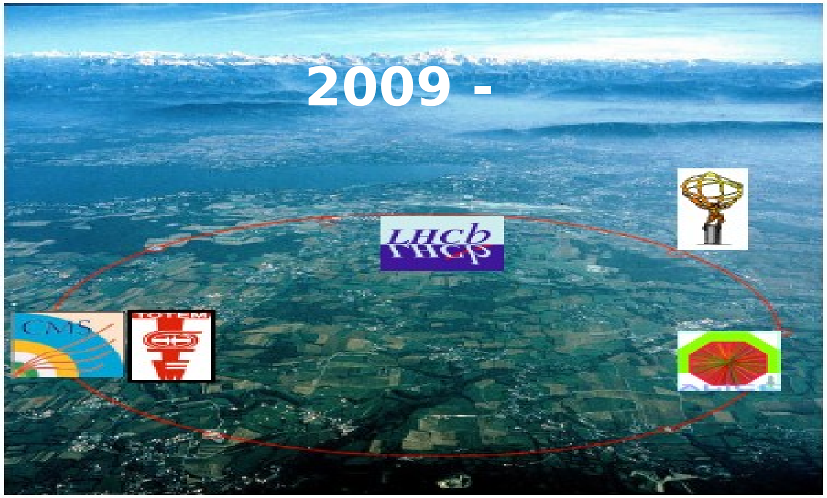
Hadron Collider Physics

Lecture 3

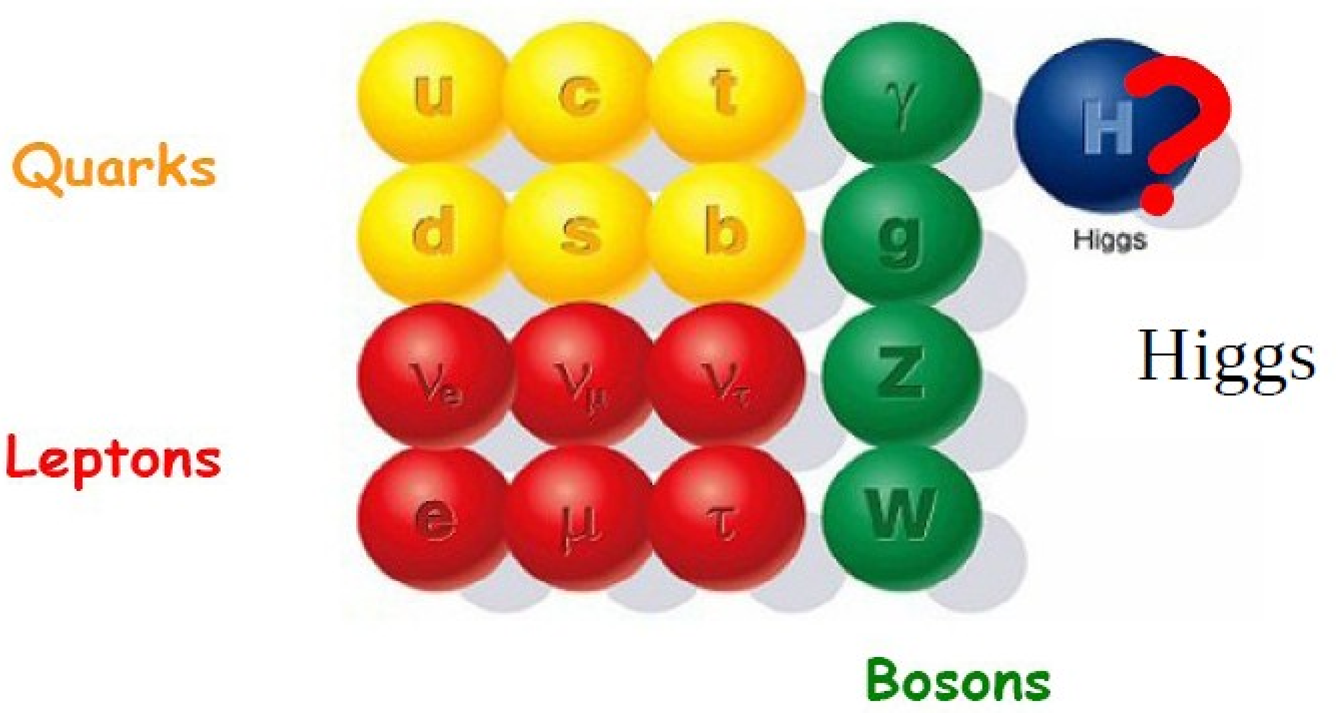
- Top quarks
- photons



Disclaimer:

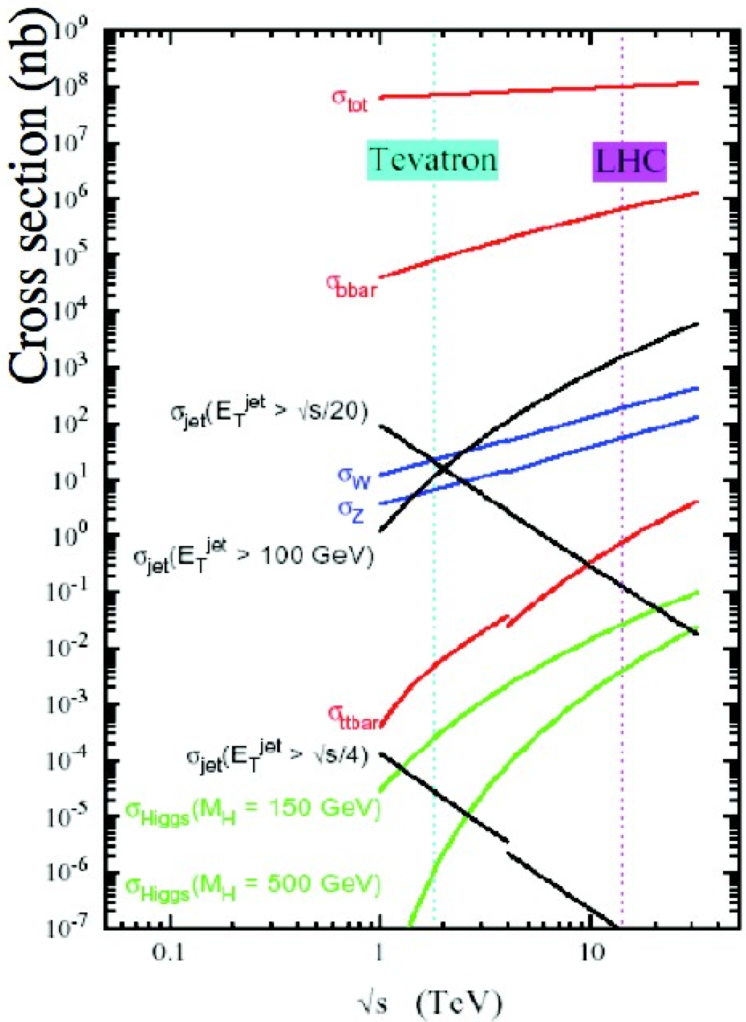
- **shown results based on 2010-2011 data for LHC**
- **the 2012 news left to topical lectures of the next week**

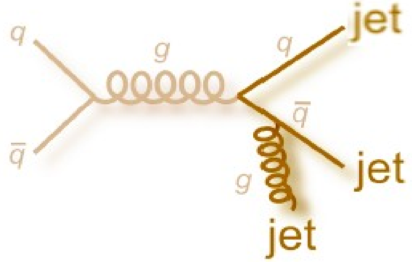
Standard Model



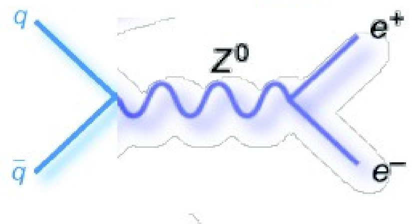
- Most quarks/leptons/bosons deeply scrutinised already
- Neutrinos not really testable at hadron colliders
- Many open issues about top quark
- Higgs (?)

Cross-section

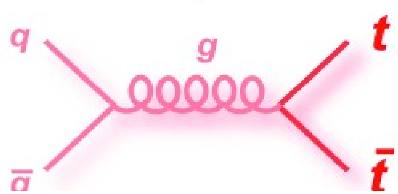




jets



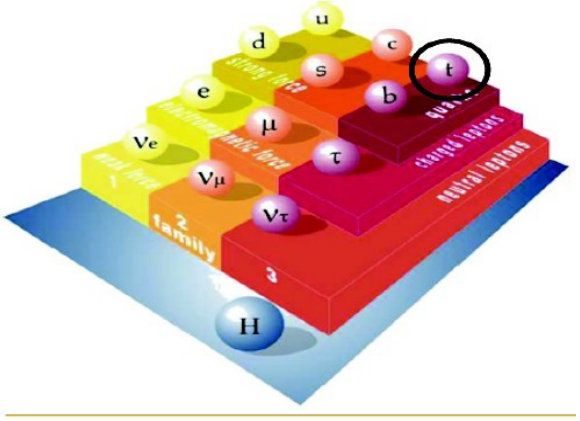
W, Z bosons



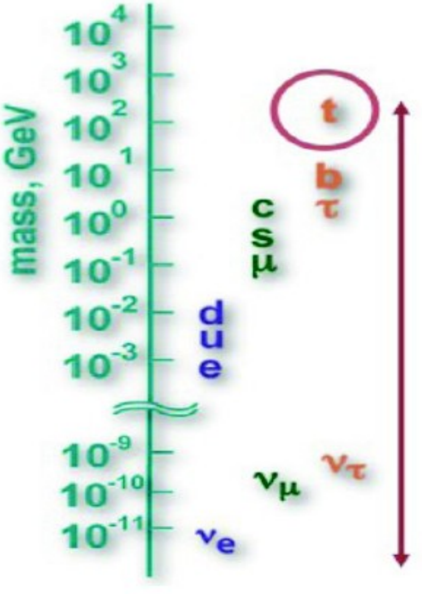
top quark

The top quark

- Needed in theory as isospin partner of b-quark
- Properties well defined by the Standard Model
- Unknown – top quark mass



Discovered at Fermilab in 1995



As heavy as the atom of gold

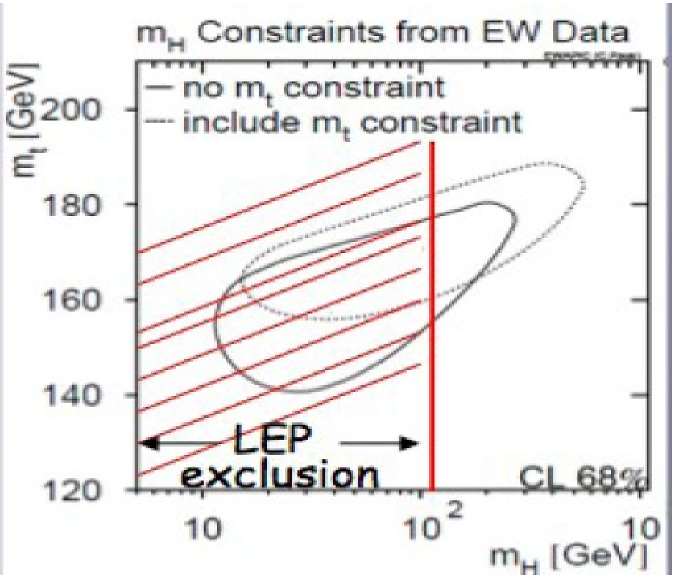
Brief history of the top quark

- 1976: **Discovery of Upsilon** at Fermilab
  - Contains a 5th quark: the **b-quark**
    - Structure of the families **suggested existence of** the 6th quark: **the top**
- From here on the race to find top quark begun
  - Petra (e^+e^-): $\mathbf{m_t > 23.3}$ **GeV** in 1984
  - Tristan (e^+e^-) in Japan: $\mathbf{m_t > 30.2}$ **GeV** in late 80s
  - SPS (p pbar): discovery of W and Z in 1983
  - UA1: $\mathbf{m_t > 44}$ **GeV** in 1988 (after having access in 1984 which they thought was evidence for the top)
  - LEP (e+e-): $\mathbf{m_t > 45.8}$ **GeV** in 1990
  - UA2: $\mathbf{m_t > 69}$ **GeV** which closed down channel
    - $W \rightarrow t\ b$ search closed down

Brief history of the top quark

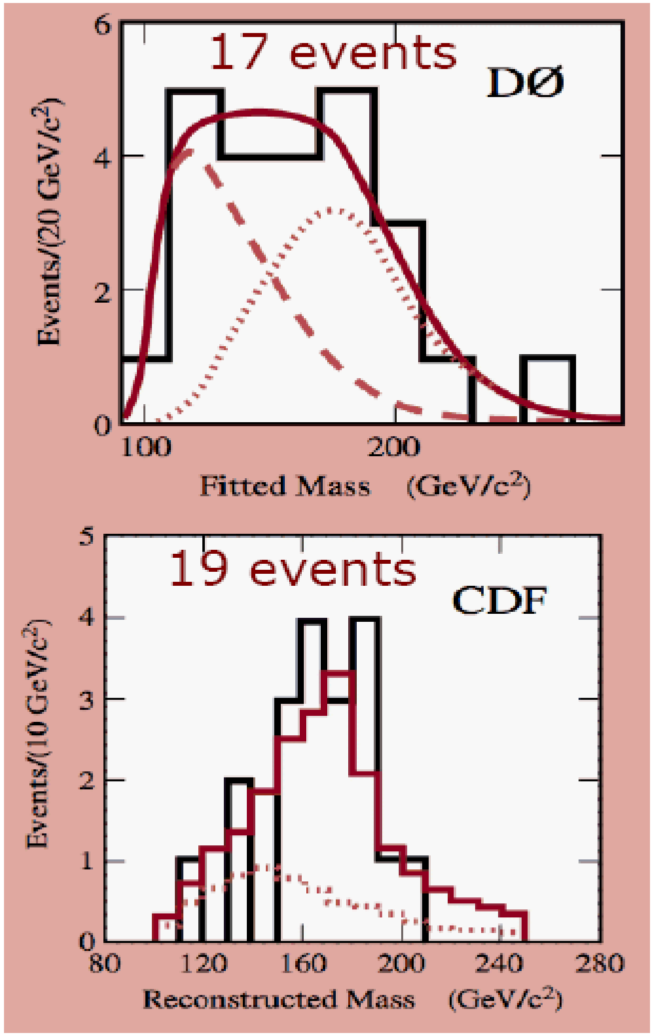
- Searching again for ttbar production with top mass above W boson mass
  - **1992:** first lower limits on top from CDF (**m_t > 91 GeV**)
  - **1994:** first lower limits on top from D0 (**m_t > 131 GeV**)
- Electroweak fits from LEP/SLS/Tevatron data:
  - **155 GeV < m_t < 185 GeV**
- Early **1994**:

  "Evidence for top at CDF"

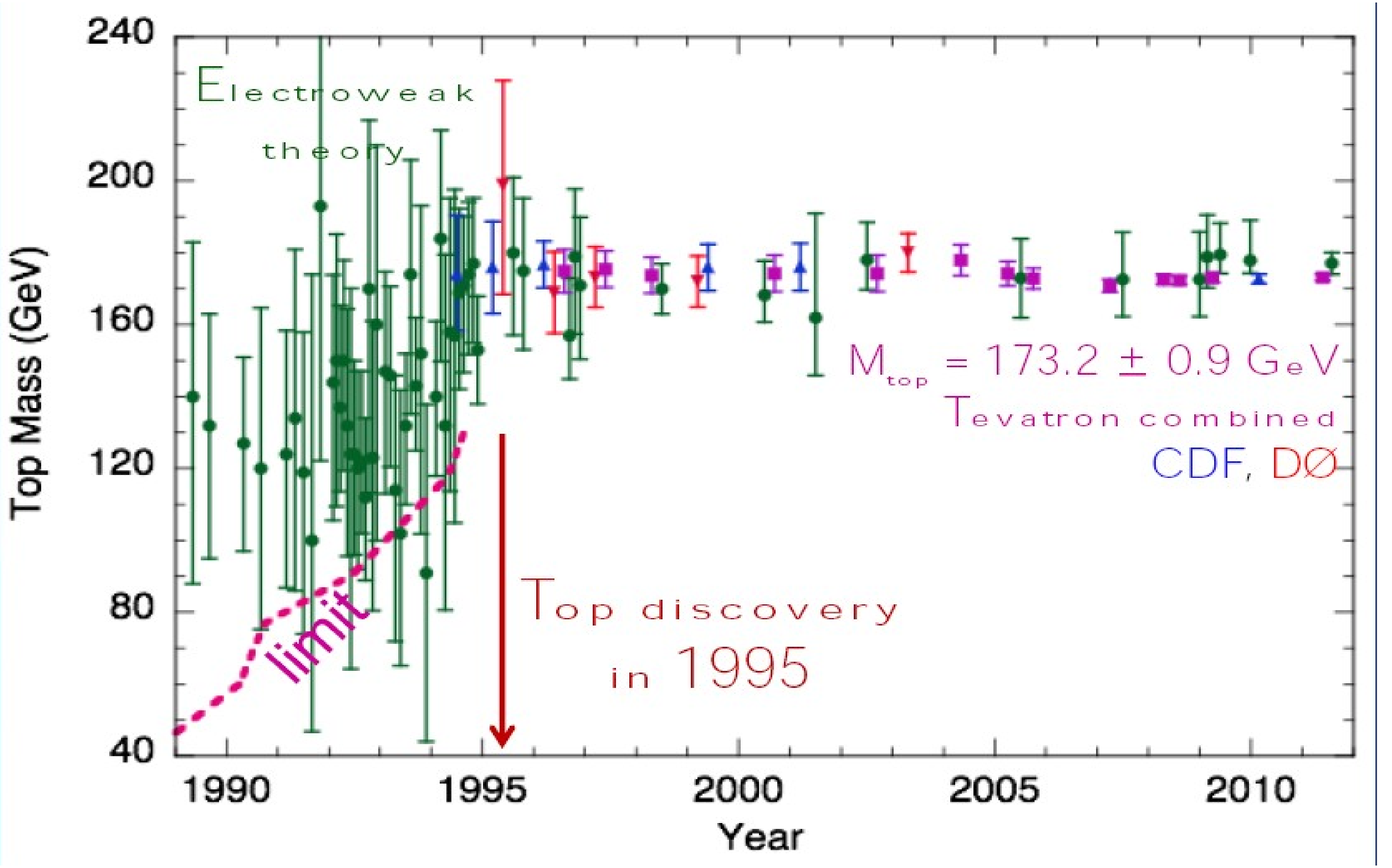


Top-quark discovery

- **February 24th 1995**: Simultaneus submission of **top discovery** papers to PRL by CDF and D0
  - 50 pb^{-1} at D0
    - m_t = 199 ± 30 GeV
    - σ_{tt} = 6.4 ± 2.2 pb
    - Background-only hypothesis rejected at 4.6σ
  - 67 pb^{-1} at CDF
    - m_t = 176 ± 13 GeV
    - $\sigma_{tt} = 6.8^{+3.6}_{-2.4}$ pb
    - Background-only hypothesis rejected at 4.8σ

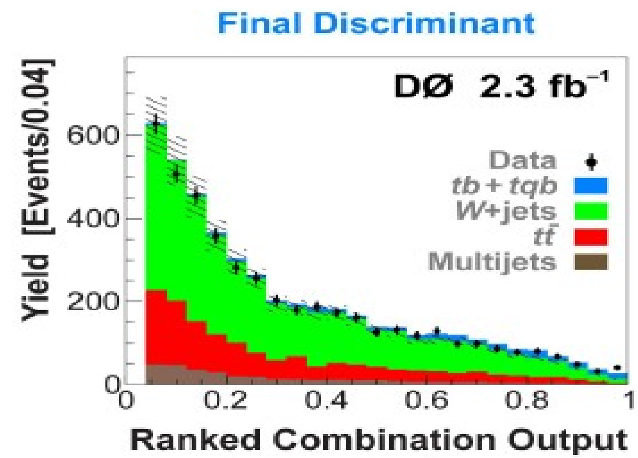


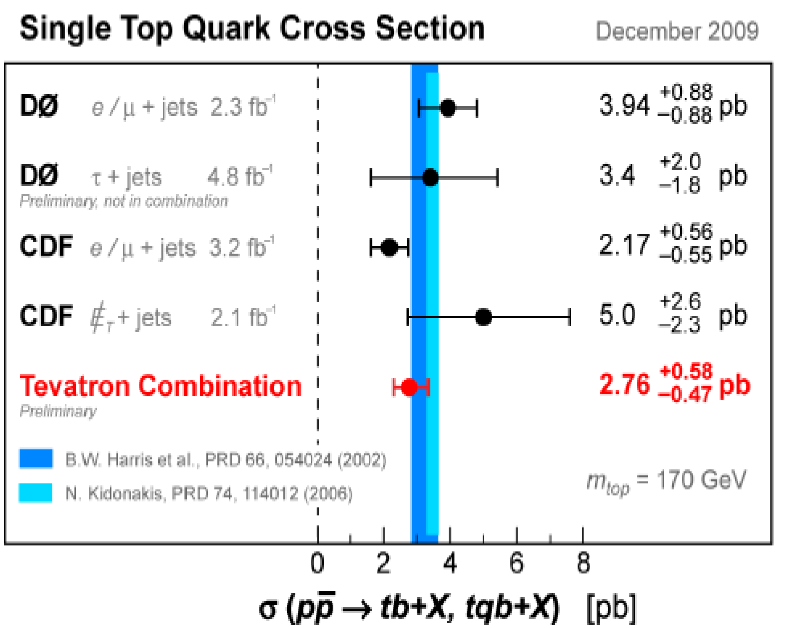
Top quark mass measurement



Single top-quark production

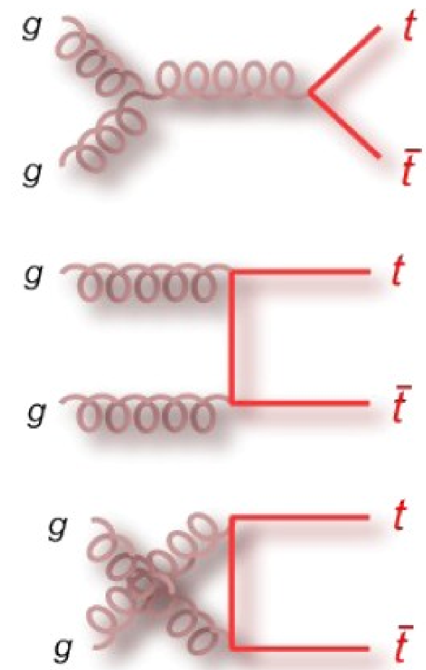
- **2009**: Observation of top quarks in single top production
  - **5σ** by CDF & D0!
- Single top: very challenging channel
  - Low signal: similar **signature like W+jets!**
  - Counting only: Uncertainty on background larger than expected signal





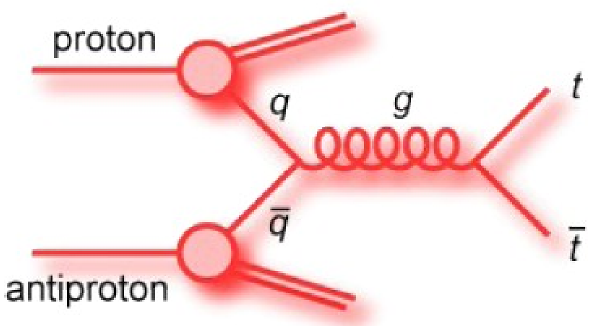
Top-quark pair production

- Most properties measured in $t\bar{t}$ events



- At Tevatron:

  85% + 15%



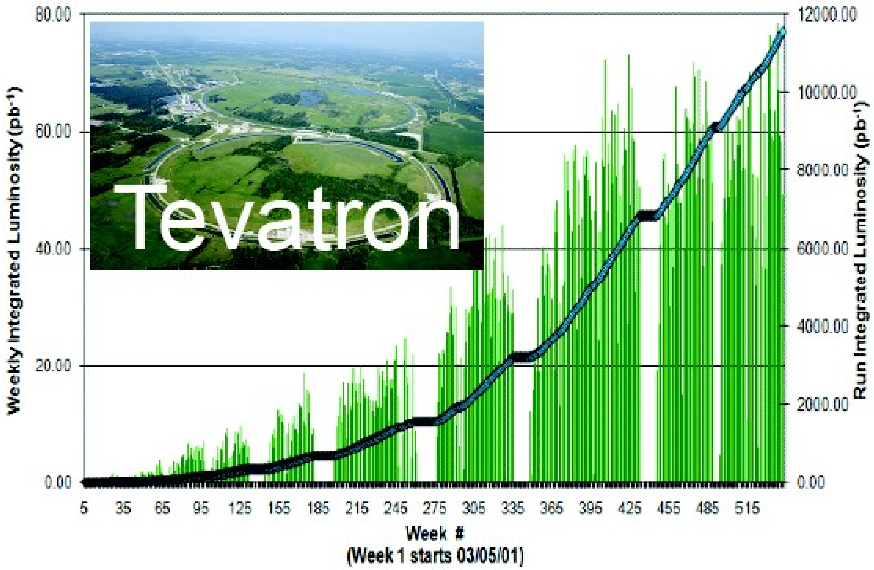
- At LHC:
  14 TeV: 10% + 90%

  7 TeV: 15% + 85%

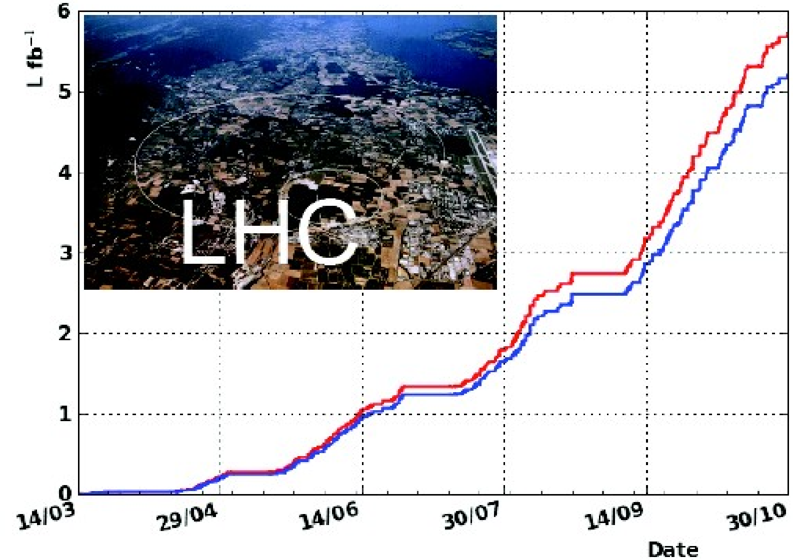
- Production cross section (@Tevatron):
  approximate NNLO: $\sigma = 7.46^{+0.48}_{-0.67}\,pb$ @ m_t=172.5GeV
  - 20 times higher @LHC (7TeV): $\sigma = 164.6^{+11.4}_{-15.7}\,pb$

Tevatron vs LHC

2011



2011



Energy: 1.96 TeV
Int. Luminosity: 12 fb^{-1}
Age: ~25 years
Events/exp (5 fb^{-1})
250 ee eμ μμ
2000 lepton + jets

x 50

Energy: 7 TeV
Int. Luminosity: 5 fb^{-1}
Age: ~2 years
Events/exp (5 fb^{-1})
12k ee eμ μμ
100k lepton + jets

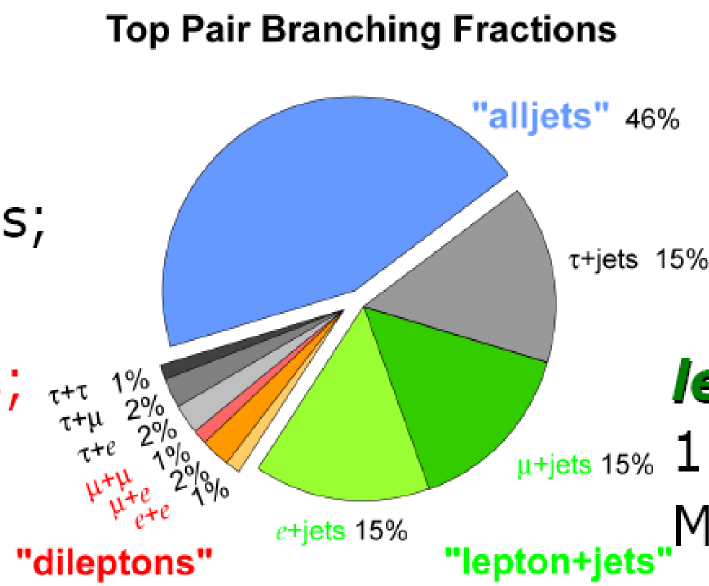
Final states in ttbar

$t\bar{t} \to W^+bW^-\bar{b}$: Final states are classified according to W decay

$B(t \to W^+b) = 100\%$

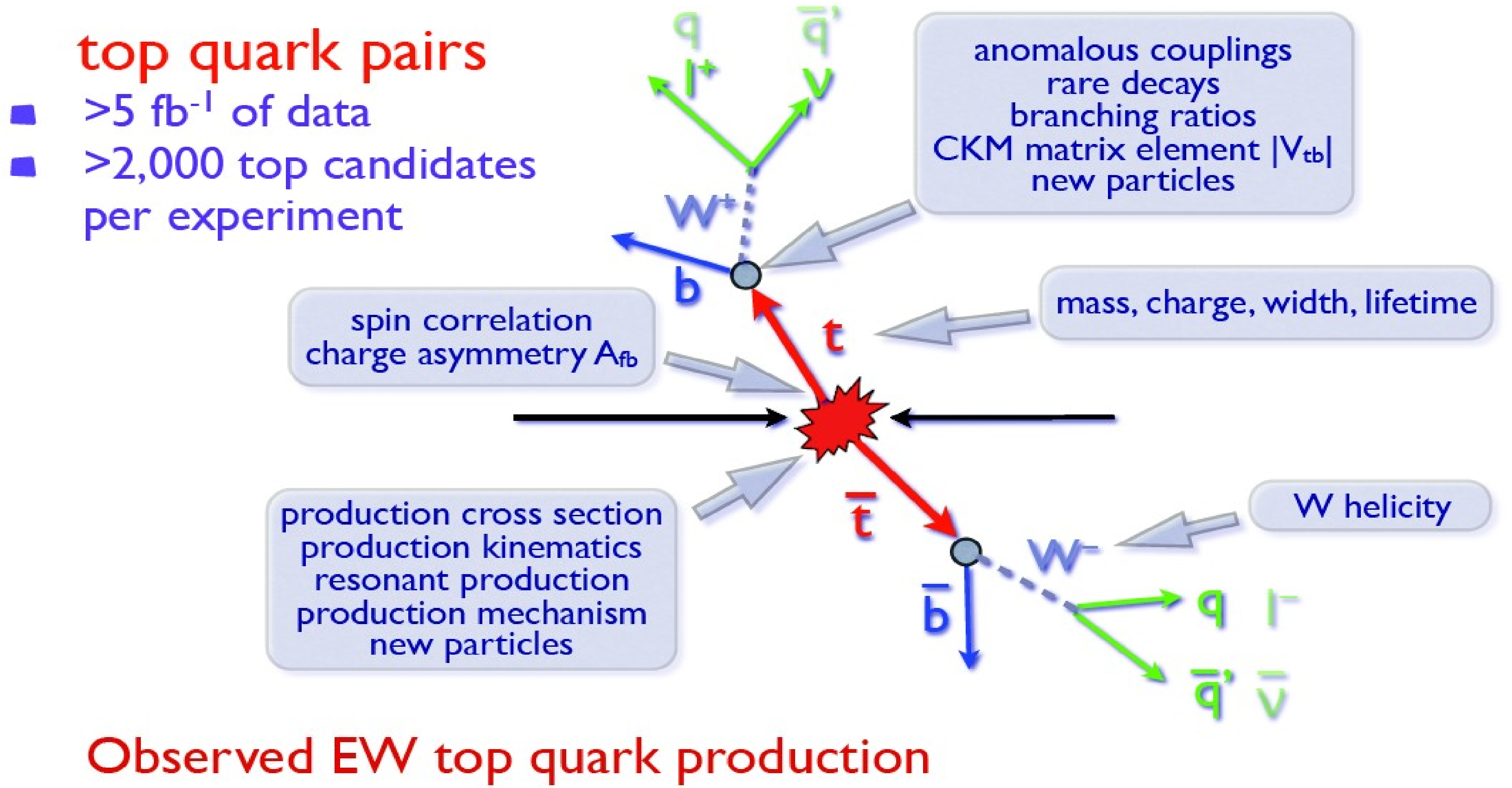
pure hadronic:
≥6 jets (2 b-jets)

dilepton:
2 isolated leptons;
High missing E_T
from 2 neutrinos;
2 b-jets



lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

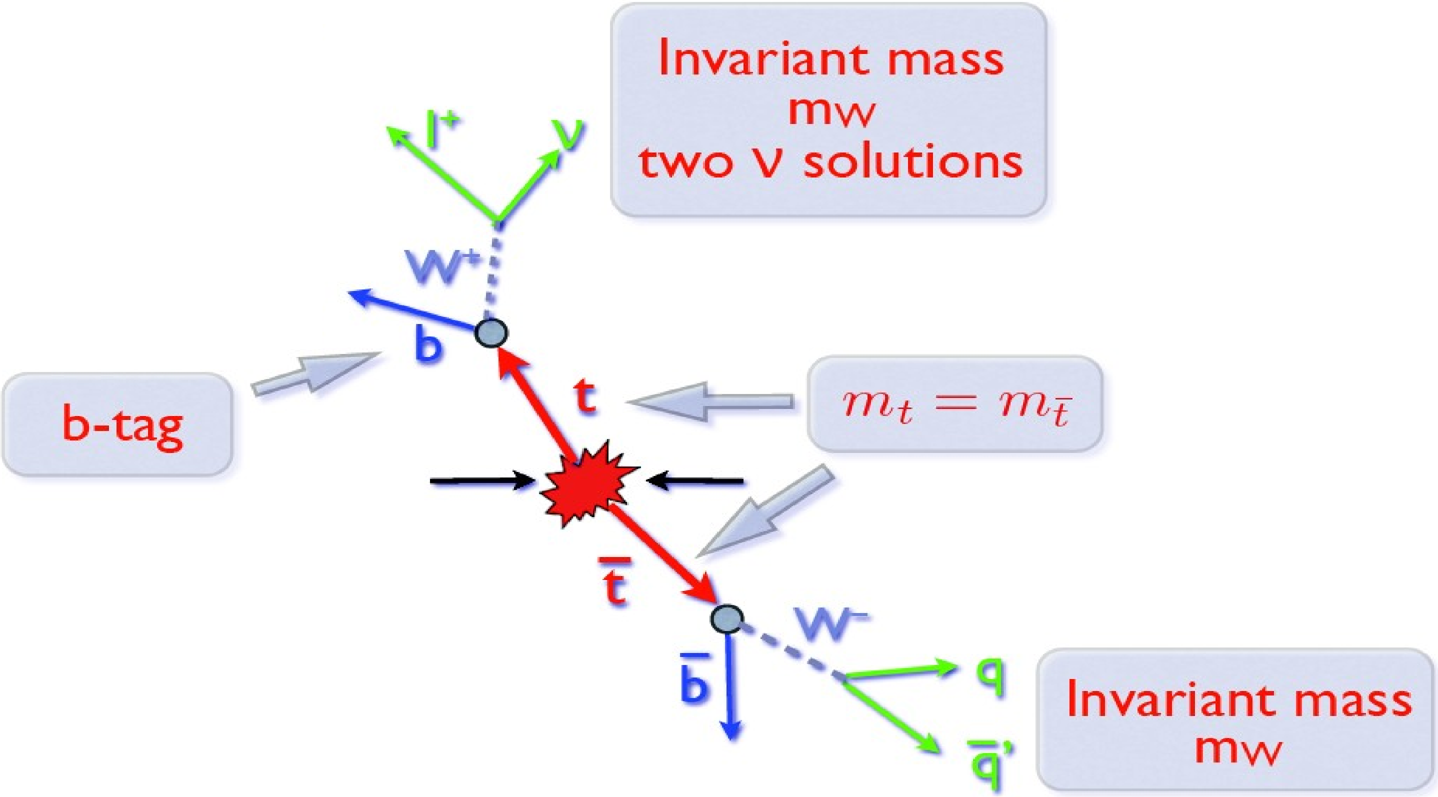
Top quark pairs at Tevatron



Measurements from Tevatron

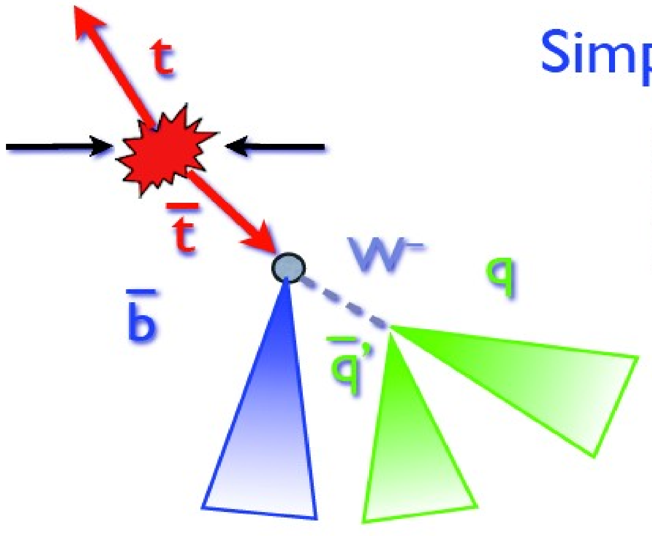
Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

Top event reconstruction l+jets

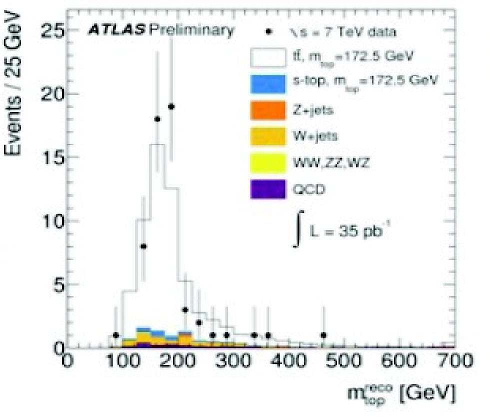


Presence of hadronic W allows to constrain JES

Top event reconstruction l+jets



Simple reconstruction - hadronic top



- take three highest p_T jets to build top mass
- if 1 b-tag in triplet take two jets with no b-tag to build W mass
- if 2 b-tags in triplet drop the event
- if no b-tag take two jets with min ΔR

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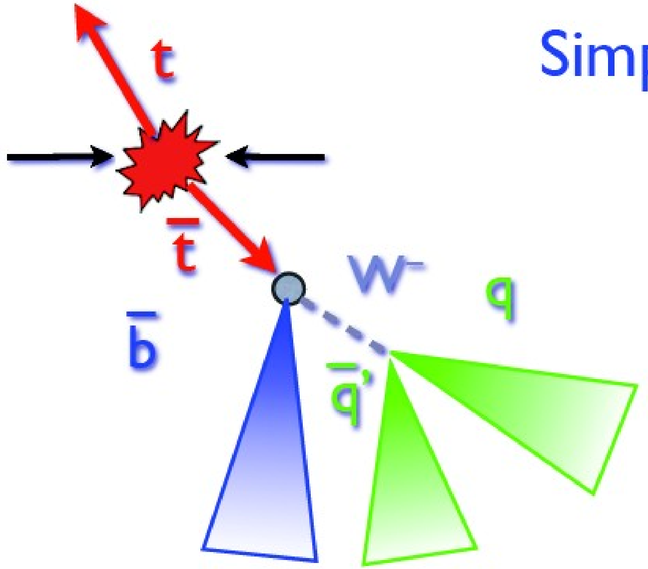
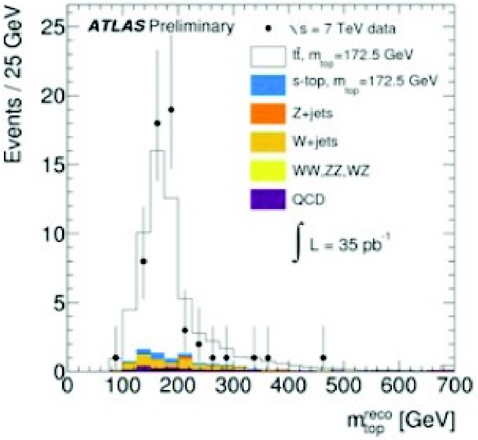
Top event reconstruction l+jets



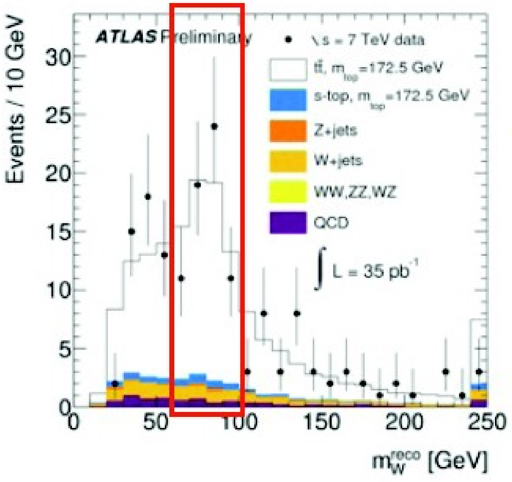
Simple reconstruction - hadronic top



- take three highest p_T jets to build top mass
- W mass window cut: $60 < m_W < 100$ GeV

45%(36%) of correctly reconstructed W(top)

- if 1 b-tag in triplet take two jets with no b-tag to build W mass
- if 2 b-tags in triplet drop the event
- if no b-tag take two jets with min ΔR



- Disadvantages:
  - loss of efficiency
  - jet resolutions are not taken into account

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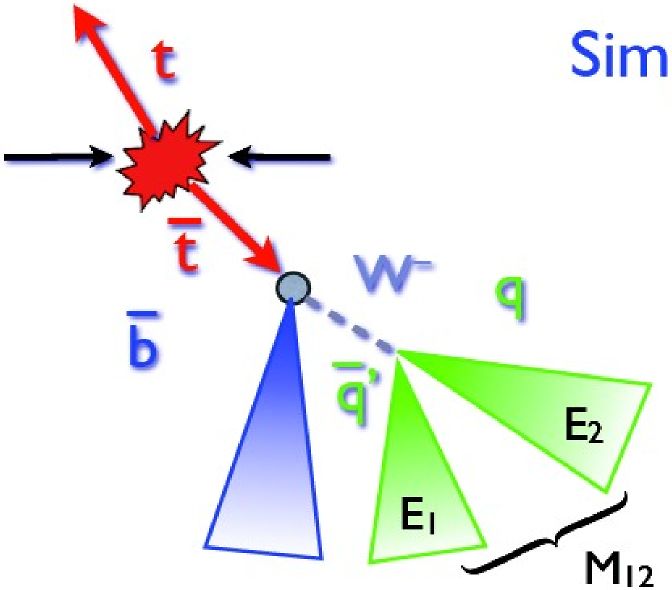
Top event reconstruction l+jets



Simple reconstruction - hadronic top

- consider light jets pair with $50<m_W<100$ GeV
- combine with b-tagged jet
- select combination with highest p_T as a top quark candidate
- perform kinematic fit of hadronic W candidate

$$\chi^2(\alpha_1,\alpha_2) = \left[\frac{E_1(1-\alpha_1)}{\sigma_1}\right]^2 + \left[\frac{E_2(1-\alpha_2)}{\sigma_2}\right]^2 + \left[\frac{M_{12}(\alpha_1,\alpha_2)-m_W}{\Gamma_W}\right]^2$$

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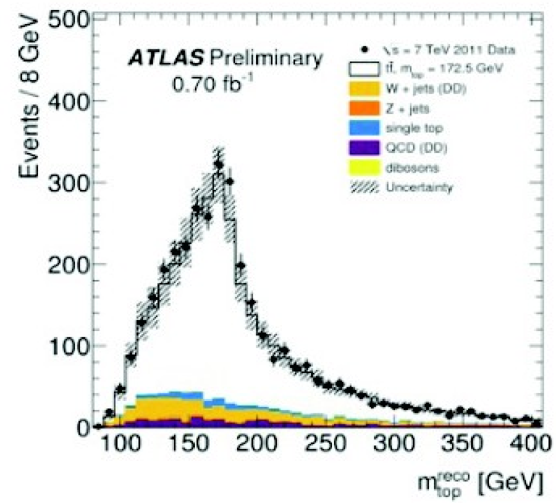
- determines α_1 and α_2
- recalibrates jet energies
- improves m_t resolution



Top event reconstruction l+jets

- χ^2 minimization
  - takes into account reconstructed objects resolutions in p_T
  - approximates W and top Breit-Wigner lineshapes with Gaussians
  - minimized with respect to all parton level kinematic quantities and m_t^{rec} for each jet-to-parton assignment

$$\chi^2 = \frac{(m_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb} - m_t^{rec})^2}{\Gamma_t^2} + \frac{(m_{\ell\nu b} - m_t^{rec})^2}{\Gamma_t^2}$$

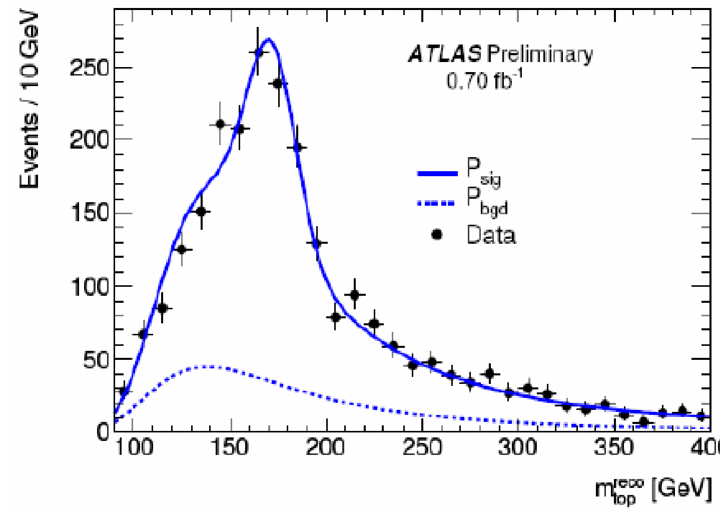
$$+ \sum_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE^2}}$$

  - definition in all hadronic channel is similar

Top mass from fit

- Analysis performed with **0.70 fb^{-1}** in **l+jets** channel,
  - asking the presence of one b-jet
- 3-jet from hadronic top: combination with higher total p_T
- Technique: **m_{top} and JES determined simultaneously**
  - W mass and width used as constraints
- m_{top}^{reco} in data have been compared to signal + backgrounds templates with ≠ JES and m_{top}
  - **m_{top} and JES from a likelihood fit**

- Main systematics:
  - signal modelling
  - JES for light jets and b-jets



$$m_{top} = \left(175.9 \pm 0.9_{stat} \pm 2.7_{syst}\right) \text{ GeV}$$

Limited by systematics

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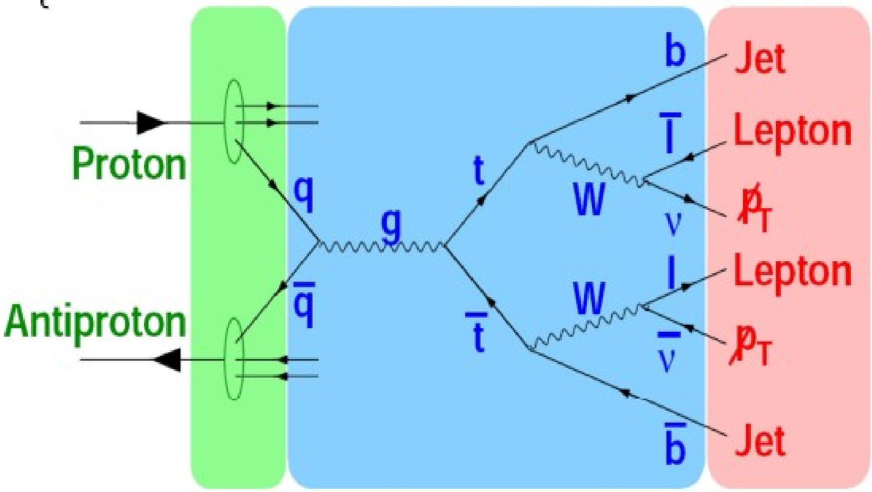
Matrix element method

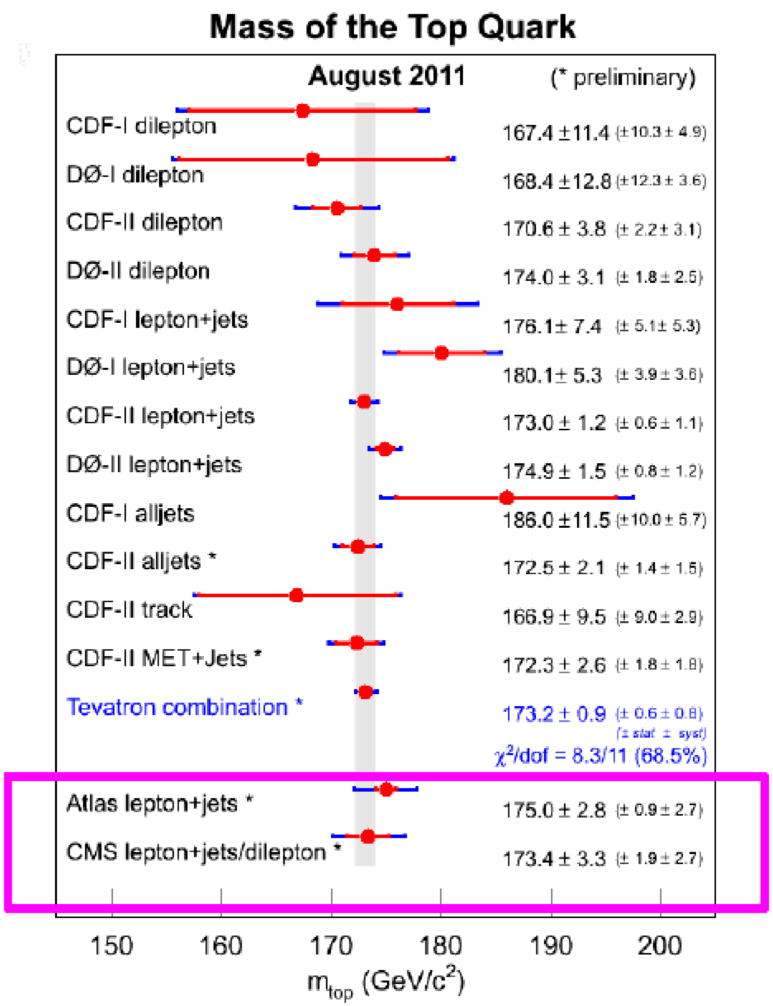
- Use full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass

$P_{sig}(x;m_t) \propto \int$ PDF x Matrix element x Transfer function



- Perform likelihood fit of event probabilities
- Probability depends on top mass (& JES for in-situ fit)
- Used in l+jets & dilepton final states

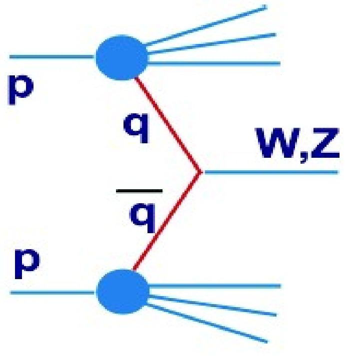
Top-quark mass combinations

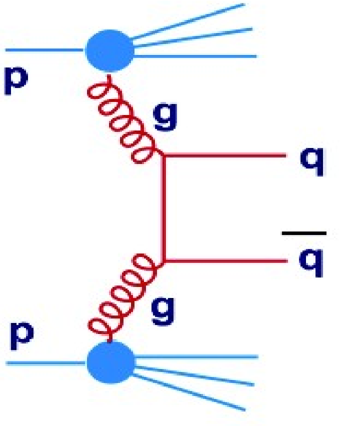


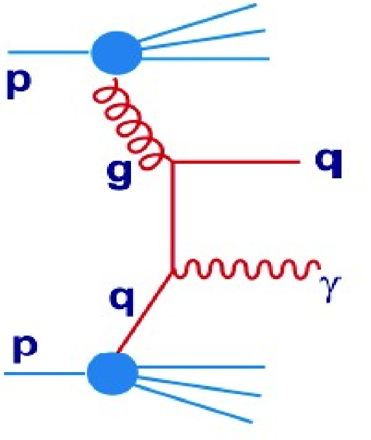
- Systematics limited!
  - Main effort for experiments: detailed understanding of systematics
  - Main systematics at Tevatron: JES-related
  - Main systematics at LHC: JES-related and ISR/FSR
- Tevatron combination: first time uncertainty below 1GeV!

QCD hard scattering processes

- EW gauge bosons Di-jets Direct photons

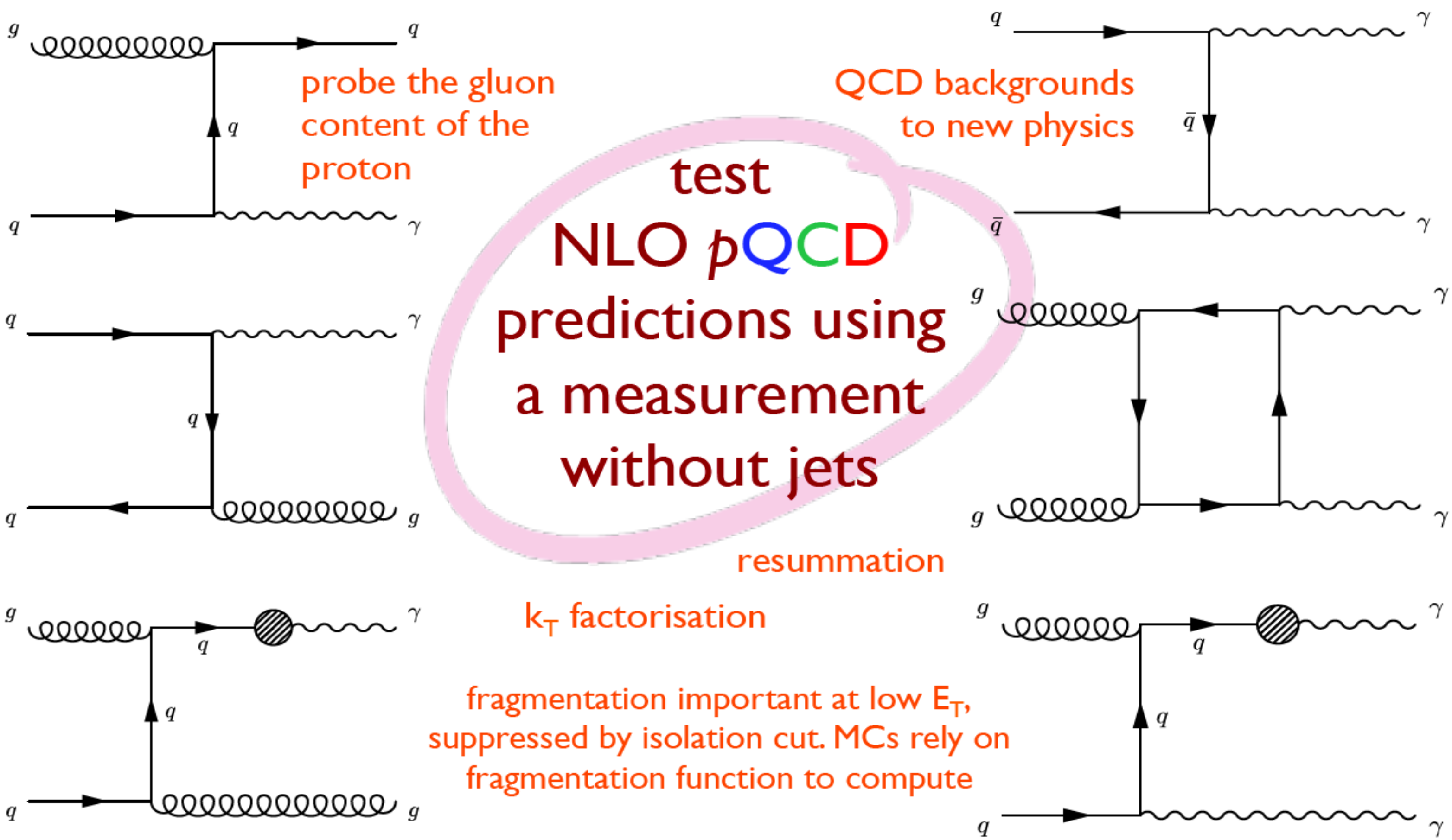






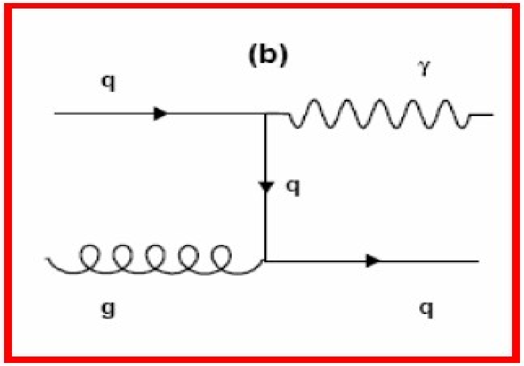
- Measuring those processes test our understanding of:
  - Partonic structure of protons
  - QCD scattering via calculations of N(NLO)
  - Hadronisation/underlying event
  - What makes a good jet algorithm
  - Data driven background estimates for rare processes

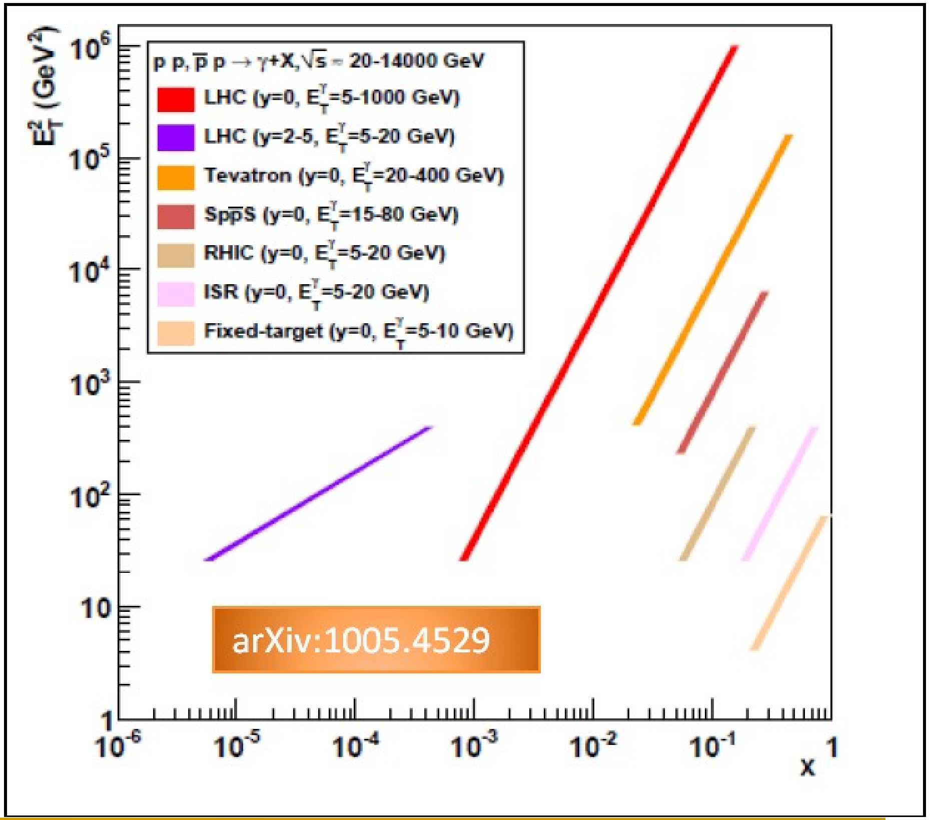
Why measure prompt photons?



Photons at LHC

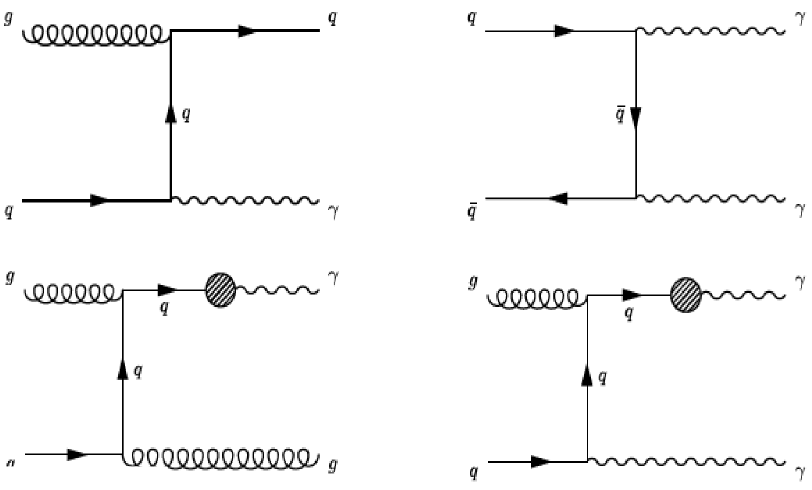
- X reach of photons at LHC is couple of orders of magnitude lower than the previous experiments
- Dominance of the Compton scattering cross-section gives possibility of clean probe to constrain gluon pdf's

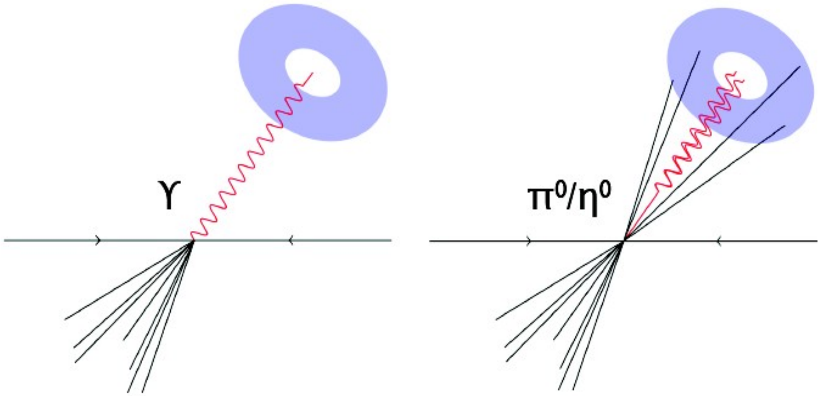




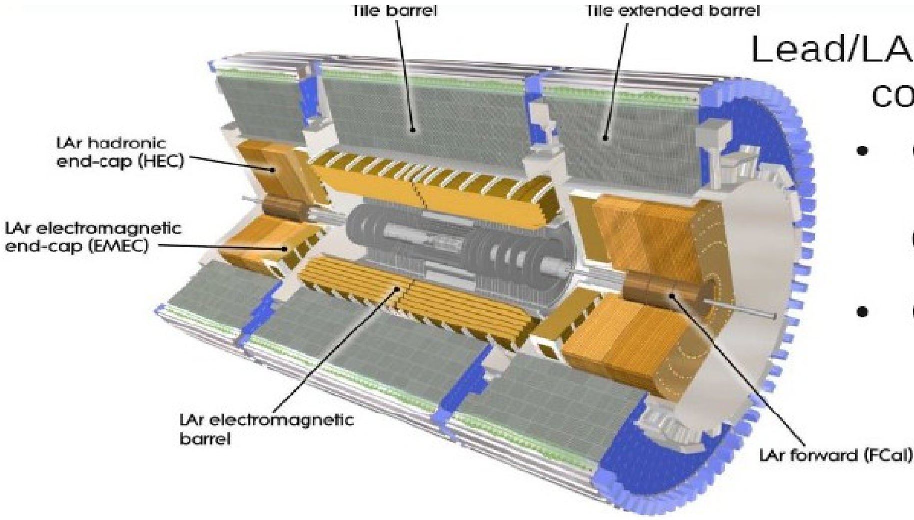
Prompt and isolated photons

- 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



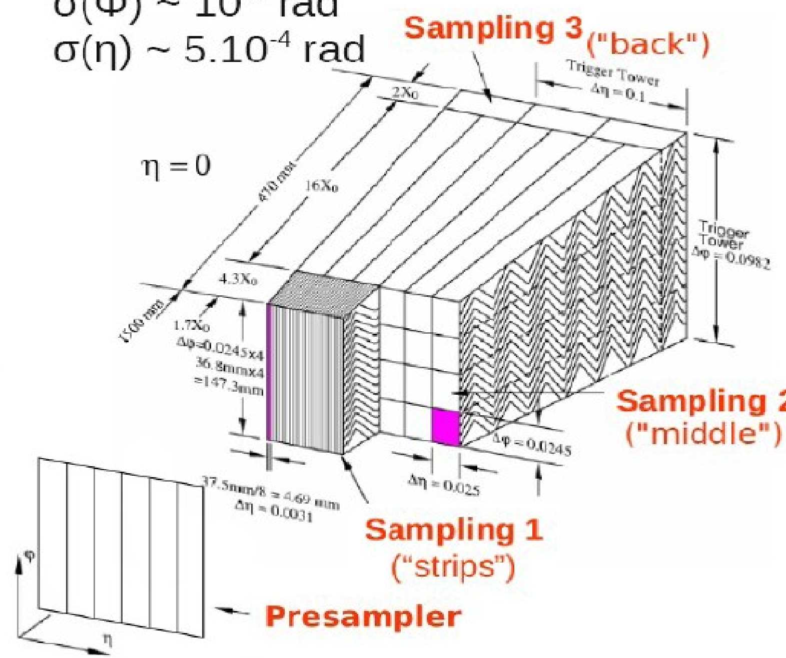


The ATLAS electromagnetic calorimeter



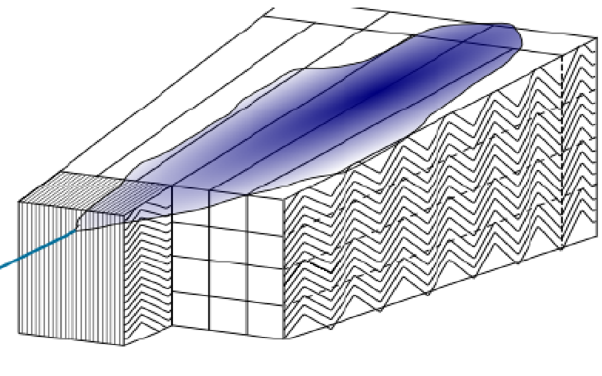
Lead/LAr EM calorimeter divided in 3 longitudinal compartments + Pre-sampler in front

- Good energy resolution :
  $\sigma(E)/E = a/E \oplus b/\sqrt{E} \oplus c$ (with a ~ 0.3 GeV, b ~ 10%, c ~ 0.7%)
- Good angular resolution :
  $\sigma(\Phi) \sim 10^{-3}$ rad
  $\sigma(\eta) \sim 5.10^{-4}$ rad



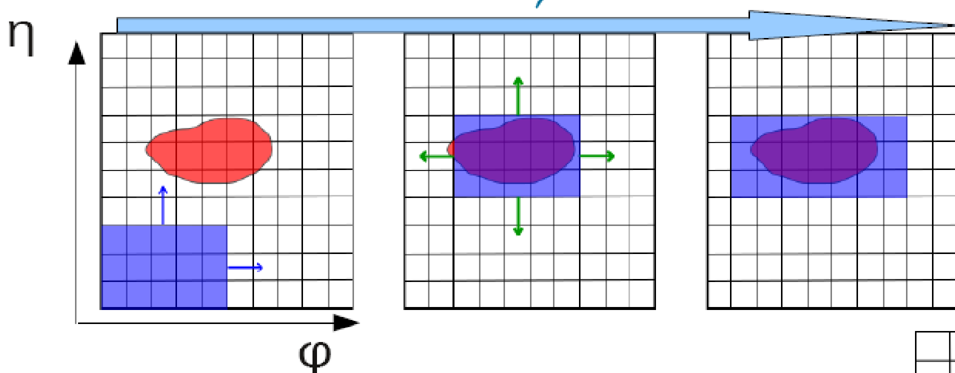
Layer	Granularity $\Delta\eta \times \Delta\varphi$	Radiation length
Pre-sampler	0.025 x 0.1	
Strips	0.003 x 0.1	4.3 X_0
Middle	0.025 x 0.025	16 X_0
Back	0.05 x 0.025	2 X_0

Electromagnetic objets

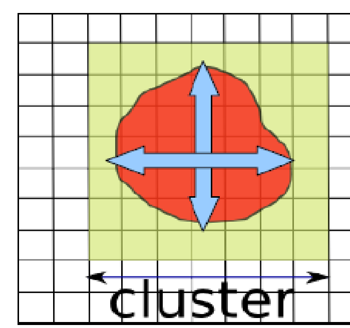


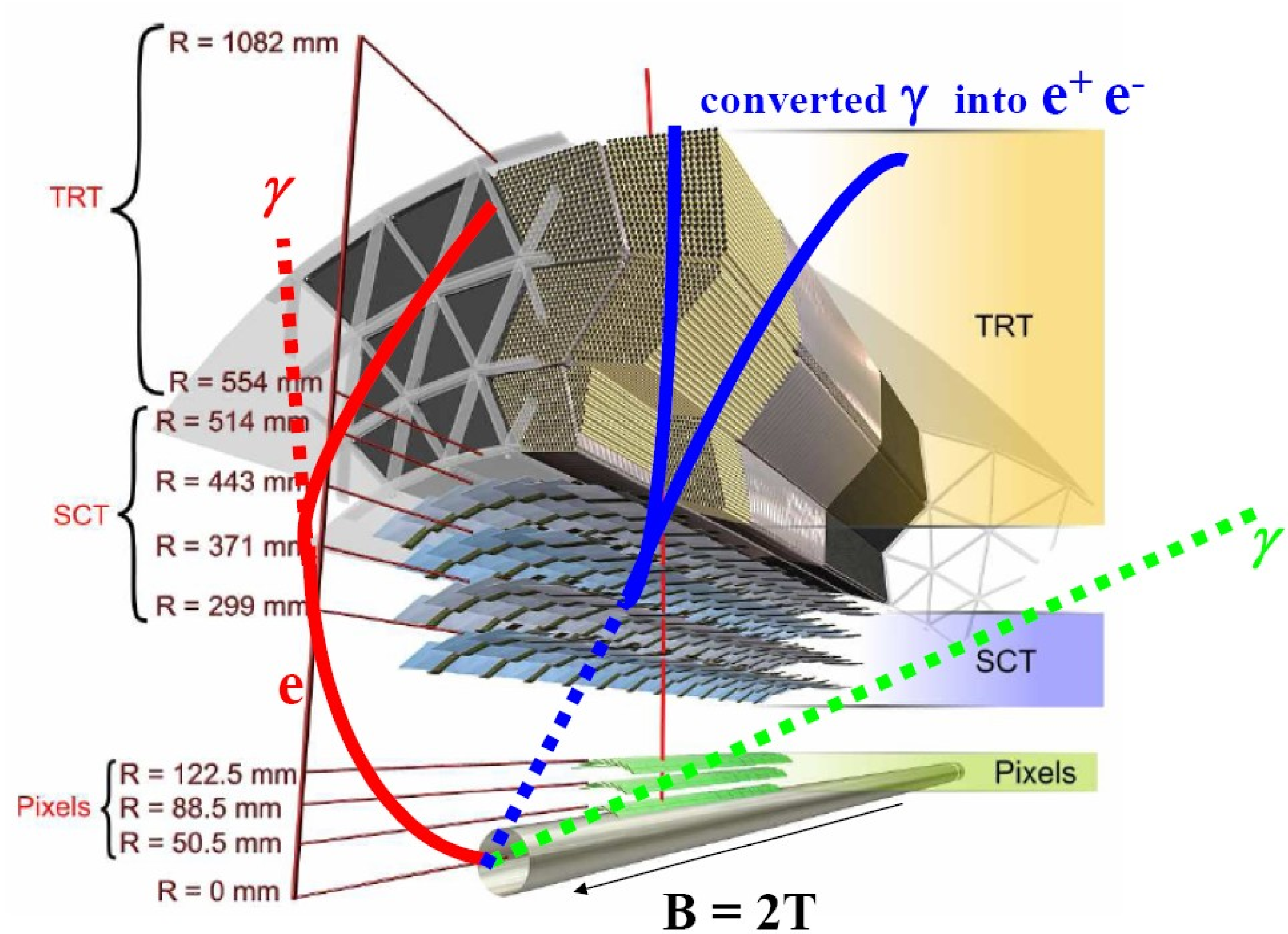
- In ATLAS an electron or a photon candidate is defined as a cluster of cells in the calorimeters representing the energy deposit to which we can associate tracks reconstructed in the inner detector

- Sliding window algorithm to reconstruct the energy deposits :

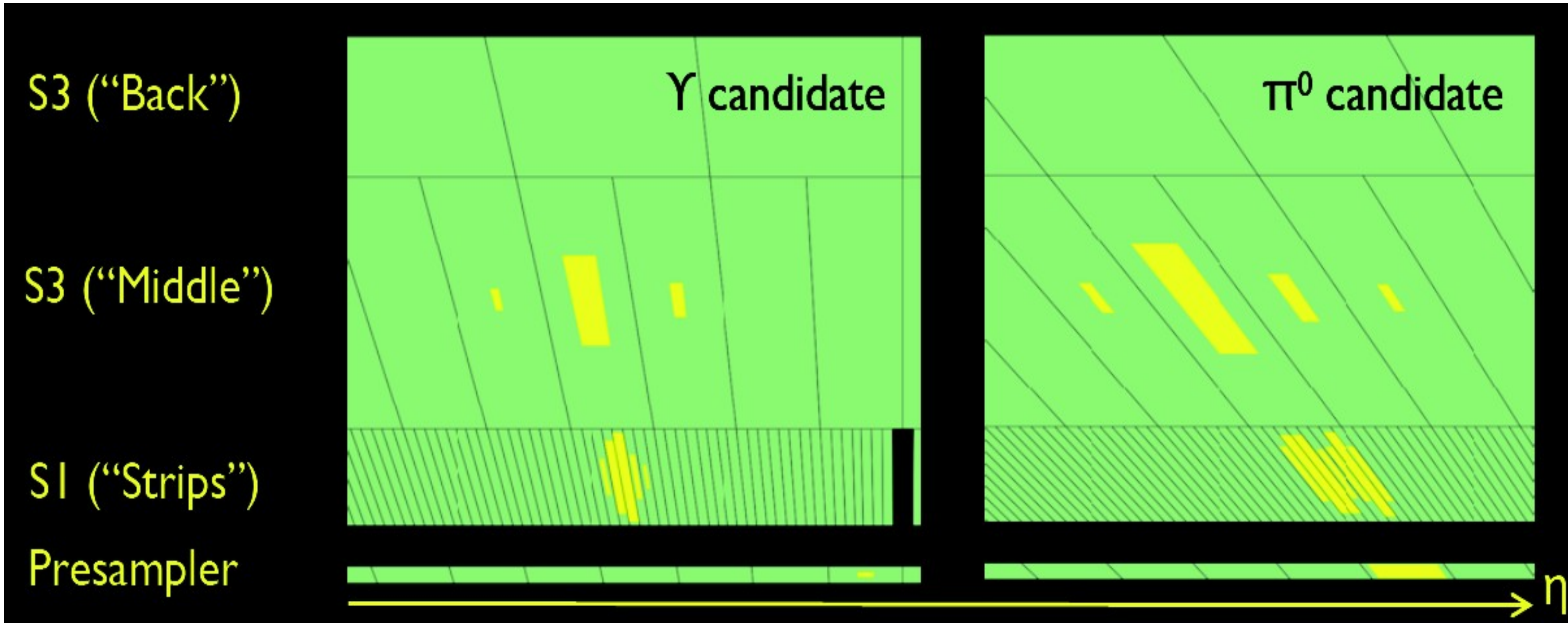


- The identification of such objects is then based on :
  - The shower shape in the calorimeter
  - Track quality (number of hits, direction wrt the cluster,...)
  - Transition radiation (TRT “high threshold hits”)
  - E/p

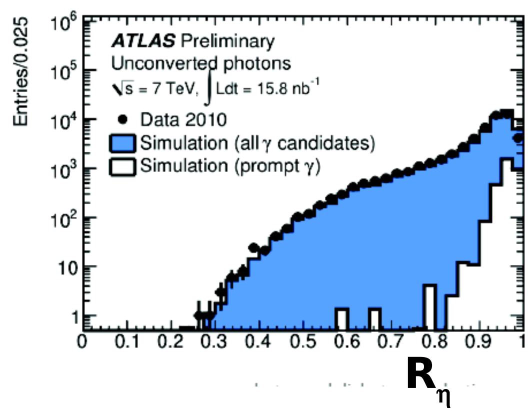


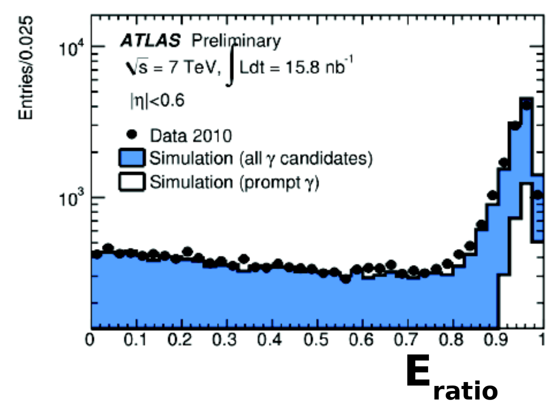

R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
γ
e
converted γ into e+ e-
TRT
SCT
Pixels
γ
B = 2T

Photon identification

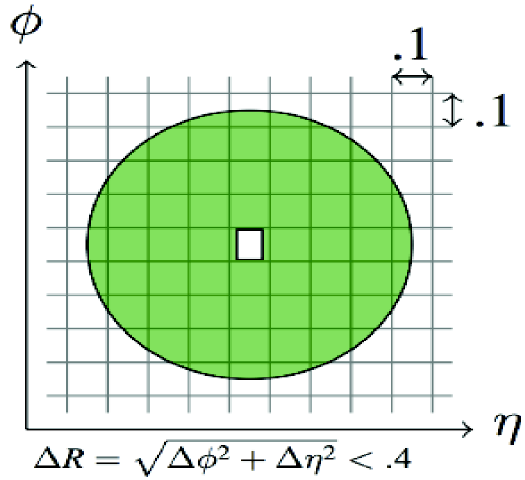


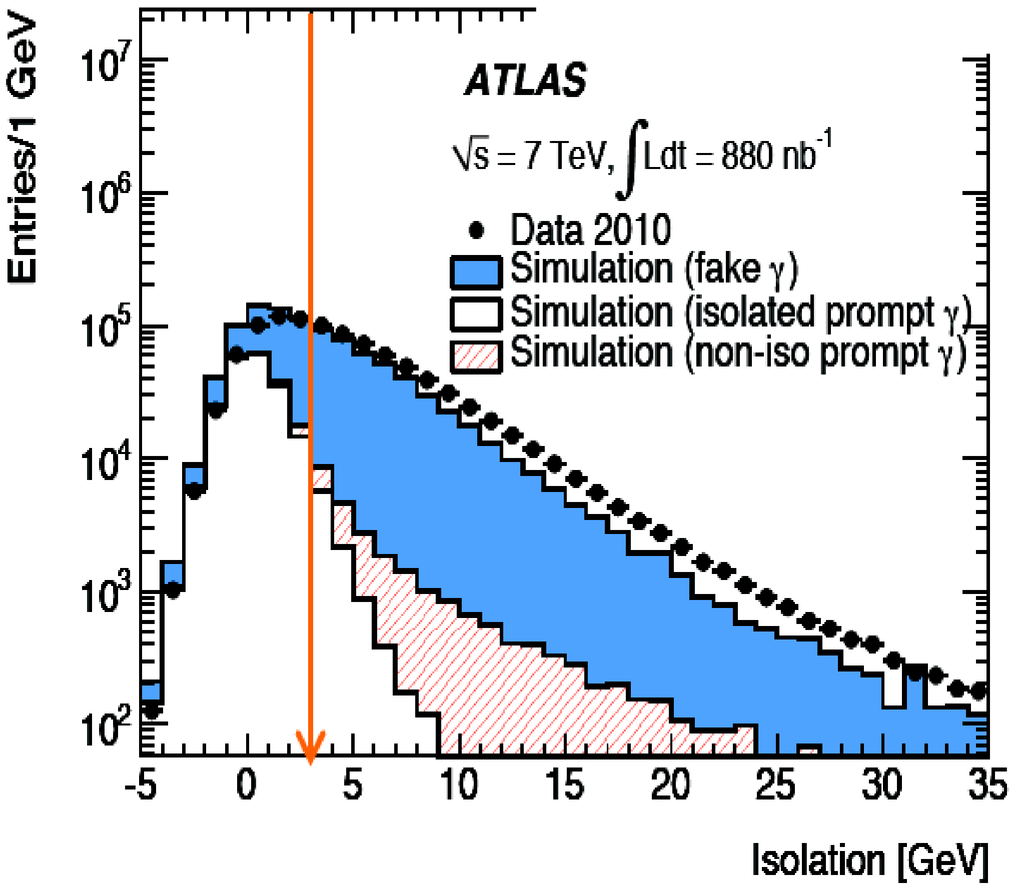
- loose and tight selection
- optimised separately for unconverted and converted photons





Photon isolation



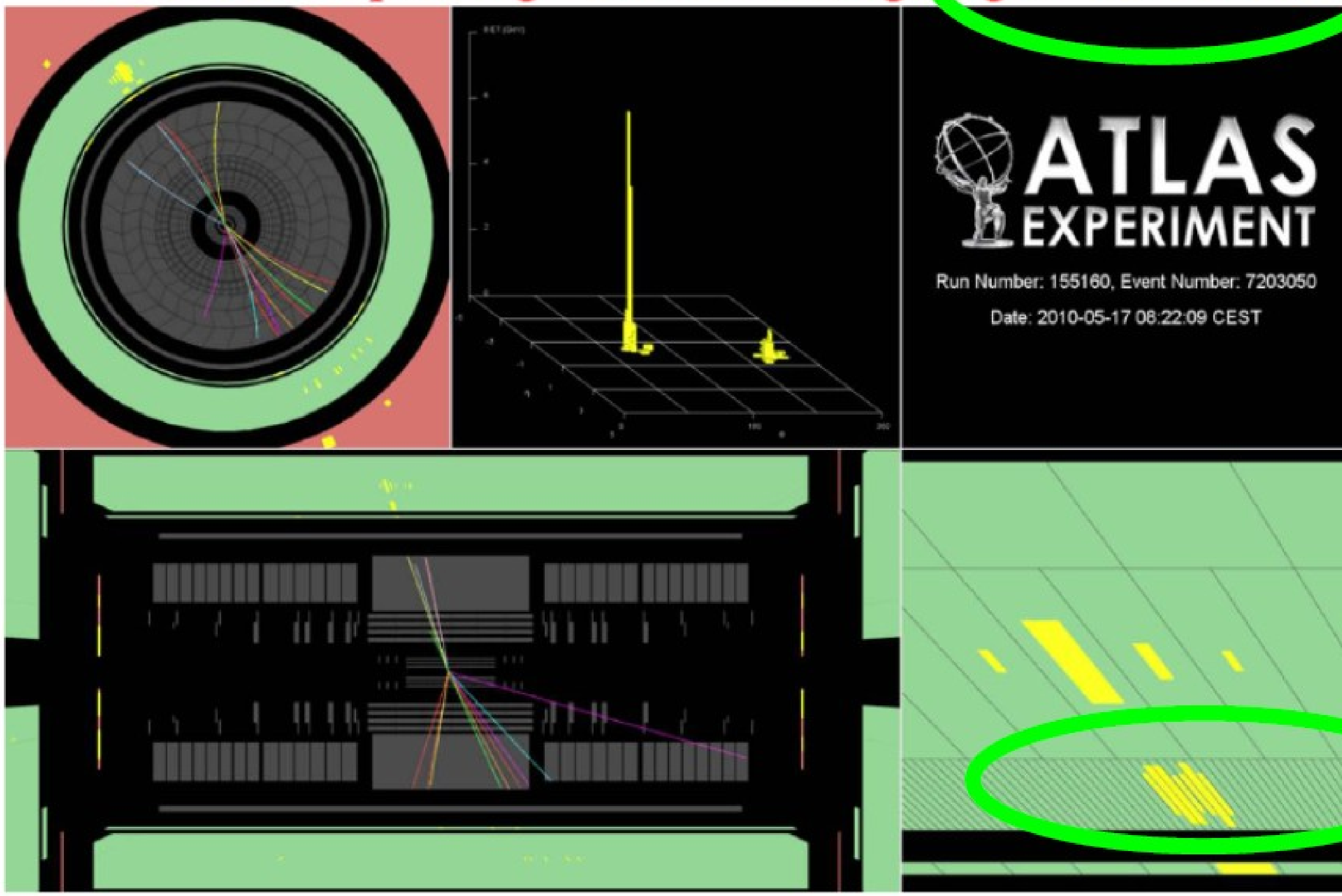


- Define isolated photon comparable to theory
- Isolation corrected event-by-event for leakage, pile-up, underlying event. Average 450-550 MeV

Photon identification with shower shapes

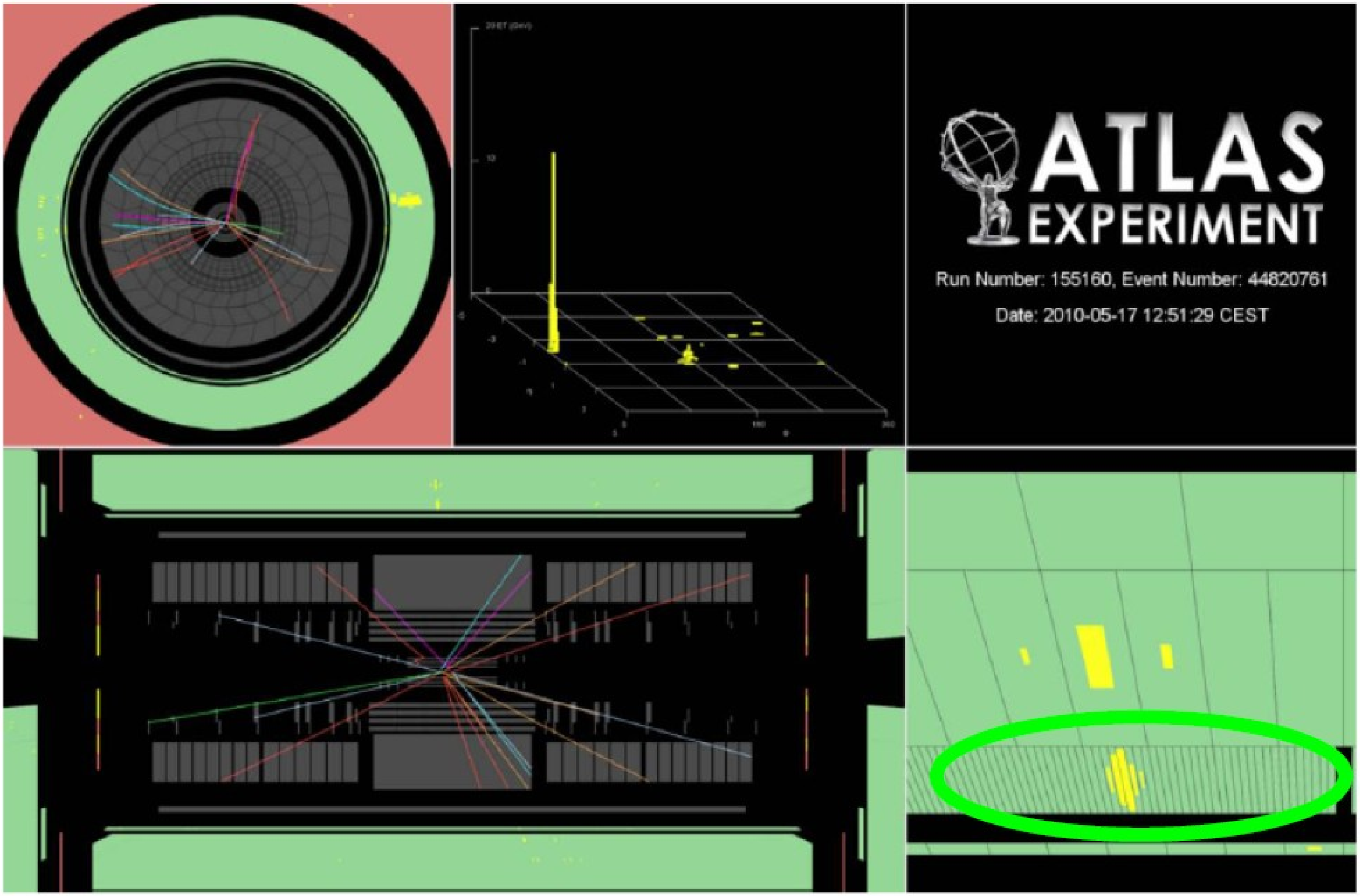
reminder: opening angle between the two photons of a π^0 of p_T =40 GeV ***is > 0.007 to be compared with size of strip calo 1^{st} sampling ~0.003***

π^0 candidate passing "loose", failing "tight" selection



tight selection uses mainly calo 1st sampling

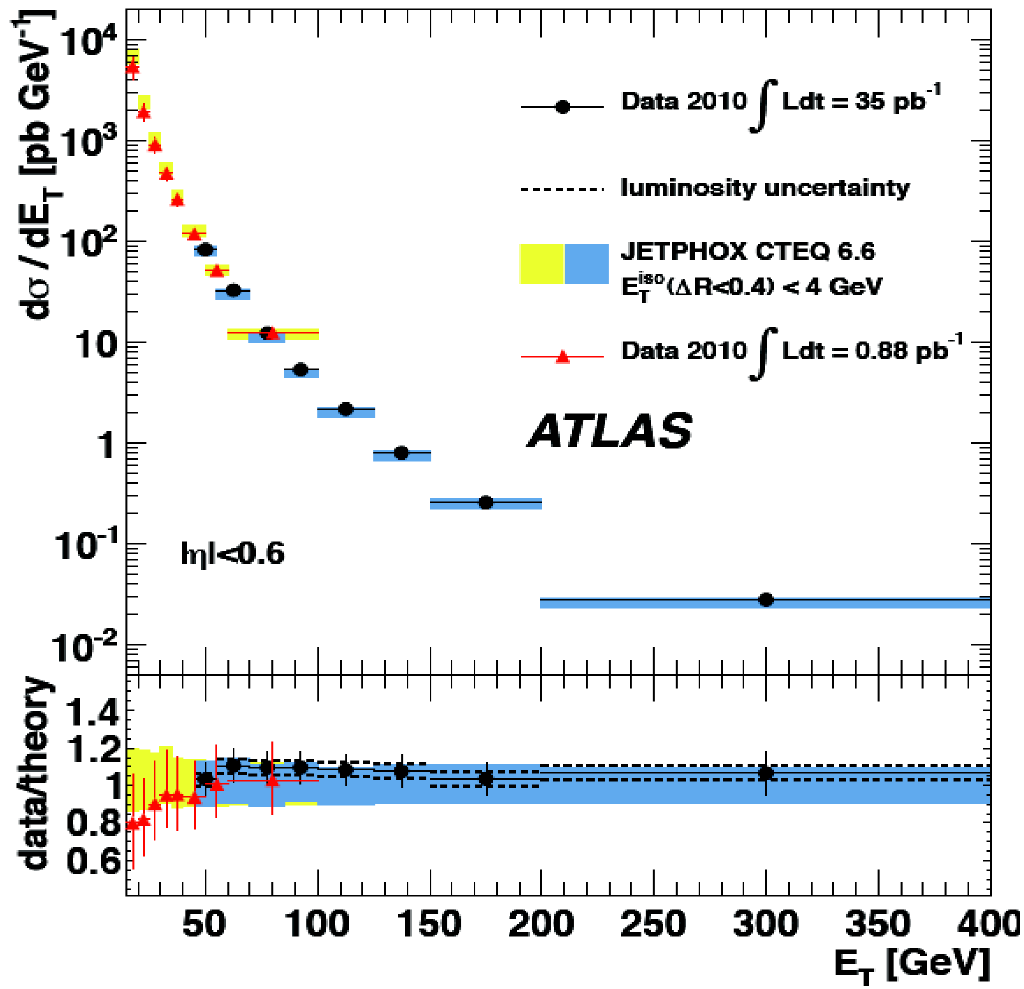
Photon candidate passing “tight” selection



Nice shape in first sampling of EM calormeter

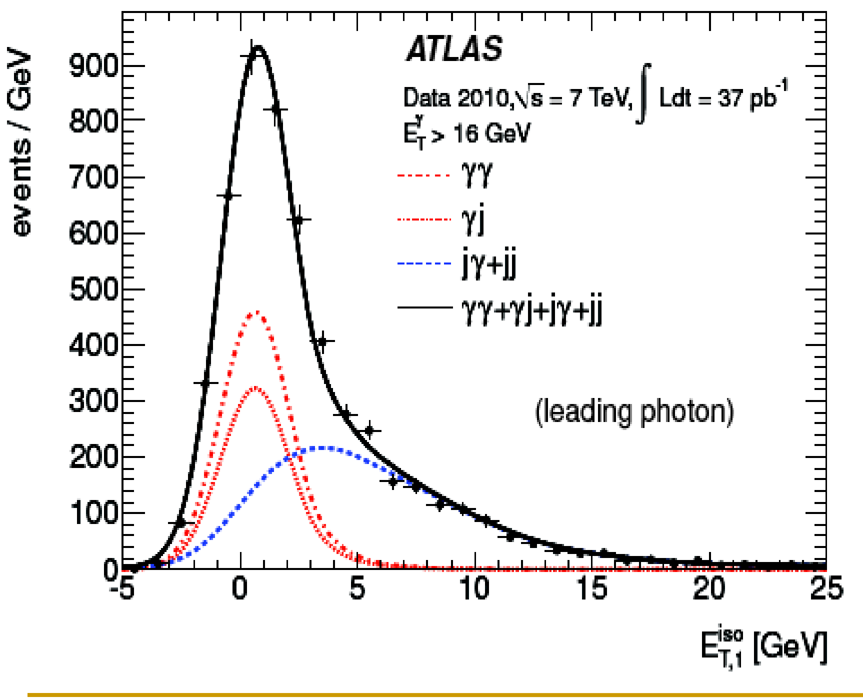
Inclusive cross-section

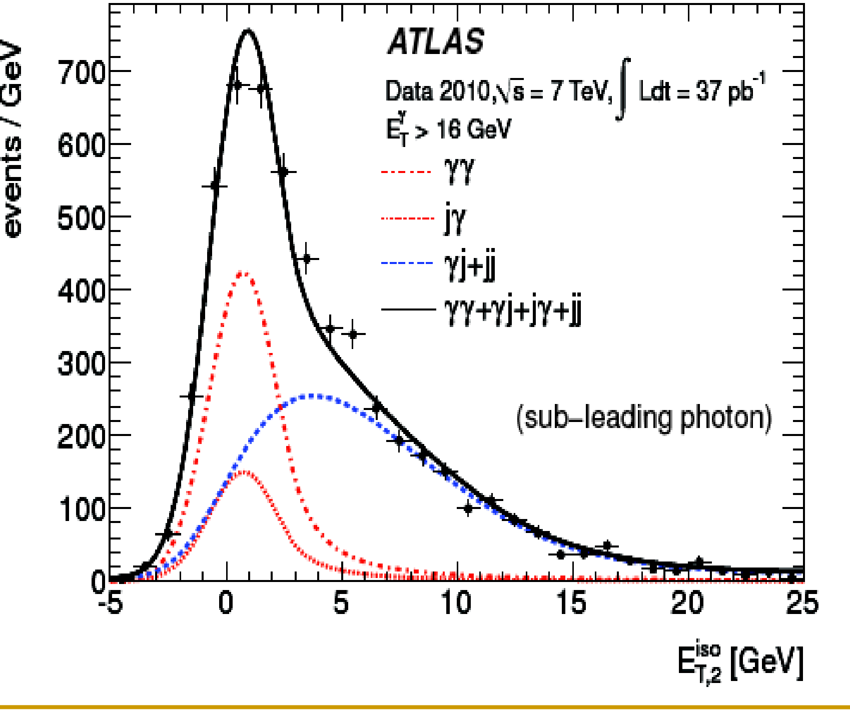
- Measured in 4 rapidity ranges
- Here example for central barrel



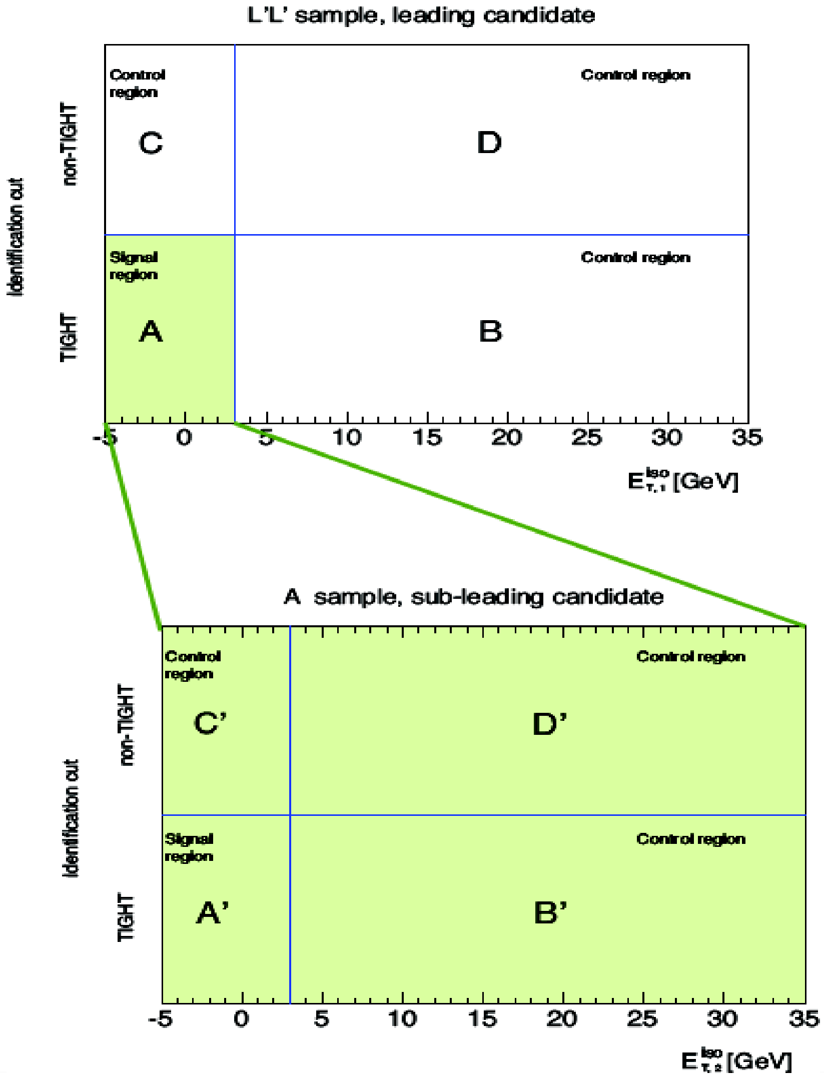
Diphoton cross-section

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





ABCD method



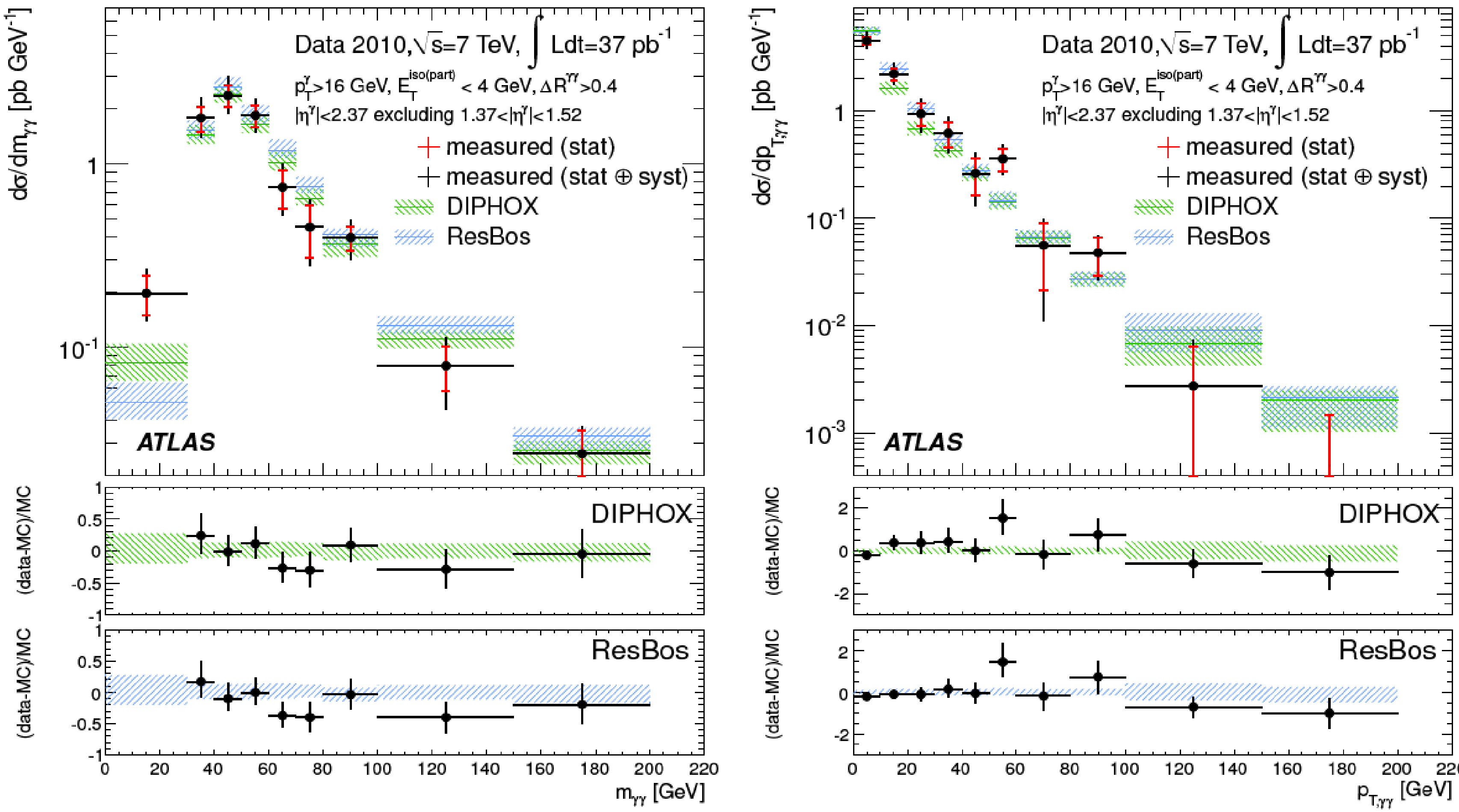
Monte Carlo

$$N^A_{\rm sig} = N^A - N^B \frac{M^A}{M^B}$$

$$P = 1 - \frac{N^B}{N^A}\frac{M^A}{M^B}$$

- Signal purity > 90% for E_T>50 GeV
- Main systematic uncertainties:
  - MC inputs (corrections to isolation definition)
  - Bgd control region definition

Isolated di-photon cross-section



Photon measurements: reach also TeV scale by now

Highest E_T (960 GeV) unconverted photon (June 2011)