# Review diffractive and electromagnetic processes in ATLAS

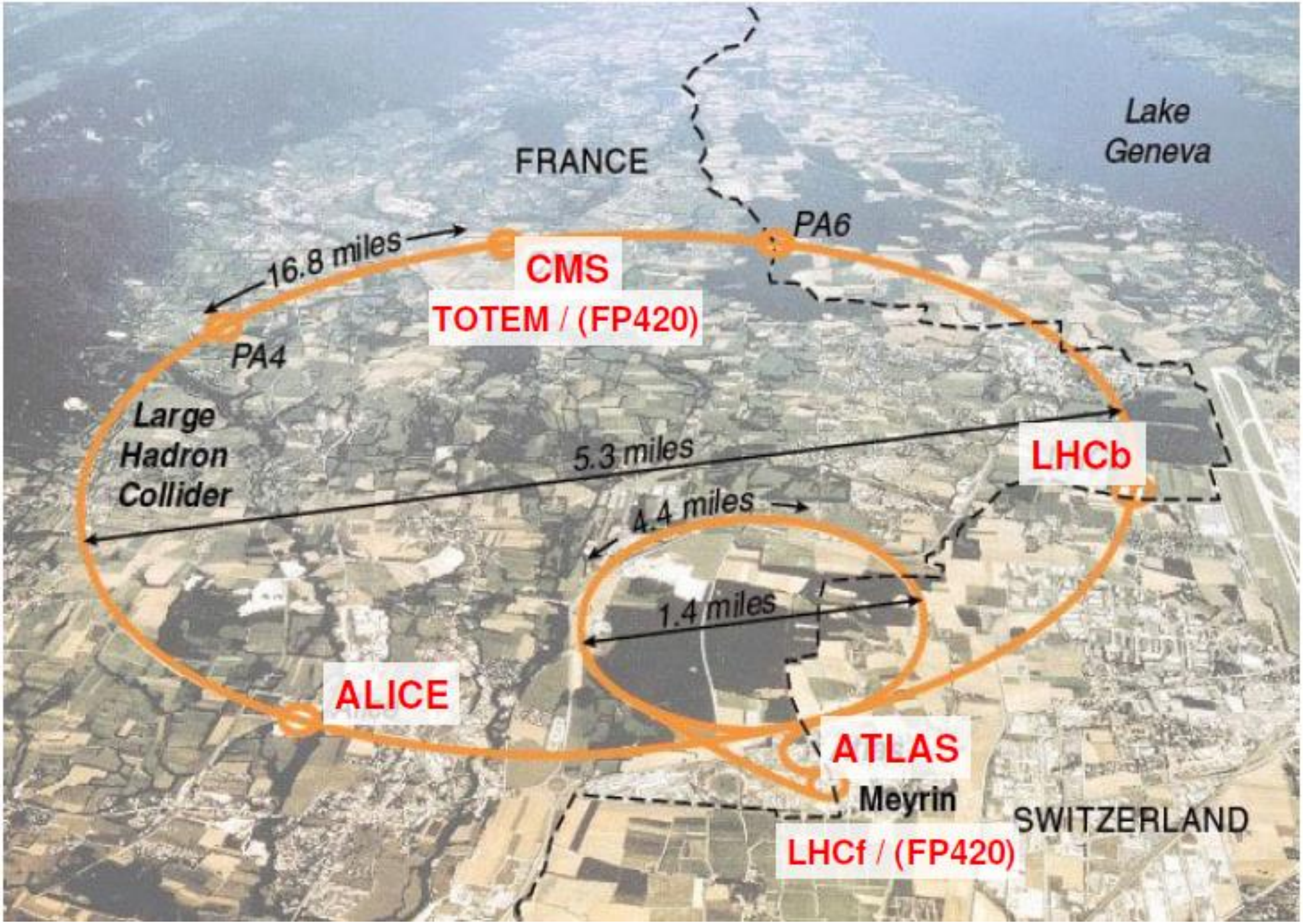
Laurent Schoeffel

Some time ago in H1/HERA (DVCS -1999-2009 –all H1 papers-, F2D 2004-2012 –the HERA2 paper-)
Now, involved in many ATLAS analyses:
convener of the physics group related to QCD and EM processes

CEA Irfu/SPP
France

**International WE-Heraeus Physics School (2015)**
**August 2015**

# The LHC experiments




40
40
MAIN ENTRANCE →

# The total cross section at the LHC

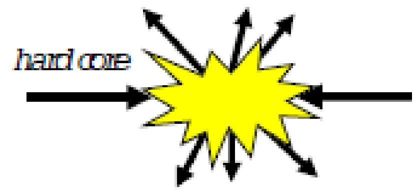
## A short anatomy of pp collisions


$\sigma_{tot}$~95 mb

$$\sigma_{tot} = \sigma_{el} + \sigma_{in}$$

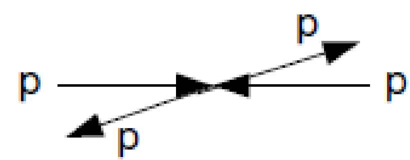
$$\sigma_{in} = \sigma_{parton} + \sigma_{SD} + \sigma_{DD} + \sigma_{DPE}$$

- ~60% of the time a "hard" collision occurs



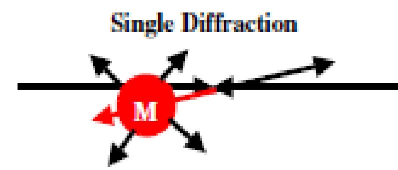

$\sigma_{hc}$~55 mb

- ~25% of the time the protons scatter elastically



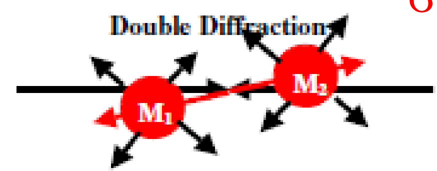

$\sigma_{el}$~25 mb

- ~10% of the time single diffraction occurs

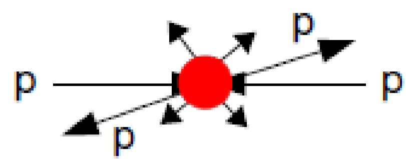



$\sigma_{diff}$~15 mb

~1% of the time double diffraction occurs




~1% of the time central (exclusive) diffraction occurs



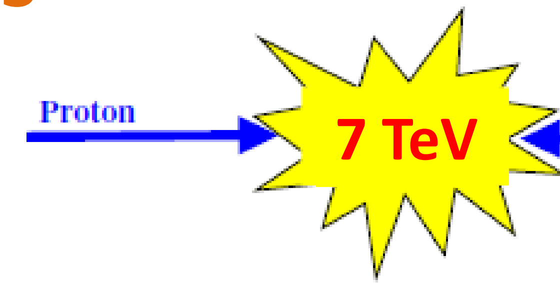
# The total cross section at the LHC

## A short anatomy of pp collisions

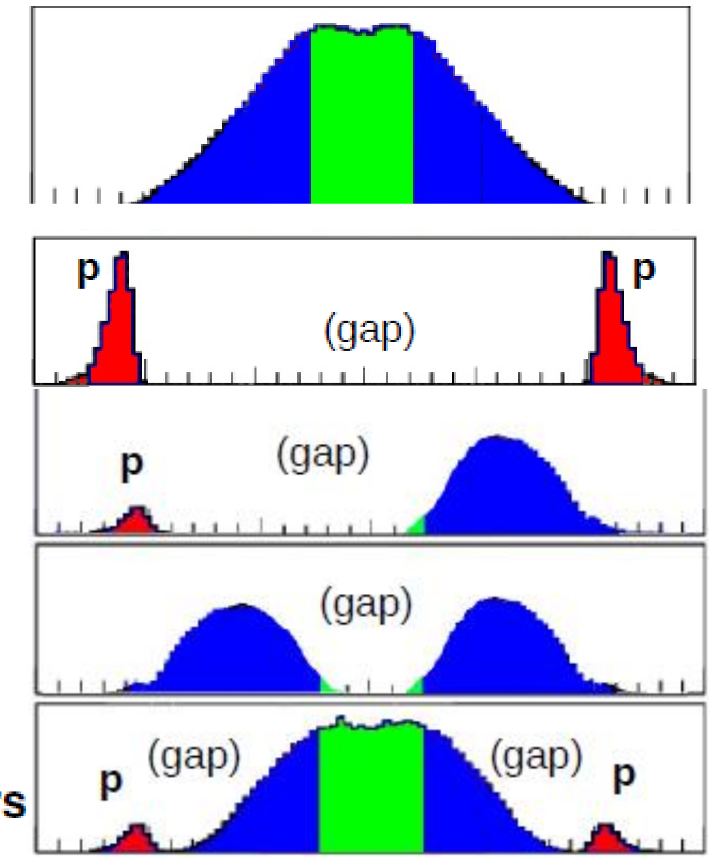
$\sigma_{tot}$~95 mb

$$\sigma_{tot} = \sigma_{el} + \sigma_{in}$$

$$\sigma_{in} = \sigma_{parton} + \sigma_{SD} + \sigma_{DD} + \sigma_{DPE}$$

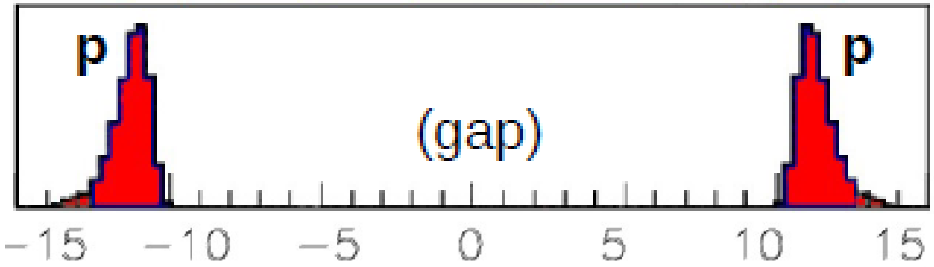



- ~60% of the time a "hard" collision occurs
- ~25% of the time the protons scatter elastically
- ~10% of the time single diffraction occurs
- ~1% of the time double diffraction occurs
- ~1% of the time central (exclusive) diffraction occurs



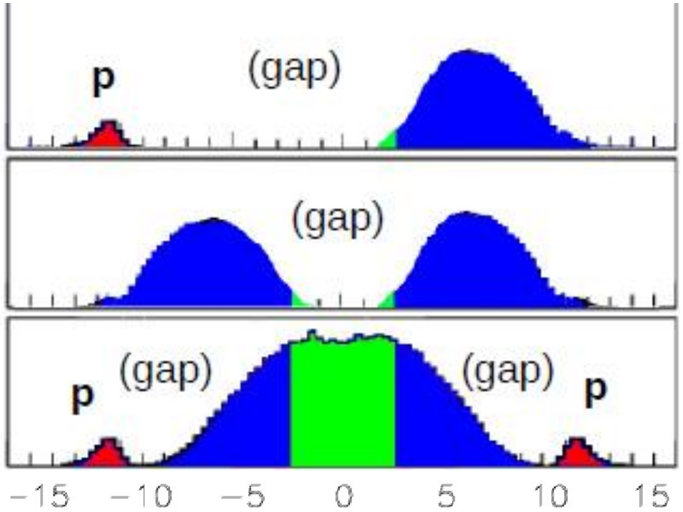
# Experimental techniques

- Either we measure scattered protons using
  forward detectors

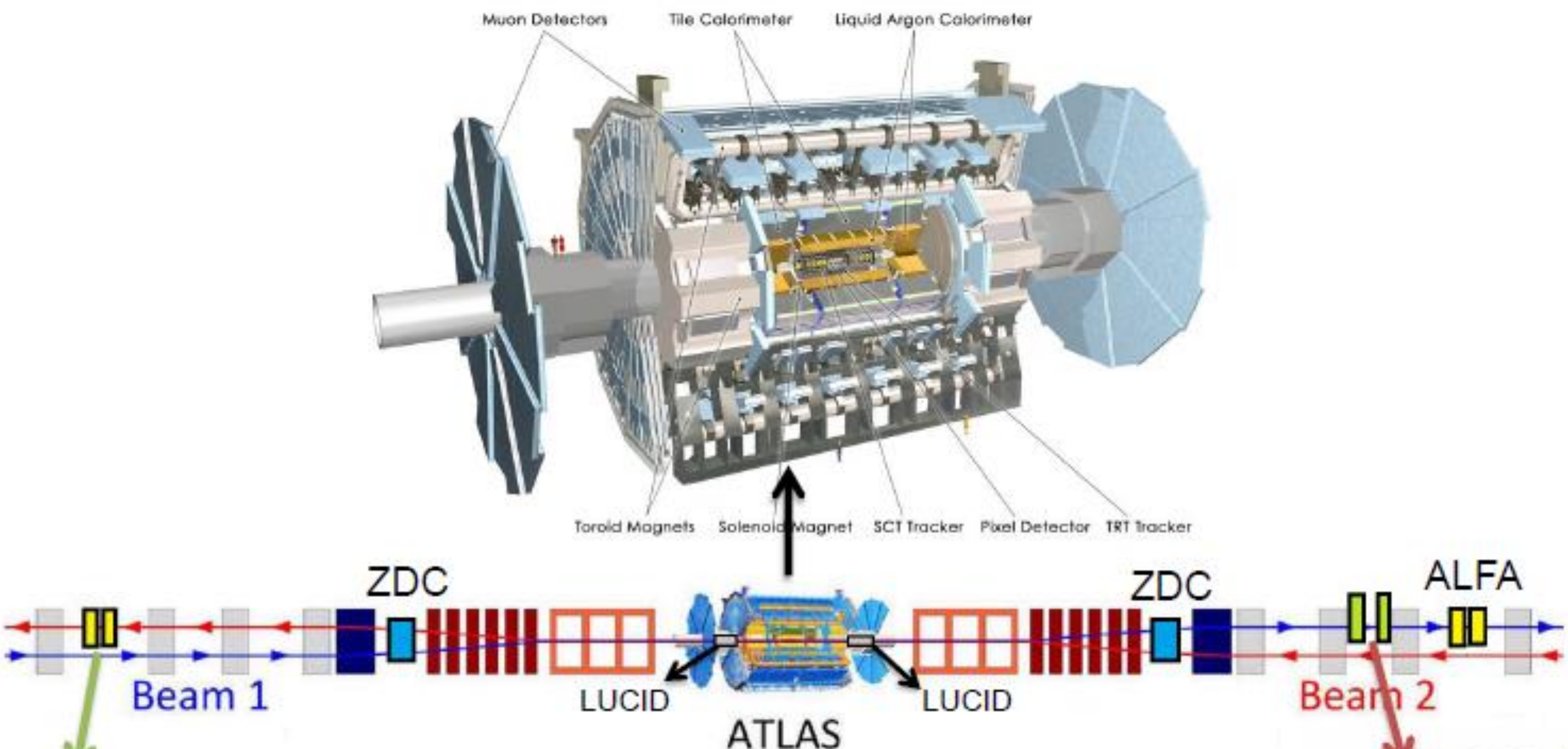


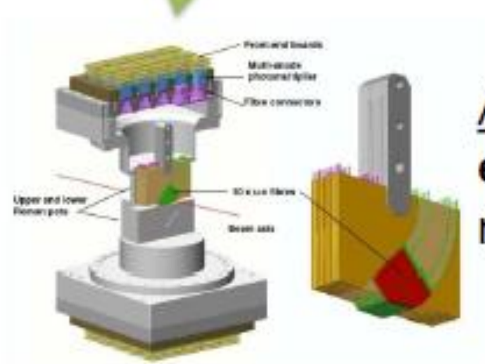

- Or we measure GAPs (veto on particles and/or energy flow)

This needs a large pseudo-rapidity coverage…



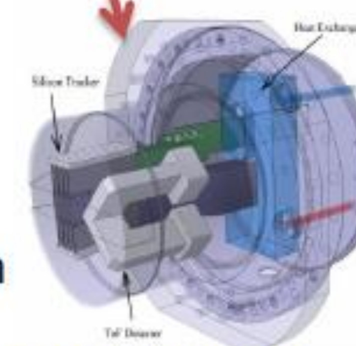
# Central/forward detectors in ATLAS



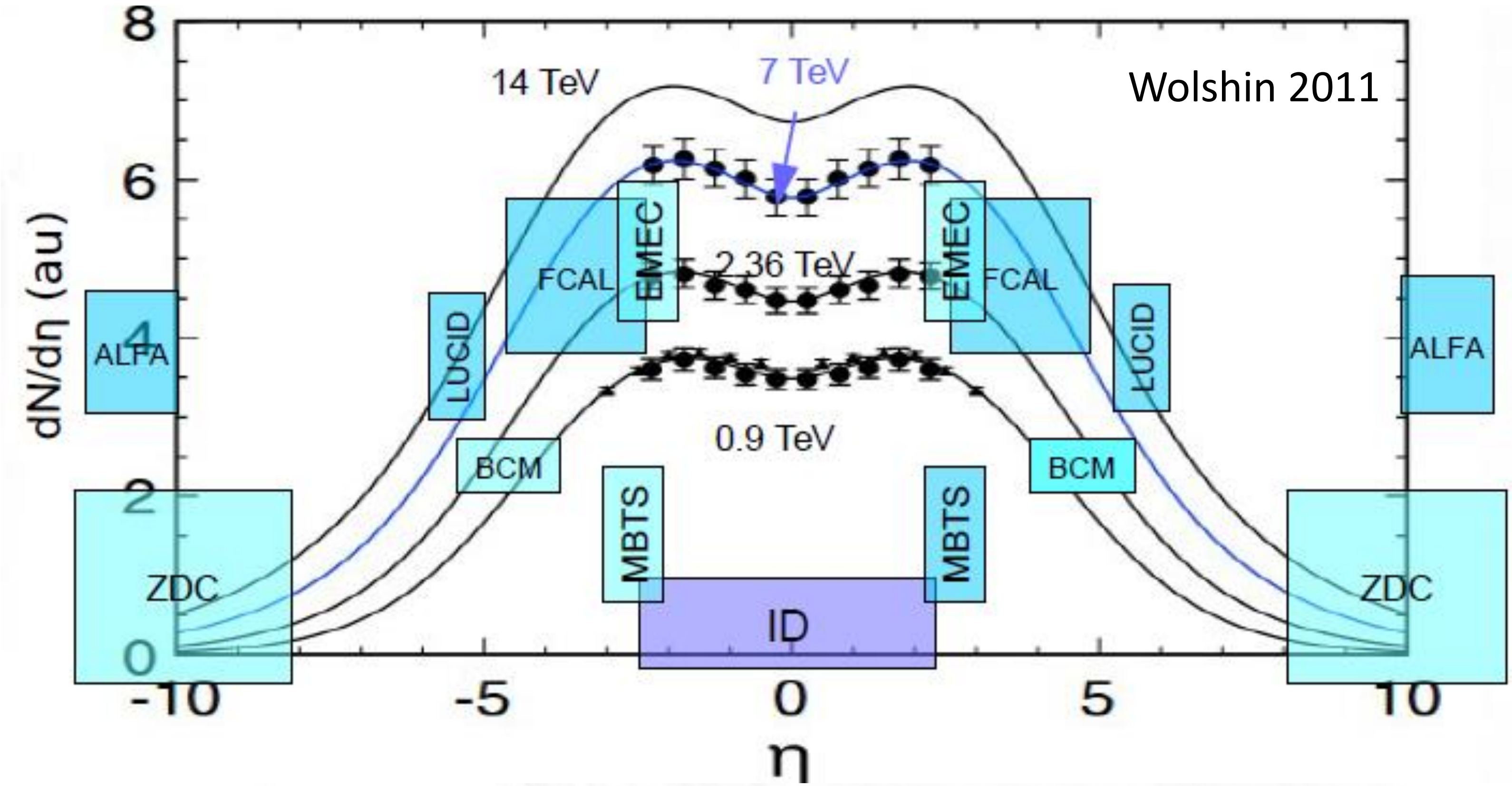



<u>ALFA</u>:
**elastic** protons measurement

<u>AFP</u>:
**diffractive** protons measurement.
A first-phase installation in 2016.
CERN-LHCC-2015-009; ATLAS-TDR-024



# Pseudo-rapidity coverage



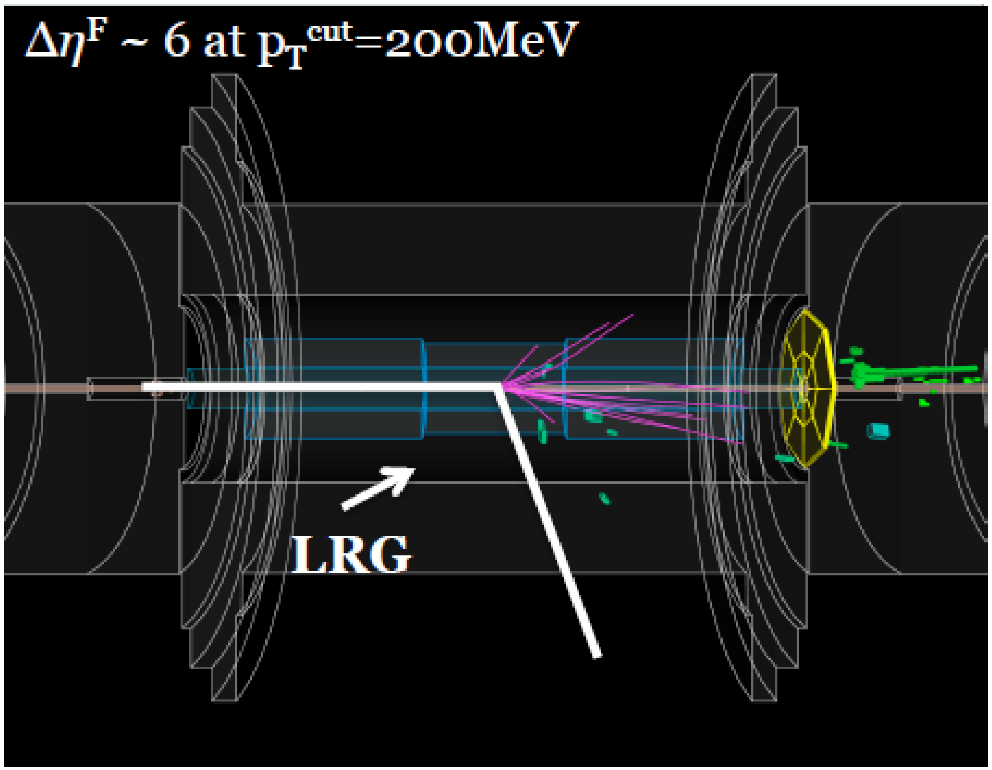

| Detector | η coverage |
|---|---|
| ID (Pix + SCT) | \|η\|<2.5 |
| ID (TRT) | \|η\|<2.0 |
| MBTS | 2.08<\|η\|<3.75 |
| Calo: EMEC | 2.5<\|η\|<3.2 |
| Calo: FCal | 3.1<\|η\|<4.9 |

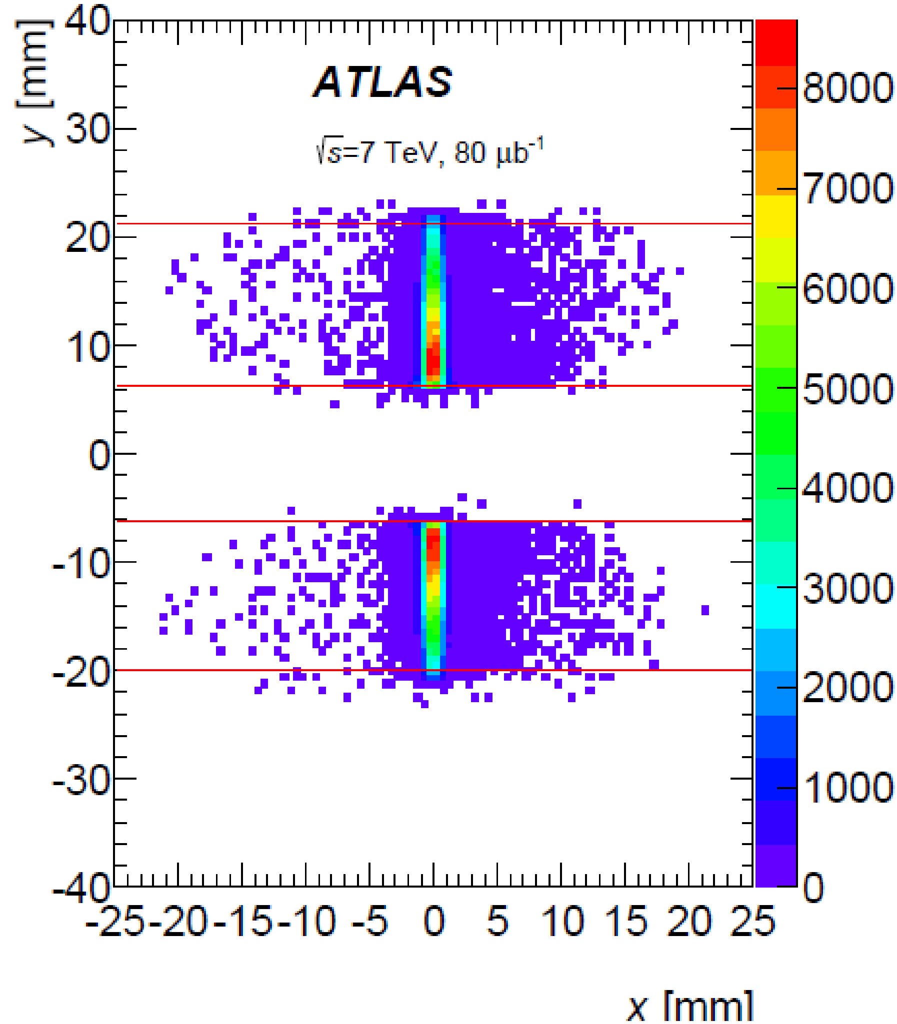
| Detector | η coverage |
|---|---|
| BCM | \|η\|=4.2 |
| LUCID | 5.6<\|η\|<6.0 |
| ZDC | \|η\|>8.3 |
| ALFA | 10.6<\|η\|<13.5 |

# LRG (large Rapidity Gaps) and proton tags

## A short anatomy of pp collisions / examples...

This will be covered in this presentation

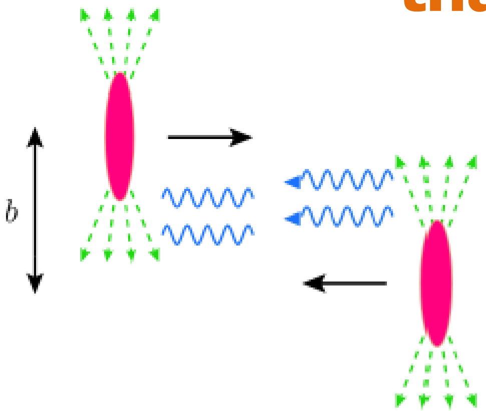


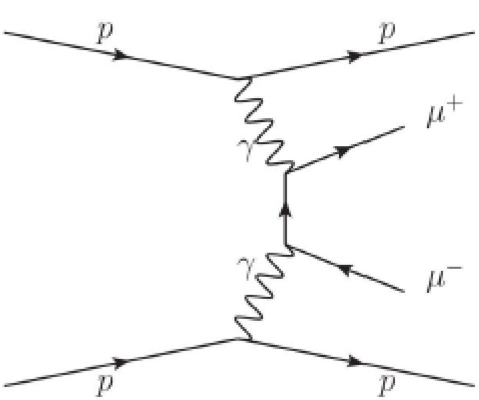

- Cross sections in mb

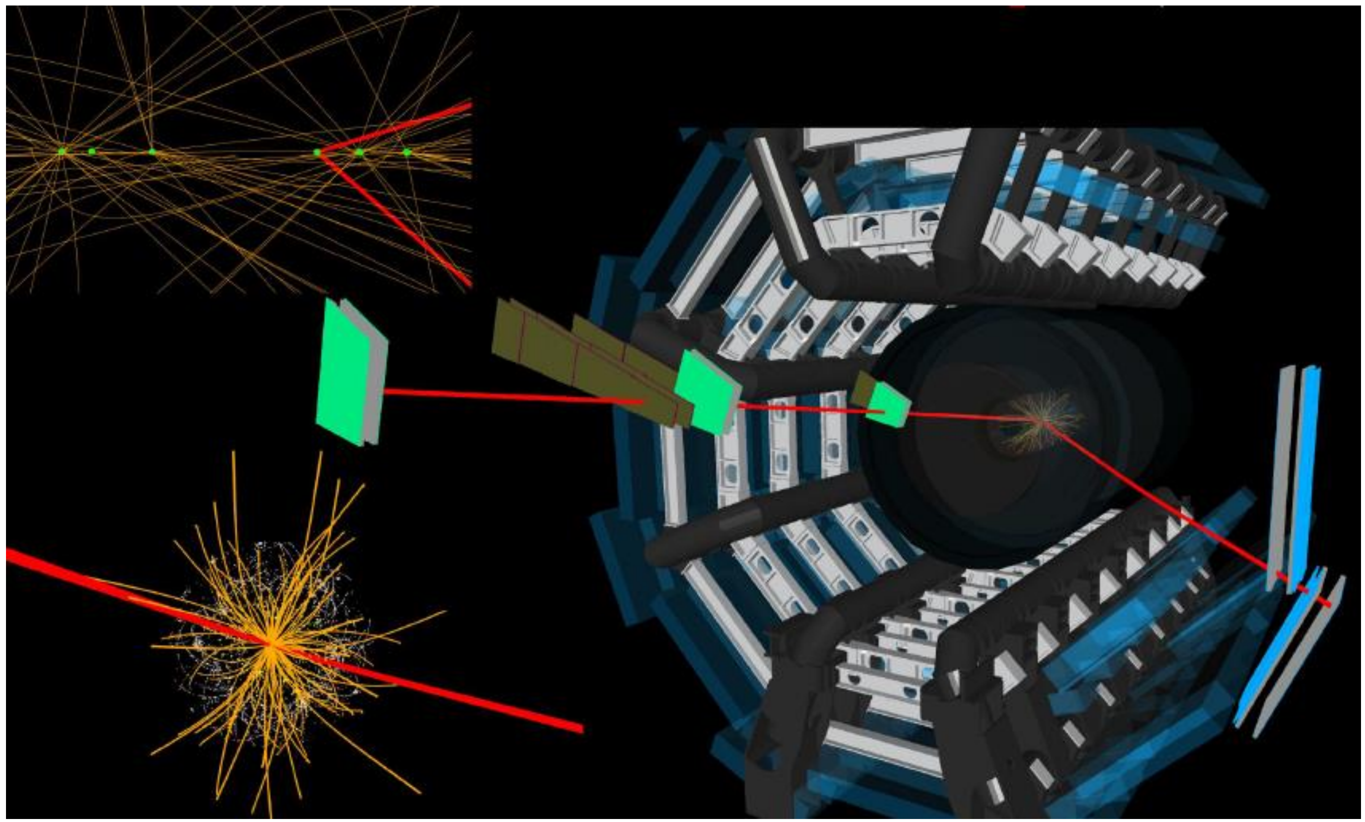
# Many other processes (EM) possible

## **that can produce GAPs and/or 'intact' protons**




This will be covered in this presentation



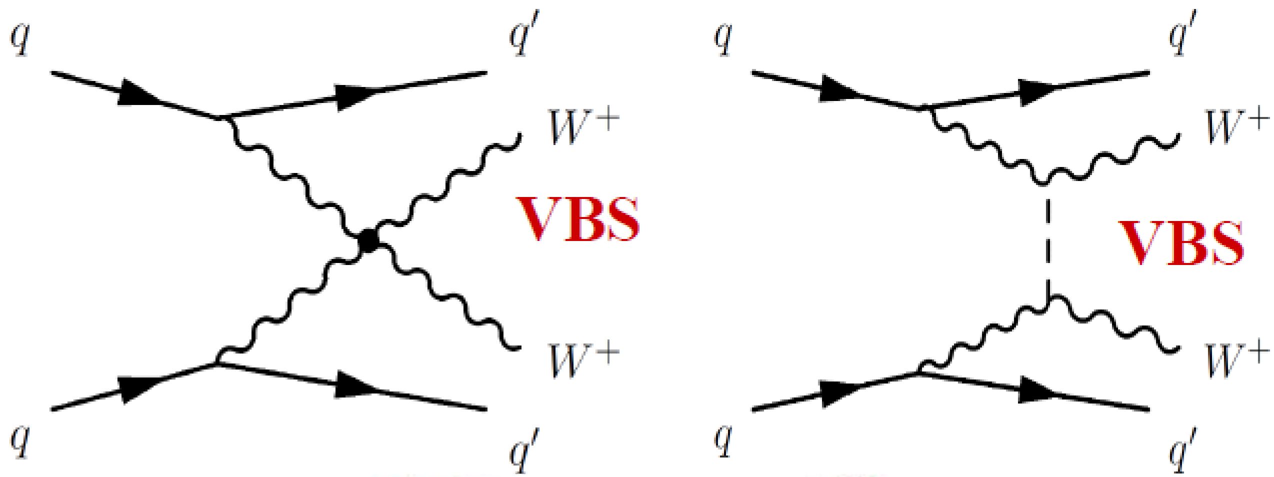



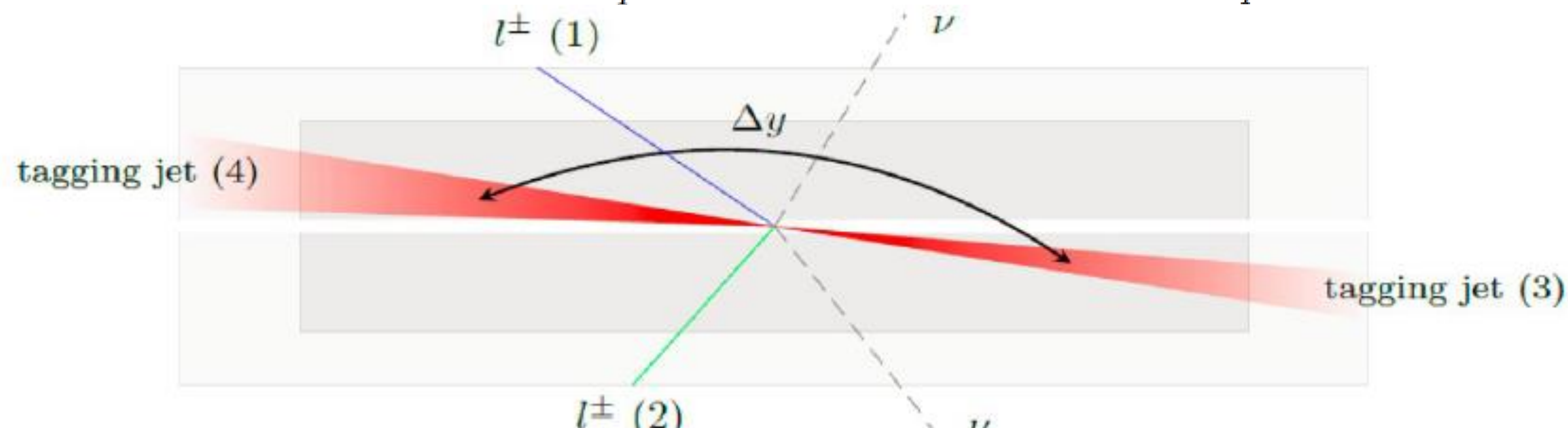
- Cross sections in pb *...deeper anatomy*

# And also…

## Vector Boson Scattering (VBS)

This will be covered in this presentation




- Cross sections in fb *…even deeper anatomy*

# Outline

- Intact protons

  -- ‘elastic’ diffractive scattering

  “The diffraction phenomena of quantum systems can however be reduced directly to a classical limit only when elastic scattering takes place…” [Alberi, Goggi 1981]

- Rapidity Gaps

  -- ‘inelastic’ diffractive scattering

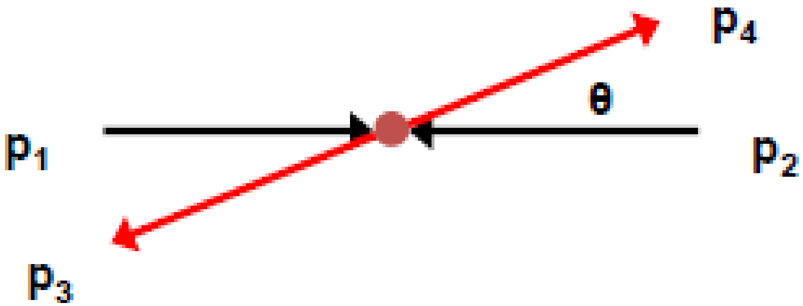
  *“As a consequence, inelastic diffraction can be reduced to elastic diffraction scattering of the basic states, in which the initial and final states can be decomposed.*
  *The fluctuations of hadronic systems over this set of basic states,*
  *typical manifestation of quantum field-theoretical objects,*
  *are the main origin of the large probability observed for inelastic diffraction…”*
  [Alberi, Goggi 1981]

- EM processes and beyond

  *(EM extended to EWK [Electro-Weak])*

−15 −10 −5 0 5 10 15

# Elastic pp->pp reaction




$t=(p_1 - p_3)^2 = (p_2 - p_4)^2 \approx -p^2\theta^2$

To determine the total cross section, it is sufficient to measure the elastic cross section down to very small |t| values ($\theta \to 0$)…

This is why it is needed to use forward proton taggers and a dedicated LHC optics (see later)

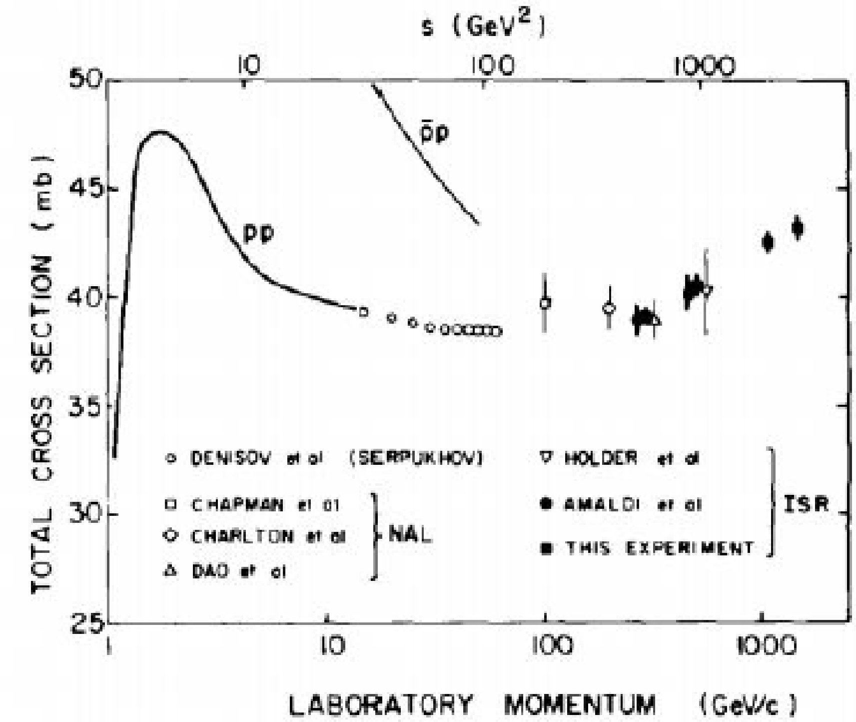
$$\sigma^2_{\rm tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{{\rm d}\sigma_{\rm el}}{{\rm d}t}\Big|_{t\to 0}$$

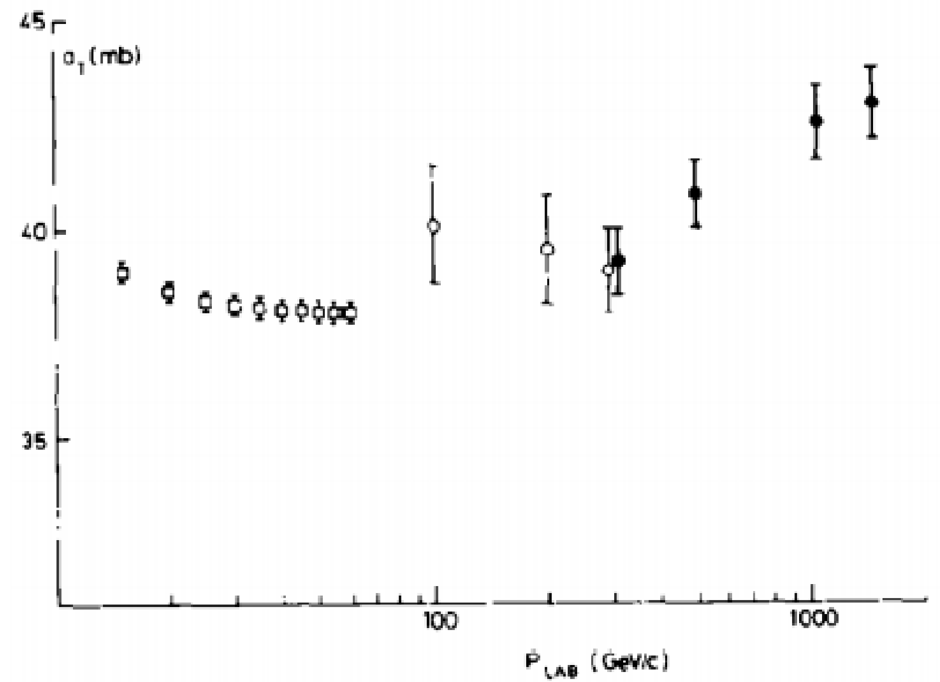
-> total pp cross section

# History: rise of $\sigma_{tot}$ at ISR

CERN Intersecting Storage Rings

At the ISR a rise of the total cross section was first observed.



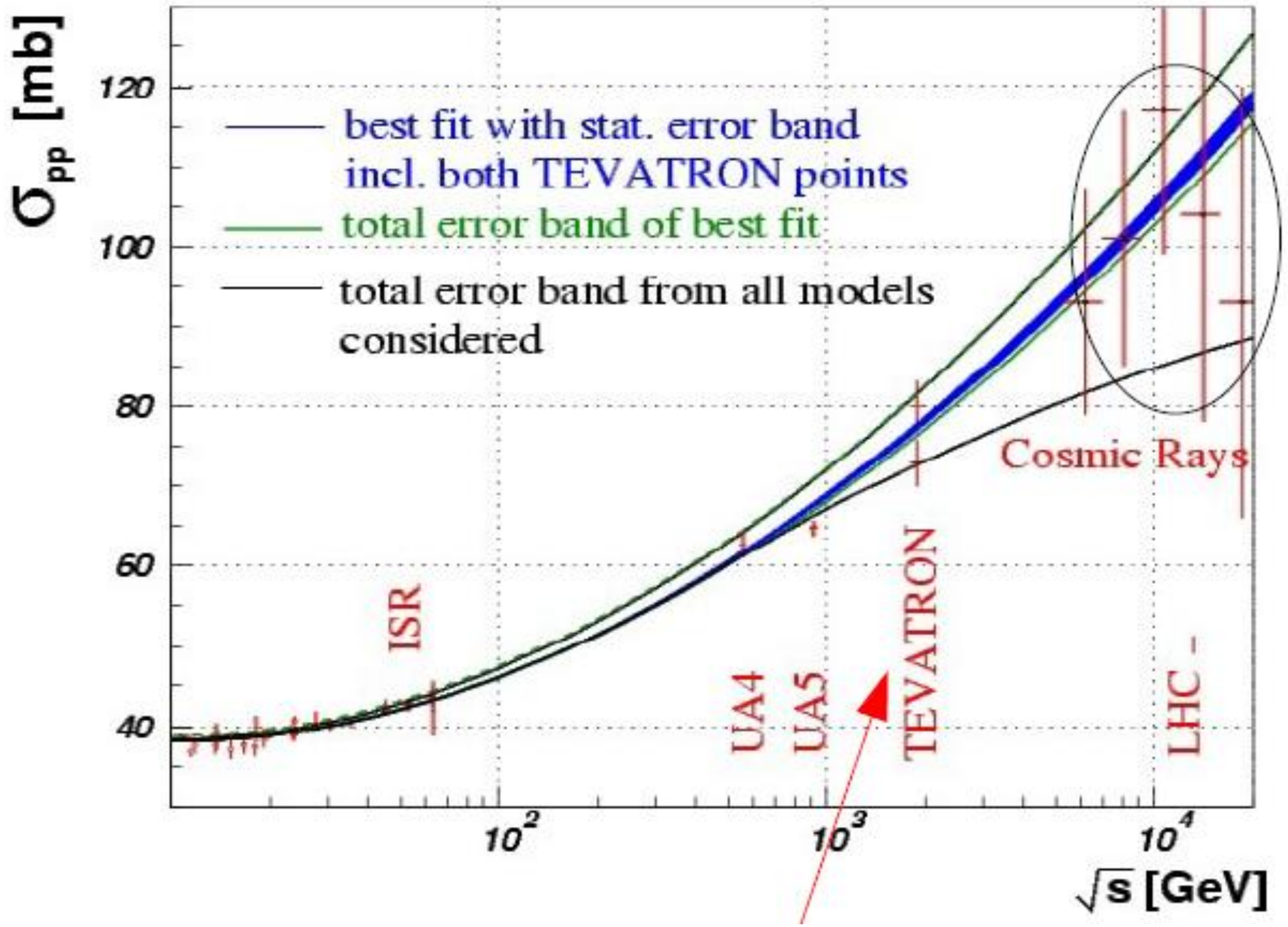




U. Amaldi et al., Phys. Lett. B 44 (1973) 192

S.R. Amendolia et al., Phys. Lett. B 44 (1973) 119

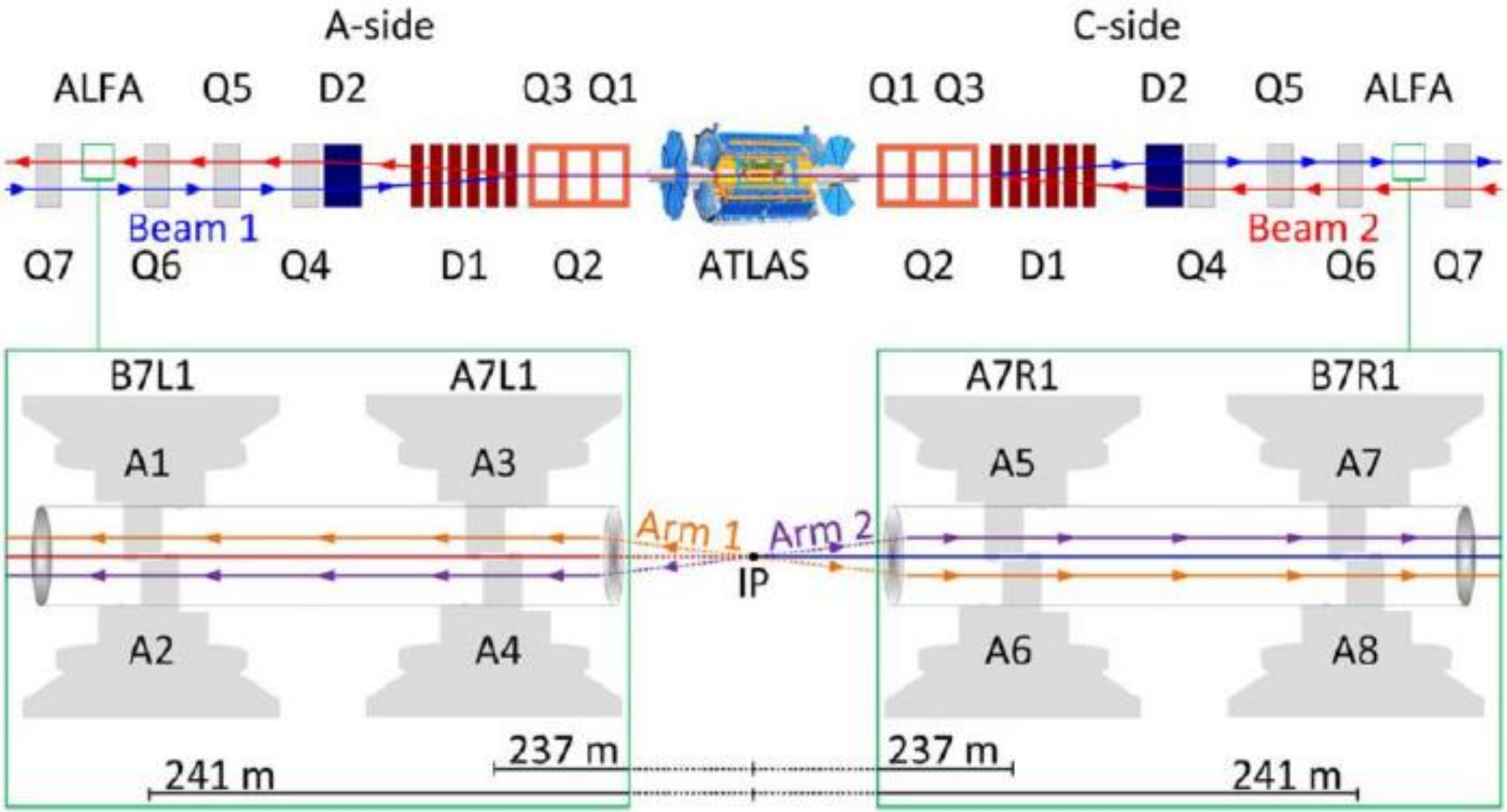
Next, we describe precisely the measurement at ATLAS using ALFA - at 7 TeV **(which kind of rise: ln(s), ln²(s),…?)**

# Pre-LHC rise of $\sigma_{tot}$



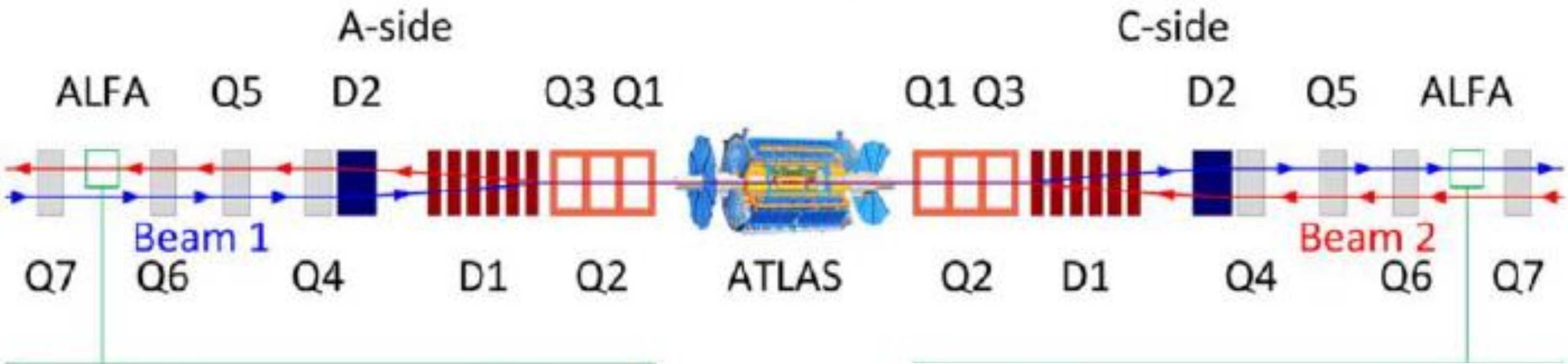

Then, Pre-LHC measurements does not constraint the rise of the total cross section very precisely…

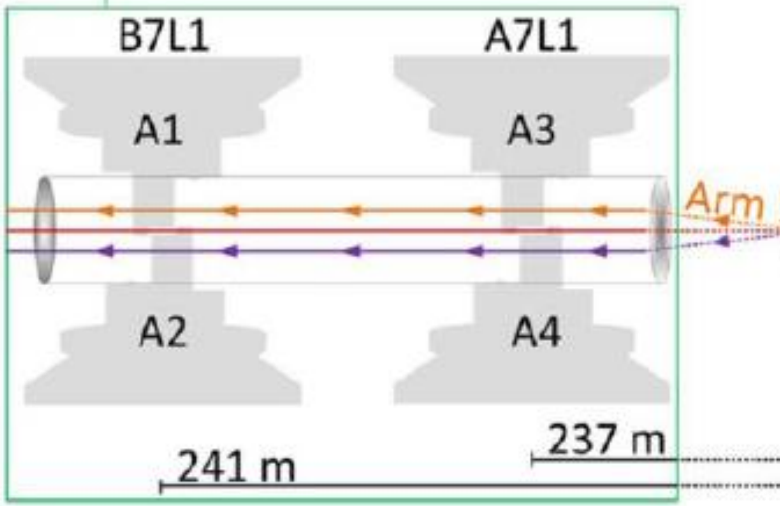
# ATLAS -- ALFA / Roman Pots

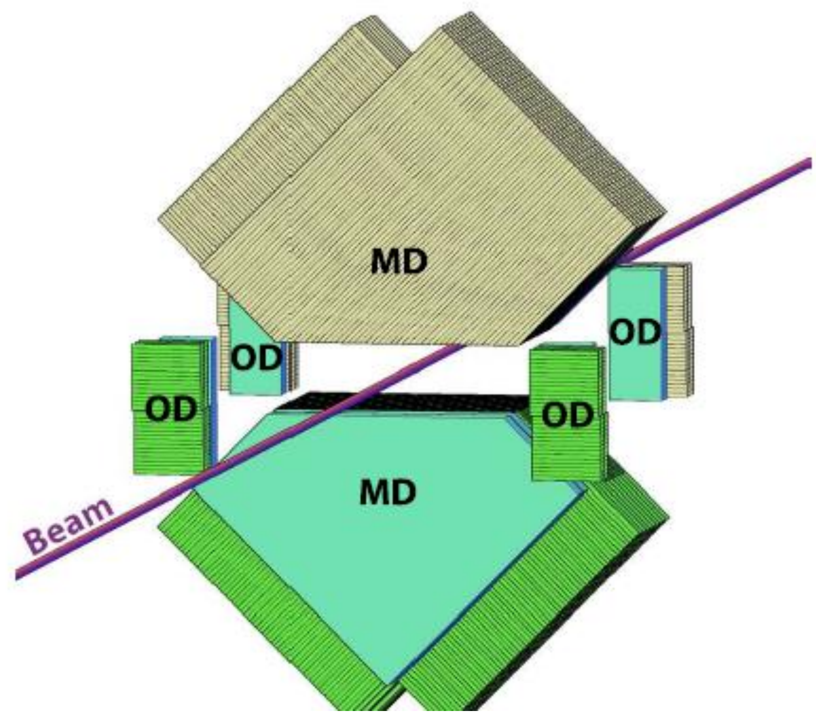



- Roman pots:
  located 240 m from the IP
- 4 stations, 8 detectors
- Detectors: scintillating fibers
  (i.e. trackers)

# ATLAS -- ALFA / Roman Pots



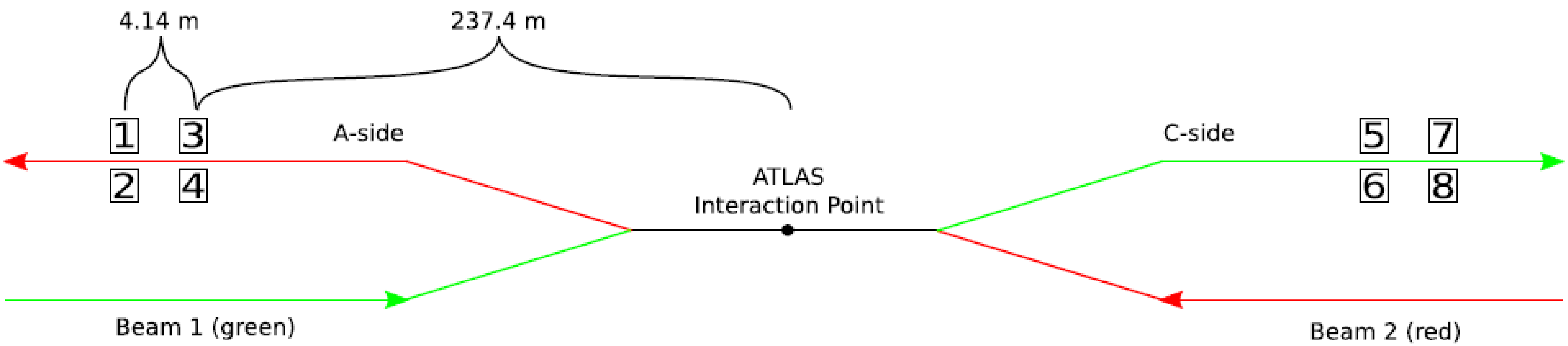




- Roman pots:
  located 240 m from the IP
- 4 stations, 8 detectors
- Detectors: scintillating fibers
  (i.e. trackers)

# ALFA / beams (protons)

- Roman Pot detectors at 240 m from IP1 approaching the beam during special runs at high β*.

**We explain this condition in a few slides**

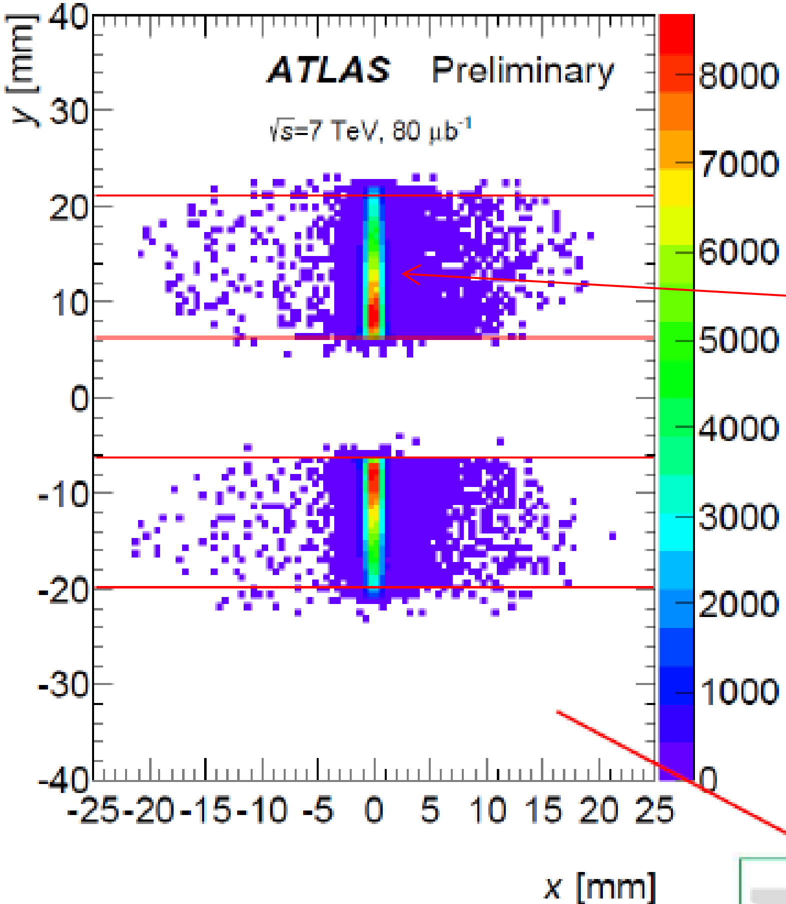



- 

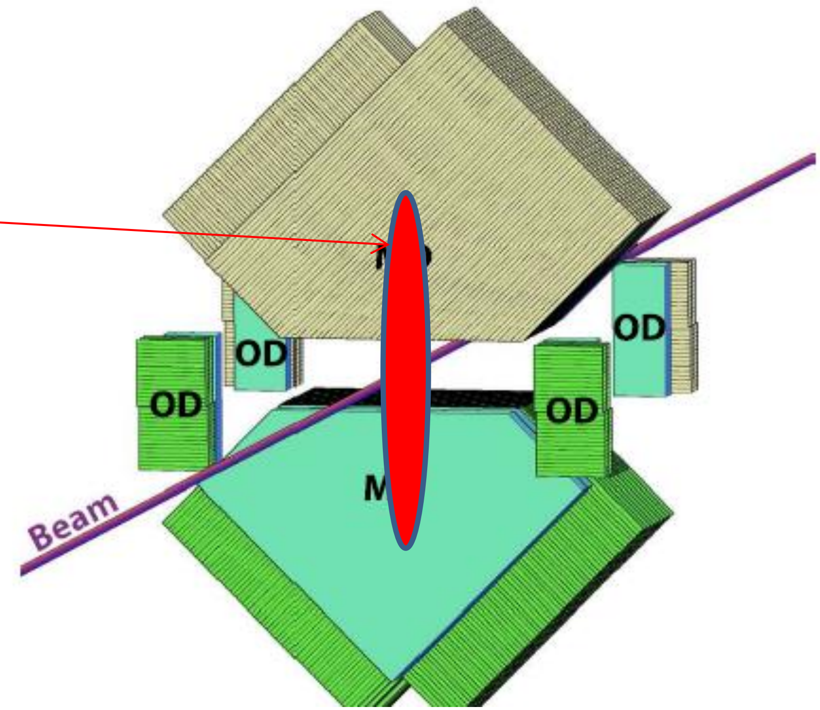
In October 2011 ALFA had the special run 191373 with β*=90m

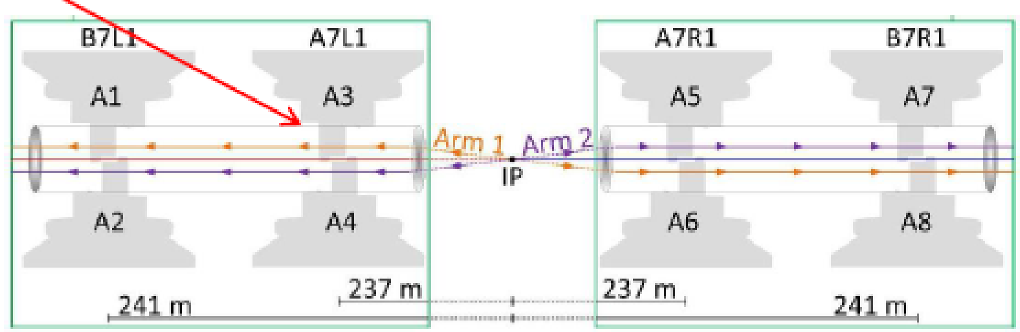
and recorded 800k *good selected elastic events* used for the analysis of the total cross section and the nuclear slope B.
At 7 TeV: each proton beam with momentum 3.5 TeV/c

# ALFA / Hit map (1)

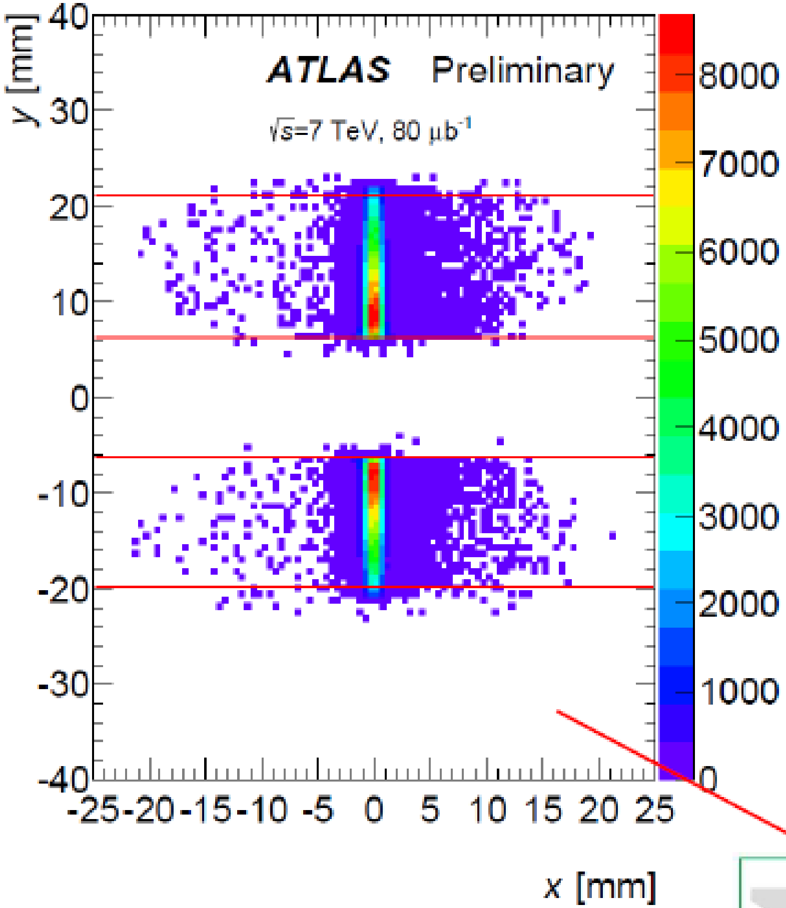



Remember the geometry or RP!



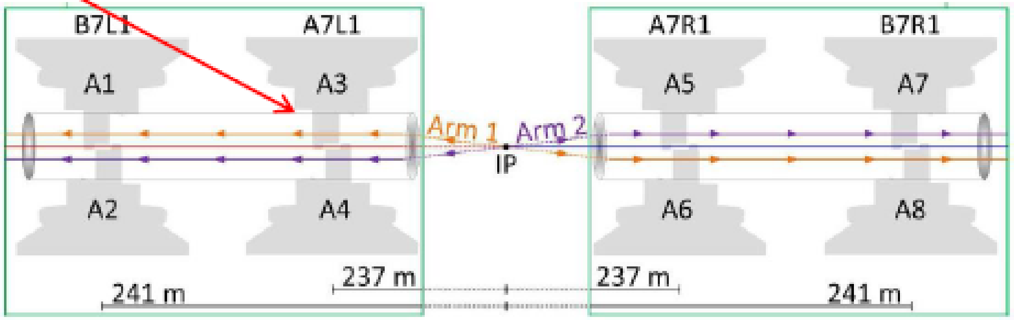
# ALFA / Hit map (1)



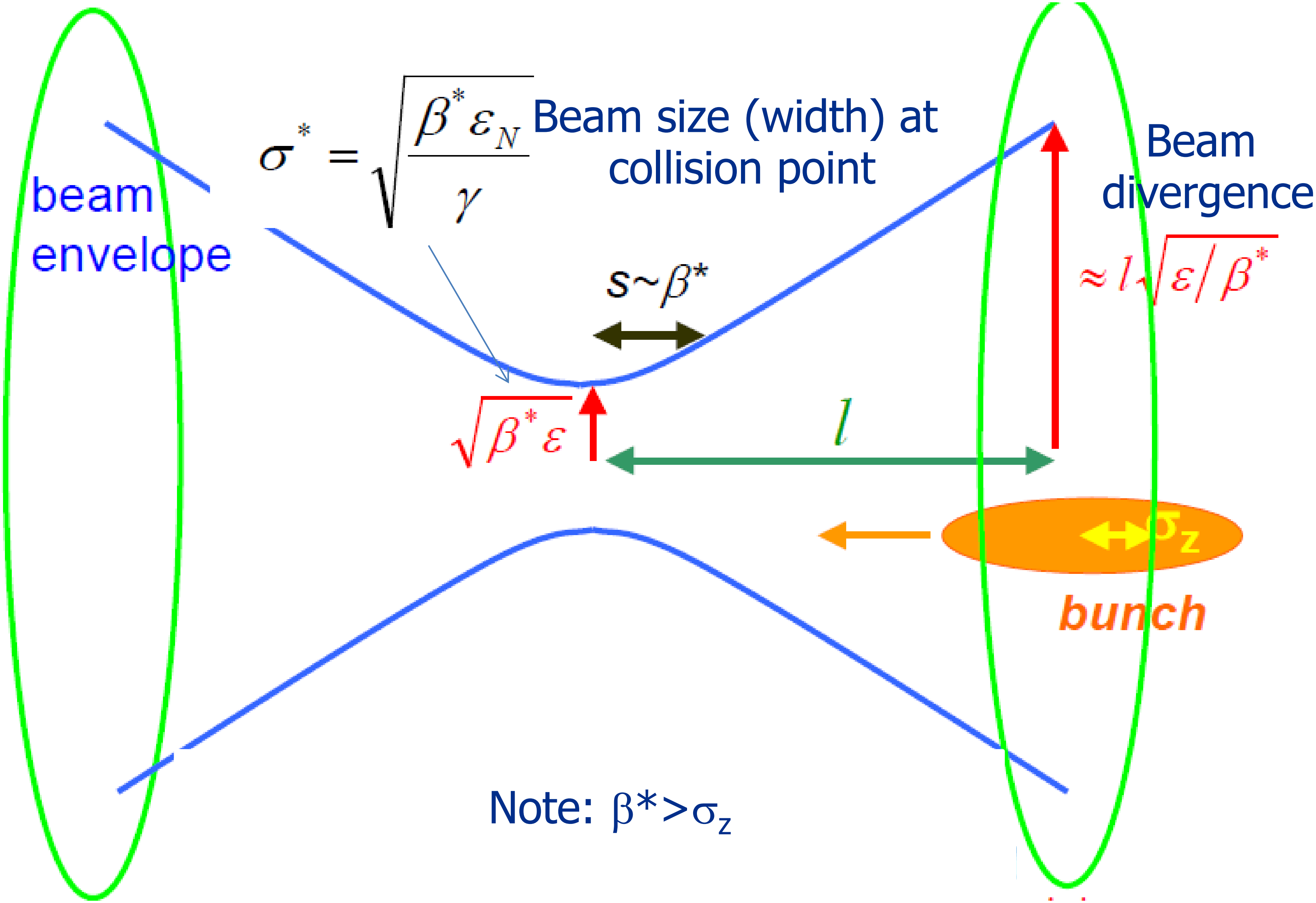

Hit pattern in one station, before elastic event selection.

Pattern shape is caused only by beam optics…

**We justify this map in a few slides**



# LHC beams (protons)




Note: $\beta^* > \sigma_z$

# LHC beams (protons)

## Special optics for ALFA w.r.t. nominal LHC optics

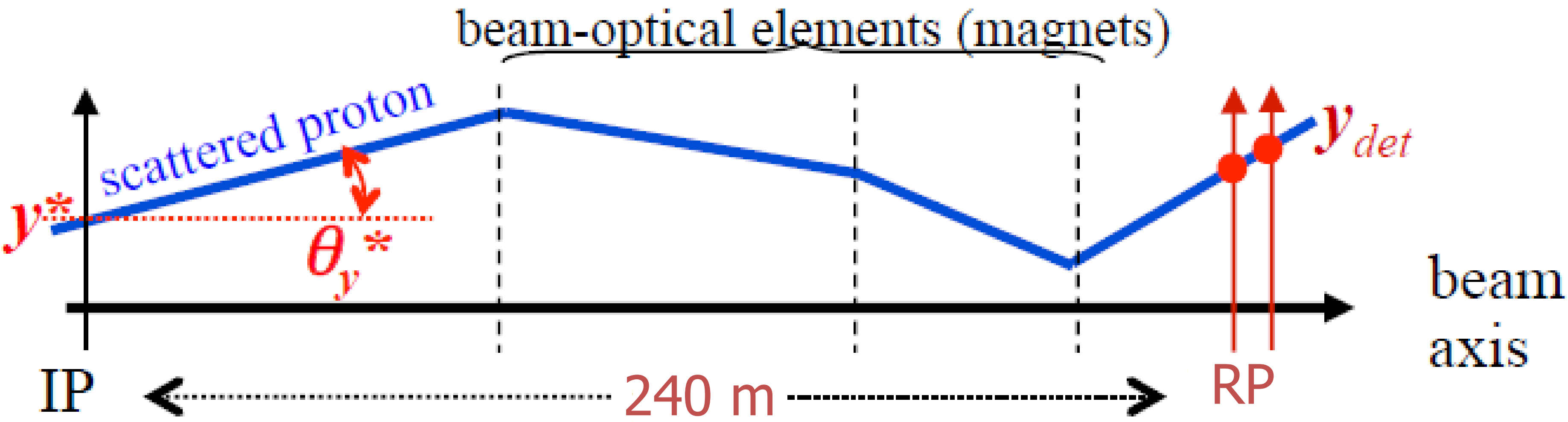
| | Beam size (width) at collision point | Beam divergence | $\|t\|_{min} \propto p\ \varepsilon/\beta^*$ |
|---|---|---|---|
| Standard optics $\beta^* = 0.5m$ | Small | Large | >0.3 $GeV^2$ |
| **Special optics $\beta^* = 90m$** | **Large** | **Small** | **~0.01 $GeV^2$** |

**This justifies the high $\beta^*$ requirement**

*higher $\beta^*$ (~1km) would lead to smaller $|t|_{min}$~0.001 $GeV^2$*

**Then, what is observed/measured in ALFA?**

# Measurements in RP [x,y]




($\theta^*_x$, $\theta^*_y$) emission angles at IP (interaction point)

($x^*$,$y^*$) vertex at IP

$$t = -\left(p\theta^*\right)^2$$

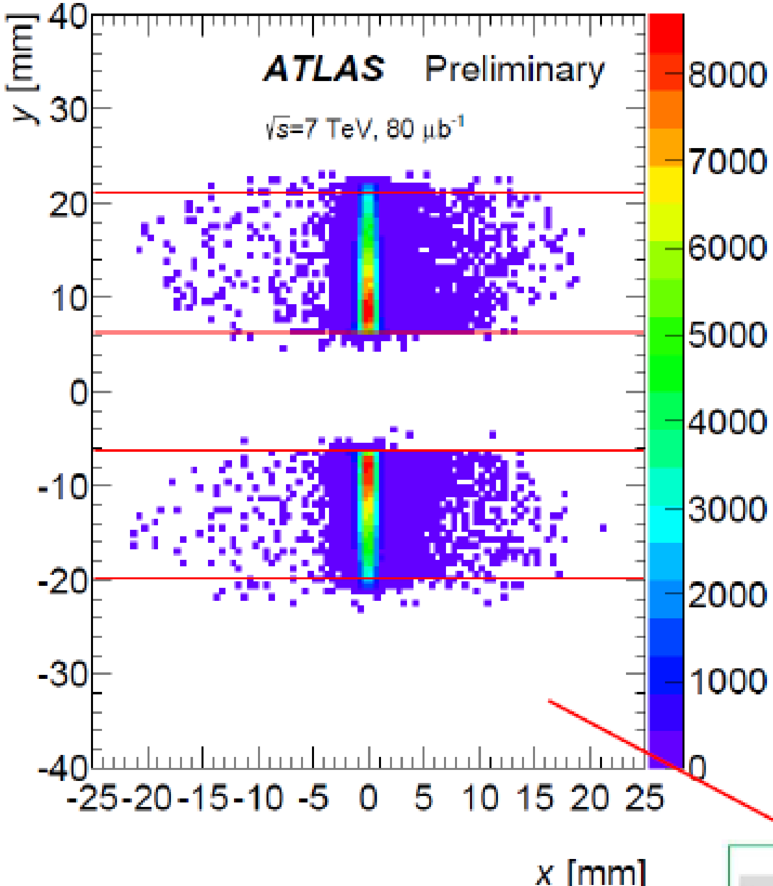
at RP

$$\begin{pmatrix} y \\ \theta_y \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} y^* \\ \theta_y^* \end{pmatrix}$$

In linear optics: det[M] := 1

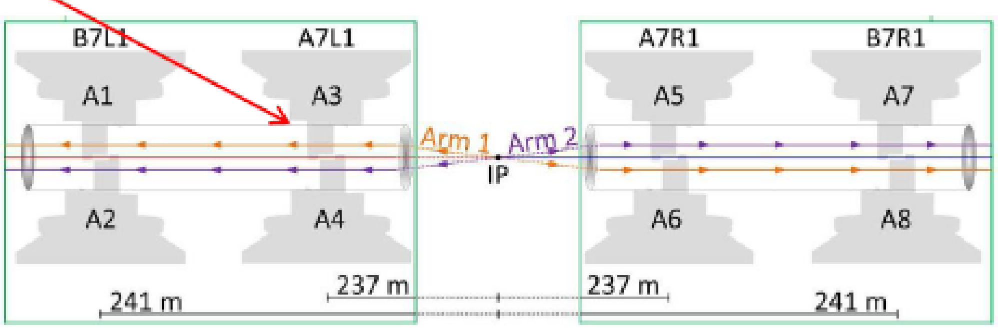
- $y \sim M_{12}\, \theta^*_y = L_y[270\text{ m}]\, \theta^*_y$
- Similarly for [x]:
  $x = L_x[13\text{m}]\, \theta^*_x + v_x\, x^* + D_x\, \xi$
  (elastic $\xi = 0$)

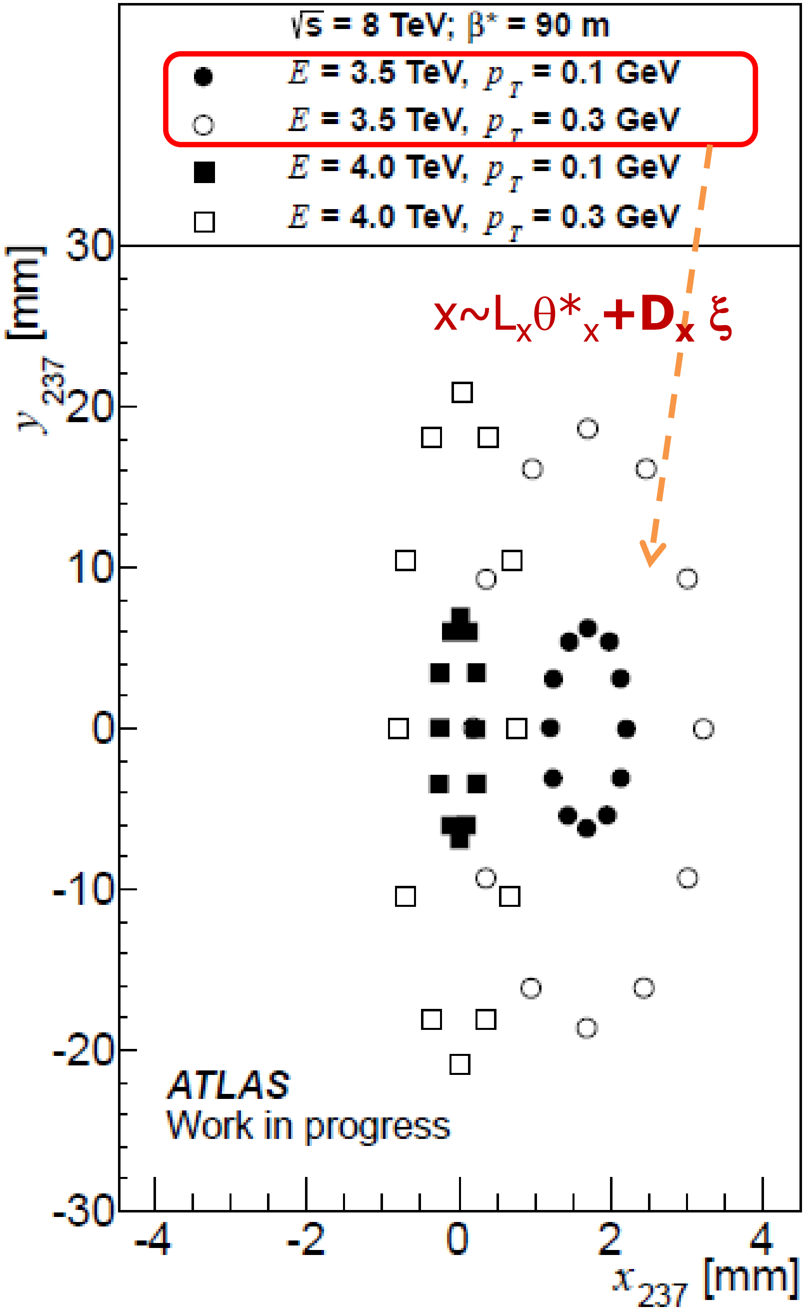
# ALFA / Hit map (2)




$y = L_y[270m]\ \theta^*_y$
$x = L_x[13m]\ \theta^*_x + v_x\ x^* + D_x\ \xi$
(elastic $\xi=0$)

Hit pattern in one station.
The shape is caused
by the beam optics only
(equations above)

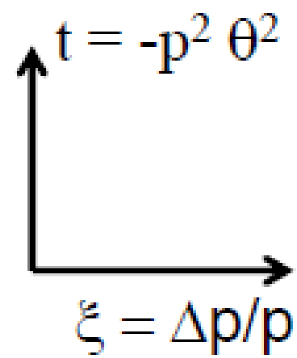





- *Note:*
  If one would like to measure non-zero ξ values -- with a good acceptance

- => New RP needed ⊥ ALFA

CERN-LHCC-2015-009; ATLAS-TDR-024




AFP:
**diffractive** protons measurement.
A first-phase installation in 2016.

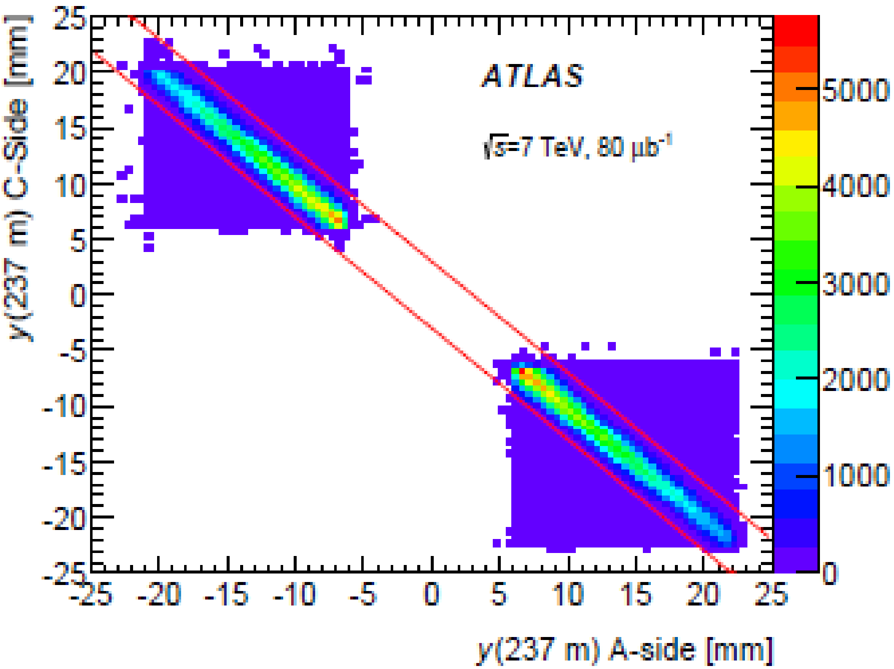
Longitudinal momemtum loss (fraction)

# Elastic cross section / Analysis strategy

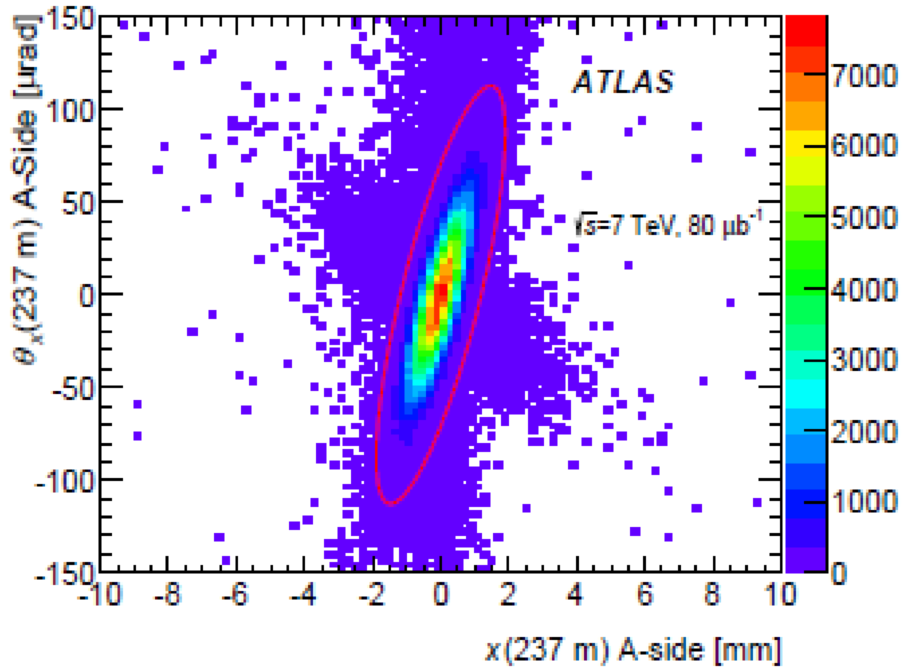
Following the previous slides =>

Selection based on constrained kinematics of elastic events:

- Left (C side)-right (A side) symmetry (in x and y)
- Correlation between trajectory position (x) and elevation angle (θ)




Correlation between $y$ on A and C sides




Correlation between $x$ and $\theta_x$ on A side

# Elastic cross section / Results

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \frac{d\sigma_{\text{el}}}{dt}\Big|_{t\to 0}$$

...can be *extended* to

$$\frac{d\sigma_{el}}{dt} = \text{Coulomb} + \text{CNI} + \boldsymbol{\sigma}^2_{\textbf{tot}} \frac{\mathbf{1+\rho^2}}{\mathbf{16\pi}} \mathbf{e^{-B|t|}}$$

Cross sections:

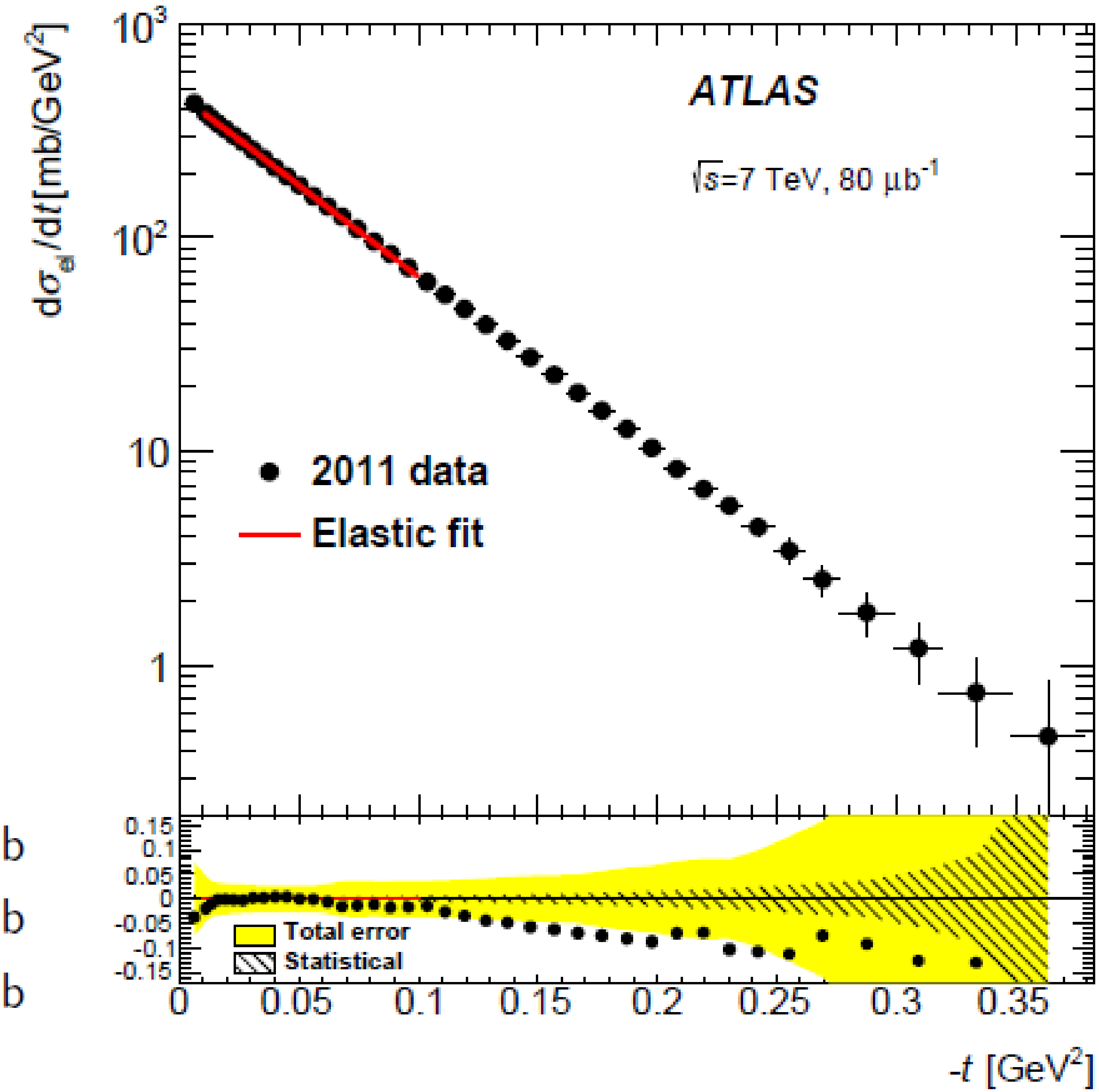
$$\sigma_{\text{tot}} = 95.35 \pm 1.36 \text{ mb}$$

$$\sigma_{\text{el}} = 24.00 \pm 0.60 \text{ mb}$$

$$\sigma_{\text{inel}} = 71.34 \pm 0.90 \text{ mb}$$

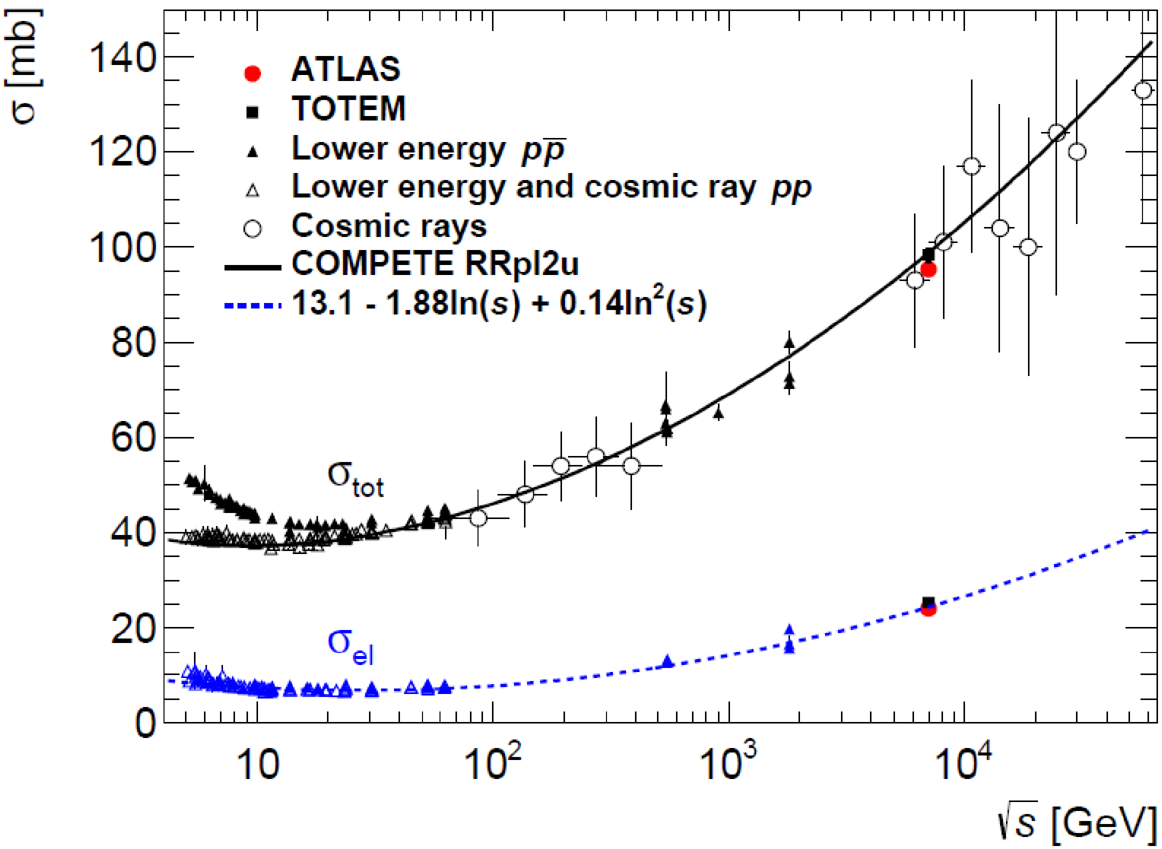
Elastic slope:

$$B = 19.73 \pm 0.24 \text{ GeV}^{-2}$$

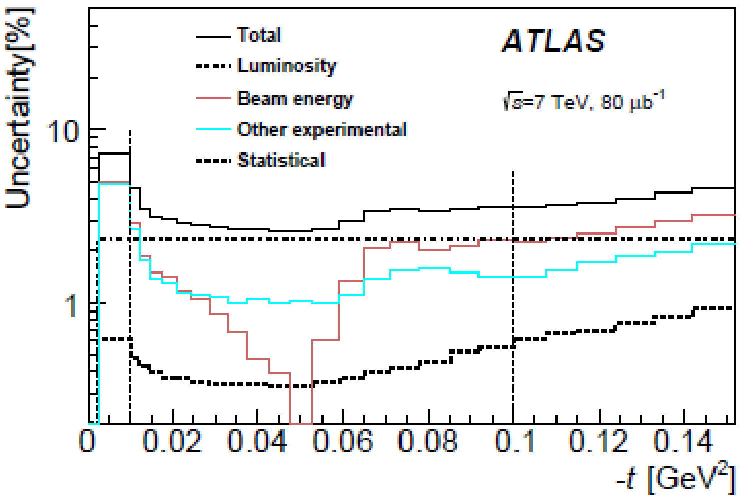


arXiv:1408.5778
NPB (2014), pp. 486-548

# Final result

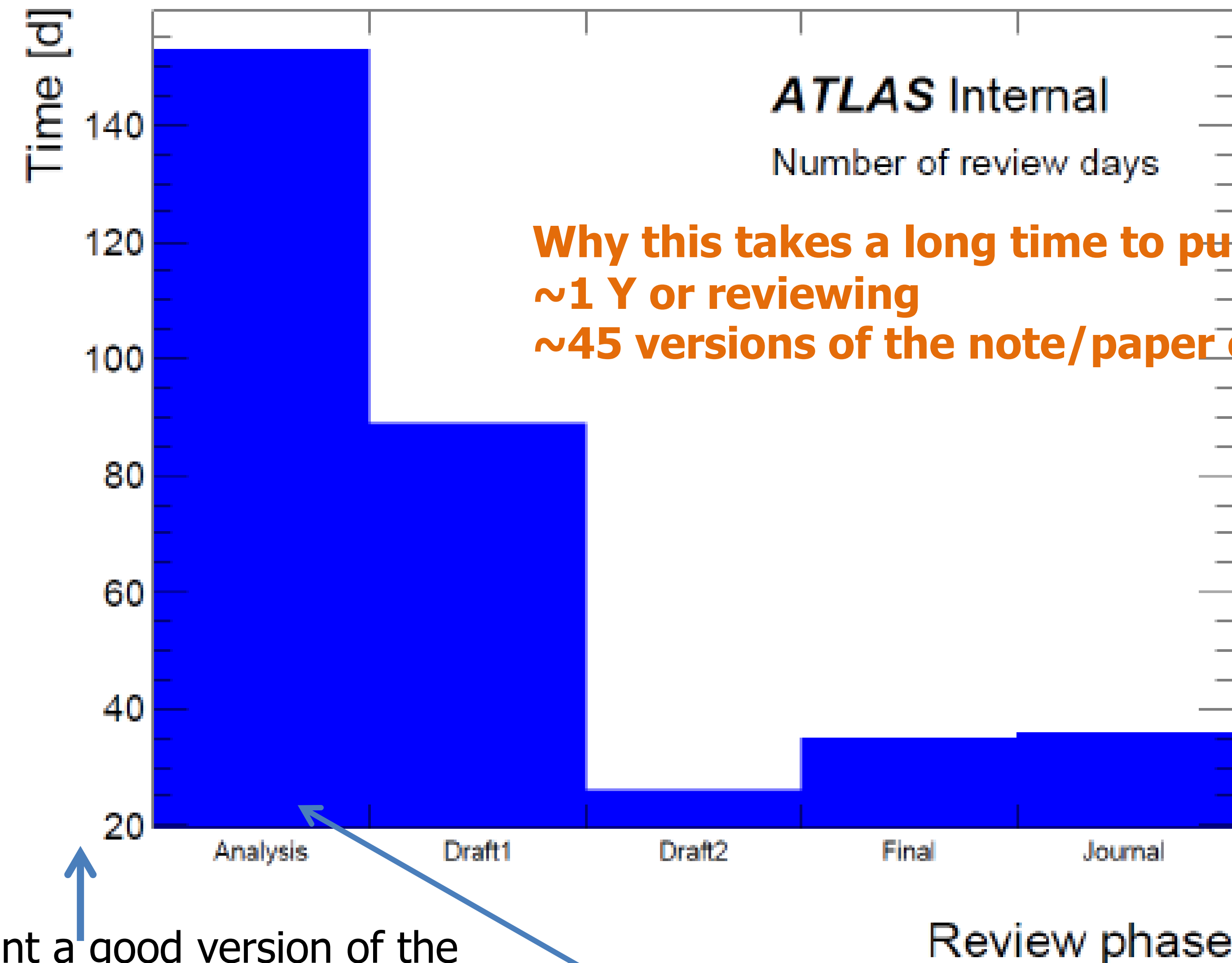



**Main systematic uncertainties:**
Luminosity: 2.3 %
=>1.1 % in $\sigma_{tot}$
Beam energy: 0.63 %
=> 0.43% in $\sigma_{tot}$




(1) **Measurements at 13 TeV** will be important (in the range of cosmic rays)
(2) **$\sigma_{el}$ growing more/less rapidly than $\sigma_{tot}$ ?**
Right now: the slope of $\sigma_{el}(E_{cm})$ is smaller than $\sigma_{tot}$ $(E_{cm})$

# Internal history of the paper in ATLAS




**Why this takes a long time to publish?**
**~1 Y or reviewing**
**~45 versions of the note/paper committed**

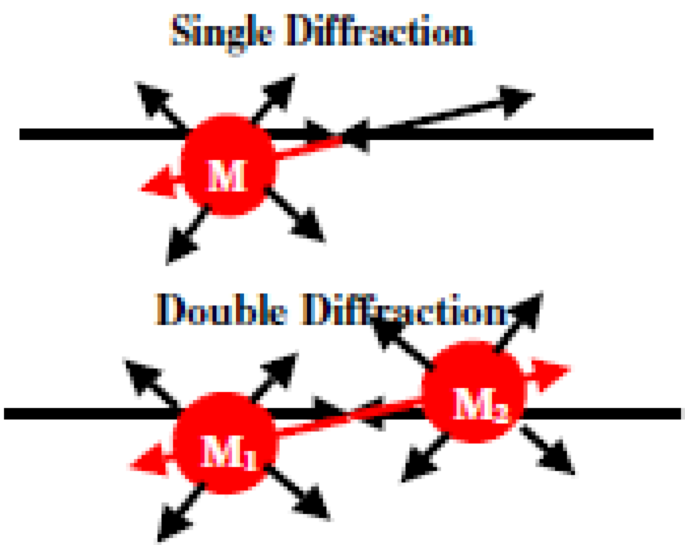
At this point a good version of the analysis is ready and accepted by the analysis group… Then, starts the reviewing process in ATLAS

# Back on the anatomy of pp collisions

From the **ALFA measurement(s):**

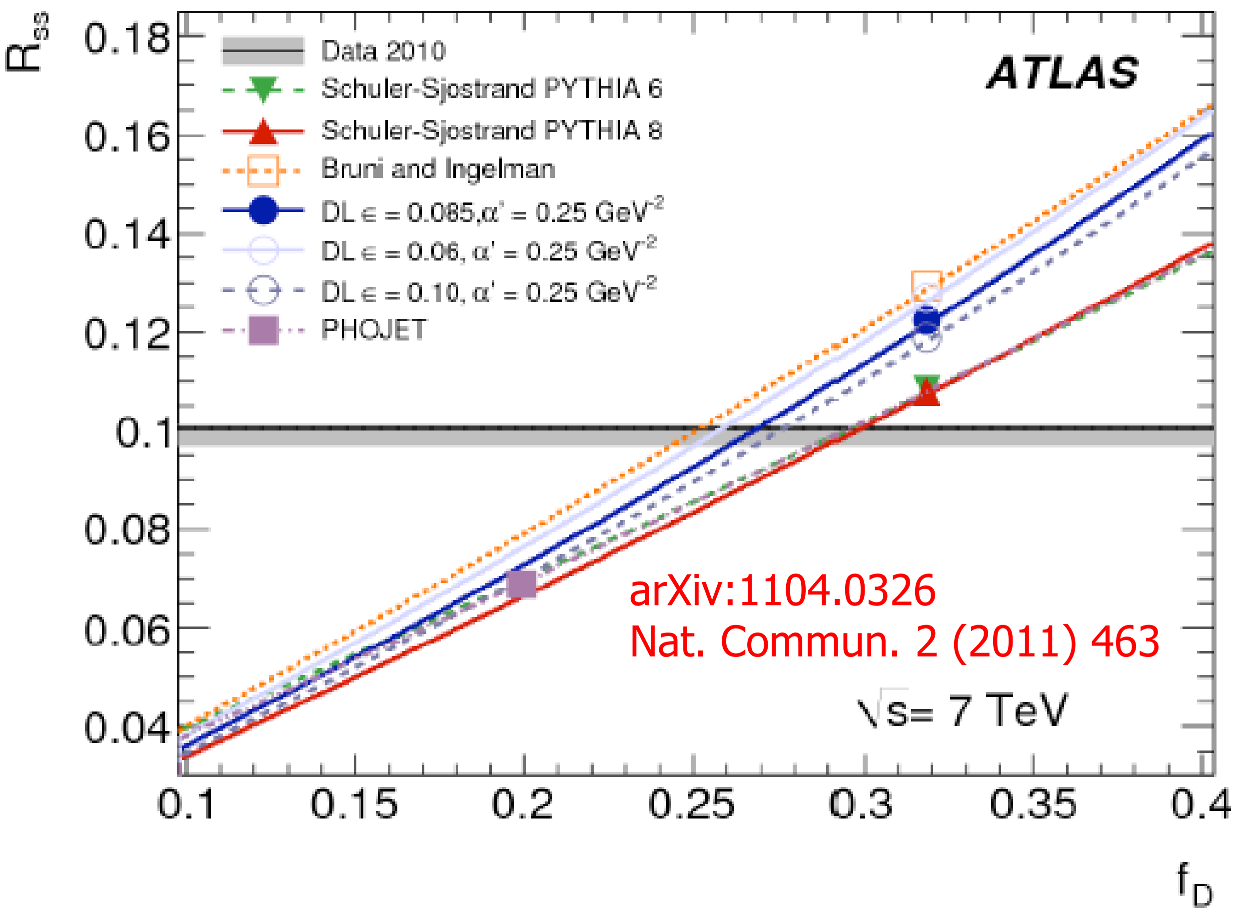
**$\sigma_{el}/\sigma_{tot}$ ~ 25% and thus $\sigma_{inel}/\sigma_{tot}$ ~ 75%**

From this 75% of inelastic cross-section,
how much of SD and DD?



The content of soft diffractive events in the inelastic cross-section can be obtained by the ratio of **single sided events (enriched in diff events)** to the total # events.

This ratio is a function of $f_D$… and this fraction can be tuned in the MC up to reproduce the value of $R_{ss}$ => **$f_D$ ~27% +/- 2%**



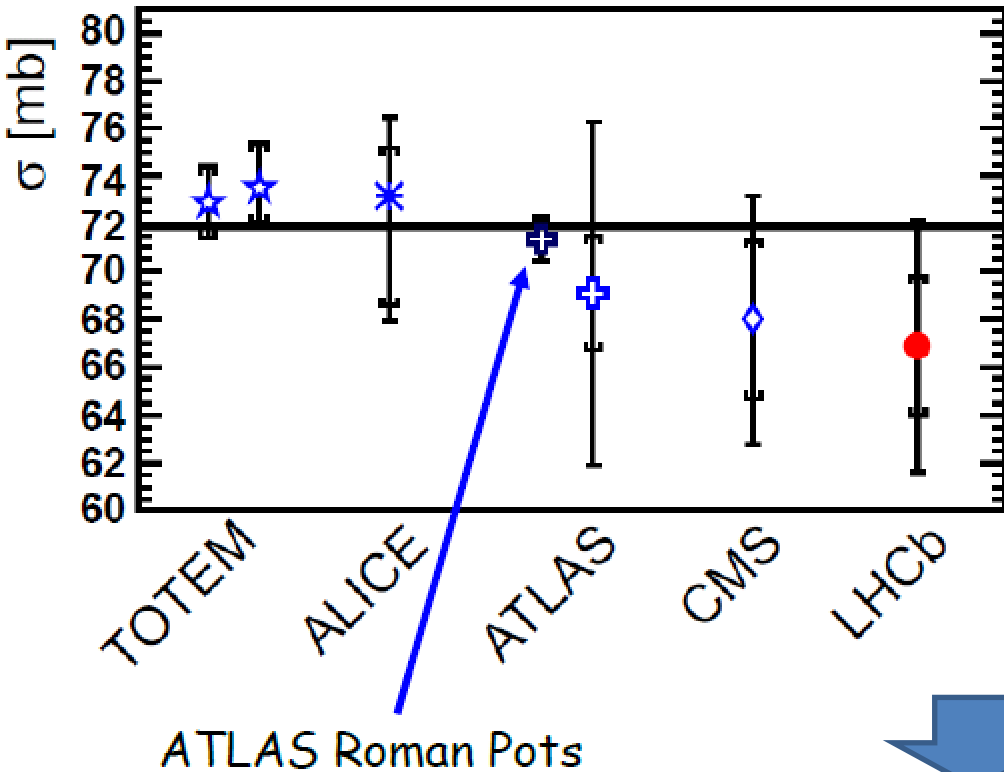

Globally we count:

(a)
8-9% to produce a gap on one side
=> 16-18% of SD

(b)
and <10% DD.

# Back on the inelastic cross-section

$\sigma_{inel}$ = 71.34 +/- 0.9 mb from ALFA at $E_{cm}$=7 TeV




An independent measurement using MBTS triggers (lower limit in $\xi$ or Mx).
=>
$\sigma_{inel}$ = 60.3 +/- 2.1 mb
for Mx>15 GeV
(also) at $E_{cm}$=7 TeV.

$\sigma_{inel}$ = 11.0. ±2.3 mb for $M_X$ < 15 GeV

(low mass inelastic cross-section)

# Back on the anatomy of pp collisions Focus on low masses

For Mx<15 GeV, $\sigma_{inel}$ = 11.0 +/- 2.3 mb

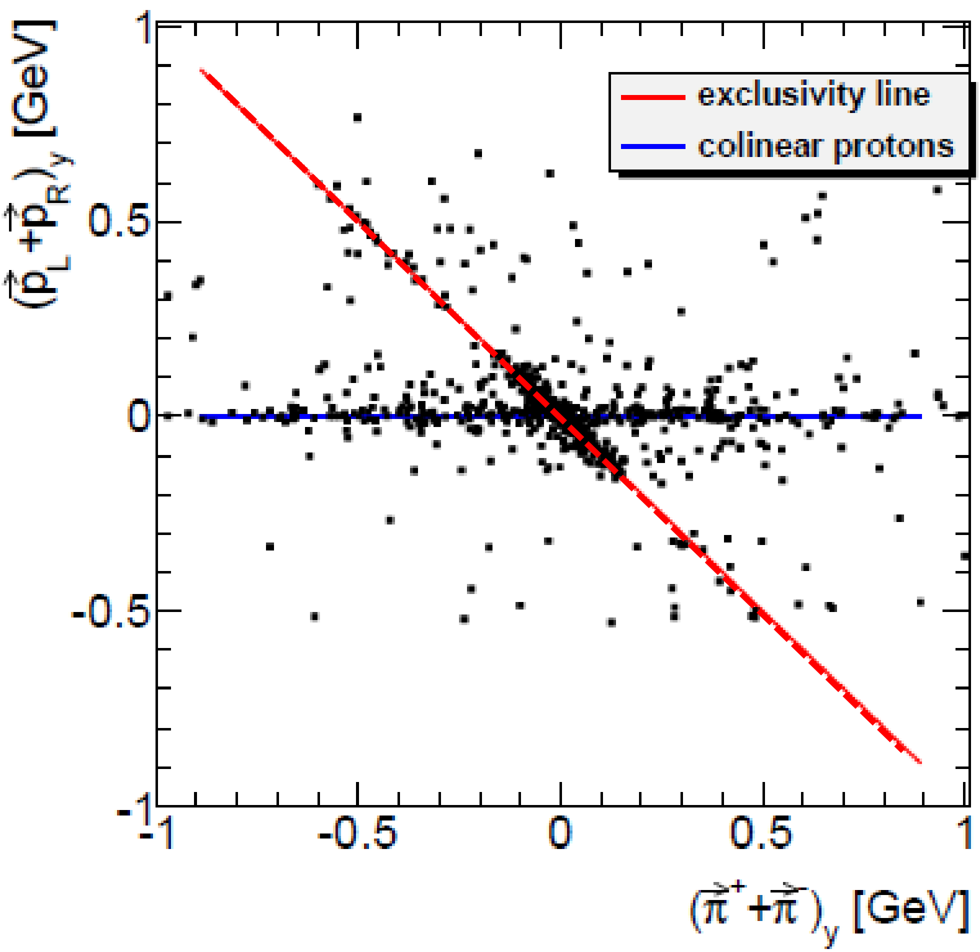
Out of these 11 mb, 27% are of SD and DD origins.
=>**3** mb (with a 20% uncertainty)

| Experiment | CERN-ISR | UA4 | TOTEM | ATLAS |
|---|---|---|---|---|
| Energy | 31-62 GeV | 516 GeV | 7 TeV | 7 TeV |
| **$\sigma_{diff}$(low mass)/$\sigma_{el}$** | ~2/7=0.3 | ~3/12=0.25 | 2.6/25=0.1 | **3**/24=0.12 |

**$\sigma_{diff}$(low mass)/$\sigma_{el}$ is decreasing with the Energy**

This is an interesting experimental result… to be re-examined…

# Additional: ALFA and *more complex* reactions




Exclusive pion production

$p\,p \rightarrow p\,p\,\pi^+\,\pi^-$

high β* = 90 m runs (206881-)
at $E_{cm}$=8 TeV  L=37.33 /nb

**Analysis strategy:**

- Two tracks from common vertex with $|\eta| < 2.5$ and $P_T > 100$ MeV/c
- No signal in MBTS above noise
- Single proton on both ATLAS sides
- Preliminary ALFA alignment

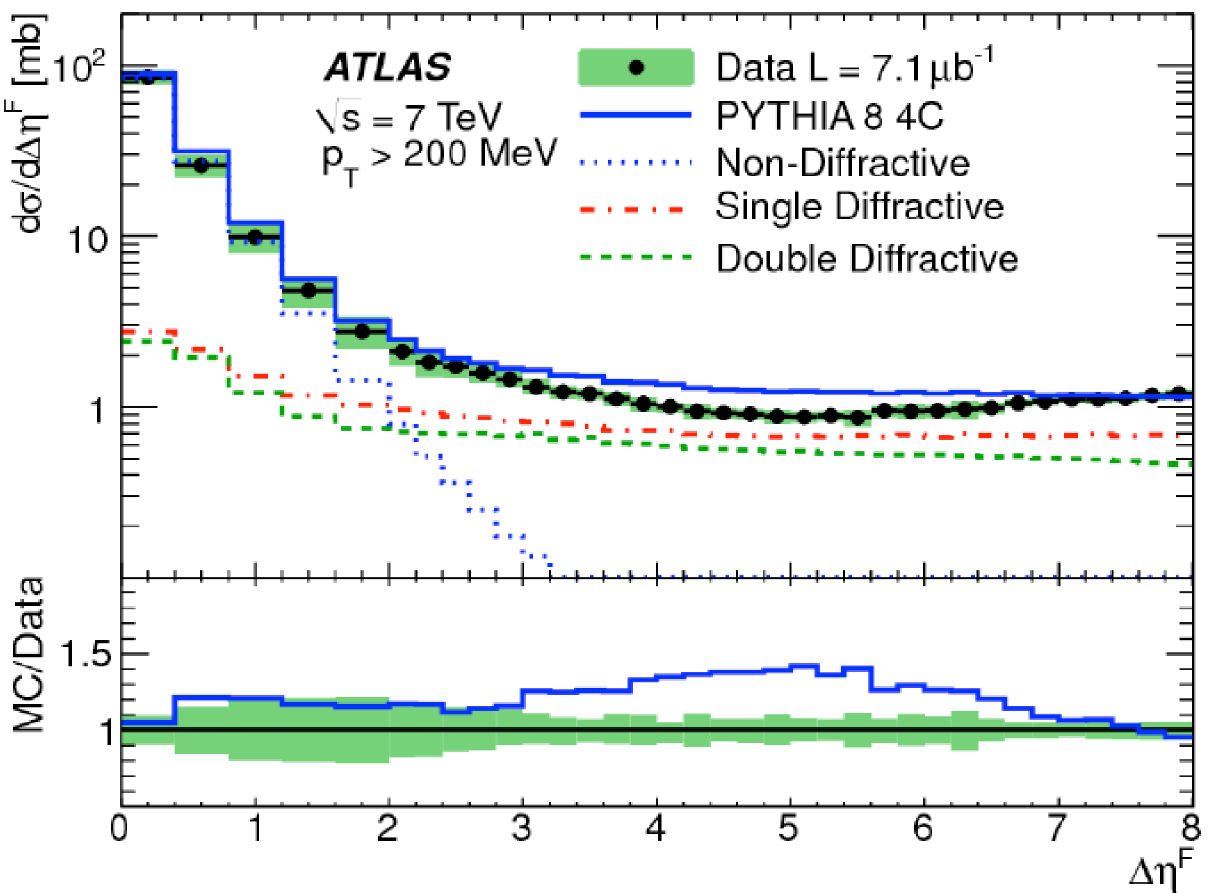
Data contains elastic pp->pp events with overlap charged particle pair not belonging to the same interaction vertex (collinear protons)

Clean exclusive signature (exclusivity line)

# Rapidity Gaps

**More on the anatomy of diffractive events**

$\Delta\eta_F$ := the largest of the 2 forward rapidity gaps between the first track (pT>200 MeV/c $|\eta|<2.5$) or the first CAL activity above noise and the edge of the detector $|\eta|=4.9$.

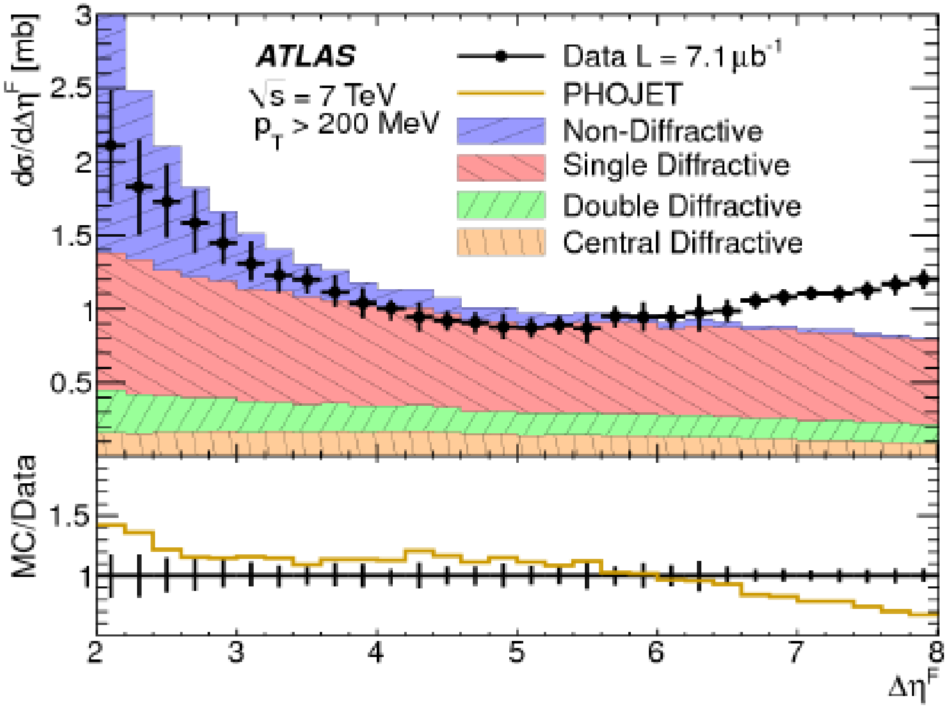


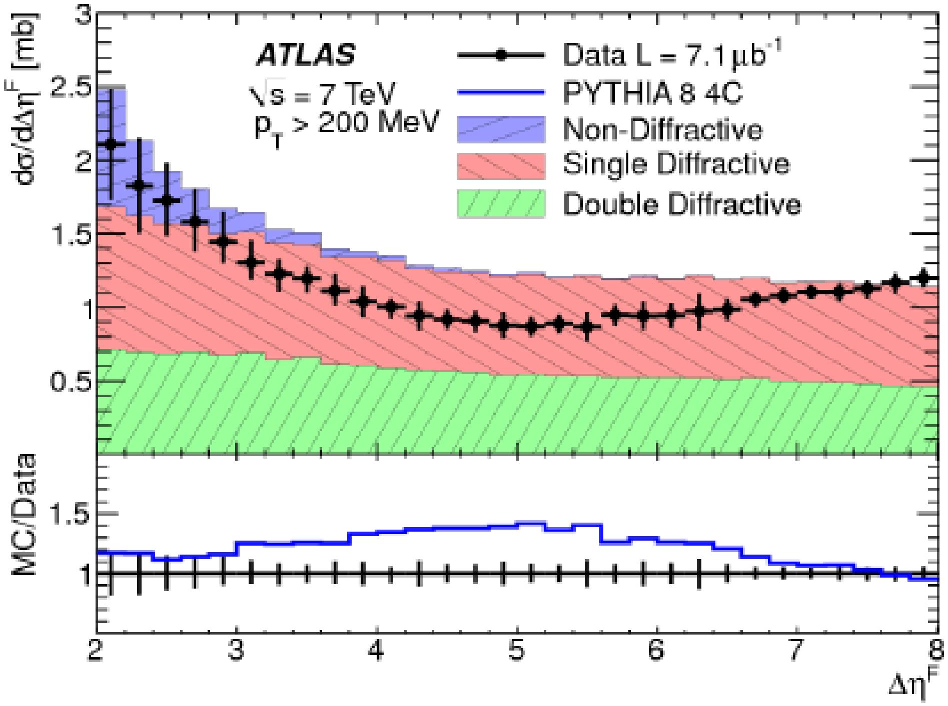

Cross section [$\Delta\eta_F$]:

- Non-diffractive fall at small $\Delta\eta_F$

- Rapidity plateau at $\Delta\eta_F>2$ => SD and DD

arXiv:1201.2808
EPJ C72 (2012) 1926




$\Delta\eta_F > 2$ => data/MC confirms that the event sample is dominated by SD (and DD)

Observed: [1,1.5] mb / unit of $\Delta\eta$

*…to be compared to:*
*(3.5 mb for Pythia and 2.7 for Phojet)*

*Note:*
*The 2 MCs does not agree…*

*And there is something more…*

# Rapidity Gaps($P_T^{cut}$)

**The diffractive plateau disappears for $p_T^{cut}$ >800 MeV**

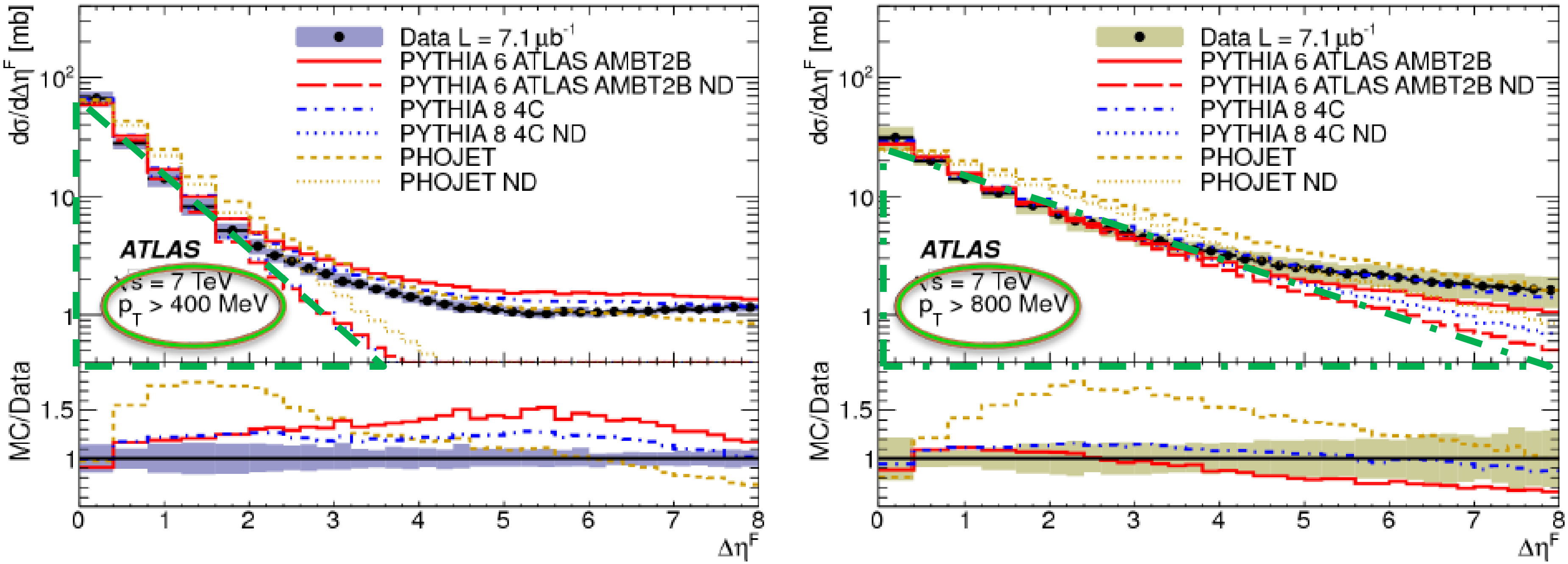
As the $p_T^{cut}$ increases, data show larger gaps

=> Sensitive to hadronization fluctuation and underlying event

Therefore, this is a measurement of $d\sigma/d\,\Delta\eta_F[\Delta\eta_F][p_T^{cut}]$

Interesting to tune MCs, certainly not to extract some physics messages

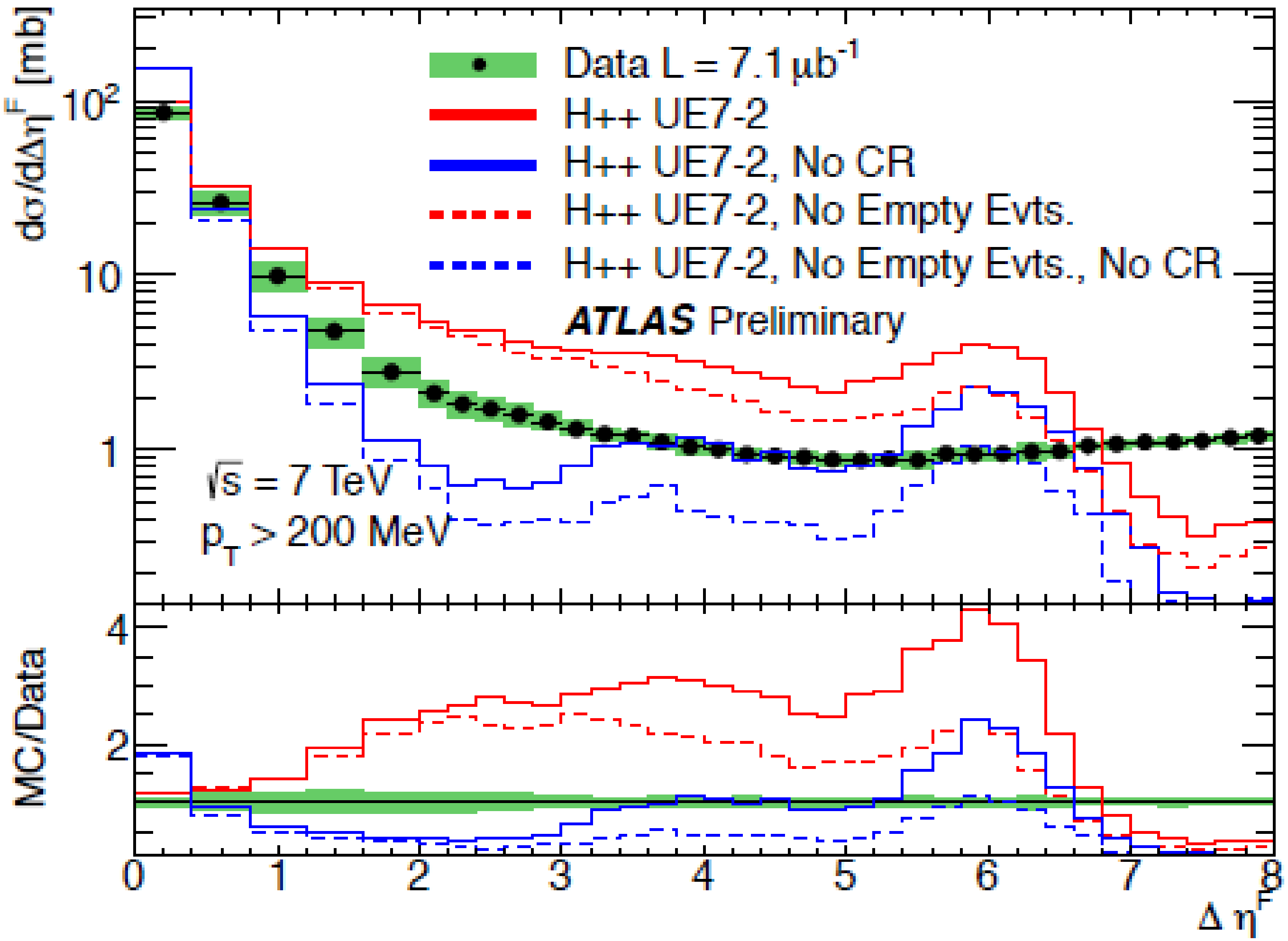
*like **tunes of MCs** based on Minimum Bias (MB) studies…*



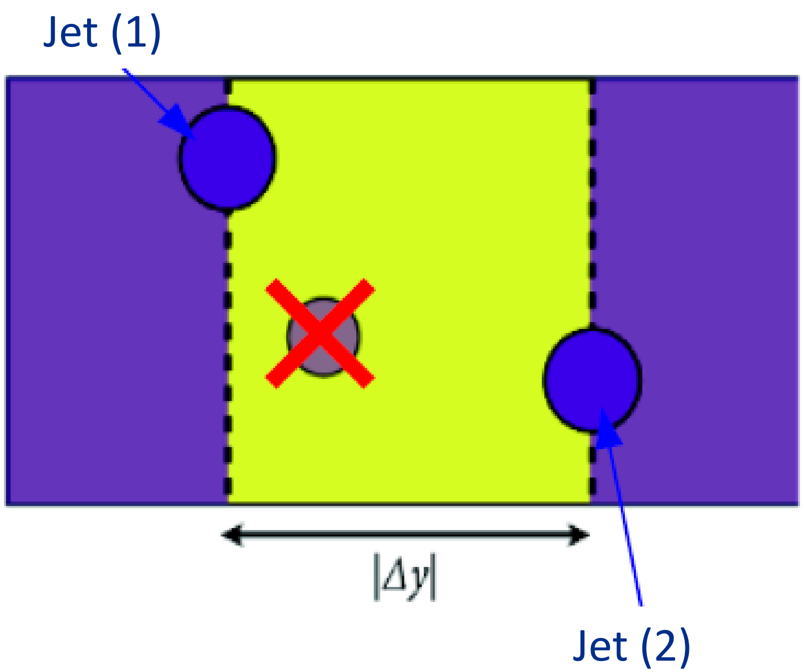
# Rapidity Gaps

<u>For example</u>, we can check that Herwig MC is not satisfactory.

<= Large gaps are produced in the absence of an explicit model of soft-diffraction in Herwig…



# Another view of Gaps




In the experimental configuration:

2 jets events with large $\Delta y$ separation (GAP)

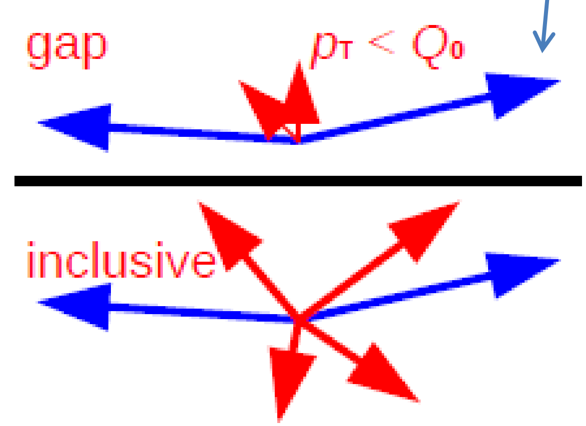
with/without a veto on jets $P_T$ in $\Delta y$

(Gap events / Inclusive events)

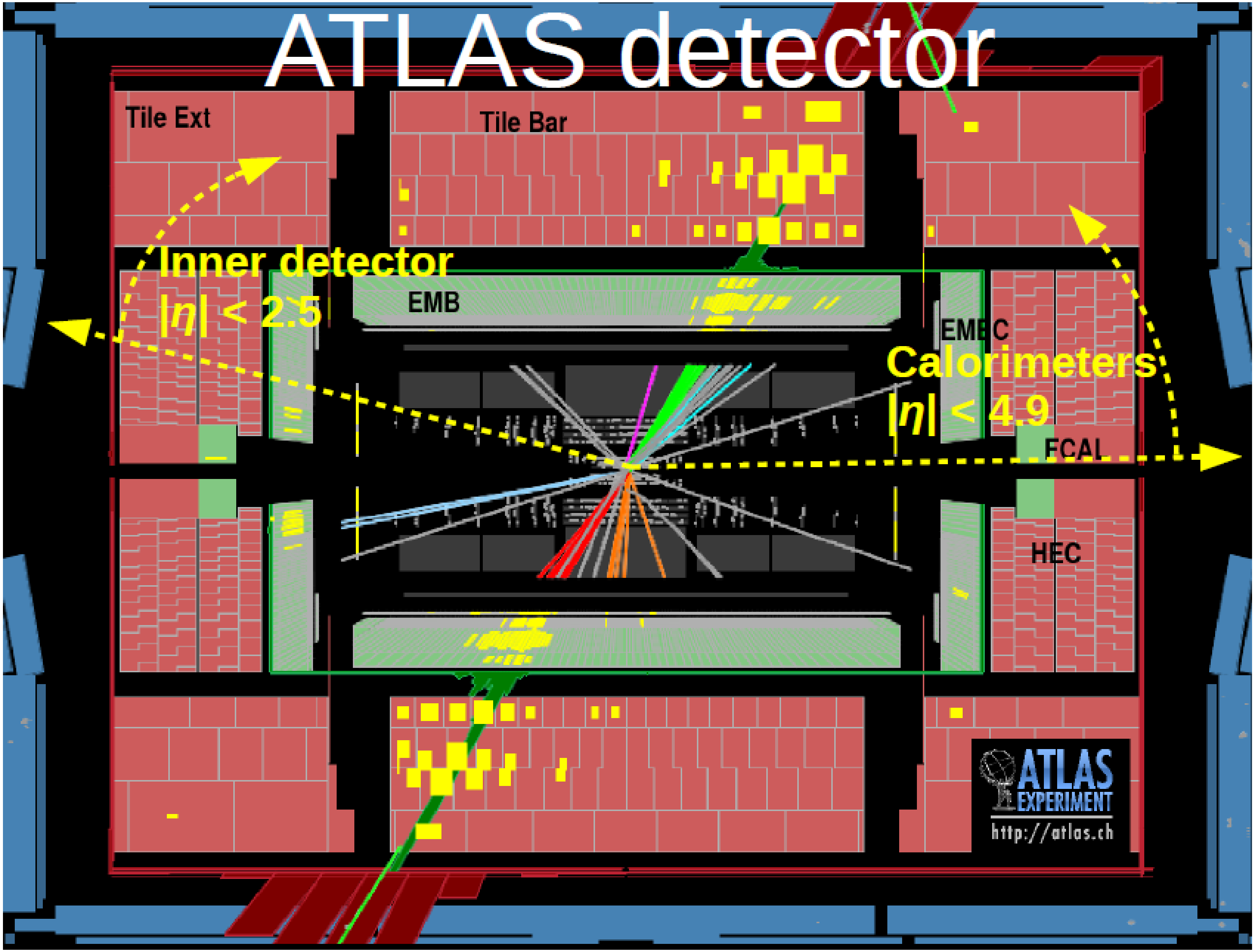
Interesting to test interesting limits on MCs?

<u>One key observable</u> is the gap fraction:

$$f(Q_0) = \sigma_{jj}(Q_0) \;/\; \sigma_{jj}$$

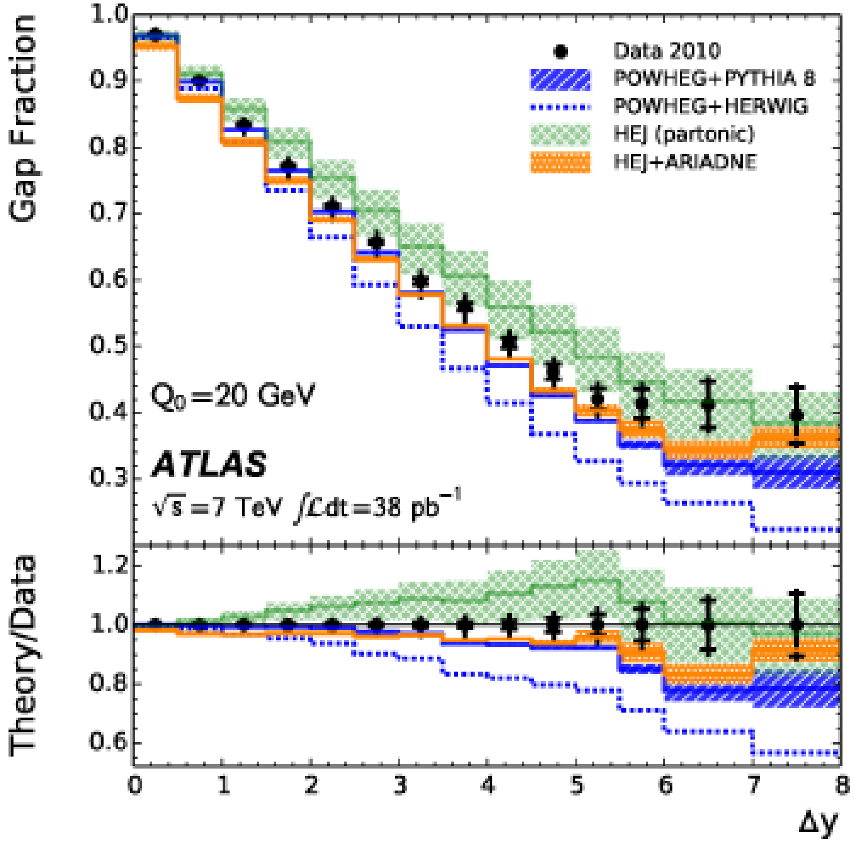


# ATLAS detector

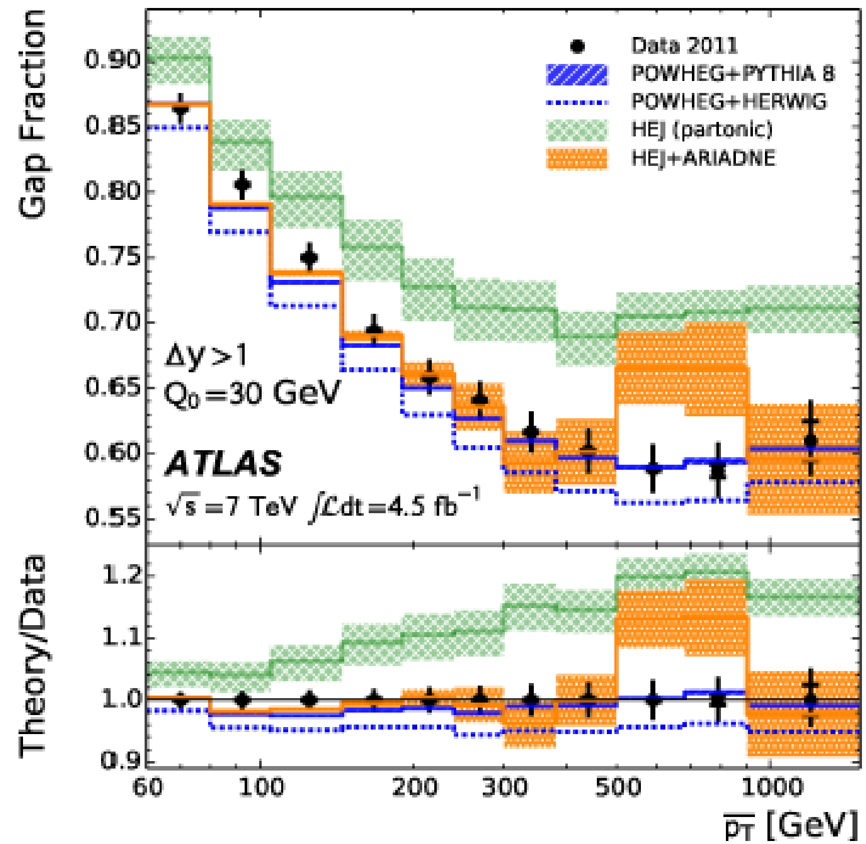


arXiv:1407.57
EPJ C (2014) 74:3117

# Gap fraction (2j)




Gap between
jets (1) and (2)

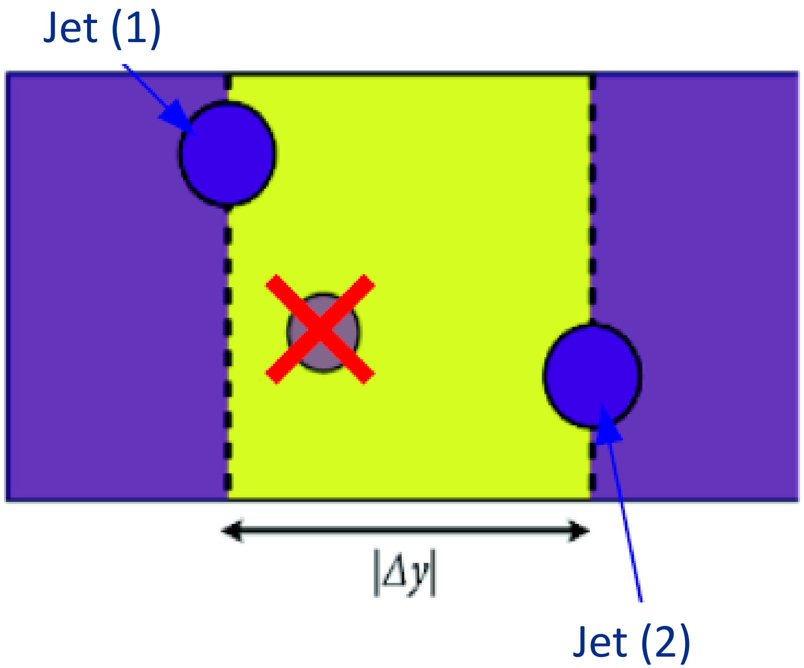



Average PT
of jets (1) and (2)

Plateau at high $\Delta y$ and ln($P_T/Q_0$)
=> Effect of PDFs and/or diffractive exchange

2 MCs are tested (POWHEG, HEJ): *can be used as an element of tuning….*

# Gaps and Azimuths

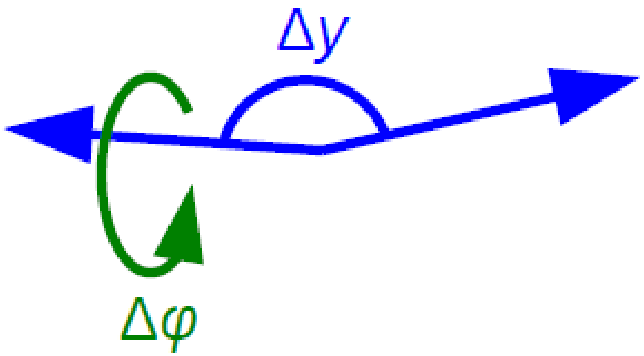



Still the experimental configuration:
2 jets events with large $\Delta y$ separation (GAP)
Define the correlation function ($\Delta\varphi$) of jets (1) and (2).

What happens when $\Delta y$ increases?
(for Gap versus Inclusive events)

The idea: if more and more gluons are emitted between the 2 jets (as $\Delta y$ increases),

this should lead to a **de-correlation** of their relative azimuthal angle.



# Gaps and Azimuths

Let us note $\Delta\varphi$ the azimuthal difference between the 2 jets.

We can always write the Fourier series of the normalized cross-section

$1/\sigma \, d\sigma/d\Delta\varphi \, (.) = 1/(2\pi) \, \{1+2\sum C_n(.) \cos[n(\pi - \Delta\varphi)]\}$

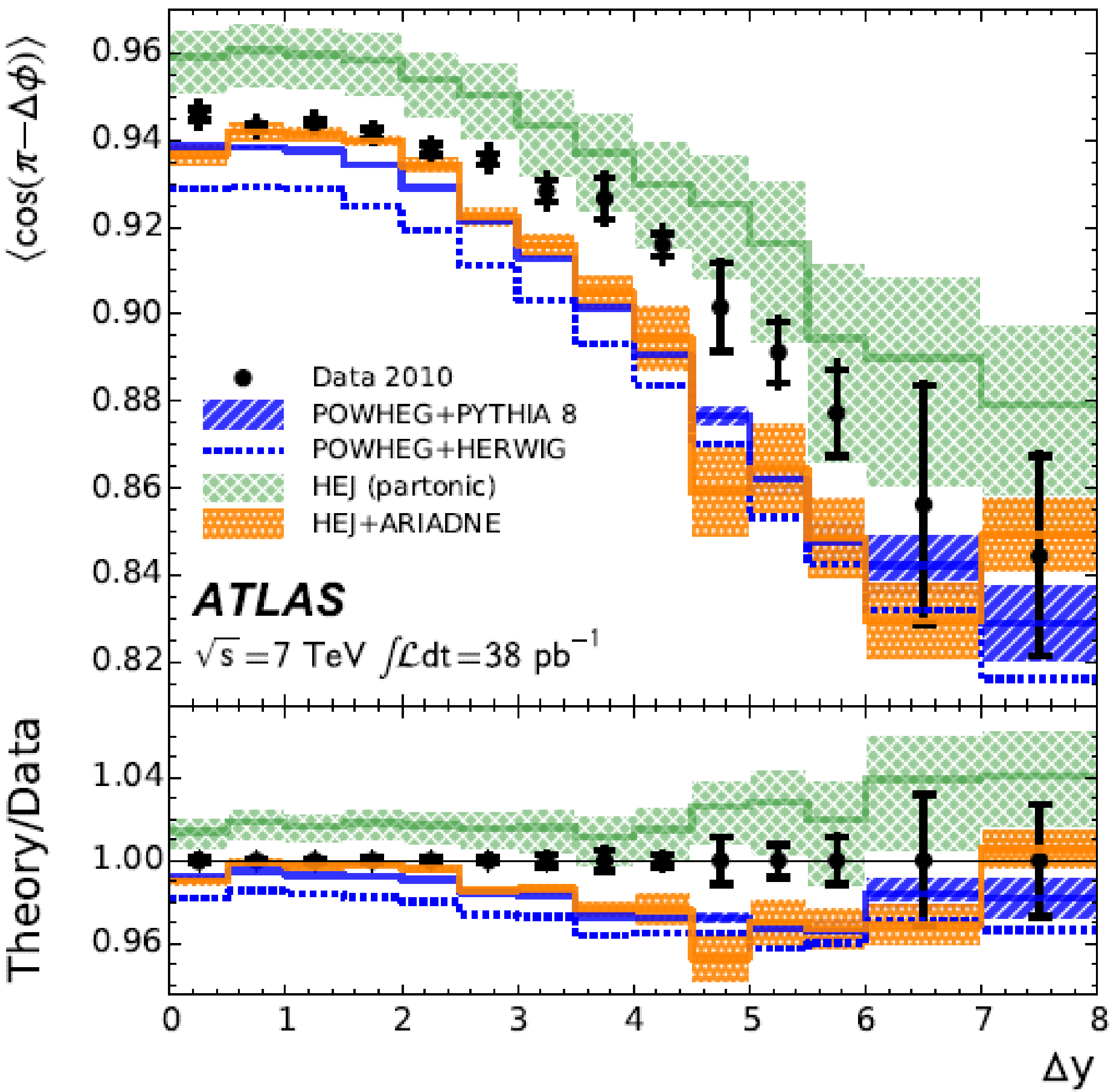
Where: $C_n(.) = \langle\cos[n(\pi - \Delta\varphi)]\rangle$

If there are only 2 jets with $\Delta\varphi = \pi \Rightarrow C_n(.) = 1$.

With the emission of partons (between the 2 jets, even with small transverse momentum) $\Rightarrow C_n(.) < 1$.

:= Stronger effect when $\Delta y = |y1-y2|$ is increased?!

# Azimuthal decorrelation: inclusive events

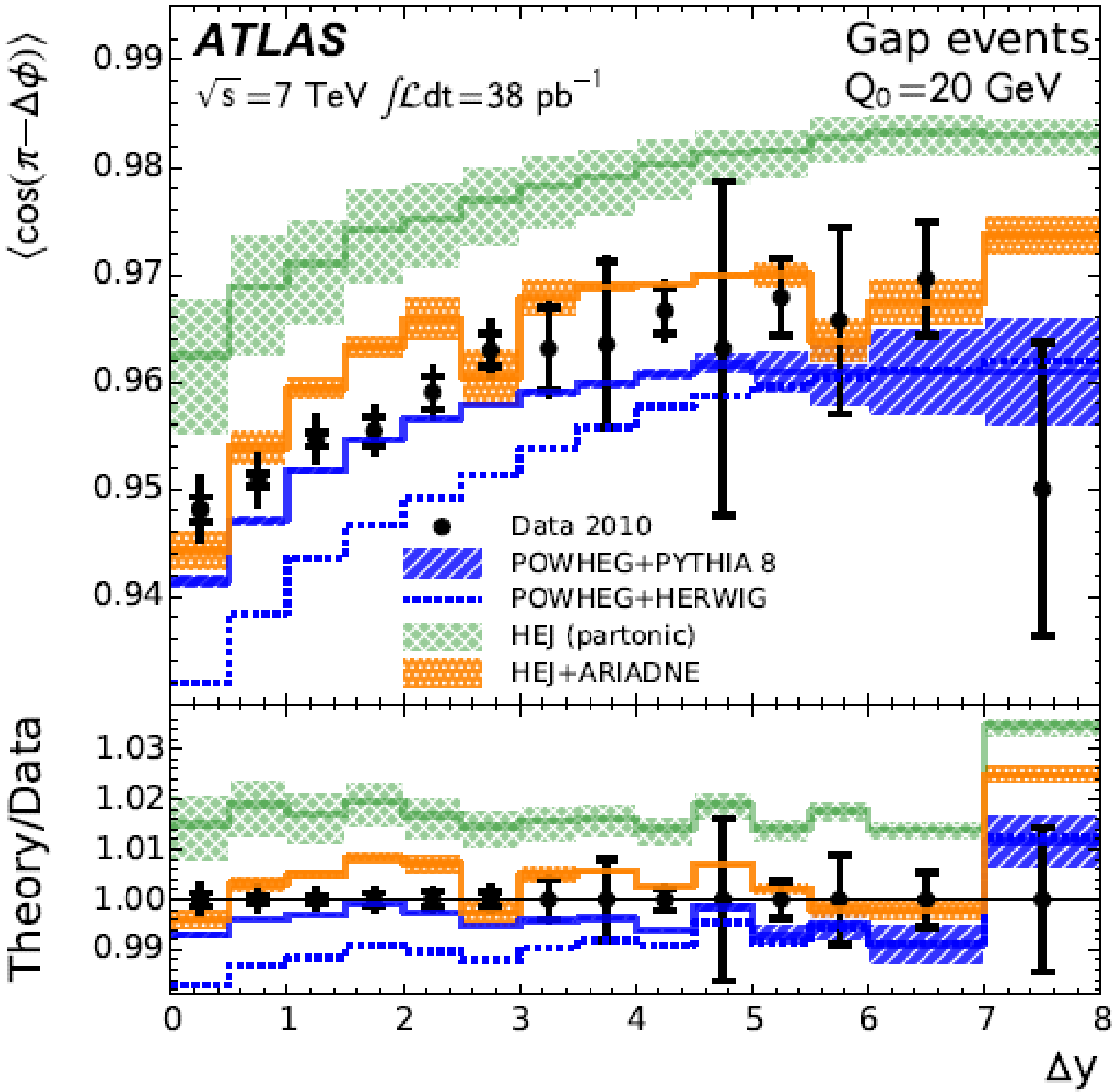



Again, some tensions can be observed between the models…

None of them provide a good description of this first moment function!

However, the general behavior is correct…

# Azimuthal decorrelation: gap events




Here, a veto is applied for potential jets between the 2 leading jets (this defines Gap events in the 2 jets configuration)

Similar conclusions as before

Note:
The veto enhances back-to-back topology with the gap size…
*[C(.) increases]*

# Intermediate summary

## A short anatomy of pp collisions


$\sigma_{tot}$~95 mb

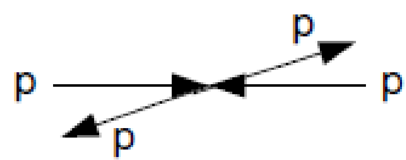
$$\sigma_{tot} = \sigma_{el} + \sigma_{in}$$

$$\sigma_{in} = \sigma_{parton} + \sigma_{SD} + \sigma_{DD} + \sigma_{DPE}$$

- ~60% of the time a "hard" collision occurs

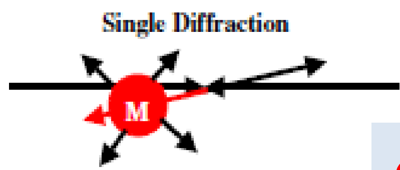

$\sigma_{inel}$~71 mb
*$\sigma_{hc}$~55 mb*

- ~25% of the time the protons scatter elastically



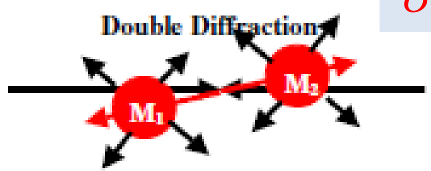

$\sigma_{el}$~24 mb

- ~10% of the time single diffraction occurs



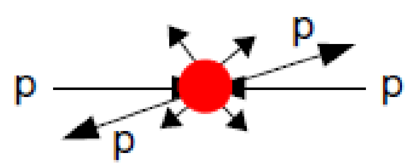

*$\sigma_{diff}$~15 mb*

~1% of the time double diffraction occurs



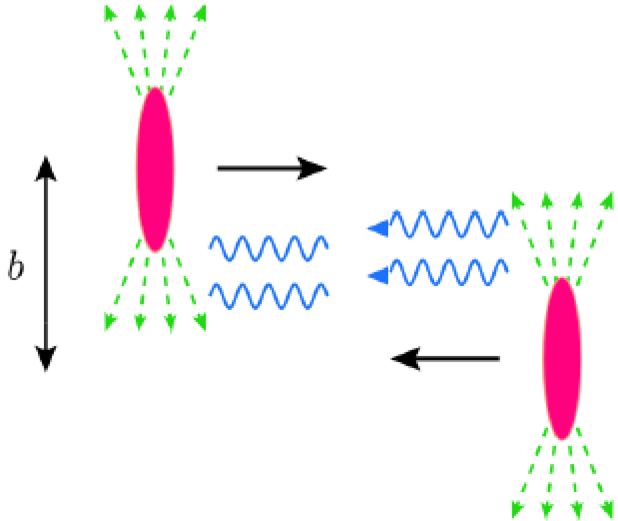

*27% inel*

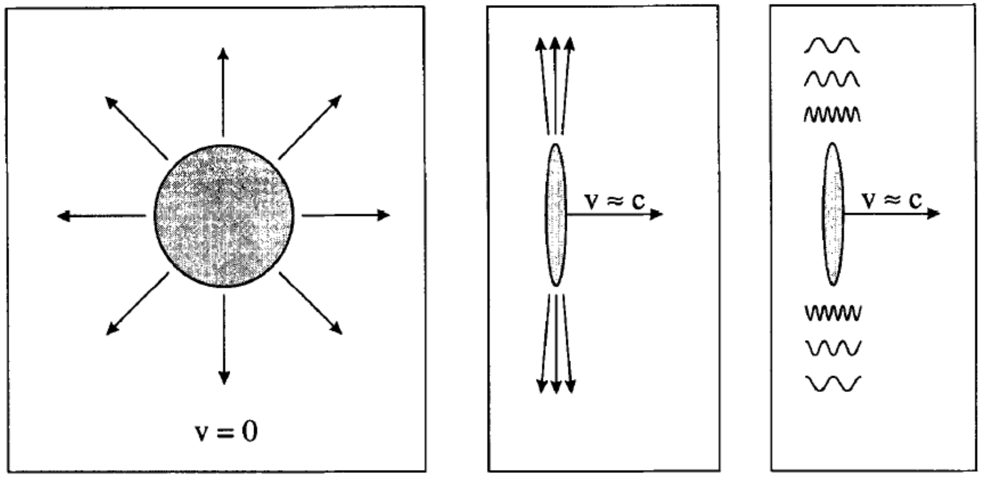
~1% of the time central (exclusive) diffraction occurs



# Probing deeper: pp->($\gamma\gamma$)->ppX

## Using photons...



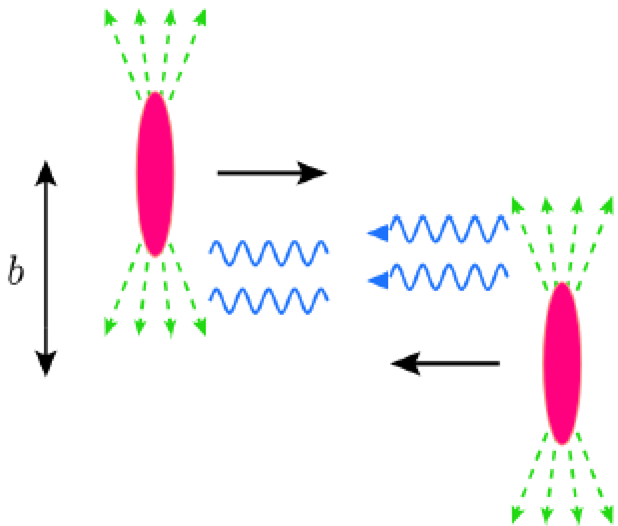



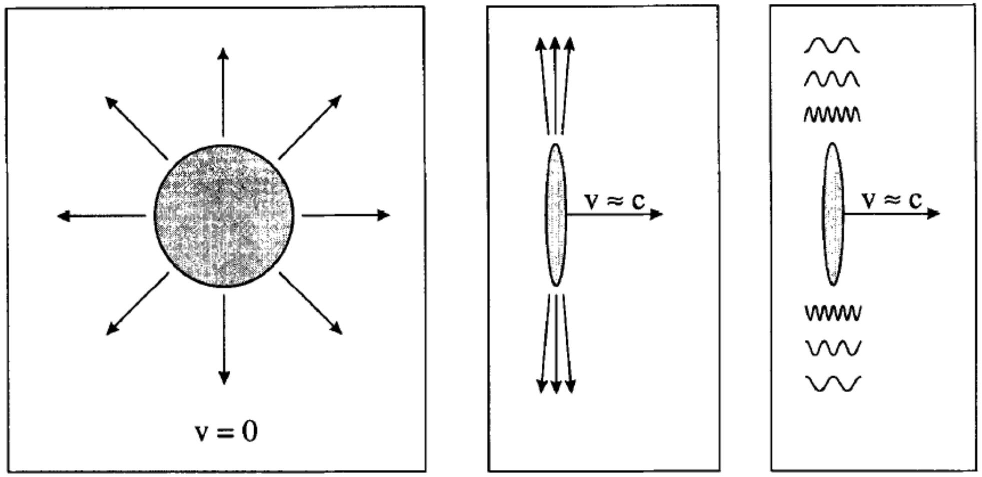

The idea is that when the velocity of a charged particle (proton, Pb) ~c, its EM field becomes Lorentz-contracted equivalent to a transverse EM (photon) field...

**This is the Equivalent Photon Approximation (EPA)**

# Probing deeper: pp->(γγ)->ppX

## Using photons…




The idea is that when the velocity of a charged particle (proton, Pb) ~c, its EM field becomes Lorentz-contracted equivalent to a transverse EM (photon) field…

**Then**, in general, we can write:

$$\sigma(p+p\rightarrow p+p+X)=\int\int f(\omega_1)f(\omega_2)\sigma_{\gamma\gamma\rightarrow X}(\omega_1,\omega_2)\frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2}$$

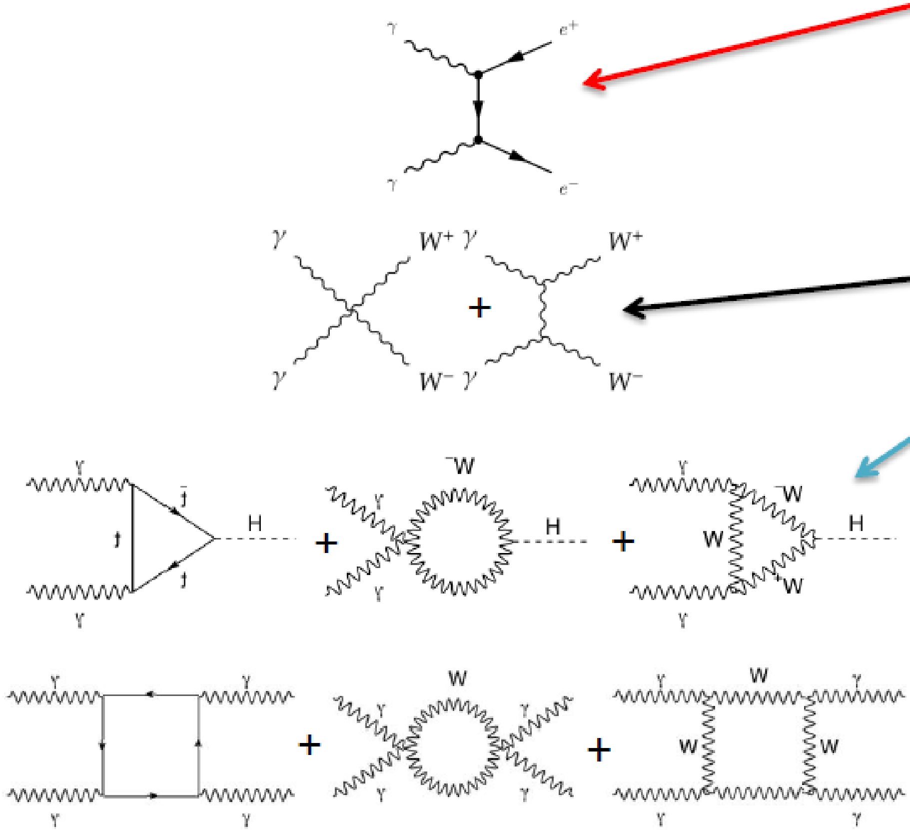
$$f(\omega_1)f(\omega_2)\rightarrow\int\int n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)P_{non-inel}(|\vec{b}_1-\vec{b}_2|)d^2\vec{b}_1d^2\vec{b}_2$$

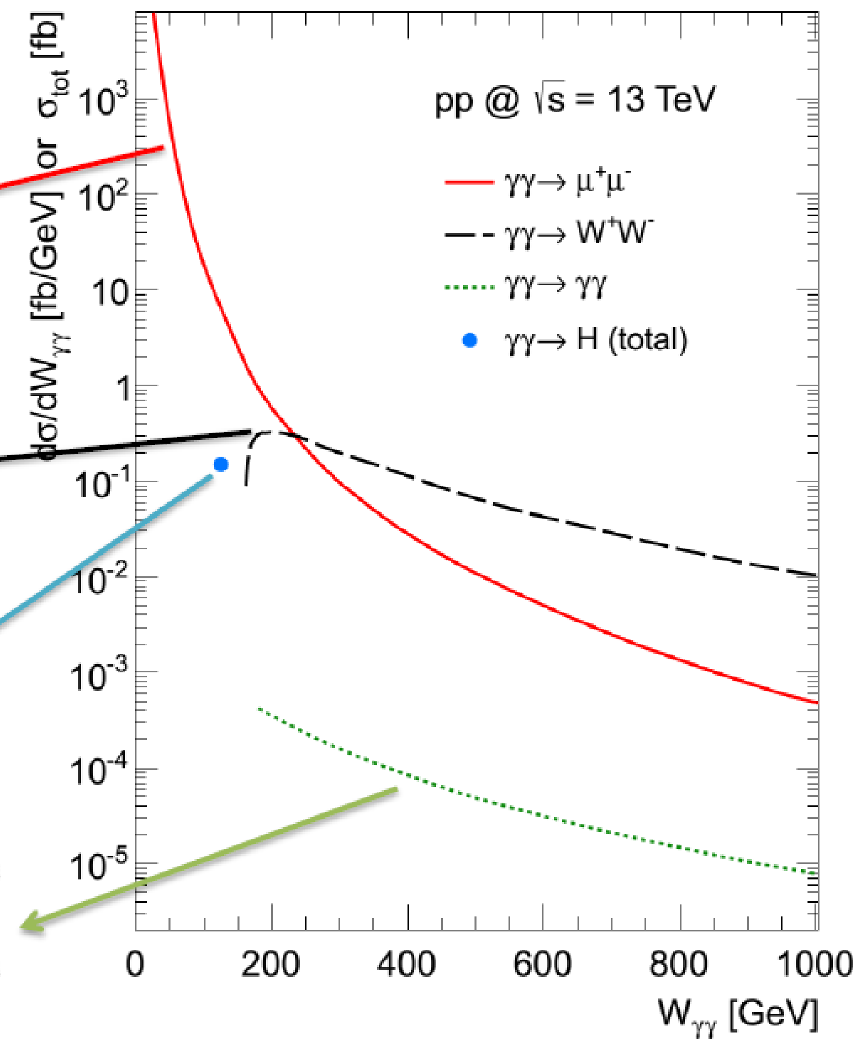
**Number(s) of equivalent photons** (impact parameter, energy)

# Example of processes @13 TeV

## Elementary cross sections: $\gamma\gamma$->X

- O(pb) for $W_{\gamma\gamma}$ > 10 GeV ($\gamma\gamma \rightarrow \ell^+\ell^-$)
- O(fb) for $W_{\gamma\gamma}$ > 200 GeV ($\gamma\gamma \rightarrow W^+W^-$)



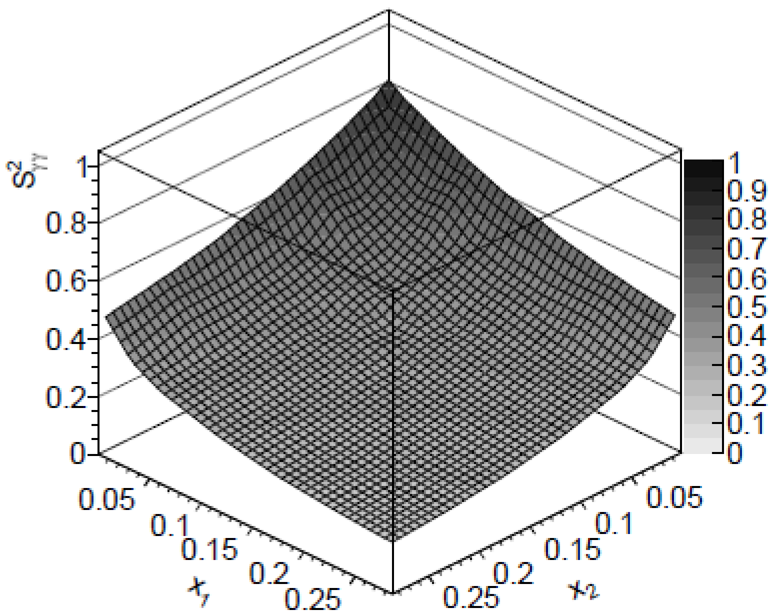


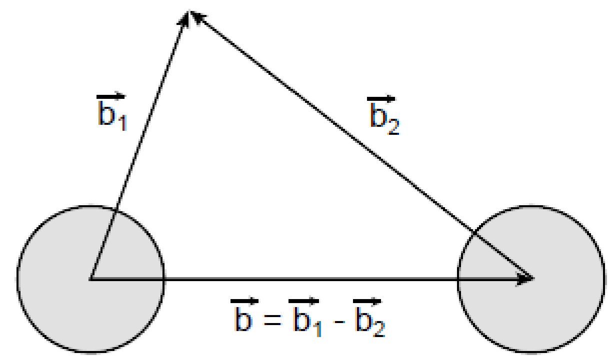
# For pp collisions: $\sigma_{\gamma\gamma} \otimes$ #photons from each proton

**- Also, we must not forget that protons have a finite size.**

- This can be translated into a survival factor of the cross section

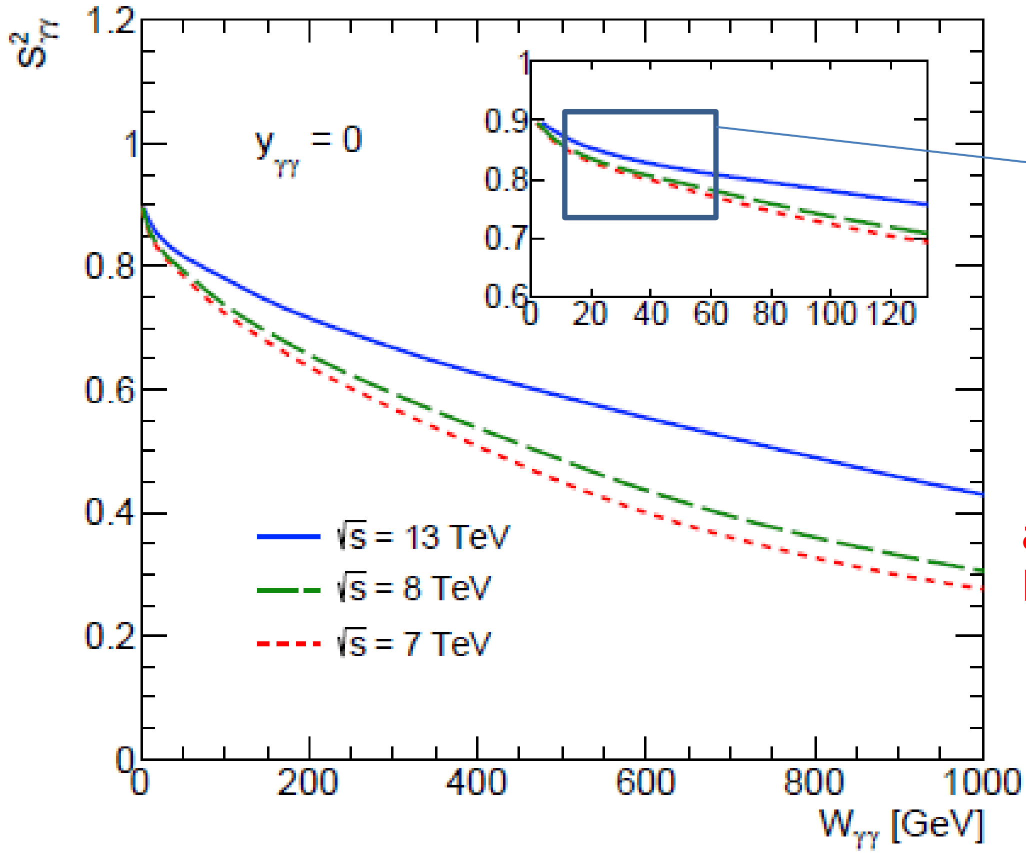
$$S^2_{\gamma\gamma} = \frac{\int_{b_1 > r_p} \int_{b_2 > r_p} n(\vec{b}_1, \omega_1) n(\vec{b}_2, \omega_2) P_{non-inel}(|\vec{b}_1 - \vec{b}_2|) d^2\vec{b}_1 d^2\vec{b}_2}{\int_{b_1 > 0} \int_{b_2 > 0} n(\vec{b}_1, \omega_1) n(\vec{b}_2, \omega_2) d^2\vec{b}_1 d^2\vec{b}_2}$$




arXiv:1410.2983
PLB 741 (2015) 66-70

*The pp->(γγ)->… cross section with no account of finite size effects will be multiplied by S²*




We can measure in this domain (at 7 TeV)

arXiv:1410.2983
PLB 741 (2015) 66-70

Prospects:

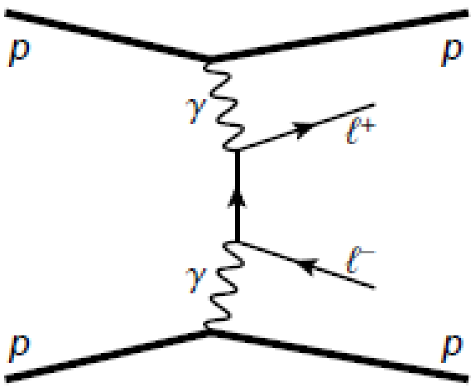
| Process | $\sigma_{tot}$ | $\sigma_{tot} \otimes S^2_{\gamma\gamma}$ | $< S^2_{\gamma\gamma} >$ |
|---|---|---|---|
| $\gamma\gamma \to H$ ($M_H = 125$ GeV) | 0.15 fb | 0.11 fb | 0.74 |
| $\gamma\gamma \to \mu^+\mu^-$ ($W_{\gamma\gamma} > 40$ GeV) | 12 pb | 10 pb | 0.8 |
| $\gamma\gamma \to \mu^+\mu^-$ ($W_{\gamma\gamma} > 160$ GeV) | 36 fb | 25 fb | 0.7 |
| $\gamma\gamma \to W^+W^-$ | 82 fb | 53 fb | 0.65 |
| $\gamma\gamma \to \gamma\gamma$ ($W_{\gamma\gamma} > 200$ GeV) | 0.06 fb | 0.04 fb | 0.64 |

$\sqrt{s} = 13$ TeV

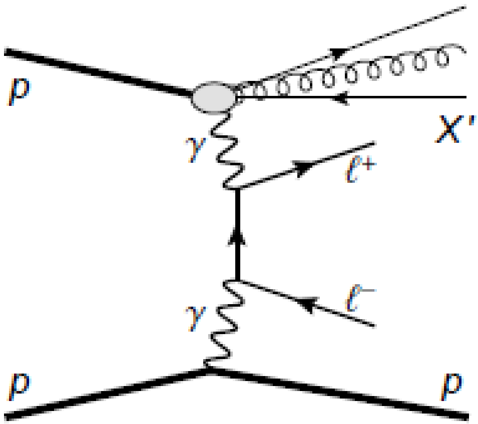
# Measurement of pp->(γγ)->ppX (at 7 TeV) with X=di-lepton

Prerequisites: The measurement (and its interpretation) are complicated by the fact that the proton does not stay necessarily intact:

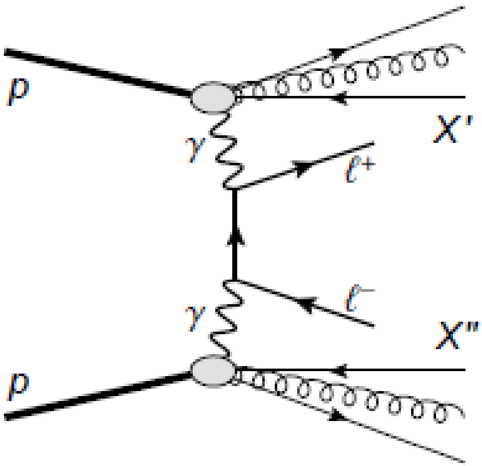
**elastic**




**SD**




**DD**

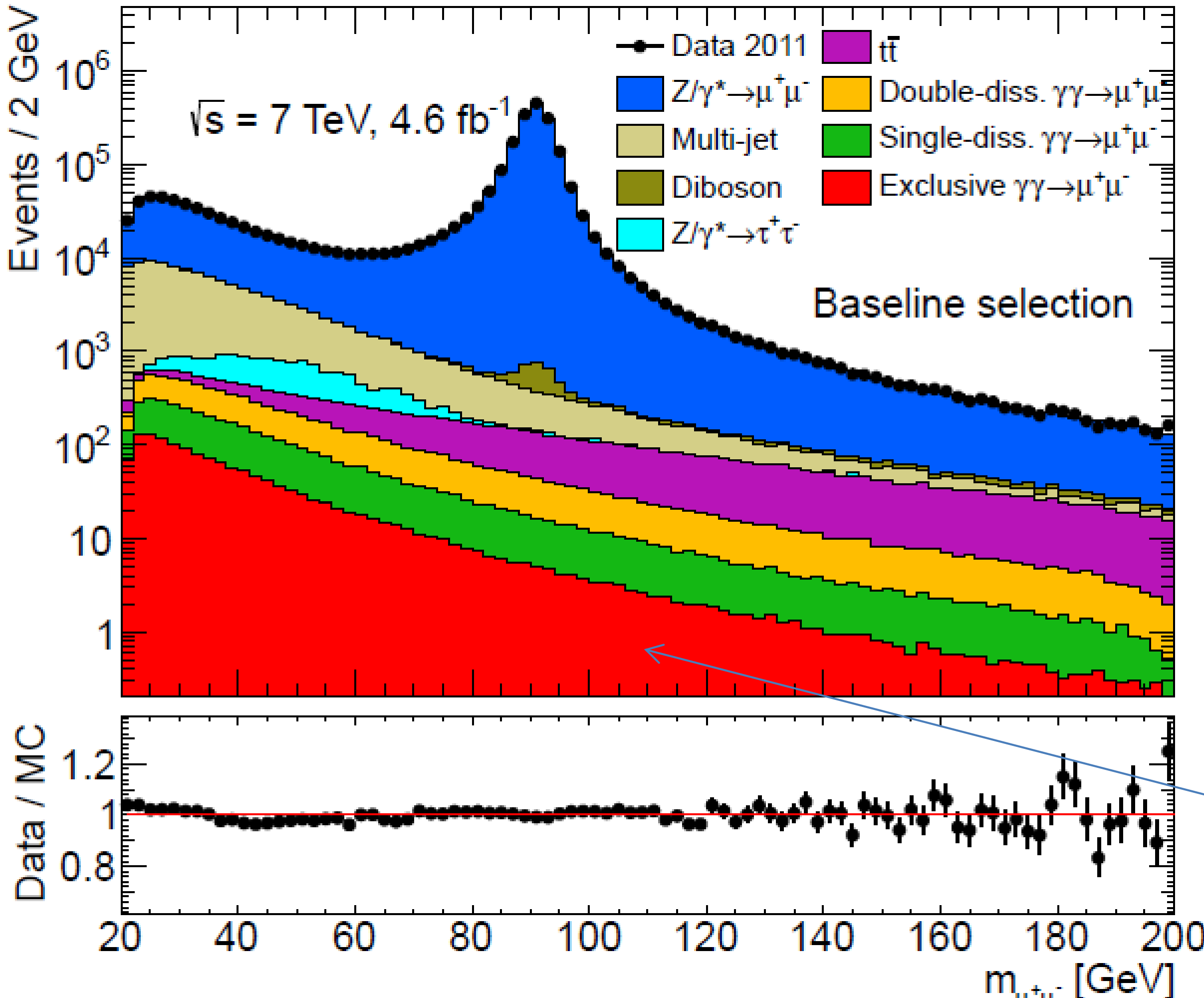



Fiducial phase-space of the analysis:

- $p_T^{\mu}>10$ GeV, $|\eta_\mu|<2.4$, $M_{\mu+\mu-}>20$ GeV
- $p_T^{e}>12$ GeV, $|\eta_e|<2.4$, $M_{e+e-}>24$ GeV

# Measurement of pp->(γγ)->ppX (at 7 TeV) with X=di-lepton

**Why this is complicated!**




Prior to any specific cuts, the selection (di-muon) is dominated by DY.

*Similarly for ee*

We are interested by the red part

# Measurement of pp->($\gamma\gamma$)->ppX (at 7 TeV) with X=di-lepton

**Analysis strategy:**

- ONLY 2 tracks (pT > 400 MeV) associated to vertex, formed by the 2 leptons (**exclusivity** selection)

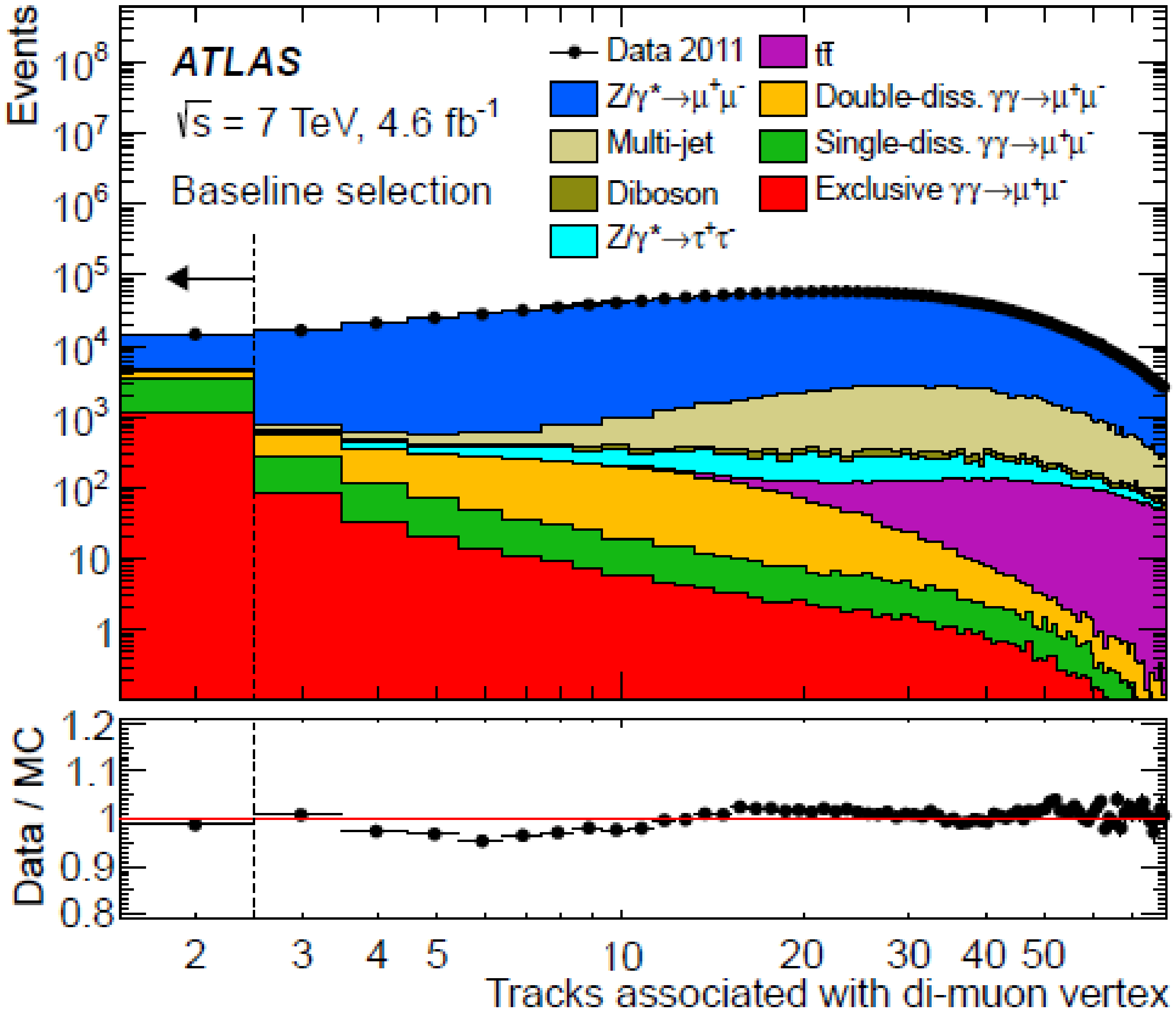
- Vertex is requested to be isolated from other possible tracks (to remove again some DY and pile-up backgrounds)

- The $p_T$ of the di-lepton system is requested to be small (<1.5 GeV) to keep elastic protons and reject (as much as possible) SD and DD.
- + cuts at the Z boson peak (to remove almost all remaining DY events)

# Measurement: X=di-lepton / Exclusivity selection

pp->(γγ)->ppX

arXiv:1506.07098
PLB 749 (2015) 242-261

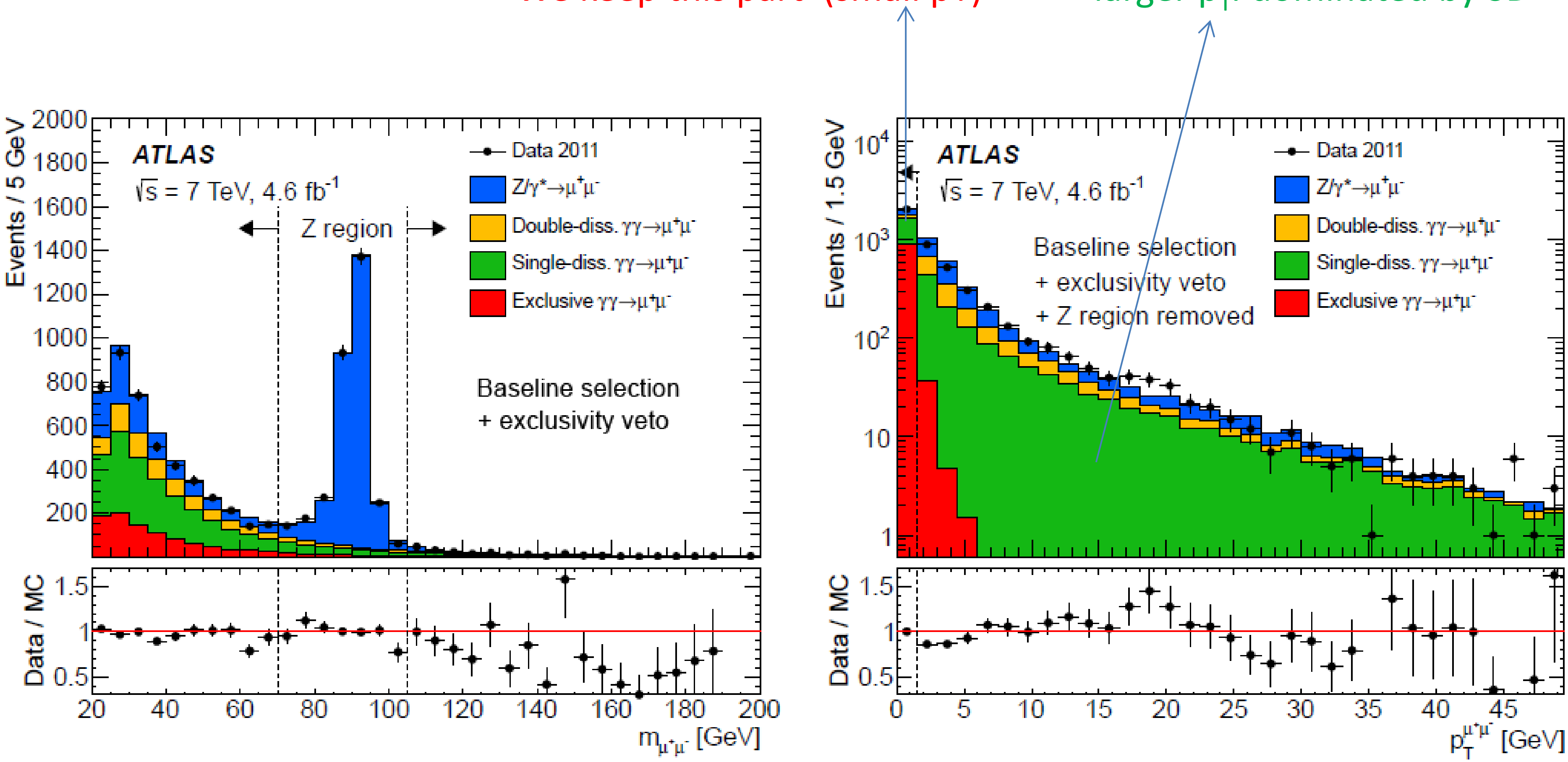


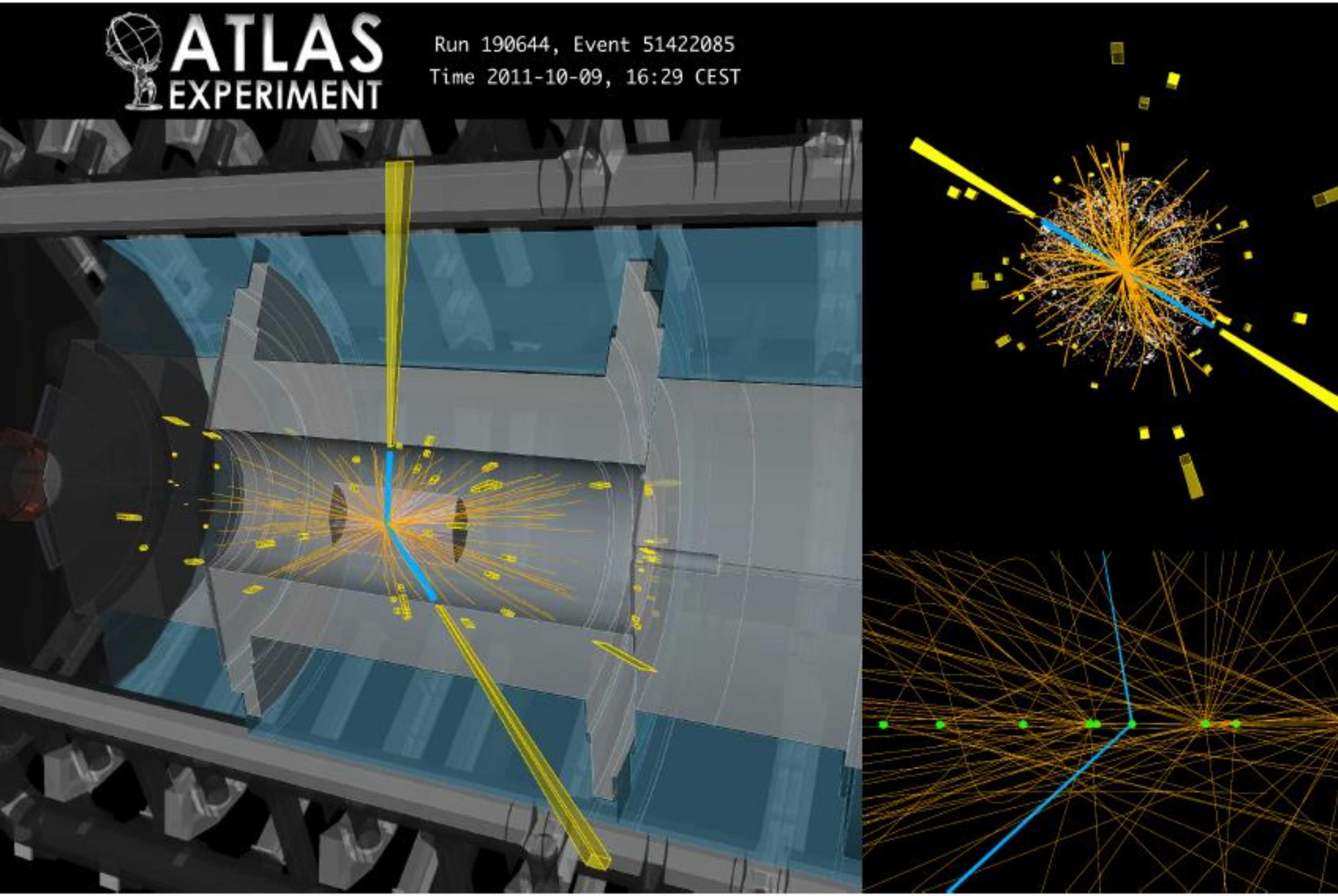
# Measurement: X=di-lepton / DY removal and $p_T$ spectrum before cut

pp->($\gamma\gamma$)->ppX

We keep this part (small pT)

larger $p_T$: dominated by SD




ATLAS
EXPERIMENT
Run 190644, Event 51422085
Time 2011-10-09, 16:29 CEST

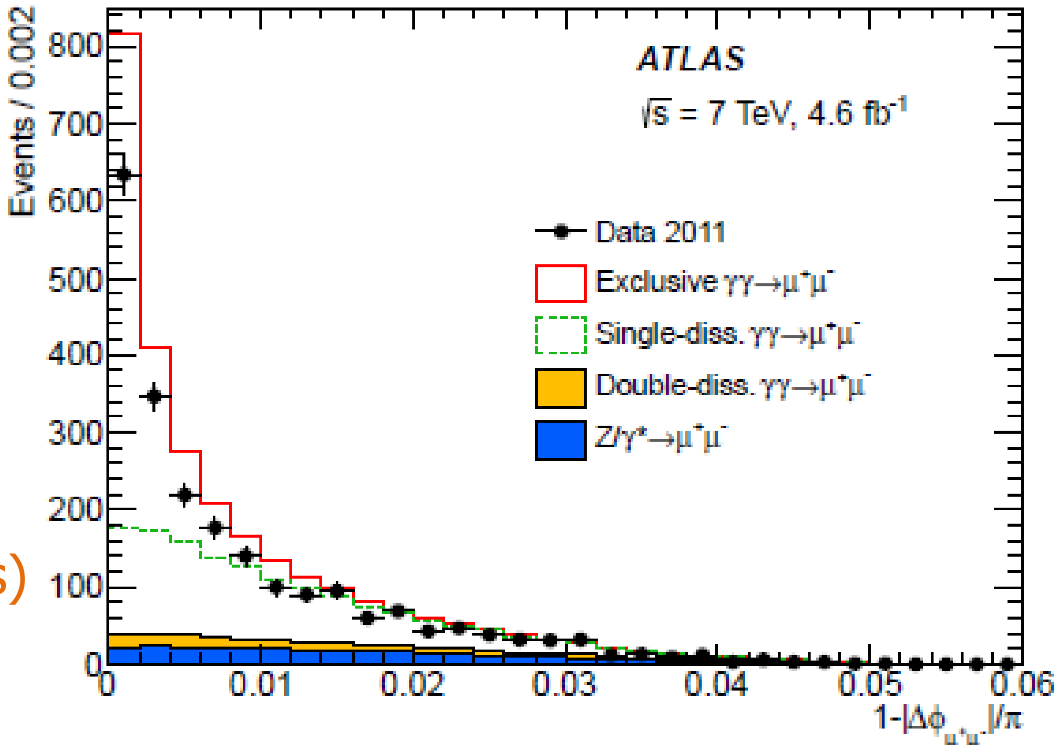
# Measurement: X=di-lepton / Final step -1-

pp->(γγ)->ppX

869 and 2124 events selected in ee/μμ channels

Signal events (elastic) ~50% of the analysis-selected sample

MC does not include finite size Effects (or absorptive corrections) => Data~80% of the prediction



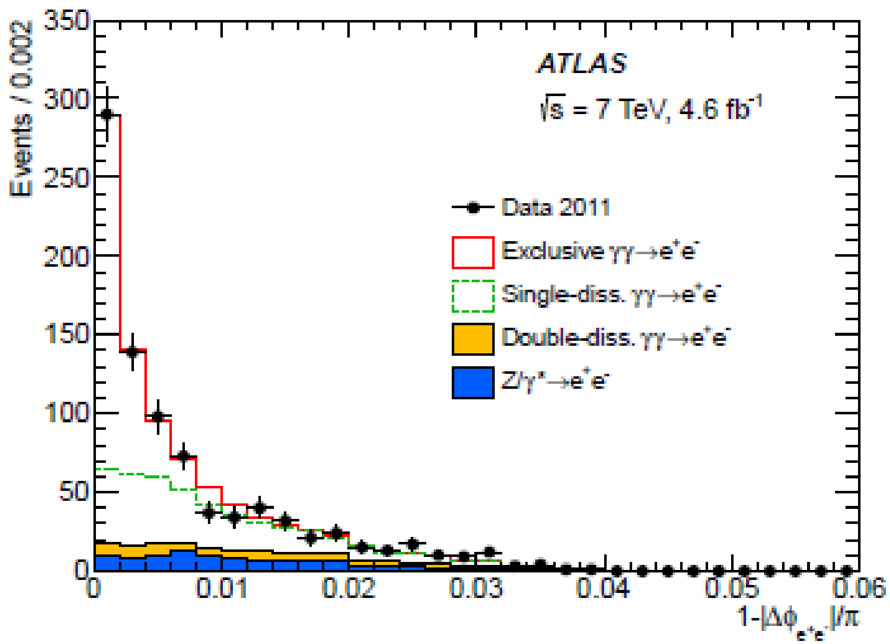

We intend to determine this number precisely!

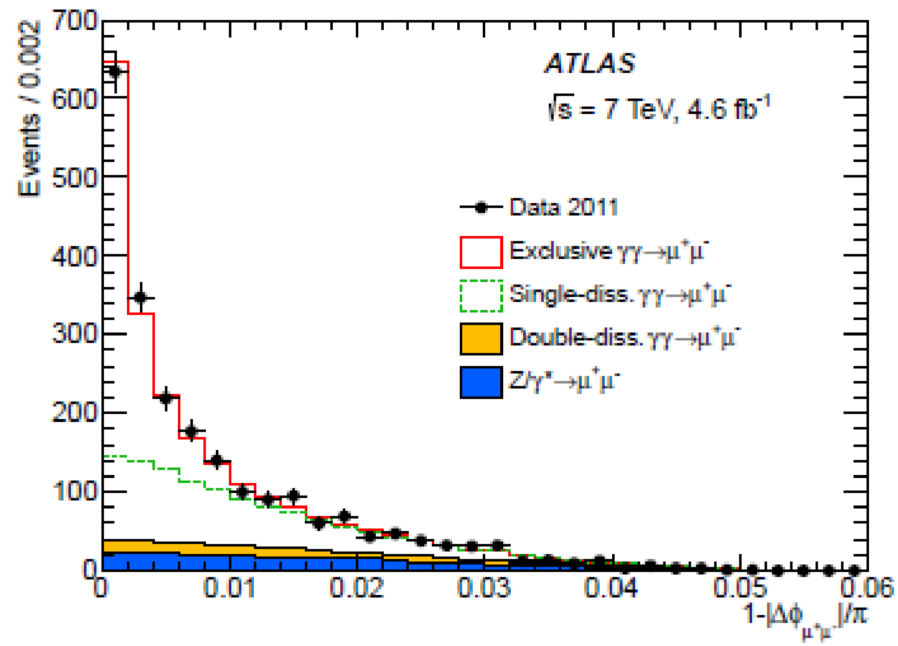
for elastic and SD processes...

# Measurement: X=di-lepton / Final step -2-

pp->(γγ)->ppX

- Binned likelihood of signal (exclusive or elastic) and background (SD)
- DY and DD fixed! *(DD from Pythia, re-scattering corrections included)*
- Both elastic and SD requires the factor ~80%




- $R^{\mathrm{excl.}}_{\gamma\gamma\to e^+e^-} = 0.863 \pm 0.070$ $\quad R^{\mathrm{s-diss}}_{\gamma\gamma\to e^+e^-} = 0.759 \pm 0.080$
- $R^{\mathrm{excl.}}_{\gamma\gamma\to \mu^+\mu^-} = 0.791 \pm 0.041$ $\quad R^{\mathrm{s-diss}}_{\gamma\gamma\to \mu^+\mu^-} = 0.762 \pm 0.049$

# Measurement: X=di-lepton / Systematic uncertainties



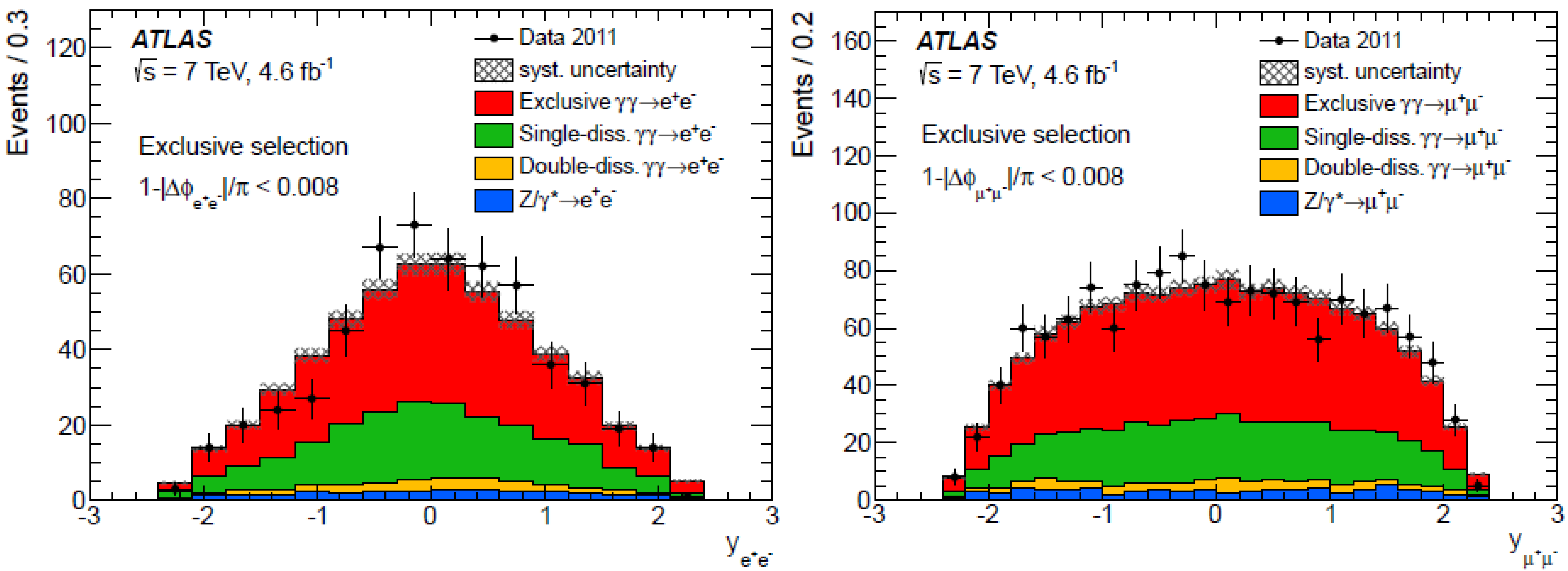
dominant sources of systematic uncertainty are from background modeling:

| Source of uncertainty | Uncertainty [%] $\gamma\gamma \to e^+e^-$ | Uncertainty [%] $\gamma\gamma \to \mu^+\mu^-$ |
|---|---|---|
| Electron reconstruction and identification efficiency | 1.9 | - |
| Electron energy scale and resolution | 1.4 | - |
| Electron trigger efficiency | 0.7 | - |
| Muon reconstruction efficiency | - | 0.2 |
| Muon momentum scale and resolution | - | 0.5 |
| Muon trigger efficiency | - | 0.6 |
| Backgrounds | 2.3 | 2.0 |
| Template shapes | 1.0 | 0.9 |
| Pile-up description | 0.5 | 0.5 |
| Vertex isolation efficiency | 1.2 | 1.2 |
| LHC beam effects | 0.5 | 0.5 |
| QED FSR in DY $e^+e^-$ | 0.8 | - |
| Luminosity | 1.8 | 1.8 |
| Total systematic uncertainty | 4.3 | 3.3 |
| Data statistical uncertainty | 8.2 | 5.1 |

# Measurement: X=di-lepton / Control distributions

pp->(γγ)->ppX

Apply the derived scaling factors to MCs (elastic and SD)
=>
The description data/MC is good!



# Measurement: X=di-lepton / Cross sections



$$R^{\text{excl.}}_{\gamma\gamma\to e^+e^-} = 0.863\pm0.070$$
$$R^{\text{excl.}}_{\gamma\gamma\to \mu^+\mu^-} = 0.791\pm0.041$$

↓

$$\sigma^{\text{excl.}}_{\gamma\gamma\to l^+l^-} = R^{\text{excl.}}_{\gamma\gamma\to l^+l^-} \cdot \sigma^{\text{EPA}}_{\gamma\gamma\to l^+l^-}$$

↓ Cross sections in the fiducial region (inside the kinematical cuts)

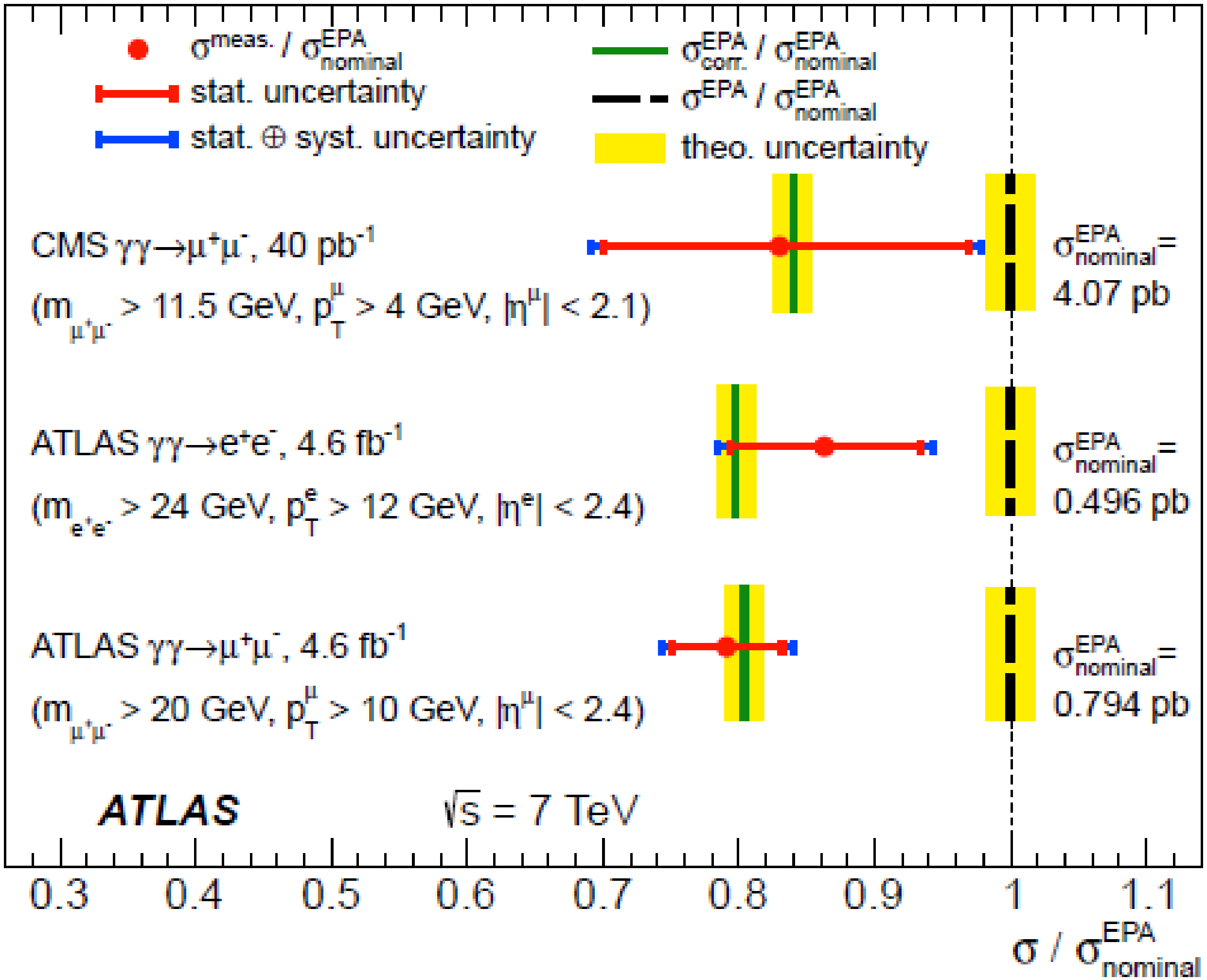
| Variable | Electron channel | Muon channel |
|---|---|---|
| $p_{\text{T}}^{\ell}$ | $> 12$ GeV | $> 10$ GeV |
| $\lvert\eta^{\ell}\rvert$ | $< 2.4$ | $< 2.4$ |
| $m_{\ell^+\ell^-}$ | $> 24$ GeV | $> 20$ GeV |

$$\sigma^{\text{excl.}}_{\gamma\gamma\to e^+e^-} = 0.428 \pm 0.035\ (\text{stat.}) \pm 0.018\ (\text{syst.})\ \text{pb}$$
$$\sigma^{\text{excl.}}_{\gamma\gamma\to \mu^+\mu^-} = 0.628 \pm 0.032\ (\text{stat.}) \pm 0.021\ (\text{syst.})\ \text{pb}$$

# Measurement: X=di-lepton / Cross sections –summary-

$$R^{\text{excl.}}_{\gamma\gamma\to e^+e^-} = 0.863\pm0.070$$
$$R^{\text{excl.}}_{\gamma\gamma\to \mu^+\mu^-} = 0.791\pm0.041$$

arXiv:1506.07098
PLB 749 (2015) 242-261



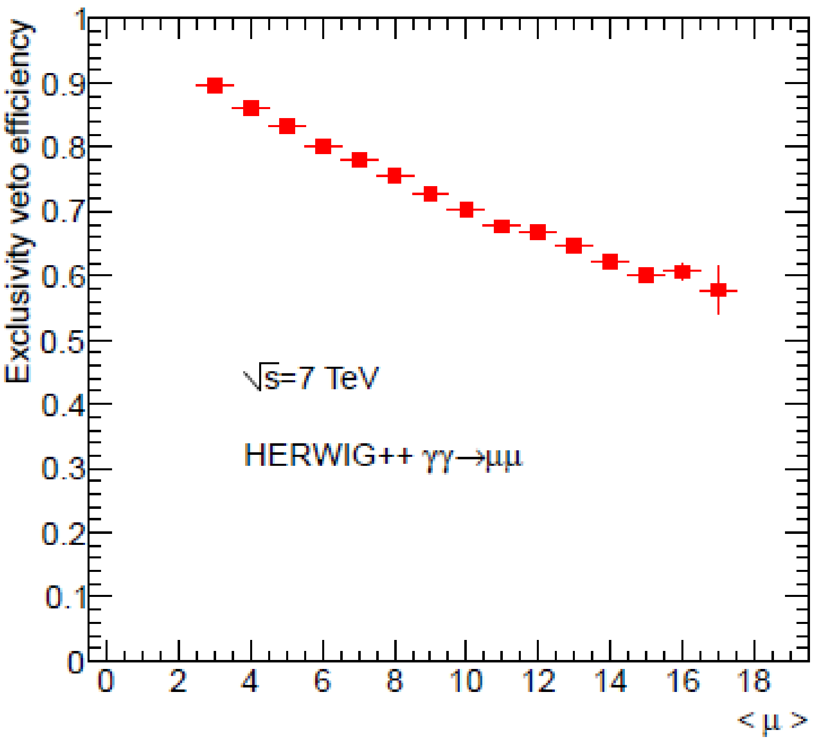
# Intermediate summary

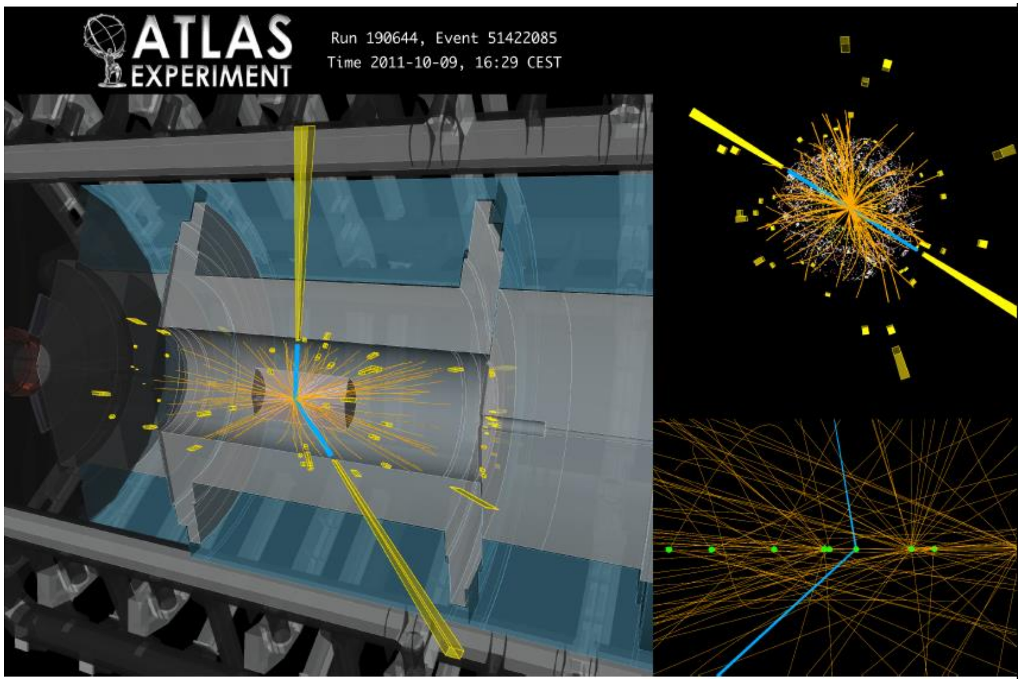
## On pp->(γγ)->… processes

We have shown experimentally that:

This is possible to <u>define an exclusivity selection</u> in order to identify 'exclusive' events with a good efficiency –in the presence of Pile Up Events <μ>-

This is something promising for any analysis of this kind!



# Intermediate summary

## On pp->($\gamma\gamma$)->ppX processes

Example of potential studies: X=WW ; X=$\gamma\gamma$ ; …
and many others in the exotic context…

**This is a wide domain of experimental research… only starting.**

A few points to keep in mind:

a) Take the correct scale for $\alpha_{EM}$ (which means 0 GeV² for elastic)

b) This is not correct to write (even implicitly) a relation like:

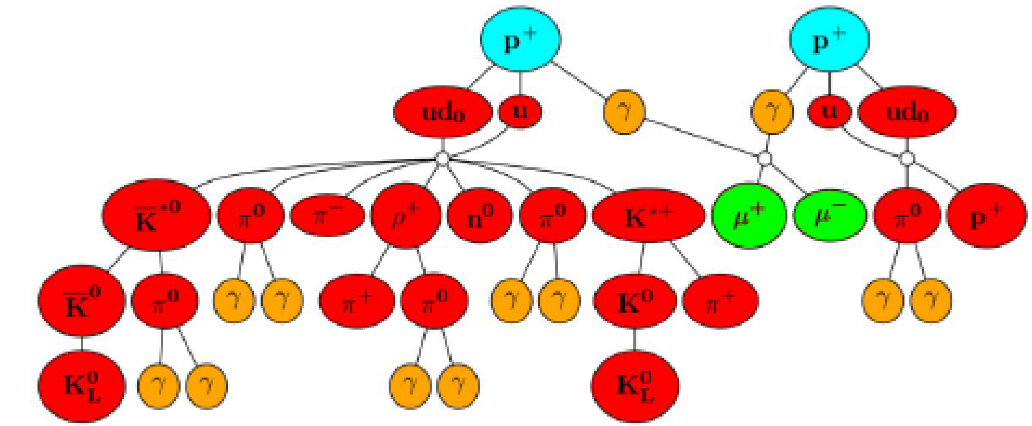
$$\sigma_{eff}(2l) / \sigma_{EPA}(2l) = \sigma_{eff}(WW)/\sigma_{EPA}(WW)$$

and then use this relation to scale predictions…

**Interestingly, all this can be done in PbPb >($\gamma\gamma$)->PbPbX**
*with advantages and drawbacks compared to pp…*

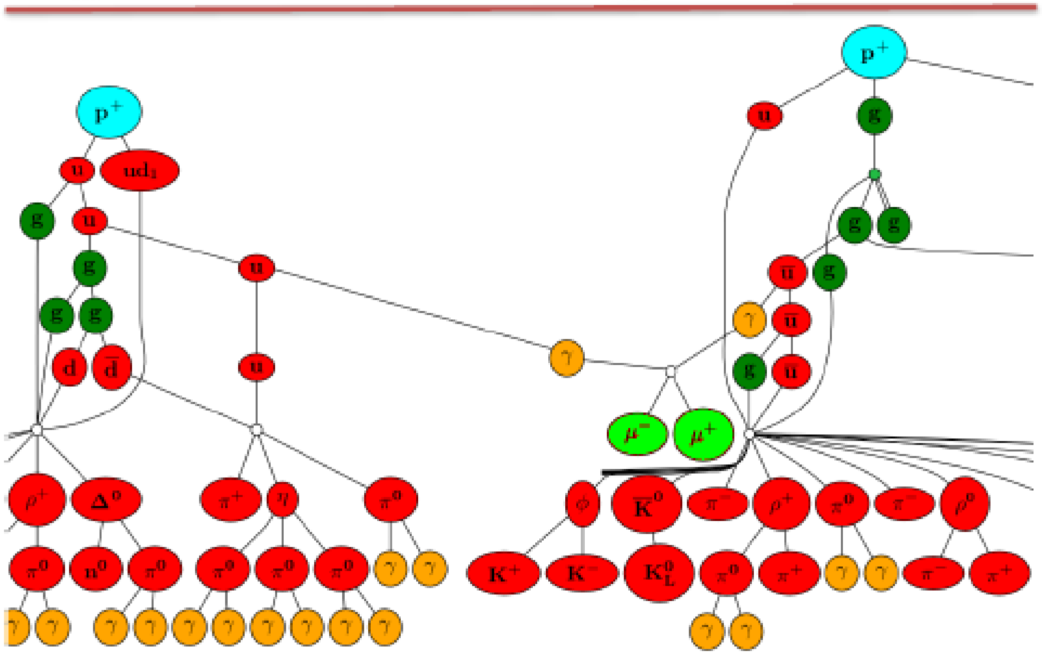
# Additional: MCs

## For pp->(γγ)->YY X processes




**Treatment in LPAIR**

This produces only particles in the forward directions

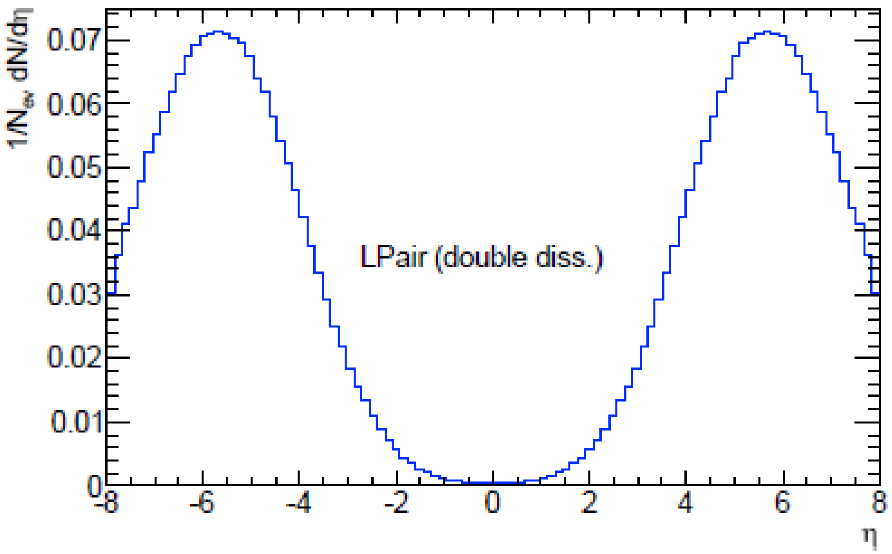


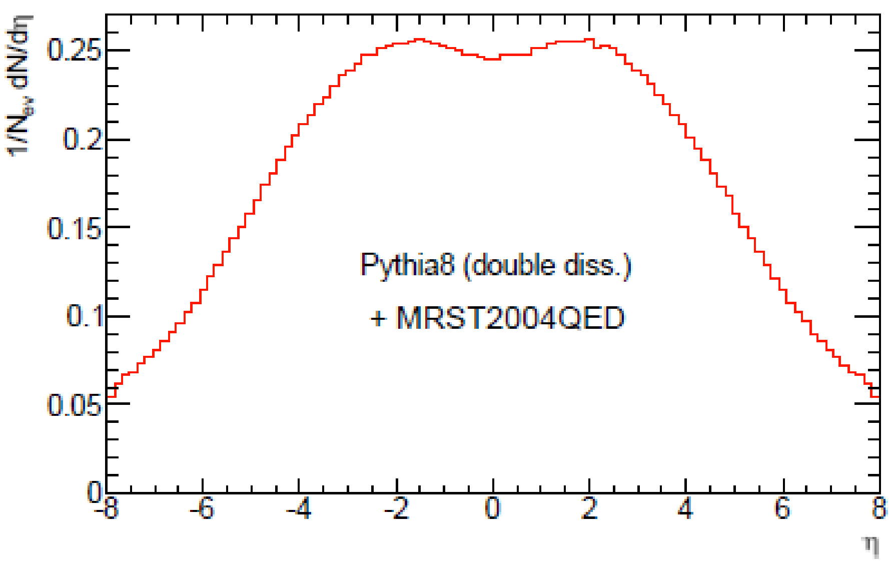

**'Correct' treatment in Pythia8**

Particles are also visible in the central part of the detector

# Additional: MCs

## For pp->(γγ)->YY X processes




Treatment in **LPAIR**
This produces only particles in the forward directions

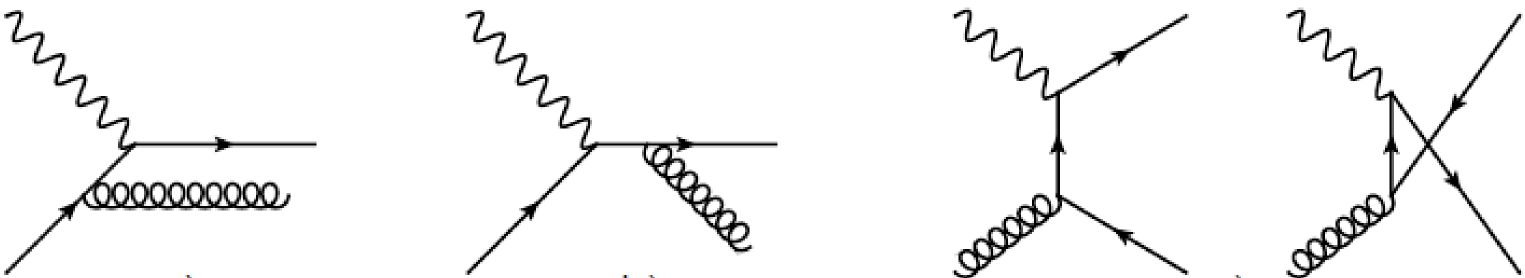
'Correct' treatment in **Pythia8**
Particles are also visible in the central part of the detector

Then:
A large part of the 'total' cross-section is missed by LPAIR (/Phythia8) or any approach à la LPAIR for proton-dissociative events…

# Additional: MCs

## For pp->(γγ)->YY X processes

- O($\alpha_S$) corrections to the $\gamma q \rightarrow q$ process should have to be also considered



a) Initial state radiaiton | b) Final state radiaiton | c) Quark pair production

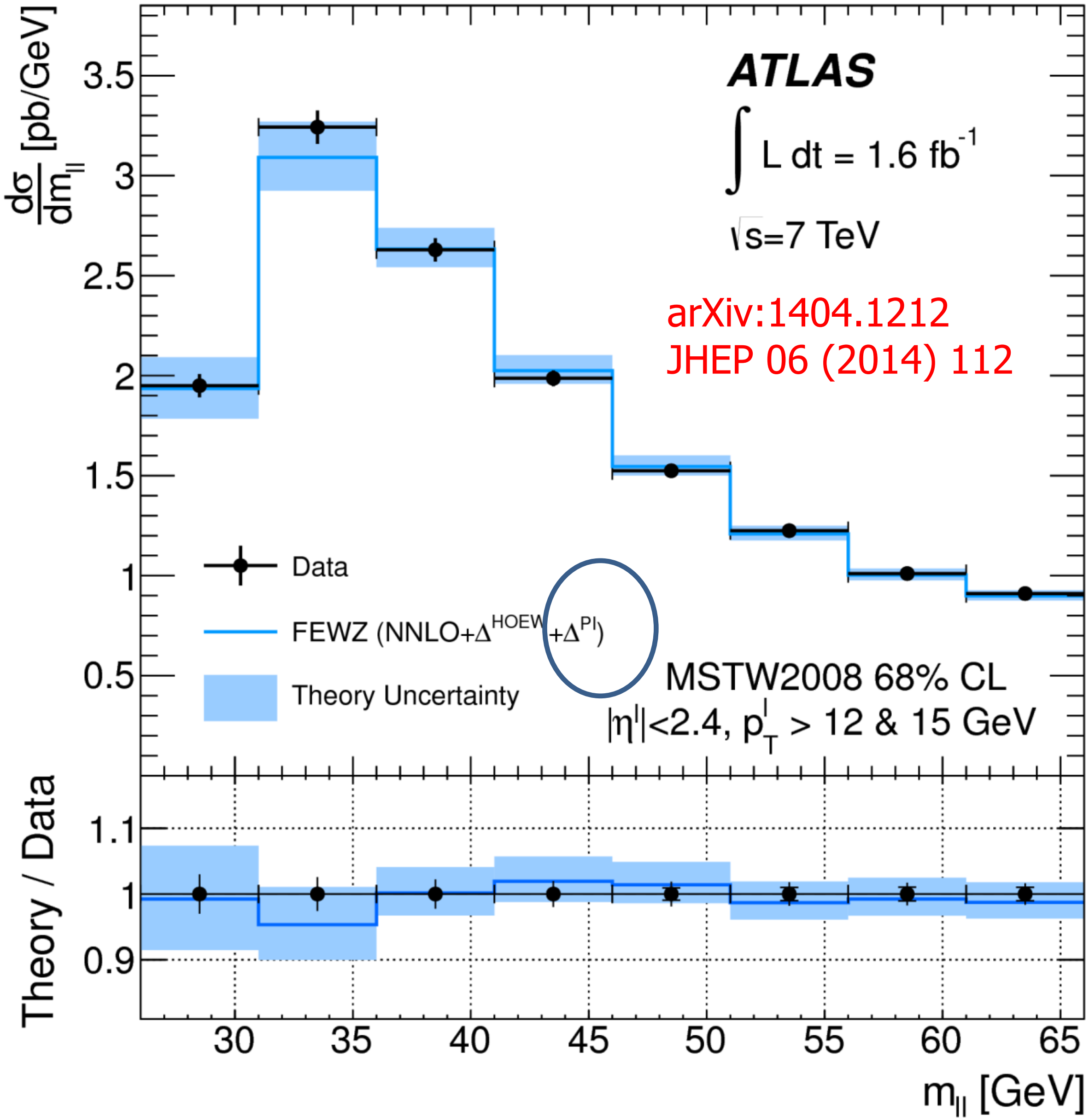
≈ **40% contribution** to the double-dissociative cross section (PYTHIA8)

- Enhancement of the cross section (diss part)
- Increased underlying event activity in the central detector
- Total cross section comparison: ($M_{\mu\mu} > 20$ GeV, $p_T^{\mu} > 10$ GeV, $|\eta_{\mu}| < 2.5$)

| Generator | LPAIR (s-diss) | LPAIR (d-diss) | PYTHIA 8 (d-diss) |
|---|---|---|---|
| Cross-section | 0.87 pb | 1.02 pb | 7.72 pb |

+ MRST2004QED

# Additional: Photon Induced reactions in DY

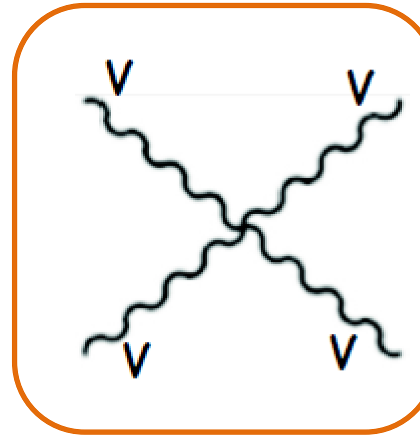



2 to 3% contribution of PI has been estimated…

and the data/theory comparison looks reasonable

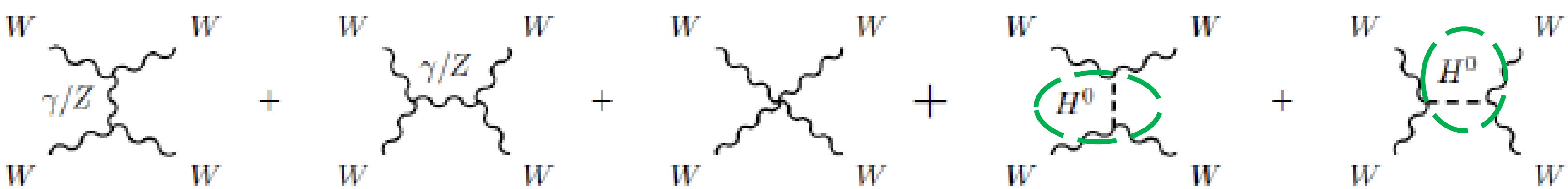
# Probing even deeper

## Using Vector Boson Scattering…




*QGC:=Quartic Gauge Coupling*

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left[-s - t + \frac{s^2}{s-m_H^2} + \frac{t^2}{t-m_H^2}\right]$$



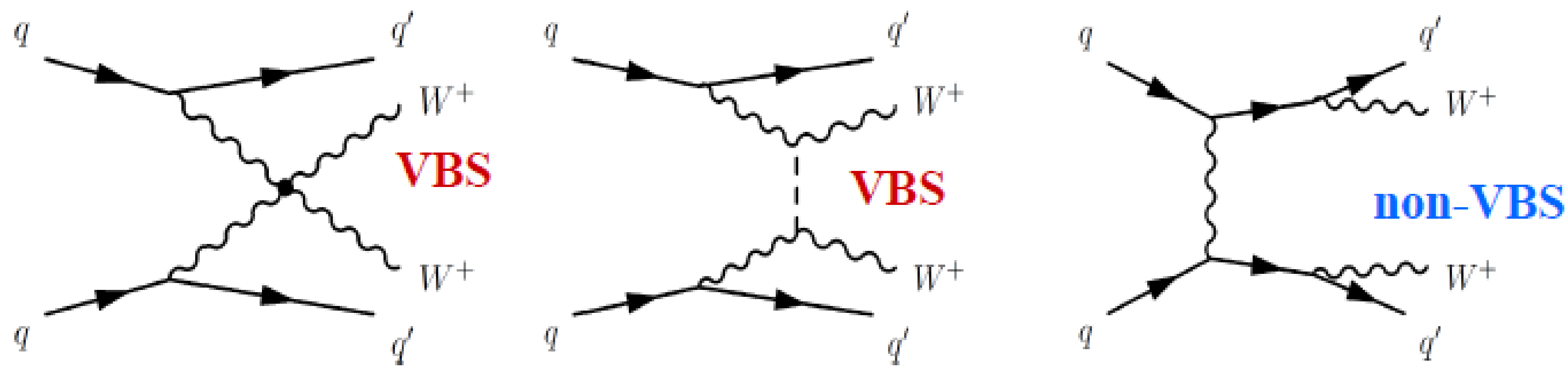

Direct probe of the nature of the electroweak symmetry breaking mechanism EWSB

*General motivation:*

This is a high priority: we need to understand QGCs to tell if the Higgs unitarizes the process WW->WW

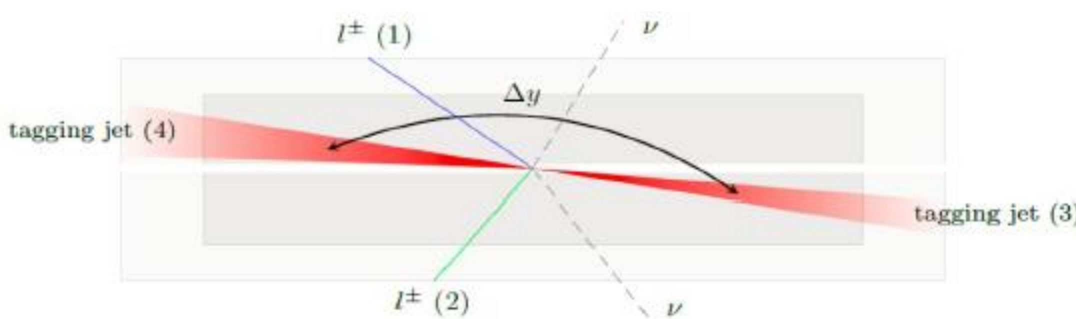
# WW scattering

Electro-weak same-sign WW production (+2 jets) gets contributions from VBS diagrams (and non-VBS):

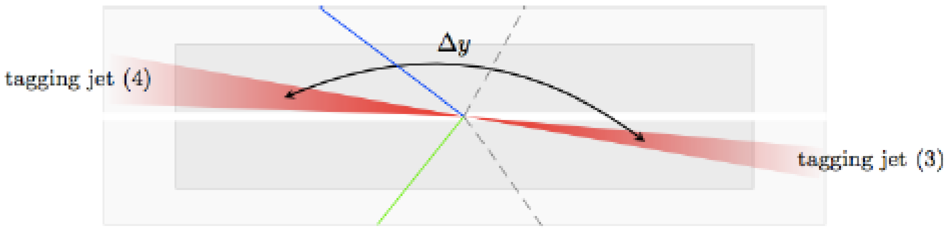


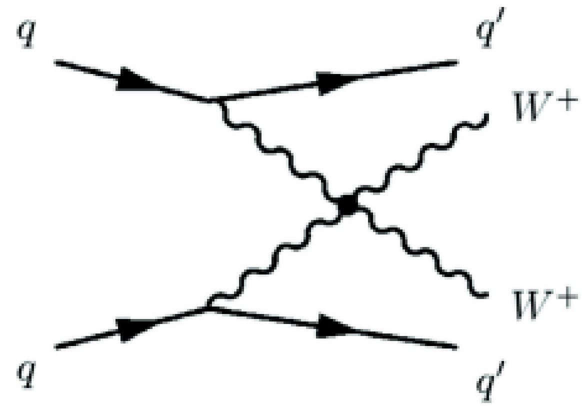

This is a promising channel for early VBS searches (low backgrounds)
The idea to identify the VBS signature**:**

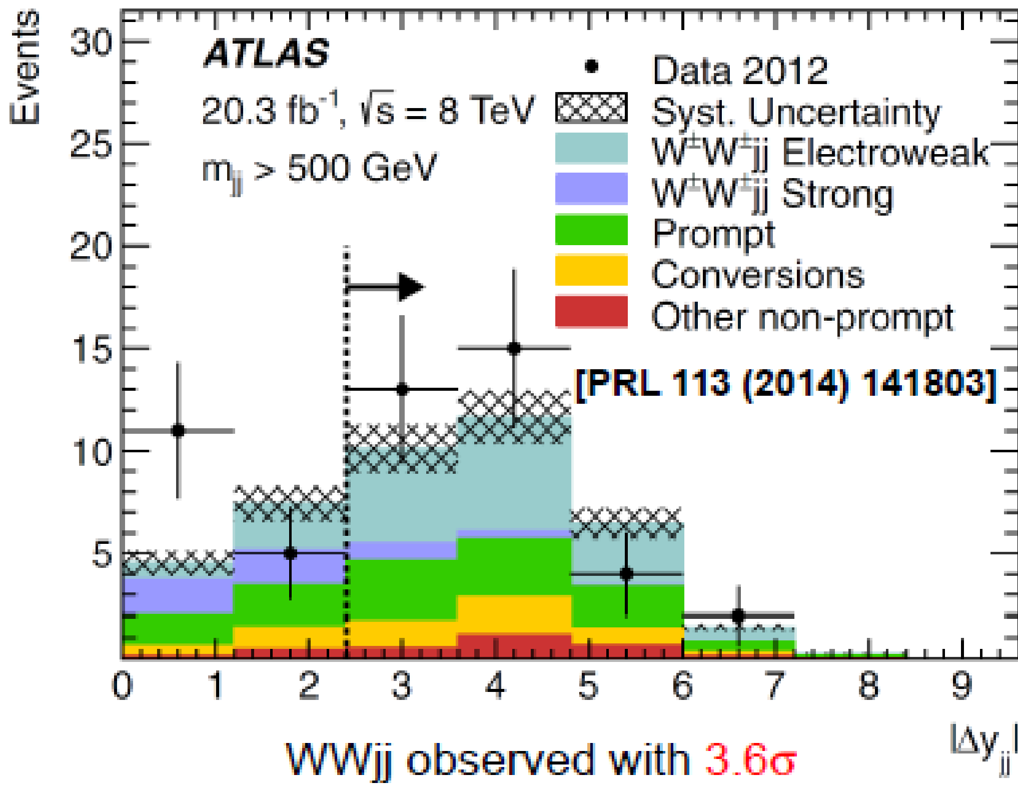
**two jets with large rapidity separation** and large mass!



# WW scattering




WWjj observed with 3.6σ

First evidence ever!

First evidence of same sign WW

Signal:

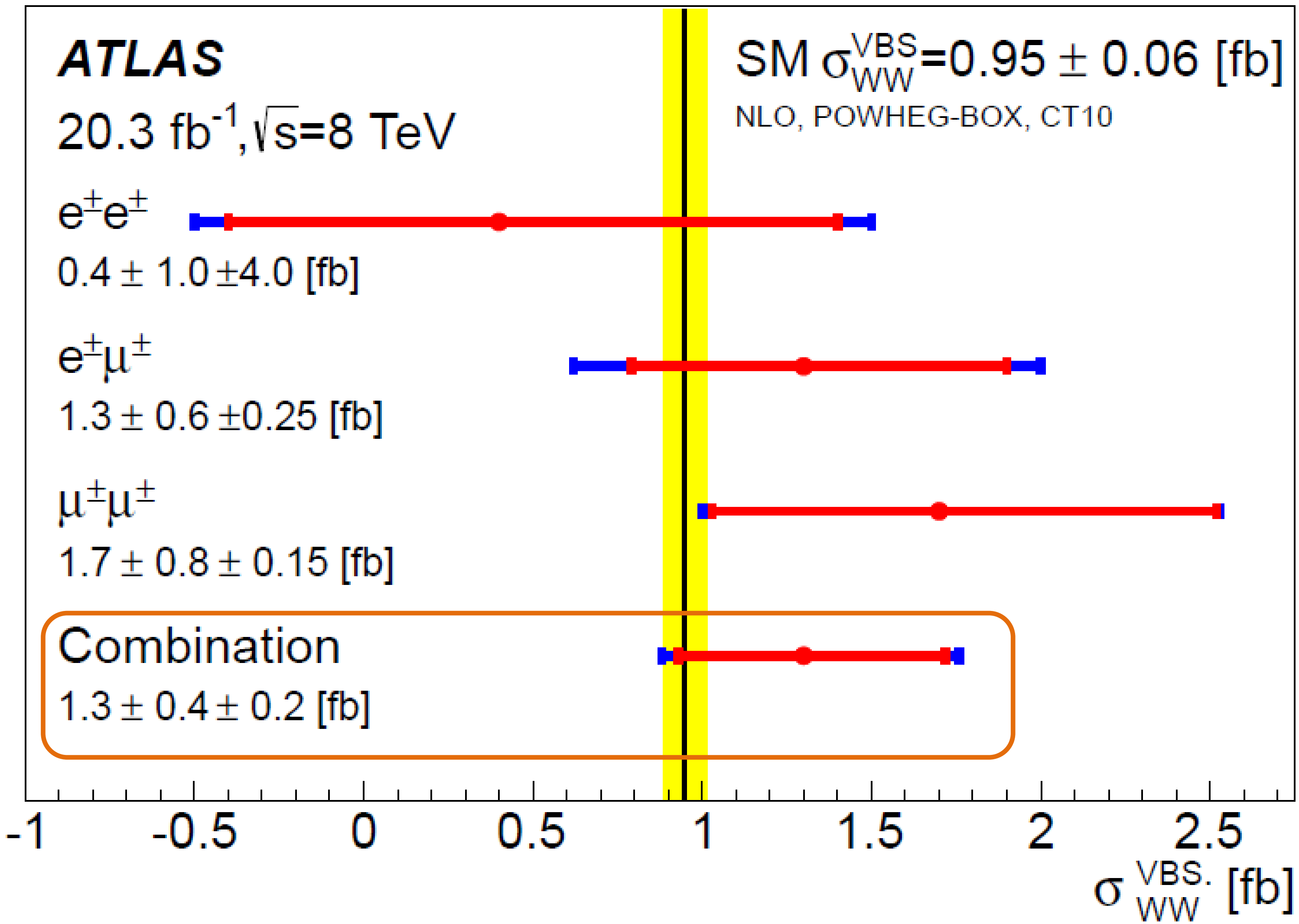
(a) Same sign di-leptons

(b) 2 high pT jets with a large gap between them

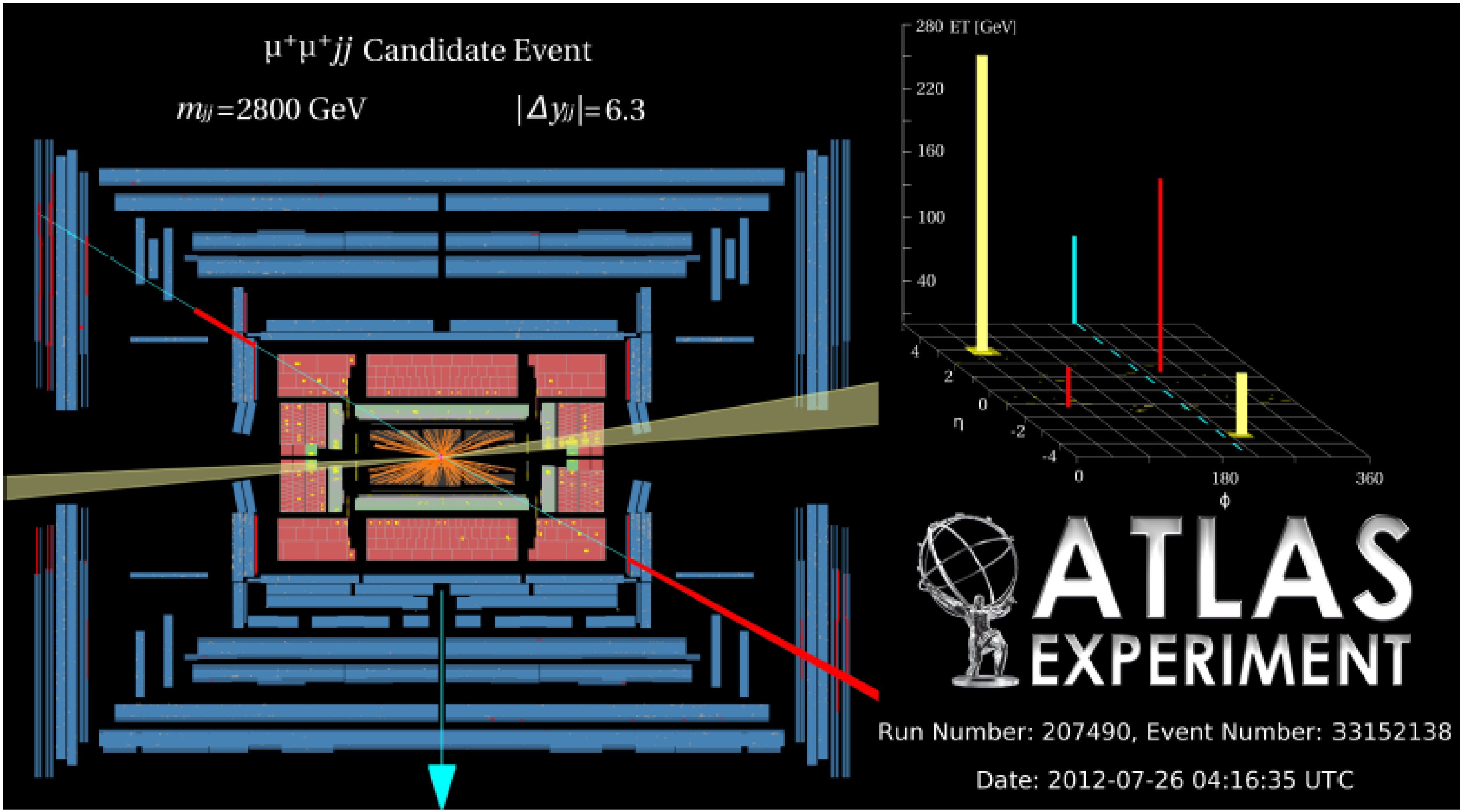
ATLAS: $\sigma^{\text{fid}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ fb

Predicted: $0.95 \pm 0.06$ fb

# WW scattering: VBS cross section



# WWjj event in ATLAS




jets: $p_T^{j1} = 271$ GeV, $p_T^{j2} = 54$ GeV, $\eta^{j1} = 2.9$, $\eta^{j2} = -3.4$ $E_T^{\text{miss}} = 75$ GeV

muons: $p_T^{\mu 1} = 180$ GeV, $p_T^{\mu 2} = 38$ GeV, $\eta^{\mu 1} = 1.4$, $\eta^{\mu 2} = -1.3$

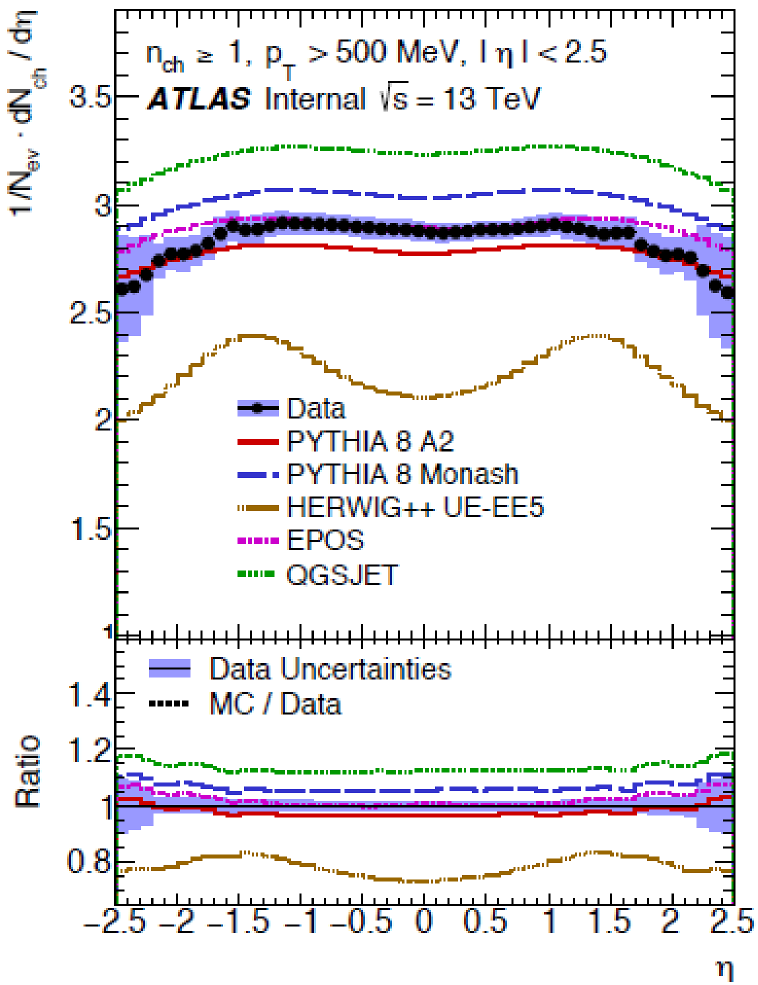
# Outlook -1-

- Soon, pp elastic measurement at 8 TeV (90m optics) :within a year
- *On going:* Some dedicated 'diffractive'-like measurements using ALFA (at higher beam intensity) instead of using LRG method (central detectors)
- New runs at 13 TeV for ALFA (nominal optics) foreseen in October: we have already discussed how this measurement is important…
- On going: new studies in $\gamma\gamma$ interactions (at 8 TeV). In parallel, we prepare some analyses for the 13 TeV data… where the large statistic expected will be decisive in the "probing deeper" topologies…
- *Uncovered in this presentation:* photo-production of VM in PbPb collisions (on going)… for Pb, the equivalent #photons is multiplied by $82^2$! Making a high intensity field… (with smaller maximal energies for photons)

# Outlook -2-

LHC/ATLAS is re-starting… sample of results using tracks in central detectors so important in all analyses!

Feynman plateau




2-particle correlations at large multiplicities => long range correlations($\phi$~0)!