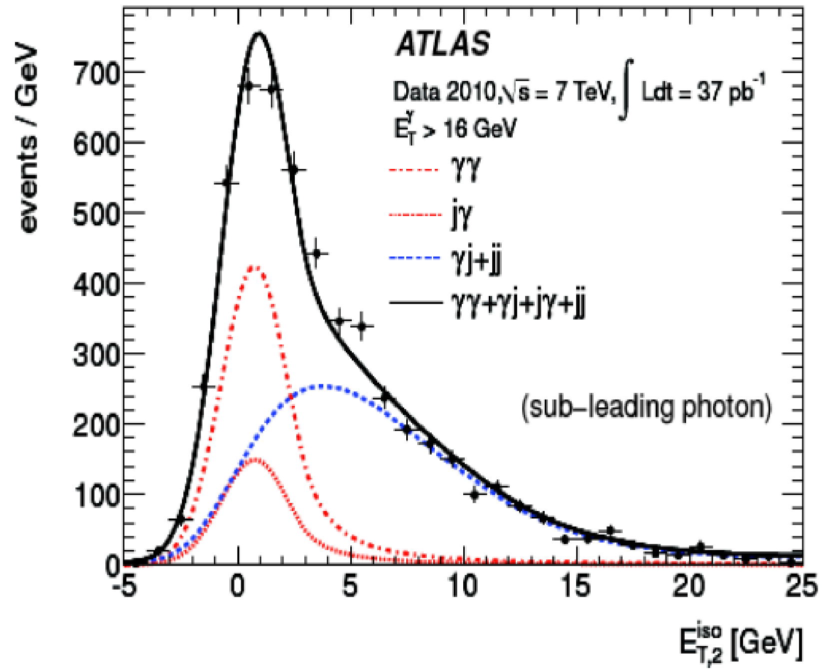


- loose and tight selection
- optimised separately for unconverted and converted photons

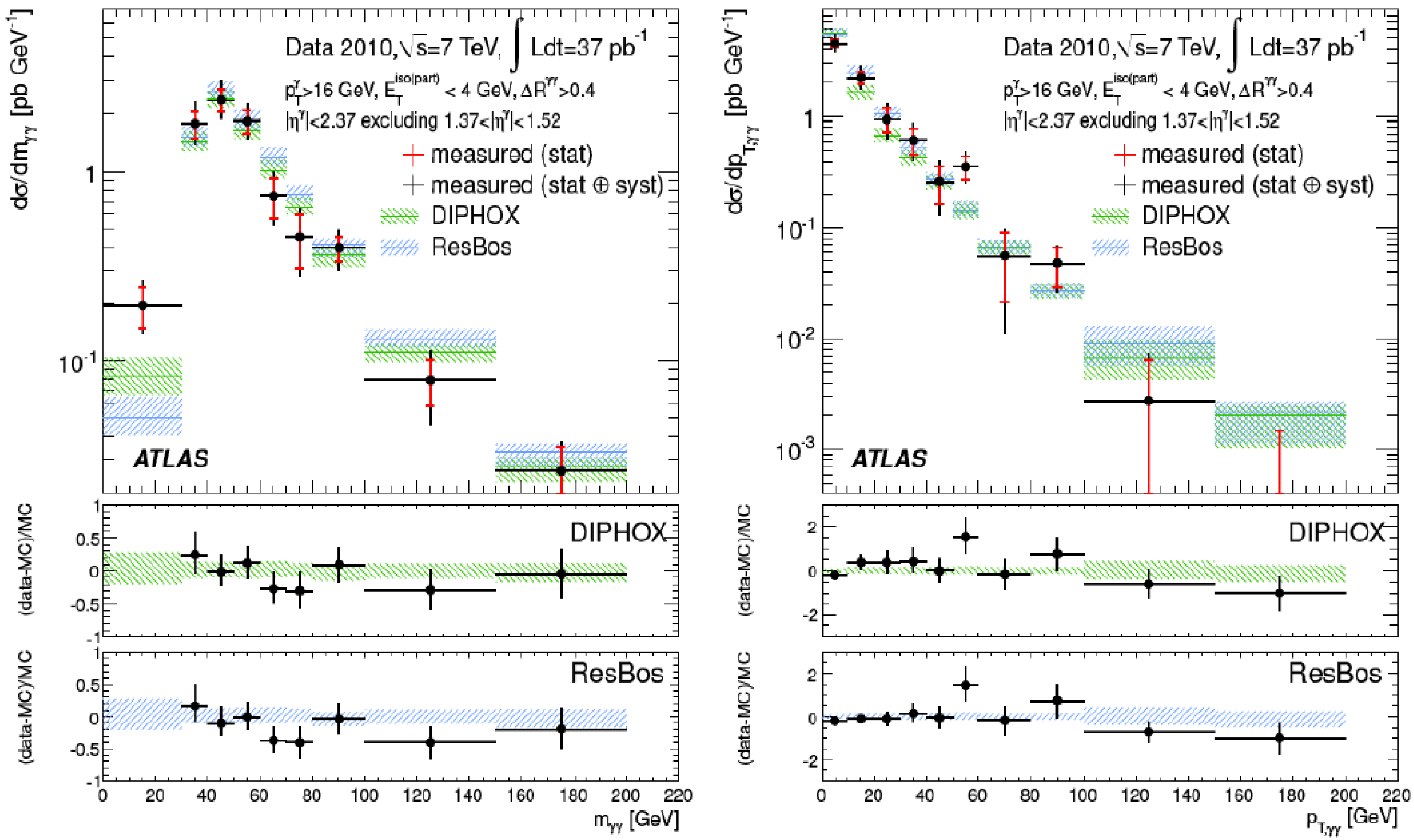
Photon isolation and background estimate

- Background estimated with two methods:
  - ABCD method: extrapolate from the bgd enriched control regions
  - here shown example of 2D template fit





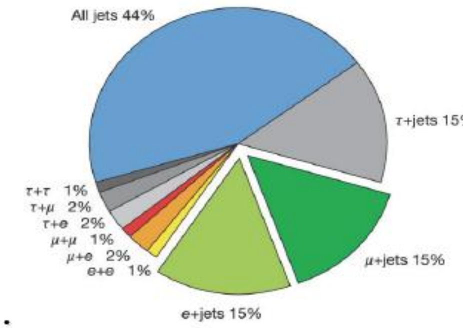
Isolated di-photon cross-section

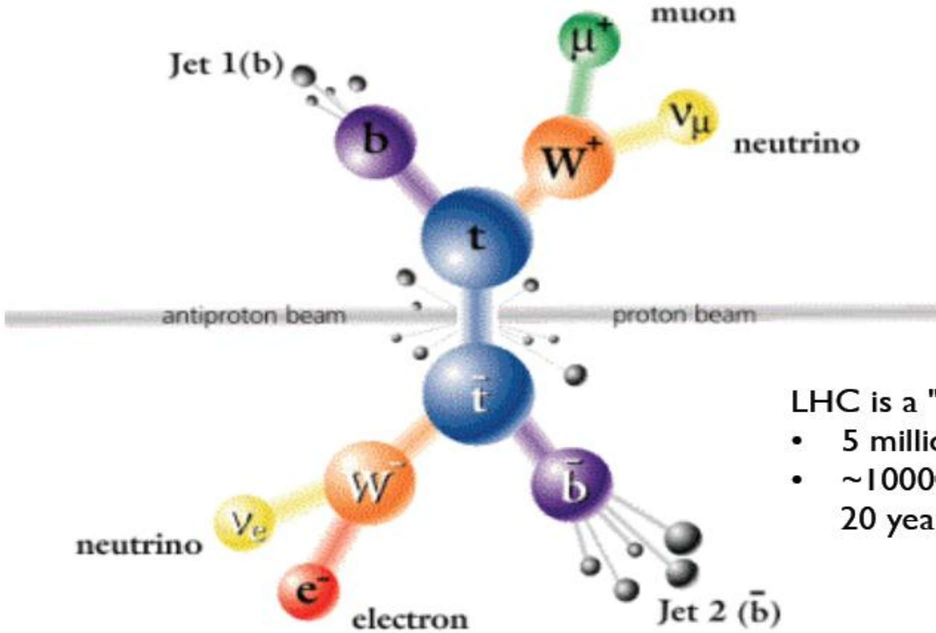


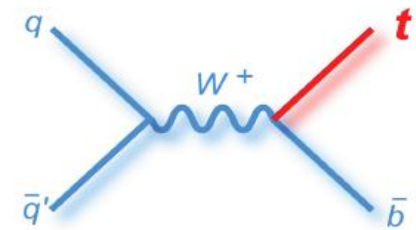
Complicated topologies….

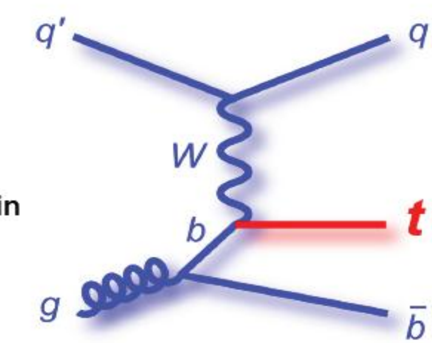
top quark

- Top quark has a mean lifetime of 5×10^{-25} s, shorter than time scale at which QCD acts: no time to hadronize!
  - ✓ It decays as $t \to Wb$
- Events with top quarks are very rich in (b) jets…





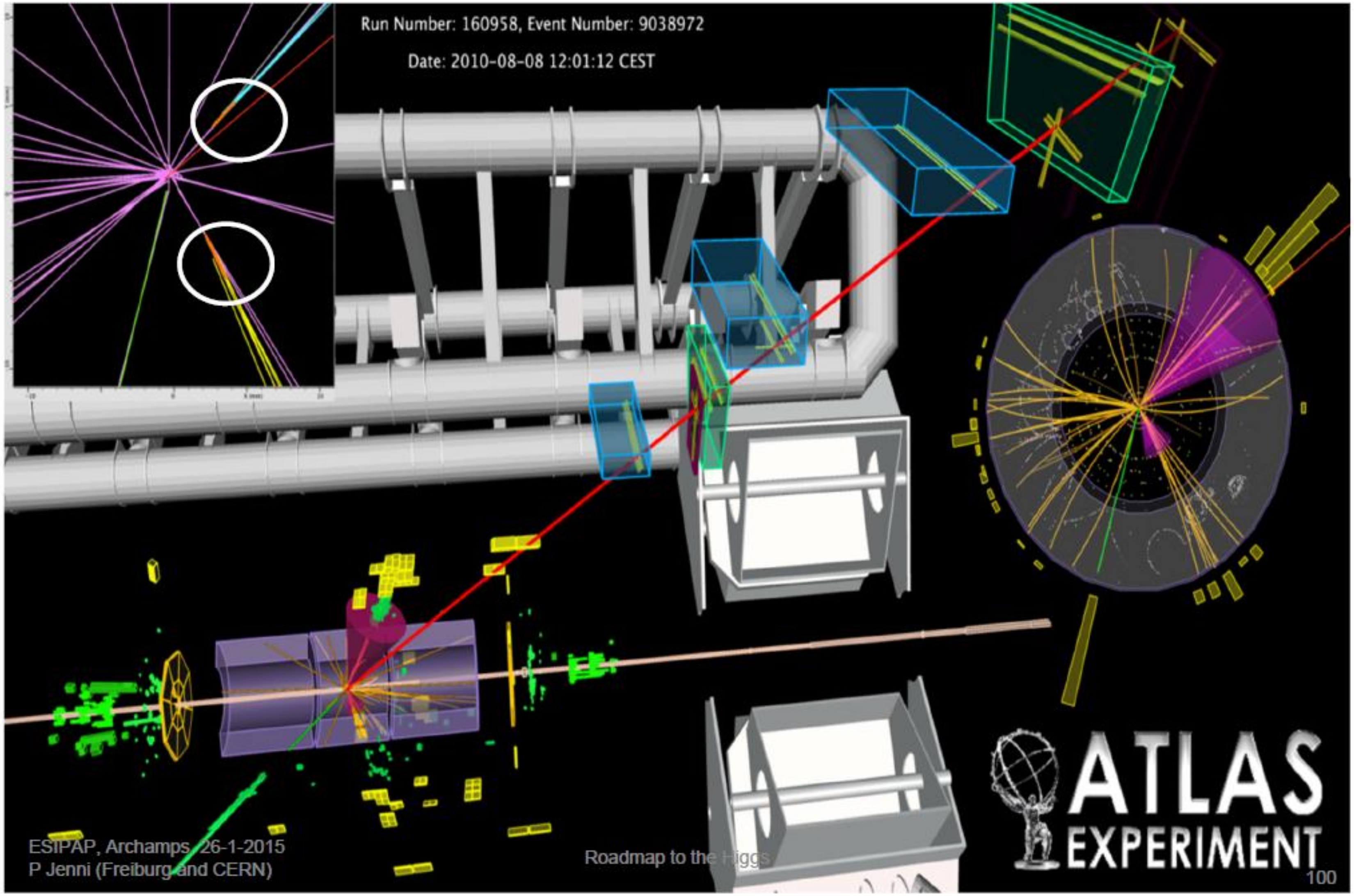




LHC is a "top factory"!
- 5 millions of tt pairs
- ~100000 in Tevatron in 20 years

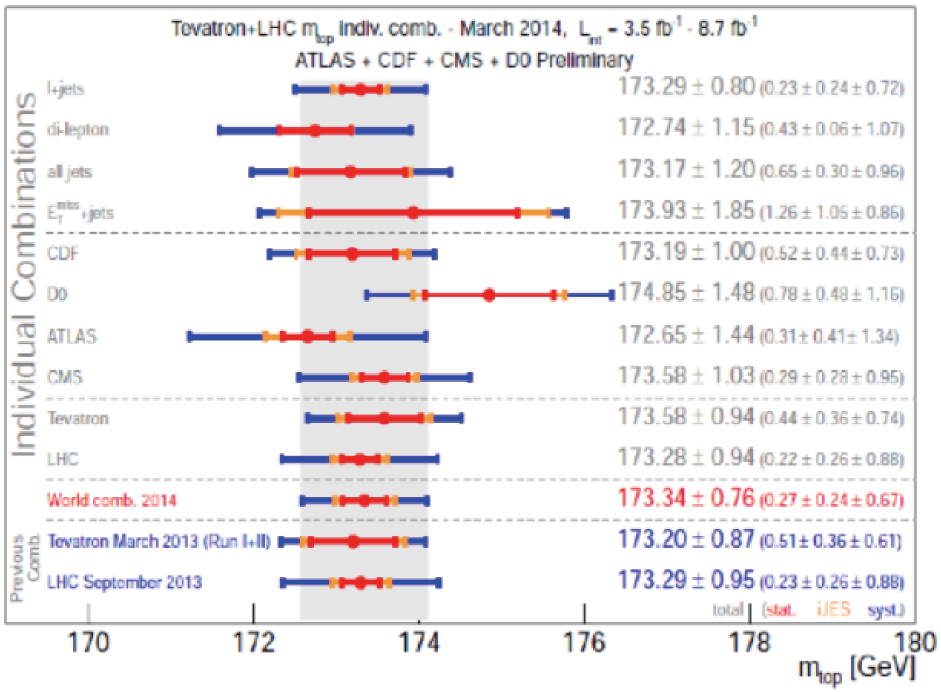
$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss

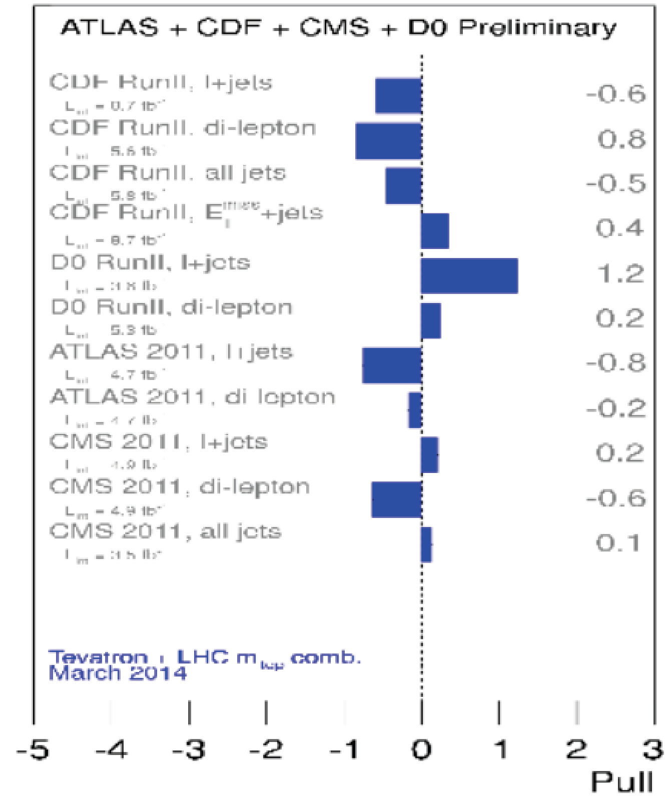


Mass of the top quark

Tevatron combination November 2012 May 2013
LHC combination July 2012 September 2013
World combination March 2014 arXiv:1403.4427



Combination using BLUE



$$m_{top} = 173.34 \pm 0.27\,(\text{stat}) \pm 0.24\,(\text{iJES}) \pm 0.67\,(\text{syst})\ \text{GeV}$$

precision on M_{top} 0.44%

Consistency χ^2=4/10

Highest precision in l+jet channel
Dilepton channel good precision
Fully hadronic channel respectable

Electroweak measurements at LHC