Latest result of Central Exclusive Production of J/ψ and ψ(2S) at 13 TeV in LHCb

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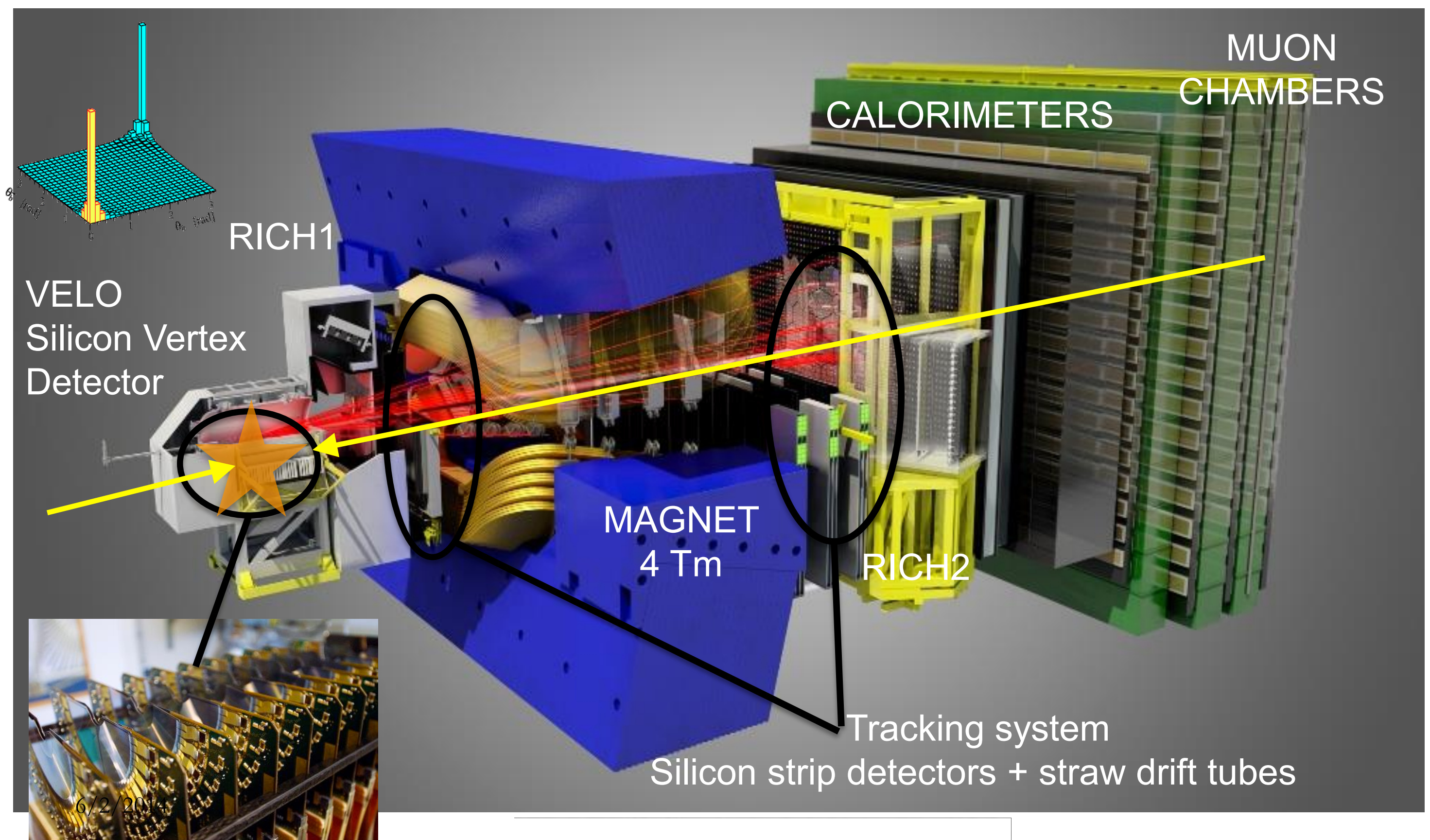
on behalf of the LHCb collaboration

In this talk:

How the use of an **additional** detector: **Herschel improves the LHCb results** in elastic Central Exclusive Production (CEP) processes

see: J.Phys. G41 (2014) 055002 (arxiv: 1401.3288v2)



LHCb: Single arm spectrometer dedicated to precision flavour physics

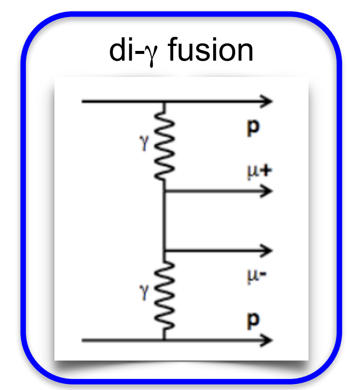
CEP elastic processes:

$$pp(\bar{p}) \rightarrow p + X + p(\bar{p})$$

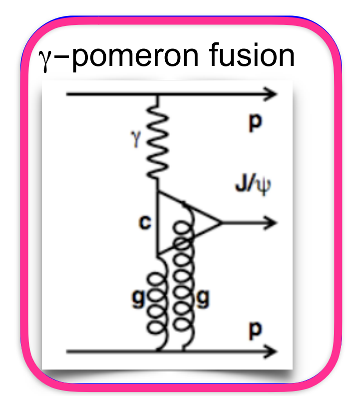
t-channel exchange of a colourless object

$$\gamma,\ \text{pomeron} \rightarrow \mathrm{X} + \text{rapidity gaps}$$

CEP elastic processes

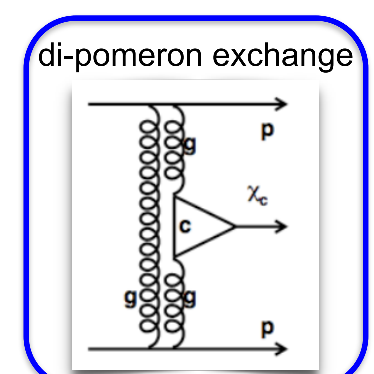


$\mu^+\mu^-$, e^+e^-, $\pi^+\pi^-$, W^+W^-



ρ, J/ψ, Υ, Z, …

In this talk



X_c, X_b, $\pi^+\pi^-$, Dijet, gg, …

The LHCb detector

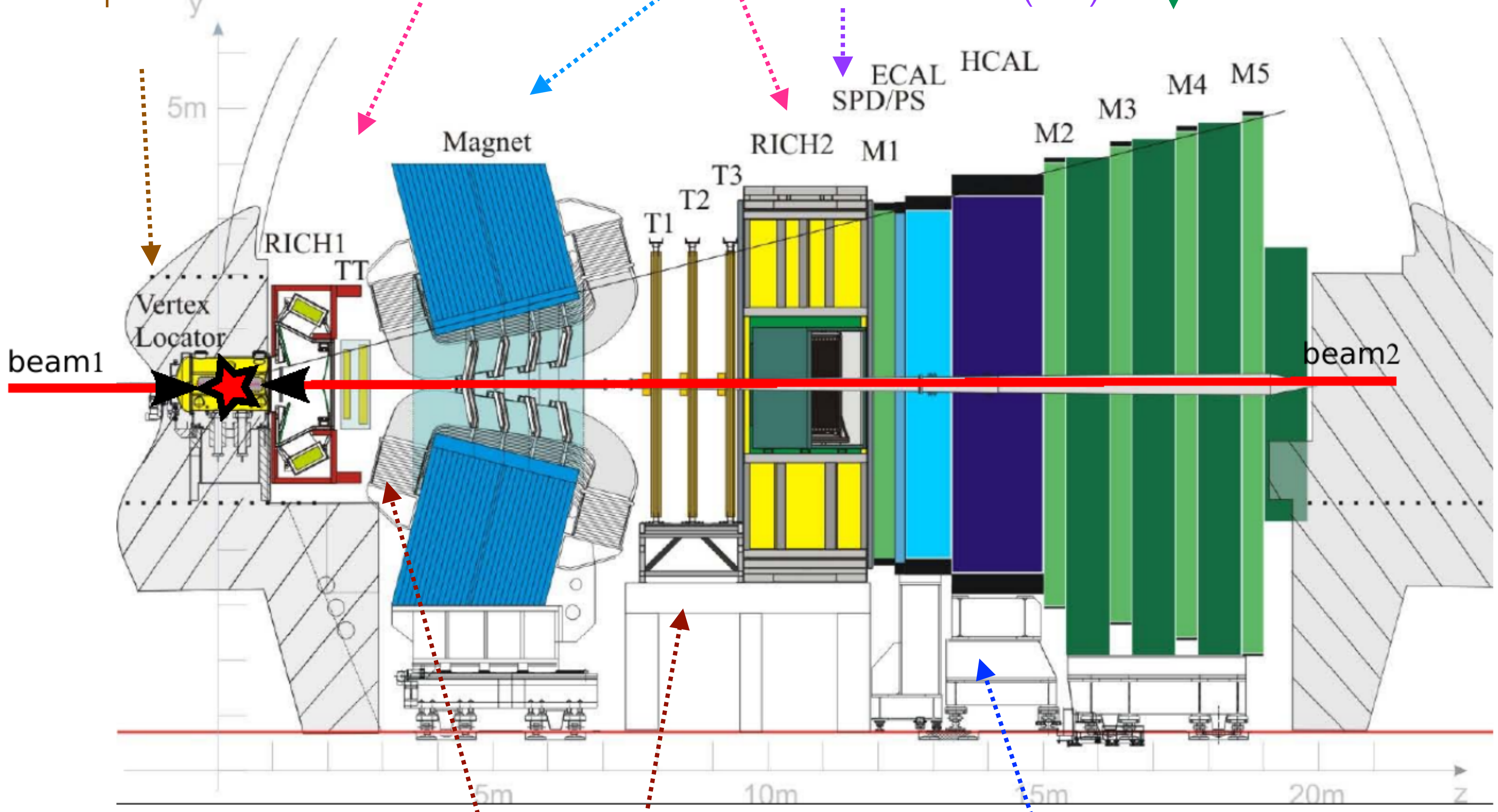
Magnet provides bending for momentum determination

Ring Imaging Cherenkov Detector for PID

Vertex Locator (VELO) around the interaction point

scintillating pad detector(SPD) and Preshower (PS)

Muon detectors



Tracking stations

$\Delta p/p = 0.4\%$ @ 5 GeV/c to 0.6% @ 100 GeV/c

Calorimeter

SPD/PS : id charged particle and separate e /γ

Very low pile-up

Precise vertex reconstruction: with a dedicated silicon detector (VELO) around the pp interaction point.

Excellent particle identification:

$\epsilon(K \to K) \approx 95\%$

$\pi \to K$ mis−id $\approx 5\%$

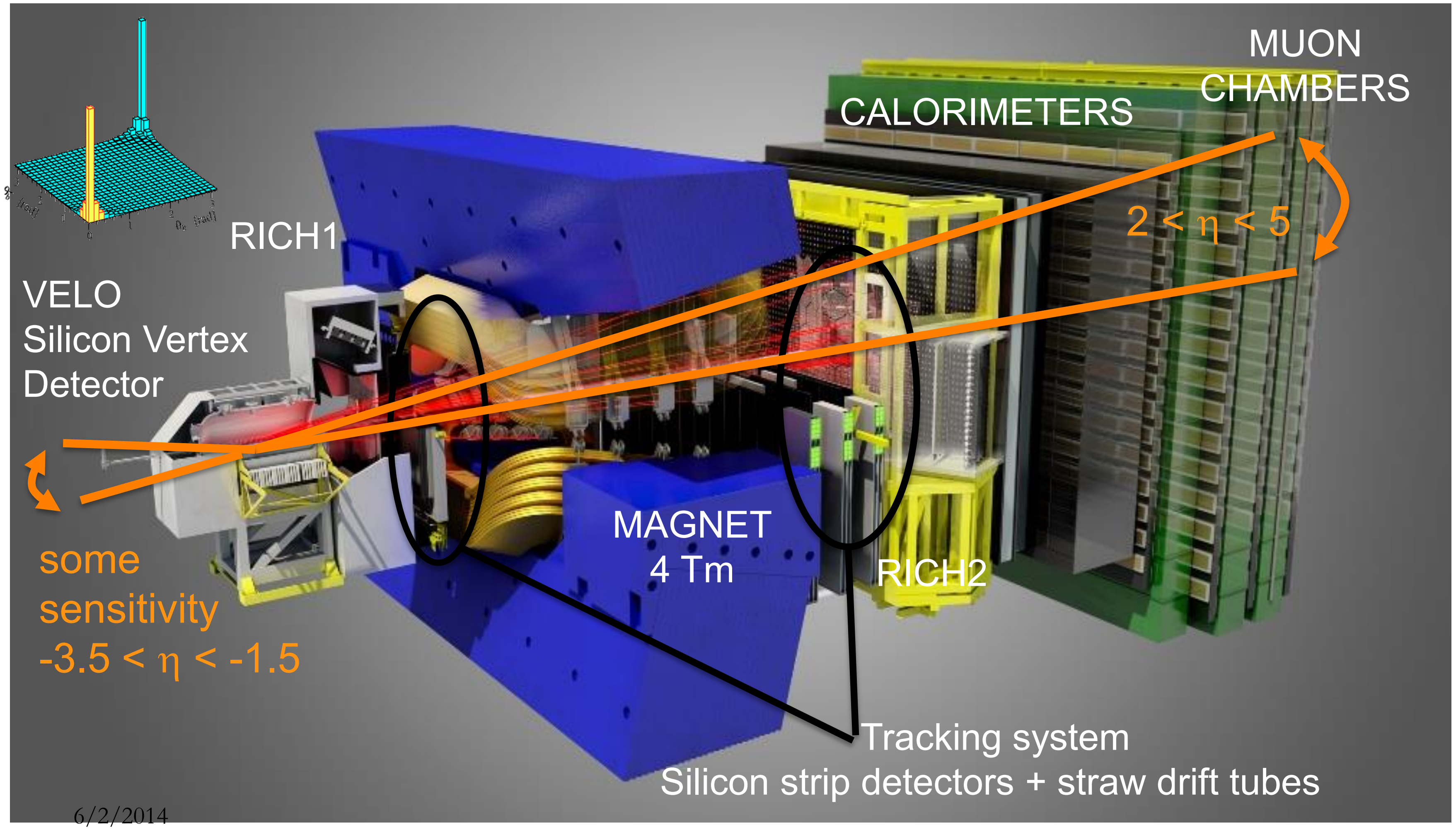
Clean muon id:

$\epsilon(\mu \to \mu) \approx 98\%$

$\pi \to \mu$ mis−id $\approx 1\%$

Excellent mass resolution: 7-20 MeV

Angular coverage and pseudo-rapidity

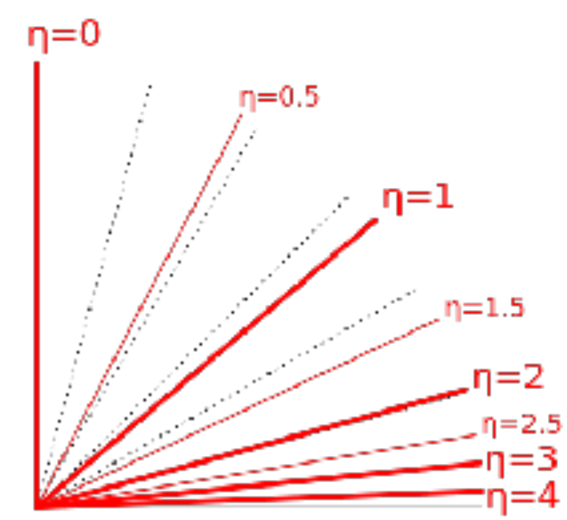


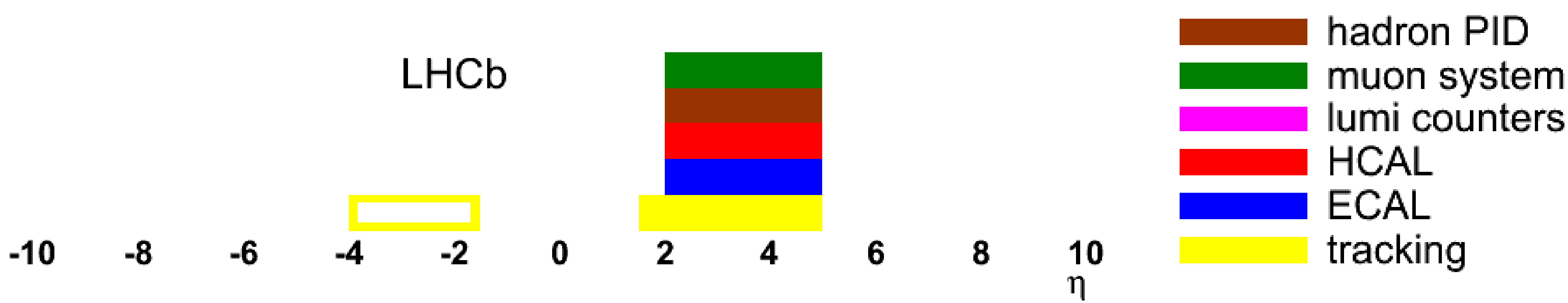
More information on the detector in the backup slides

pseudo-rapidity:

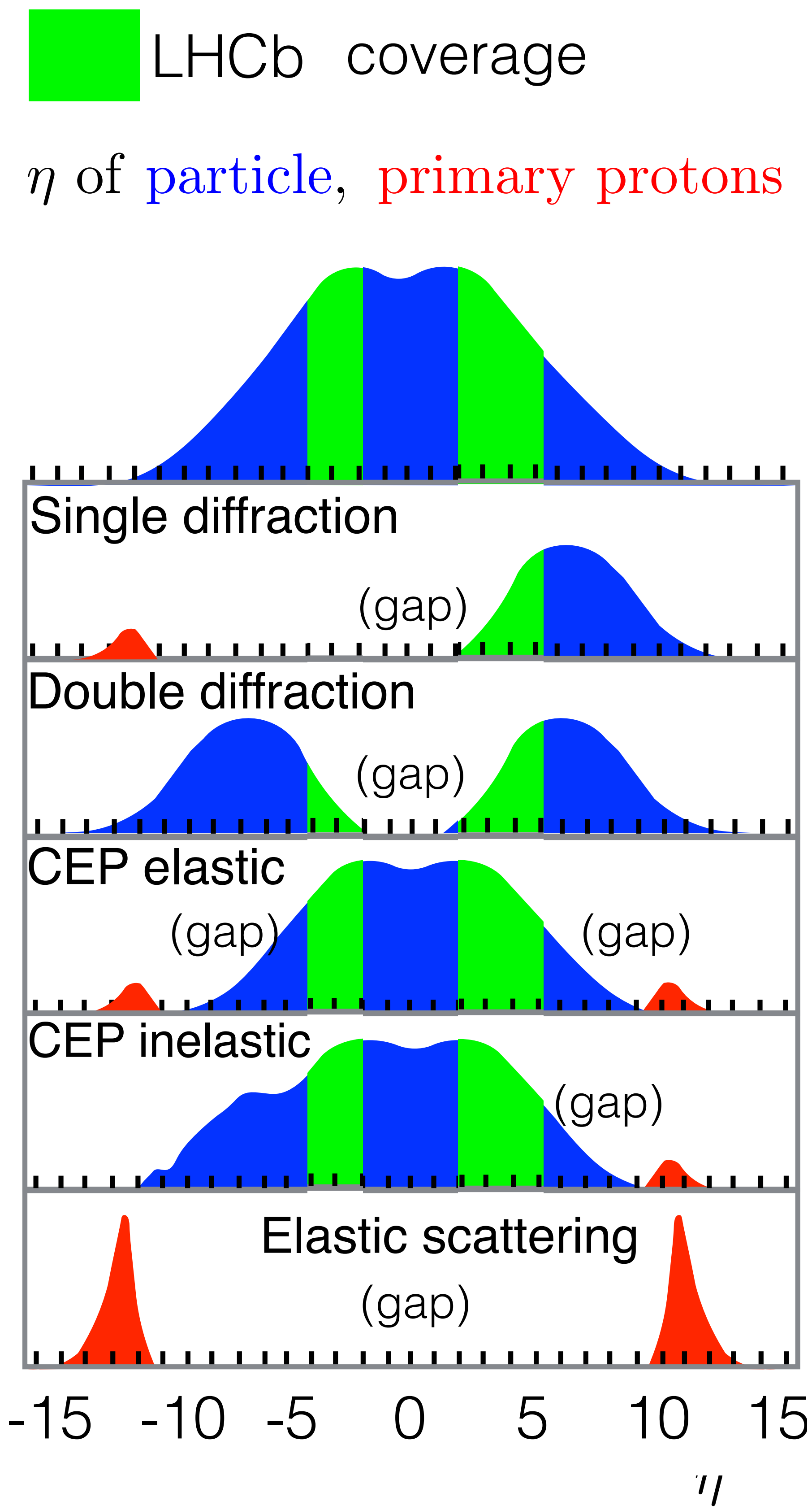
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

where θ is the angle between the particle momentum $\vec{p}$ and the beam axis



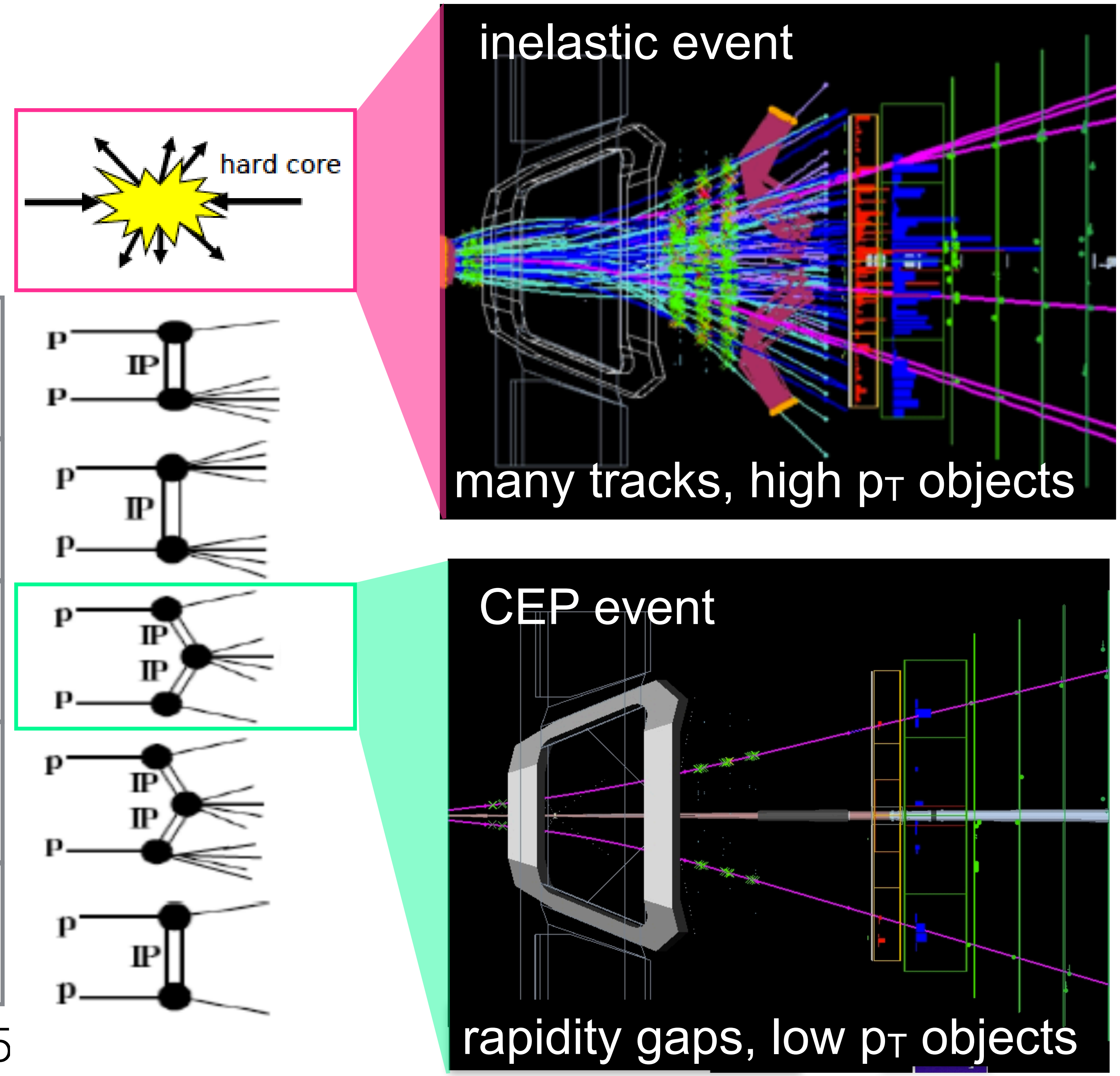


Pseudo-rapidity coverage & experimental signature

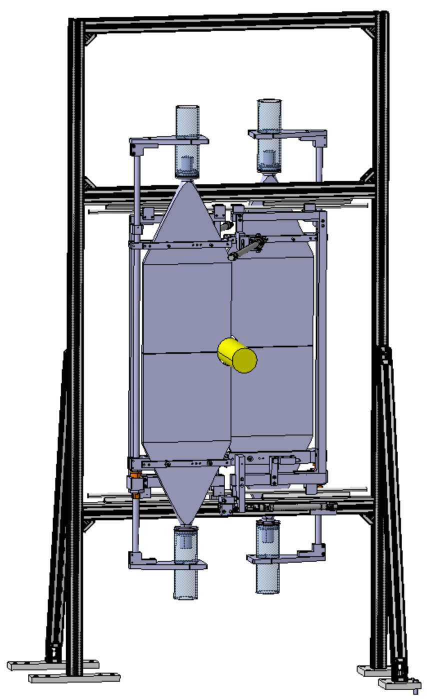


After D. d'Enterria arxiv 0806.0883

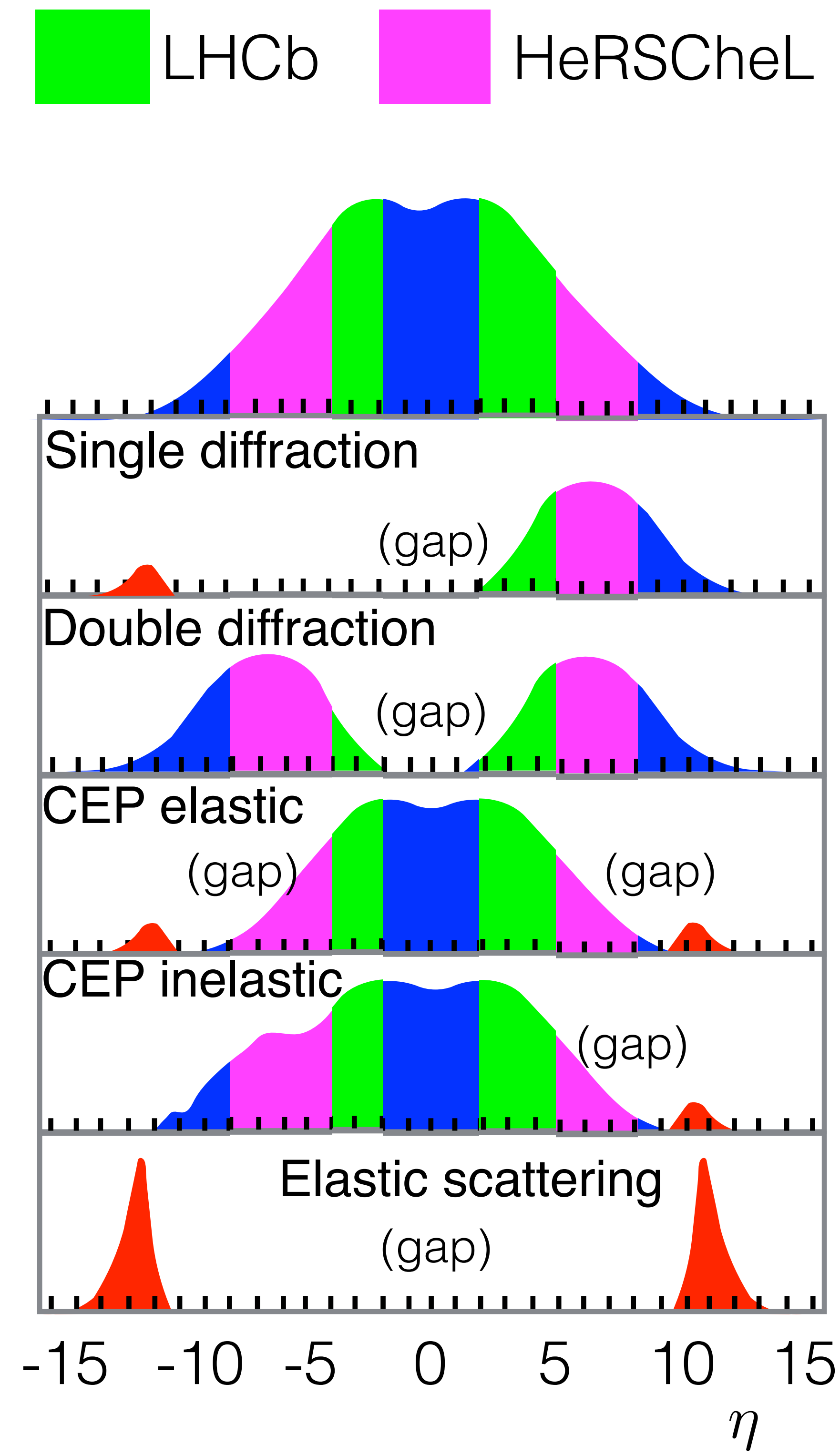
Example of LHCb events

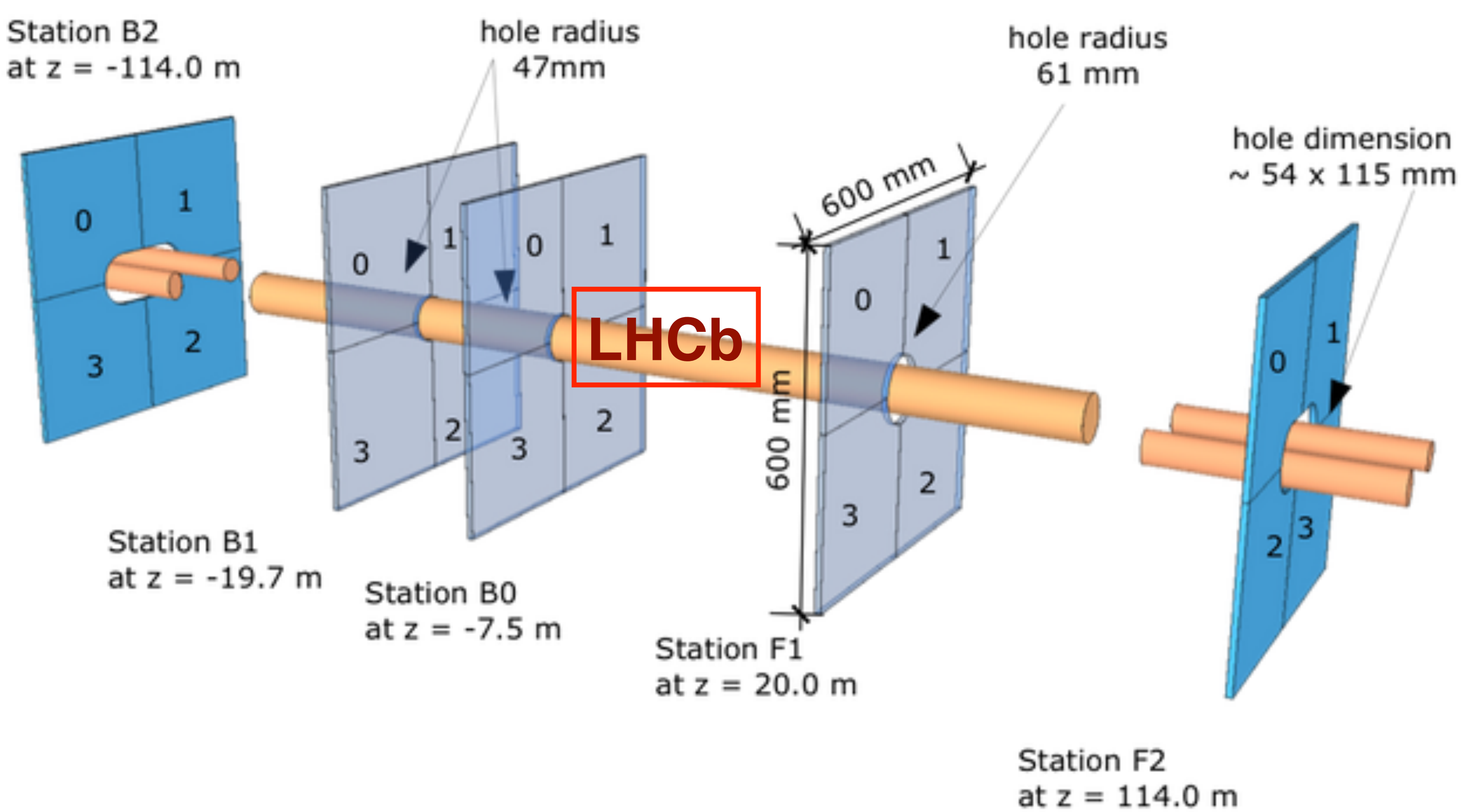


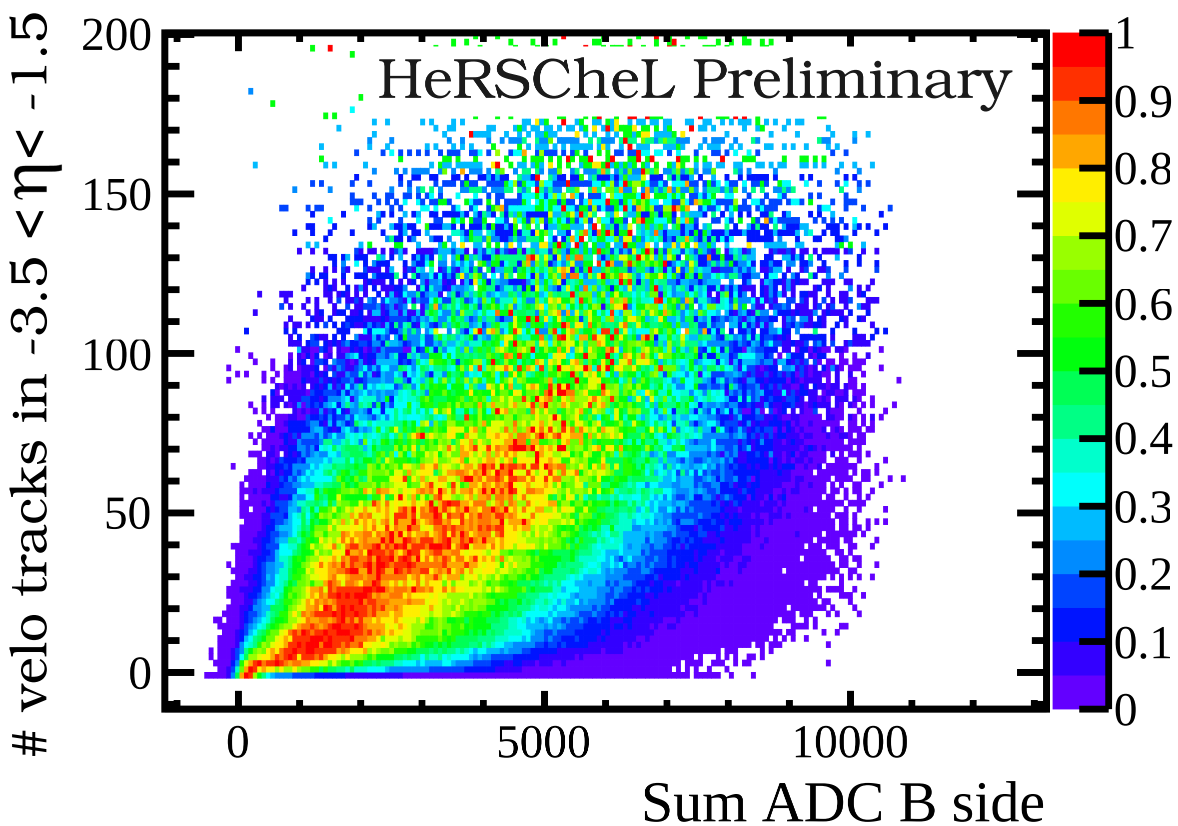
HeRSCheL detector = High Rapidity Shower Counter for LHCb

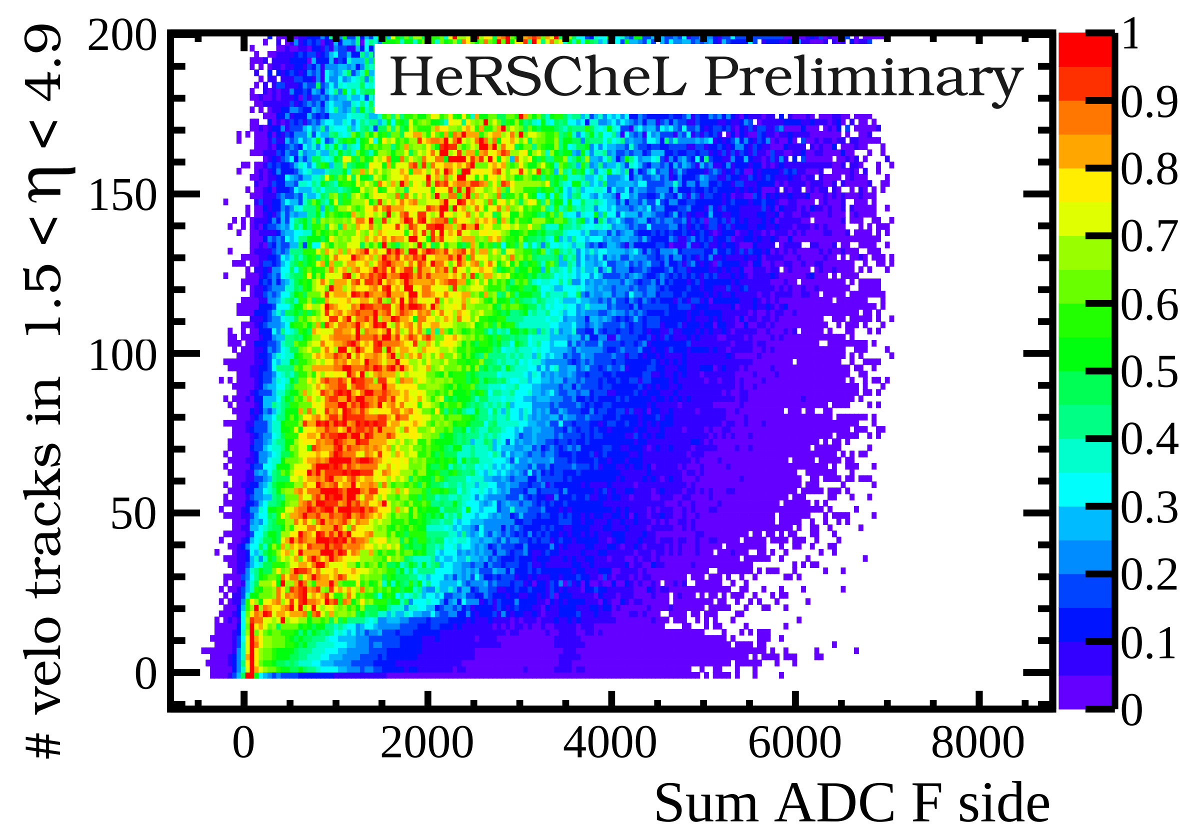


- Increase pseudo-rapidity coverage
  - ➡ to reduce background in CEP analyses
- 5 retractable stations:
  - with 20 scintillating shower counters
- Detect showers from high rapidity particles interacting with the beam-pipe elements









Visible correlation between VELO activity and Herschel activity

➡ More activity seen in Herschel when more tracks are reconstructed

Central exclusive photo production of J/ψ and ψ(2S) selection

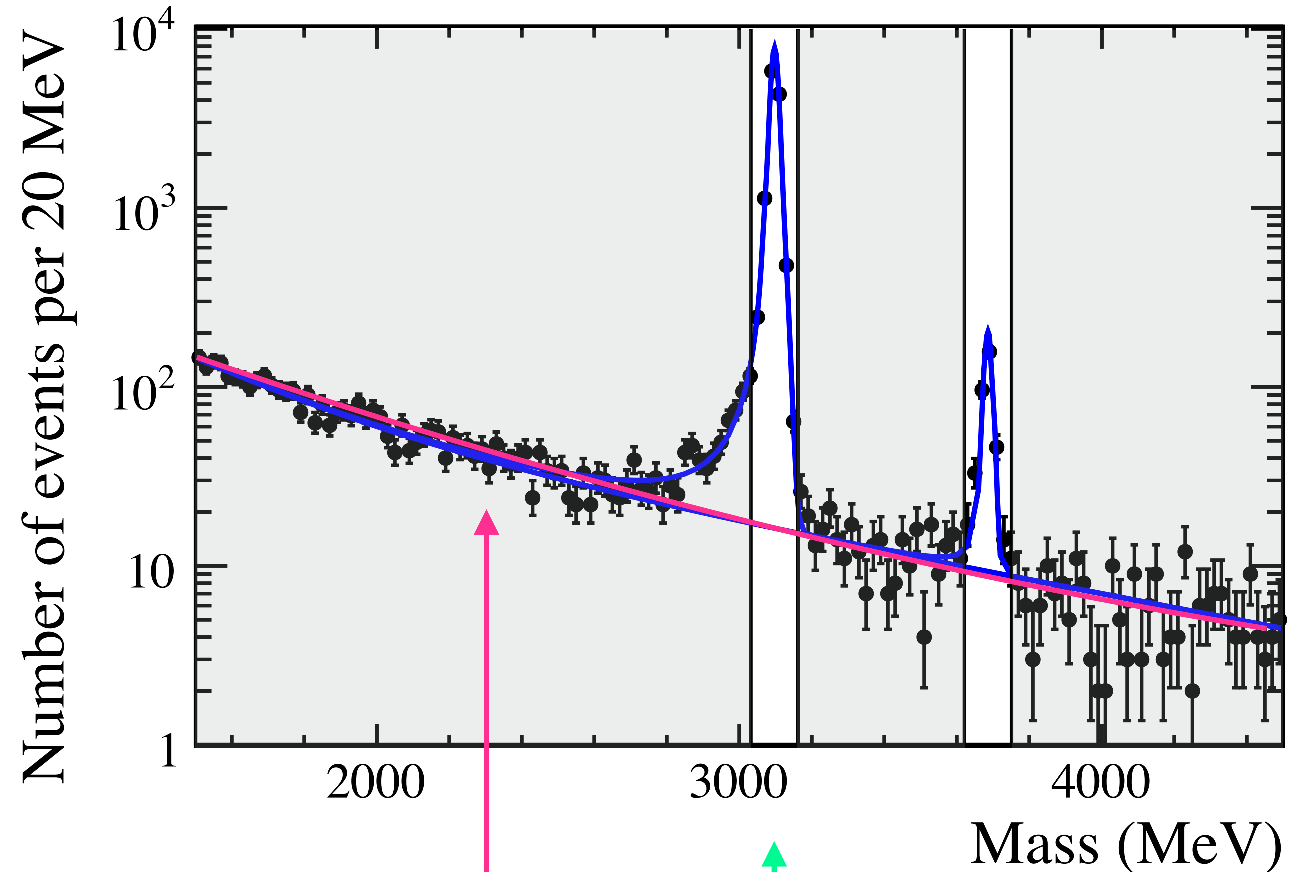
Consider exclusive process: $pp \to p + \mu\mu + p$

Charmonium selection:

- **2 reconstructed muons** with $2 < \eta < 4.5$
- **No additional tracks or energy**
- **Within 65 MeV/c² of the $m_{J/\psi}$**
- **Herschel VETO** (explained in the next slide)

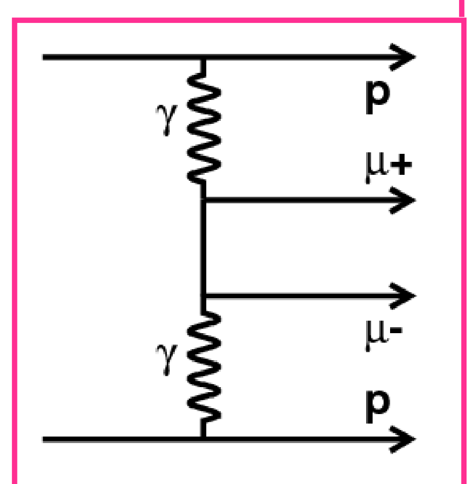
CEP γ-prod. J/ψ

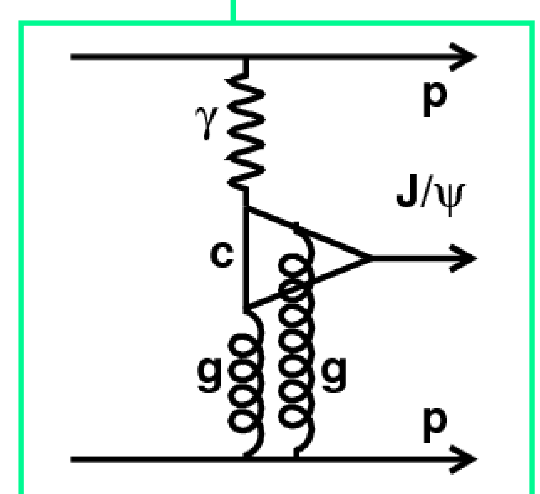
CEP γ-prod. ψ(2S)



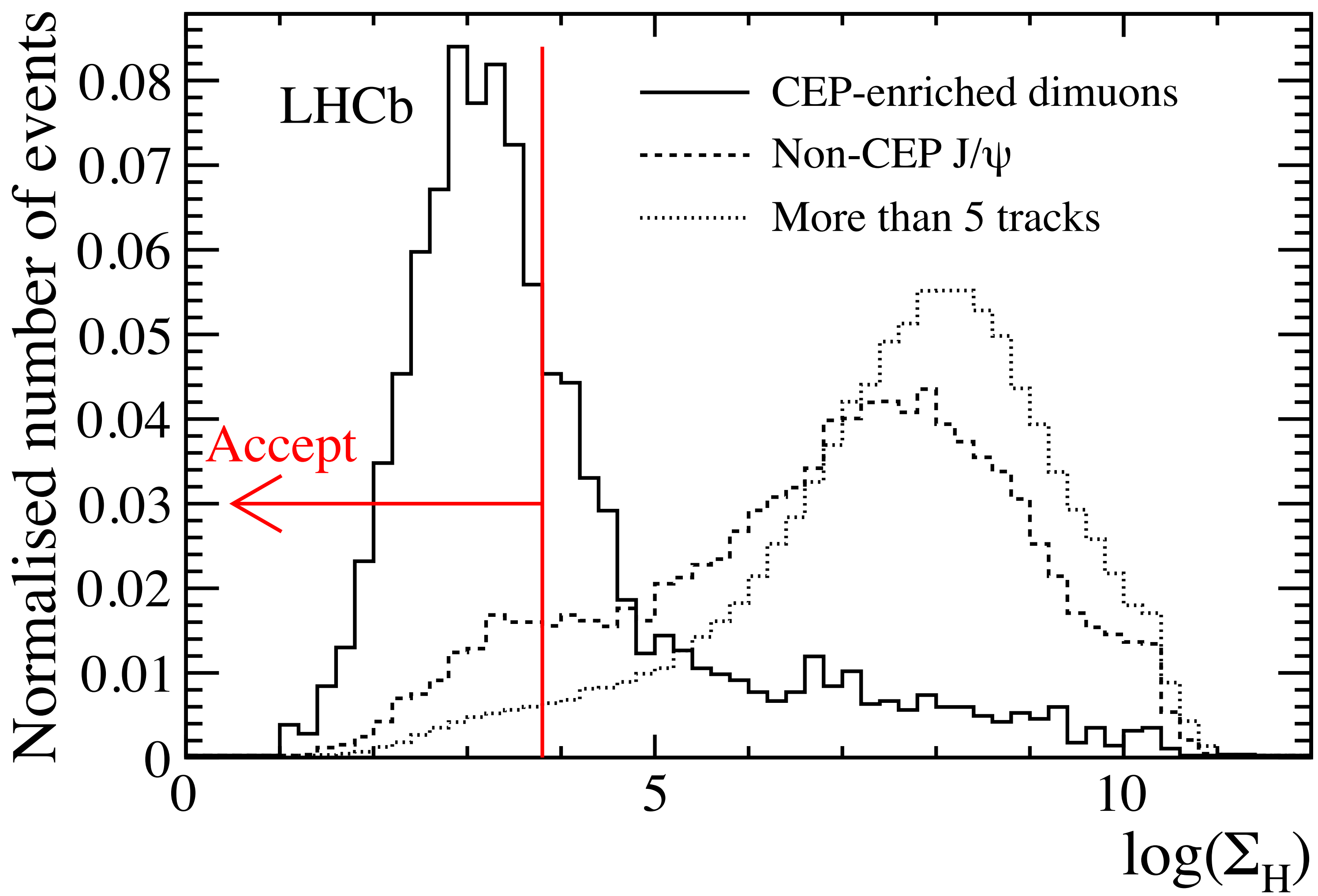
2015 dataset @13 TeV(200pb^{-1})+Herschel

Continuum lepton pair production
➡ Non Resonant Background
EM CEP(QED)





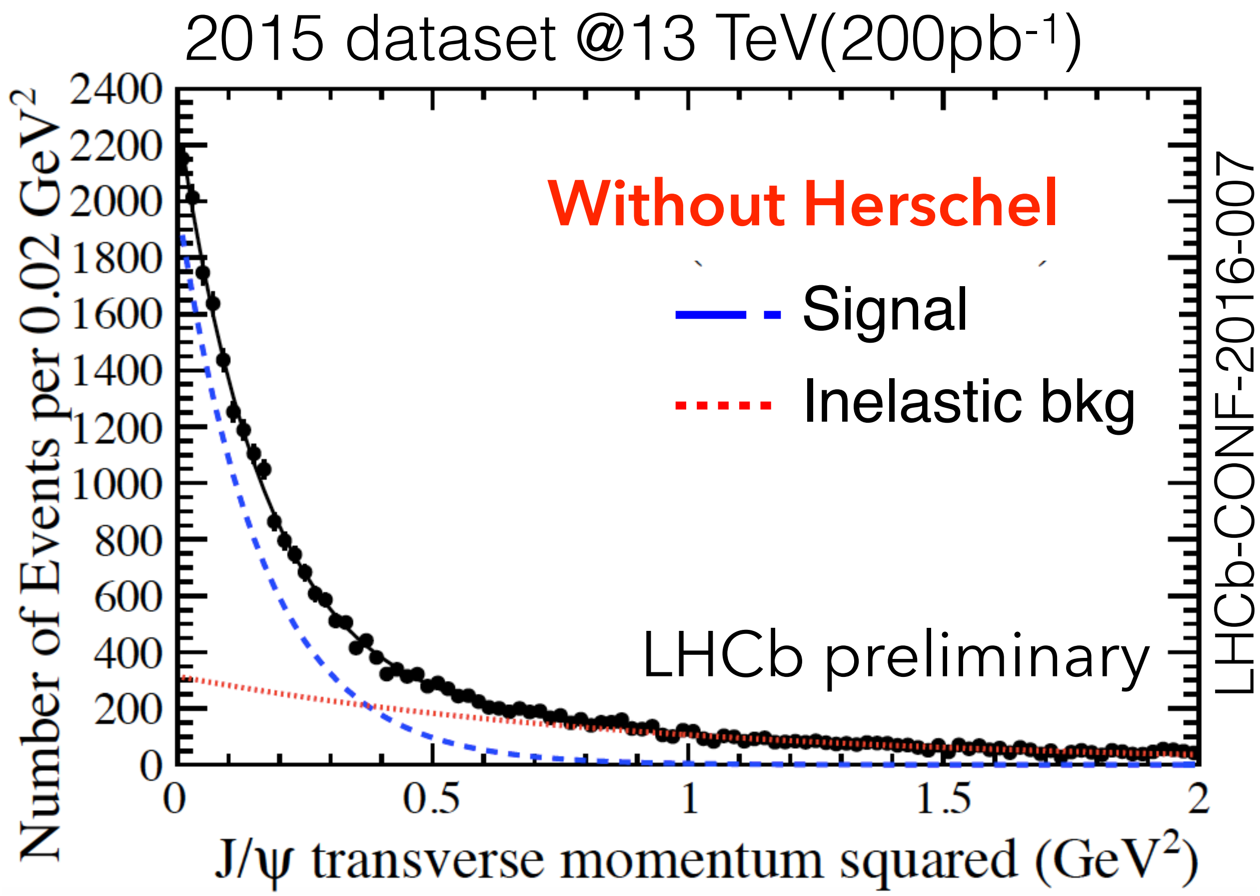
CEP γ-prod. J/ψ

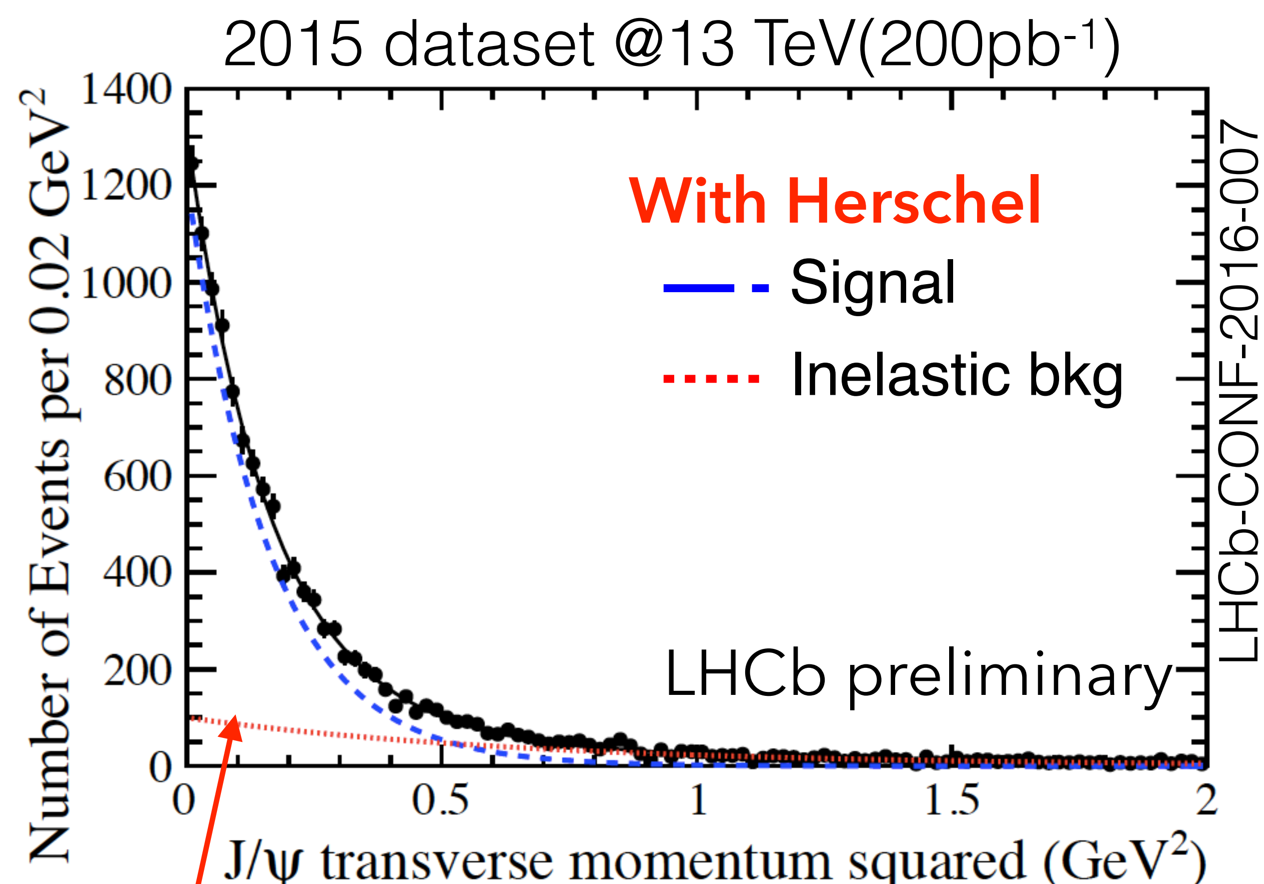


Quadratic sum of normalised signals (Σ_H) used to **create veto**

- Response checked against 3 classes of events:
    1. Non-Res. CEP with $p_T^2 < 0.01 GeV^2$
    2. J/ψ sel. $p_T^2 > 1 GeV^2$ (inelastic events with proton dissociation)
    3. J/ψ more than 5 tracks
- Clear signal/background enhancement

Transverse momentum squared distribution for J/ψ candidates

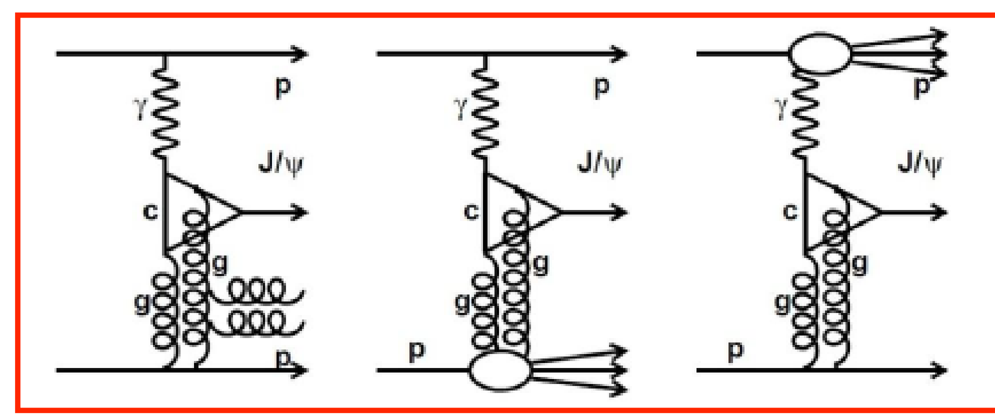




Background halves relative to previous analyses !

Background:

- **Inelastic production of mesons** where one or more protons dissociate
- **Non-resonant background** primarily coming from QED



- **Feed-down from exclusive production** χ_c or $\psi(2S)$ that can mimic exclusive J/ψ production when remaining particles produced in association with the J/ψ remains undetected or goes outside detector

Systematic uncertainties

Source	J/ψ analysis Uncertainty (%)	$\psi(2S)$ analysis Uncertainty (%)
Proton dissociation	4.0	4.0
Tracking efficiency	4.0	4.0
Non-resonant background	0.1	1.4
Feed-down background	0.6	-
Mass-window	0.4	0.4
HeRSCheL Veto	1.5	1.5
Luminosity	3.9	3.9
Total excluding luminosity	5.9	6.1

ongoing work

ongoing work
may decrease to 1%

Proton dissociation source of uncertainties comes from the assumptions made for the shape of the signal and background

- Signal is assumed to be a single exponential function, Regge theory suggest a mild dependance of the slope with W. $\Longrightarrow$assessed with simulated events ➡ 3.1%
- Proton dissociation component (inelastic background): ➡ 2 %
- Feed-down correction using the calibration sample of χ_c ➡ 1.6%

Tracking efficiency: inclusion in the simulation of the VELO detector of the double metal layer layout may reduce systematic uncertainty

HRC veto systematic uncertainty

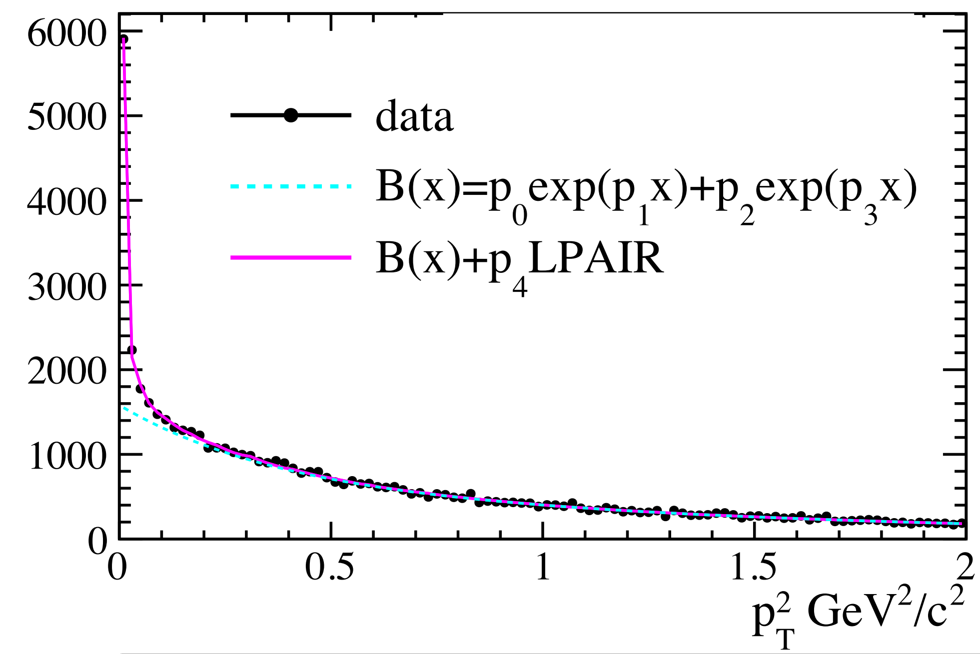
The efficiency is obtained from the EM CEP (non-resonant) sample

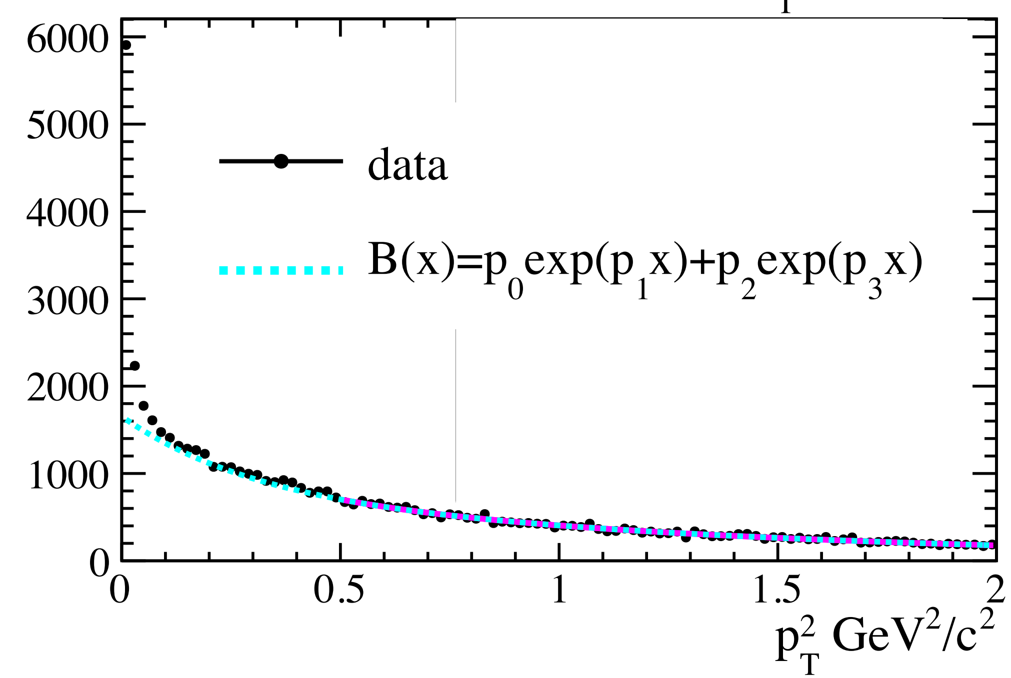
$$\epsilon = \frac{N_{\mathrm{HRC}}}{N}$$

N_{HRC}: from the p_T^2 fit with HRC cut

N: from the p_T^2 fit without HRC cut

EM CEP (non-resonant) sample





Systematic uncertainty on the efficiency, obtained from p_T^2 fit :

- using LPAIR as signal
- using SuperChic v2 as signal
- using the tail of the distribution and no MC
  - ➡ the slopes are fixed and obtained from the extrapolation of the fit results with additional VELO tracks

Difference between the 3 approaches gives the systematic uncertainty on the HRC cut

Cross-section measurement J/ψ and $\psi(2S)$

Purity (found from data)
1) non-resonant
2) Feeddown
3) Inelastic J/psy production

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{\mathcal{P}N}{A\epsilon\mathcal{L}\Delta y}$$

Number of events observed

Luminosity

Acceptance (MC)

Efficiency:
Trigger, Tracking and muon ID,
single interaction per beam crossing

$$P(n) = \frac{e^{-\mu}\mu^{n}}{n!}$$

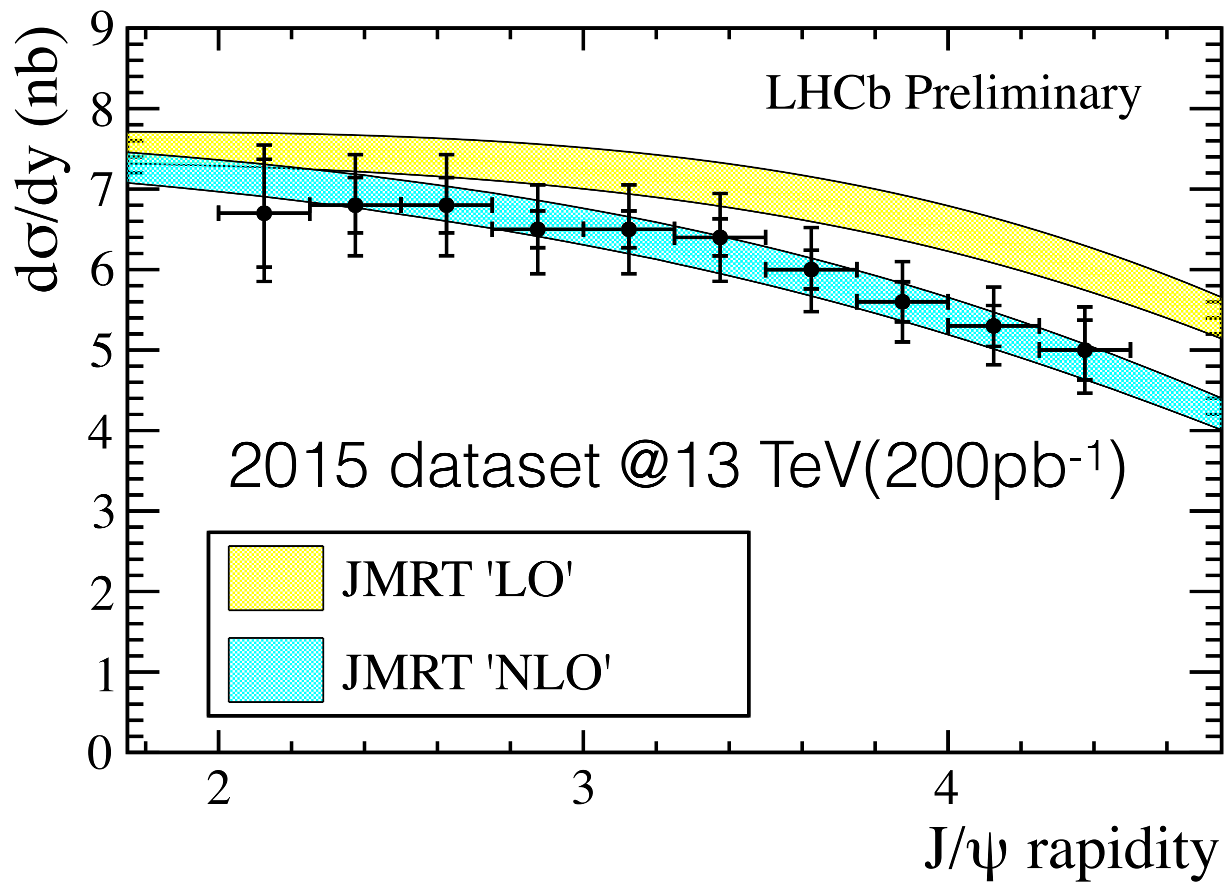
$$\Rightarrow P(1) = 35\%(2015),\ 25\%(2011)$$

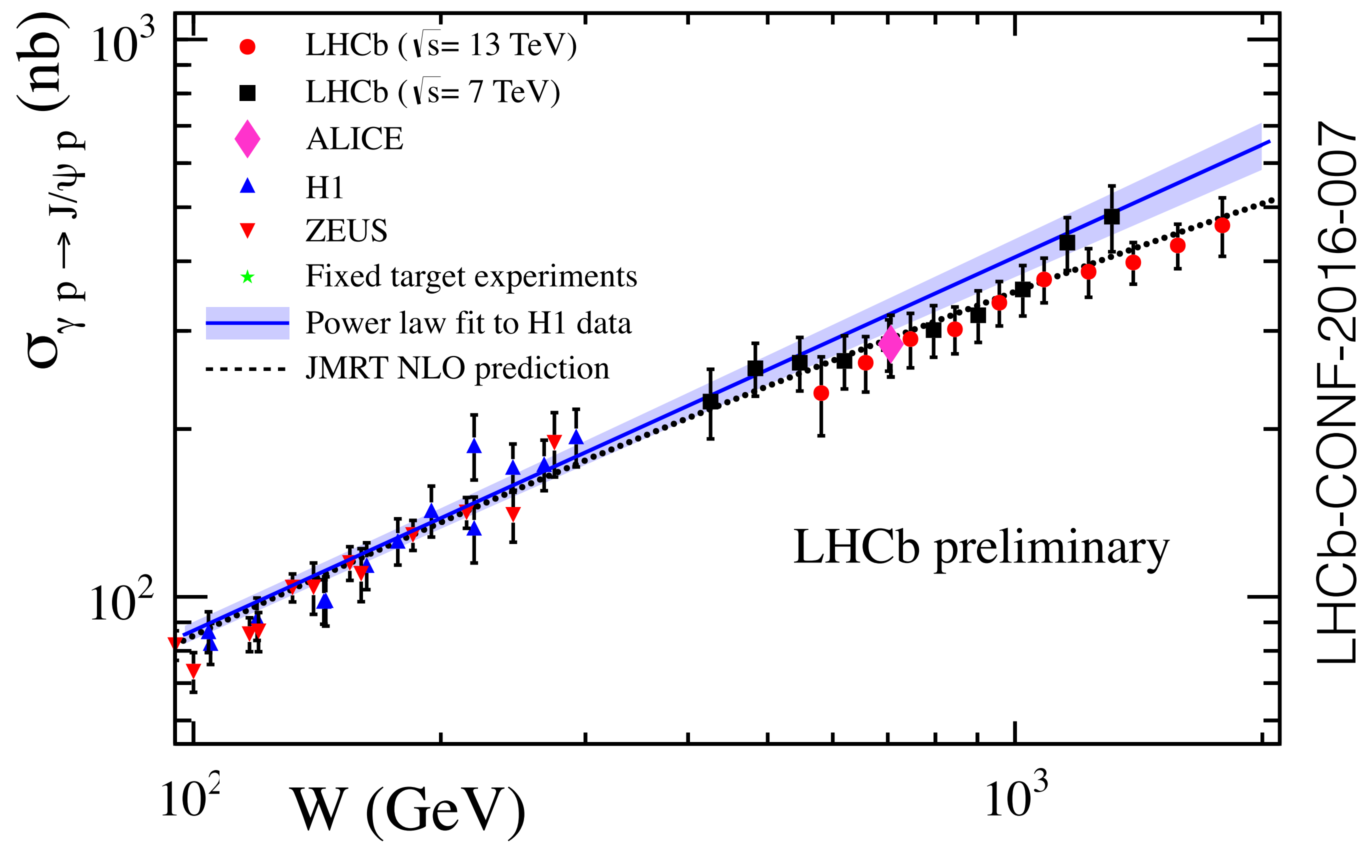
LHCb preliminary cross section

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$

(stat) (syst) (luminosity)

JMRT LO: power law description of the process (Leading Order)
JMRT NLO: Next to Leading Order corrections added to the LO description





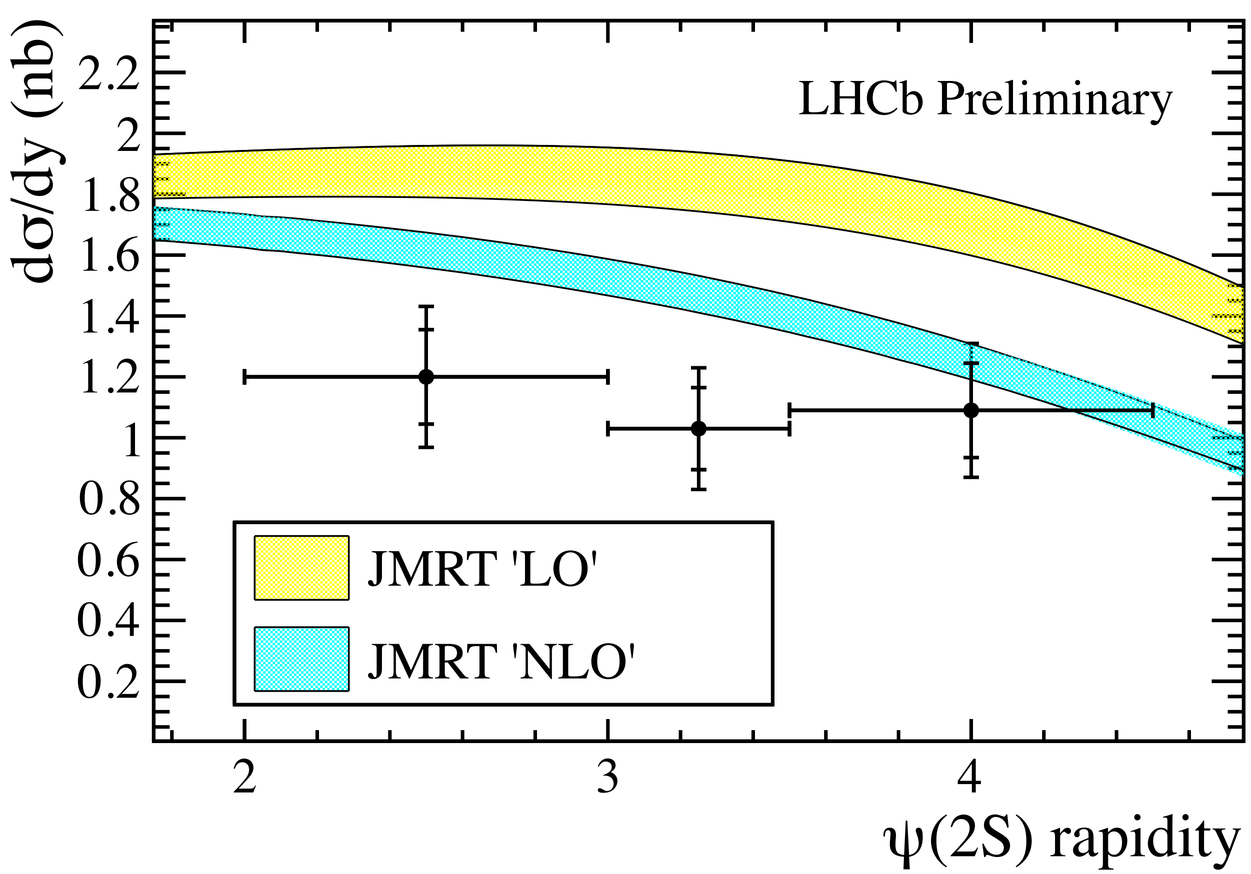
=centre-of-mass energy of the photon-proton system

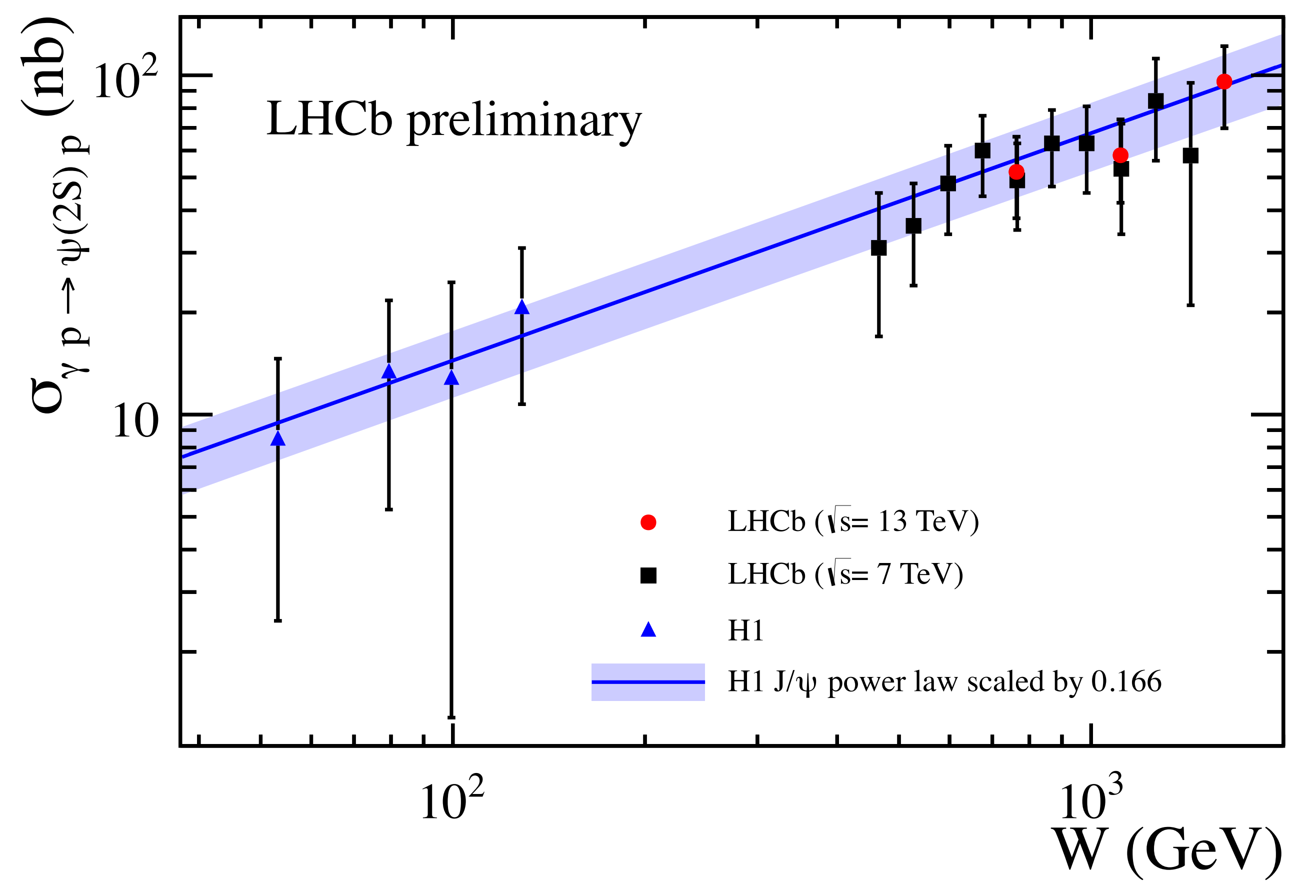
- Differential cross section in agreement with JMRT NLO rather than LO's
- Power law not sufficient to describe the data at high energies
- Extension of the reach in W with 13 TeV data (now up to 2 TeV)

LHCb preliminary cross section

(stat) (syst) (luminosity)

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \pm 0.6 \pm 0.4 \text{ pb.}$$





- Seems more in agreement with NLO
- In agreement with power law extrapolation from H1 (HERA) data
- More data needed for critical comparison

Conclusion

We have done the first measurement using the Herschel detector

Although Herschel+LHCb can cover 12 unit in rapidity there is still a reasonable background getting through the J/ψ analysis.

- Full simulation of the detector is very difficult/impossible due to the very large distances in consideration.
- We are a little surprised that the implementation of Herschel reduce the background by a factor 2.
    - ➡ Is this due to detector response or physics processes?
        - are all the backgrounds really so close to the beam?
    - ➡ Understanding the background of the elastic CEP processes is very important and would decrease systematic uncertainties.

New measurements favour the next to leading order description, a simple power law is not enough

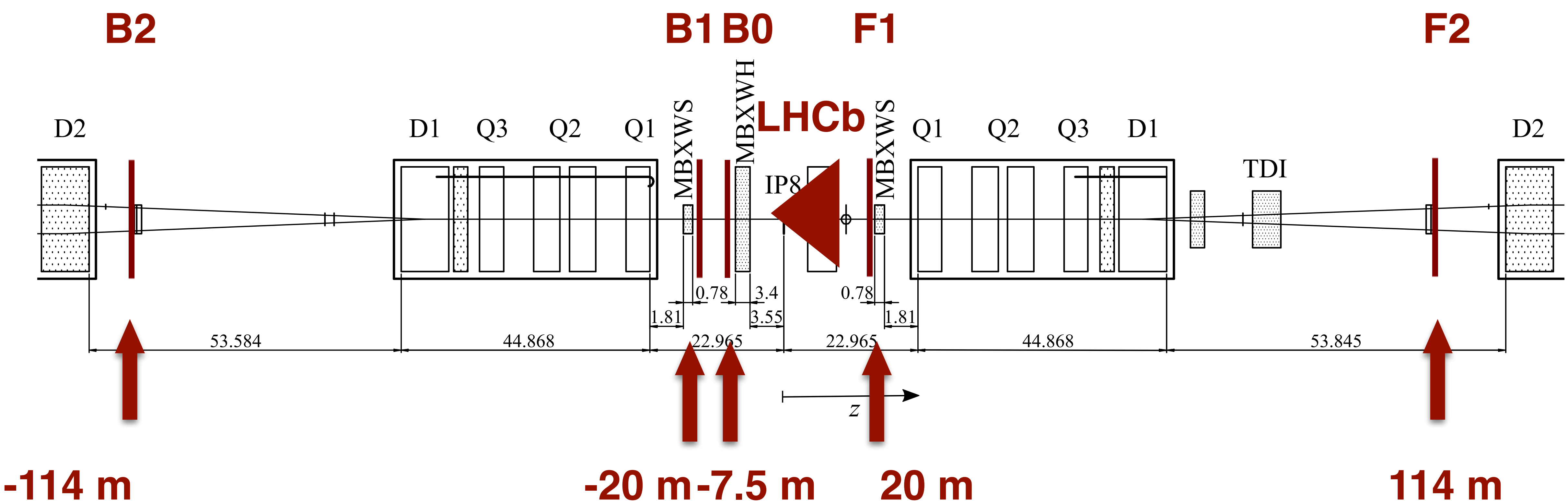
More data needed for ψ(2S) to make more detailed comparisons

Thank you

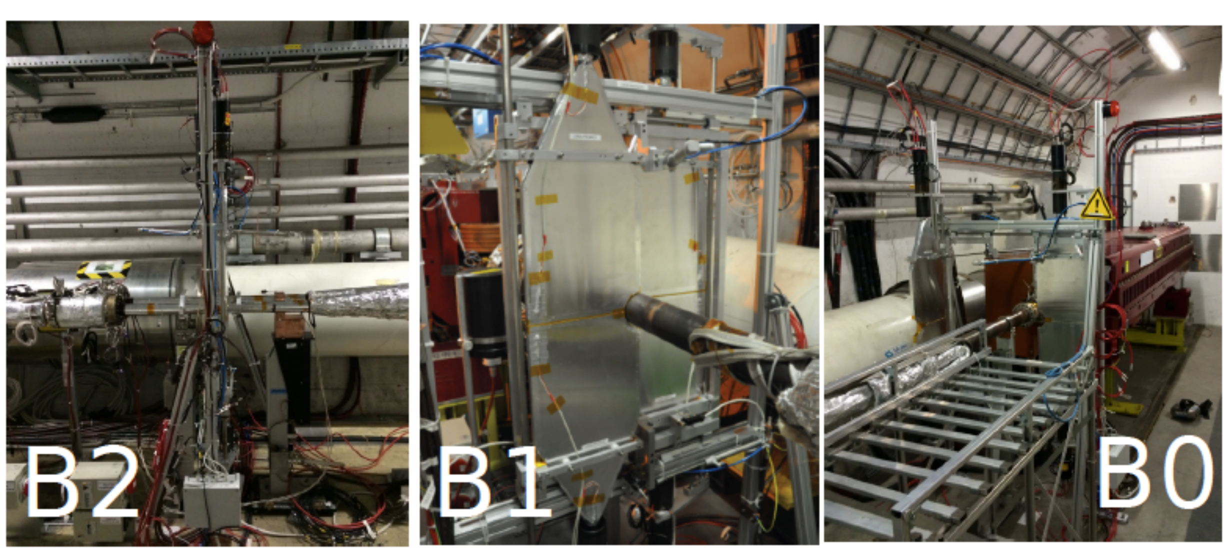
BACK UP

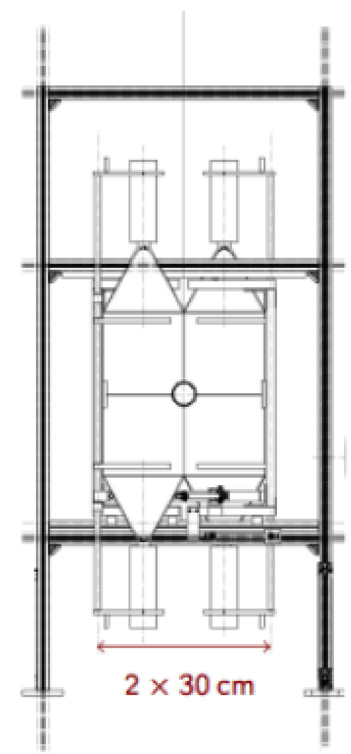
To get an idea of the distances…

- Installation finished in 2014
- Taking data throughout LHC run2 (2015-2018)

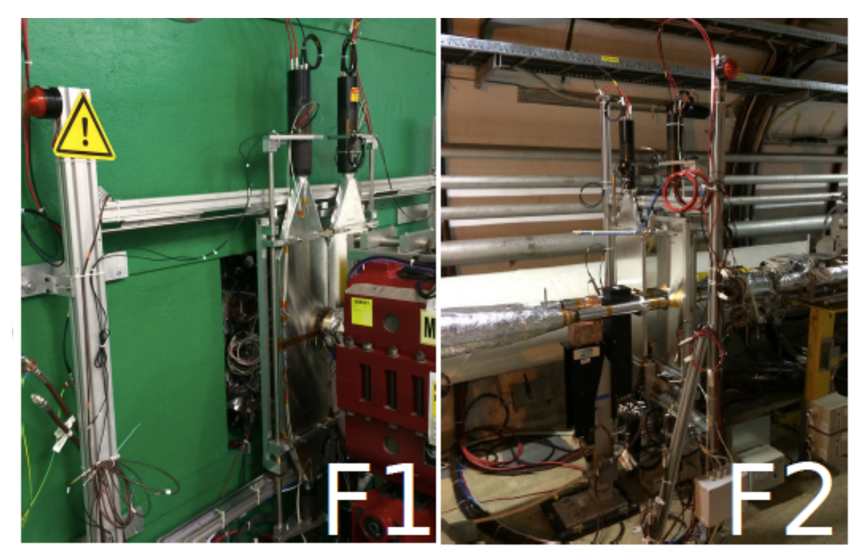


Backward Stations





Forward Stations



March 2014:
Engineering Change Request

Spring 2014
Fabricate scintillator panels

Summer 2014:
Hydraulic frame

July 2014:
PMT & divider assembly

Autumn 2014:
Scintillator calibration

November 2014:
Tunnel installation

Winter 2014:
Crate positioning

Jan/Feb 2015:
New read-out electronics
Grounding

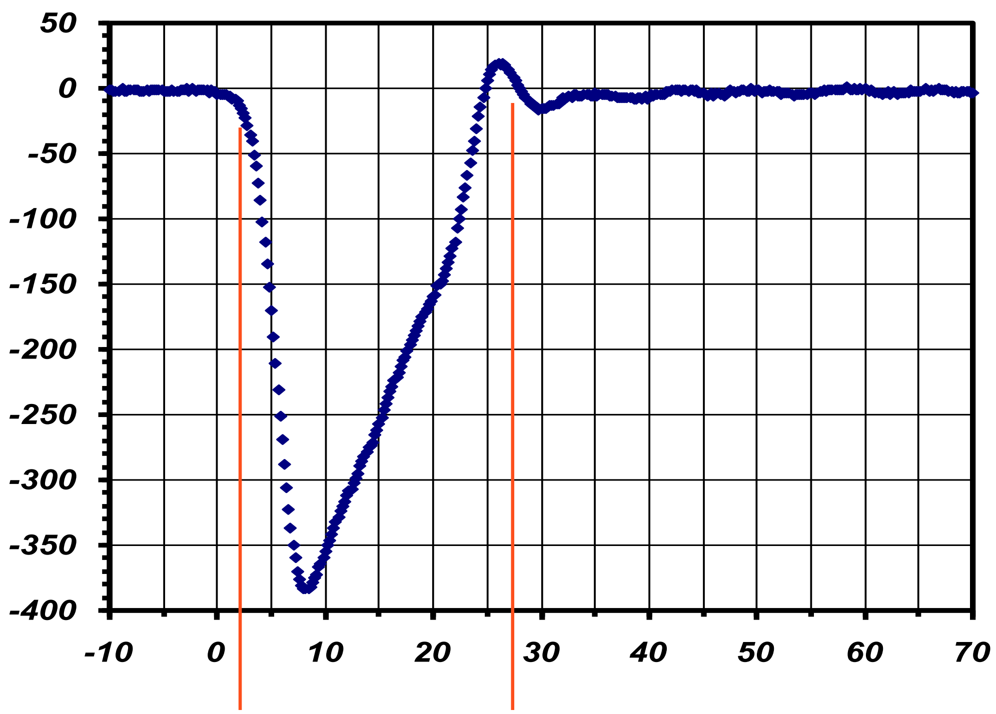
Summer 2015:
Data-taking begins

September 2015:
Herschel stable & available offline!

Specifications

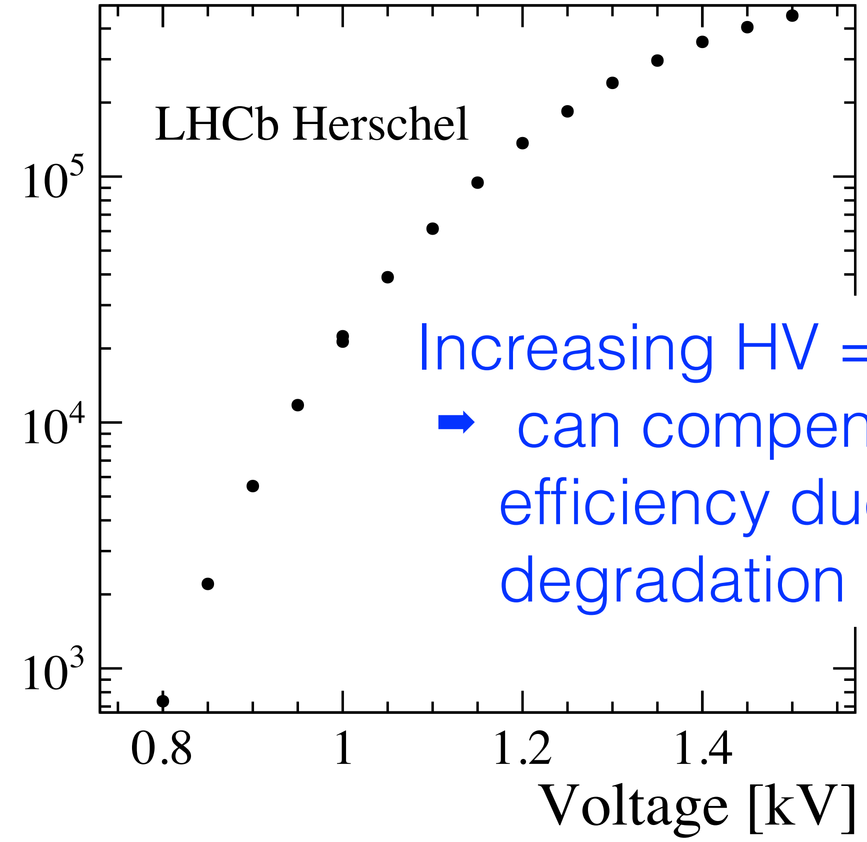
- 20 mm thick **plastic scintillator** glued to fishtail light guides
- **PMT**: Hamamatsu R1828-01, 51 mm, anode current limit ~ 200μA
- Customised **high rate** base (40 MHz)
- **Calibration with comics**, 1 mip ~170 photon-electrons
- All PMT pass **LED calibration** at different HV (Gain vs HV obtained)
- Pneumatic motion system to **retract scintillators** from high fluency region

Counter signal fit within 25 ns gap
➡ 40MHz rate

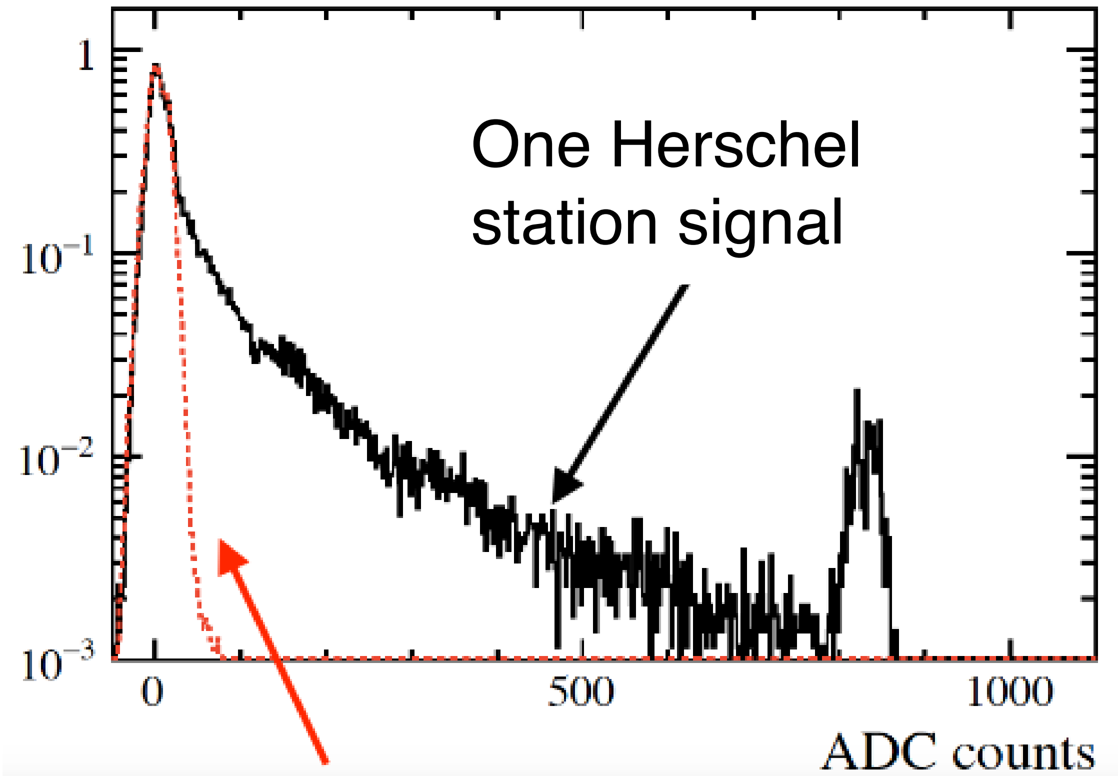


25 ns

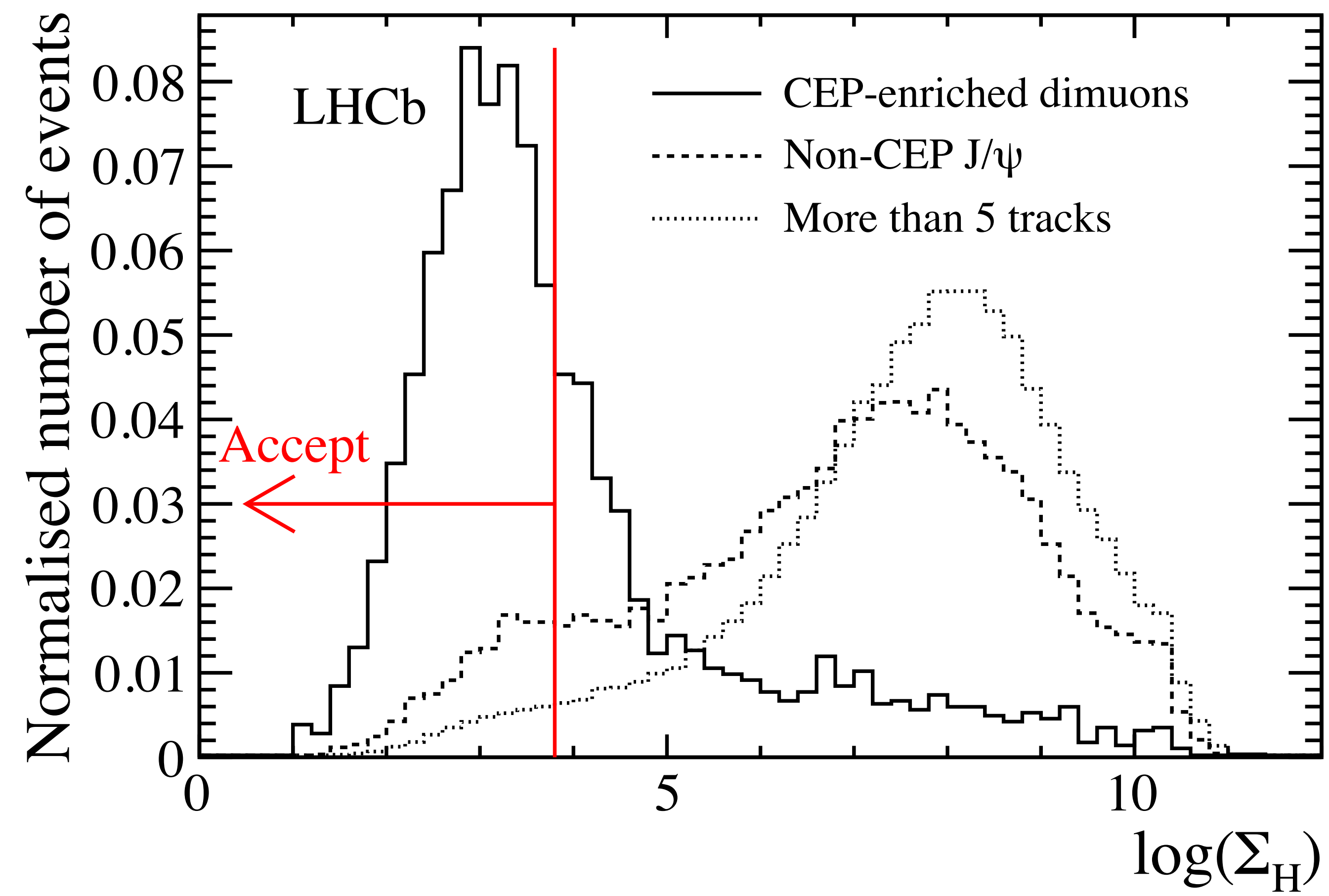
PMT gain



Increasing HV => higher gain:
➡ can compensate the lose of efficiency due to radiation degradation



Herschel Pedestal

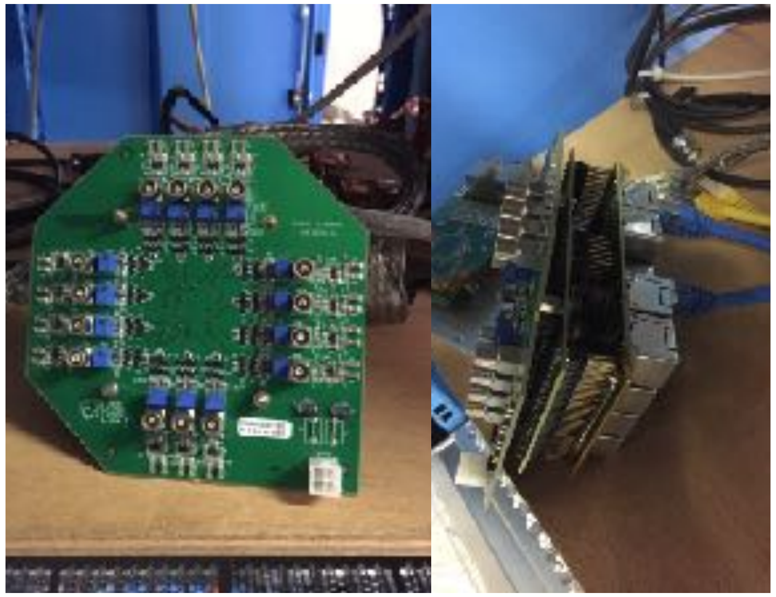


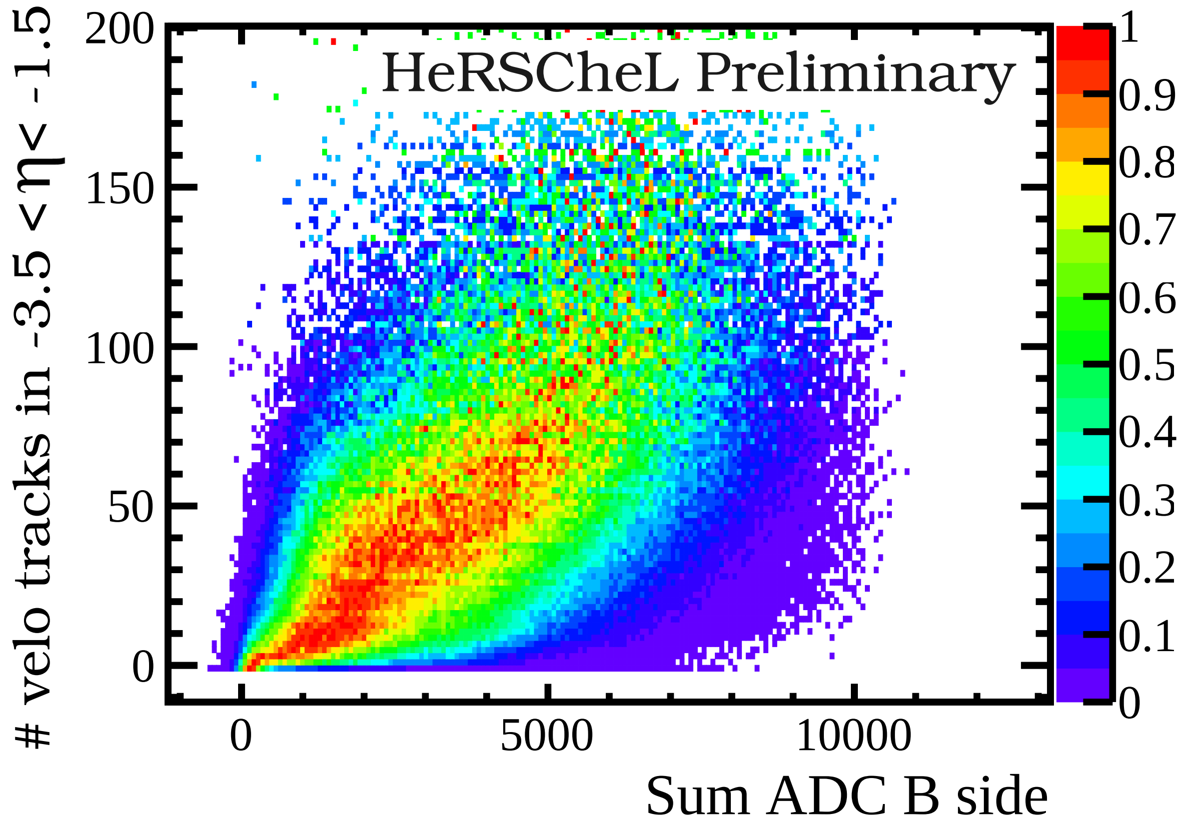
- Clean pedestals and almost complete suppression of pileup
- Common noise subtraction using non connected channels (only necessary in 2015)

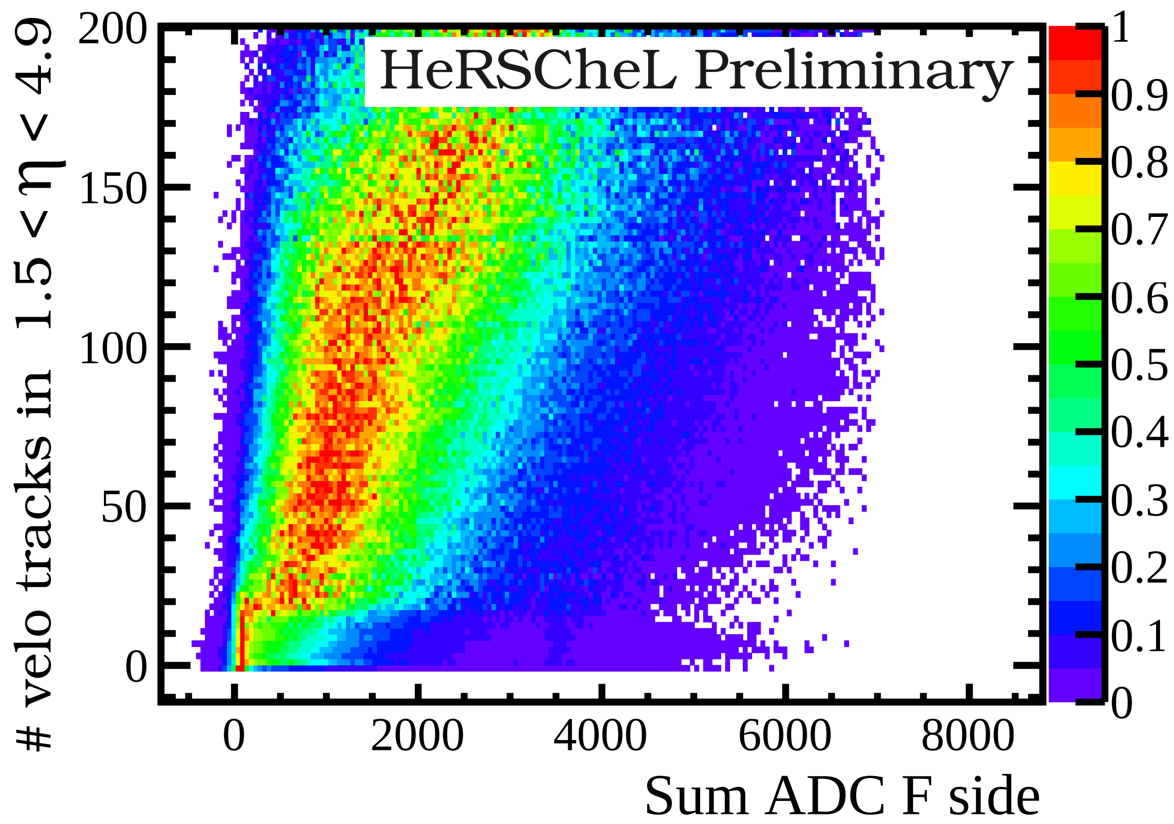
- Quadratic sum of normalised signals (Σ_H) used to create veto
- Response checked against 3 classes of events
- Clear signal/background enhancement

Electronics & Herschel performance

- Re-use electronic from PS and calorimeter
- The very front-end cards have two interleaved integrators, each running at 20 MHz which helps to avoid spill-over
- Dedicated adaptor board since the signal is coming over long coaxial cables (not the case for PS detector)





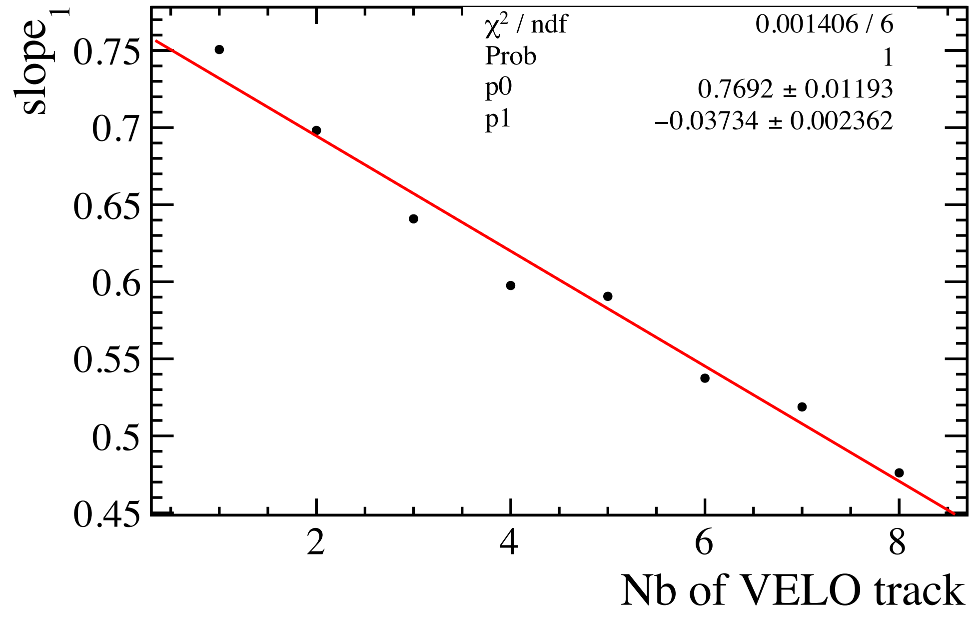


Visible correlation between VELO activity and Herschel activity
➡More activity seen in Herschel when more tracks are reconstructed

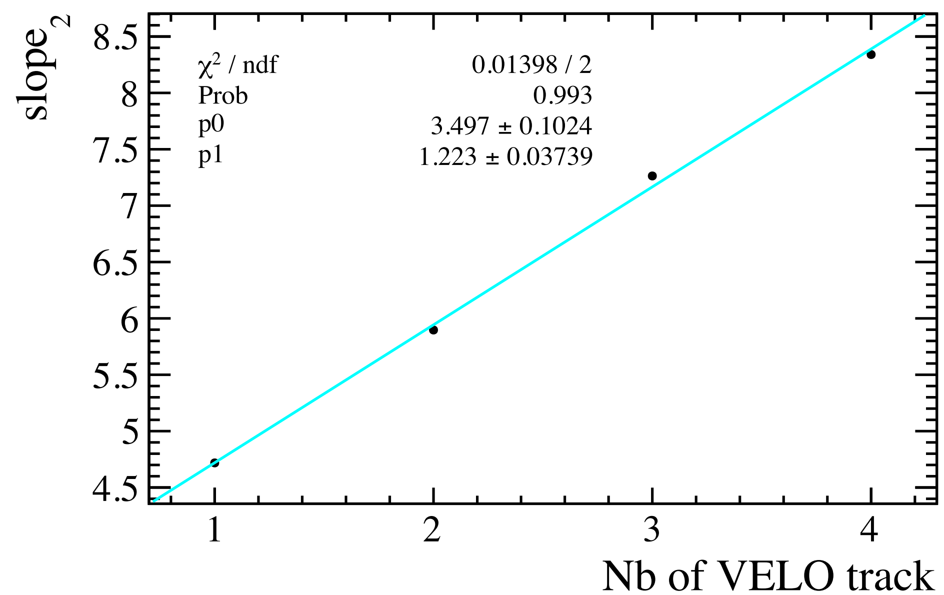
Determination of the background from data

Use Non-Resonant EM CEP control sample with extra VELO tracks, to extrapolate the background shape for the Non-Resonant Dimuon sample

1) Fit only the tail of the distribution from 1 extra track to 8 extra tracks
2) Store the slopes as a function of the number of extra tracks

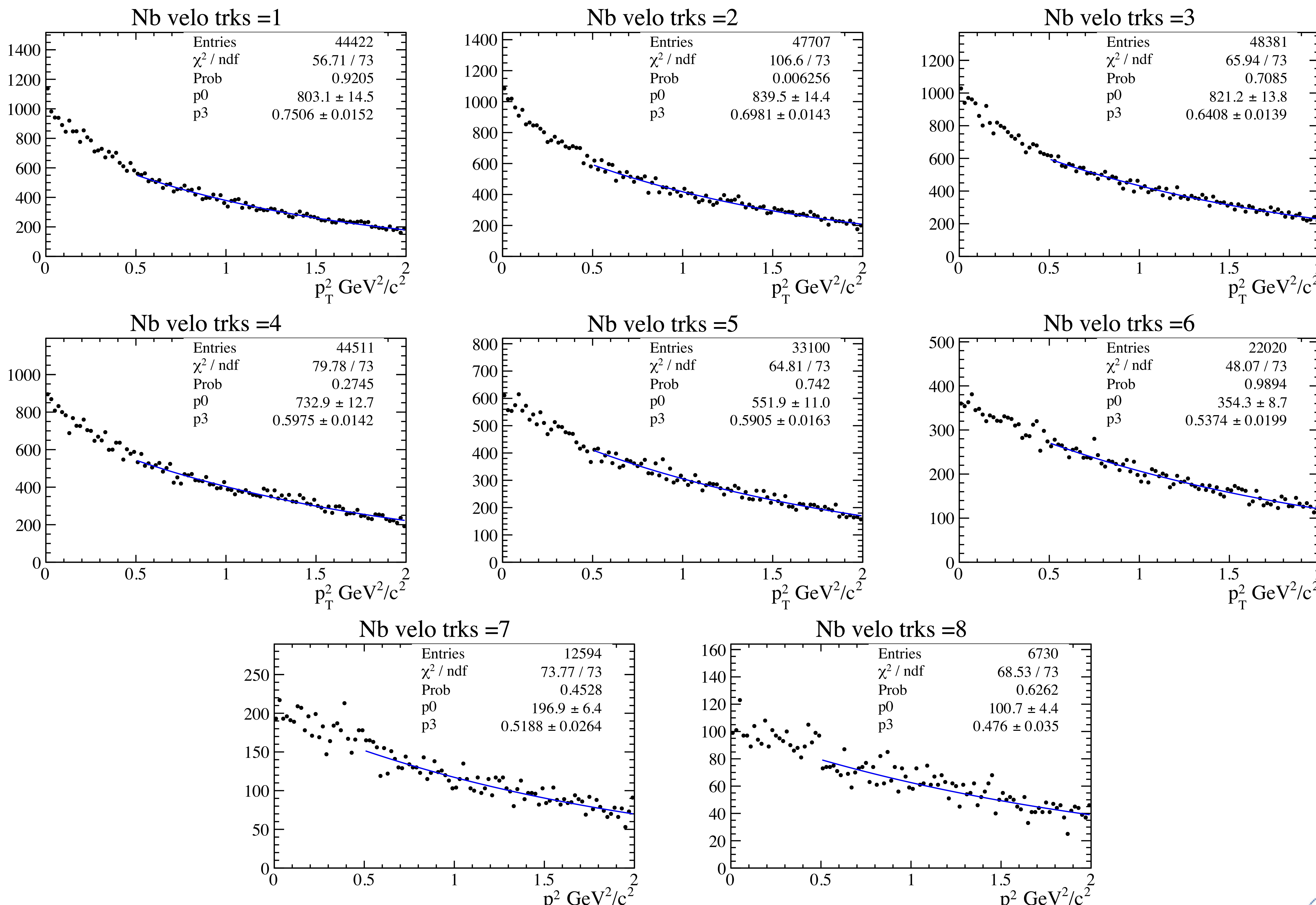


1) Fit the whole distribution from 1 extra track to 4 extra tracks with a double exponential
2) Store the second slope as a function of the number of extra tracks



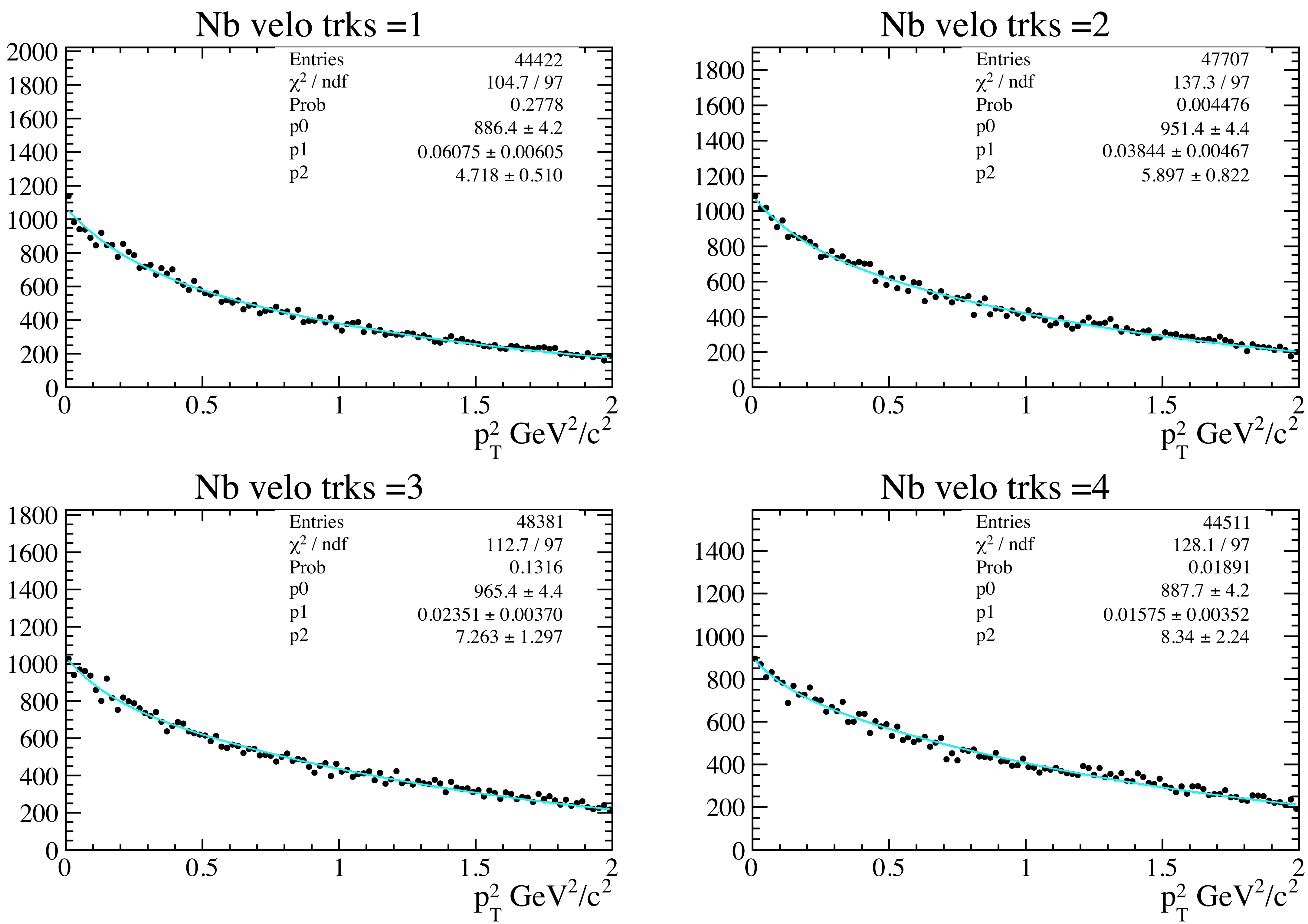
Use the result of the extrapolation to 0 track to fix the two slopes of the background described by a double exponential.

Background determination from data only

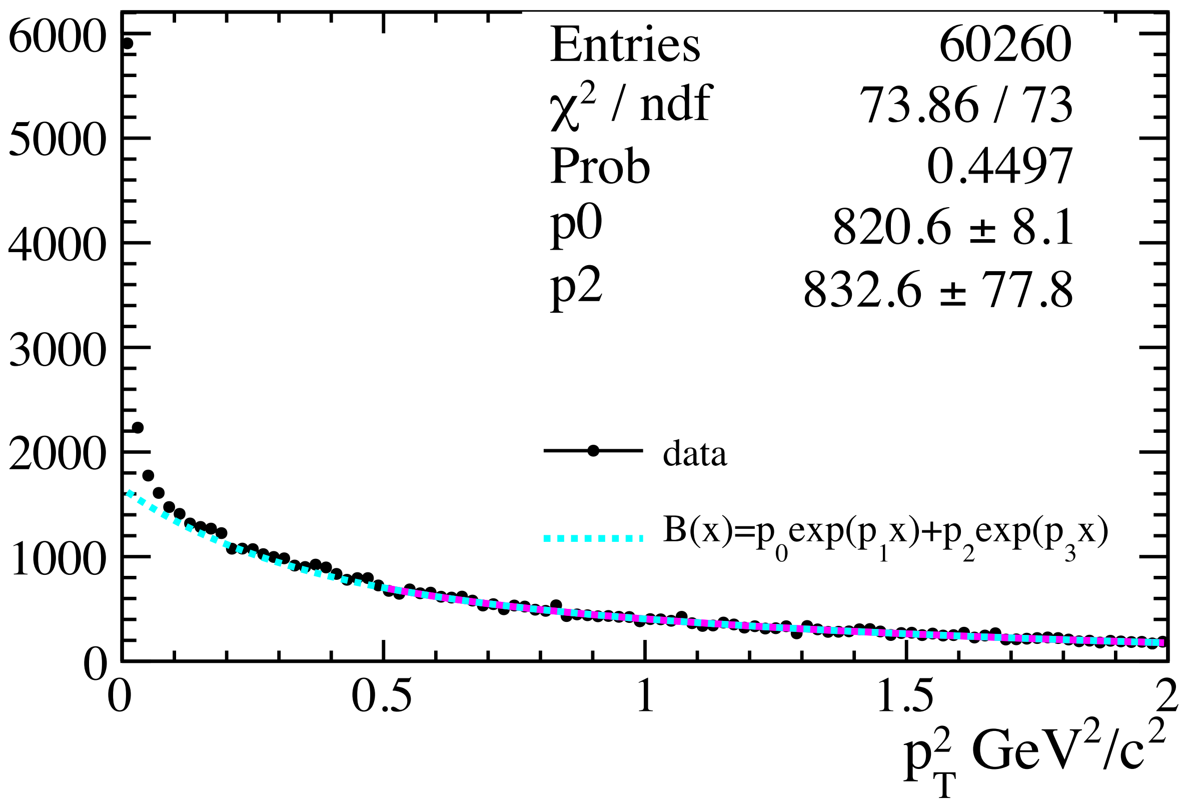


Background determination from data

Fit with two exponentials, fix one slope to the one obtained from previous slide

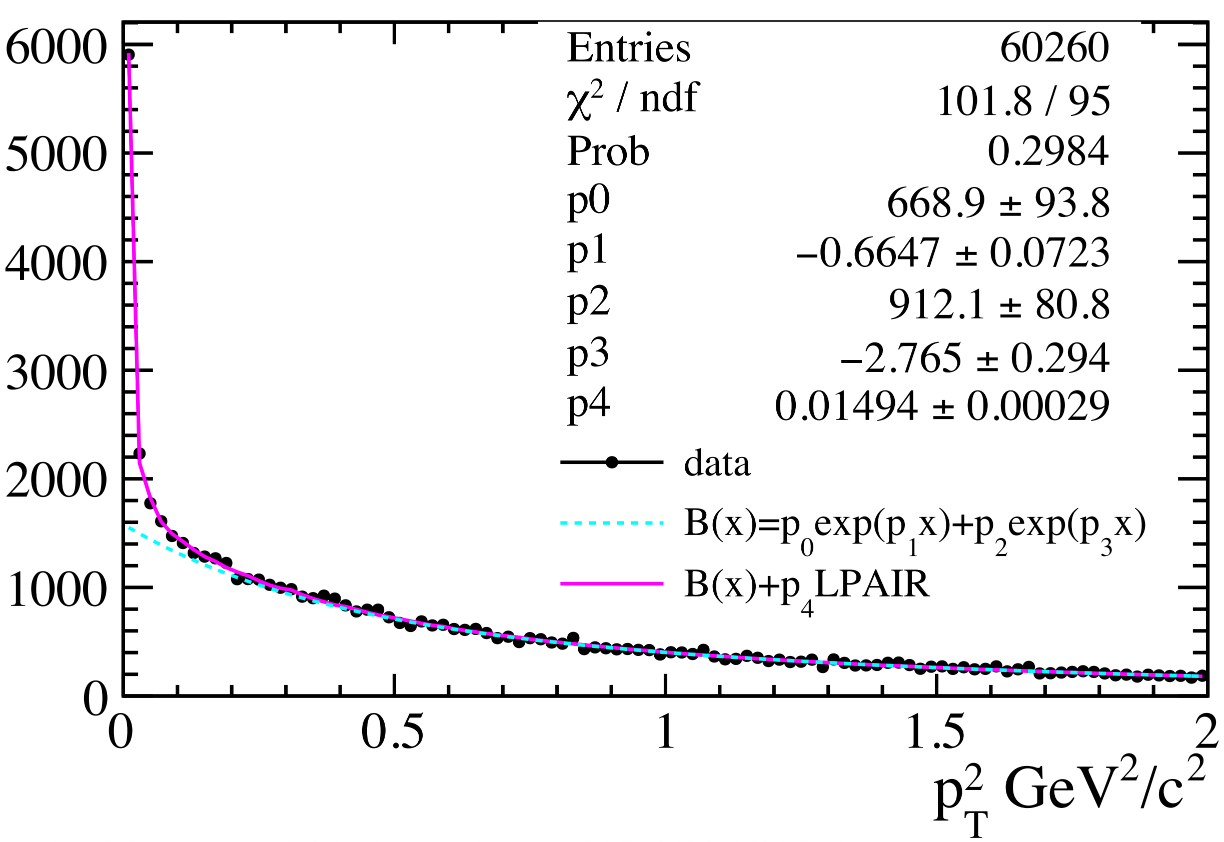


Signal NO Herschel cut

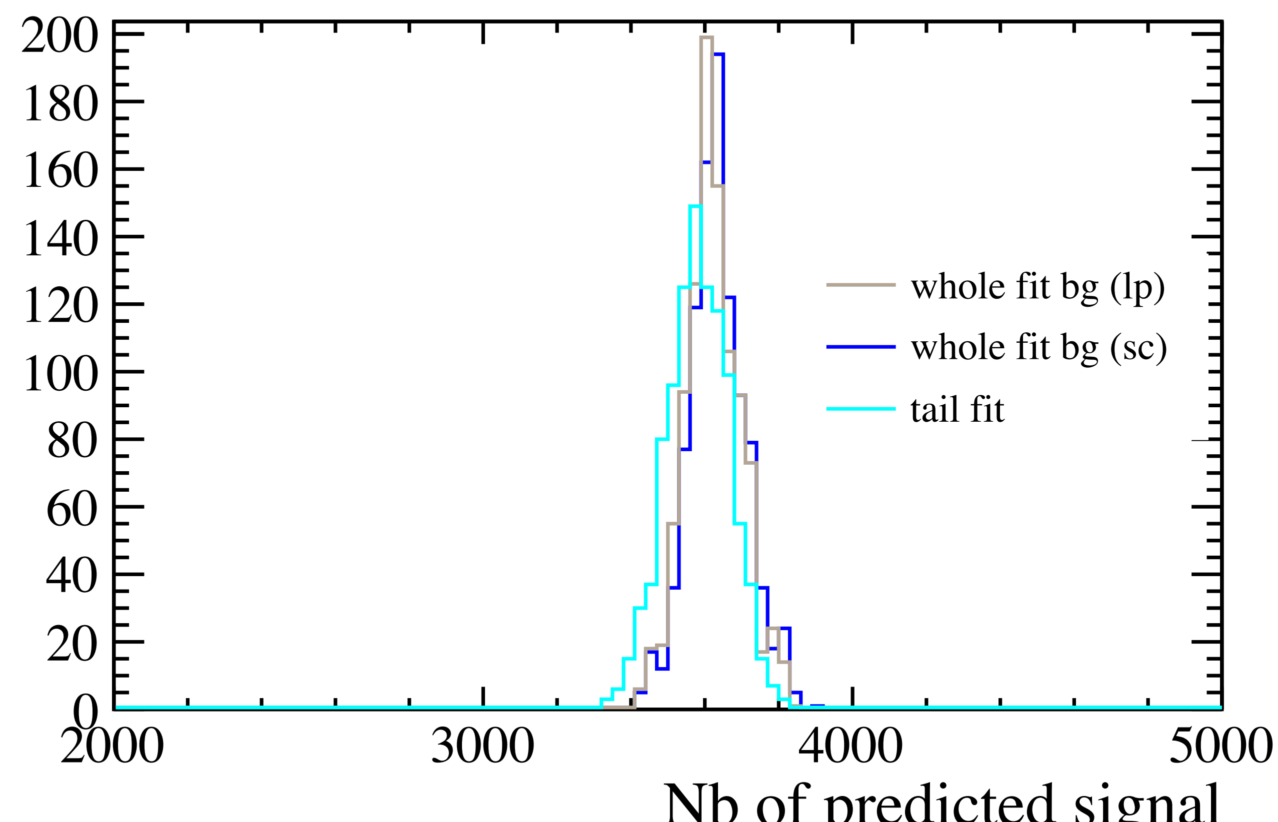


Background description using a fit of the tail, and slopes fixed to the values obtained from the control sample.

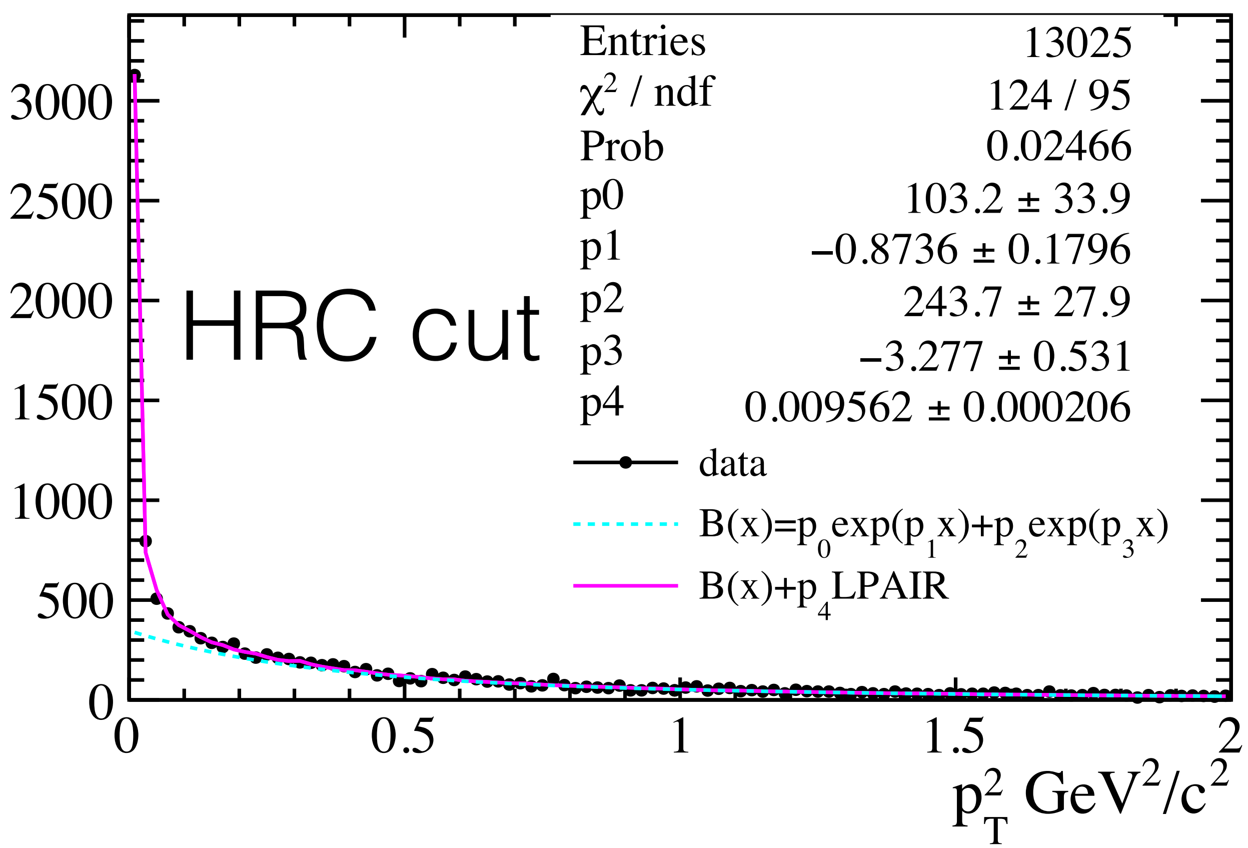
Fit with background described with two exponential + LPAIR/SuperChic2 signal



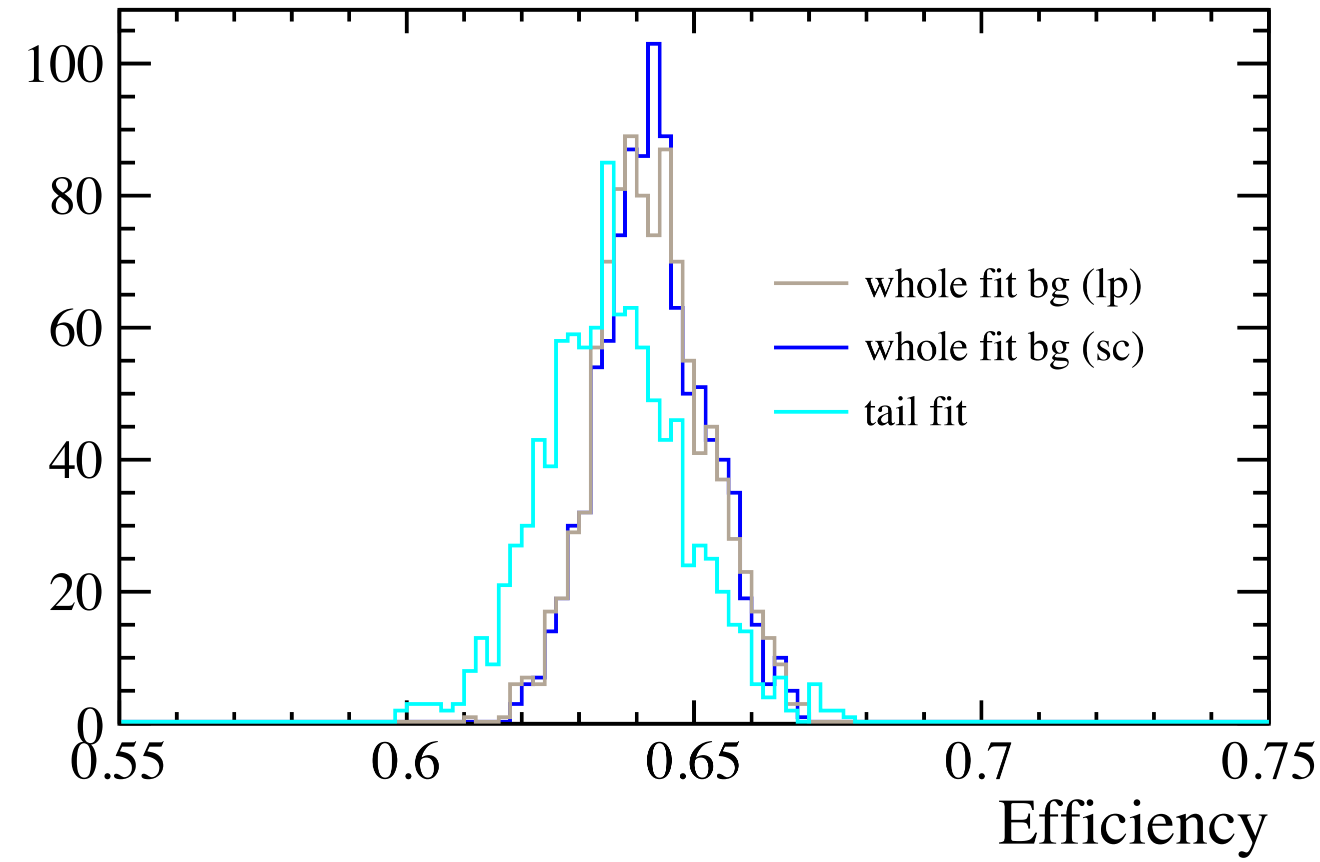
$P_T{}^2<0.01$



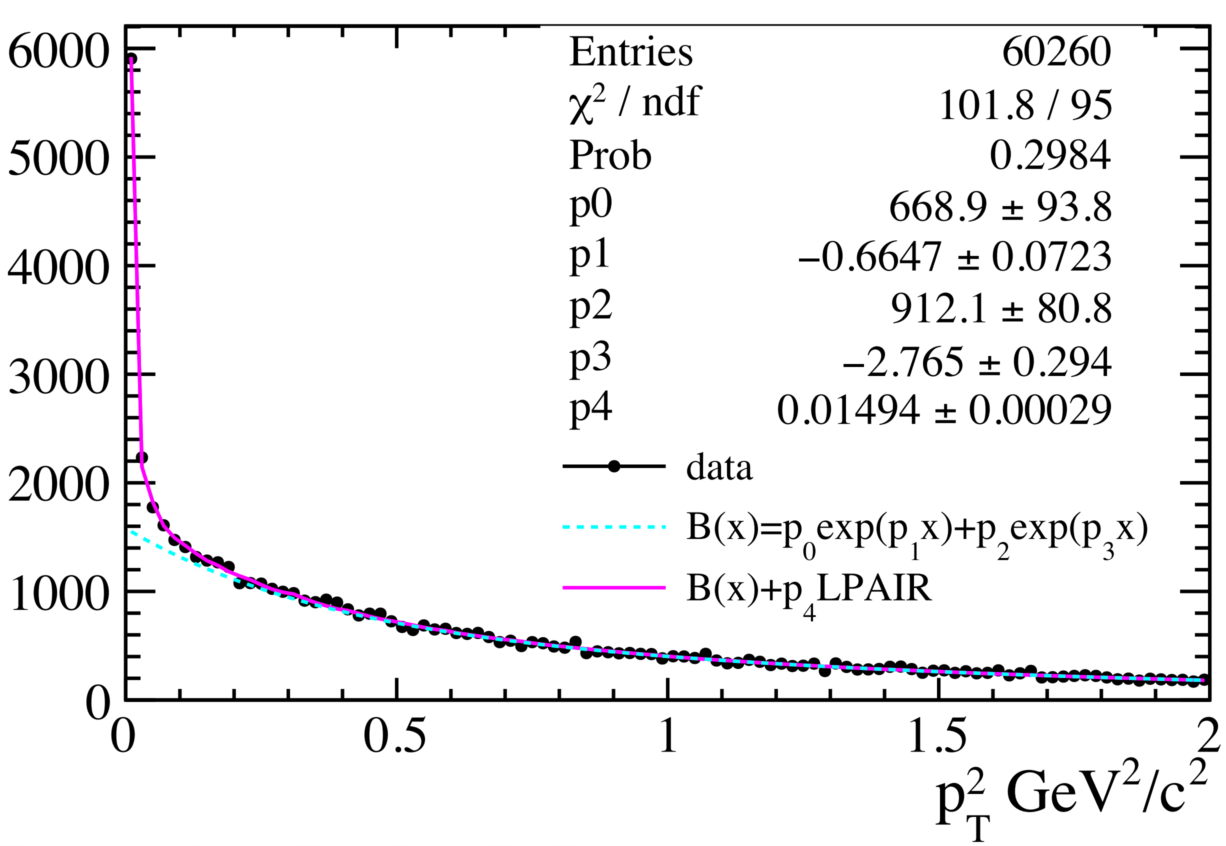
Efficiency



Entries 13025
χ^2 / ndf 124 / 95
Prob 0.02466
p0 103.2 ± 33.9
p1 −0.8736 ± 0.1796
p2 243.7 ± 27.9
p3 −3.277 ± 0.531
p4 0.009562 ± 0.000206
HRC cut
data
$B(x)=p_0\exp(p_1x)+p_2\exp(p_3x)$
$B(x)+p_4$LPAIR
p_T^2 GeV^2/c^2



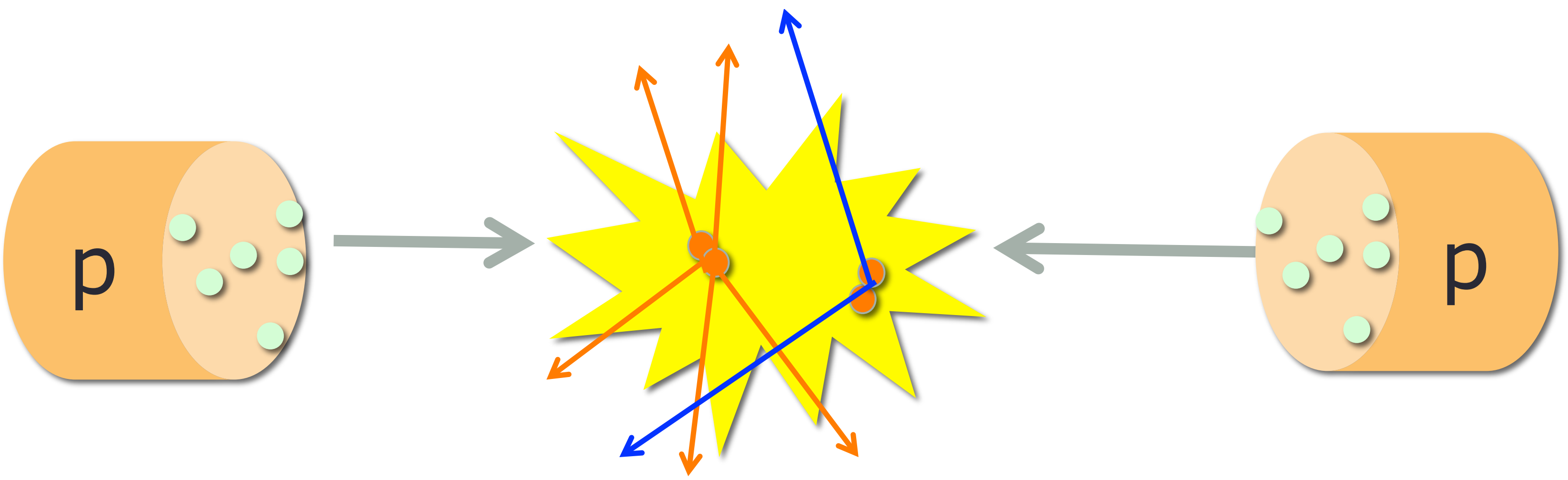
whole fit bg (lp)
whole fit bg (sc)
tail fit
Efficiency



Entries 60260
χ^2 / ndf 101.8 / 95
Prob 0.2984
p0 668.9 ± 93.8
p1 −0.6647 ± 0.0723
p2 912.1 ± 80.8
p3 −2.765 ± 0.294
p4 0.01494 ± 0.00029
data
$B(x)=p_0\exp(p_1x)+p_2\exp(p_3x)$
$B(x)+p_4$LPAIR
p_T^2 GeV^2/c^2

Beam pile-up

High luminosity requires multiple proton interactions per beam crossing



Poisson distribution of the nb of interactions (n) per beam crossings is:

$$P(n) = \frac{e^{-\mu}\mu^n}{n!}$$

← average nb of *visible* pp interactions per beam crossing

$$\text{Pile-up} = \frac{\mu}{1-P(0)}$$

Consider only single visible pp interaction

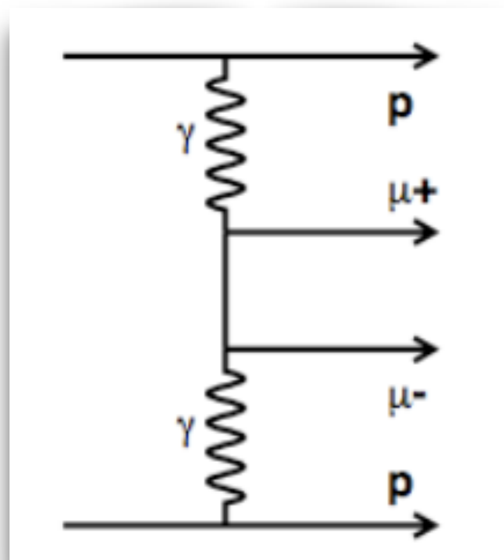
For LHCb (2011), $<\mu>$=1.4 (25% of interactions useful)
For LHCb (2015), $<\mu>$=1.08 (35% of interactions useful)

Central Exclusive Production (CEP) Processes

$$pp(\bar{p}) \to p + X + p(\bar{p})$$

t-channel exchange of a colourless object: γ, pomeron → X + rapidity gaps
Single elastic process → protons escape undetected in beampipe

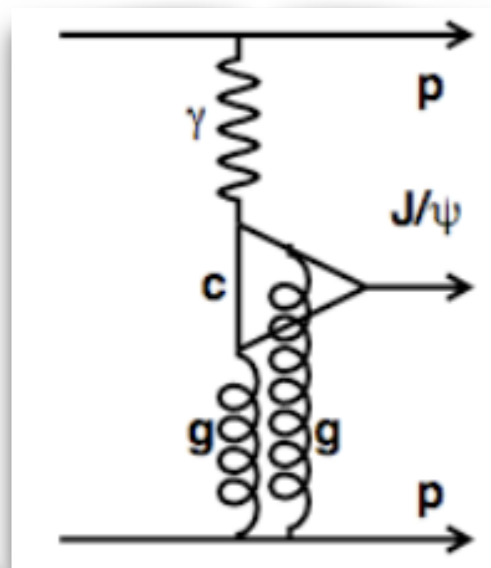
di-γ fusion



$\mu^+\mu^-$, e^+e^-, $\pi^+\pi^-$, W^+W^-

QED "standard candle" process continuum lepton pair production

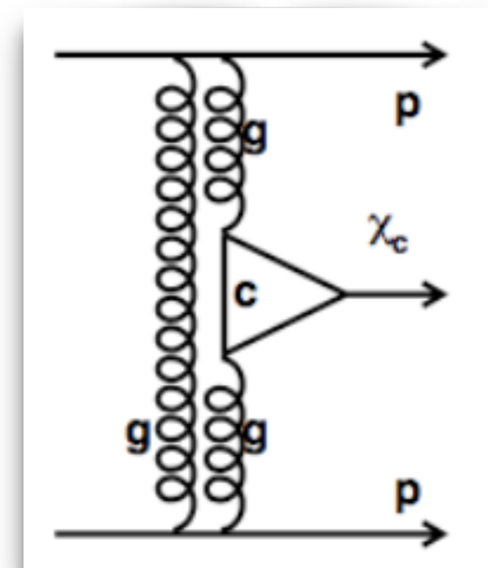
γ−pomeron fusion



ρ, J/ψ, Y, Z, …

Photoproduction: Test of QCD and description of diffraction and soft processes. Sensitive to diffractive PDF at very low x (to 5 x 10^{-6})

di-pomeron exchange



χ_c, χ_b, $\pi^+\pi^-$, Dijet, gg, …

Test of QCD,and hadron spectroscopy Pomeron content at low Q^2 dominated by gluons; access to scalar and tensor glueballs

The measurement of CEP of J/ψ and ψ(2S) mesons provides a test of QCD, an investigation of the nature of the pomeron, and a mean for constraining the gluon PDF

Bjorken variables (Lorentz invariant)

0<x<1 => inelastic, x=1 elastic

$$x \equiv \frac{Q^2}{2p_2 \cdot q}, \text{where } Q^2 \equiv -q^2 > 0$$

Fractional energy loss by the incoming particle

$$y \equiv \frac{p_2 \cdot q}{p_2 \cdot p_1} = 1 - \frac{E_1}{E_3} (\text{in the lab frame})$$

Energy loss by the incoming particle

$$\nu \equiv \frac{p_2 \cdot q}{M} = E_1 - E_3 (\text{in the lab frame})$$

$$x = \frac{Q^2}{2M\nu}, y = \frac{2M\nu}{s - M^2}, s = (p_1 + p_2)^2$$