Forward physics and two-photon interactions in the ATLAS experiment

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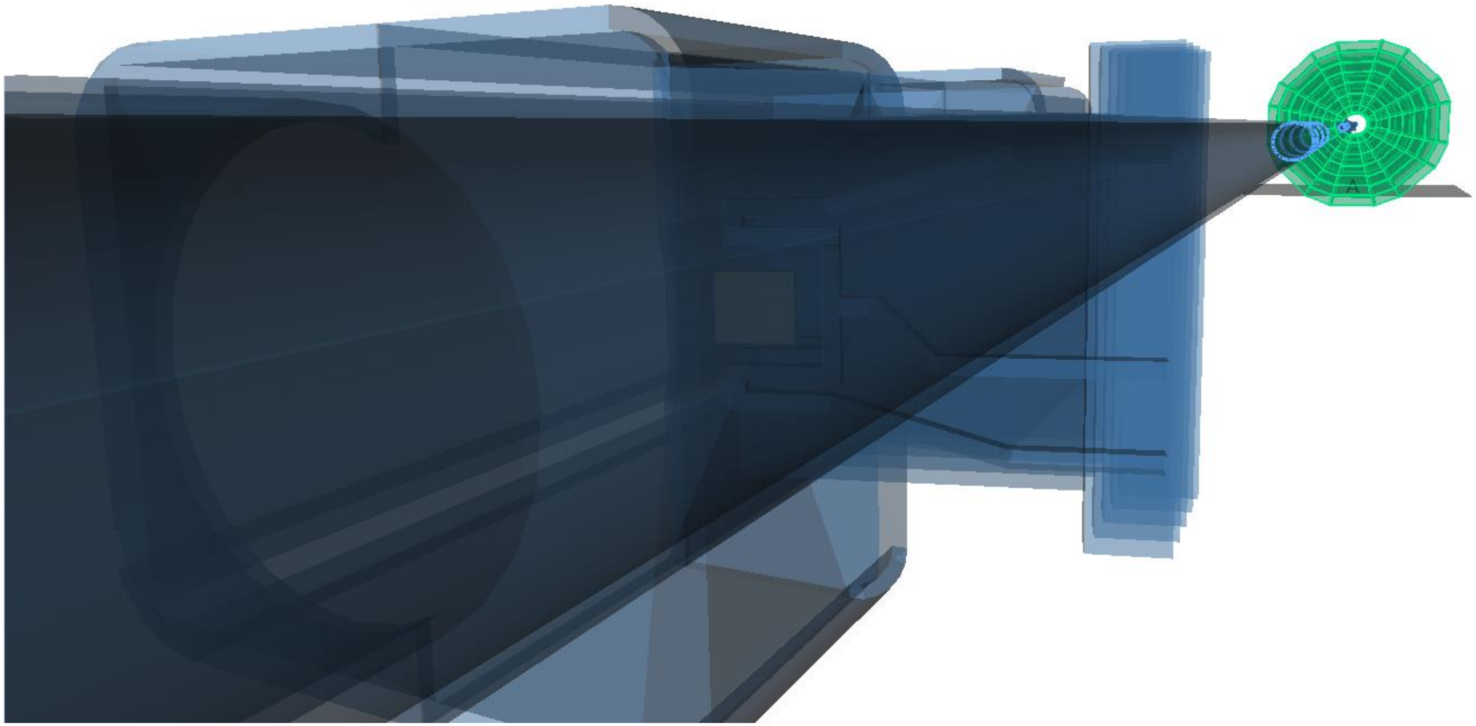
Outline

- Atlas Forward Detectors Full Simulation
  - Qualification work for the ATLAS experiment
  - Then, convener of the forward detectors simulation sub-group

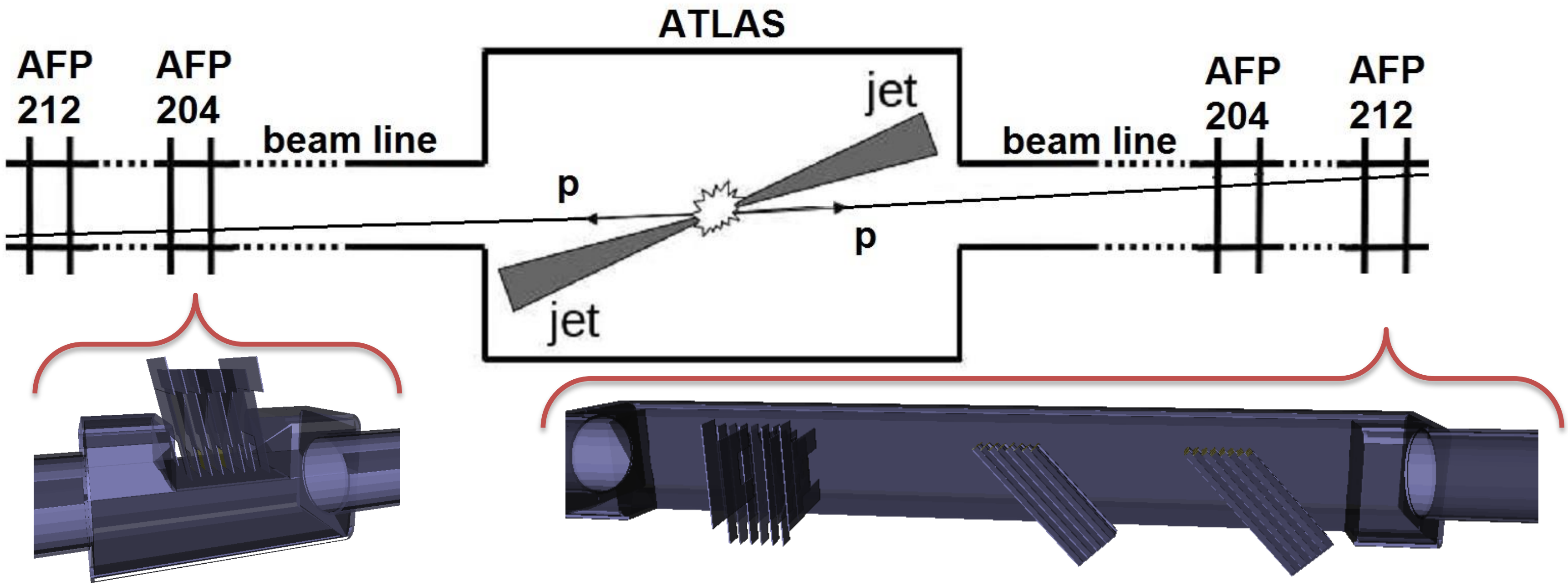
- Measurement of exclusive $\gamma\gamma \rightarrow l^+l^-$ production
  - Ongoing ATLAS data analysis
  - Long-term prospects: $\gamma\gamma \rightarrow W^+W^-$ with experience gained from l^+l^-

AFP Detector Full Simulation

- Core idea: measure intact proton far away from the interaction point



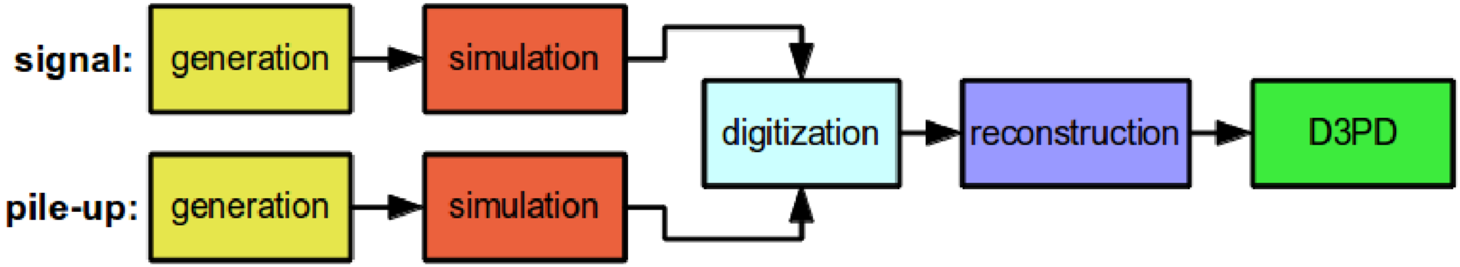
AFP Detector Simulation



- Simulation is based on the Hamburg Beam Pipe approach
  - two HBPs per ATLAS side: inner station with Silicon Detector and outer station with Silicon and two Timing Detectors
- The design will change in the future to Roman Pots (RP) setup and different layout of Timing Detectors
  - It is expected this will reduce the material scattering effects

AFP Detector Simulation

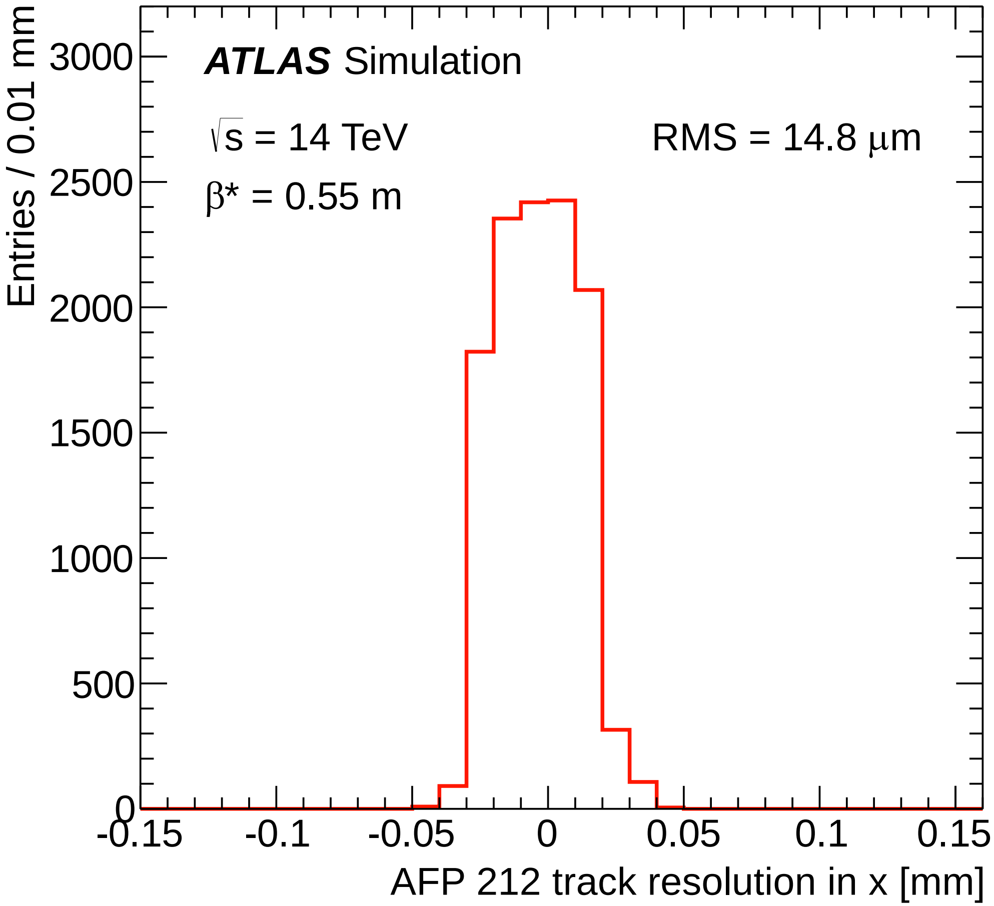
- Full **Geant4** simulation of **Forward Region + AFP Stations** in the ATLAS Athena framework:
  - **Geo Models** of: Forward Region, Hamburg Beam Pipes (HBPs), AFP Silicon (SiD) and Timing (TD) Detectors
  - Forward Region simulation (for the 1st time)
    - Magnetic field specification
    - Contains beam pipe, collimators and beamscreens models
    - Plan to study the effect of dead material, starting from the closest (most affecting) regions
  - Description of **Sensitive Detectors** (+ data models)
  - **Reconstruction** algorithms for SiD and TD
  - **AFP D3PD** scheme prepared (D3PD maker for AFP)
    - D3PD dumper for AFP + ATLAS made



AFP SiD performance

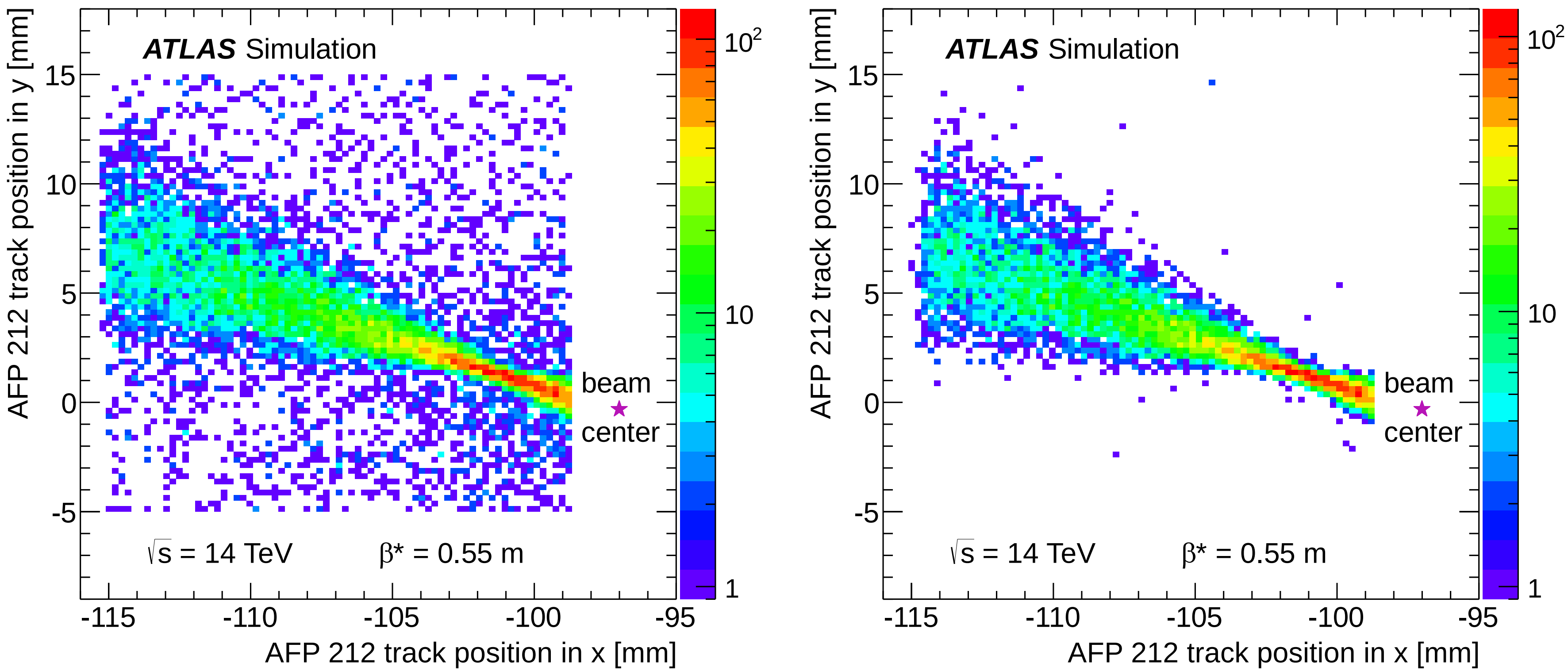
- SiD tracking resolution
- **15 µm** RMS in **x** (plot)
- **72 µm** RMS in **y**
- Numbers above consistent with the formula: RMS = pixel_size / √12

- Staggering of the layers will improve the resolution, even with 4 Si layers configuration
- Expected tracking resolution wrt 4 staggered layers: 8 µm in x, 20 µm in y



AFP SiD performance

- **x-y track positions hitmap** for outer SiD station before (left) and after (right) track matching included for outer (AFP 212) station
- Tracks matched between inner and outer SiD stations are considered
- Positions are calculated in the ATLAS Coordinate System – beam center at x = -97mm

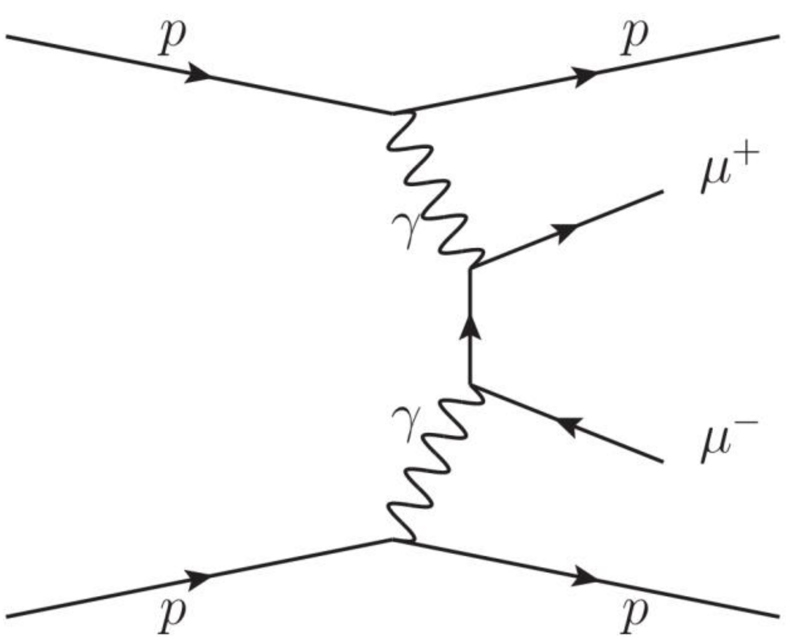


Summary (AFP Simulation)

- Full Geant4 simulation of ATLAS Forward Region + AFP Stations in the Athena framework is ready
  - Support for the simulation of all forward detectors in ATLAS
- Simulated detector performance in agreement with the expectations - based on the basic material calculations / estimates
- Big potential of ATLAS Forward Region full simulation
  - p+p, p+Pb collisions (synergy with existing forward detectors in ATLAS)
  - Background studies

Measurement of exclusive $\gamma\gamma \rightarrow \ell^{+}\ell^{-}$

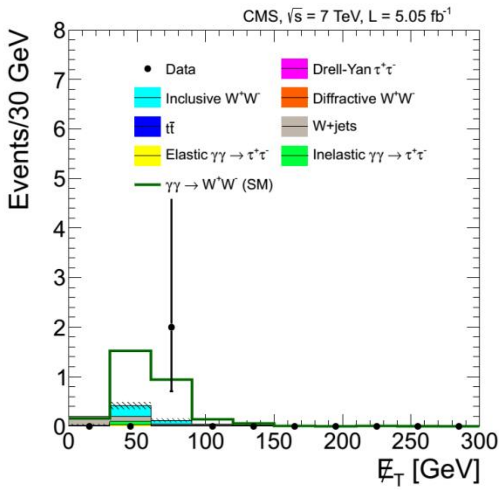
- <u>Core idea</u>: measure cross sections for elastic and dissociative processes, determination of the photon content in the proton



Analysis context (CMS results)

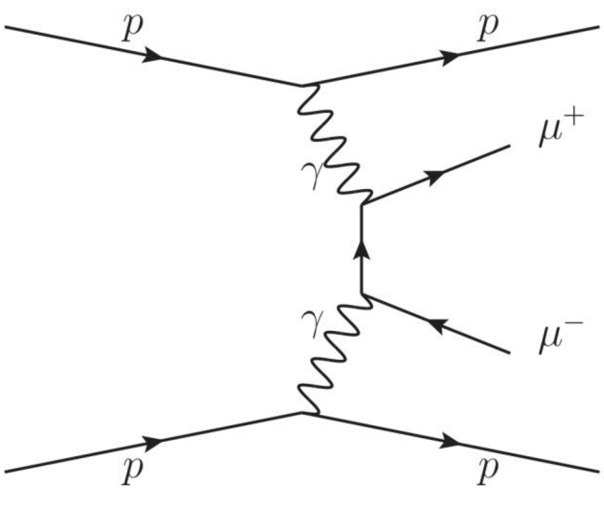
- *Exclusive $\gamma\gamma \to \mu\mu$ production in pp collisions at √s=7TeV* [arXiv:1111.5536]
- **$\gamma\gamma \to \mu^+\mu^-$** -> definition of exclusivity cuts to select such events with a good efficiency (2010 data; 40/pb)
- Determination of the pp $\to$ pp $\mu^+\mu^-$ cross section

- *Study of exclusive $\gamma\gamma$ production of W(+)W(-) in pp collisions at √s=7TeV and constraints on anomalous quartic gauge couplings* [arXiv:1305.5596]
- Using the exclusivity requirements from the previous studies, select exclusive events: **$\gamma\gamma \to W^+W^-$**
- Best limits on anomalous couplings in QGC are then obtained
- (2011 data; 5/fb)



- Perspectives: more statistics needed, more work on the physics - MC generators (dissociative part)

Elastic processes: pp → p μμ p



<u>Via quasi-real photons exchange (diagram)</u>

The cross section for this process is calculated:

(1) Using the number of equivalent photons (EPA) by integration over the whole virtuality range:

$$Q^2_{min} \simeq m_p^2 \frac{x^2}{1-x}; \qquad Q^2_{max} = 2\,\mathrm{GeV}^2$$

Integrand contains the proton EM form factors (calculations done by Budnev et al., 74')

(2) And the QED $\gamma\gamma \to \mu^+\mu^-$ cross section

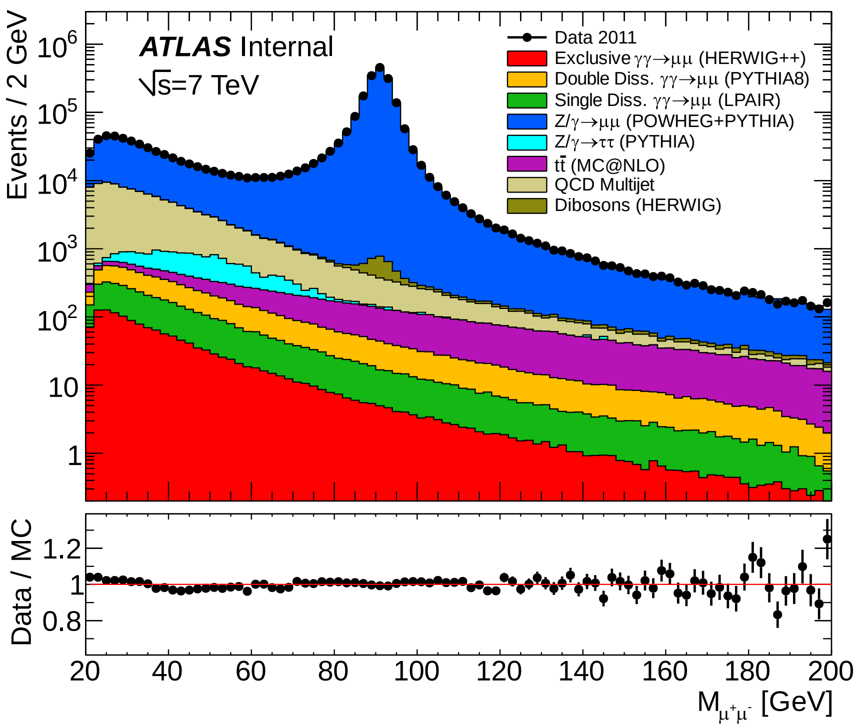
Implemented in HERWIG++, LPAIR (used at HERA, Tevatron and CMS) and FPMC

Cross checks between HERWIG++ (ATLAS) and LPAIR done

Impact on the other SM (EW) results

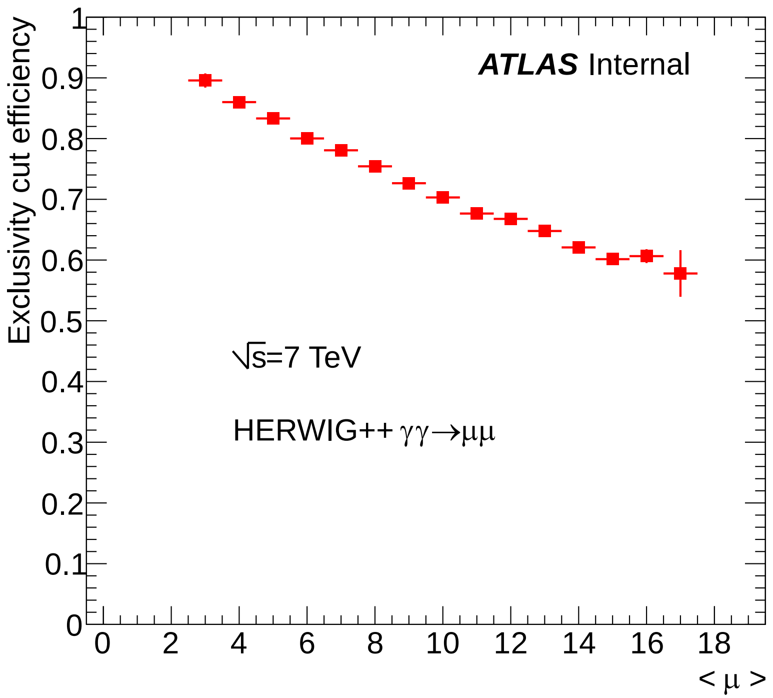
- Low mass Drell-Yan analysis
  - FEWZ+MRST2004QED PDF used to estimate photon induced (PI) contribution
  - Δ^{PI} corrections contribuite **2-3%** of the NNLO theory predictions
- Remark:
  - No **exclusive** and **single-diss** PI parts in FEWZ -> they should contribute **≈ 50%** of the total PI cross section

$m_{\mu\mu}$ [GeV]	FEWZ $\frac{d\sigma}{dm_{\mu\mu}}$ [pb/GeV]	Δ^{PI} [pb/GeV]
$12-17$	12.09	0.000 ± 0.000
$17-22$	21.22	0.190 ± 0.070
$22-28$	13.56	0.240 ± 0.087
$28-36$	6.74	0.150 ± 0.054
$36-46$	3.10	0.085 ± 0.030
$46-66$	1.28	0.037 ± 0.013



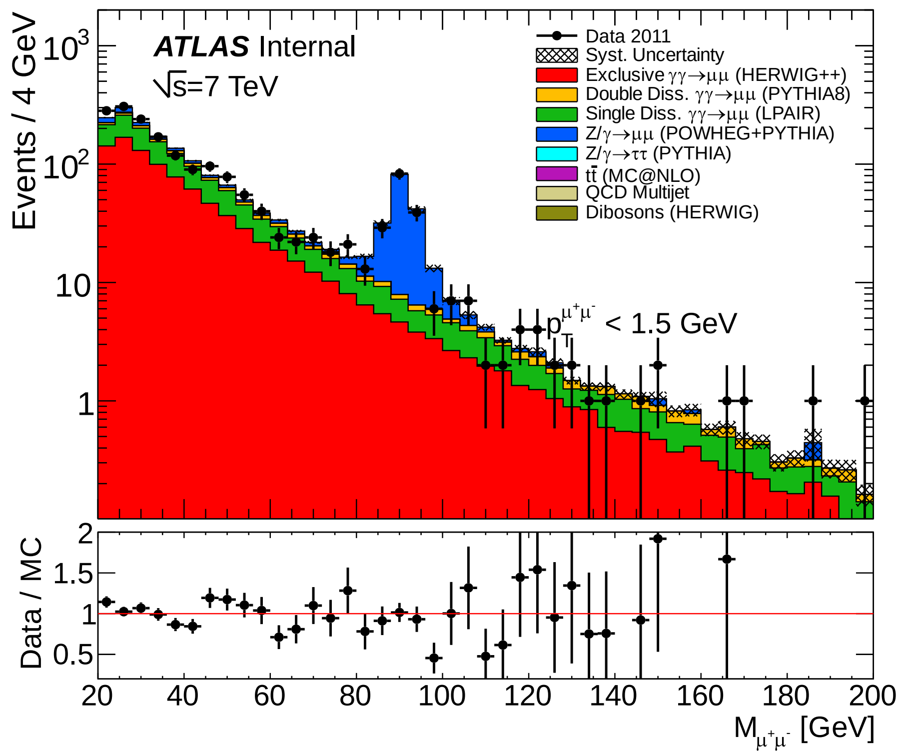
Event selection

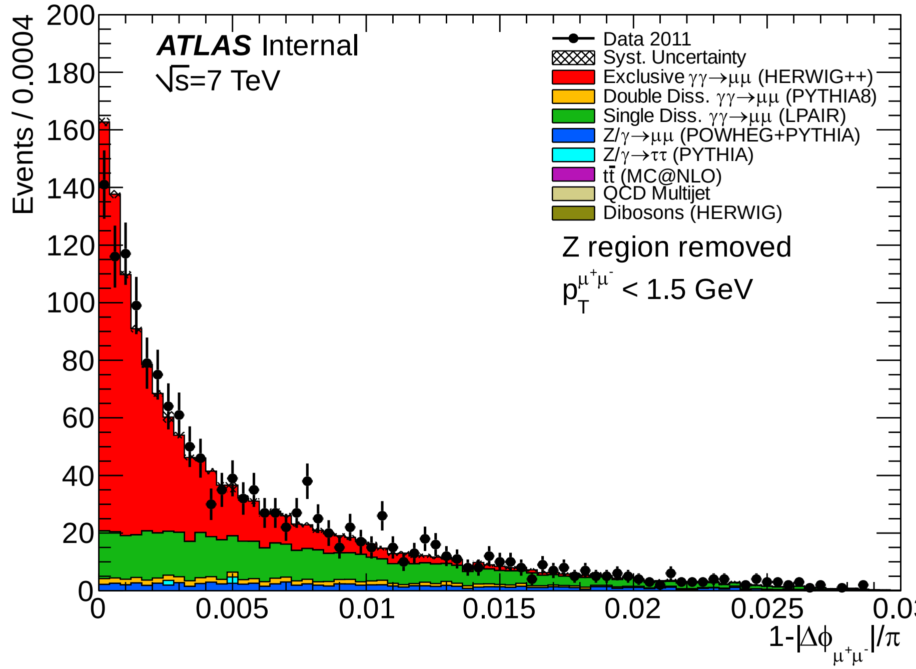
- 2011 period B-M GRL
- Triggers : EF_2mu(e) || EF_mu(e)
- **Dilepton** events:
  - Opposite charge
  - Kinematic cuts depend on the trigger thresholds (different for ee and mumu)
- Exclusivity selection:
  - Exactly **2 tracks** in the dimuon vertex
  - Standard p_T>400 MeV tracking cuts
  - **Exclusivity veto**: distance dimuon vtx - closest vtx (or track) > **3 mm**
- Elastic selection:
  - p_T of the dilepton system < 1.5 GeV -> **effective, single cut**



Muon channel

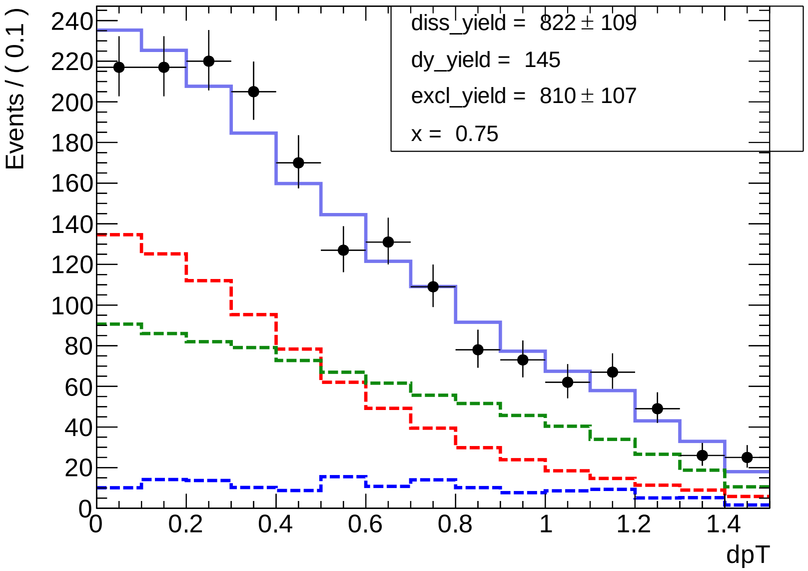
- Dimuon selection:
  - Medium staco cuts
  - $\mathbf{p_T^{\mu} > 10}$ **GeV**, $|\eta_\mu| < 2.4$, $\mathbf{M_{\mu\mu} > 20}$ **GeV**
  - Working in the trigger turn-on region…

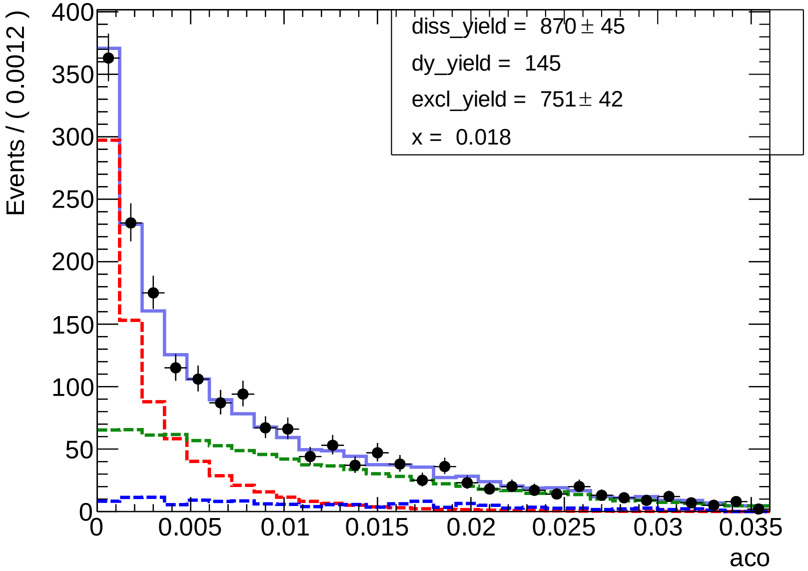


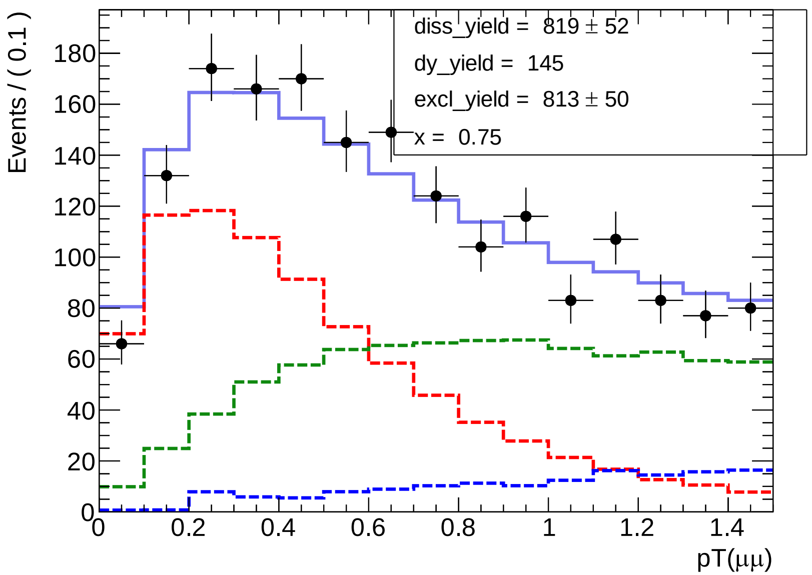


Muon channel

- Binned log-likelihood method used to extract excl. and diss. factors
- Single and double-diss. parts added
- DY contribution assumed to be well described (Z region check)
- Tried on different distributions



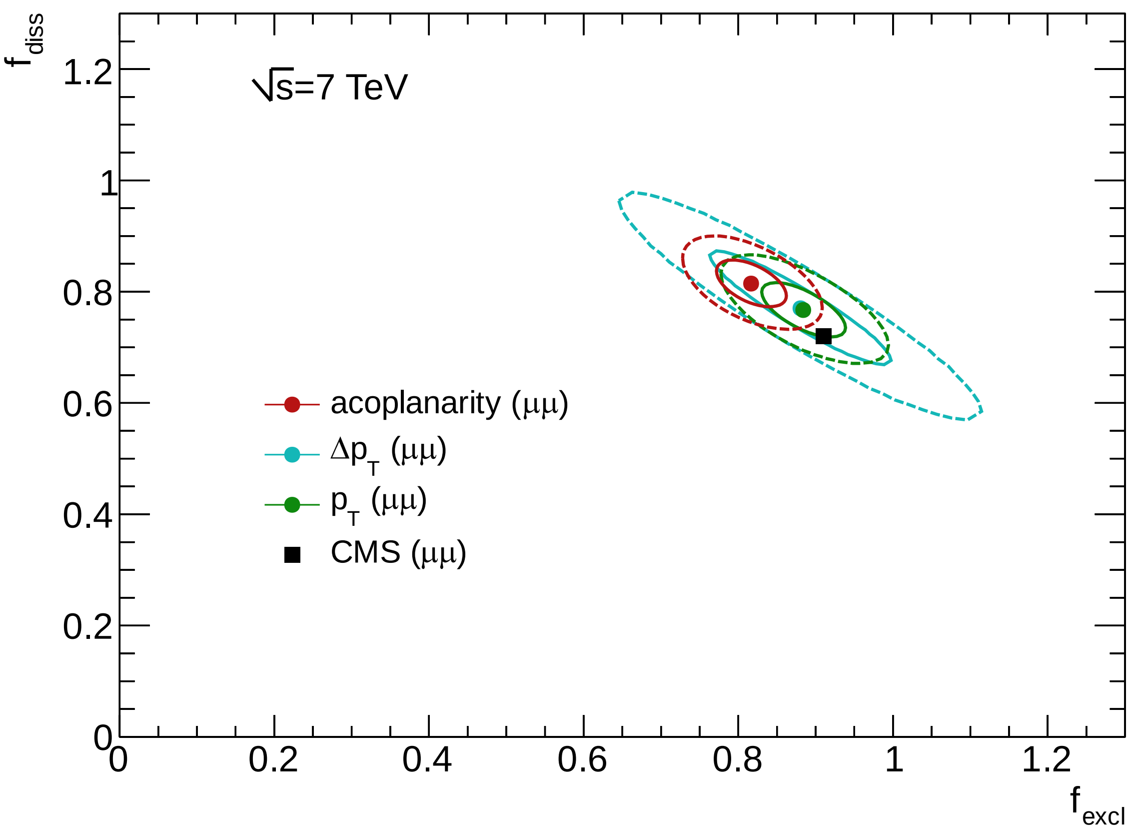




Muon channel

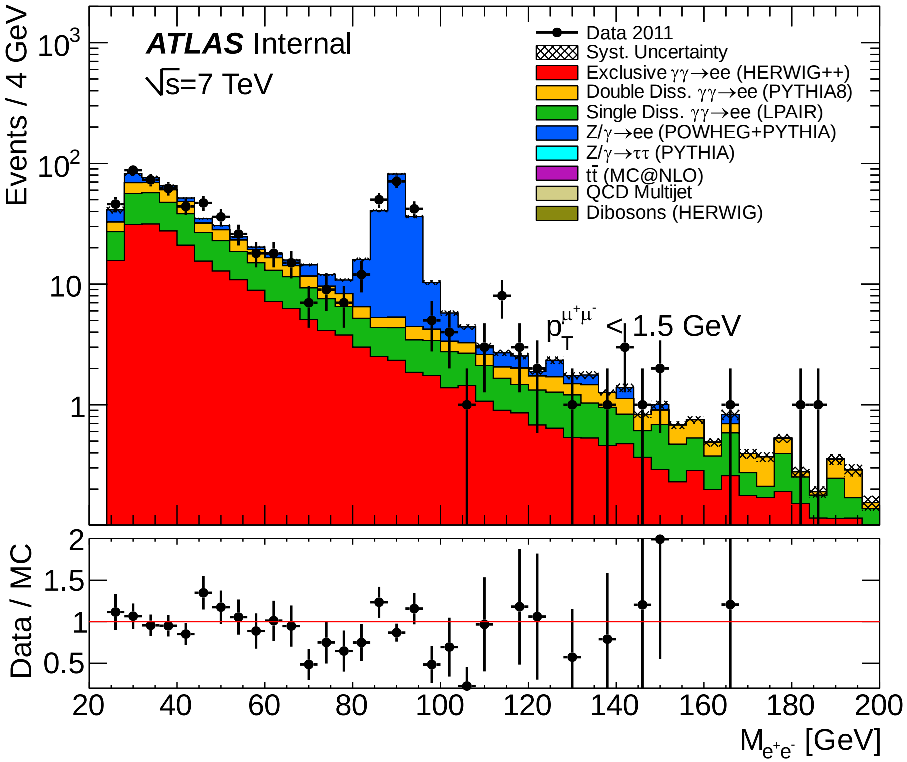
- All distributions give reasonable values
- Agreement with factors obtained by CMS
- Exclusive cross-section = **0.70 ± 0.05 (stat) pb** (M > 20GeV, p_T > 10GeV, |η| < 2.4)
- Equivalent Proton Approximation predictions: **σ = 0.79 pb**

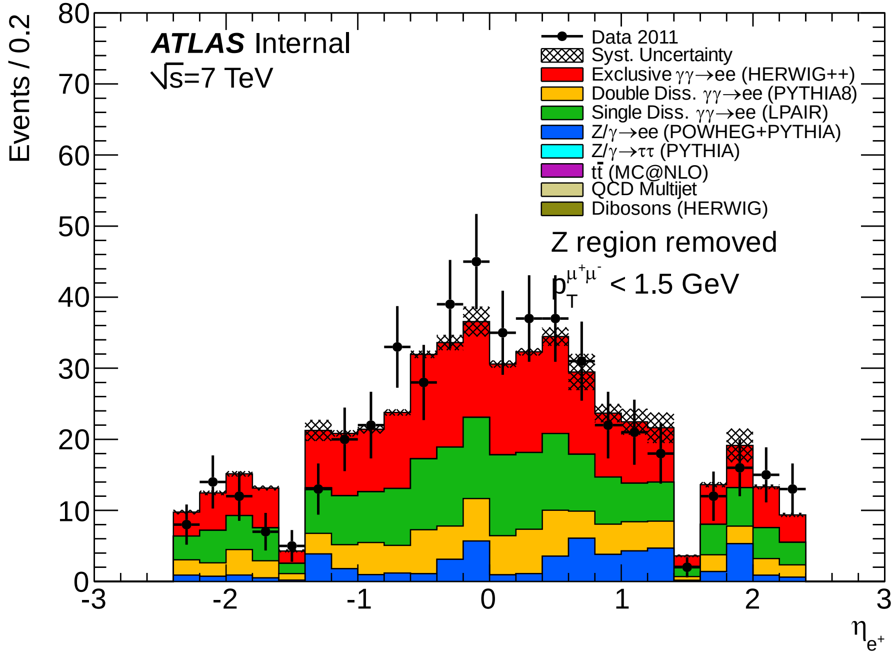
Distribution	Excl. fraction	Diss. fraction
Aco.	**0.817** + 0.046 - 0.045	**0.815** + 0.043 - 0.042
ΔpT	**0.880** + 0.117 - 0.117	**0.770** + 0.104 - 0.102
pT(μμ)	**0.884** + 0.055 - 0.054	**0.767** + 0.049 - 0.048
CMS values	0.91	0.73



Electron channel

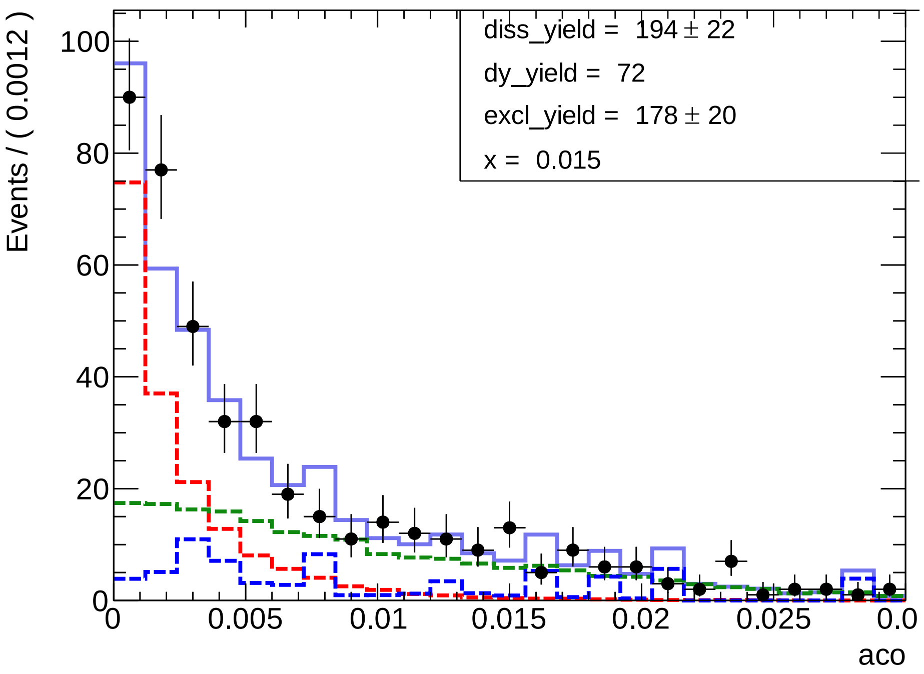
- Dielectron selection:
  - Medium++ electrons
  - $\mathbf{p_T^e > 12}$ **GeV**, $|\eta_e| < 2.4$, $\mathbf{M_{ee} > 24}$ **GeV**
  - Also working in the trigger turn-on region

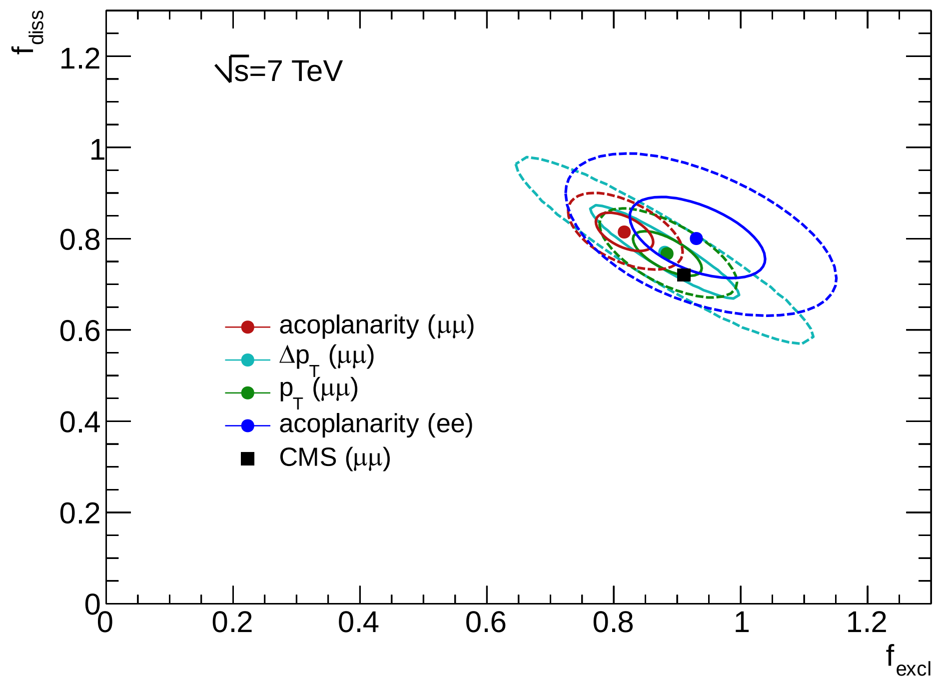




Electron channel

- Same procedure to extract scaling factors (RooFit)
- Due to the lower statistics in this channel extraction possible only with acoplanarity distribution





Systematics

- Systematics related with muons (similar for electrons):
  - Momentum resolution / energy scale
    - `MuonMomentumCorrections` package is used -> **0.5 %** effect on exclusive yield
  - Reconstruction efficiency
    - `MuonEfficiencyCorrections` package is used -> **0.2 %** effect on exclusive yield
  - Muon Trigger efficiency
    - Evaluated using SF's uncertainties -> **0.3 %** effect on exclusive yield
- Pileup correction / exclusivity cut
  - Varying the nominal 3 mm veto distance from 2 to 4 mm -> **3.3 %** effect
- Nonzero beam crossing angle:
  - Boost of the dimuon system in the y direction -> **0.3 %** effect
- Background uncertainties:
  - DY part varied by ± 10% to check the impact of this contribution -> **1.4 %** effect

- Work is still ongoing on this part…

Summary (Exclusive dileptons)

- $\gamma\gamma \rightarrow \ell^+\ell^-$ is an important process to cosider to achieve high precision measurement of DY
- Potential source of background for any other dilepton analysis

- Analysis is based on full 2011 pp dataset (both muon and electron channels)

- Exclusive cross section extracted, first results on the photon PDF in the proton

- Supporting note almost ready (we will ask for an Ed Board)

Conclusions / outlook

- Simulation of AFP detectors
  - 3 internal notes written in order to document all the details / algorithms
  - This work is also a support for simulation of exisiting forward detectors

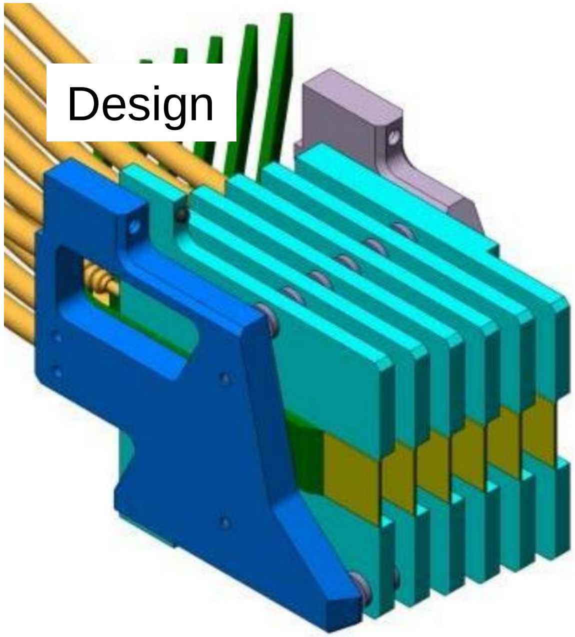
- Exclusive dileptons analysis
  - Analysis is well advanced
  - <u>Editorial Board will be set up soon</u>
  - Long-term prospect: exclusive diboson analysis

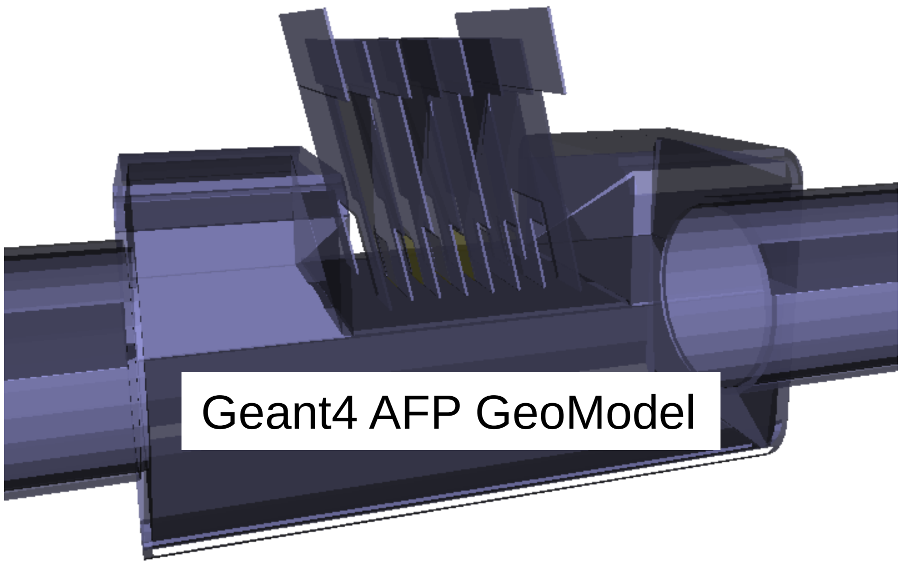
- <u>In parallel</u>: finalization of Pb-Pb forward-backward correlations analysis (2010 ATLAS data)
  - Testing the physics of particle production in heavy ion collisions
  - <u>Ed Board already set up</u>

Backup

Simulation Setup

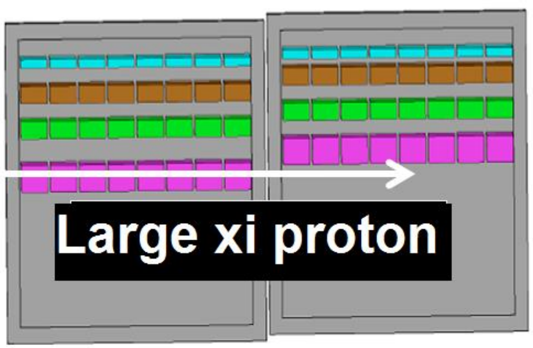
- Actual SiD setup:
  - 2 AFP stations with Si detectors per ATLAS side (**SiD 0 - 1** <– **IP** –> **SiD 2 - 3**)
  - 6 Si layers/station separated by 10 mm (13 deg tilt in the x-z plane)
  - No staggering of the layers (yet)
  - 336 x 80 array of **50 x 250** μm^2 pixels per layer
  - **Kalman filter** is used for the tracking reconstruction

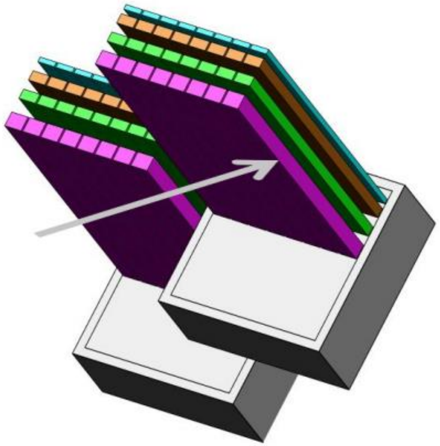


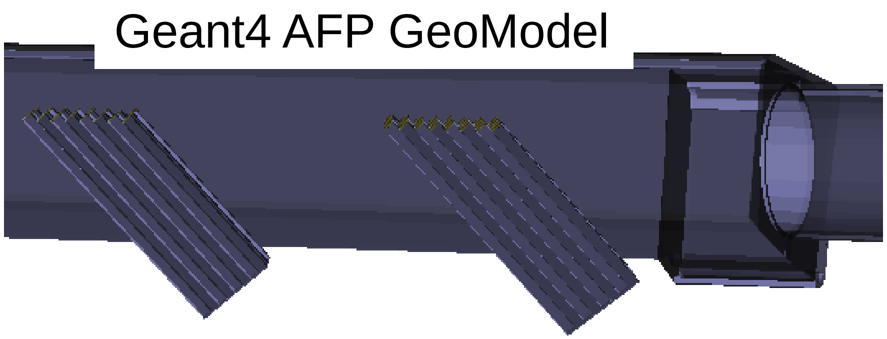


Simulation Setup

- Actual TD Setup:
  - 2 staggered (non overlapped) Timing Detectors per side, placed in the outer stations (AFP 212)
  - 4 trains with 8 bars /detector configuration
  - Straight Qbar geometry ($\theta_c \approx 48$ deg, 2mm x 6mm x 150 mm)
  - Fast Cherenkov algorithm developed to transport optical photons in Geant4 (≈ 100 times faster wrt full G4 simulation!)

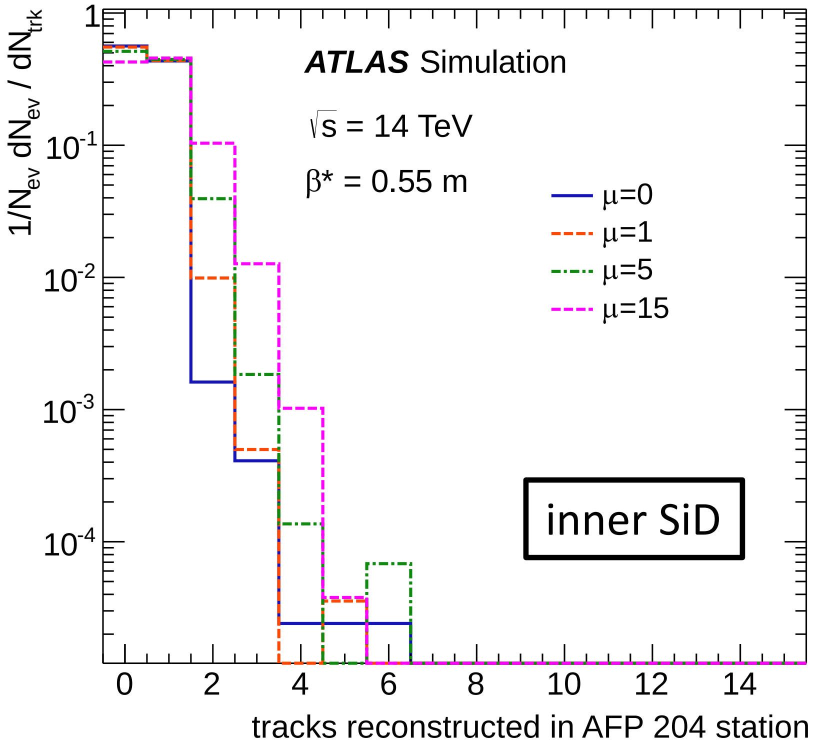


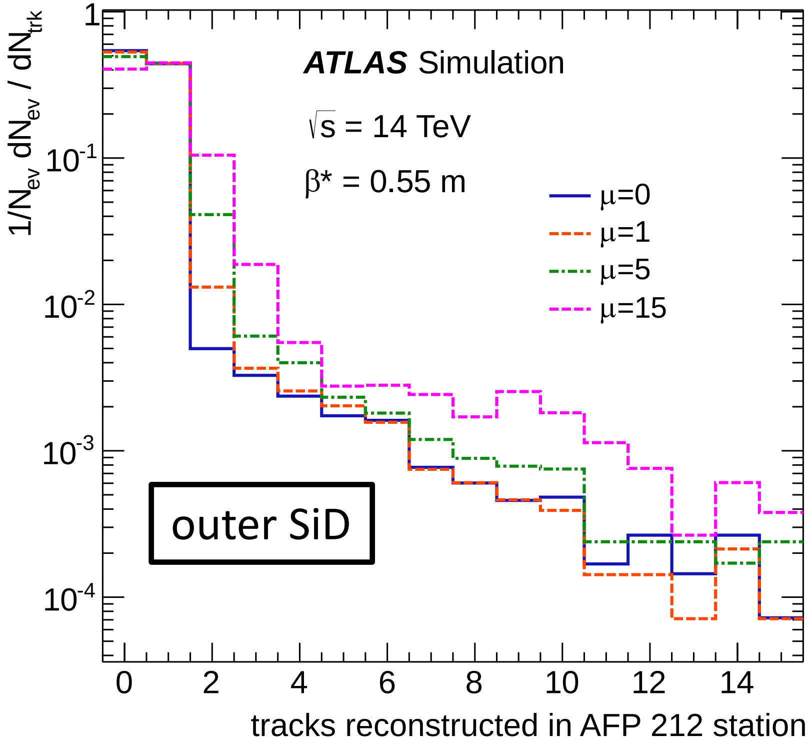




AFP SiD performance

- **Reconstructed track multiplicity** with $|x_{slope}| < 0.003$ and $|y_{slope}| < 0.003$ cut (per station) to separate proton tracks from showers
- Events are generated without any cut on the proton kinematics (i.e. $\xi < 1$)
- Approximately **50%** of protons in the sample **do not enter** the AFP acceptance region (**$0.015 < \xi < 0.15$**) which results in no reconstructed tracks





Backup

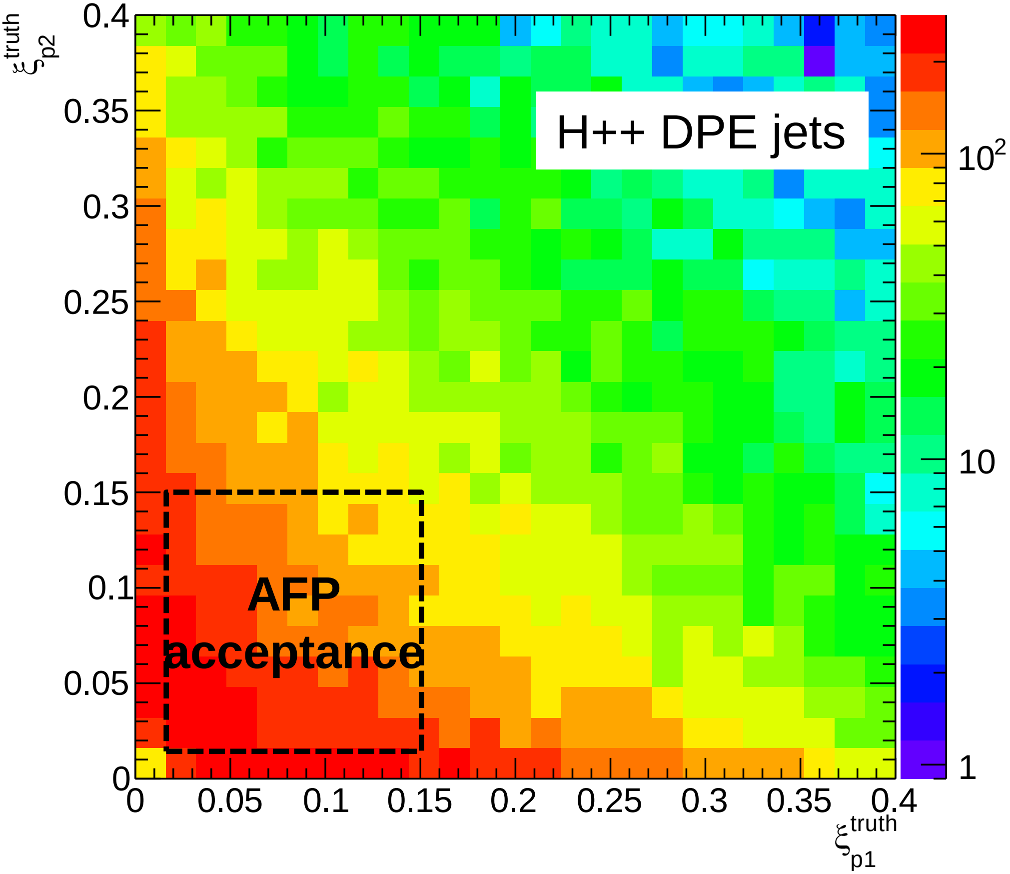
- AFP SiD tracking cuts:
  - Tracks are reconstructed when $N_{pix} < 1000$ (per station)
  - Trk_quality > 6 $\left(quality = N_{hits} + \frac{chi2_{\text{max}} - chi2_{trk}}{chi2_{\text{max}} + 1}\right.$, with $chi2_{max}$ = 2.0 and cut on $chi2_{trk}$ = 2.0)
  - |Trk_x_slope| < 0.003, |Trk_y_slope| < 0.003
  - **Trk_n = 1 / station** (**Trk_n ≤ 2** in inner + **Trk_n ≤ 5** in outer station as a pileup robust setup)
  - $|Trk_x_{SiD0} - Trk_x_{SiD1}| < 1.5$mm
  - $|Trk_y_{SiD0} - Trk_y_{SiD1}| < 1.5$mm

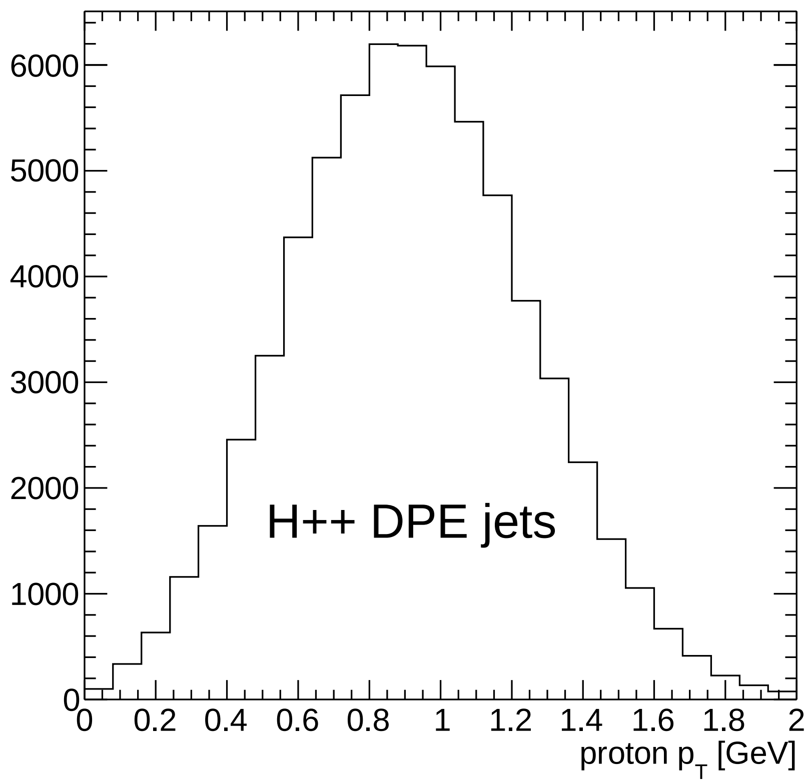
  (same for the other pair of stations)

- AFP TD cuts:
  - Signal: 1 train with **8 fired** and **≤ 4 saturated** bars (per side)
  - Pile-up robust setup: **≤ 2** trains with SiD+TD geo matching (wrt track x position)

Backup

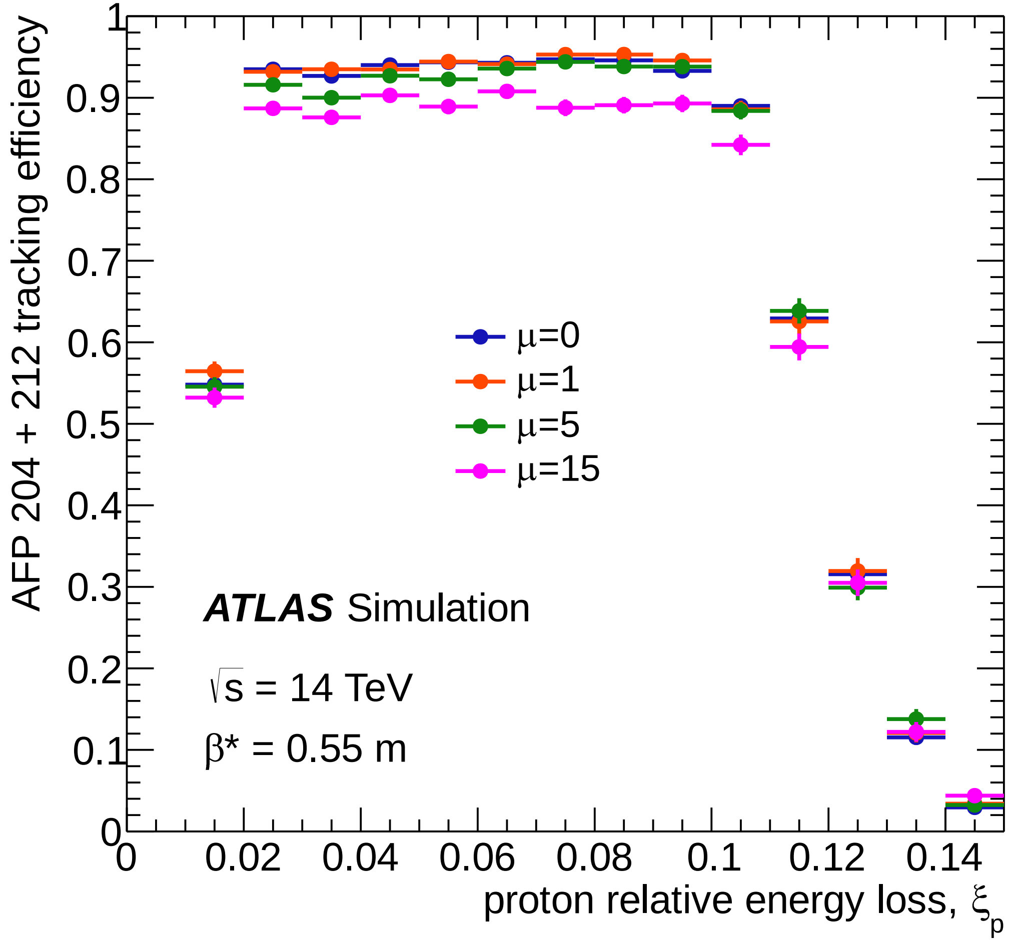
- 4 x 30k **HERWIG++** DPE jets sample (with 20 < p_T^{jet} < 80 GeV cut)
- Different pile-up conditions: **μ = 0** (signal only), **1, 5, 15**
- Pile-up events are generated using **PYTHIA8**





AFP SiD performance

- **AFP proton track reconstruction efficiency** for different pile-up scenarios
- **≈ 95%** in **$0.02 < \xi < 0.11$** and **$\mu = 0/1$**
- Tracks matched between the inner (AFP 204) and outer (AFP 212) stations are included
- Events with track multiplicity ≤ 2 in inner and track multiplicity ≤ 5 in outer station are considered
- Optimization of cuts will further improve the tracking efficiency



AFP TD performance

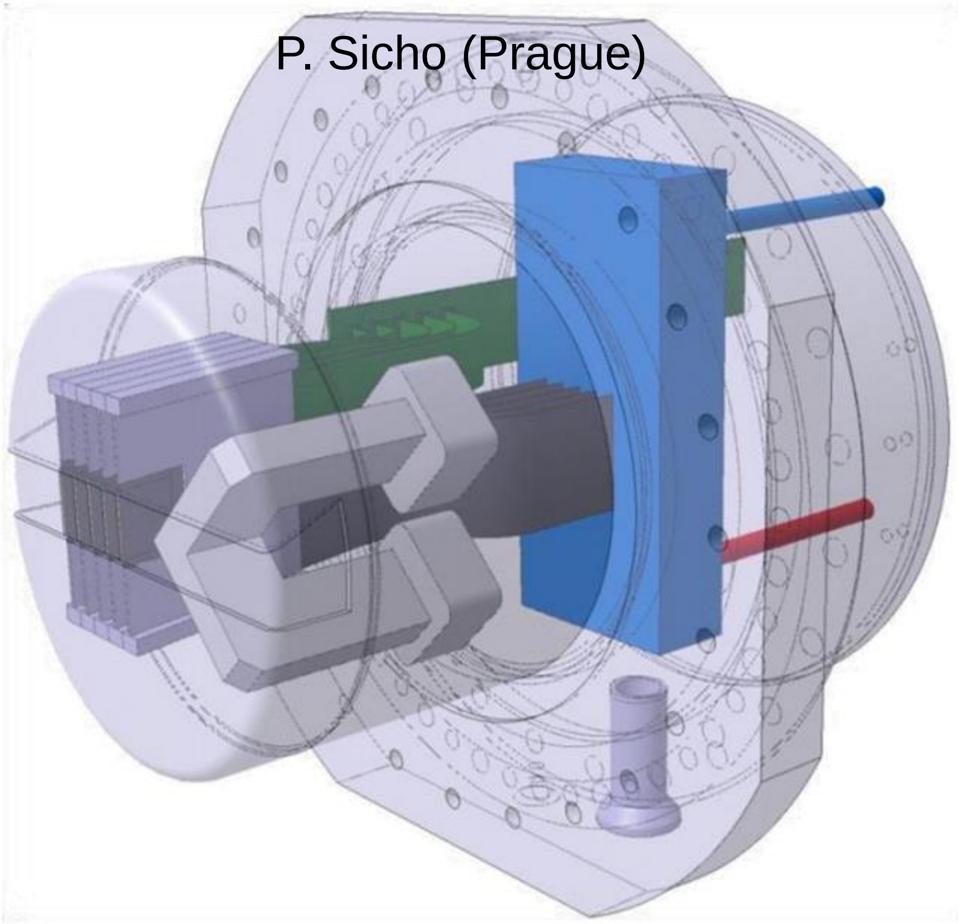
- SiD + TD combined efficiency in the range **$0.02 < \xi < 0.11$**:
  - ≈ **85%** for **μ = 0/1**
  - ≈ **80%** for **μ = 5**
  - ≈ **77%** for **μ = 15**
- SiD + TD geo matching included
- TD ToF correction for the reconstructed track y position is also applied
- Agreement with the previous studies and expectations, e.g. for low μ:
  - TD eff. = 90% (2% ineff./ bar + 3% for rest of material)
  - SiD eff. = 95%

  } SiD eff. * TD eff. = 85%

- TD z-vertex reconstruction resolution for double tag events:
  - **2.3 mm** resolution for low μ case
  - This value corresponds to **10 ps** TOF resolution per TD station

AFP simulation: plans, prospects

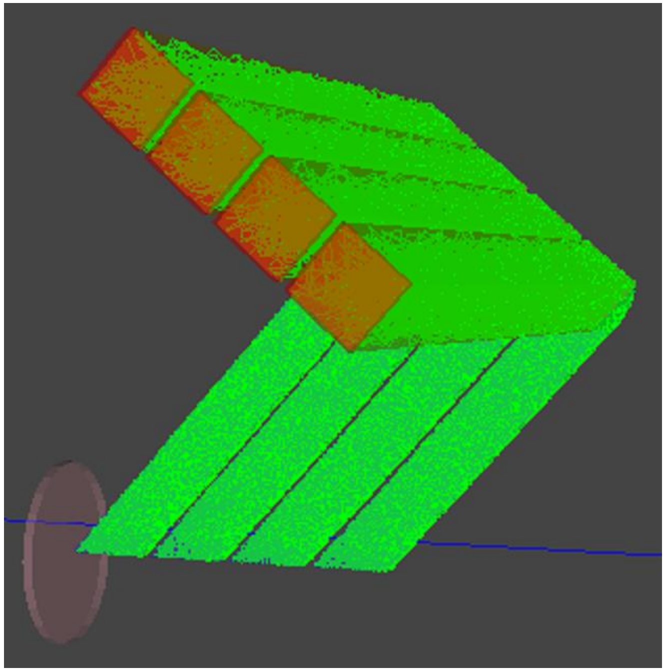
- Migration to Roman Pots configuration
- First Geant4 GeoModel of AFP Pot is ready

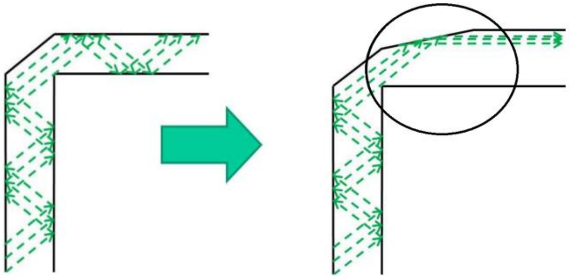


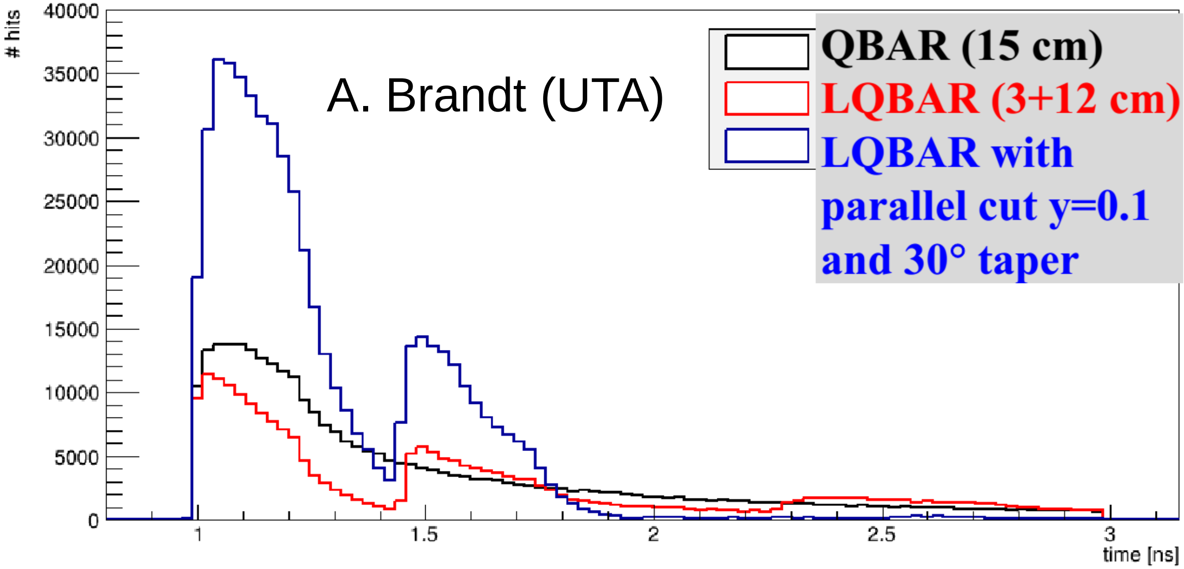
- <u>SiD</u>: study the optimal number of layers (depends on space available in RP, dead material, resolution achieved, ...)
- <u>TD</u>: prepare the LQbar design of ToF detectors
- Implement a new version of Fast Cherenkov algorithm – speeding up the simulation

Backup

- Standalone Geant4 simulation of LQbars – very promising results
- New ideas for a ’’taper’’ to speed up the 2nd peak
- 2-3 times more light in the same time window as the Qbar case







Backup

- Kalman filter - **optimal estimator** of the state vector of a linear dynamical system <- minimization of the mean square estimation error
- State vector $\boldsymbol{x}_k$:

$$\boldsymbol{x}_k \equiv \boldsymbol{F}_{k-1}\boldsymbol{x}_{k-1} + \boldsymbol{w}_{\mathrm{k}-1}$$

  - $\boldsymbol{F}_{k-1}$ - track propagator from layer *k-1* to *k*
  - $\boldsymbol{w}_{\mathrm{k}-1}$ - process noise (e.g. multiple scattering)
- Track parametrization for AFP SiDs -> 2D position + slopes:
  - $\boldsymbol{x}_k = \left(x_k, \frac{dx_k}{dz}, y_k, \frac{dy_k}{dz}\right)^T$
  - $\boldsymbol{F}_{k-1} = \begin{pmatrix} 1 & \Delta z_k & 0 & 0 \\ 0 & 1 & \Delta z_k & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$, Δz_k - distance between layers *k* and *k-1*

Backup

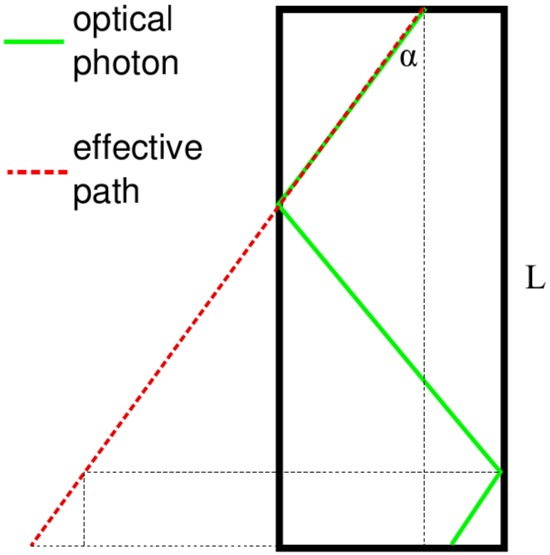
- Generation and transportation of optical (Cherenkov) photons in GEANT4 is very **time-consuming**
- Main idea of Fast Cherenkov algorithm:
  - Generation of Cherenkov photons w.r.t. known formulas , e.g. the number of photons per cm of radiator:

$$dN = 370 \cdot Z^2 \left[\frac{\text{photons}}{\text{eV} \cdot \text{cm}}\right] \left(1 - \frac{1}{\beta^2 \cdot n^2(\epsilon)}\right) d\epsilon dx$$

  - Transportation - multiple reflections of photons inside the quartic bar
    -> Calculation of **effective path length**
    -> Calculation of time

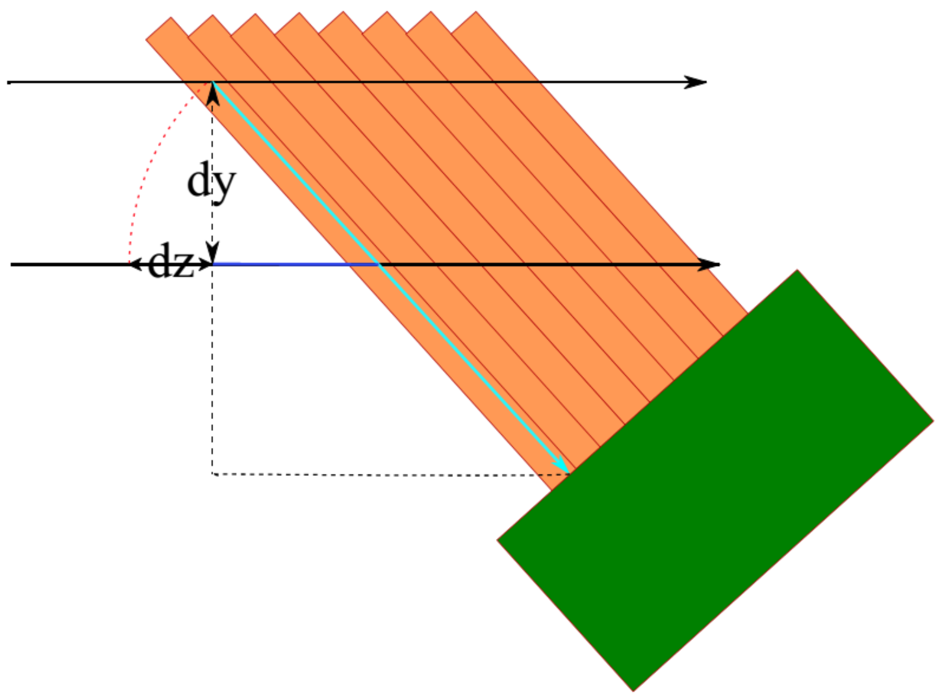
2D: $$L_{\text{eff}} = \frac{L}{\cos\alpha}$$

3D: $$L_{\text{eff}} = \frac{y_0}{\cos\alpha \cdot \cos\delta}$$



Backup

- TD ToF correction for the trk_y position
- $\frac{dt}{dy} = \frac{n/\sin\theta_{ch} - 1/\tan\theta_{ch}}{c} \approx 3.7$ [ps/mm]

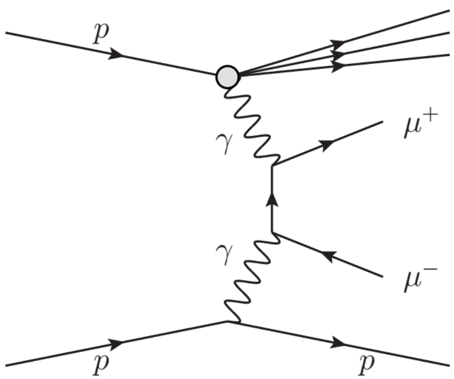


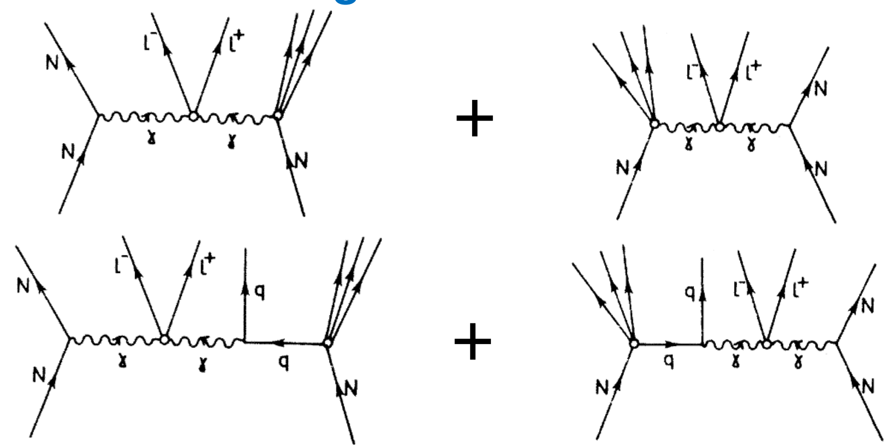
Backup

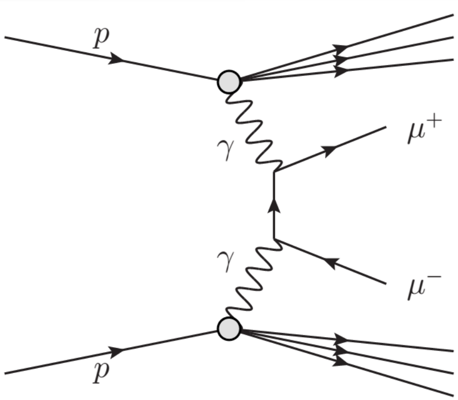
Photons in the proton(s) can also couple to quark/anti-quarks (diagrams below)

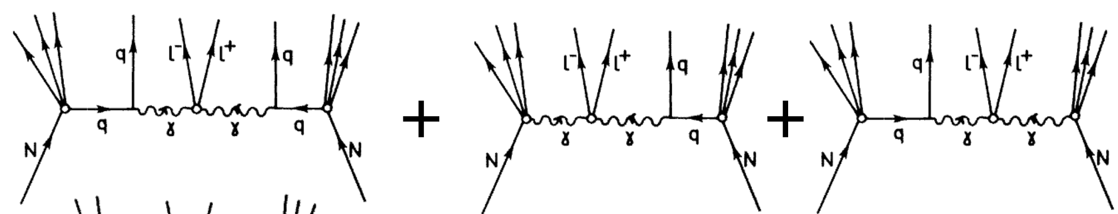
- Calculations need to be done using QED corrections: like PDF MRST2004QED
- here <Q²> depends also on the partons momenta => spread in Delta_pT of the muons, very subtle check of the proton structure

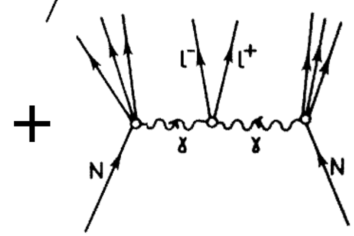
Single dissociation







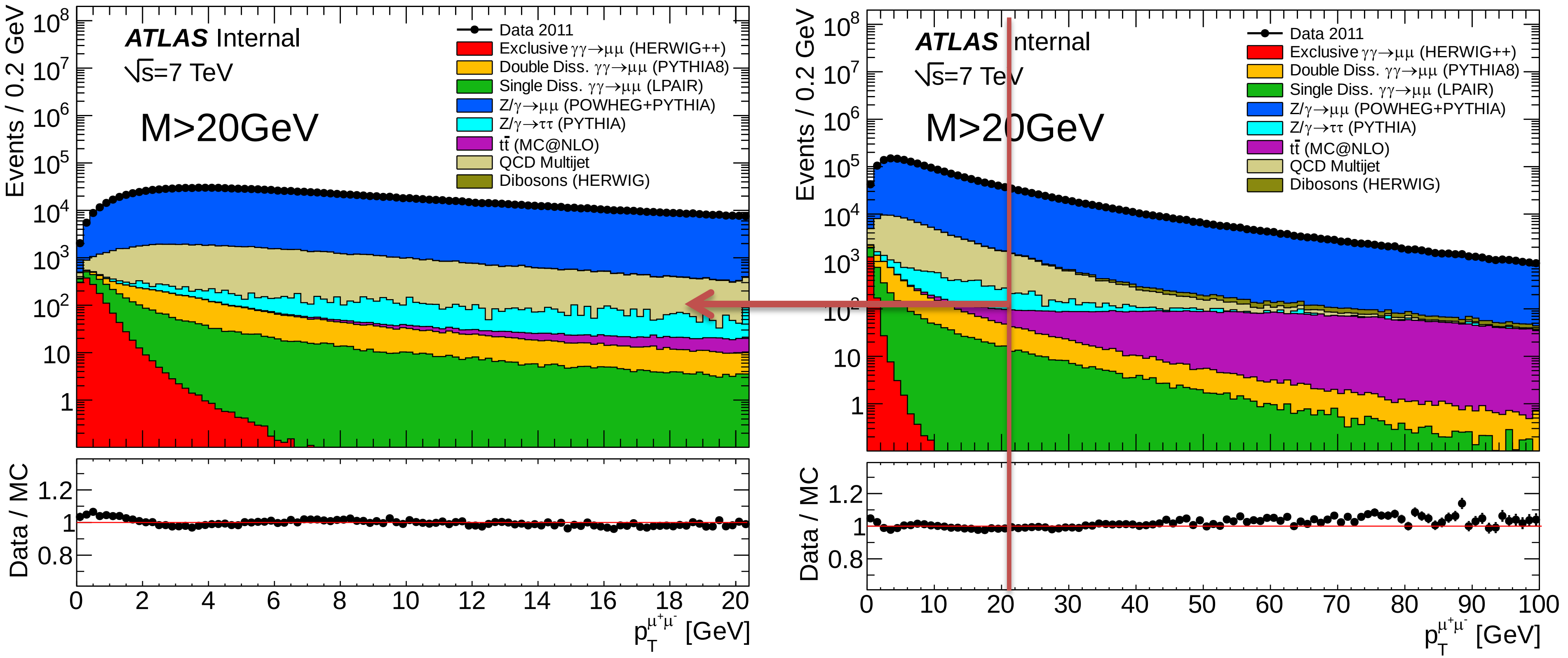




Double dissociation

Backup

- Z boson transverse momentum analysis
  - Up to 1% contribution in the first pT(Z) bins



Backup

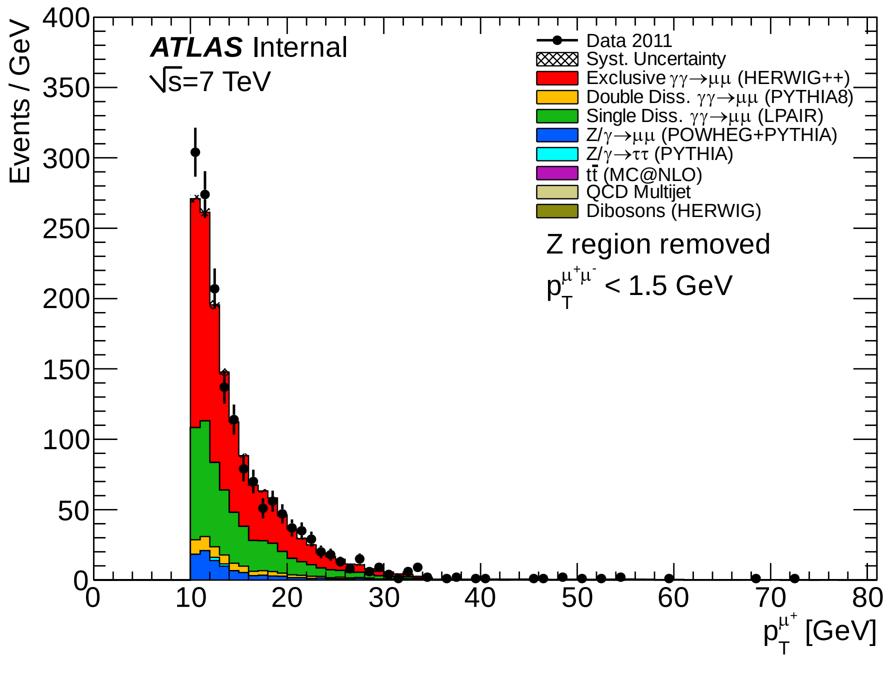
2011 Period	Muon Triggers
B-I	EF_2mu10_loose || EF_mu18_MG
J	EF_2mu10_loose || EF_mu18_MG_medium
K	EF_2mu10_loose || EF_mu18_MG_medium
L-M	EF_2mu10_loose || EF_mu18_MG_medium

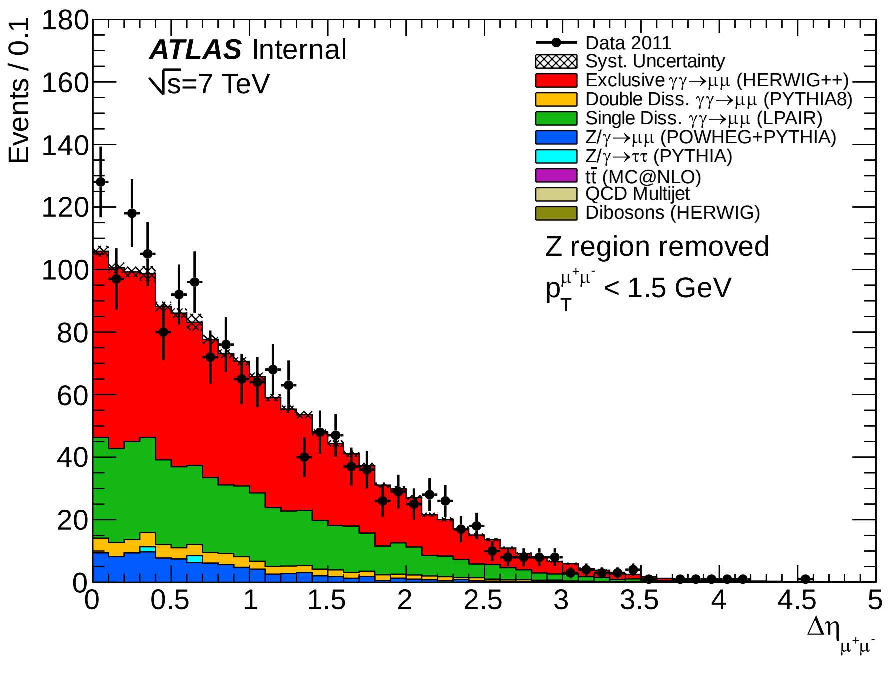
2011 Period	Electron Triggers
B-I	EF_2e12_medium || EF_e20_medium
J	EF_2e12_medium || EF_e20_medium
K	EF_2e12T_medium || EF_e22_medium
L-M	EF_2e12Tvh_medium || EF_e22vh_medium1

- Note: dilepton triggers prescaled in periods K-M (≈ 66% of 2011 int. lumi)

Muon channel

- 1778 events after all selection criteria





Backup

- Double-diss PYTHIA8 (MRST2004QED) vs LPAIR comparison (**after** scaling factors imposed)
- pT($\mu^+\mu^-$) description:
  - At low pT's LPAIR gives better agreement (left)
  - Higher pT's: PYTHIA8 is better (right plot)