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Overview of hadron flavour production

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Covering results from LHCb, ATLAS and CMS

FPCP 2017
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Outline

I will cover a selection of recent results (broad topic)
Apologies if your preferred topic has been neglected!

- LHCb: J/ψ prodution (prompt and from b)
- LHCb: open charm production
- ATLAS: ψ(2S) and X(3872) production at 8 TeV

- CMS: B+ production at 13TeV
- ATLAS: b-hadron pair production at 8 TeV
- LHCb: b-hadron production asymmetry

- Central Exclusive Production at LHC

I will not cover:

- Exotica and pentaquark (see dedicated talk by B. Dey)
- Associated production (see dedicated talk by E. Bouhova-Thacker)
- Flavour Production in pA and AA collision (see dedicated talk by A.Festanti)
- Spectroscopy of conventional SM hadrons

Heavy Flavour Production

- At LHC main mechanism is gluon-gluon fusion
- Production measurements are vital for understanding of QCD
  - Provide empirical fragmentation functions
  - Probe proton structure at low-x (partonic momentum fraction)
  - Required for MC tuning
  - Help understanding SM backgrounds → NP searches

Selected Recent Results

ATLAS latest results:

- ψ(2S) and X(3872) production at 8 TeV — JHEP01 (2017) 117
- b-hadron pair production at 8 TeV — arXiv:1705.03374

CMS latest results:

- B+ production at 13 TeV — arXiv:1609.00873

LHCb latest results:

- b-hadron production asymmetry at 7 and 8 TeV — arXiv:1703.08464
- Open charm production at 5 TeV — arXiv:1610.02230 **[Erratum sub.]**

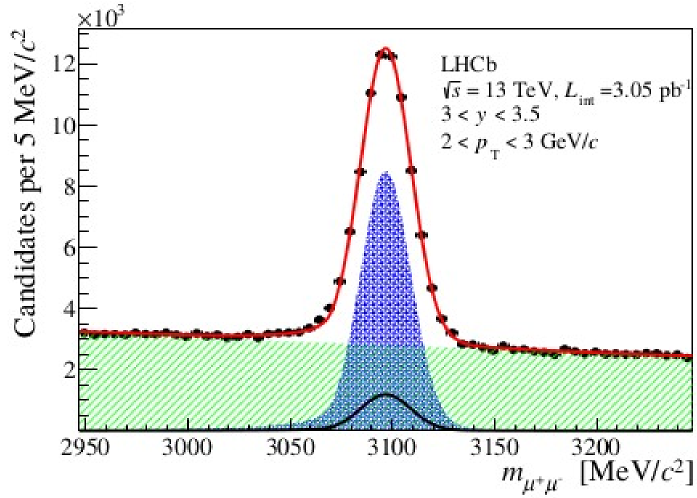
LHCb: J/ψ cross-section at 13TeV

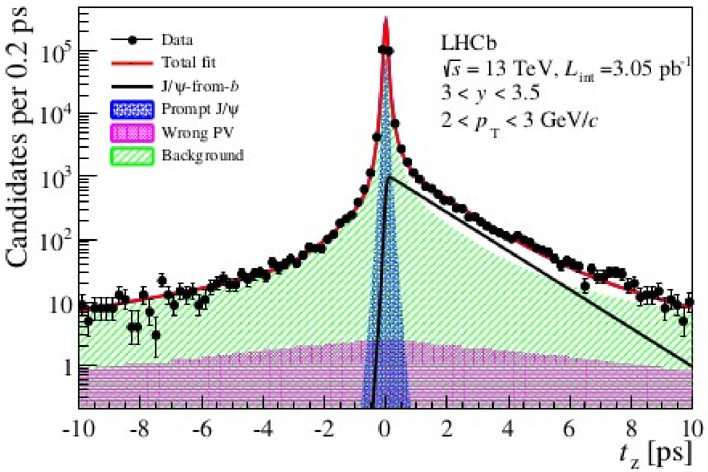
JHEP 1510 (2015) 172, arXiv:1509.00771 (ERRATUM SUB)

- Integrated luminosity of 3.05 ± 0.12 pb^{-1}
- Measure differential cross-sections

- Two major sources of charm
- Prompt: Produced at primary interaction
  - Direct production
  - Feed-down from higher resonances
- Secondary: Produced in the decay of a b-hadron
- Separation of prompt J/ψ and J/ψ form b
- To separate them → use pseudo-decay time

$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}})M_{J/\psi}}{p_z}$$





LHCb: ERRATUM

- An issue was identified in the MC simulated samples
- Sampled used to calculate the track reconstruction efficiencies in LHCb

- Affects a small number of Run 2 production papers

- LHCb VELO simulation updated prior to Run 2 to account for radiation damage
    - Charge collection affected by induction on second metal layer routing lines,
    - Error made in the parametric correction for the effect

- Track efficiency calibration procedure was unable to correct mis-modelling

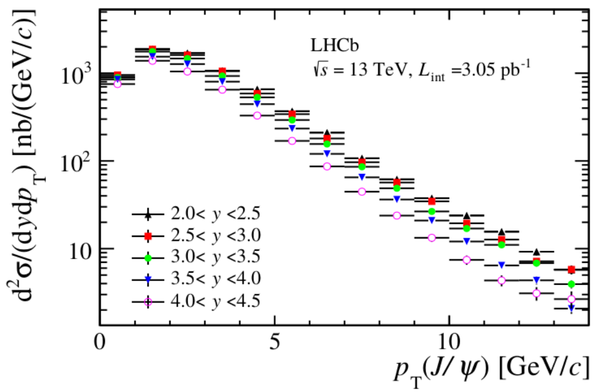
- Track reconstruction efficiency underestimated in simulation

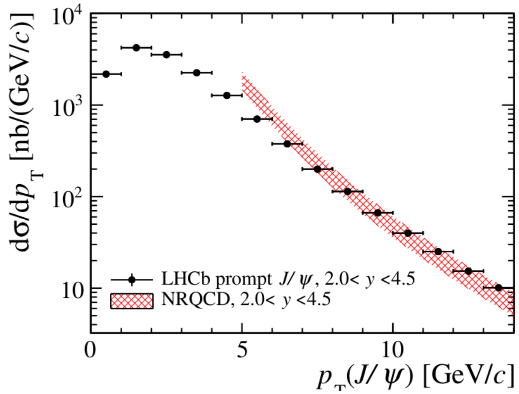
- Problem affects primarely tracks at low pseudorapidity

LHCb: J/ψ cross-section at 13TeV

Prompt J/ψ

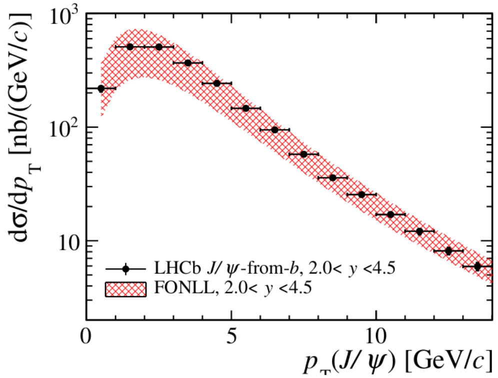
JHEP 1510 (2015) 172, arXiv:1509.00771 (ERRATUM SUB)





- Integrated over the acceptance of the analysis
- σ(prompt J/ψ, pT < 14 GeV, 2.0 < y < 4.5) = 15.03 ± 0.03 ± 0.94 μb
- Compared to NRQCD calculations (Shao et al., JHEP 1505 (2015) 103)

J/ψ From b



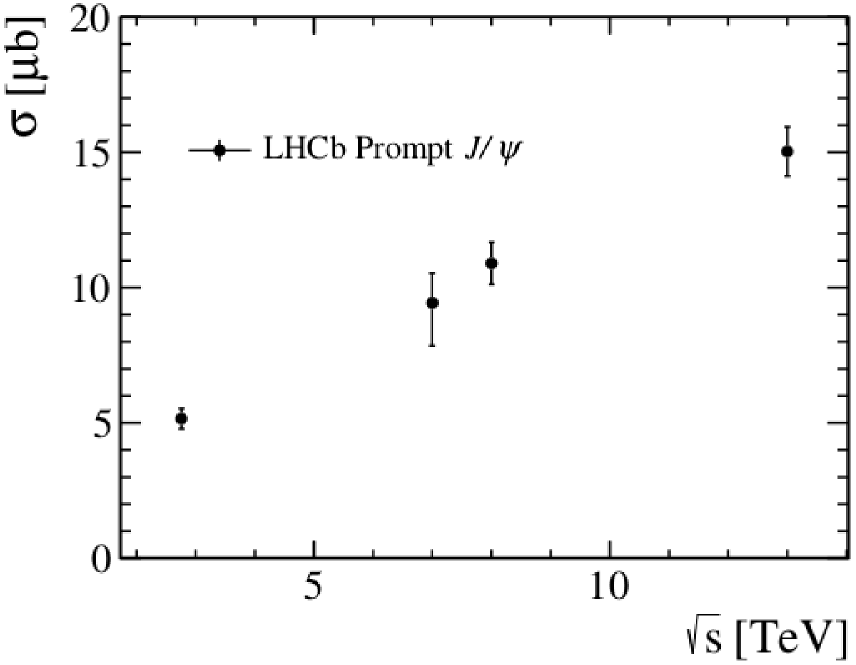
- Differential cross-sections, $d\sigma/dp_T$, integrated over 2.0 < y < 4.5
- Compared to FONLL calculations (Cacciari et al., EPJ C75 (2015) 12, 610)

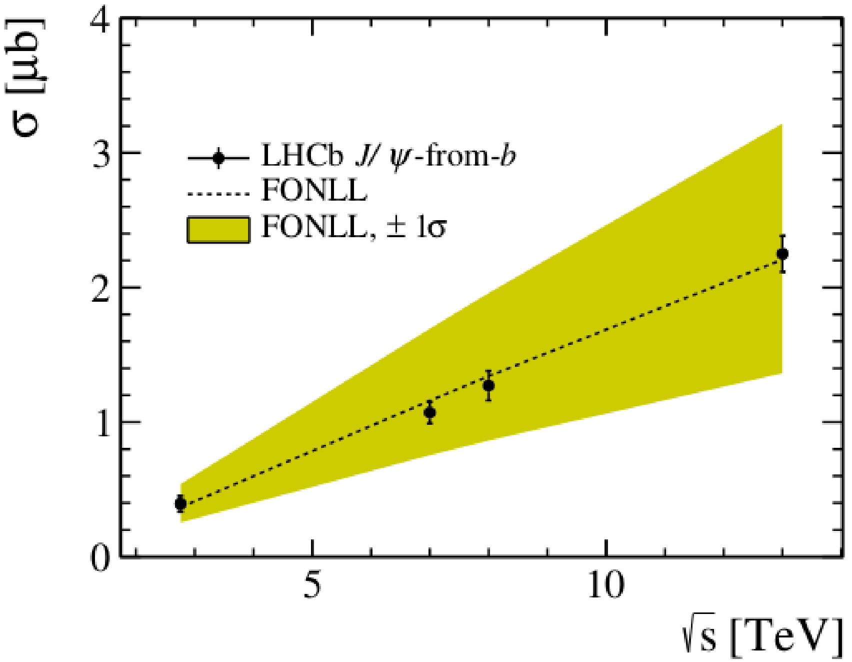
LHCb: J/ψ cross-section (Energy)

JHEP 1510 (2015) 172, arXiv:1509.00771 (ERRATUM SUB)

Prompt *J/ψ* production cross-sections integrated over LHCb fiducial region
σ(prompt *J/ψ* , LHCb, 13 TeV)
15.03 ± 0.03 ± 0.94 μb

σ(*J/ψ*-from-b, LHCb, 13 TeV)
2.25 ± 0.01 ± 0.14 μb
Using a model based on PYTHIA6, extrapolate to a total 4π bb cross-section:
σ(pp → bbX,4π,13 TeV) = 495 ± 2 ± 52 μb





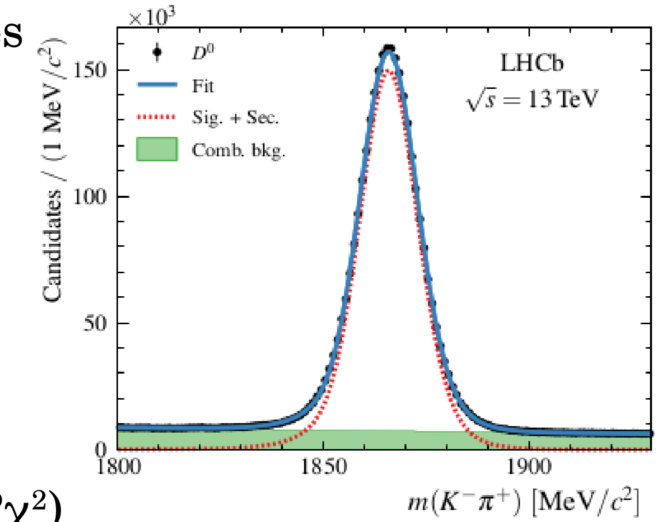
FONLL: Cacciari *et al.*, EPJ C75 (2015) no.12, 610

LHCb: Open Charm Production

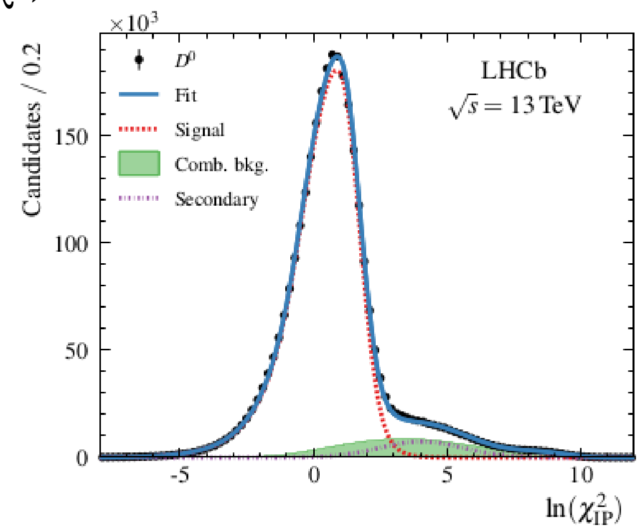
JHEP 1603 159, JHEP 1609 013, arXiv:1510.01707 (ERR. SUB.)

- D^0, D^+, Ds^+ and D^{*+} cross sections
- D meson cross-sections now measured at 3 energies

$\sqrt{s} = 7\,\text{TeV}$: $\mathcal{L}_{\text{int}} = 15\,\text{nb}^{-1}$
Nucl.Phys. B871 (2013) 1-20,
$\sqrt{s} = 13\,\text{TeV}$: $\mathcal{L}_{\text{int}} = 5\,\text{pb}^{-1}$
JHEP 1603 159, JHEP 1609 013,
$\sqrt{s} = 5\,\text{TeV}$: $\mathcal{L}_{\text{int}} = 9\,\text{pb}^{-1}$
arXiv:1610.02230 [hep-ex], submitted to JHEP.



- Separation of prompt/secondary charm with log($IP\chi^2$)
- Secondary component shows at higher $IP\chi^2$

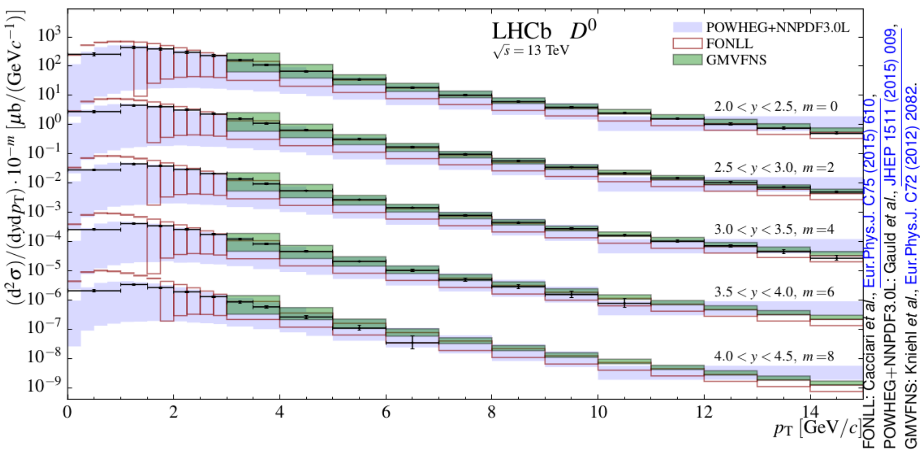


D^0 production at $\sqrt{s} = 13$ TeV (JHEP 1603 (2016) 159)

LHCb: Open Charm Production

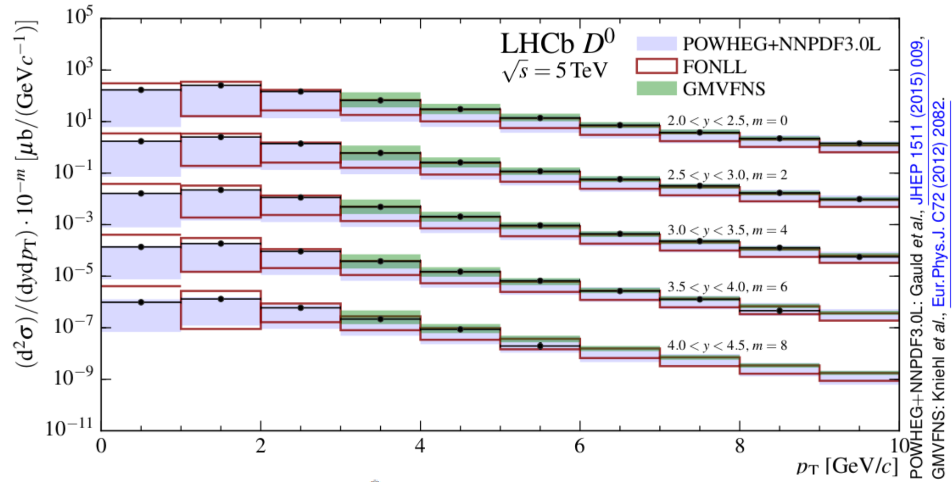
JHEP 1603 159, JHEP 1609 013, arXiv:1510.01707 (ERR. SUB.)
arXiv:1610.02230, submitted to JHEP

Prompt D^0 cross sections at 13TeV



$$
\begin{aligned}
\sigma(pp \to D^0 X) &= 2072 \pm 2 \pm 124\,\mu\text{b} \\
\sigma(pp \to D^+ X) &= 834 \pm 2 \pm 78\,\mu\text{b} \\
\sigma(pp \to D_s^+ X) &= 353 \pm 9 \pm 76\,\mu\text{b} \\
\sigma(pp \to D^{*+} X) &= 784 \pm 4 \pm 87\,\mu\text{b}
\end{aligned}
$$

Prompt D^0 cross sections at 5TeV



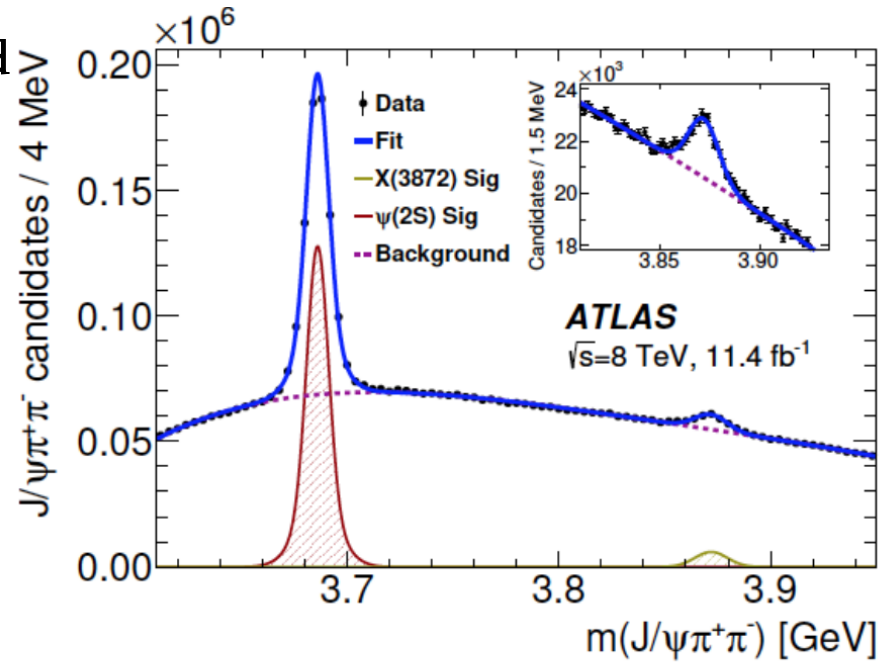
$$
\begin{aligned}
\sigma(pp \to D^0 X) &= 1004 \pm 3 \pm 54\,\mu\text{b} \\
\sigma(pp \to D^+ X) &= 402 \pm 2 \pm 30\,\mu\text{b} \\
\sigma(pp \to D_s^+ X) &= 170 \pm 4 \pm 16\,\mu\text{b} \\
\sigma(pp \to D^{*+} X) &= 421 \pm 5 \pm 36\,\mu\text{b}
\end{aligned}
$$

Production of ψ(2S) and X(3872) at 8 TeV

ATLAS, JHEP01 (2017) 117

- Structure of X(3872) → debate ongoing
- Improve our understanding with precision measurements
- Mass, width and production cross-section

- ATLAS analysis uses 2012 data (11.4 fb^{-1})
- $|y|<0.75$ and $10 < p_T < 70$GeV
- ψ(2S) as control sample
- Final state $J/\psi\,(\mu^+\mu^-)\pi^+\pi^-$
- Prompt/non-prompt components separated by pseudo-lifetime (in transverse plane)



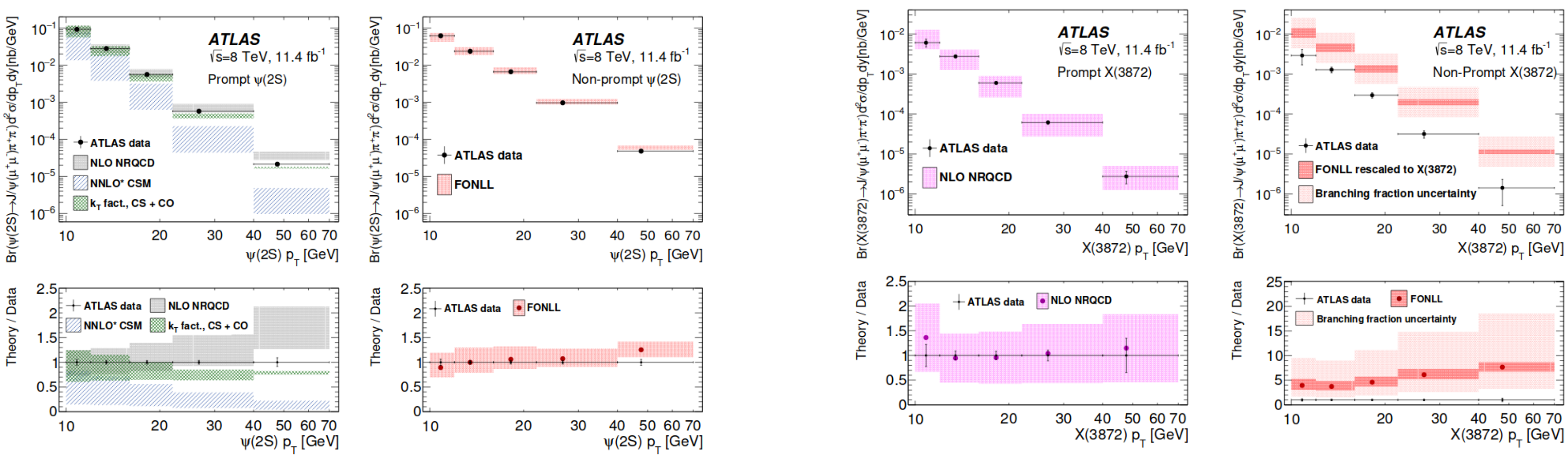
Production of ψ(2S) and X(3872) at 8 TeV

ATLAS, JHEP01 (2017) 117

- ψ(2S) production
  - Good agreement with NLO NRQCD for prompt
  - Good agreement with FONLL for non-prompt
- X(3872) production
  - Prompt X(3872) good agreement with NLO NRQCD calculations
  - But FONLL overestimates non-prompt X(3872) production

$$R_B = \frac{\mathcal{B}(B\to X(3872)+\text{any})\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)}{\mathcal{B}(B\to\psi(2S)+\text{any})\mathcal{B}(\psi(2S)\to J/\psi\pi^+\pi^-)} = (3.95\pm0.32(\text{stat})\pm0.08(\text{sys}))\times10^{-2}$$

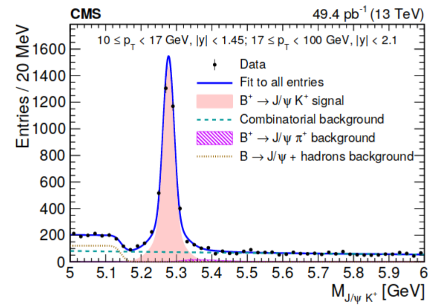
ψ(2S) prompt | ψ(2S) non-prompt | X(3872) prompt | X(3872) non-prompt



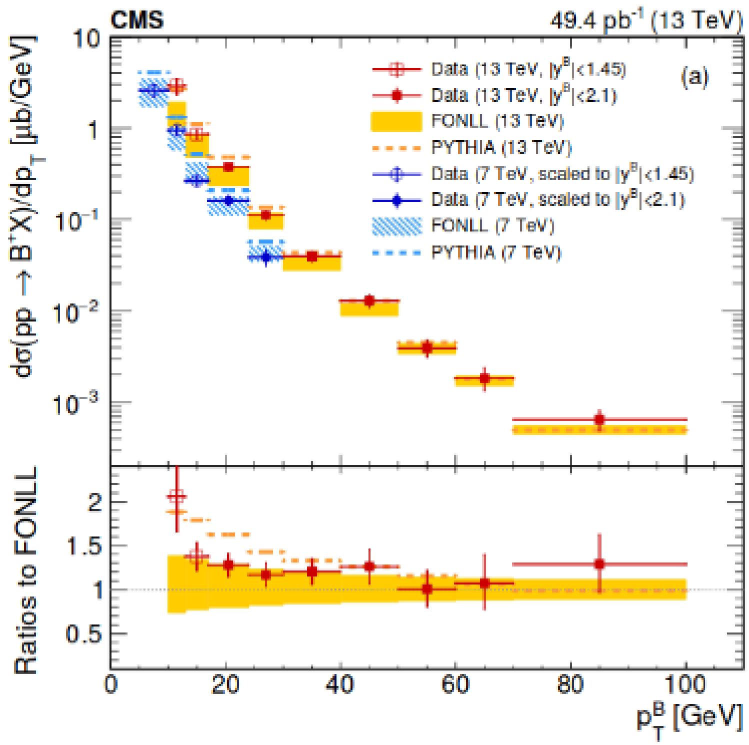
CMS: B+ production at 13TeV

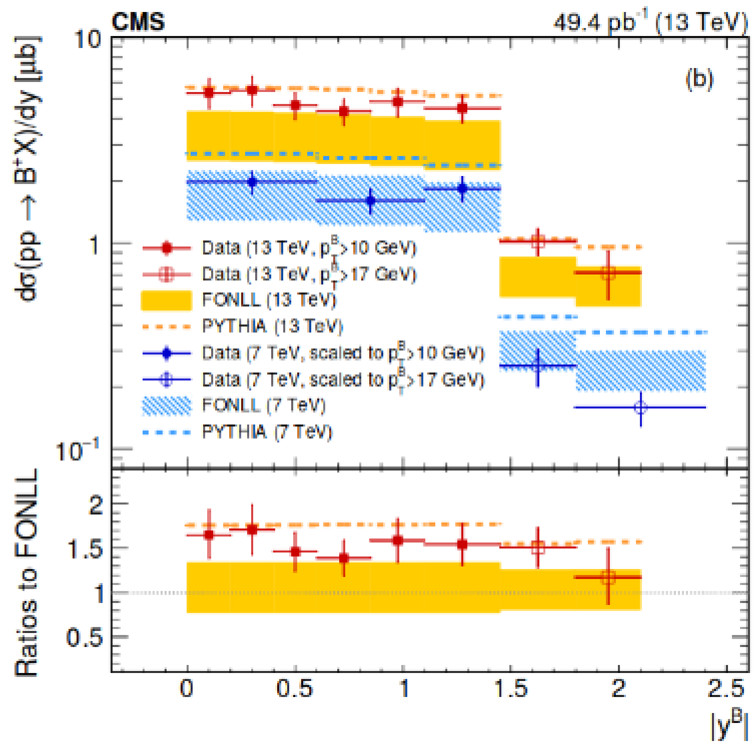
arXiv:1609.00873

- Total and differential cross sections for inclusive production
- Use only the exclusive decay channel $B^+ \to J/\psi K^+$
- Integrated luminosity of 49.4 pb^{-1}



	n_{sig}	$A\epsilon$ [%]	σ [μb]	FONLL [μb]	PYTHIA [μb]
Inclusive bin	3477^{+86}_{-84}	3.9 ± 0.5	$14.9 \pm 0.4 \pm 2.0 \pm 0.4$	$9.9^{+3.3}_{-2.2}$	17.2



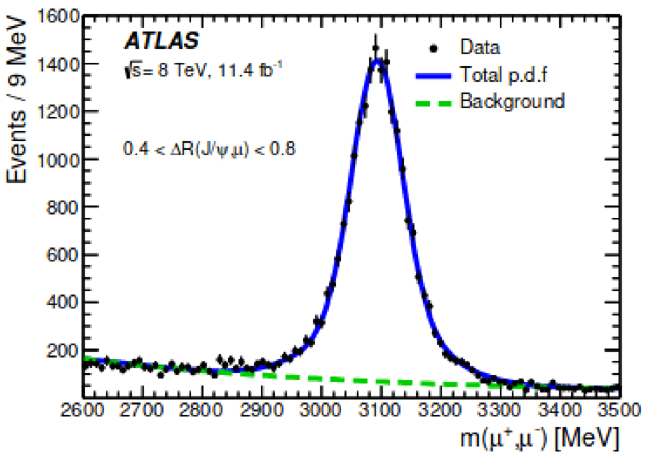


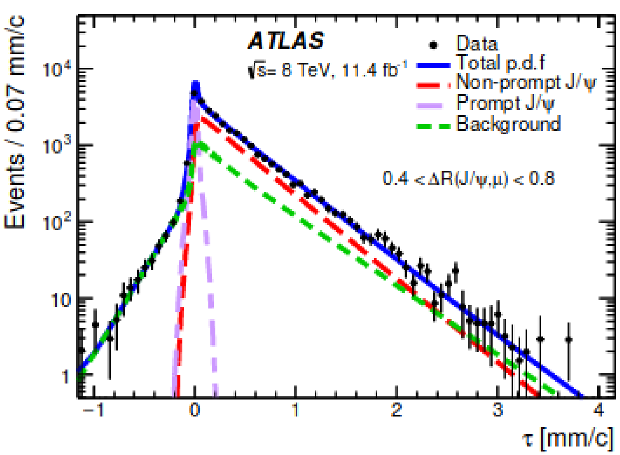
ATLAS:b-hadron pair production at 8 TeV

arXiv:1705.03374

- Integrated luminosity of 11.4 fb^{-1}
- b-hadron selected requiring:
  - first b-hadron → $J/\psi(\to\mu\mu)$+X
  - second b-hadron → μ+X
  - Very convenient 3muon final state
- Parameterise in terms of several kinematic variables
- BDT based selection
- Results compared with predictions from many generators

$$\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X)) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst})\ \text{nb}$$

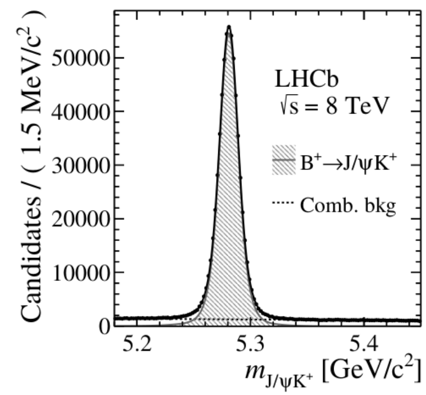




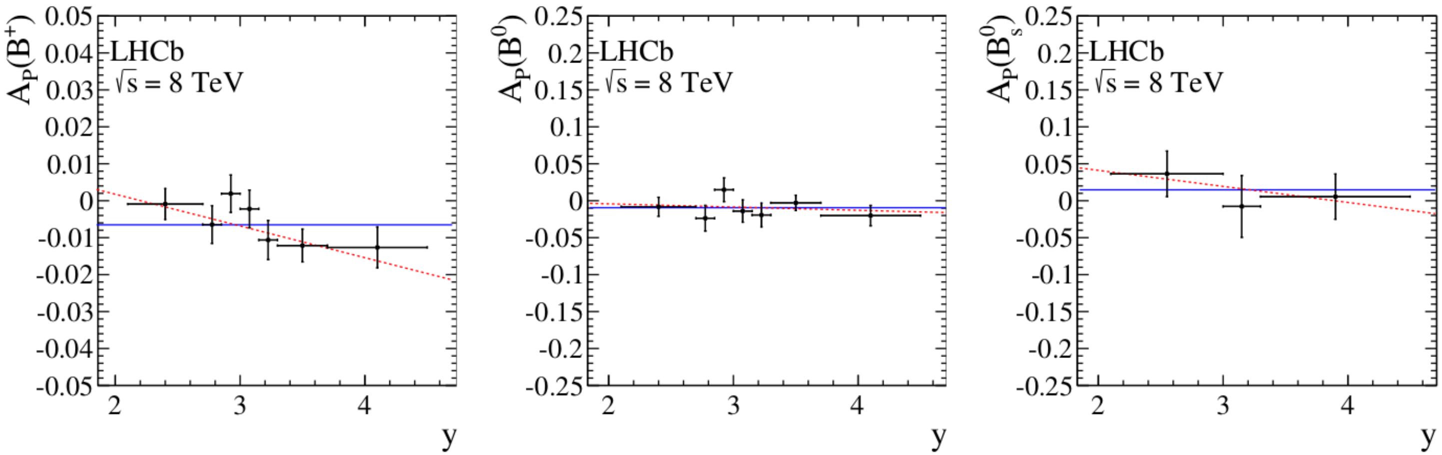
B-hadron production asymmetries

- Pair production of $b\overline{b}$ → valence quarks introduce asymmetries
- Important inputs for precise CP violation measurements
- Parameterise asymmetry wrt p_T and y

LHCb
arXiv:1703.08464



$$A_{\mathrm{P}} \equiv \frac{\sigma(\overline{H}_b) - \sigma(H_b)}{\sigma(\overline{H}_b) + \sigma(H_b)}$$



- Numerical results integrating over fiducial range of measurements

	$A_{\mathrm{P}}\ \sqrt{s} = 7\,\mathrm{TeV}$	$A_{\mathrm{P}}\ \sqrt{s} = 8\,\mathrm{TeV}$
B^+	$-0.0023 \pm 0.0024 \pm 0.0037$	$-0.0074 \pm 0.0015 \pm 0.0032$
B^0	$0.0044 \pm 0.0088 \pm 0.0011$	$-0.0140 \pm 0.0055 \pm 0.0010$
B_s^0	$-0.0065 \pm 0.0288 \pm 0.0059$	$0.0198 \pm 0.0190 \pm 0.0059$
Λ_b^0	$-0.0011 \pm 0.0253 \pm 0.0108$	$0.0344 \pm 0.0161 \pm 0.0076$

CEP

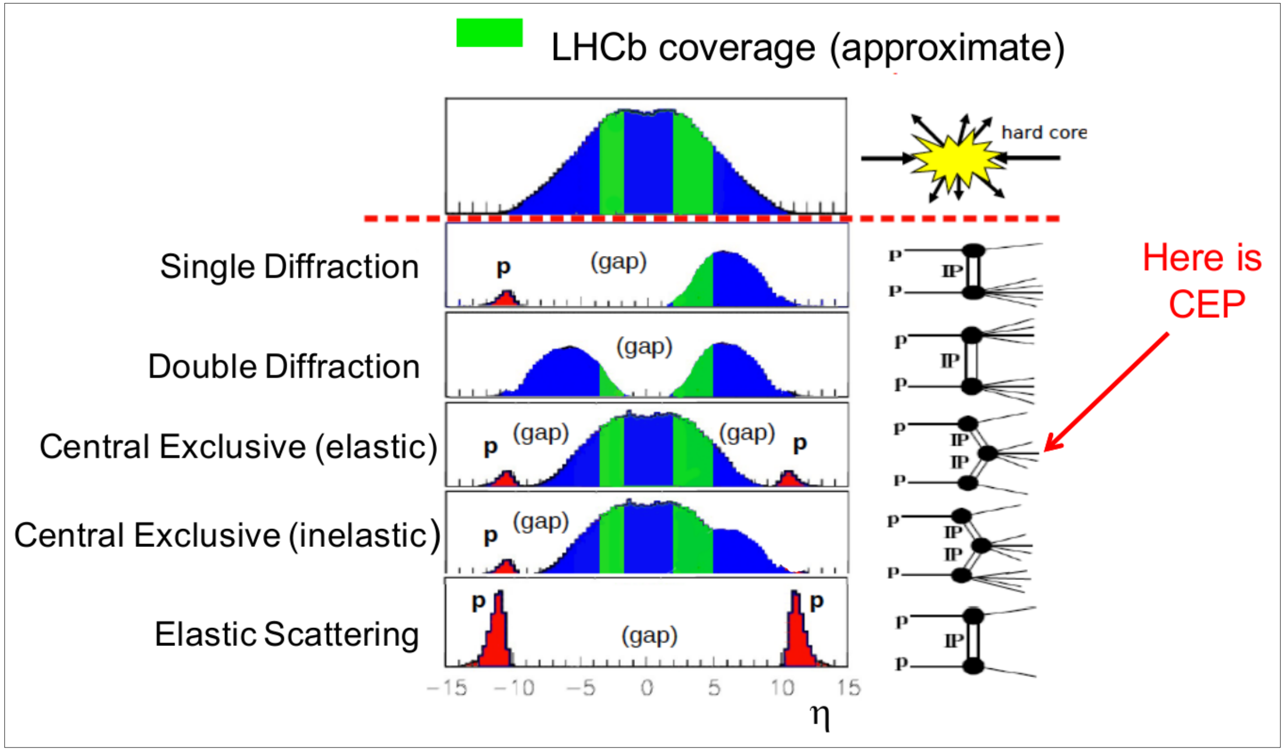
Central Exclusive Production at LHC

CEP – Introduction

- Central Exclusive Production can be done at LHC → What do we look for?

$$pp \rightarrow p + X + p \text{ (rapidity gaps and protons intact)}$$

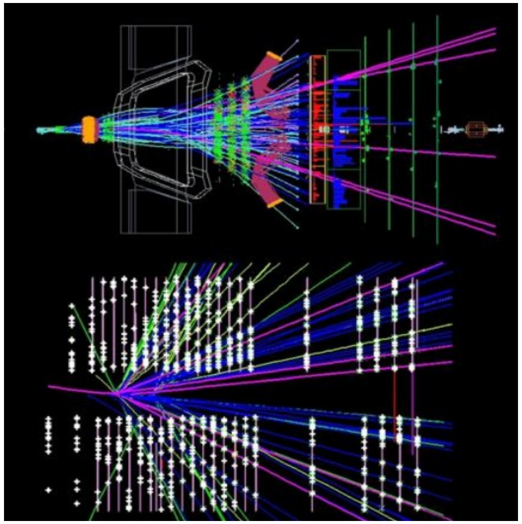
- Colourless objects in QCD, Very low PT objects, Clean experimental environment
- Rich Physics: Photon-Pomeron, Double-Pomeron, Photoproduction, Glueballs, Exotica
- Just to give an idea of "coverage" of various processes (e.g. compared with LHCb)



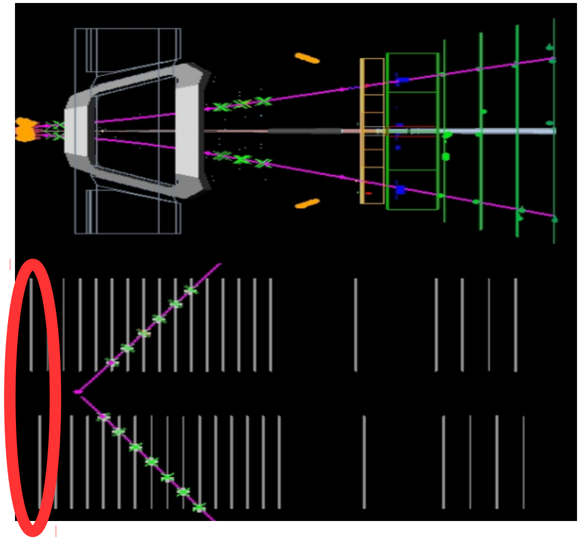
CEP - Signatures

- Clearly one needs a low pileup → LHCb or dedicated high β^* runs
- How do we select / trigger these events?
- Protons → escape in the beam pipe
- Events with low activity in detector
- In LHCb: we can look at backwards tracks in the VELO (some η coverage)
- Unique features compared to "standard" LHC event → very attractive

Typical Event



CEP-like event: 2muons



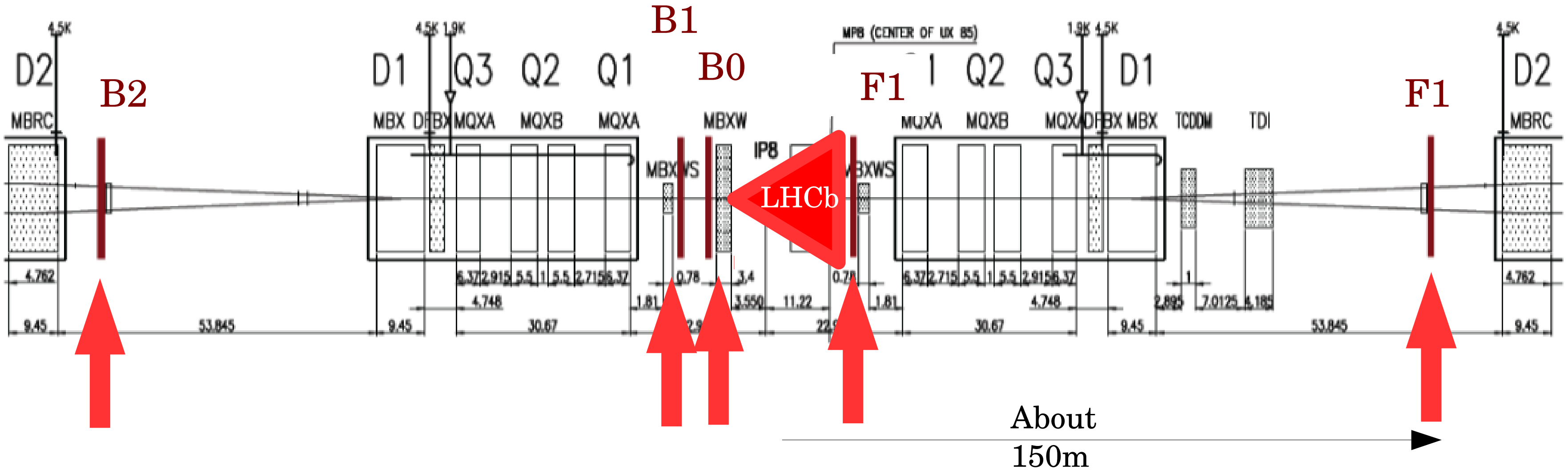
LHCb is forward, but we can detect backward tracks in the VELO (no p information for those)

Herschel Detector at LHCb

- New detector installed for Run2 in 2015.
- Five planes of plastic scintillators in the tunnel
- Use same electronics of Preshower Detector
- Start of 2016: new better electronics installed
- Start of 2017: counters replaced (radiation ageing)

- Increase η coverage in the forward/backward region
- IDEA is to **veto events with activity at high η**

To get an idea on distances



LHC-wide effort

- Forward detectors installed/co-used by other collaborations as well
- CMS+TOTEM (special runs), ATLAS+ALPHA
- Mutual interests documented in joined document → J. Phys. G: Nucl. Part. Phys.43(2016)110201
- A lot of effort both theoretical and experimental communities
- Two methods
  - Tag the protons and momentum balance
  - Veto forward activity and fit the pt^2 spectrum

CERN-PH-LPCC-2015-001
SLAC-PUB-16364
DESY 15-167

September 3 2015

LHC Forward Physics

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

CMS and TOTEM

Excellent calometric rapidity coverage:

- Hadronic Forward Calorimeter & CASTOR
- ZDC (zero degree calorimeter)

Forward Shower Counters

Embedded Totem telescopes T1/T2 and Roman Pots

CT-PPS (CMS-TOTEM Proton Precision Spectrometer) for double arm proton tagging at high pile-up

CMS-TOTEM Precision Proton Spectrometer (CT-PPS)
Now replaced by pixels
2016 JINST 11 C11027

ATLAS and ALFA/AFP

Calorimetry at high η

- LUCID (LUminosity Cerenkov Integrating Detector)
- ZDC

ALFA (Absolute Luminosity for ATLAS): RP stations placed 240m from IP

CEP-type analyses at LHCb

- LHCb can't "reconstruct" the forward/backward intact protons
- Select signal requiring no other activity in the detector
- Extract purity looking at the pt^2 distribution (CEP/nonCEP fractions)
- Irreducible backgrounds dominated by inelastic backgrounds
- Undetectable events where the proton breaks up in the forward direction

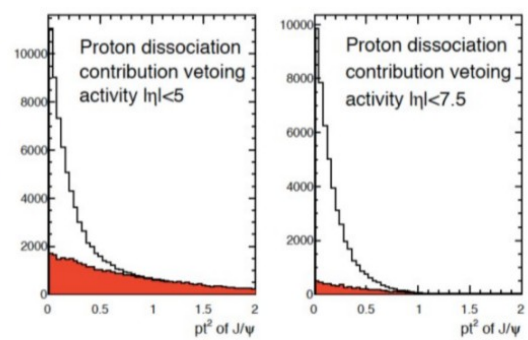
Example of 2013 Jspi paper
[JPG: Nucl. Part. Phys. 41 (2014) 055002]
NO HERSCHEL

Updated measurements of exclusive J/ψ and $\psi(2S)$ production cross-sections in pp collisions at $\sqrt{s} = 7$ TeV

Correlated uncertainties expressed as a percentage of the final result	
ϵ_{sel}	1.4%
Purity determination (J/ψ)	2.0%
Purity determination ($\psi(2S)$)	13.0%
$^*\epsilon_{single}$	1.0%
*Acceptance	2.0%
*Shape of the inelastic background	5.0%
*Luminosity	3.5%
Total correlated statistical uncertainty (J/ψ)	2.4%
Total correlated statistical uncertainty ($\psi(2S)$)	13.0%
Total correlated systematic uncertainty	6.5%

CERN-PH-EP-2013-233
LHCb-PAPER-2013-059

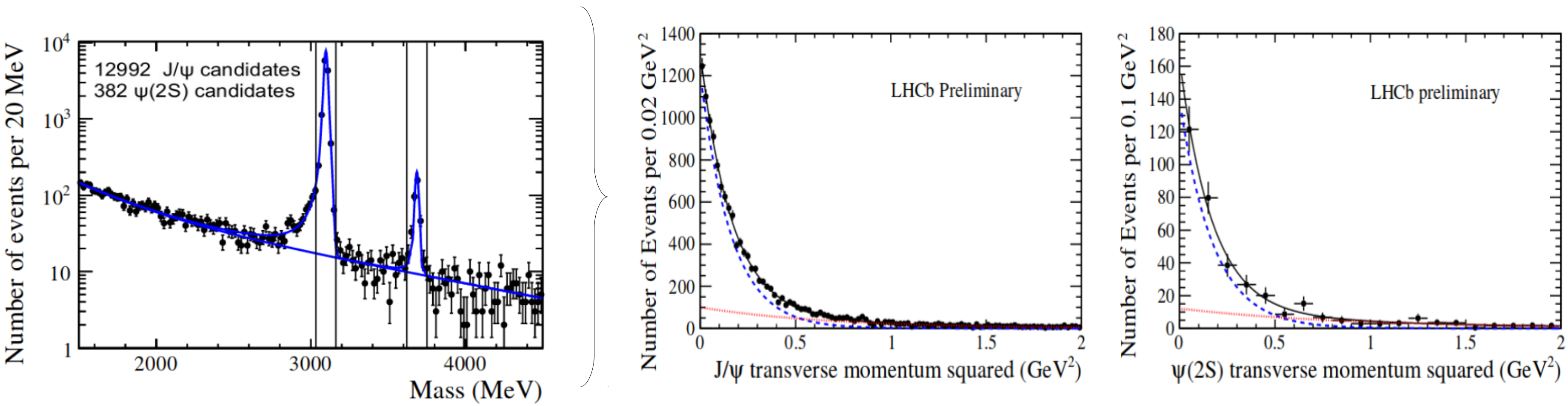
Estimate of potential benefit of vetoeing particles up to η<7.5



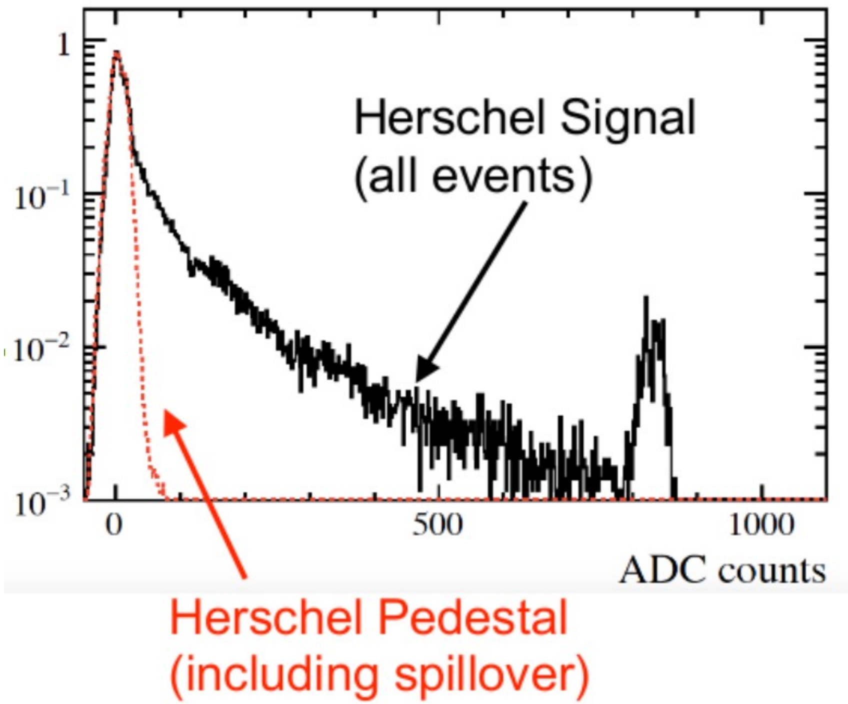
CEP of J/ψ at 13TeV

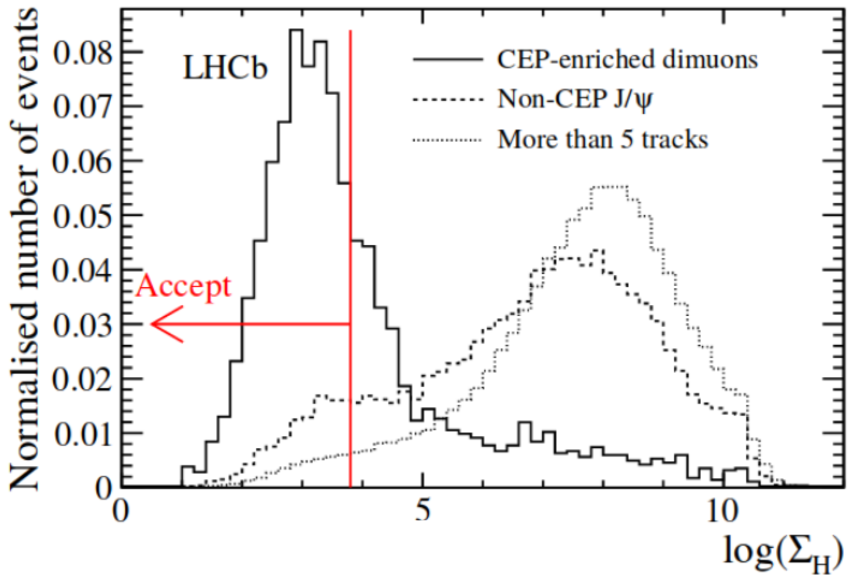
LHCb-CONF-2016-007-001

- **Use 2015 dataset @13TeV (200pb^{-1}) + Herschel information**
- Nearly all numbers (efficiencies, etc) come from data driven approaches
- Selection:
    - Muon Triggers for CEP (require low multiplicity on SPD)
    - Two reconstructed muons with $2 < \eta < 4.5$
    - No additional tracks/energy
    - Within 65 MeV/c^2 of the J/ψ
    - Herschel VETO applied (and validated with different approaches)
    - Background halved relative to previous analyses



CEP of J/ψ at 13TeV





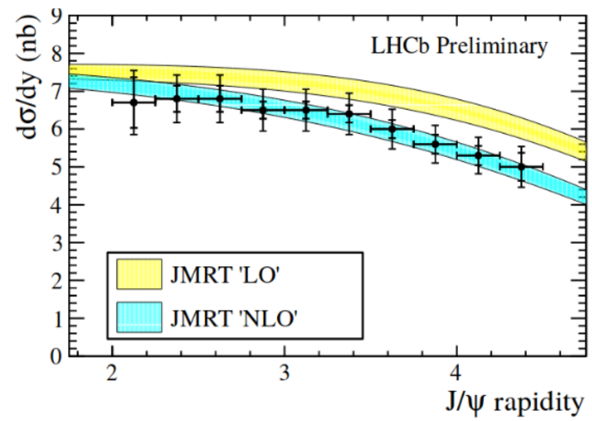
- Clean pedestals and complete suppression of pileup
- Pedestals calibrated using non connected channels
- Quadratic sum of normalised signals (Σ_H) used to create veto
- Response checked against 3 classes of events
- Clear signal/background enhancement

CEP of J/ψ at 13TeV

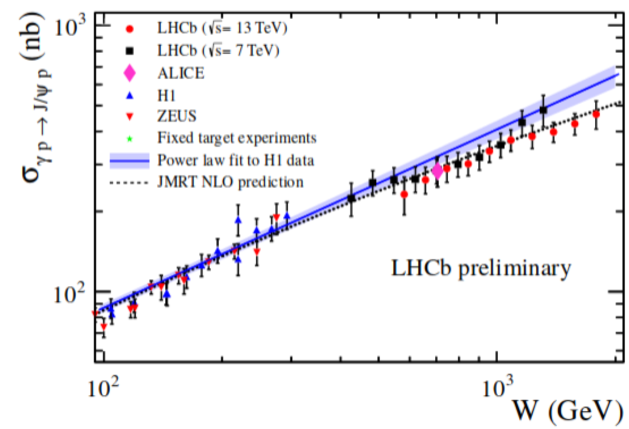
LHCb-CONF-2016-007-001

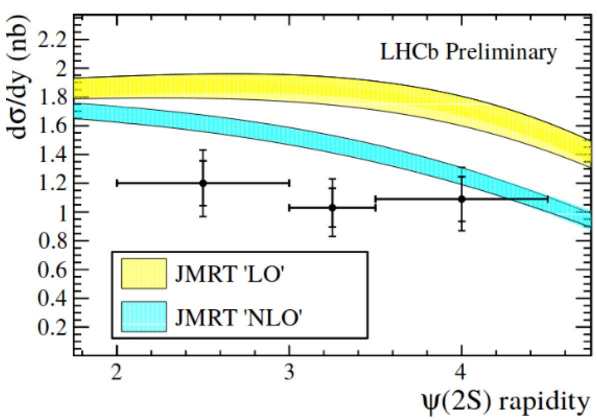
Results in a CONF note

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



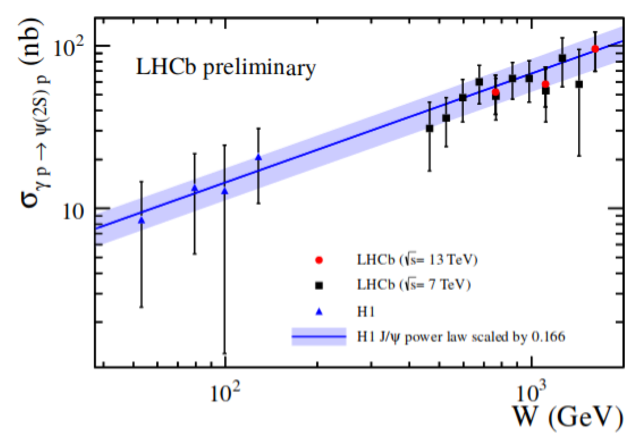
Differential cross section in better agreement with JMRT NLO rather than LO predictions





13 TeV data allows significant extension of the reach in W

Simple power law insufficient but data well described by NLO



Conclusions

LHC is a very good gym for production measurements

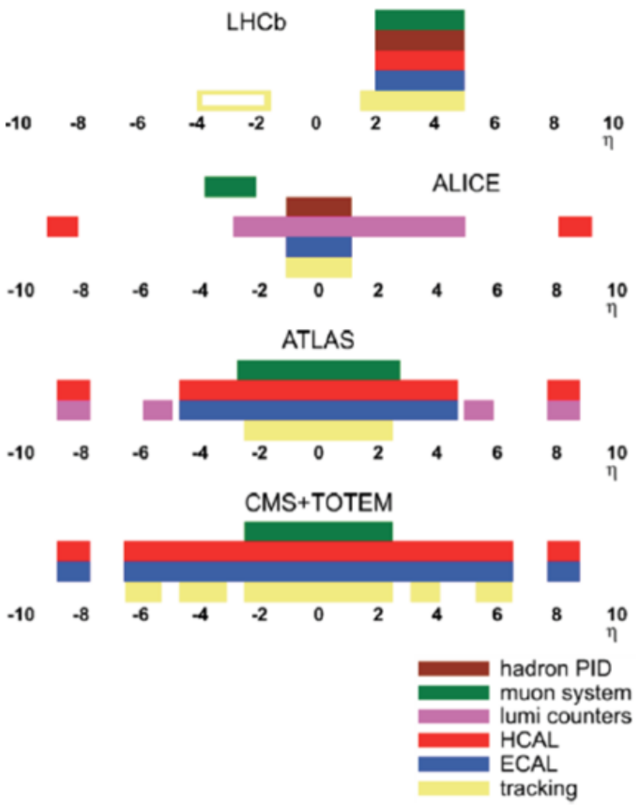
- Many results in the b and c sector updated
- Only had time to cover a very small selection of recent results
- Single and Double meson production measurements
- Different rapidiy ranges are investigated according to detector properties
- Many ongoing analyses: Bc Y production, jet momentum fraction for prompt J/psi

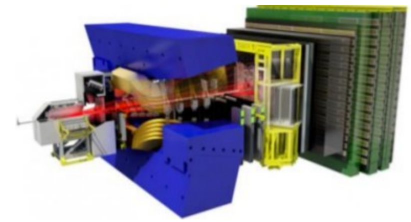
CEP of heavy flavour

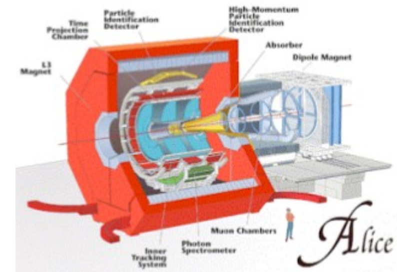
- LHC is essentially a gluon collider
- But also a gamma collider → photoproduction!
- Provides selection rules for production: e.g pomeron-pomeron 0^{++},2^{++}
- In brief, a very good laboratory for clean direct production of many states (exotica?)
- Many other searches are possible!

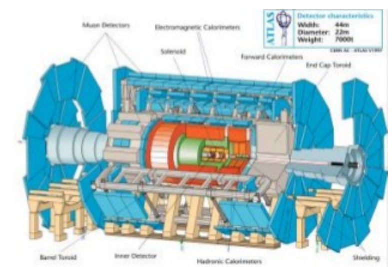
Backup Slides

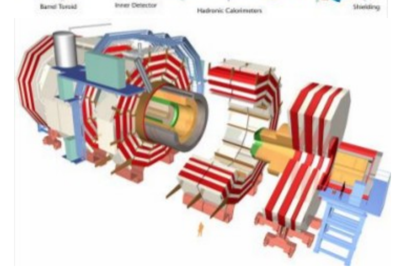
Detector Coverage



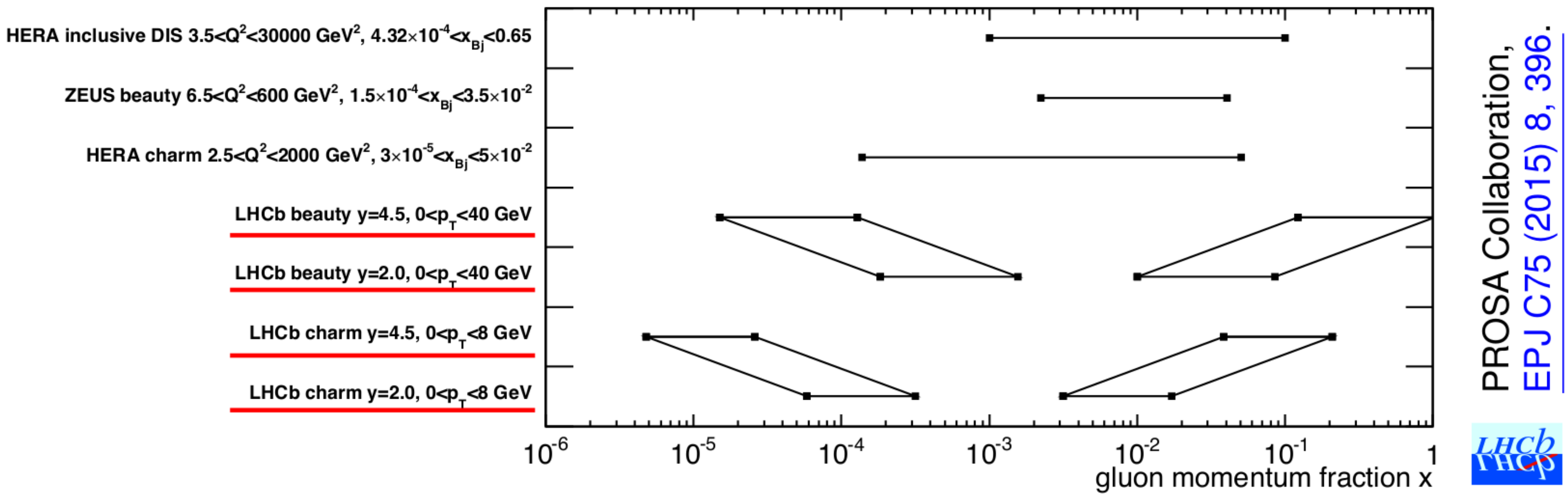








Low-x coverage



LHCb Errata

Affects the following recently updated papers

- Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s}$ = 13 TeV
  JHEP 1603 (2016) 159, JHEP 1609 (2016) 013, arXiv:1510.01707

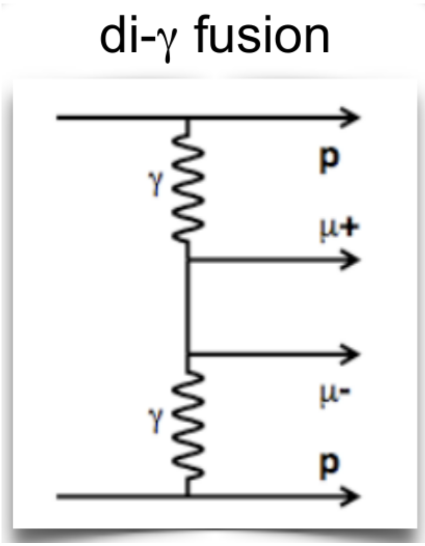
- Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s}$ = 13 TeV
  JHEP 1510 (2015) 172, arXiv:1509.00771

- Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s}$ = 5 TeV
  arXiv:1610.02230, submitted to JHEP

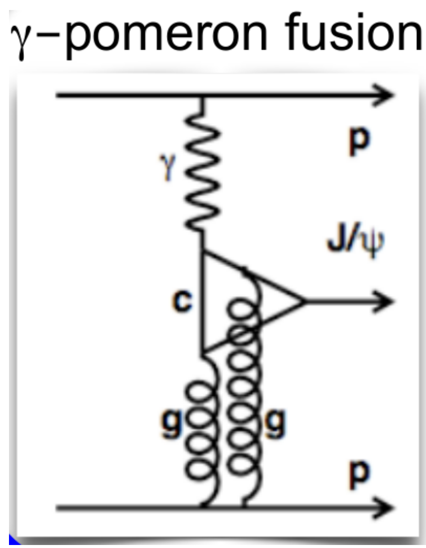
- Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV
  arXiv:1612.07451, submitted to JHEP

Errata have been submitted to JHEP for papers
JHEP 1510 172
JHEP 1603 159
preprints on arXiv have been updated

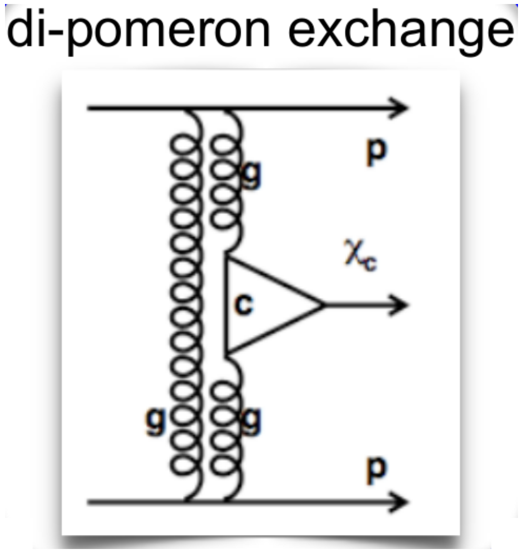
CEP processes



μ + μ - , e + e - , π + π - , W + W -
QED “standard candle” process
continuum lepton pair production



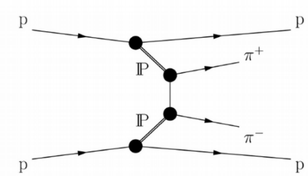
ρ, J/ψ, Y, Z, ...
Photoproduction: Test of QCD and description of diffraction and soft processes. Sensitive to diffractive PDF at very low x (to 5 x 10 -6)



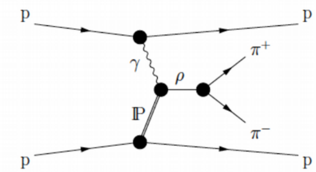
Xc , Xb , π+π- , Dijet, gg, ...
Test of QCD,and hadron spectroscopy
Pomeron content at low Q 2 dominated by gluons; access to scalar and tensor glueballs

Central Exclusive π+π- production

CMS: Dedicated data sample (2010)
with 450 μb^{-1} in low pileup conditions
Large cross sections
Access to spectroscopic study of low mass resonances
search for glueball candidates
Large backgrounds; estimated from calo multiplicities

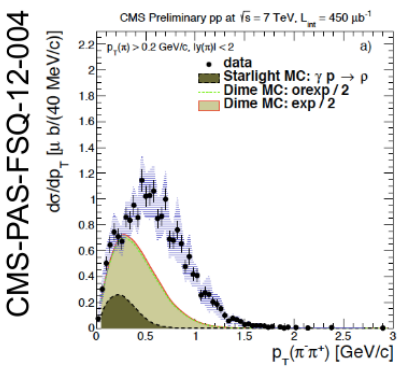


Double Pomeron Exchange - dominant process

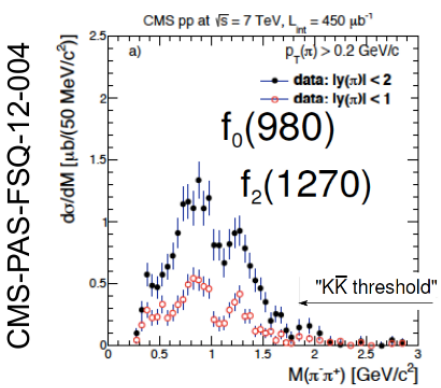


exclusive ρ meson photoproduction

Total cross section: σ_{Vis} = 20.5± 0.3(stat.)± 3.1(sys.)± 0.8(lumi) μb



DPE production predictions from IME MC and STARLIGHT (stacked) data enhancement at higher p_{T})



Differential Cross section,for |y(π)| < 2 and |y(π)| < 1
some evidence of resonant structures

Unfolded cross sections:

$|y(\pi^{\pm})| < 2.0$: $\sigma_{\text{vis}} = 20.5 \pm 0.3\ (\text{stat.}) \pm 3.1\ (\text{sys.}) \pm 0.8\ (\text{lumi})\ \mu\text{b}$

$|y(\pi^{\pm})| < 1.0$: $\sigma_{\text{vis}} = 8.1 \pm 0.2\ (\text{stat.}) \pm 1.2\ (\text{sys.}) \pm 0.3\ (\text{lumi})\ \mu\text{b}$