CENTRAL EXCLUSIVE PRODUCTION

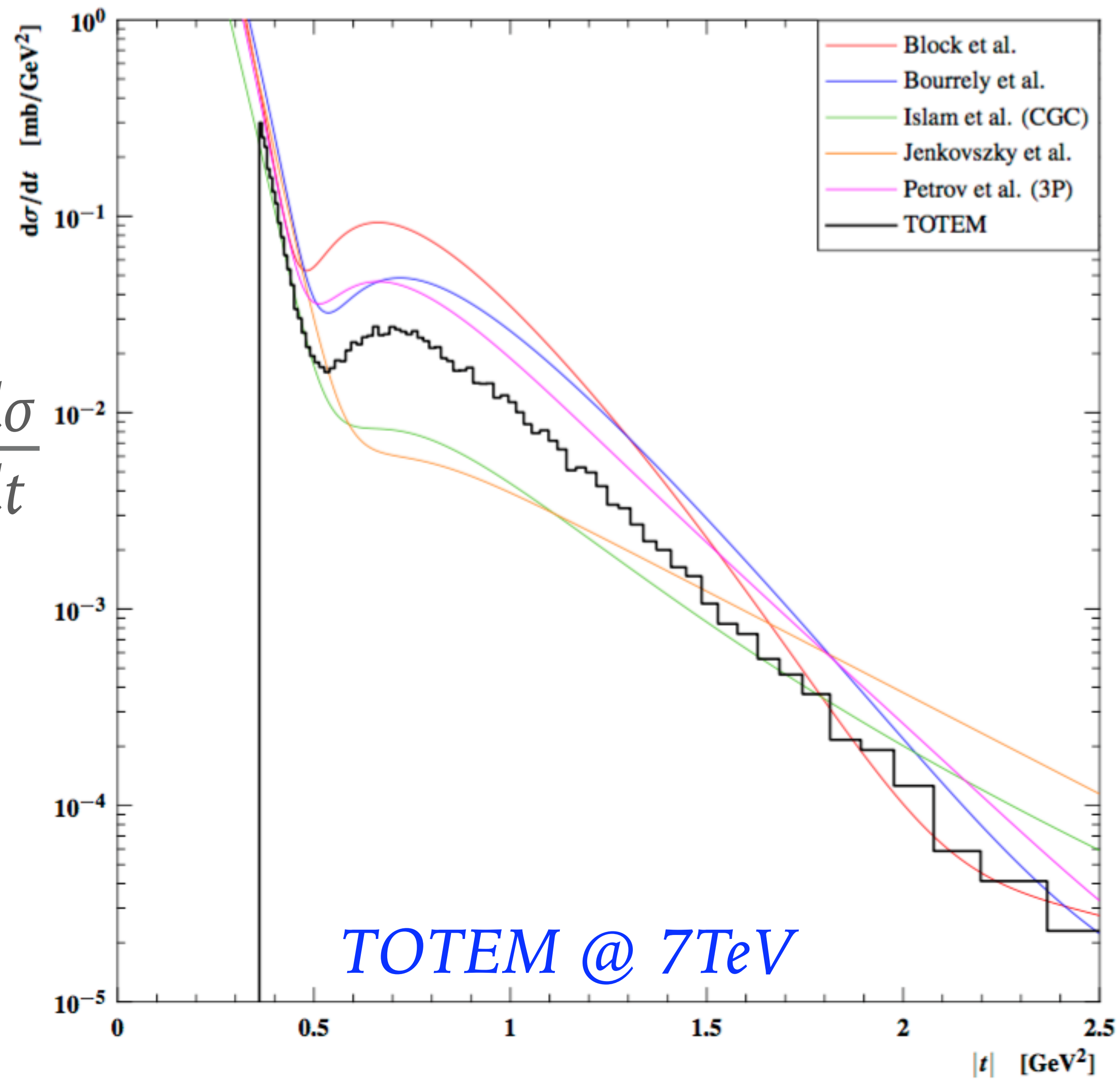
Daniel Johnson

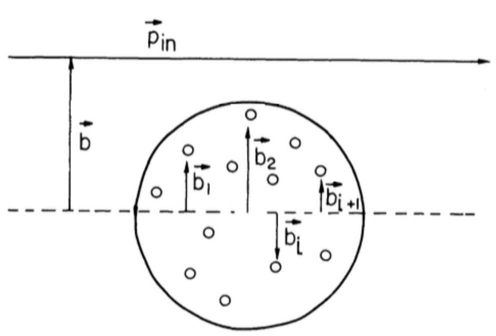
Warwick EPP seminar, 21st January 2016

WHY IS CENTRAL EXCLUSIVE PRODUCTION EXCITING?

Consider the elastic p-p differential cross-section

$$\frac{d\sigma}{dt}$$





$|t|$: square of elastic scatter four-momentum transfer

: inversely related to impact parameter, b

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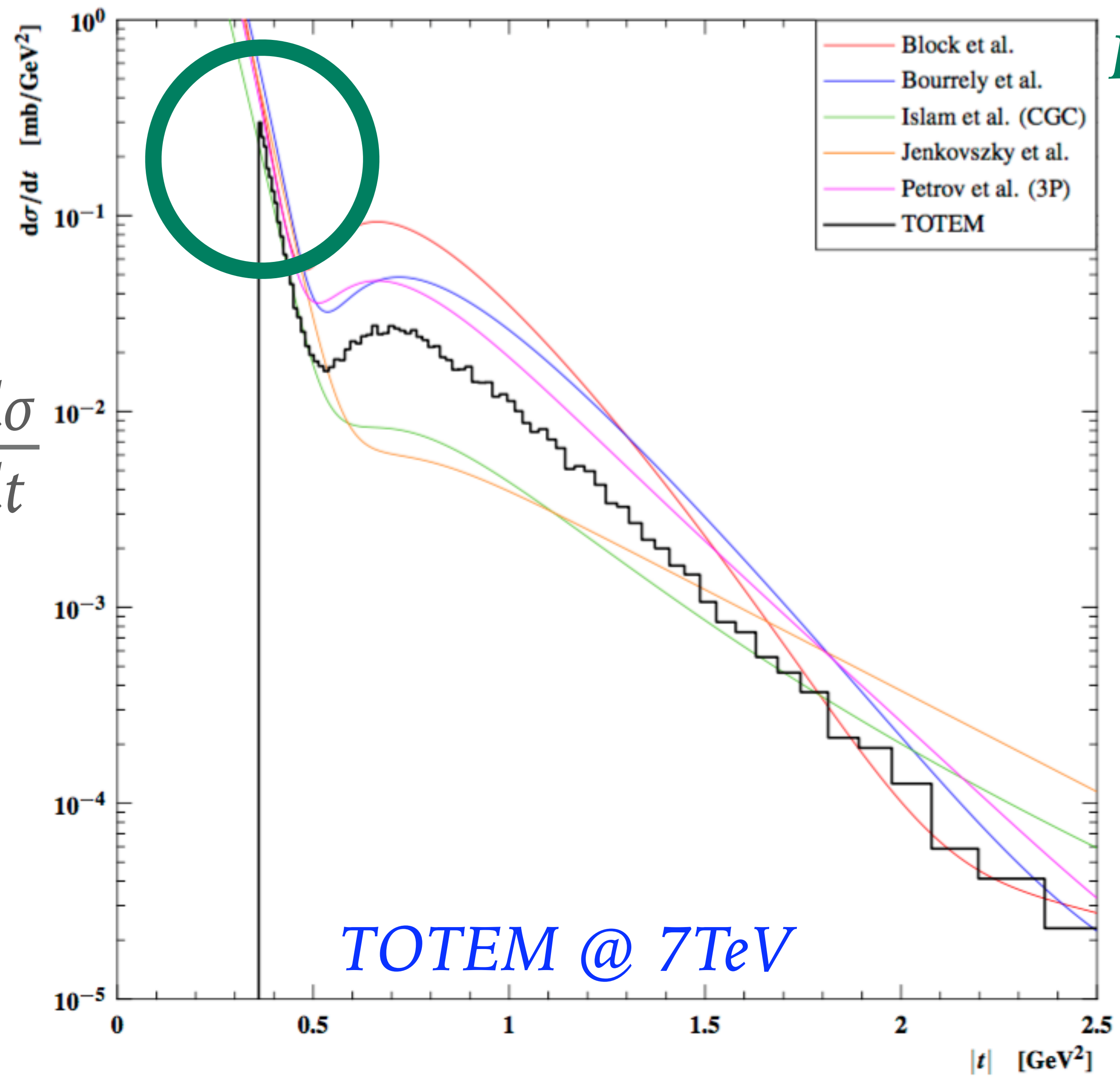

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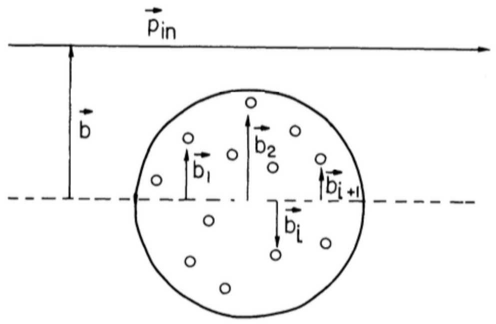

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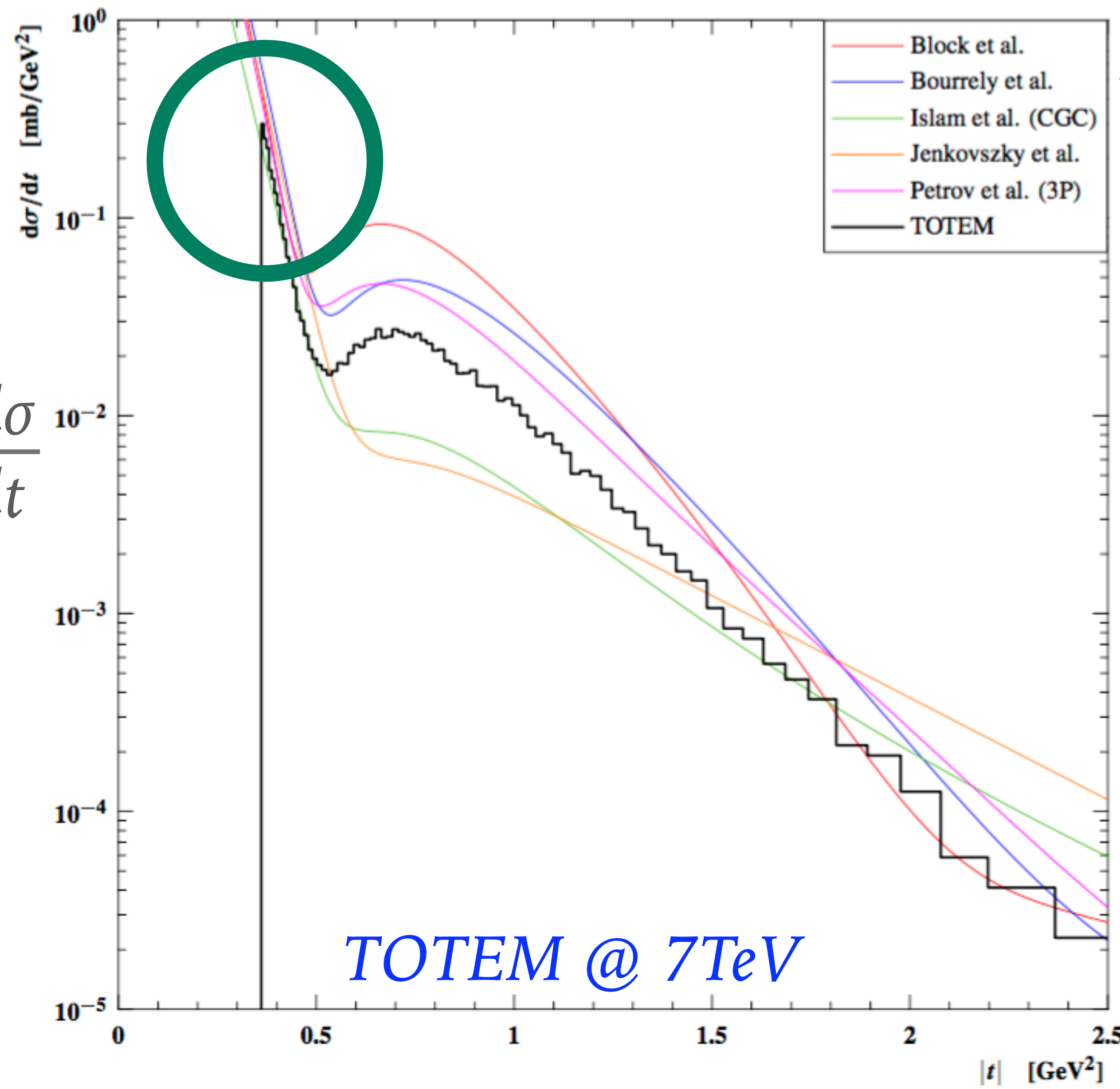

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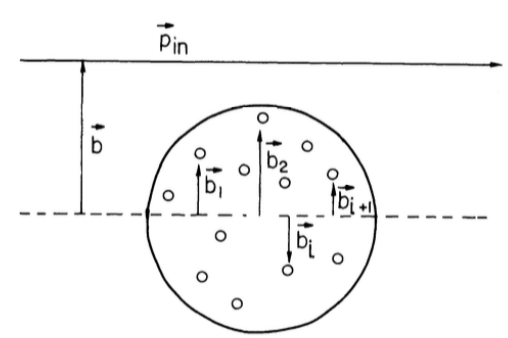

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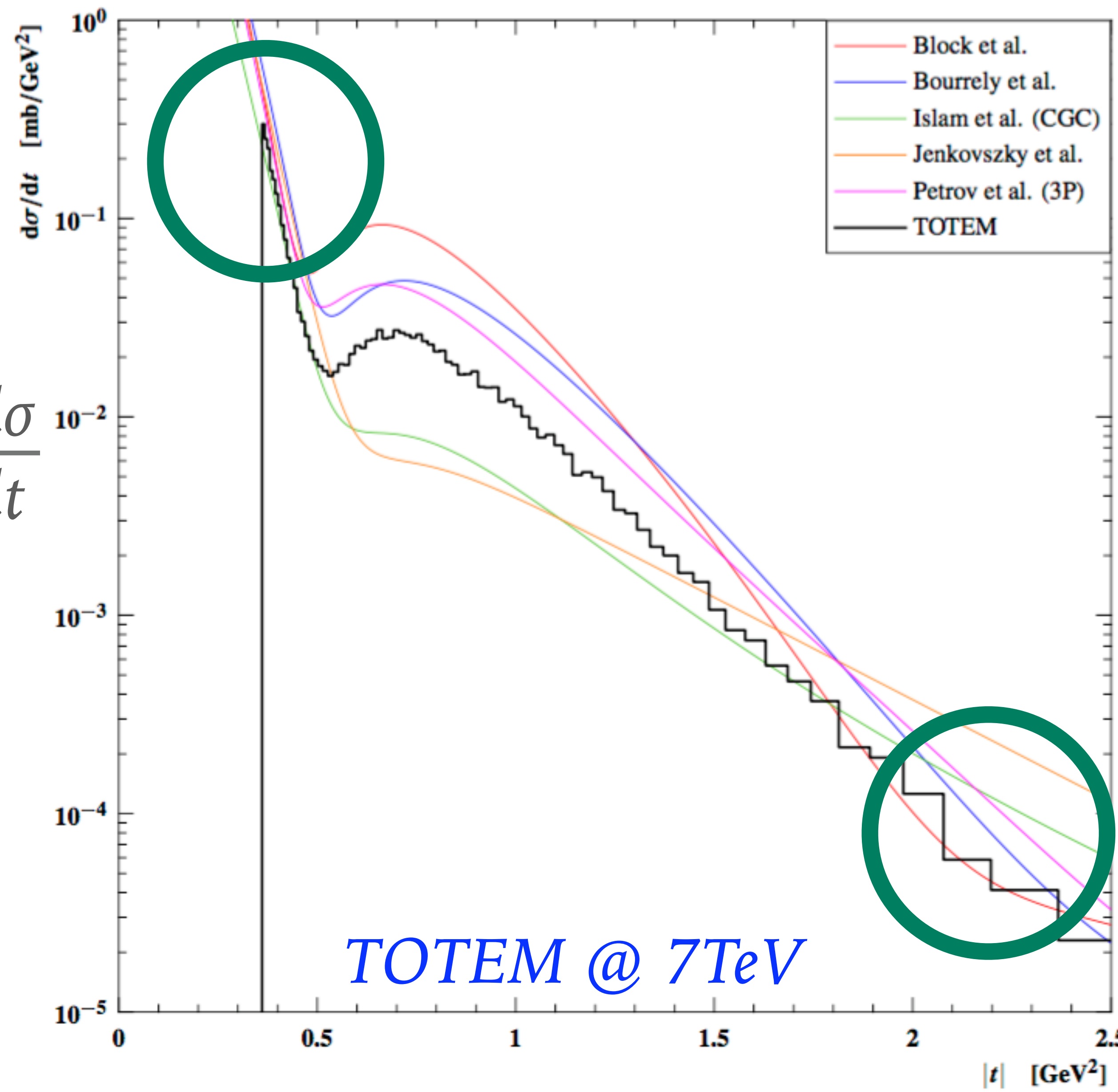

Large b (small t): Coulomb scattering

Small b (high t): Perturbative QCD

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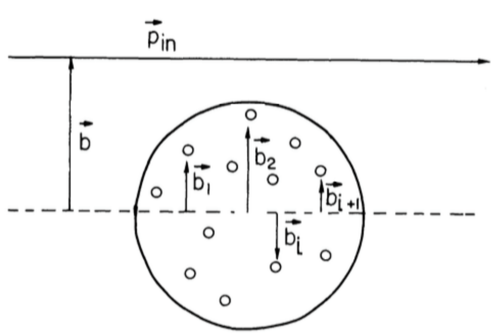

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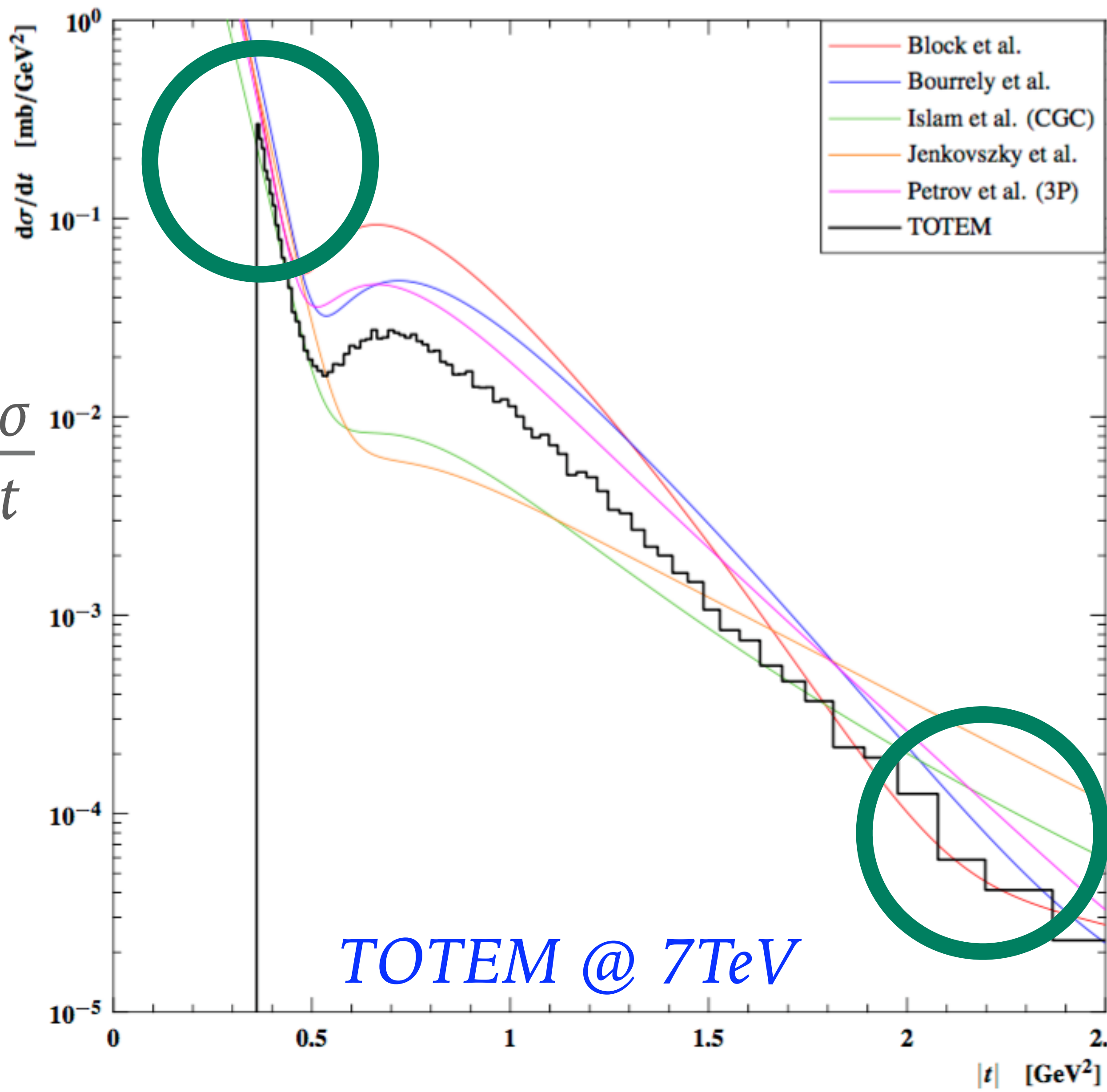

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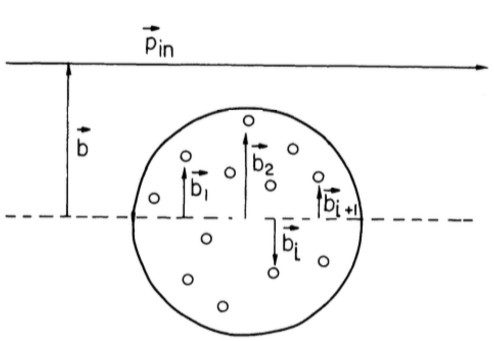

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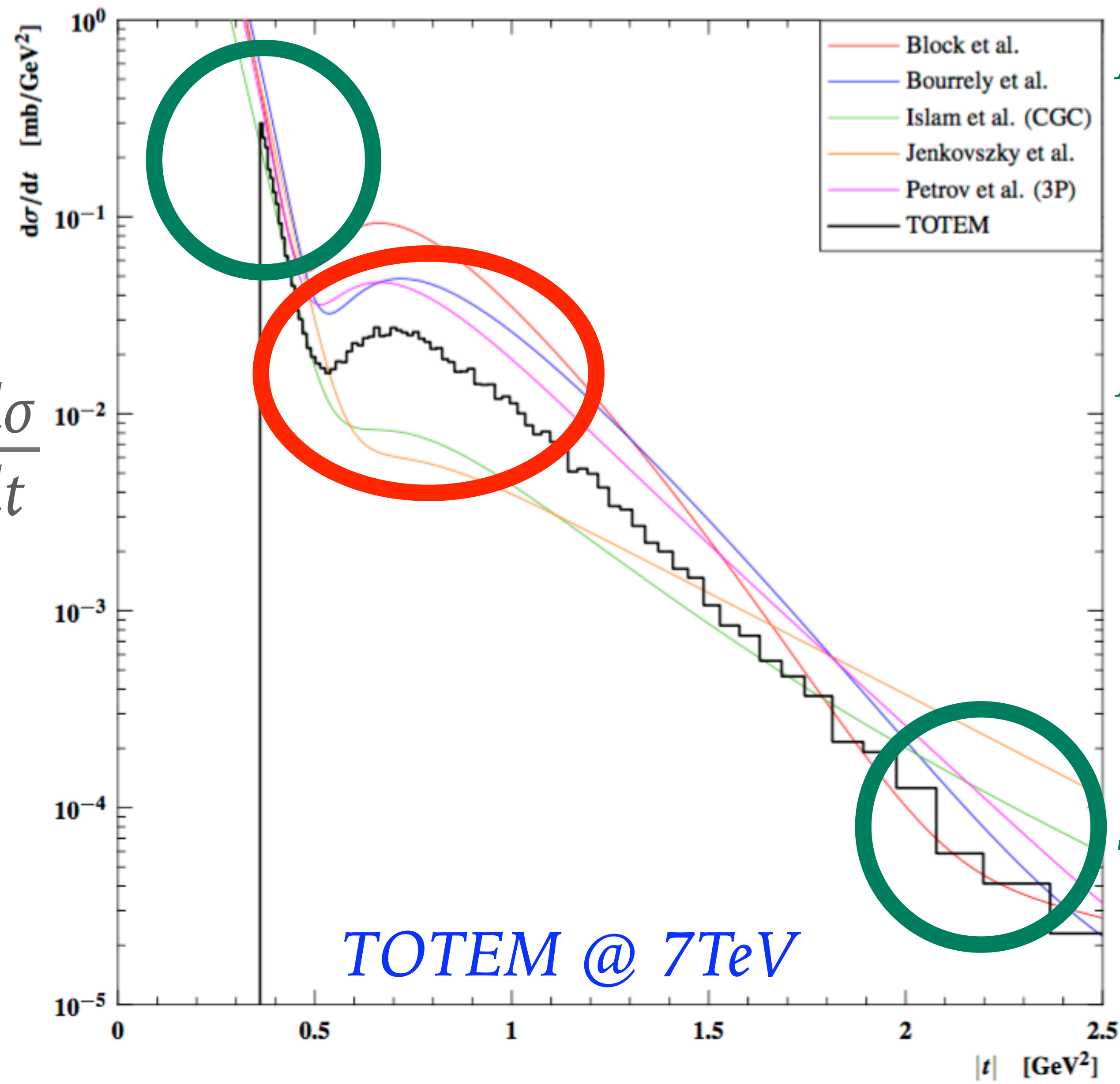

Large b (small t): Coulomb scattering ✓

In between: diffractive minimum

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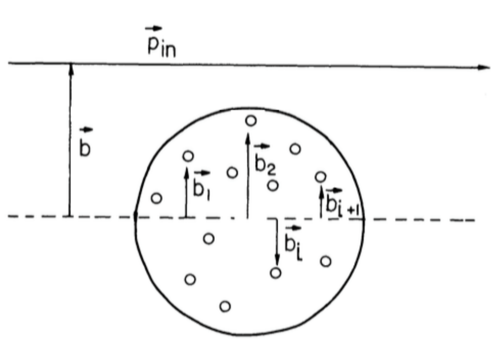

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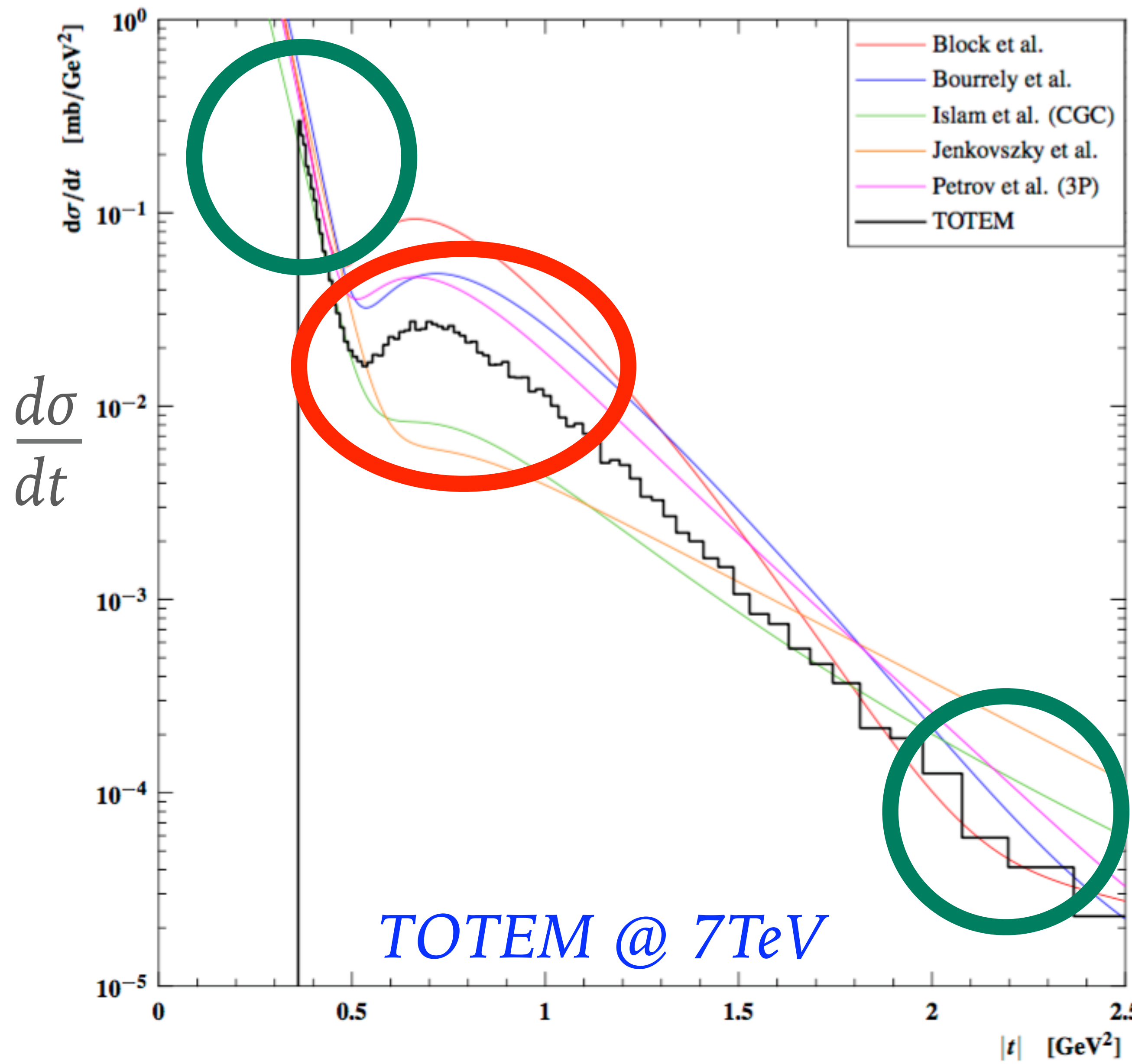

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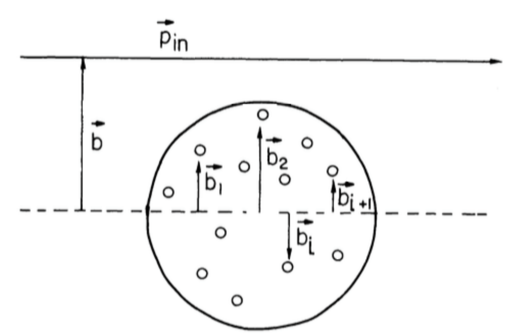

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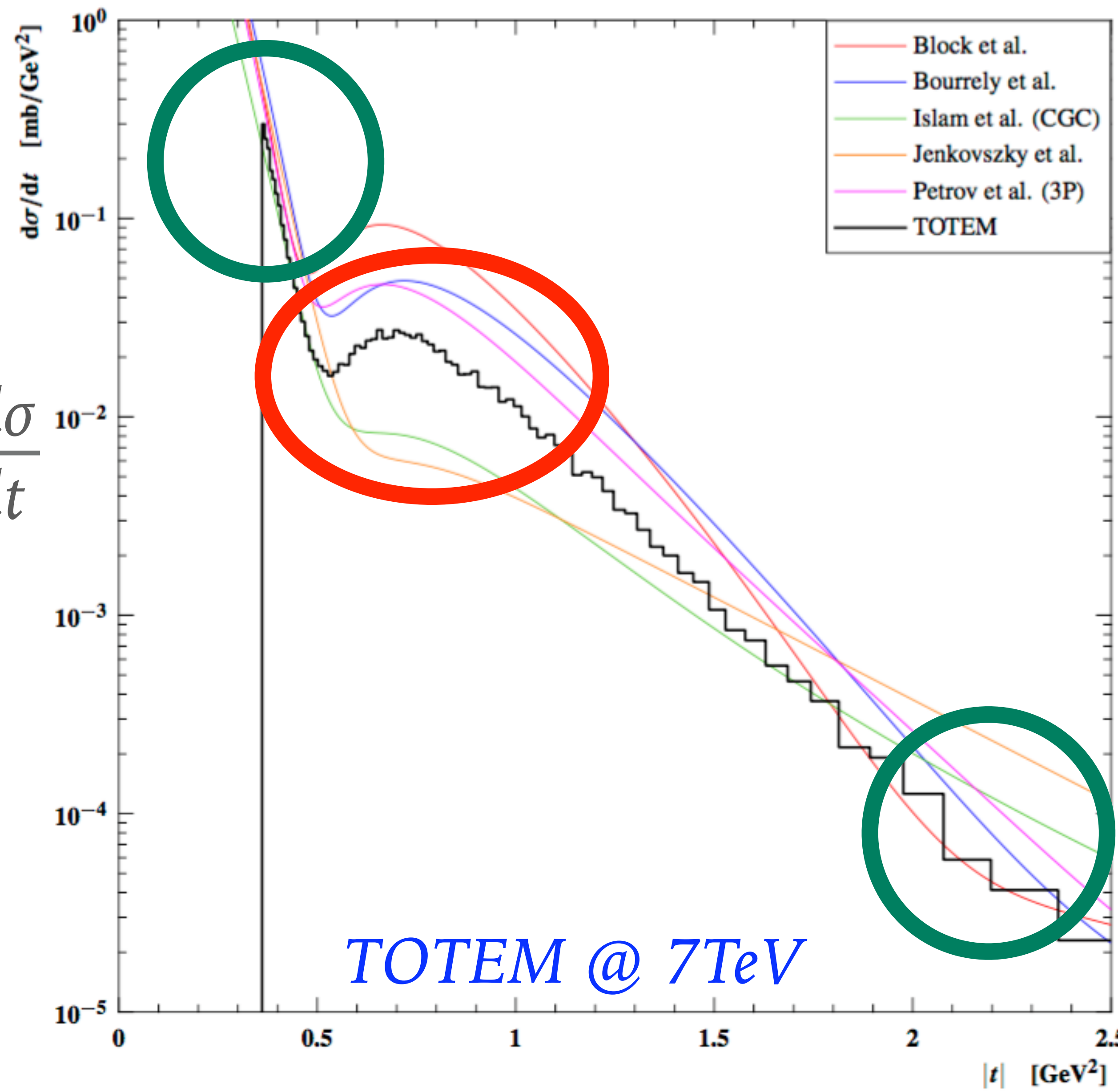

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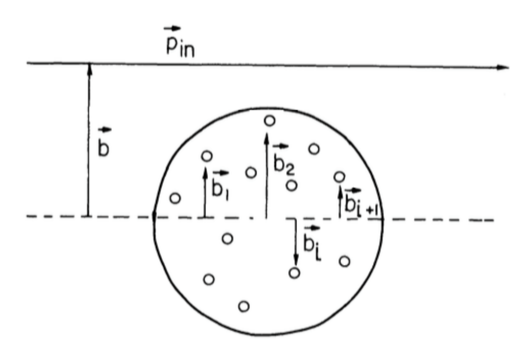

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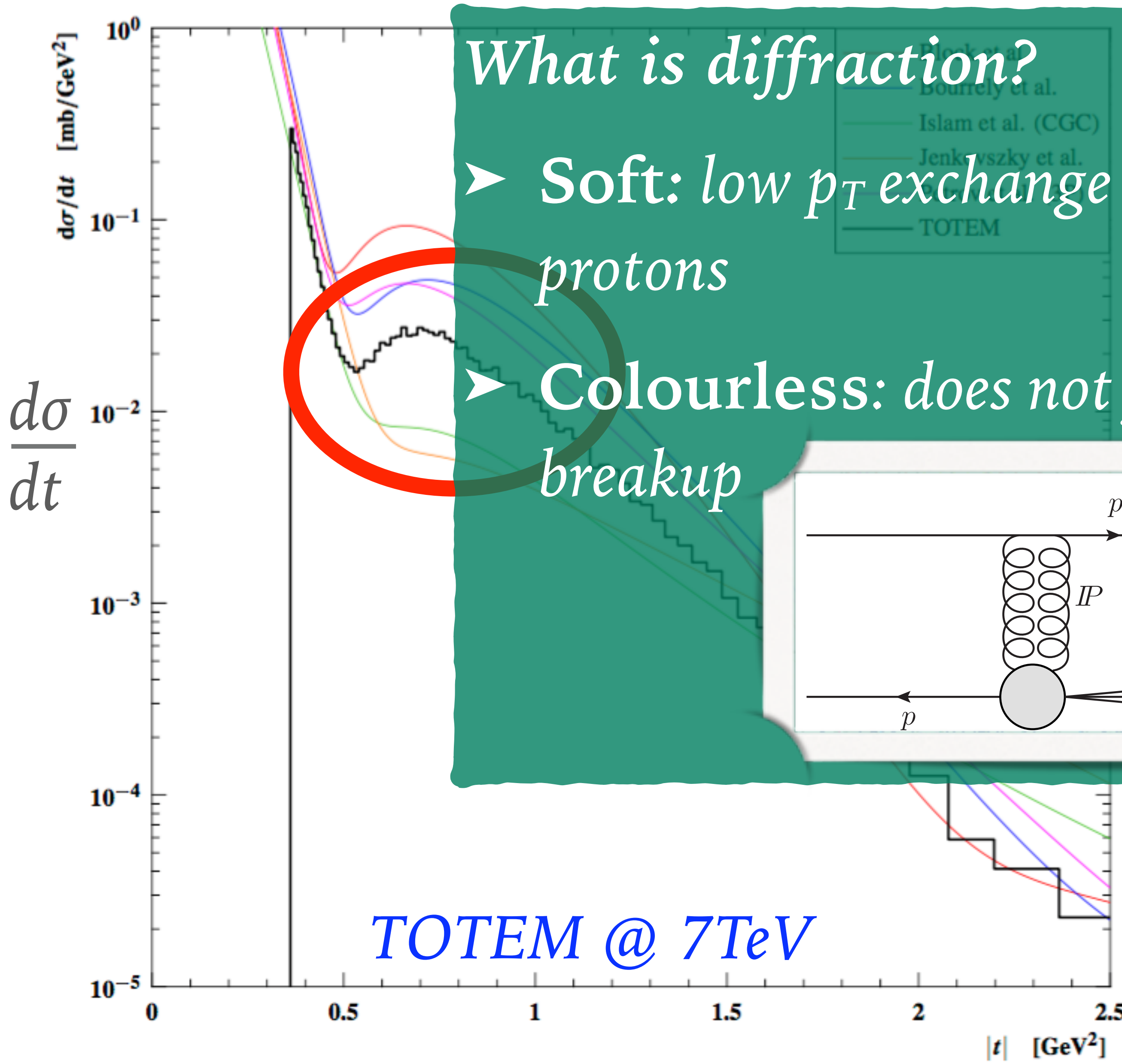
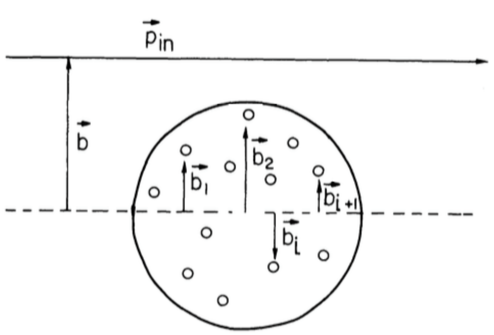


What is diffraction?

- **Soft:** *low p_T exchange between protons*
- **Colourless:** *does not force proton breakup*

|t| : *square of elastic scatter four-momentum transfer*

: *inversely related to impact parameter, b*



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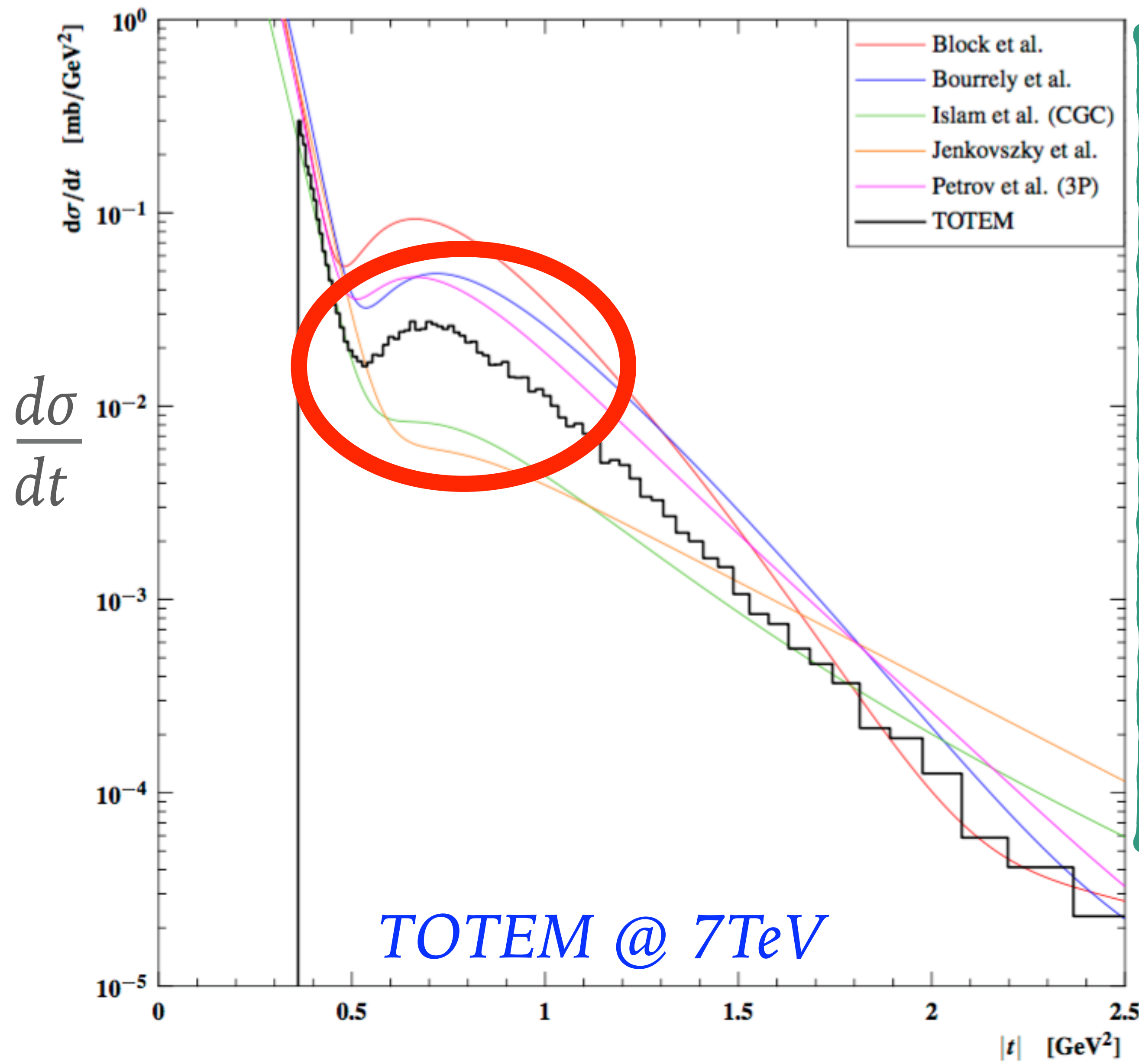

Why study diffraction:

- *Models fail* **disastrously!**
- *Responsible for* ***40%*** *of total cross-section for high-energy pp collisions*
- *Accompanies our hard processes (i.e. improve MC underlying event)*

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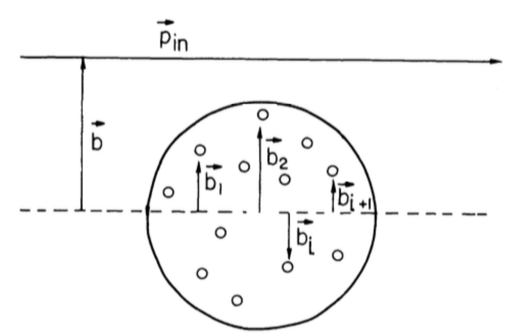

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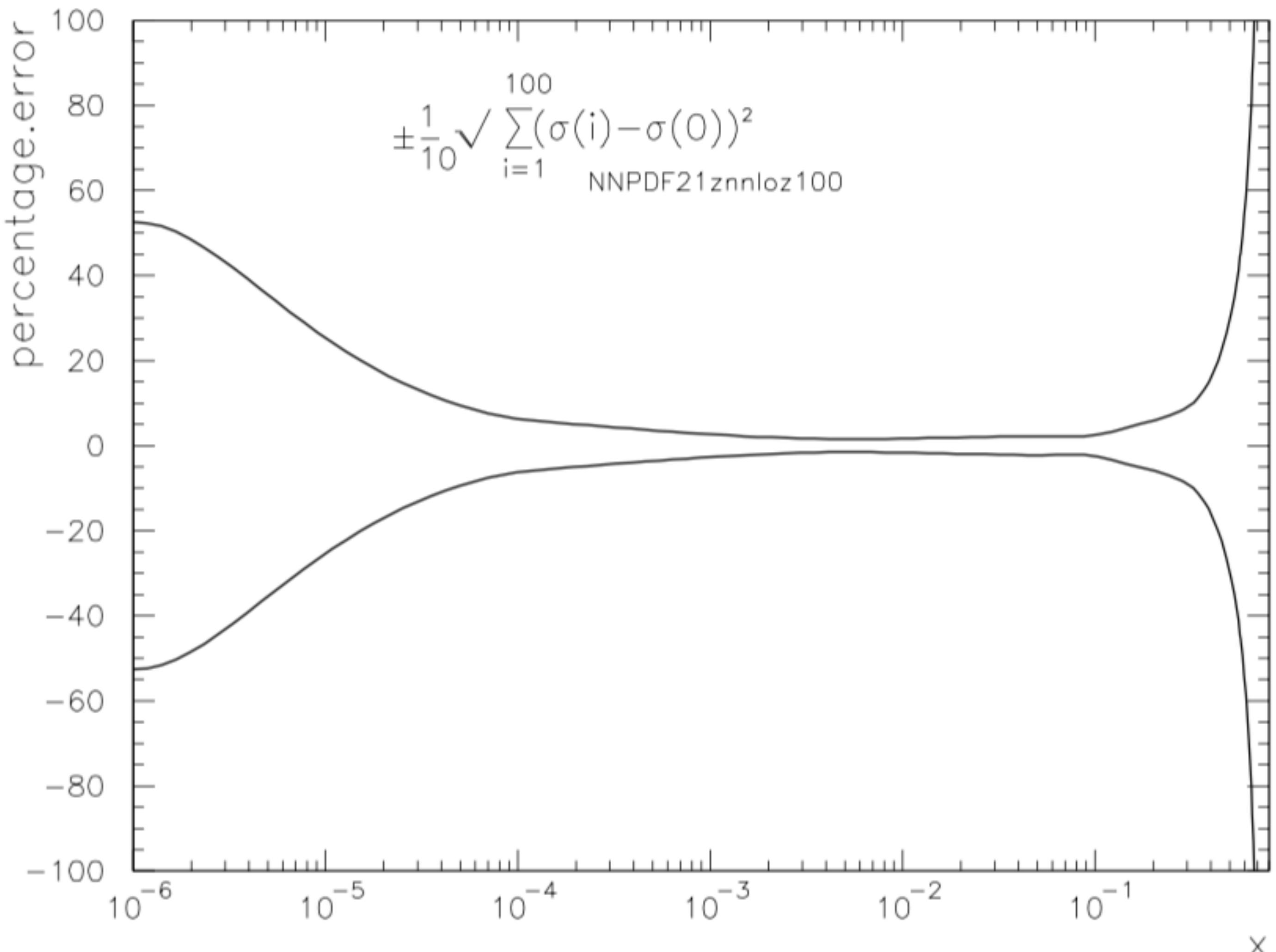
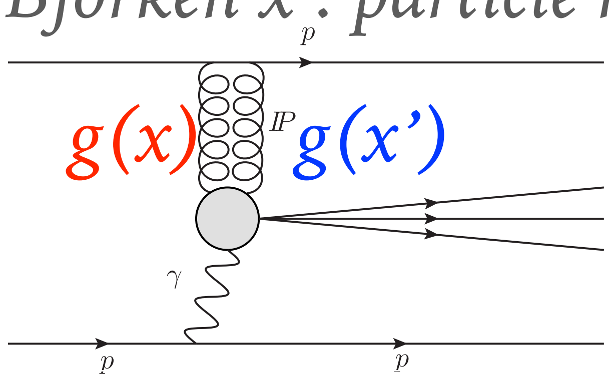
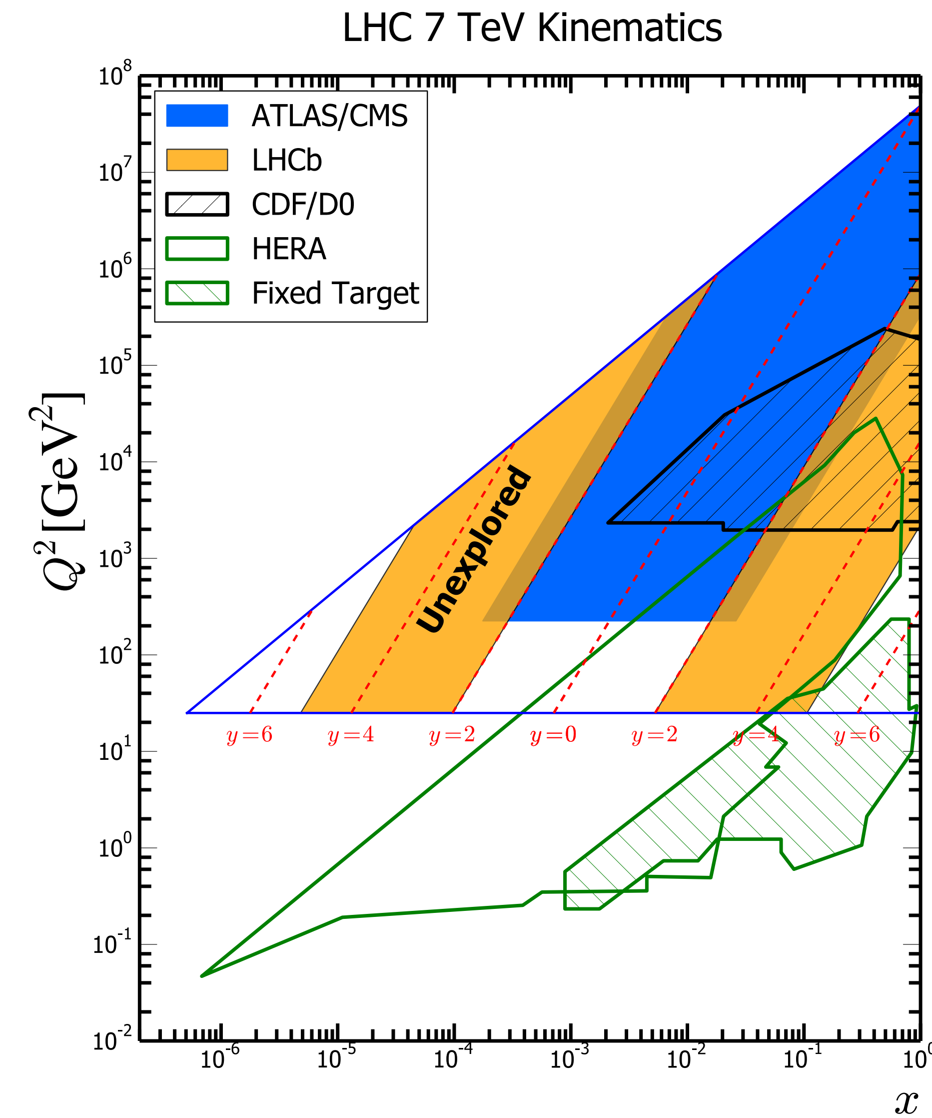
Consider the gluon PDF, g(x)





Bjorken x : particle momentum fraction carried by the parton

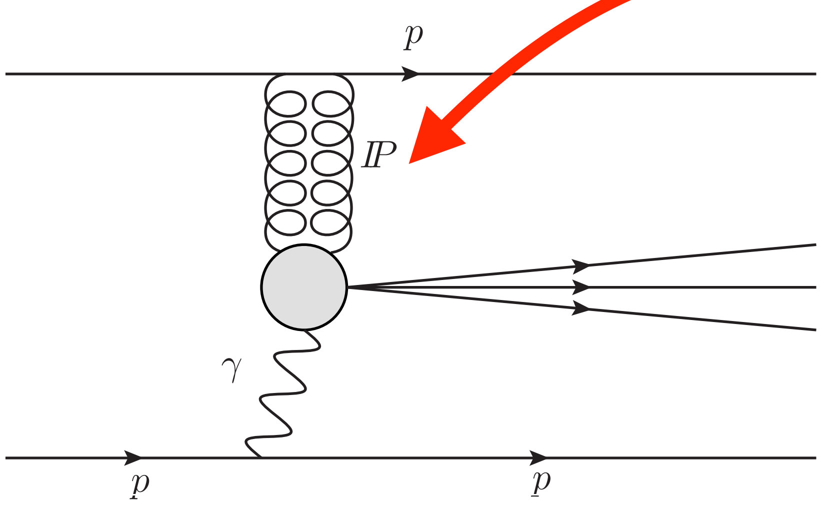


Exploring complementary phasespace at low-x

$$x = \frac{Q\,e^{\pm y}}{\sqrt{s}}$$

WHAT DOES CEP LOOK LIKE?

To a theorist:



A ***diffractive***, ***elastic*** *scatter; production of a particle system dominantly populating the central rapidity region*

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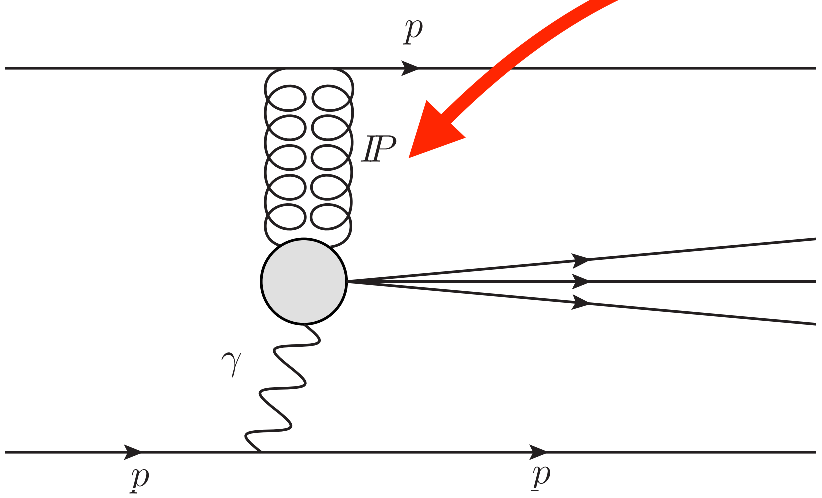

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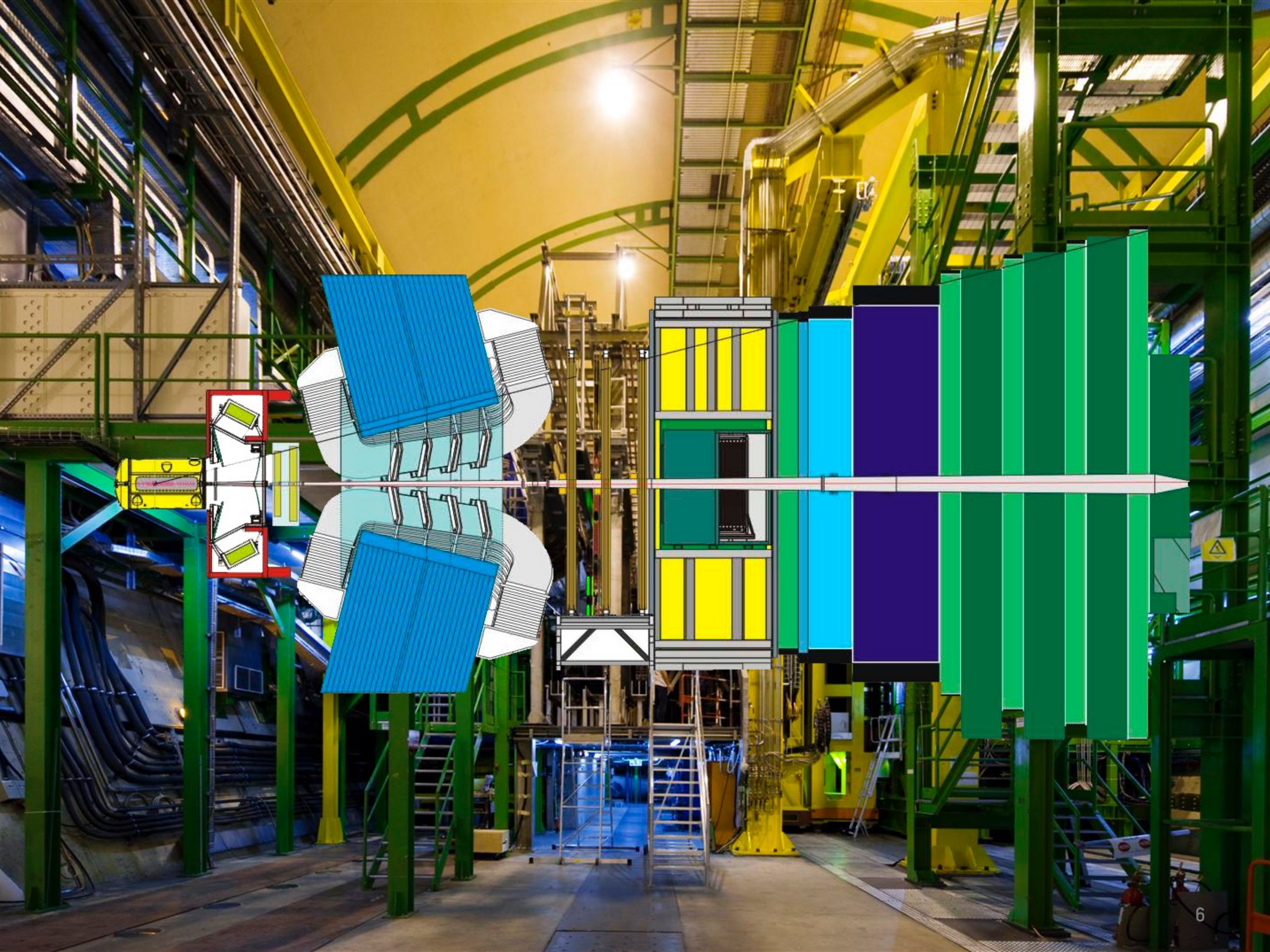
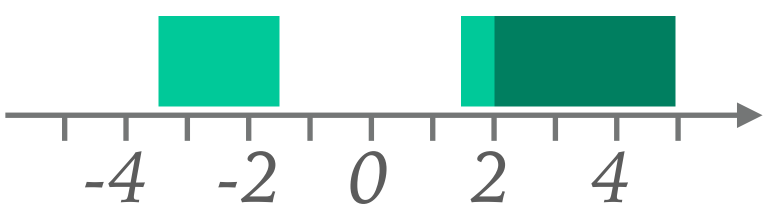
To an LHCb experimentalist?

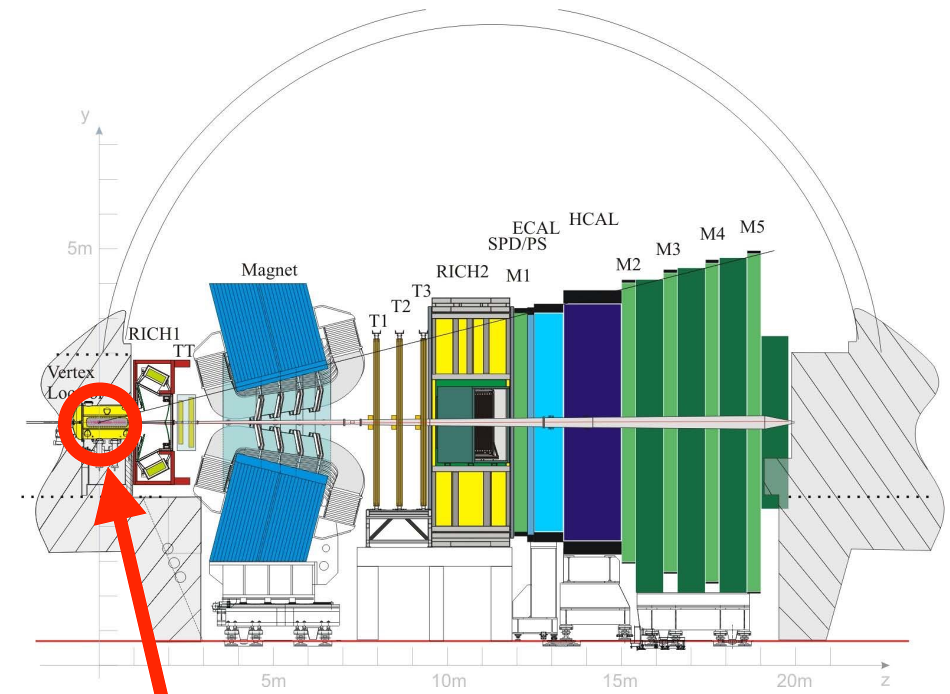


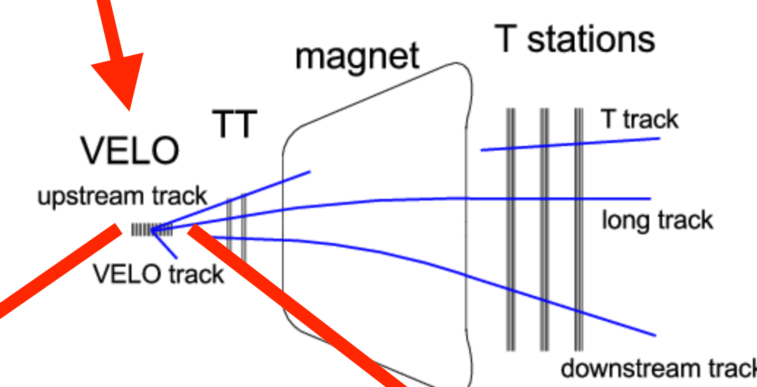
LHCB: A DETECTOR FOR CEP

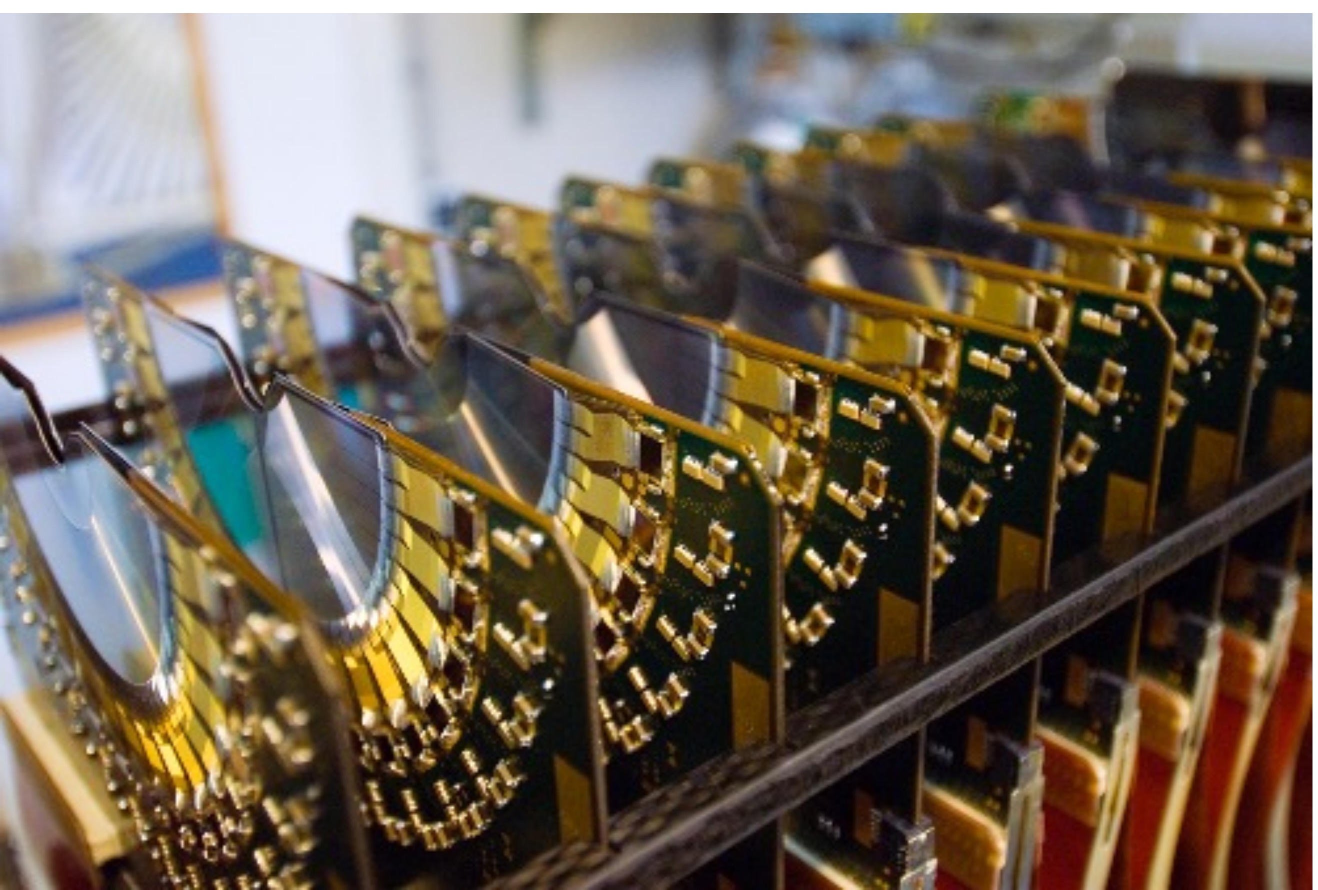
Tracking for CEP

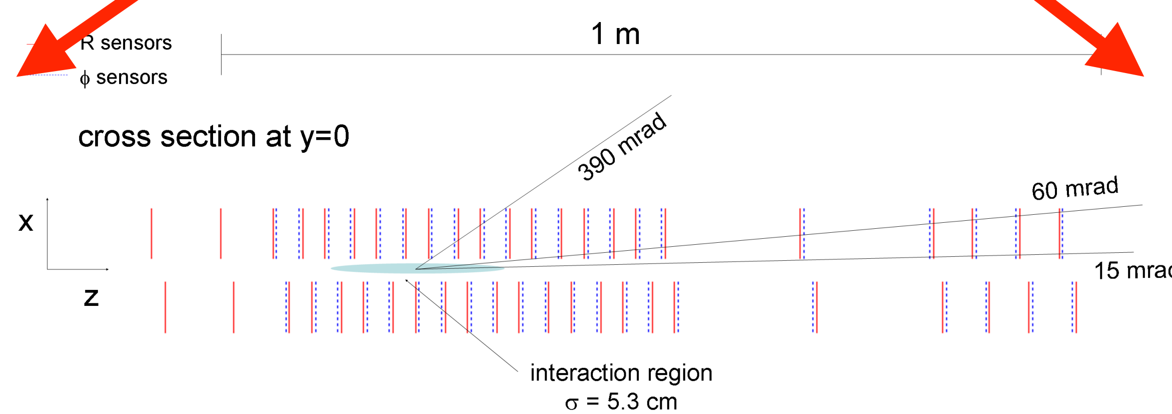
- *Silicon detector around pp interaction point*
- *Four downstream tracking stations:*
  - *silicon microstrips: TT + centre T1-3*
  - *straw tube drift chambers: outer T1-3*







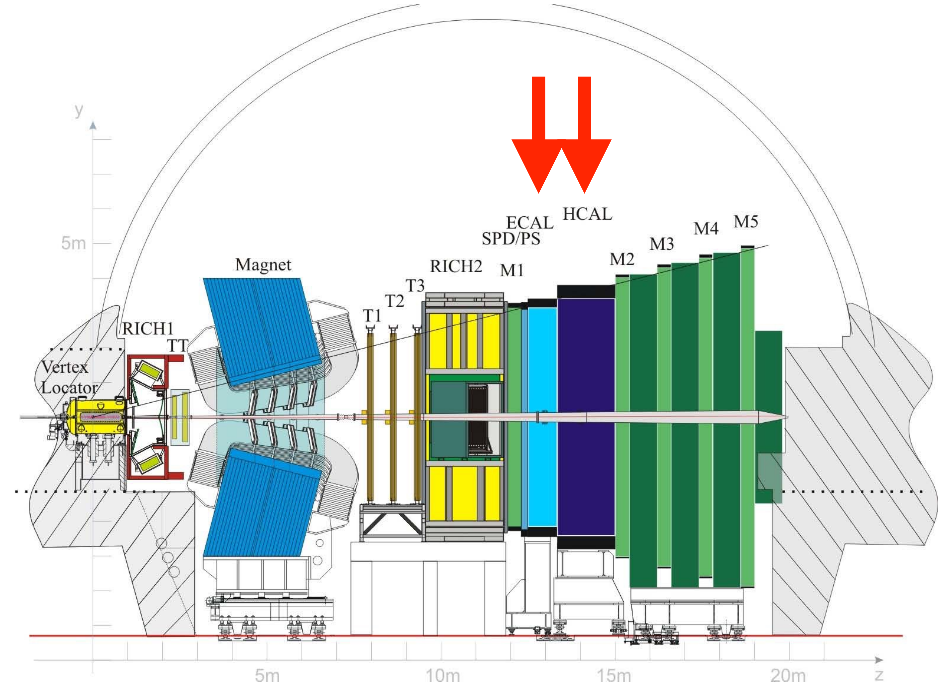




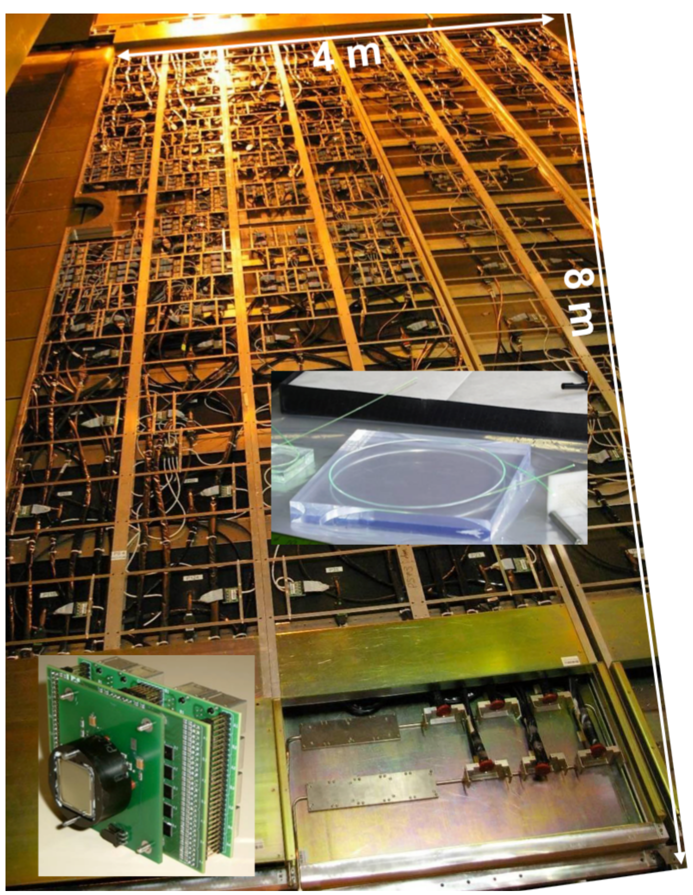
LHCB: A DETECTOR FOR CEP

Calormetry

- *Scintillating pad detector (charged multiplicity)*
  - *N_{hits} : 1 of the 3 L0 trigger quantities!*
- *ECAL and HCAL*

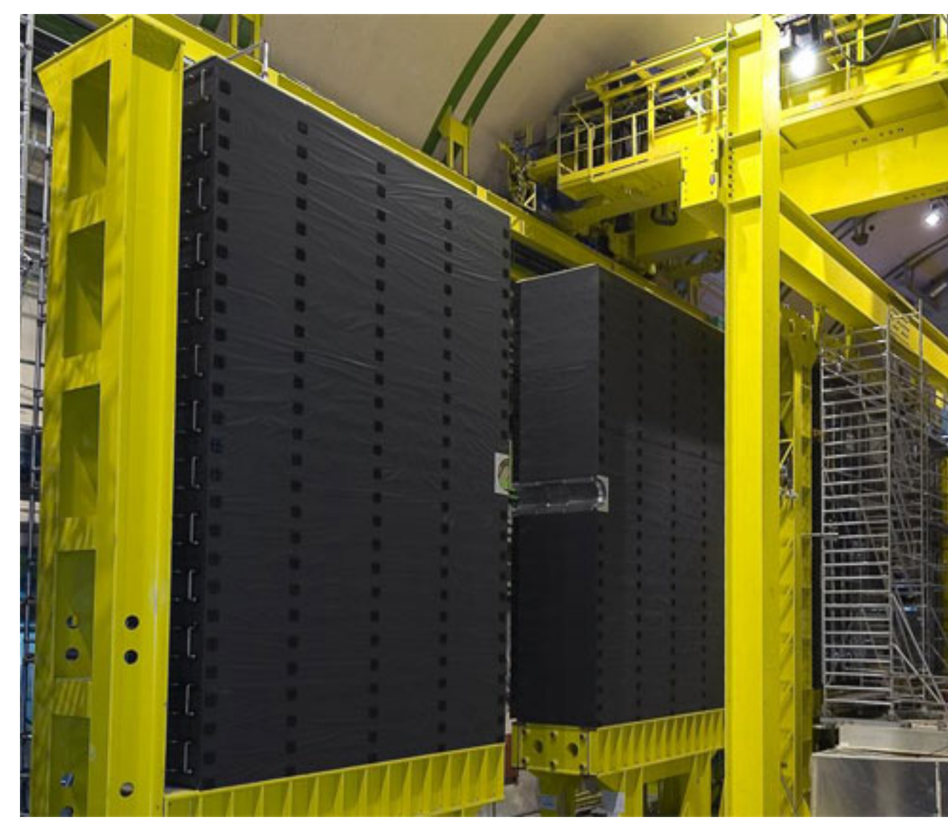


SPD: Event multiplicity limit



ECAL: Threshold for electron/photon CEP

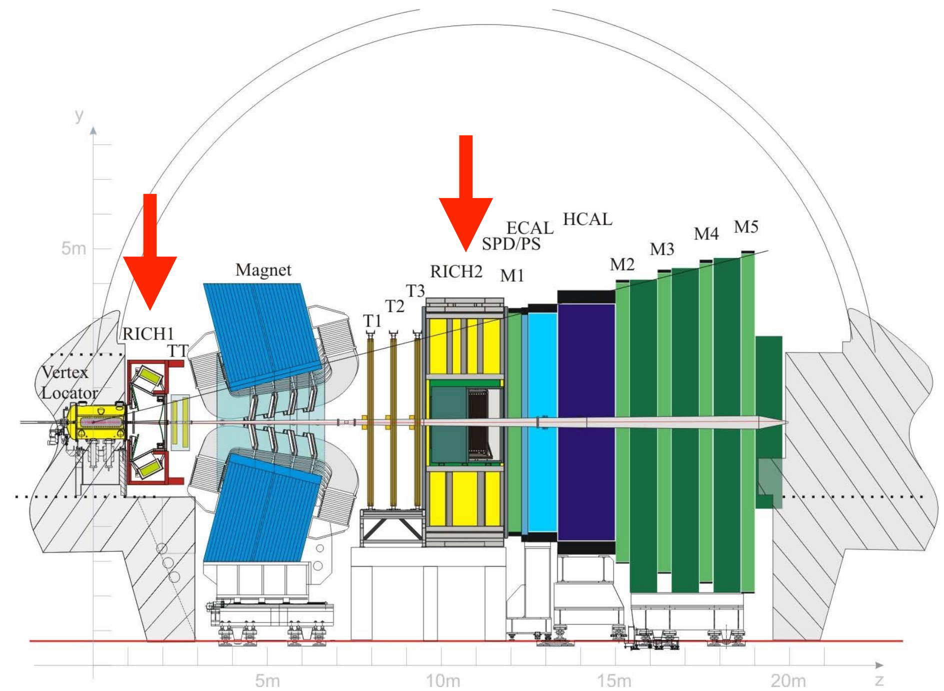
HCAL: Threshold for hadron CEP



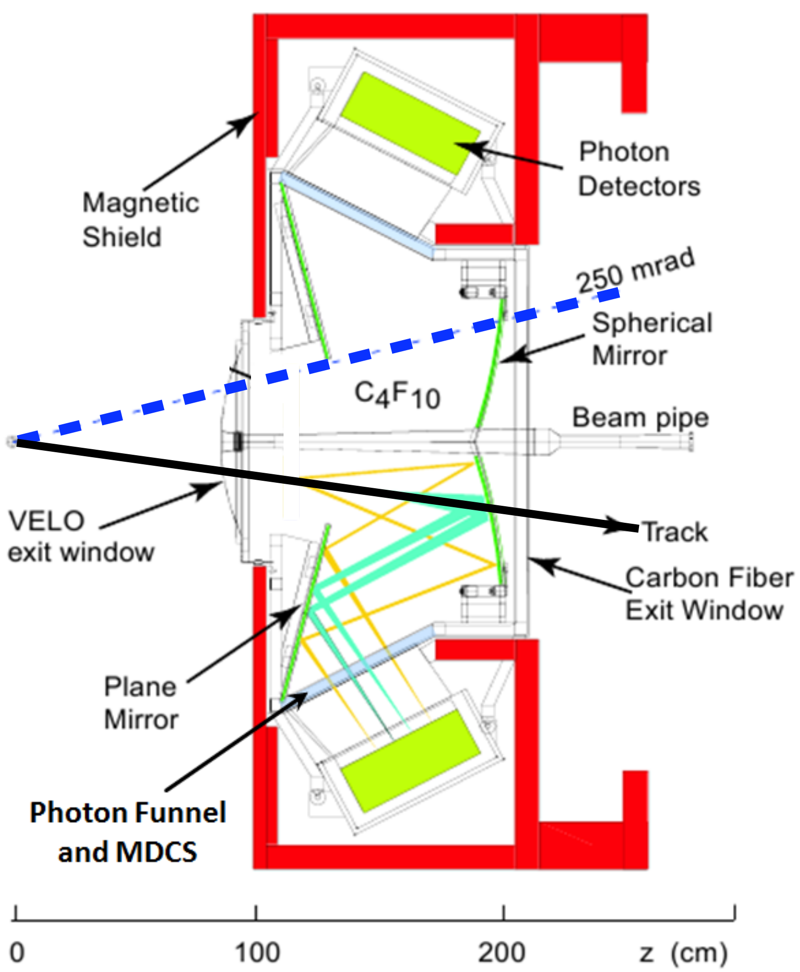
LHCB: A DETECTOR FOR CEP

Distinguishing hadrons

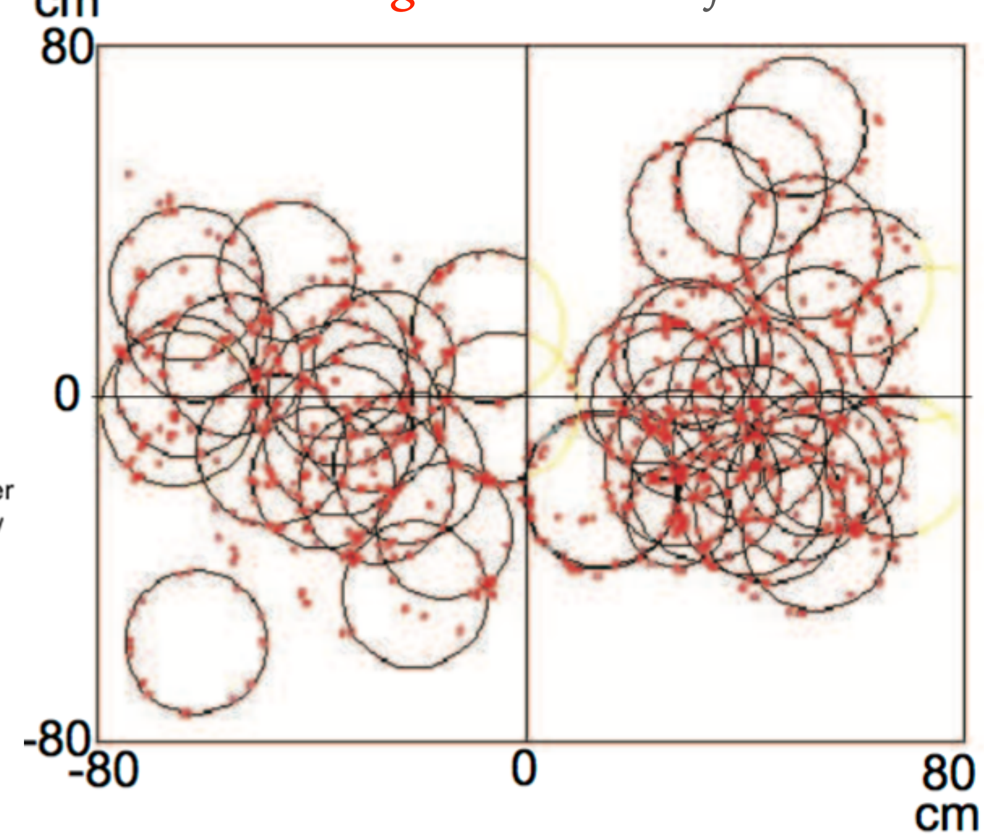
- *Two cherenkov detectors, before and after magnet*
  - *1) C_4F_{10}: track momentum 10→65 GeV/c*
  - *2) CF_4: track momentum 15→100 GeV/c*
- *Better discrimination in 'empty' CEP events*



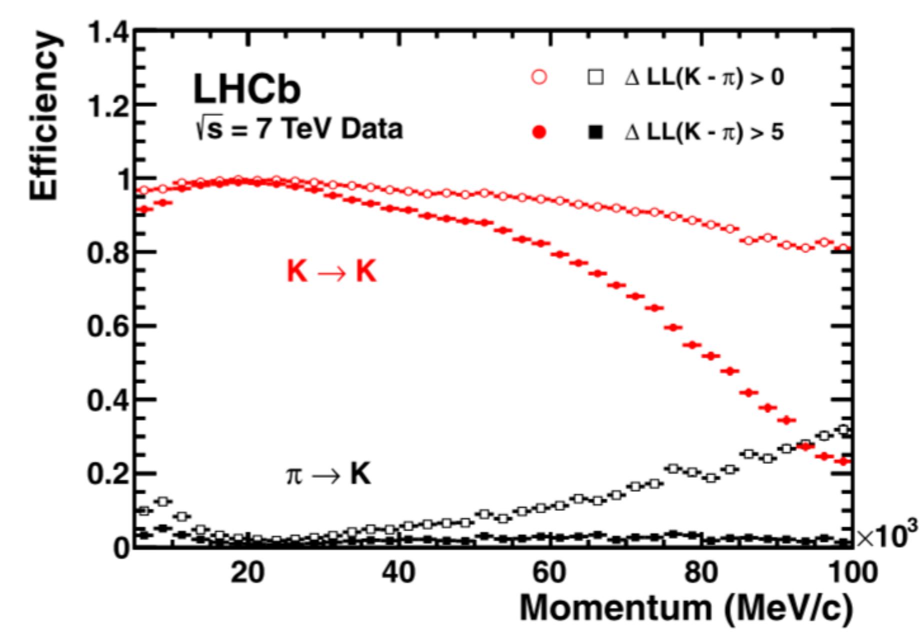
RICH: Principles



Pattern recognition: easier for CEP!



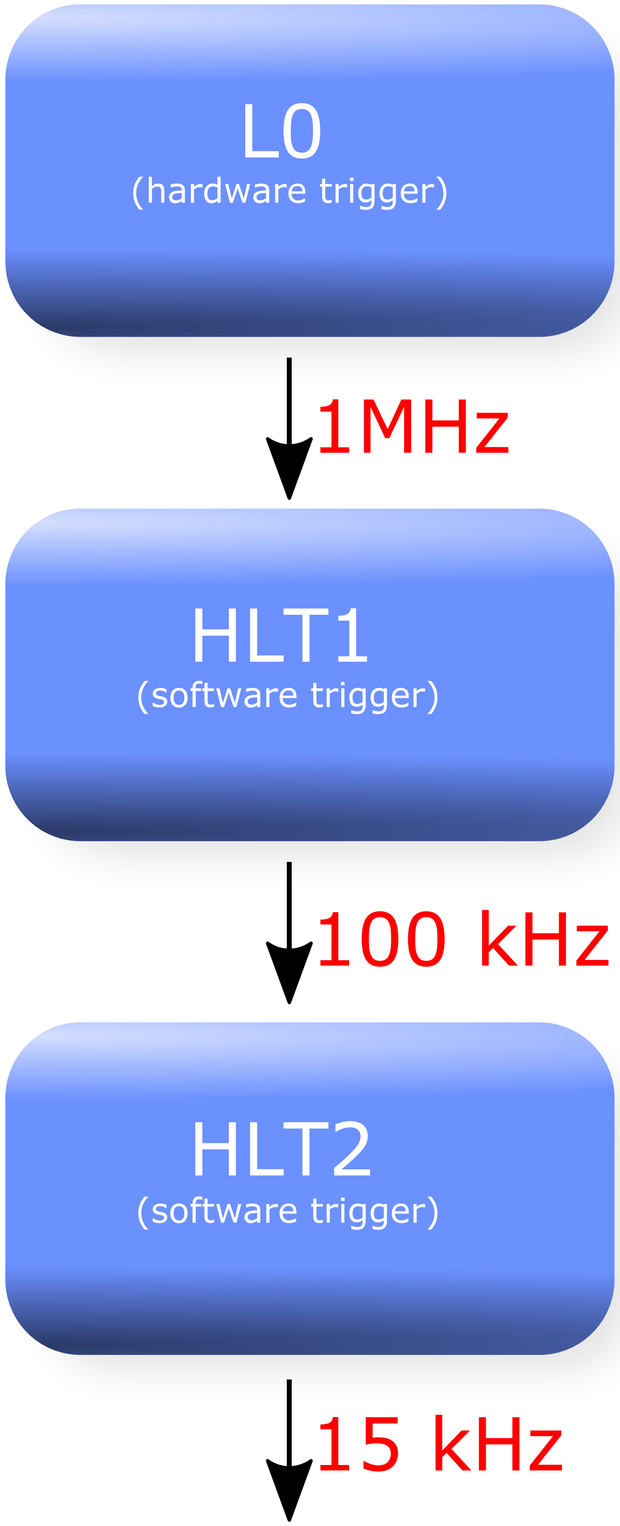
π/K: excellent separation



LHCB: A DETECTOR FOR CP

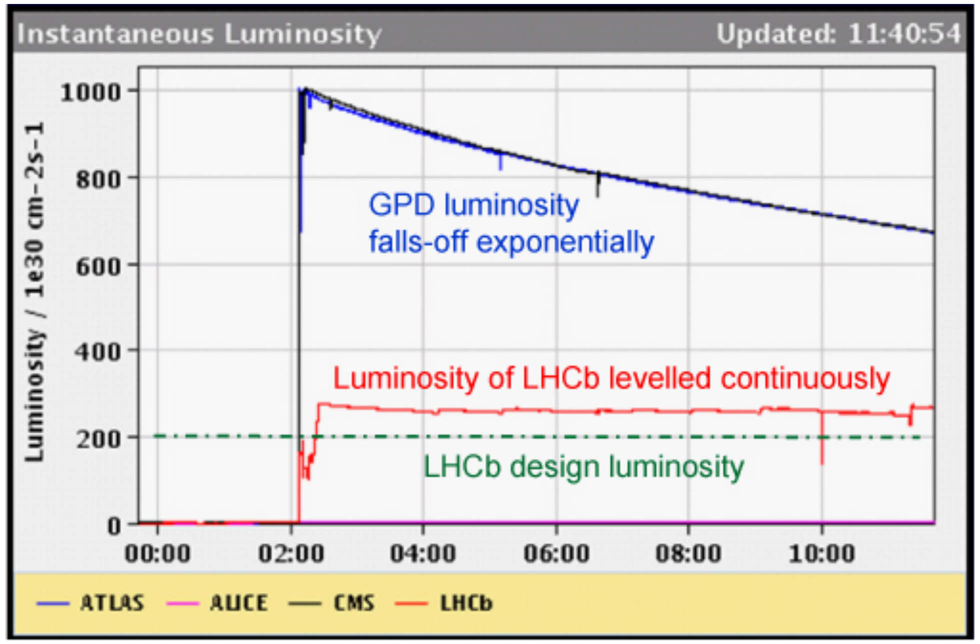
Trigger

- ***L0:*** *SPD hits < 10 ; PU hits < 3 ; min e/h/μ activity*
  - *Orthogonal to the rest of LHCb programme*
- ***HLT1:*** *Pass-through*
- ***HLT2:*** *Tracking (p_T>300 MeV/c) & dedicated selections*



Luminosity

- *Average number of interactions per crossing ~ 1.5*
- *'Empty detector' requirements reject events with >1 int.*
- *"Luminosity levelling":*



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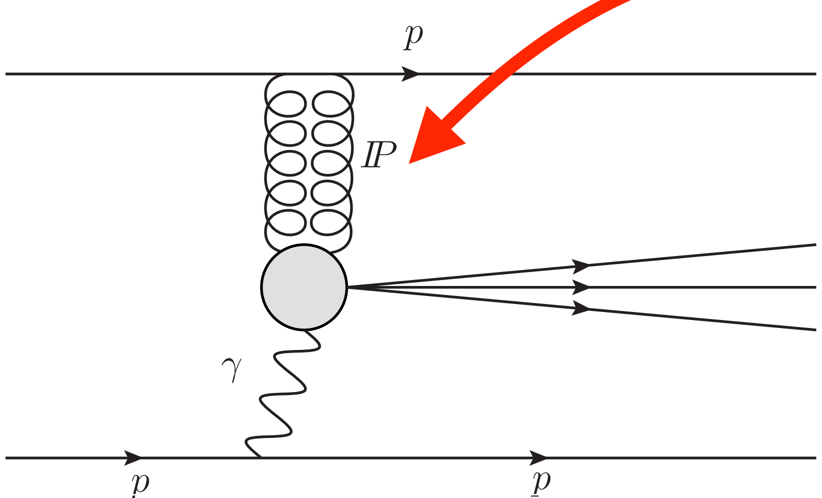

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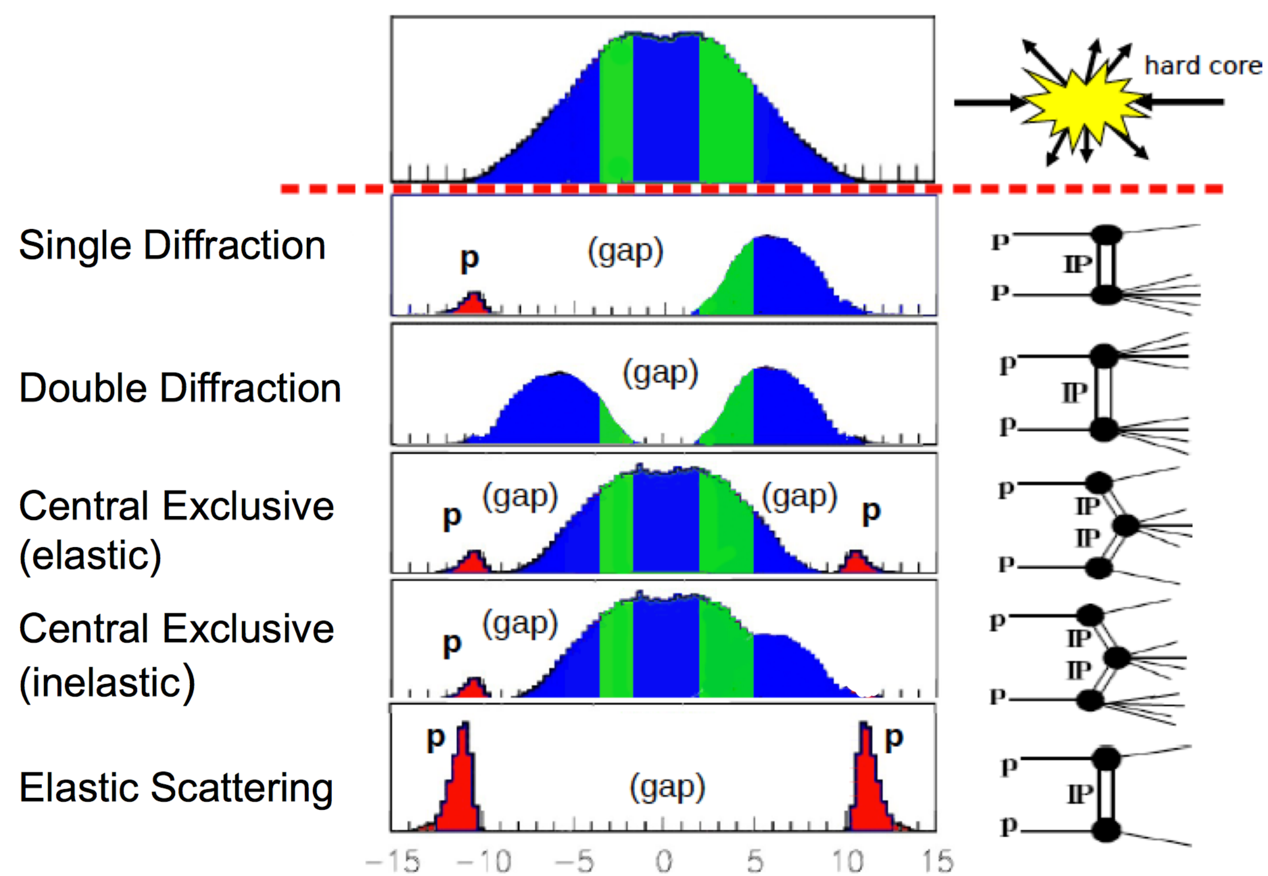

*We infer **pomeron** exchange by searching for events with **large rapidity gaps***

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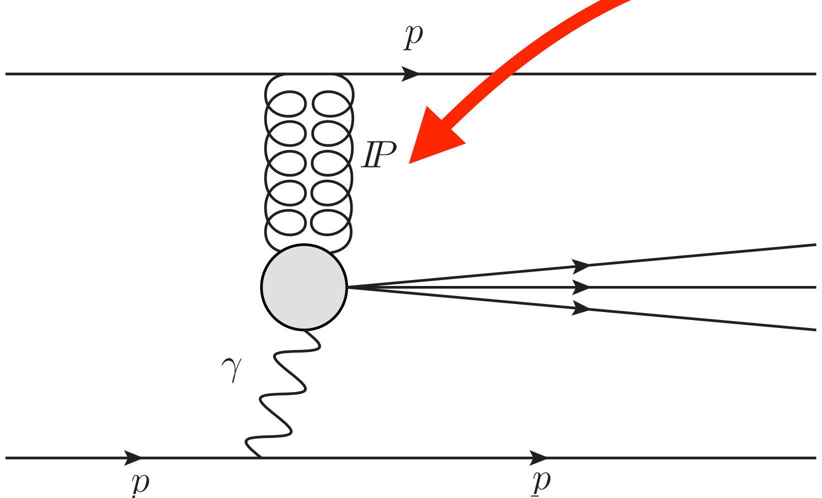

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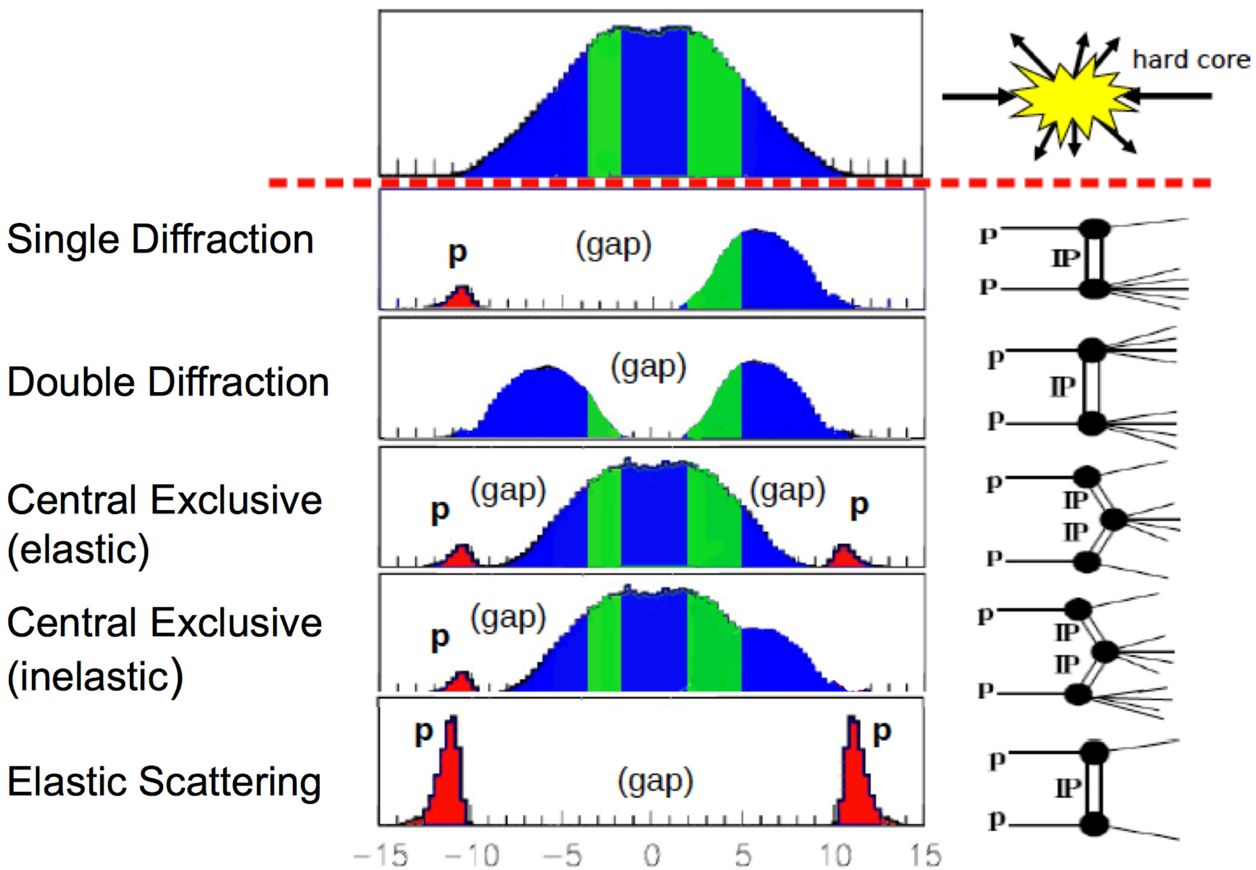
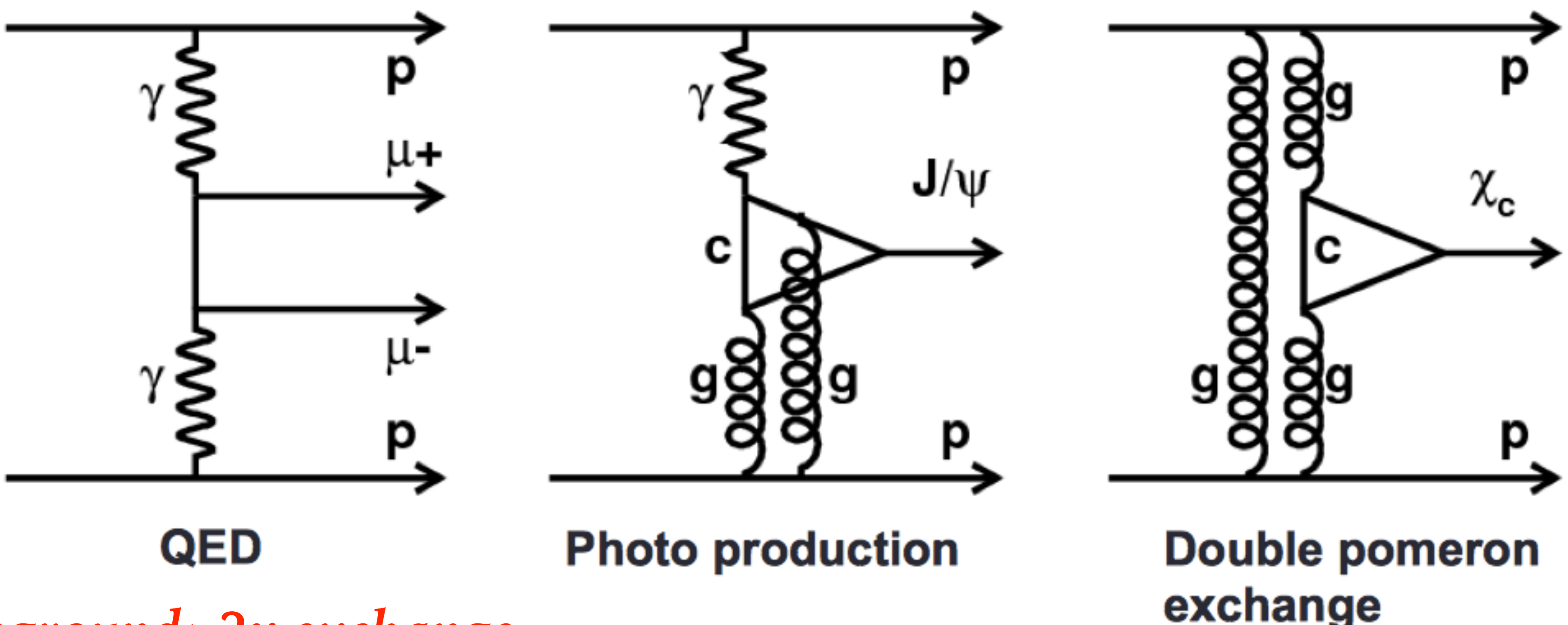


*We infer **pomeron** exchange by searching for events with **large rapidity gaps***

but we have tunnel vision…

CEP PROCESSES AT LHC

Interactions of the form pp →p[exclusive]p



QED background: 2γ exchange

➤ *QED process with small proton form-factor corrections*

Pomeron exchange:

- *Photoproduction: Photon-pomeron fusion*
  ➤ *Probe g(x) at small Bjorken x*
  ➤ *More perturbative at higher* [exclusive] *mass*
- *Double pomeron exchange: Pomeron-pomeron fusion*
  ➤ [exclusive] *preferred be neutral $J^{PC}=0^{++}$; no net flavour: $f_{0,2}$, $\chi_{c,b}$, $\gamma\gamma$, JJ, H*

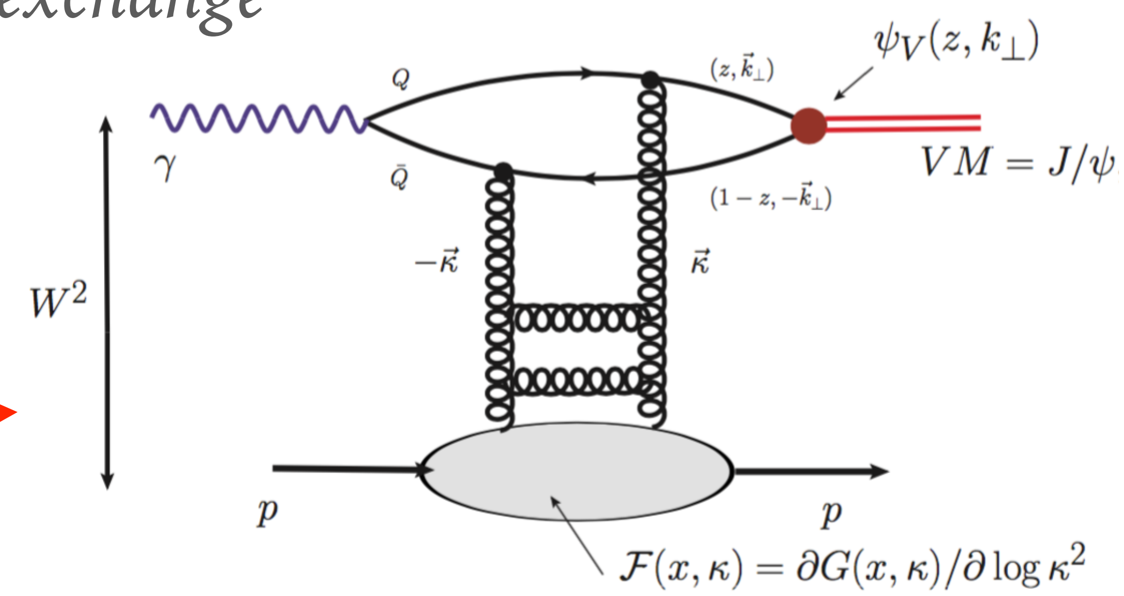
1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION *JPG 41 055002*

High energy charged particles as a source of Weizsacker-Williams photons

- *study photon-hadron interactions at unprecedented energies w.r.t. HERA*
- *one proton interacting strongly; one by photon exchange*

$$\frac{d\sigma^{\rm th}(pp)}{dy} = S^2(W_+)\left(k_+\frac{dn}{dk_+}\right)\sigma_+^{\rm th}(\gamma p) + S^2(W_-)\left(k_-\frac{dn}{dk_-}\right)\sigma_-^{\rm th}(\gamma p).$$

generalised PDFs
small 'skew' corrections



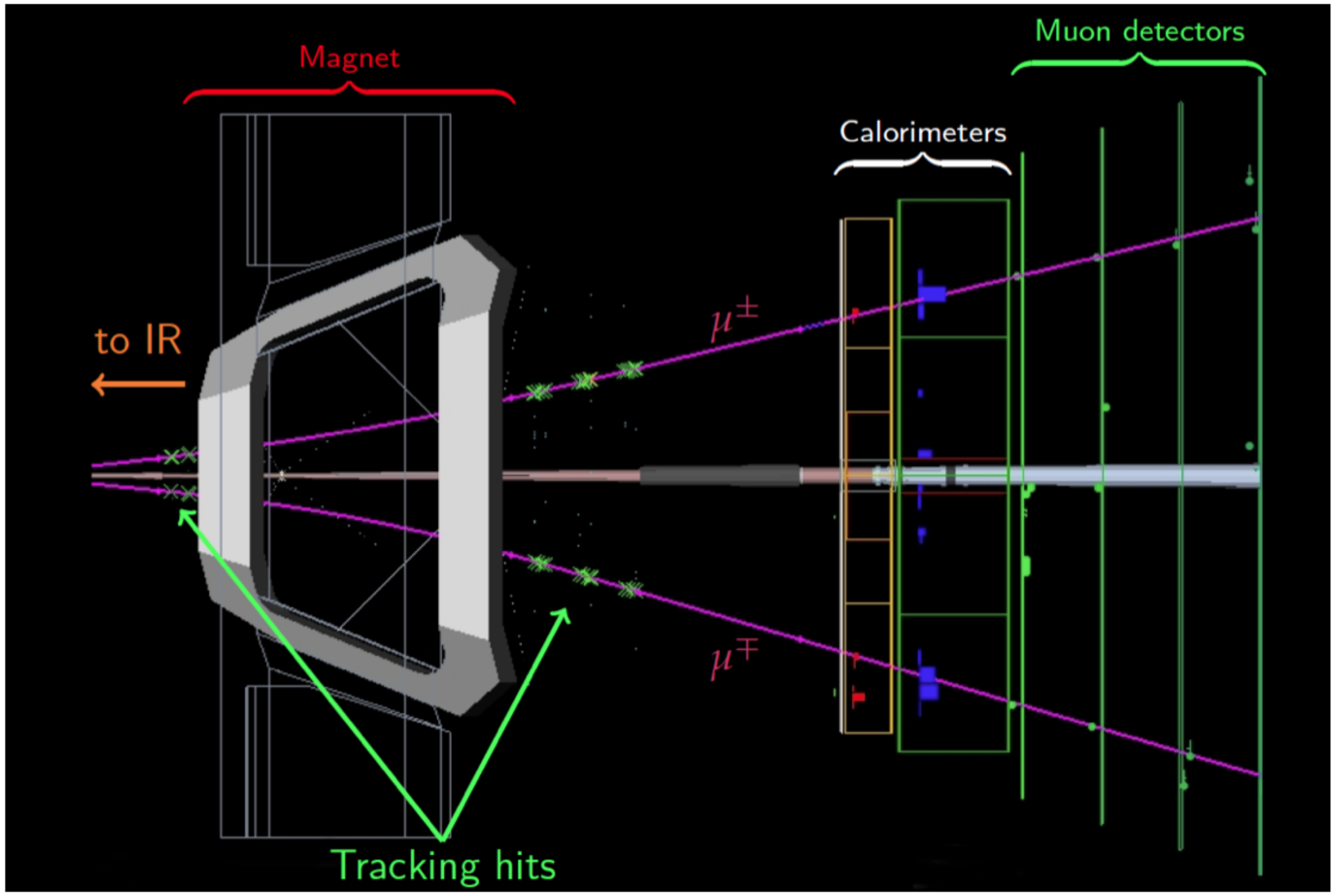
Assume factorisation of the soft and hard strong interactions

- *Need probability for elastic p-p rescattering : mod. indep. using LHC measurements*
    - *smaller impact parameter ⇒ reduced survival probability*
- *Ignore saturation effects (low saturation scale)*
- *Ambiguous source of photons!*

Differential cross-section (J/ψ rapidity) probes photoproduction scale, W

1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION *JPG 41 055002*

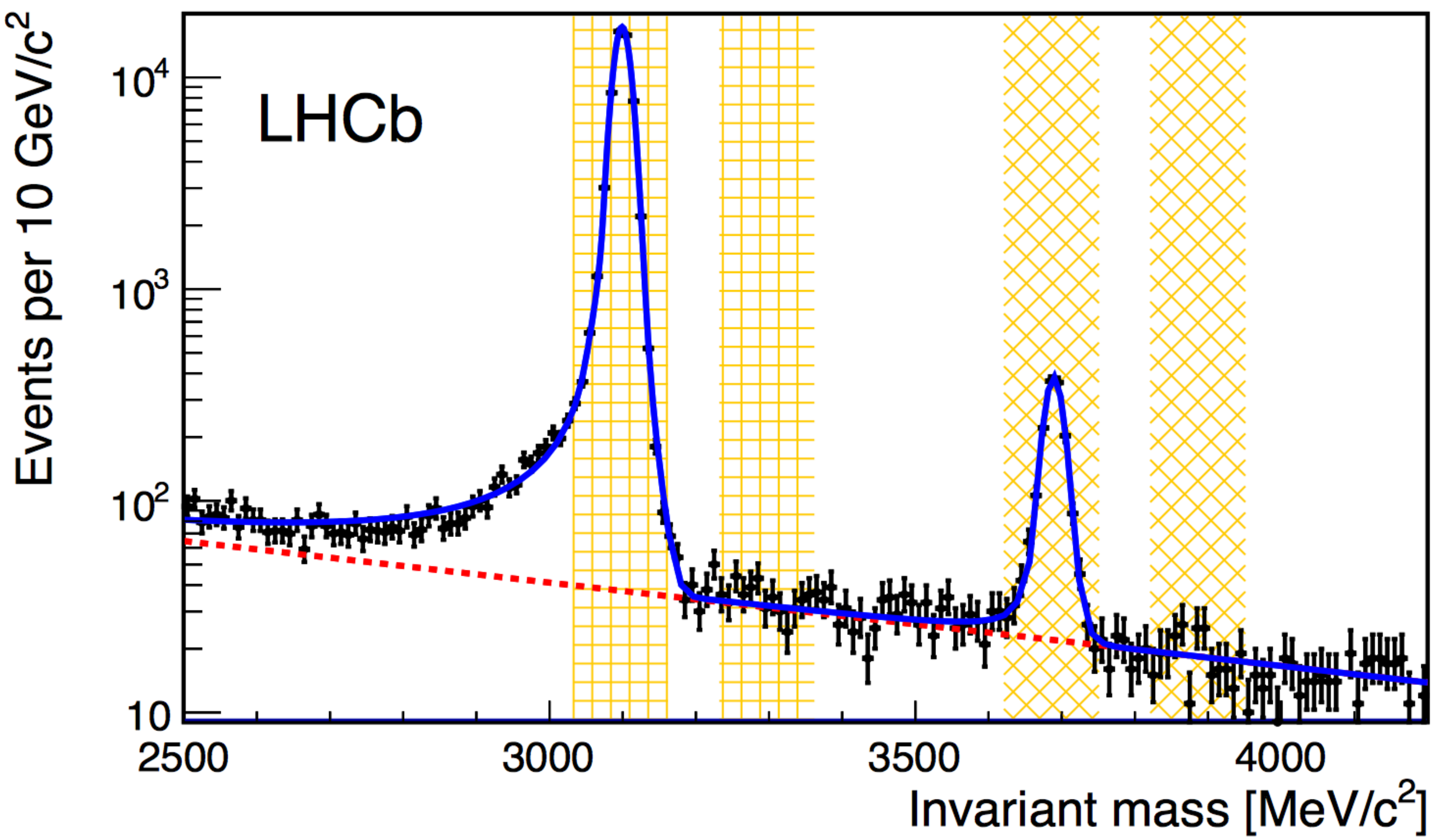
Selection: *J/ψ or $\psi(2S) \rightarrow \mu^+\mu^-$ in 930 pb^{-1} p-p 7 TeV data*



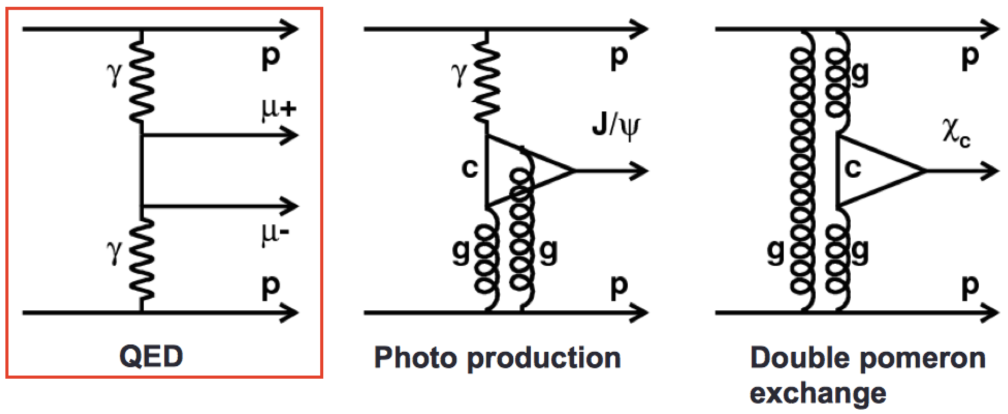
- *Hardware trigger:*
  - *Single muon $p_T > 400$ MeV/c*
  - *Number of SPD hits < 10*
- *Software trigger:*
  - *Both muons $p_T > 400$ MeV/c*
- *Offline:*
  - *Two identified muons in $2<\eta<4.5$*
  - *No photons or other forward tracks*
  - *No backward tracks*
  - *65MeV/c^2 mass window for J/ψ or $\psi(2S)$*

1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION *JPG 41 055002*

'Empty-detector' signal



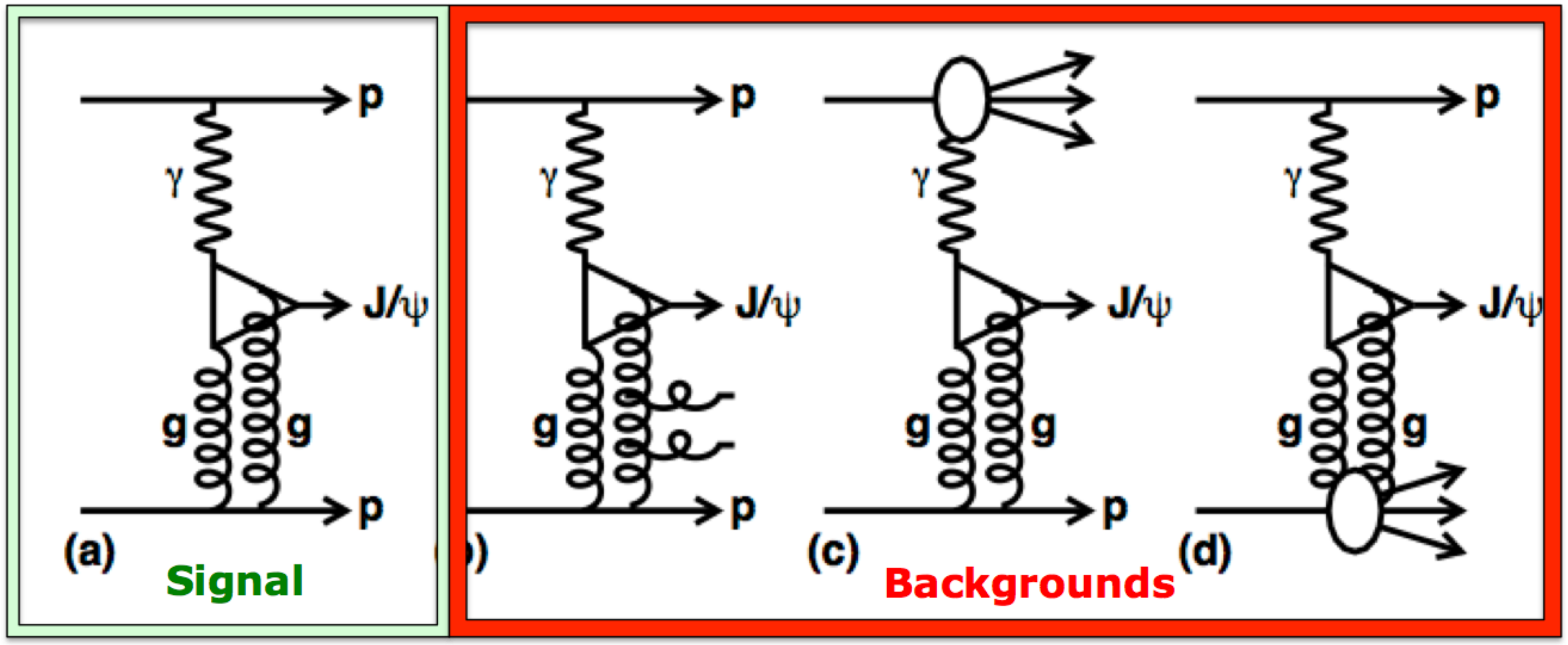
- *Fit invariant mass: isolate QED background*
  - *Signal: Crystal ball: 56,000 J/ψ; 1,600 $\psi(2S)$*
  - *QED background: Exponential: 1% J/ψ; 17% $\psi(2S)$*



1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION *JPG 41 055002*

A number of peaking backgrounds remain:

- *'Feed-down' decays: contamination can be estimated*
  - $\psi(2S) \rightarrow J/\psi\pi\pi$: $2.5 \pm 0.2\%$
  - $\chi_c \rightarrow J/\psi\gamma$: $7.6 \pm 0.9\%$
  - $X(3872) \rightarrow \psi(2S)\gamma$: $2.0 \pm 2.0\%$
- *Inelastic CEP background*

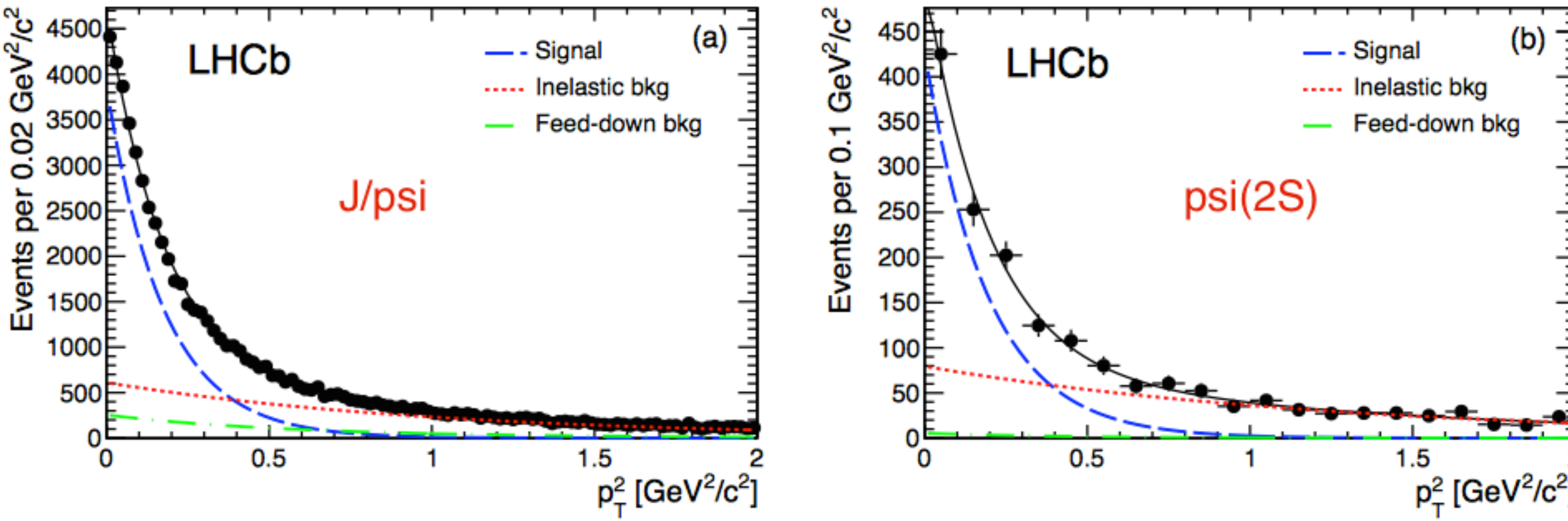


- *These backgrounds tend to produce J/ψ or $\psi(2S)$ with harder p_T than signal*

1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION *JPG 41 055002*

Determining exclusive contribution

- *Fit the p_T^2 distribution of the exclusive candidates*

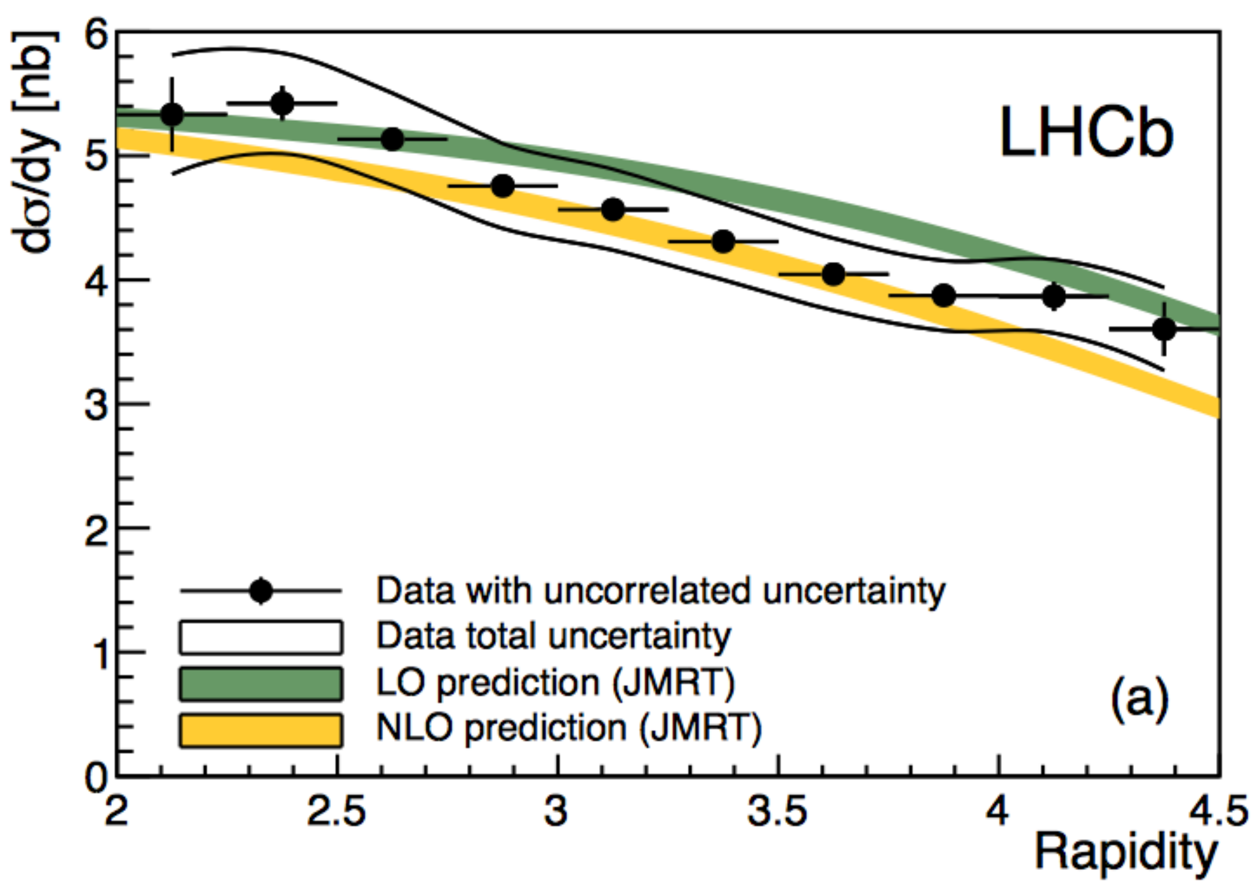


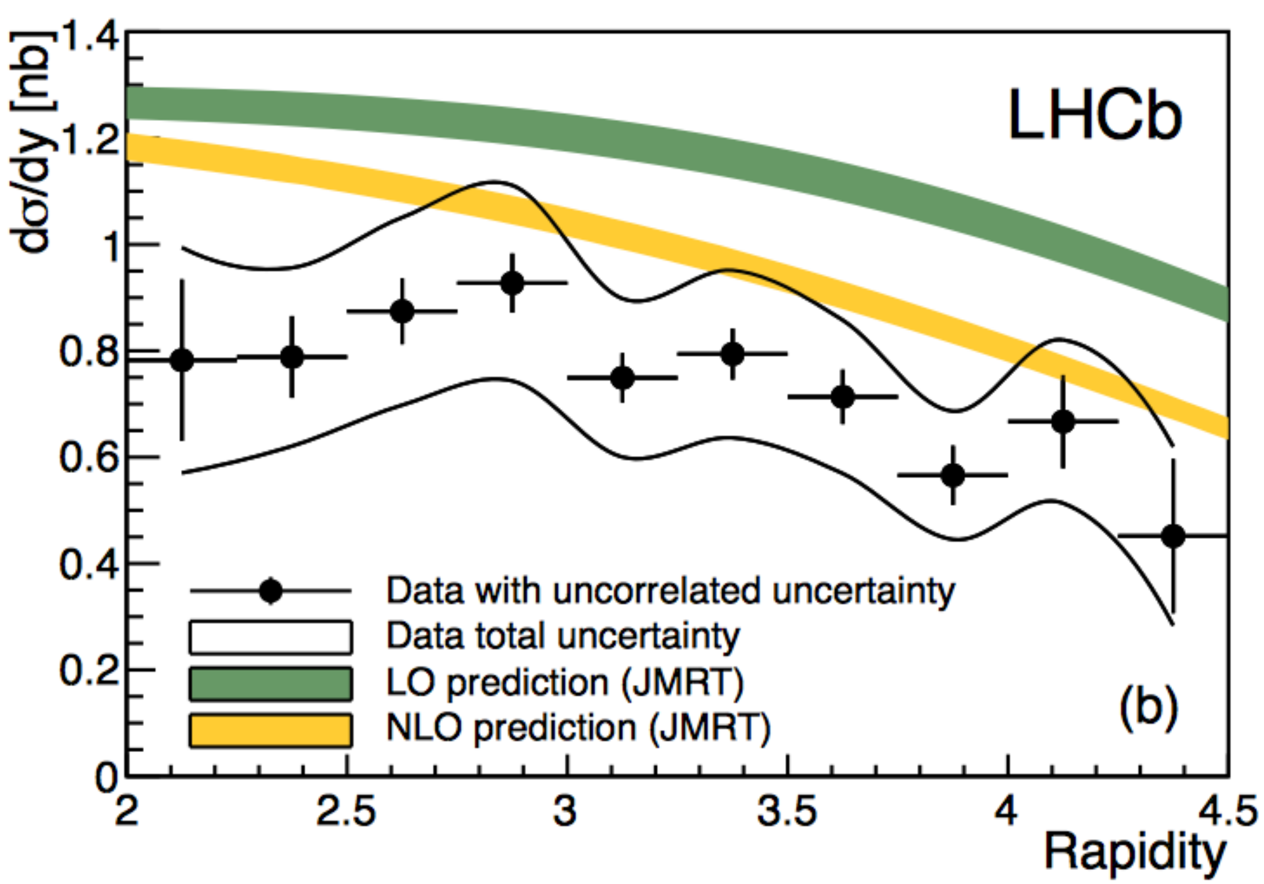
- ***Feed-down background:*** *Yield and shape determined using data*
- ***Inelastic background:*** *Yield and shape vary*
  - *J/ψ slope 0.97 ± 0.04 and ψ(2S) slope 0.8 ± 0.2, consistent with HERA*
- ***Exclusive signal:*** *Yield and shape vary*
  - *Signal slope 5.7 ± 0.1 and 5.1 ± 0.7, consistent with HERA data via Regge theory extrapolation*
  - *Signal purity: 59 ± 1% (J/ψ) and 52 ±7% (ψ(2S))*
- *Largest systematic uncertainties arise through the description of the p_T^2 fit*

1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION *JPG 41 055002*

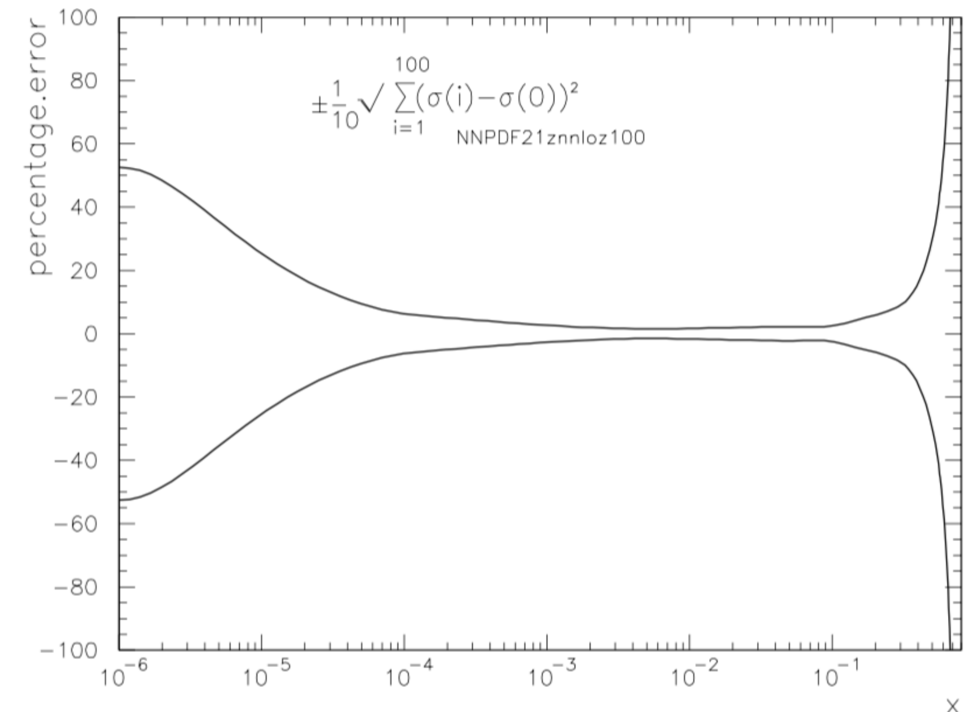
Interpretation

- *LO and NLO extrapolations from HERA data have been performed*
- *J/ψ (left) and $\psi(2S)$ (right) data superimposed: good agreement at NLO*



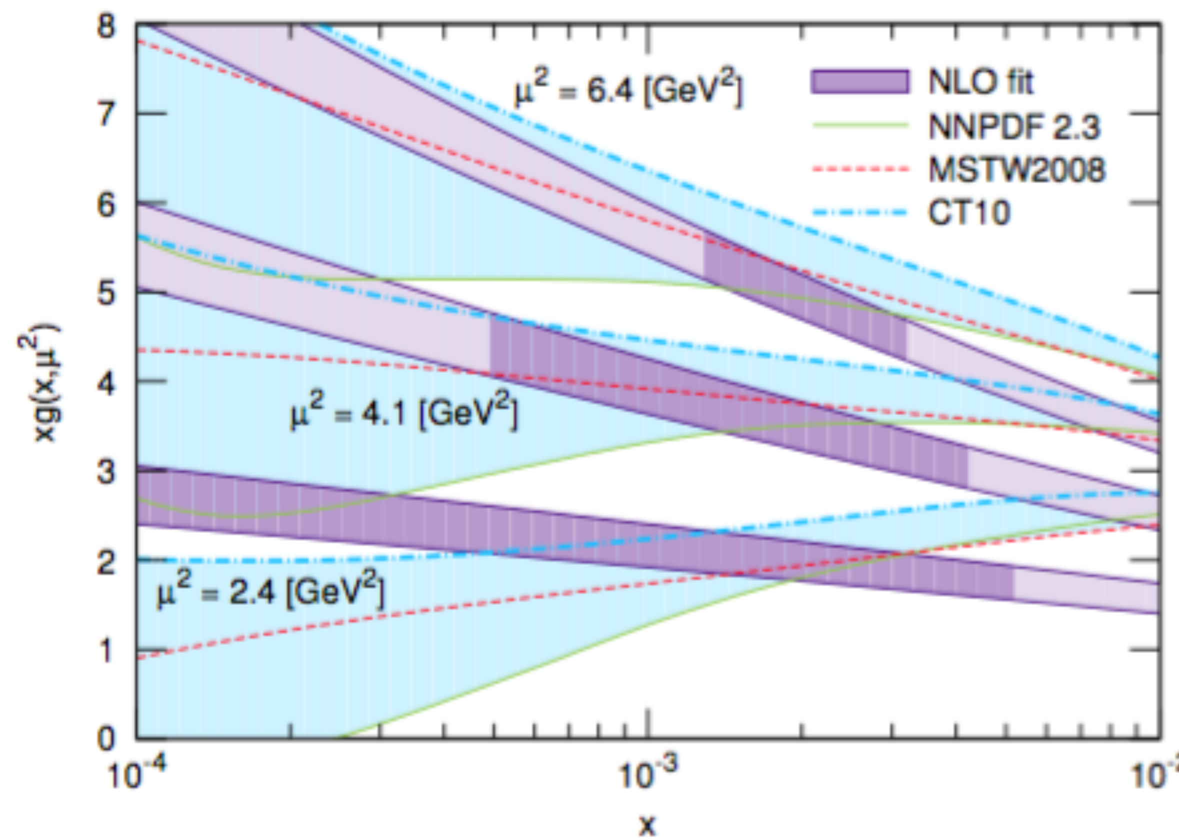


1] EXCLUSIVE J/Ψ AND Ψ(2S) PRODUCTION



Implications for the gluon PDF, g(x)

- *Sensitive in region $x \sim 10^{-6}$*
- *Not used in general PDF fits yet*
  - *skewing effects treated using Shuvaev transform* *hep-ph/9902410*
  - *⇒ 'Sudakov factor' - no extra gluon emission*
  - *Accurate to $O(x)$*
- *Cross-section depends on square of $g(x)$*
- *Sensitivity to $g(x)$ at low x demonstrated:*

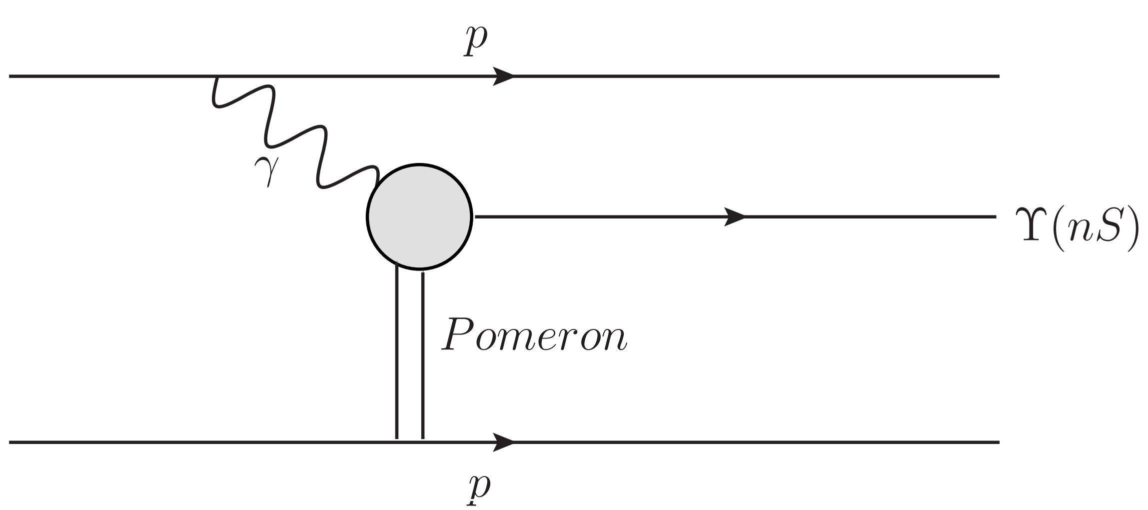


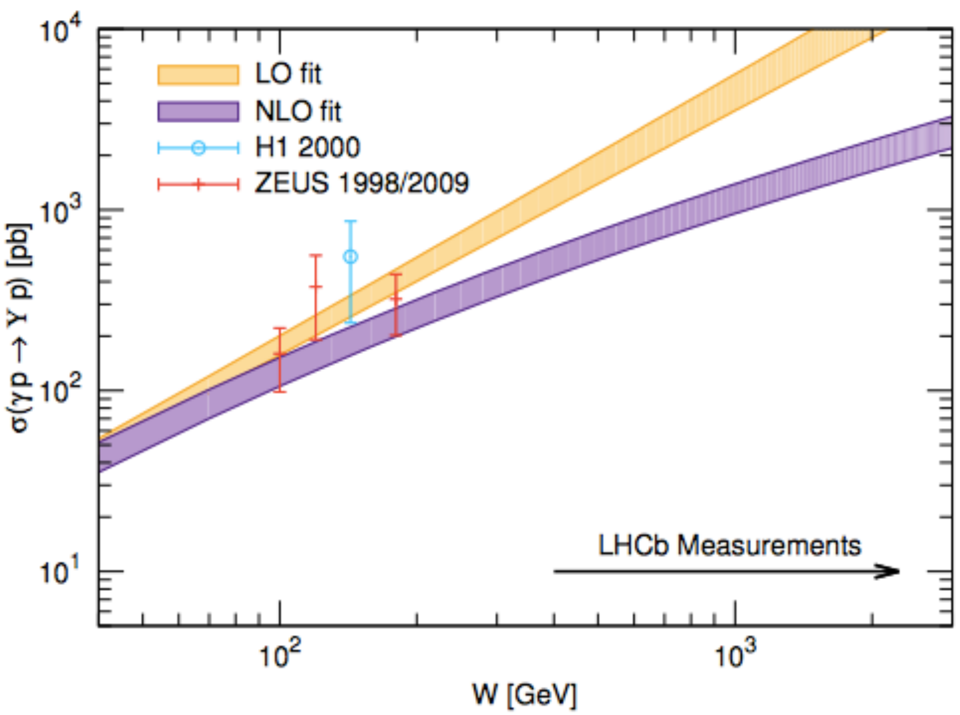
2] EXCLUSIVE Υ(1S,2S,3S) PRODUCTION

JHEP 09 084

Motivation similar to J/ψ and ψ(2S)

- *Occurs by photoproduction*
- *Perturbatively calculable hard process; depends on $g(x)^2$ to $x=1.5 \times 10^{-5}$*
- *Photoproduction predictions exist at LO and NLO, differ greatly at this W*
- *Compare different models for* **Υ** *wave function and t-channel exchange*
- *LHCb probes a new kinematic region ($W_\pm = \sqrt{(M_\Upsilon \sqrt{s}\, e^{\pm y})}$)*





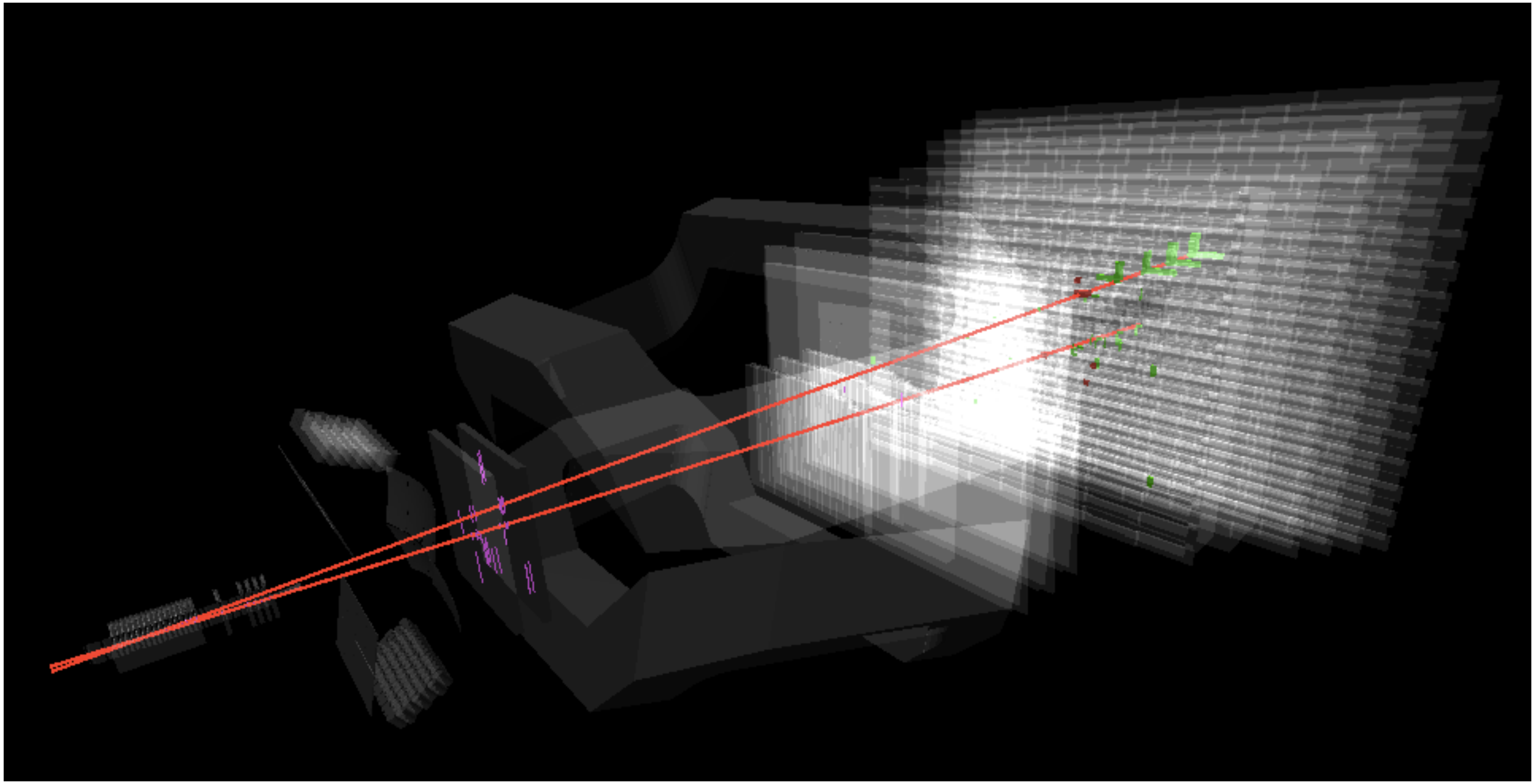
- *Data set: 2.9 fb^{-1} pp collisions at pp $\sqrt{s} = 7, 8$ TeV*

2] EXCLUSIVE Υ(1S,2S,3S) PRODUCTION

JHEP 09 084

Selection very similar to that for J/ψ analysis

- Two well-reconstructed muons with mass 9 - 20 GeV/c^2
- No other forward or backward charged tracks



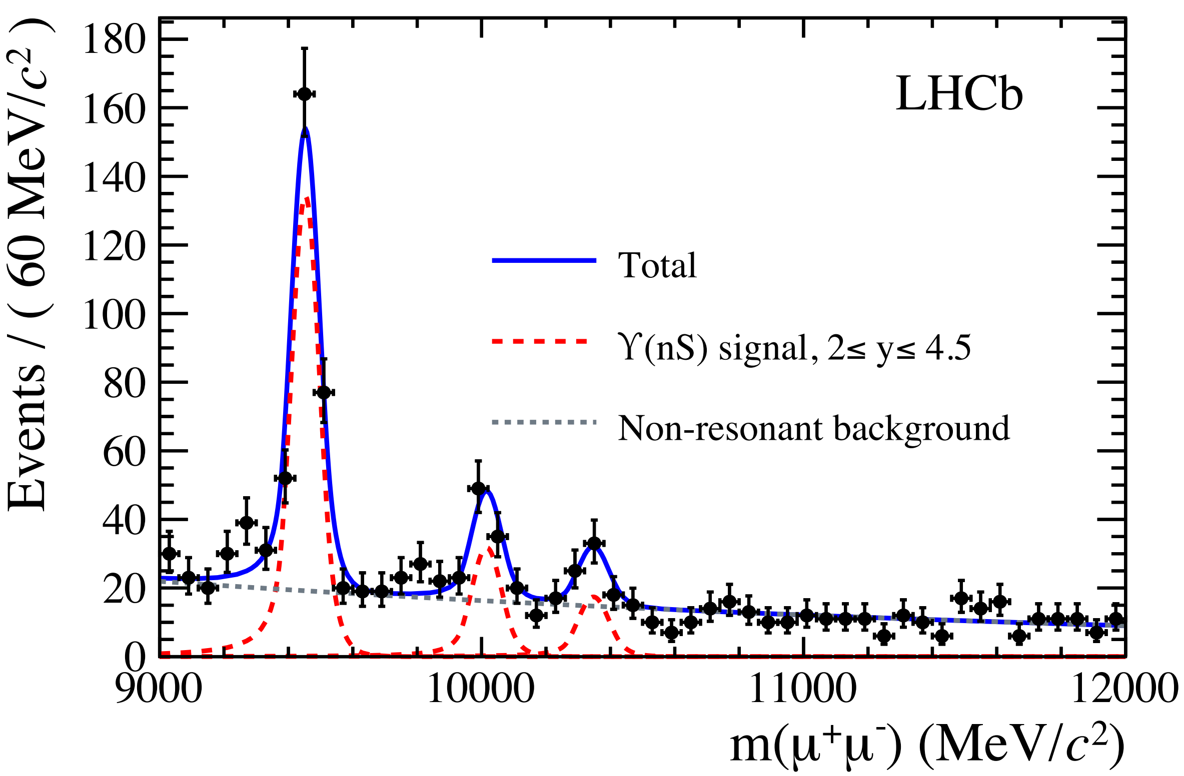
- Candidate: 06:57, July 29th 2011. $m_\Upsilon = 9457\ MeV/c^2$ and $p_T{}^2 = 0.2\ GeV^2/c^2$

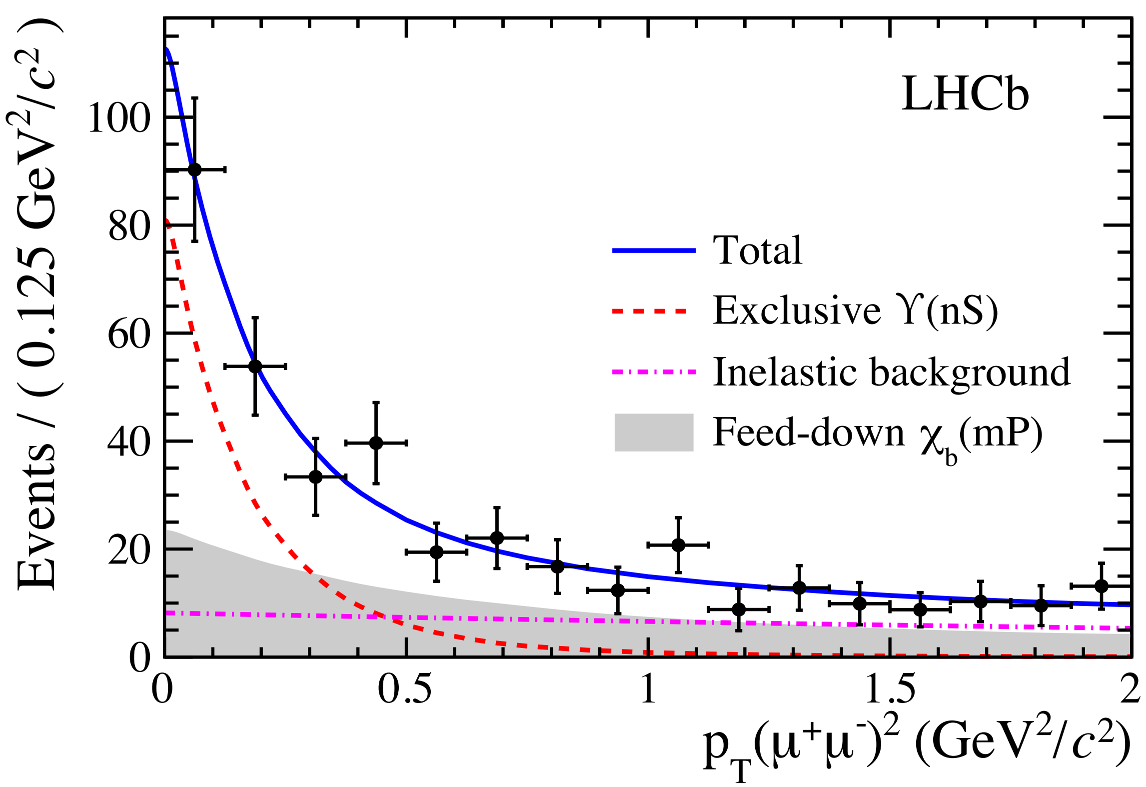
2] EXCLUSIVE Υ(1S,2S,3S) PRODUCTION

JHEP 09 084

Two-stage fitting procedure:

- *Invariant mass distribution: isolate continuum dimuon production*
- *Determine background contamination from $\chi_b \to \Upsilon\gamma$ feed-down in data*
- *p_T^2 distribution: inelastic b.g. has harder spectrum*
  - *Exclusive signal and χ_b background modelled using SuperChiC*





Efficiencies

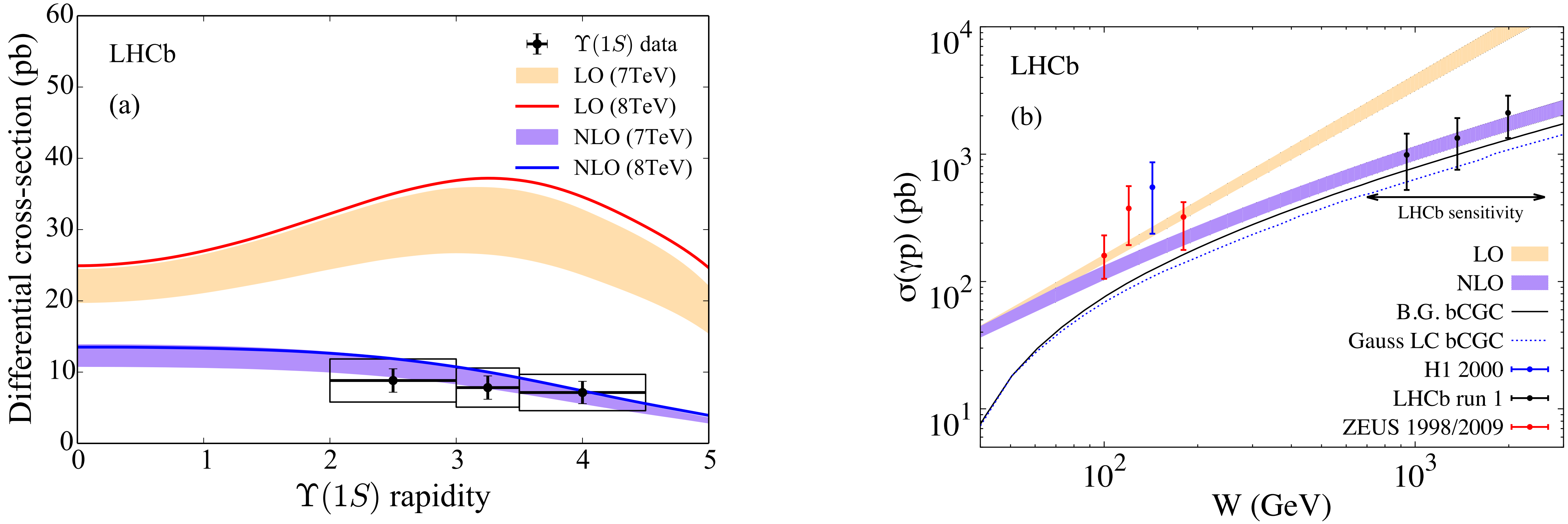
- *Correct using simulated samples: trigger and reconstruction: ~80% efficient*
- *Event-level requirements imply single-interaction events only: 20% of data*

2] EXCLUSIVE ϒ(1S,2S,3S) PRODUCTION

JHEP 09 084

Systematic uncertainties

- *Largest uncertainties due to description of χ_b background p_T^2 behaviour*
- *Subdominant contribution from description of exclusive signal*



Results

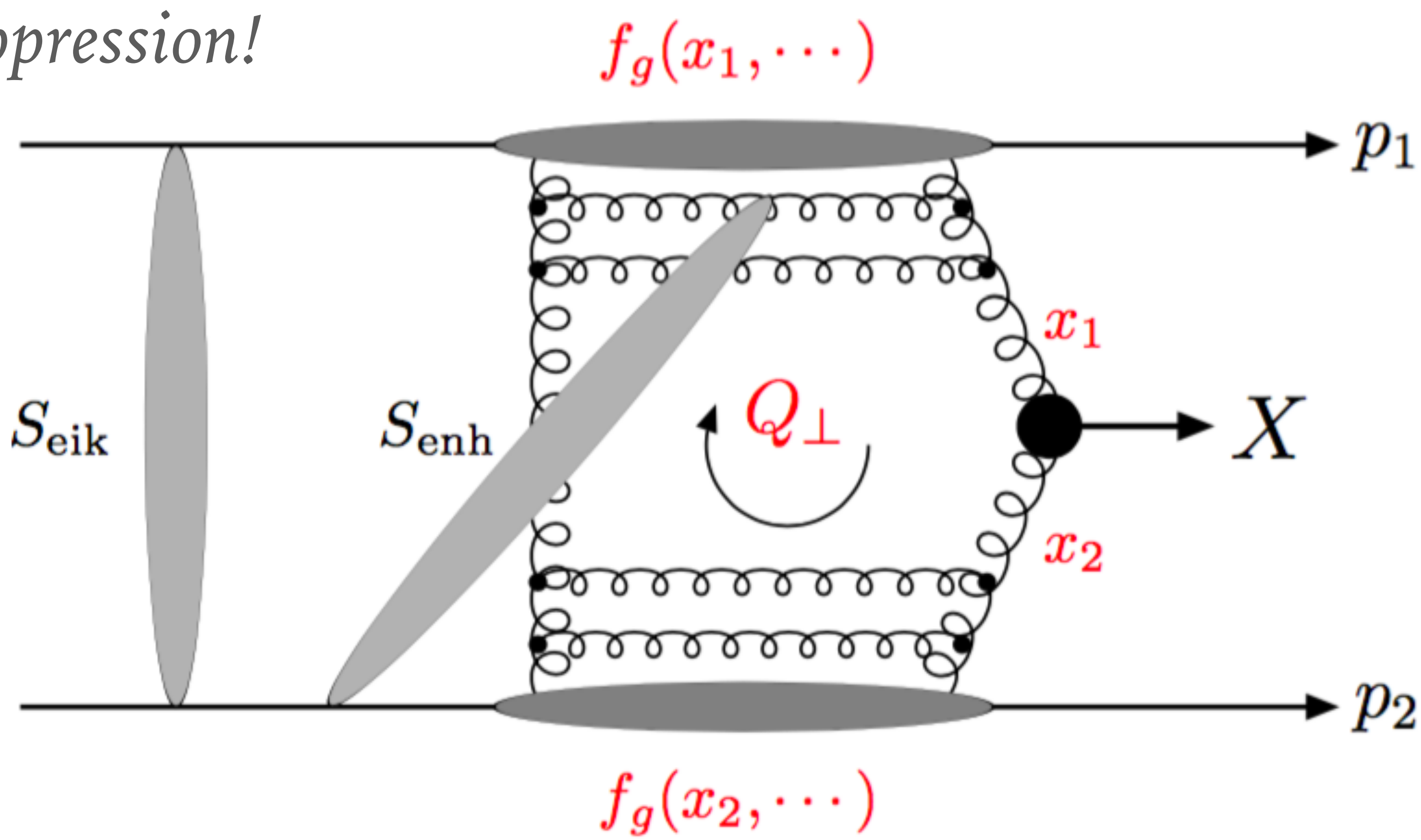
- *Compare rapidity distribution with predictions at LO and NLO*
- *Extract underlying photon-proton cross-section and compare to different models*
- *NLO predictions agree well; slight preference for BG* **ϒ** *w.f. model*

3] DOUBLE CHARMONIUM PRODUCTION

JPG 41 115002

Motivation

- Proceeds by double-pomeron fusion. Born-level prediction ~2-7pb
- Test selection rule for CEP within 'Durham model' $J_z^{PC}=0^{++}$
  - 1% suppression!



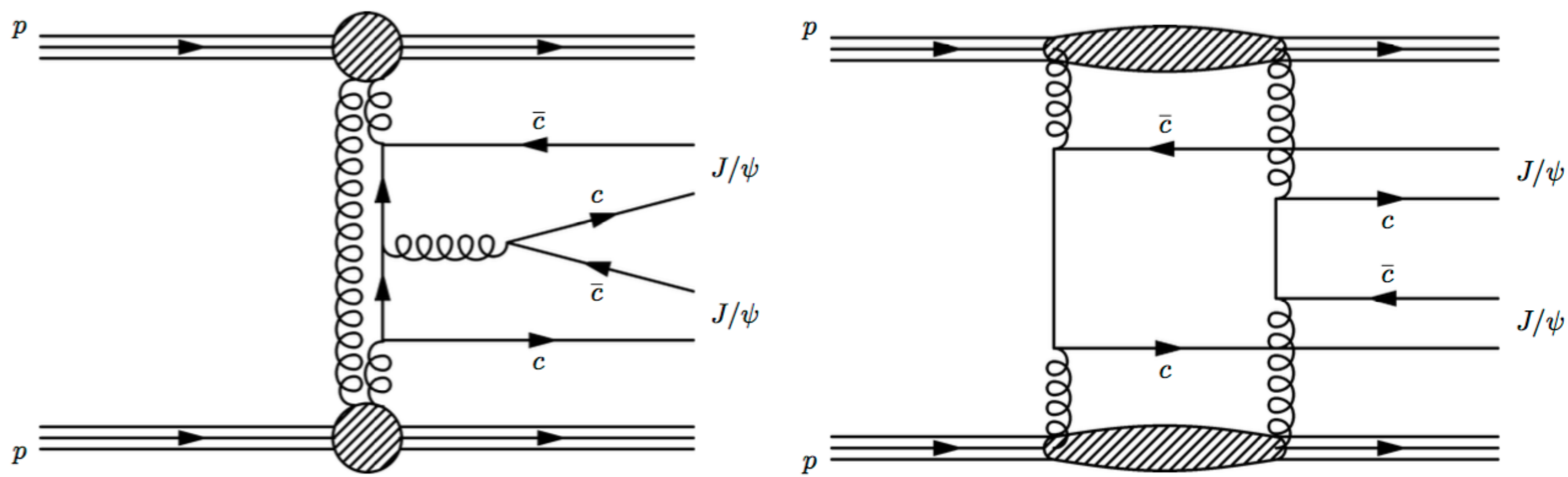
- Shape of J/ψ J/ψ mass distribution has lower theory uncertainty

3] DOUBLE CHARMONIUM PRODUCTION

JPG 41 115002

Selection:

- *3 fb^{-1} pp collisions at 7 and 8 TeV*
- *Trigger identical to previous analyses*
- *No additional VELO tracks*
- *No additional photon activity*
- *Reconstruct $\chi_c \to J/\psi\gamma$*

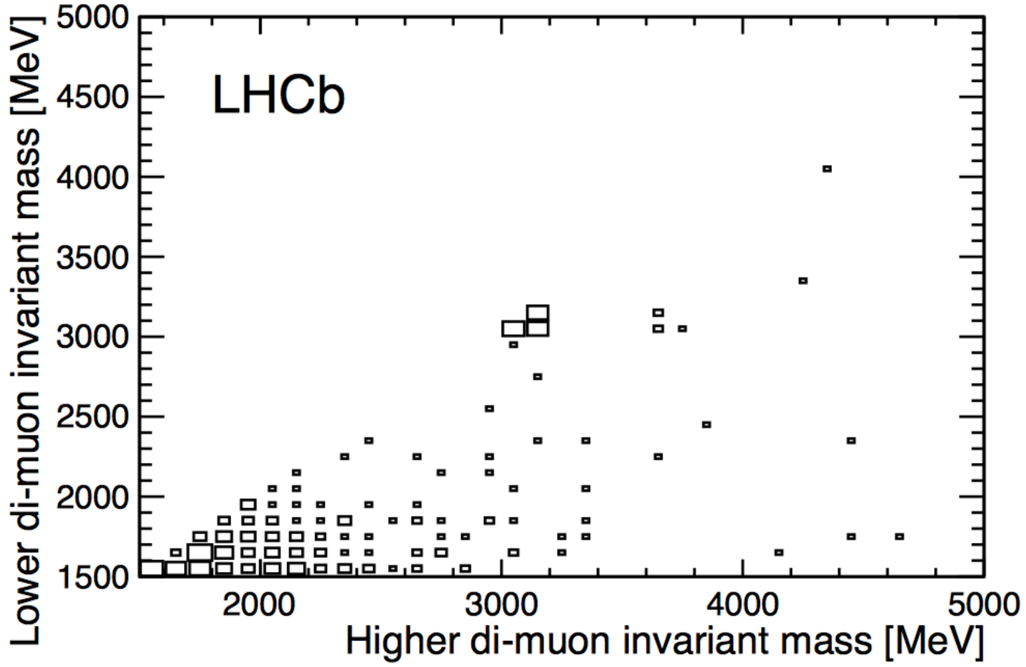


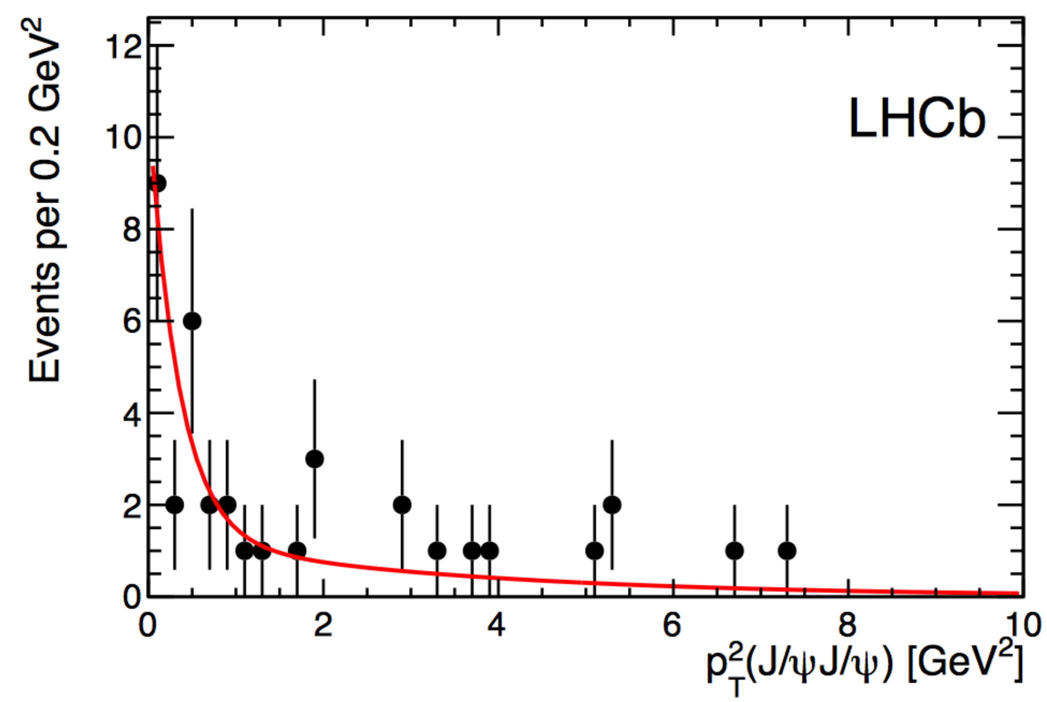
One t-channel gluon participates in hard interaction, other shields colour charge

3] DOUBLE CHARMONIUM PRODUCTION

JPG 41 115002

'Empty-detector' signal





- *Cross-section calculated for a range of double-charmonium states*
- *Largest systematic uncertainty related to final state geometrical acceptance*

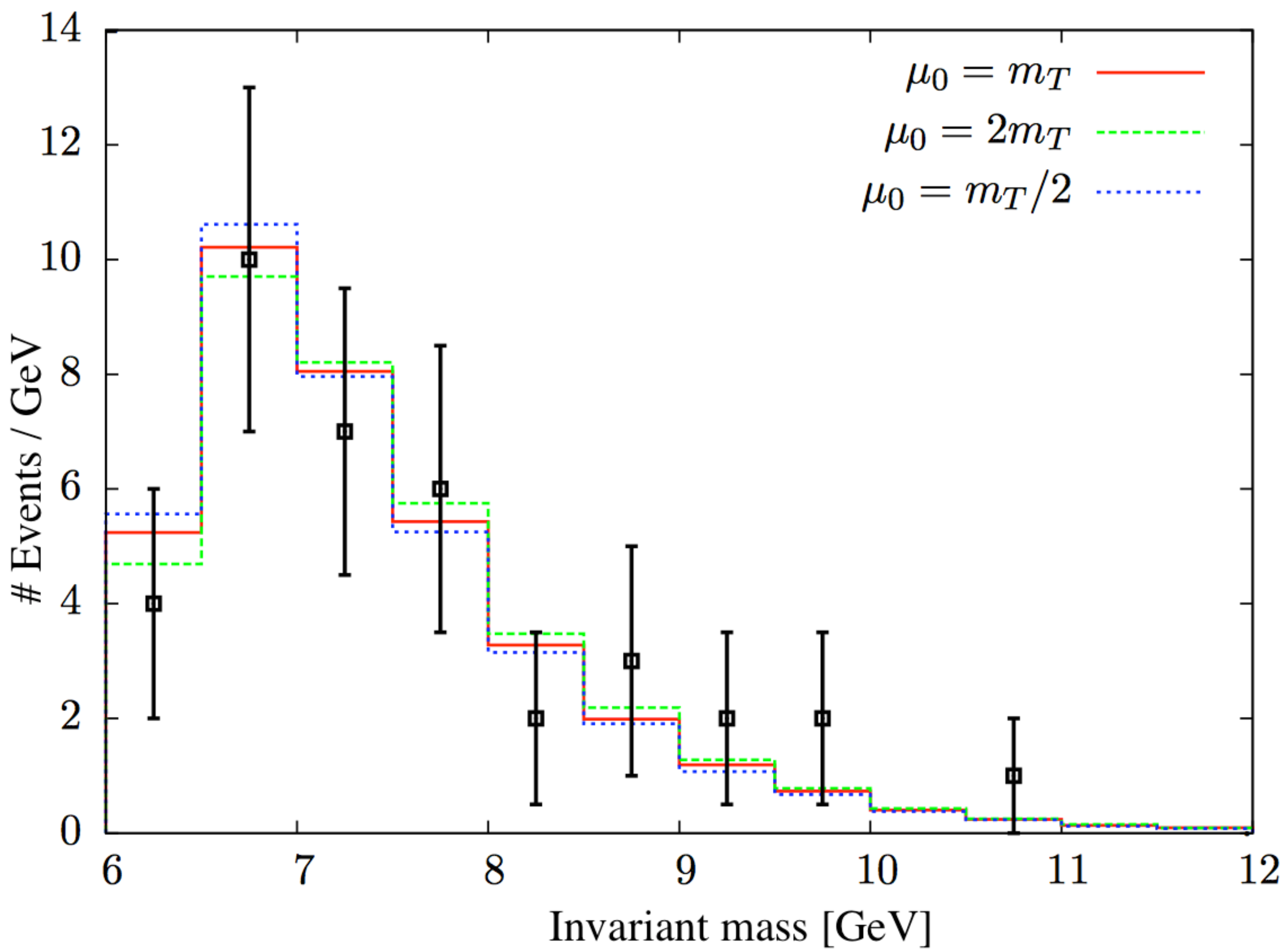
$$
\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 65 \pm 11\ (\mathrm{stat})^{+6}_{-13} (\mathrm{syst})\ \mathrm{pb}, \\
\sigma^{J/\psi\, \psi(2S)} &= 72^{+30}_{-20} (\mathrm{stat})^{+10}_{-16} (\mathrm{syst})\ \mathrm{pb}, \\
\sigma^{\psi(2S)\psi(2S)} &< 255\,\mathrm{pb} \quad \text{at } 90\% \text{ c.l.}, \\
\sigma^{\chi_{c0}\chi_{c0}} &< 75\,\mathrm{nb} \quad \text{at } 90\% \text{ c.l.}, \\
\sigma^{\chi_{c1}\chi_{c1}} &< 49\,\mathrm{pb} \quad \text{at } 90\% \text{ c.l.}, \\
\sigma^{\chi_{c2}\chi_{c2}} &< 150\,\mathrm{pb} \quad \text{at } 90\% \text{ c.l.}.
\end{aligned}
$$

3] DOUBLE CHARMONIUM PRODUCTION

JPG 41 115002

Interpretation

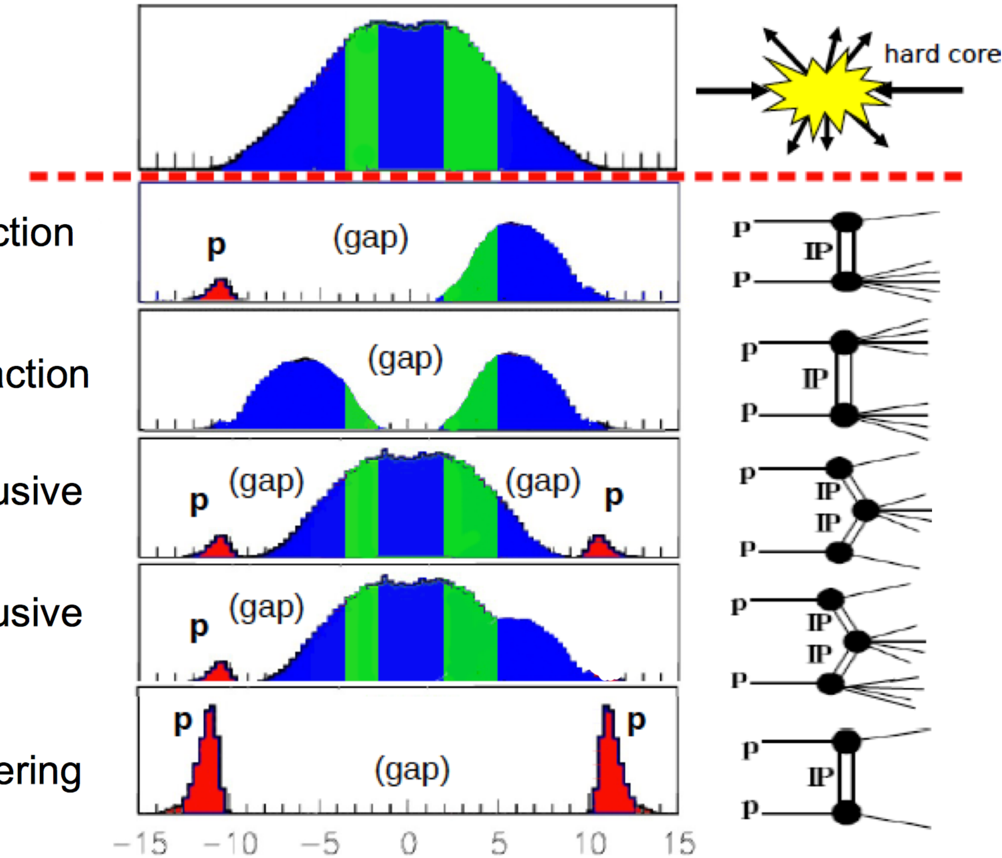
- *First evidence for double-charmonium CEP*
- *Estimate of exclusive component is 42 ±13%*
- *Total cross-section and relative size of $J/\psi\ \psi(2S)$ signal agree with theory*
  - *errors are large and theory only Born-level*
- *Observed double charmonium mass spectrum agrees with prediction*



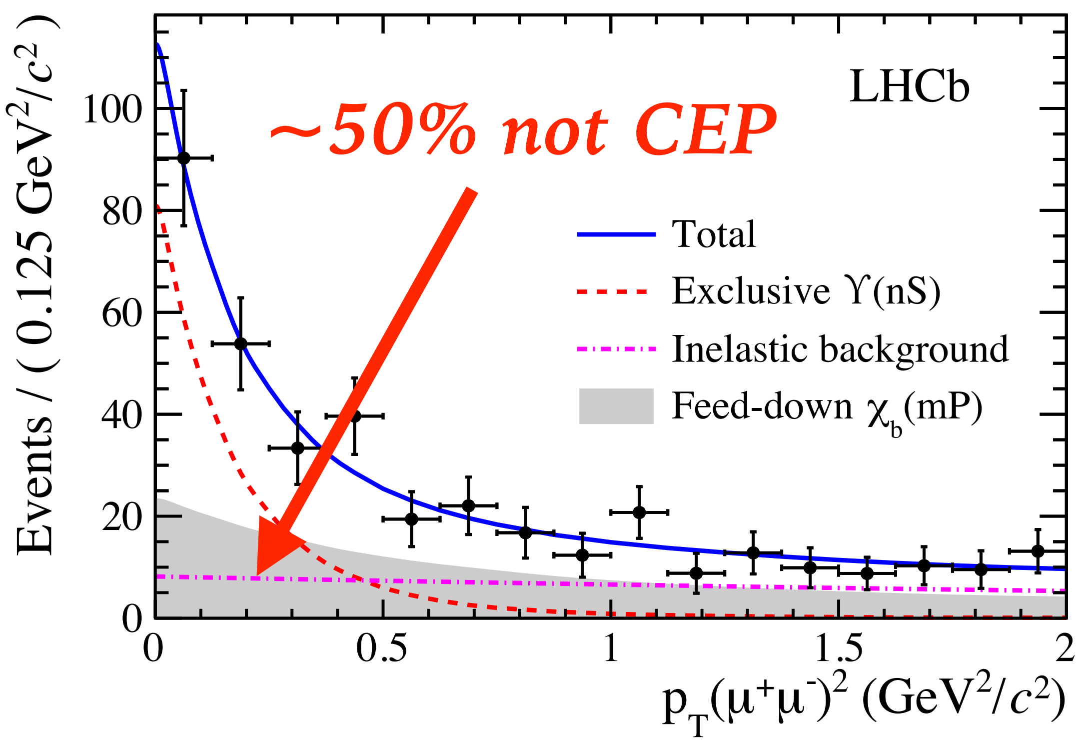
WE NEED WIDER VISION (THE 'HERSCHEL' PROJECT)

*We infer **pomeron** exchange by searching for events with **large rapidity gaps***

…but proton dissociation or gluon emission with activity outside LHCb contaminates our samples



Run 1 solution: fit p_T^2 distribution e.g.



- *Fit can be model dependent*
- *Large biases for small samples*
- *Background level depends on final state*

Must tag the protons or extend LHCb coverage!

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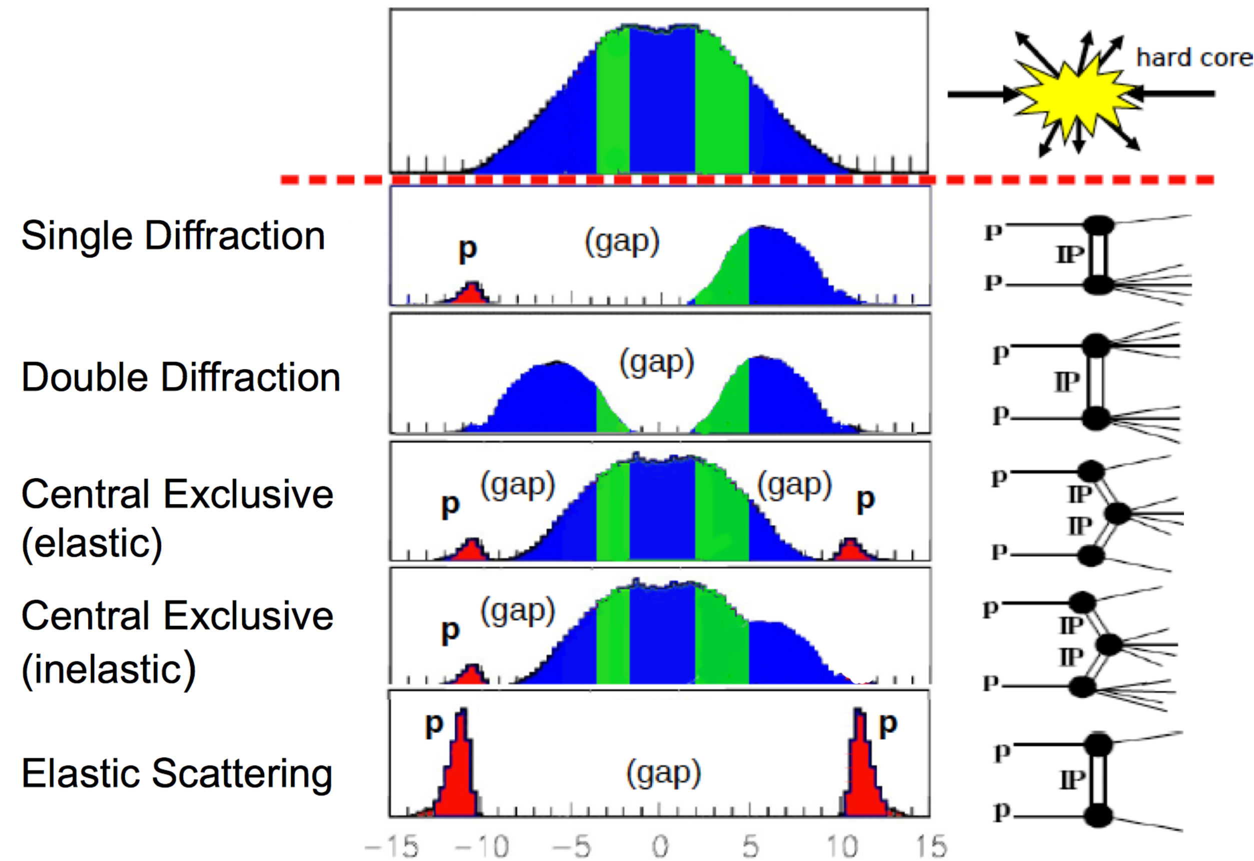

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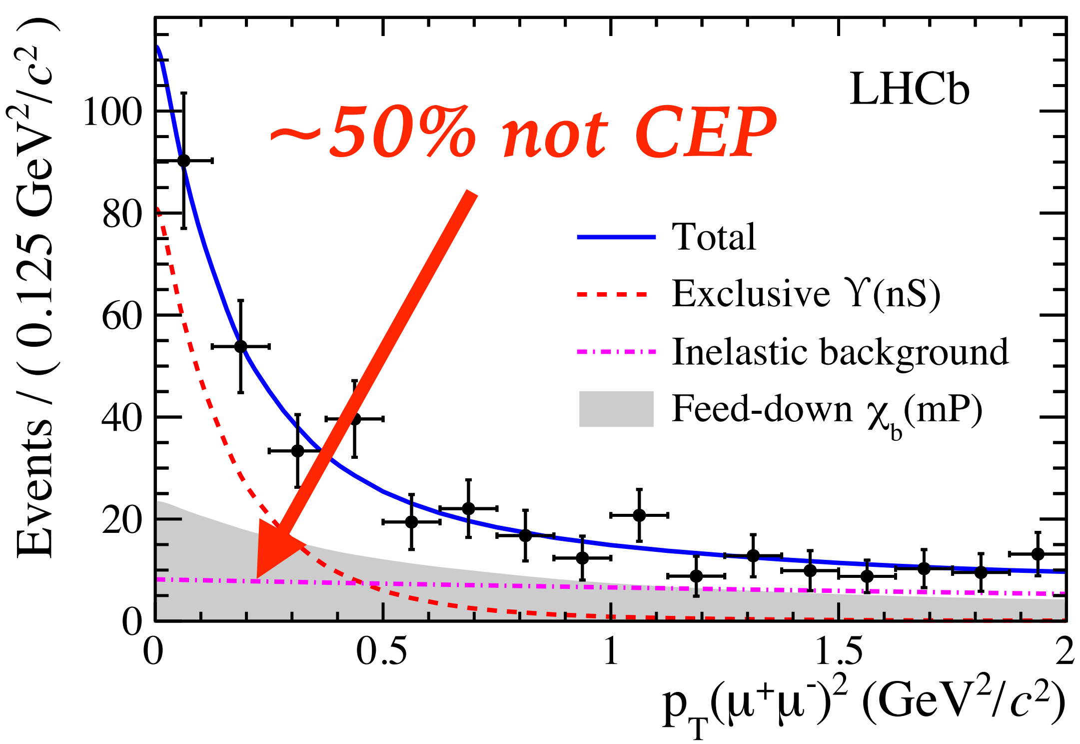

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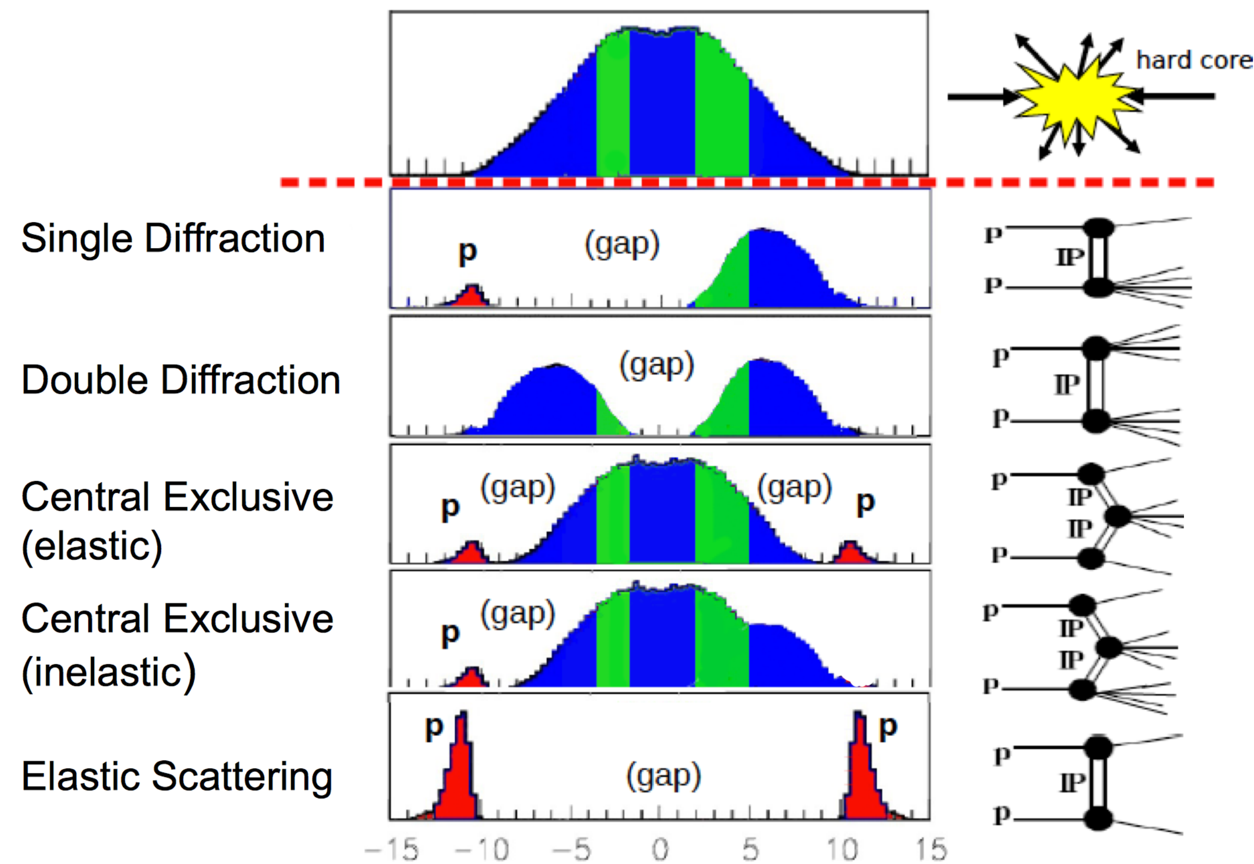
…but *proton dissociation* *or* *gluon emission* *with activity outside LHCb* *contaminates* *our samples*



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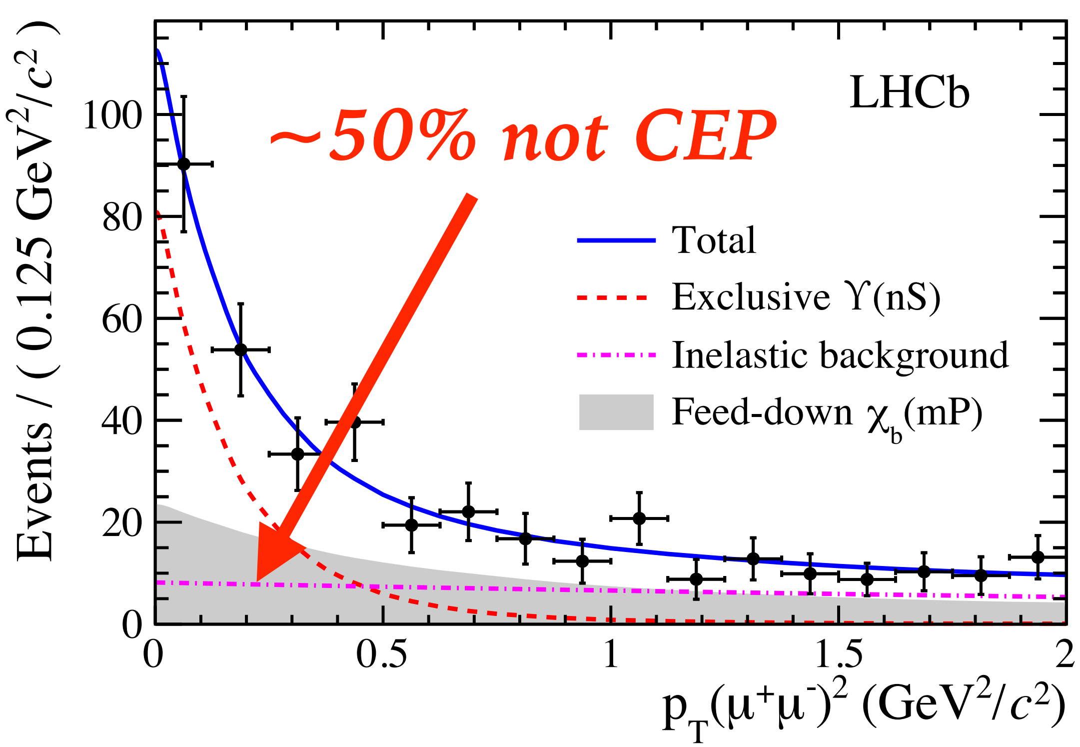
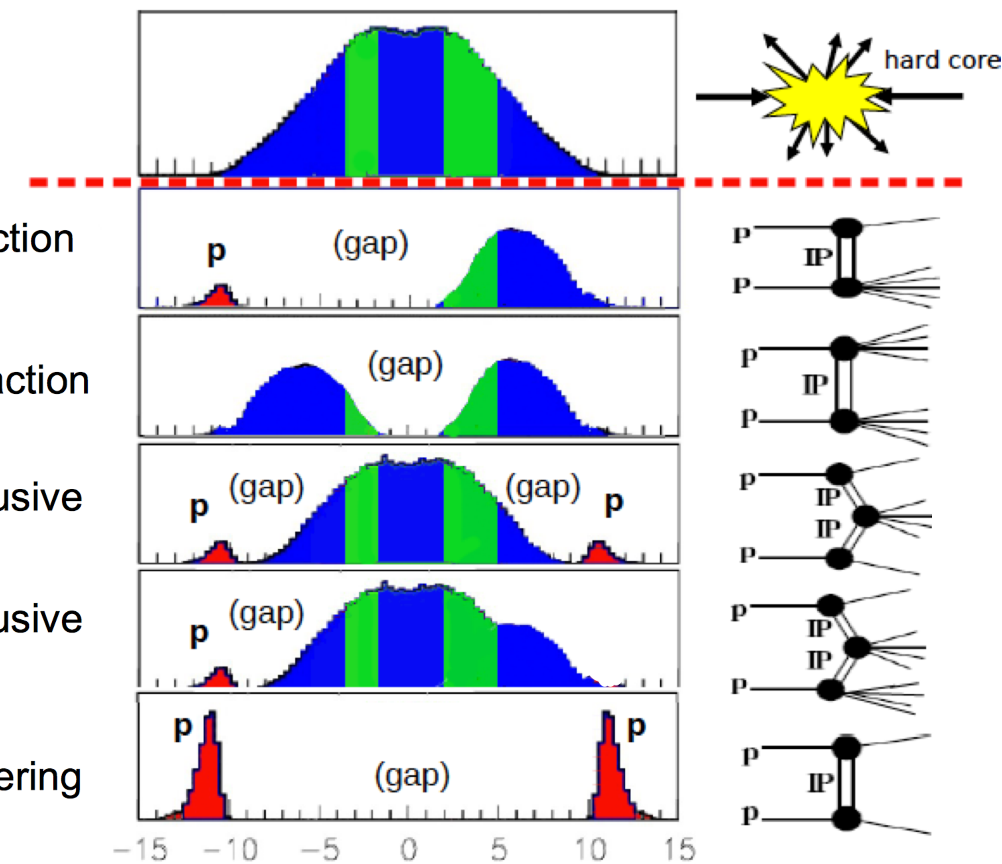


- *Fit can be model dependent* ✗
- *Large biases for small samples* ✗
- *Background level depends on final state*

Must tag the protons or extend LHCb coverage!

WE NEED WIDER VISION (THE 'HERSCHEL' PROJECT)

*We infer **pomeron** exchange by searching for events with **large rapidity gaps***



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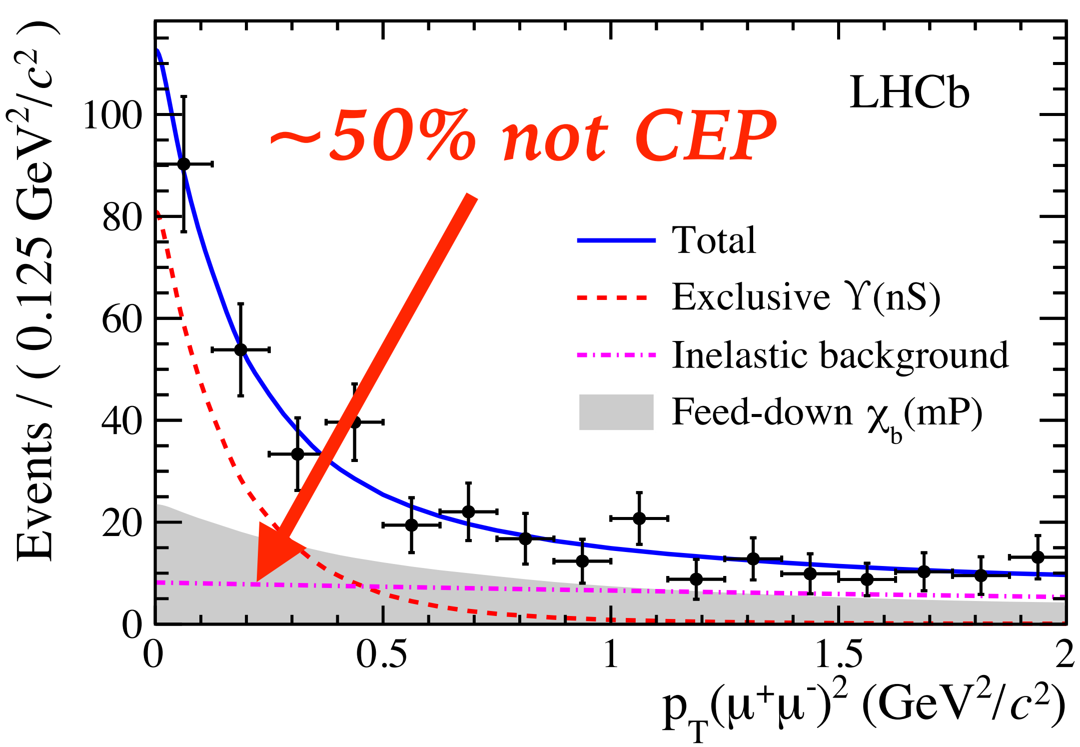
Run 1 solution: fit p_T^2 distribution e.g.

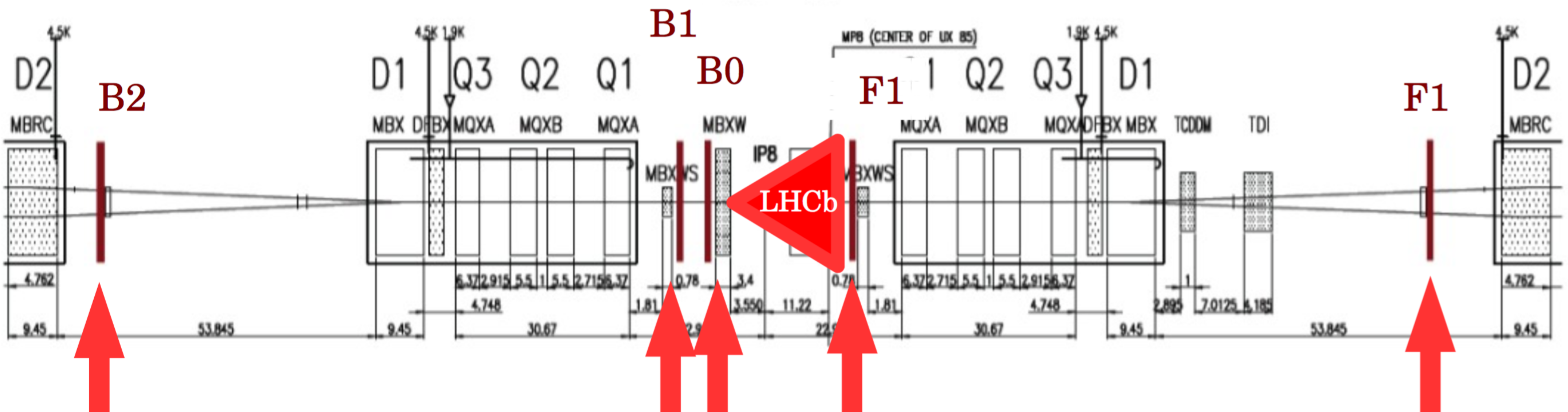


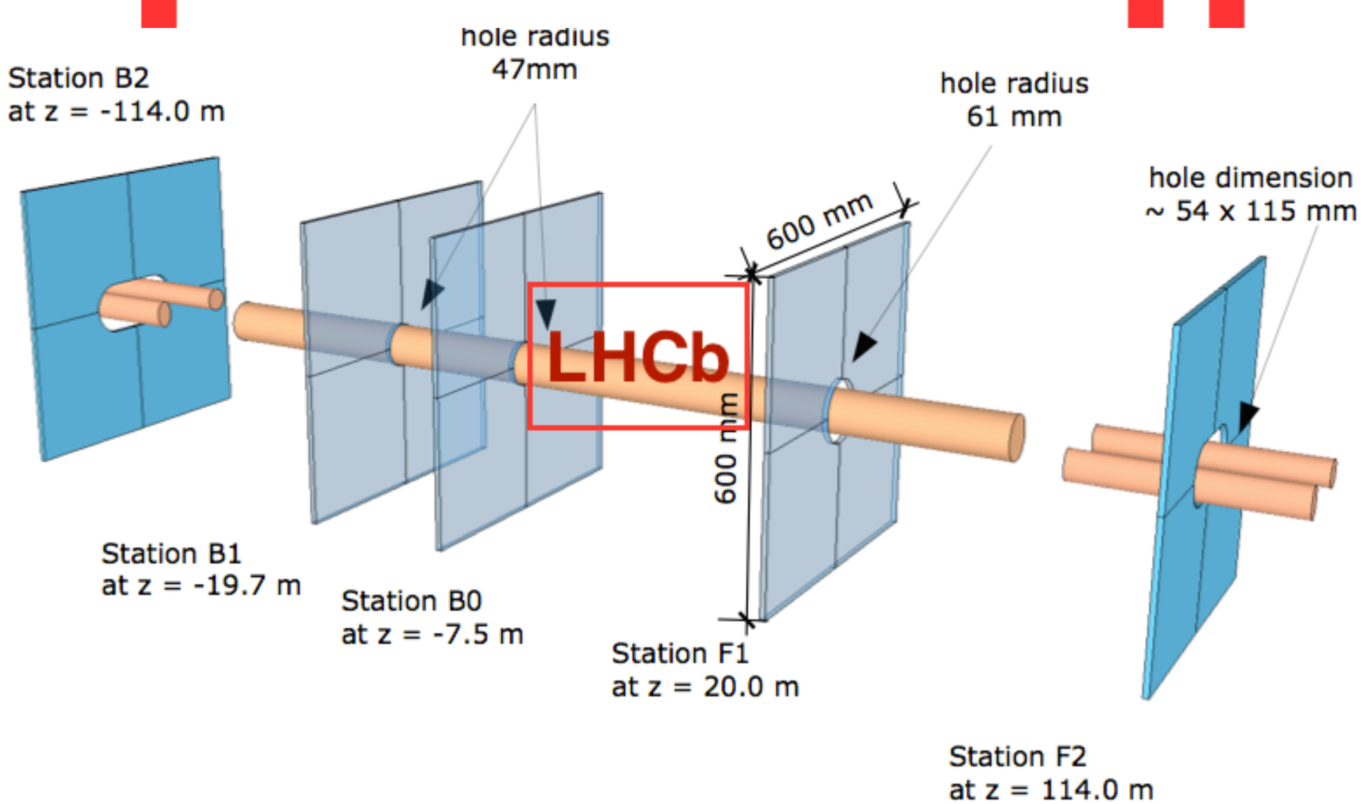
- *Fit can be model dependent* ✗
- *Large biases for small samples* ✗
- *Background level depends on final state* ✗

Must tag the protons or extend LHCb coverage!

WHAT IS HERSCHEL (1/2)

Five sets of scintillators, in the tunnel either side of LHCb

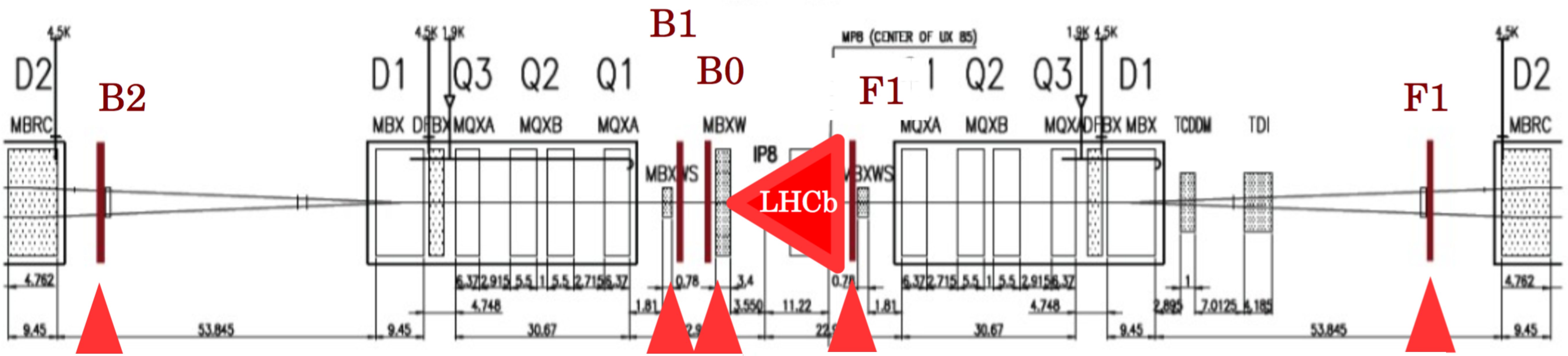


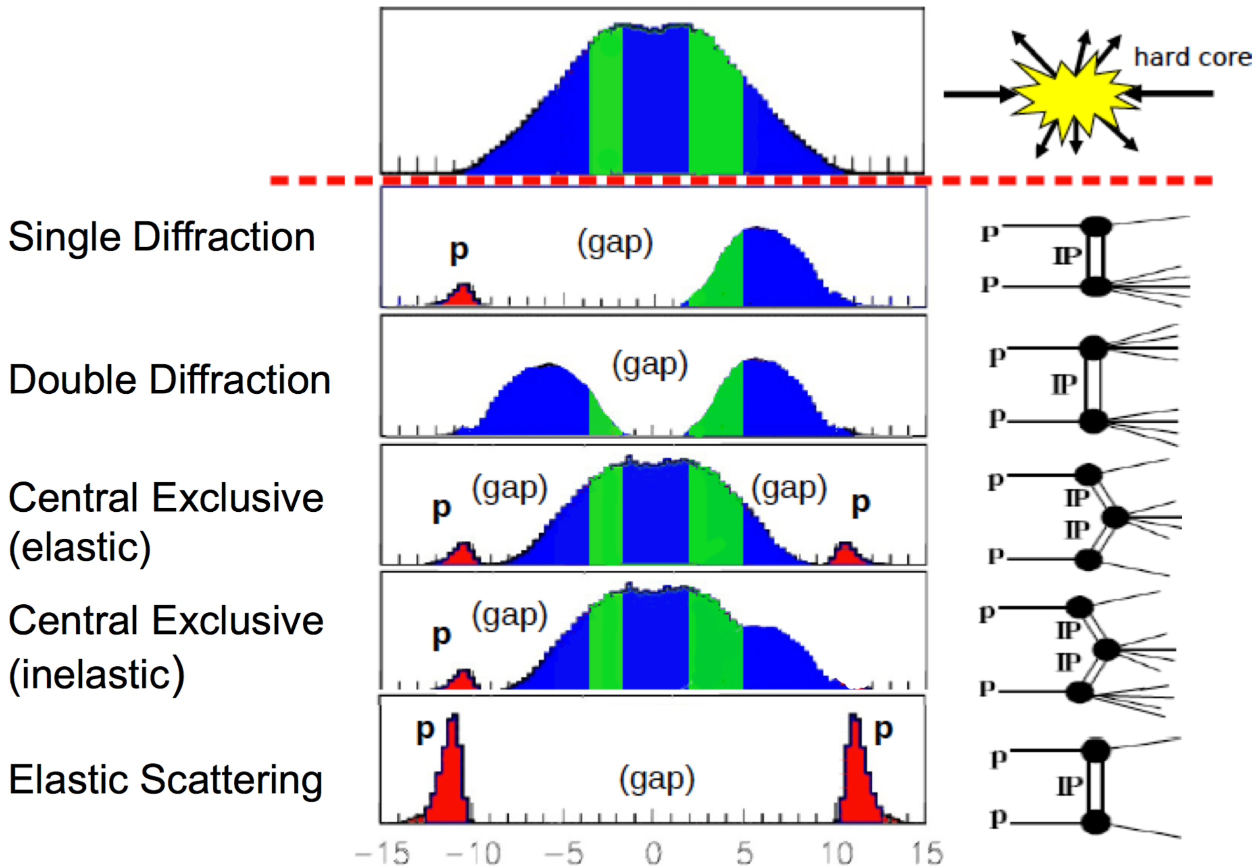


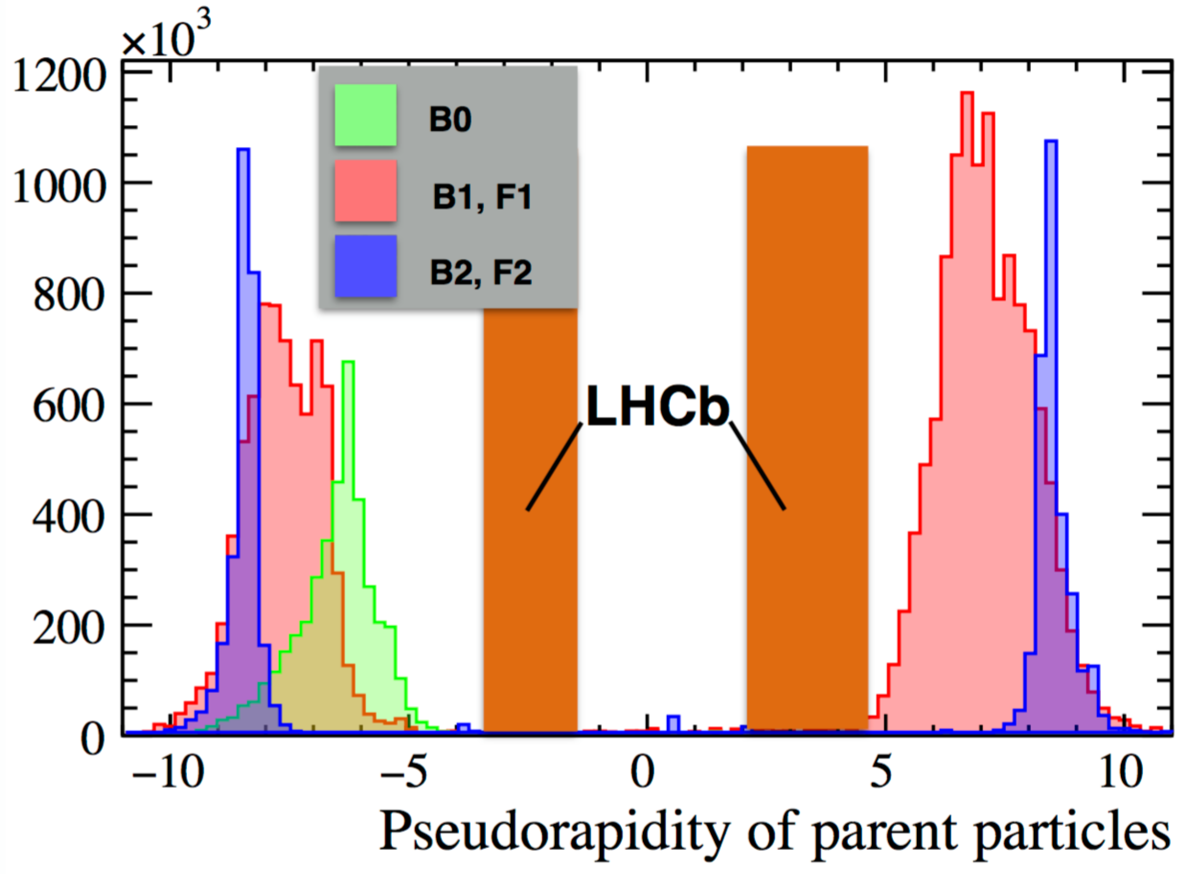
Detect showers from high rapidity particles interacting with the beam-pipe elements

WHAT IS HERSCHEL (2/2)

Greatly increased rapidity coverage







HISTORY

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

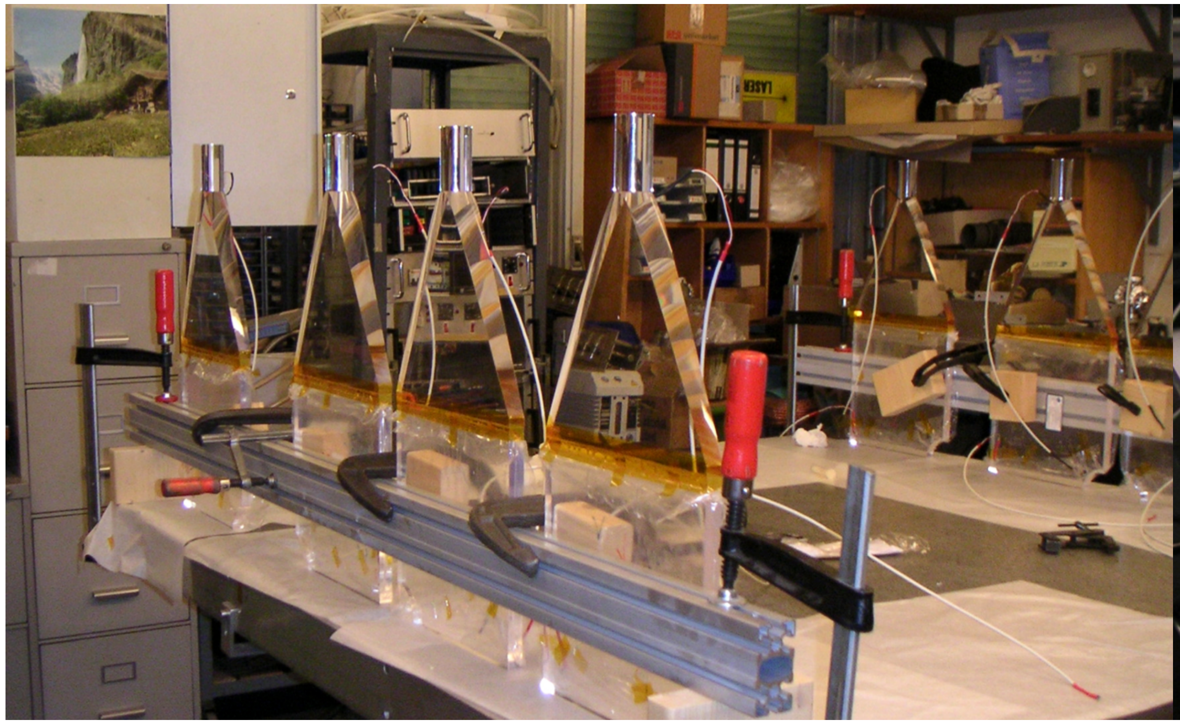
Jan/Feb 2015:
New read-out electronics
Grounding

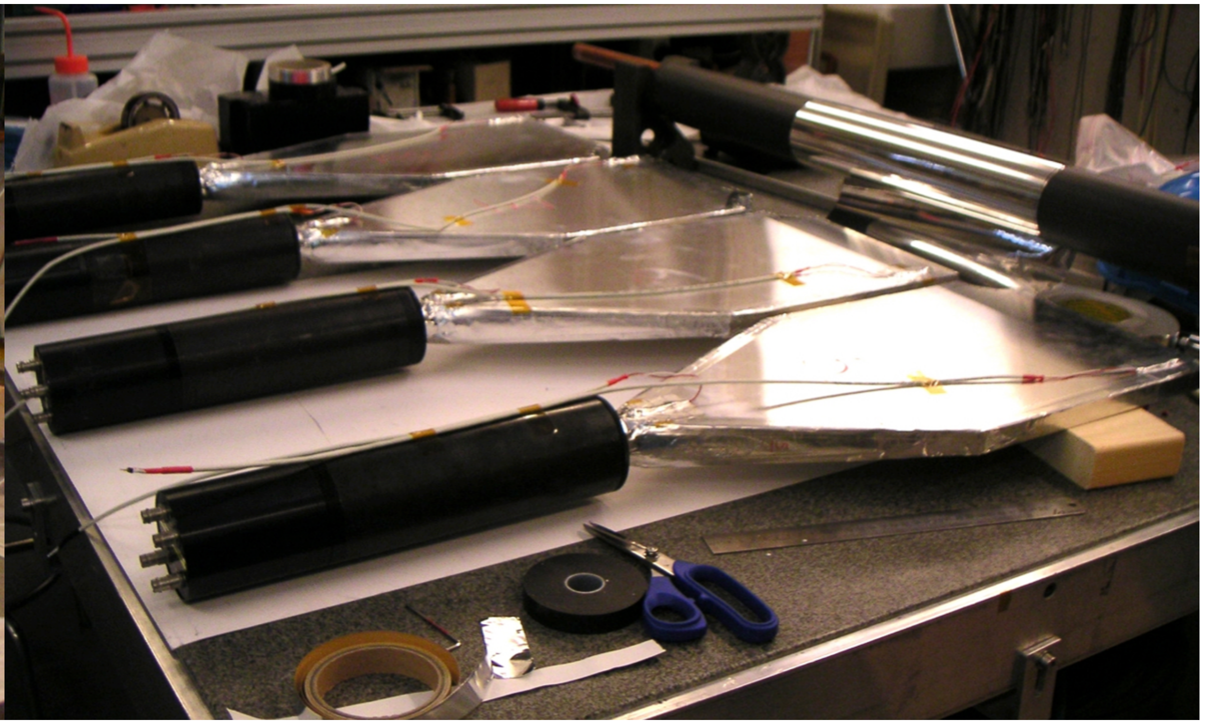
Summer 2015:
Data-taking begins

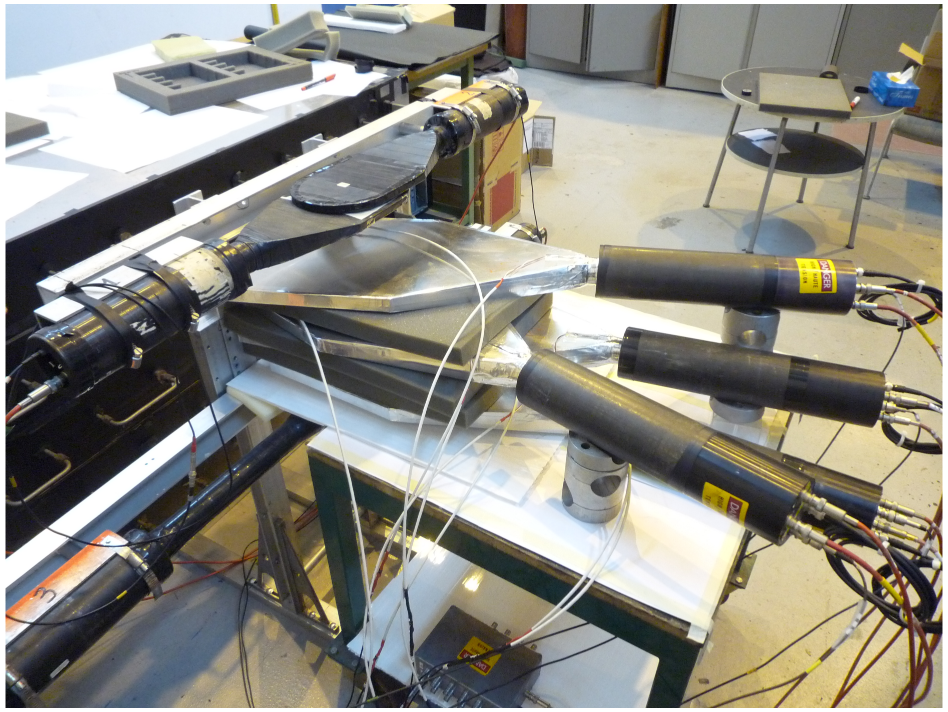
September 2015:
Herschel stable &
available offline!

BUILDING HERSCHEL

Manufacturing the scintillating counters



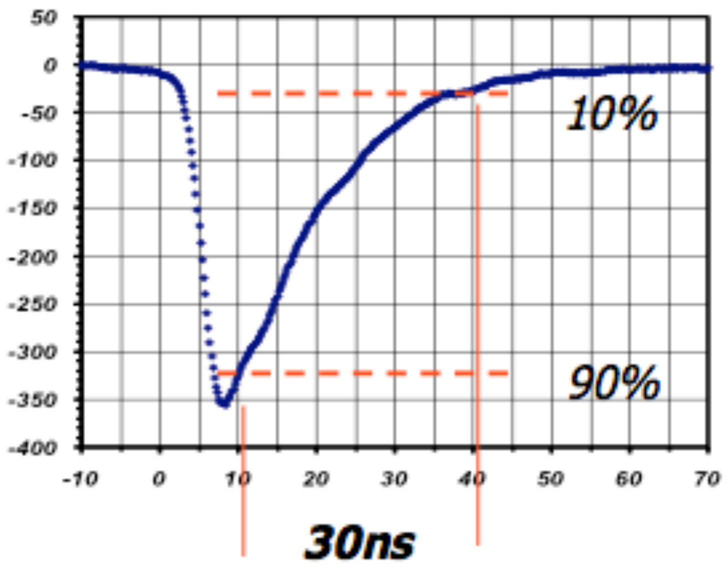


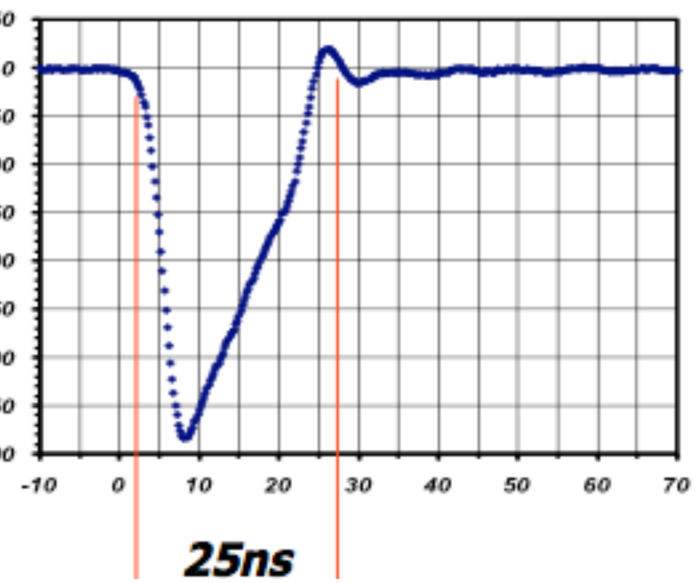


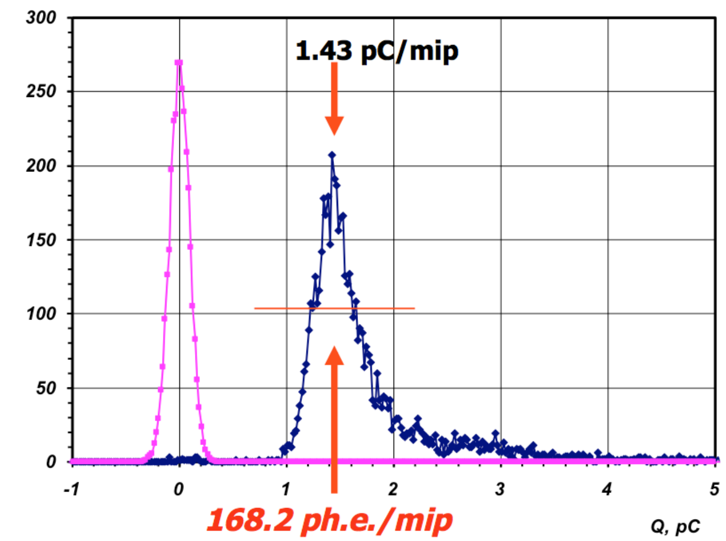
- *Light-guides attached*
- *2 LEDs per counter to aid calibration and to monitor ageing*
- *PMT calibration over range of HV and counter calibration using a cosmic stand*

BUILDING HERSCHEL

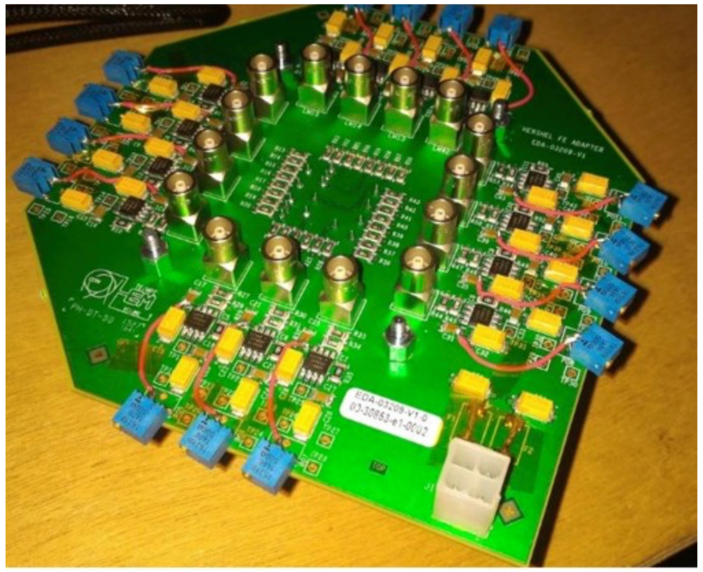
Signal calibration

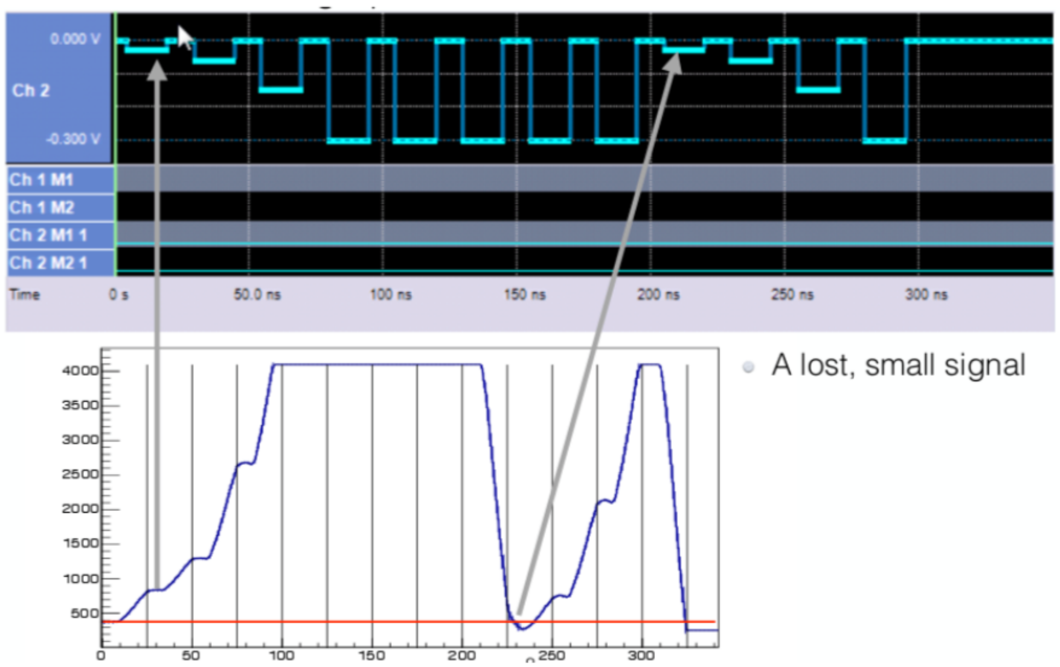






- *Signal, after clipping, fits within 25ns*
- *Ample light yield: ~170 photo-electrons per MIP*
- *Read-out electronics changed to fix pedestal drift*

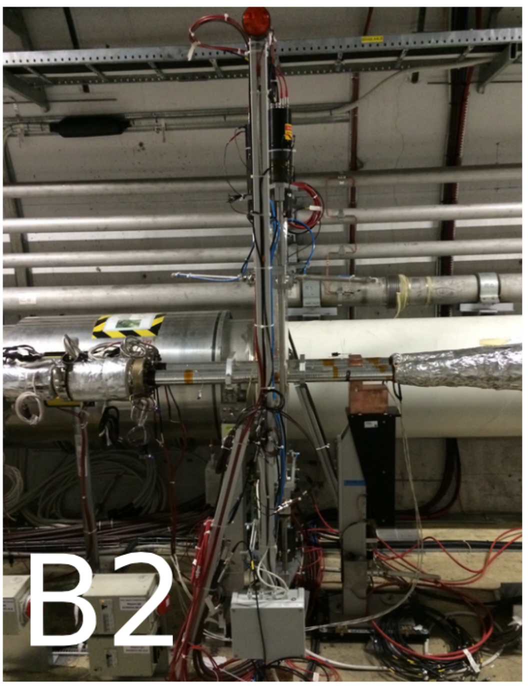




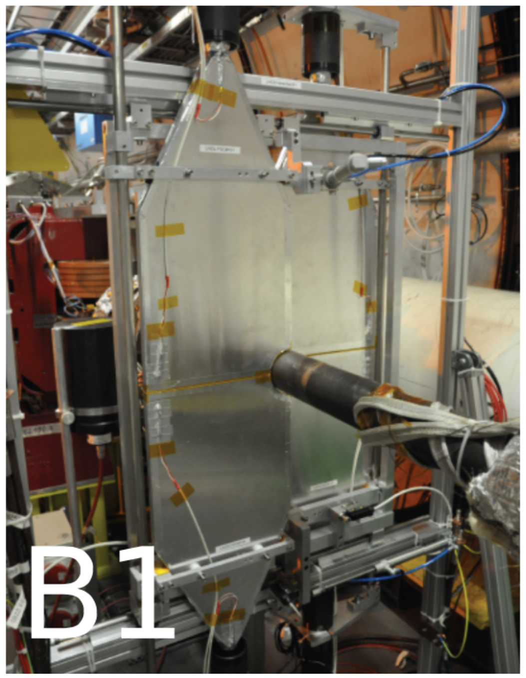
BUILDING HERSCHEL

Tunnel installation

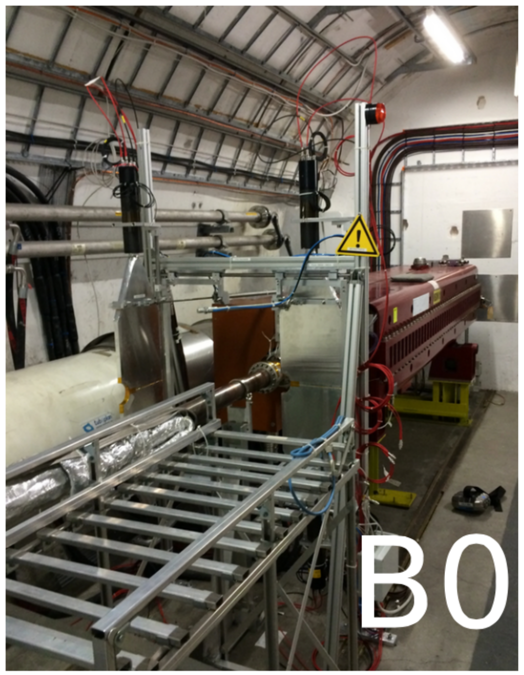
-114m



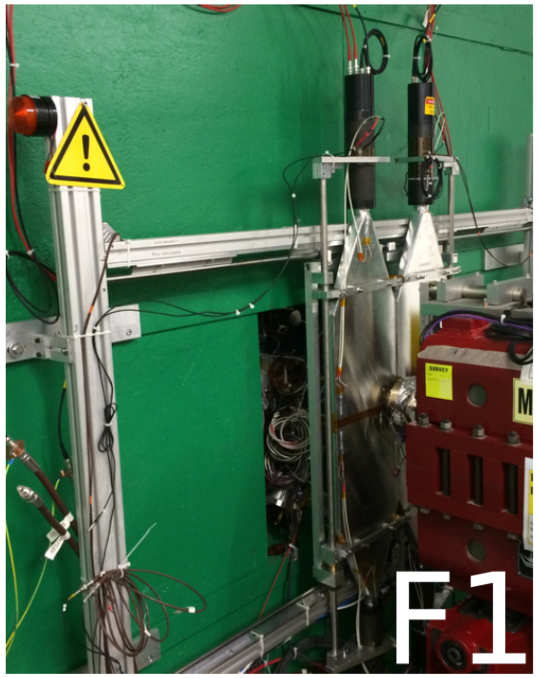
-19.7m



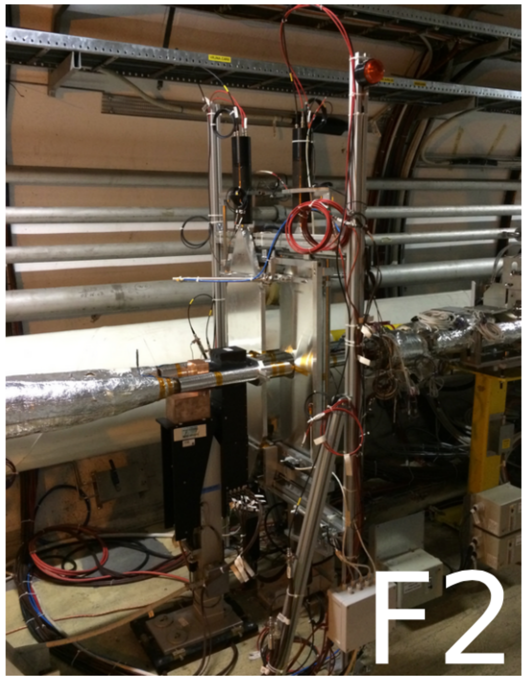
-7.5m



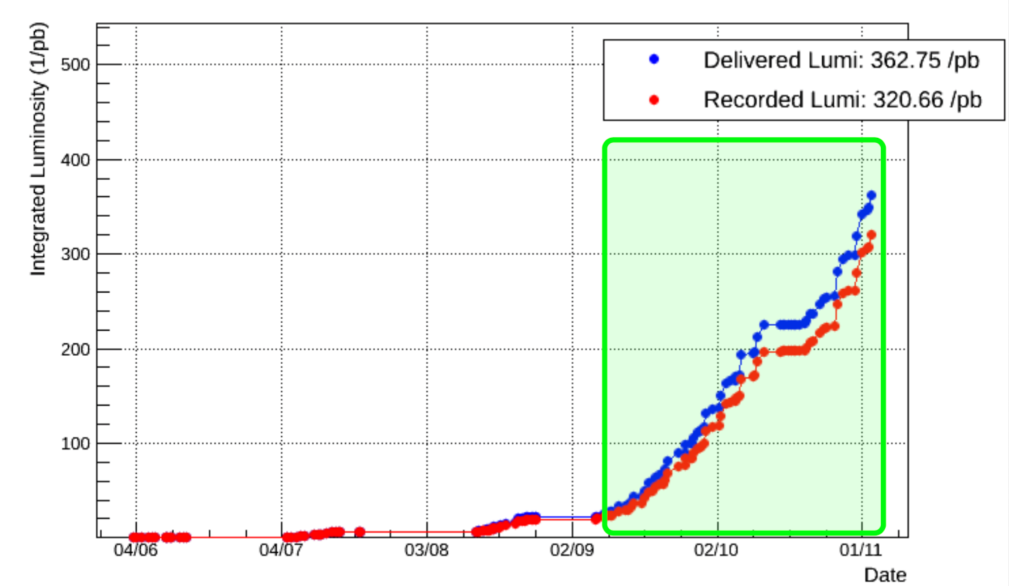
20m



114m



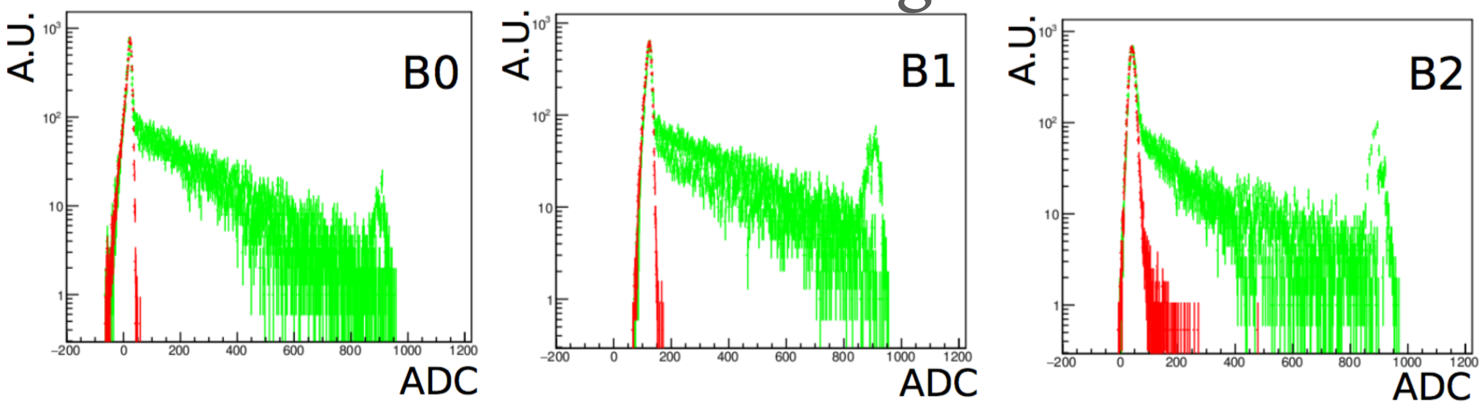
LHCb Integrated Luminosity at p-p 6.5 TeV in 2015



- *Hardware fully installed and operational*
- *DAQ complete*
- *In stable state for offline analysis! $L^{-1} \sim 300\ pb^{-1}$*
- *Work to integration in the Level-0 trigger ongoing*

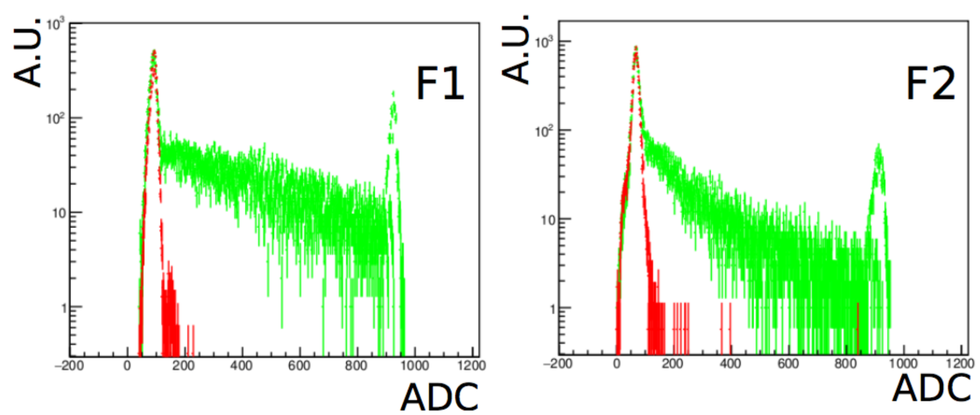
IMPACT IN RUN 2

What does our exclusive signal look like in Herschel?

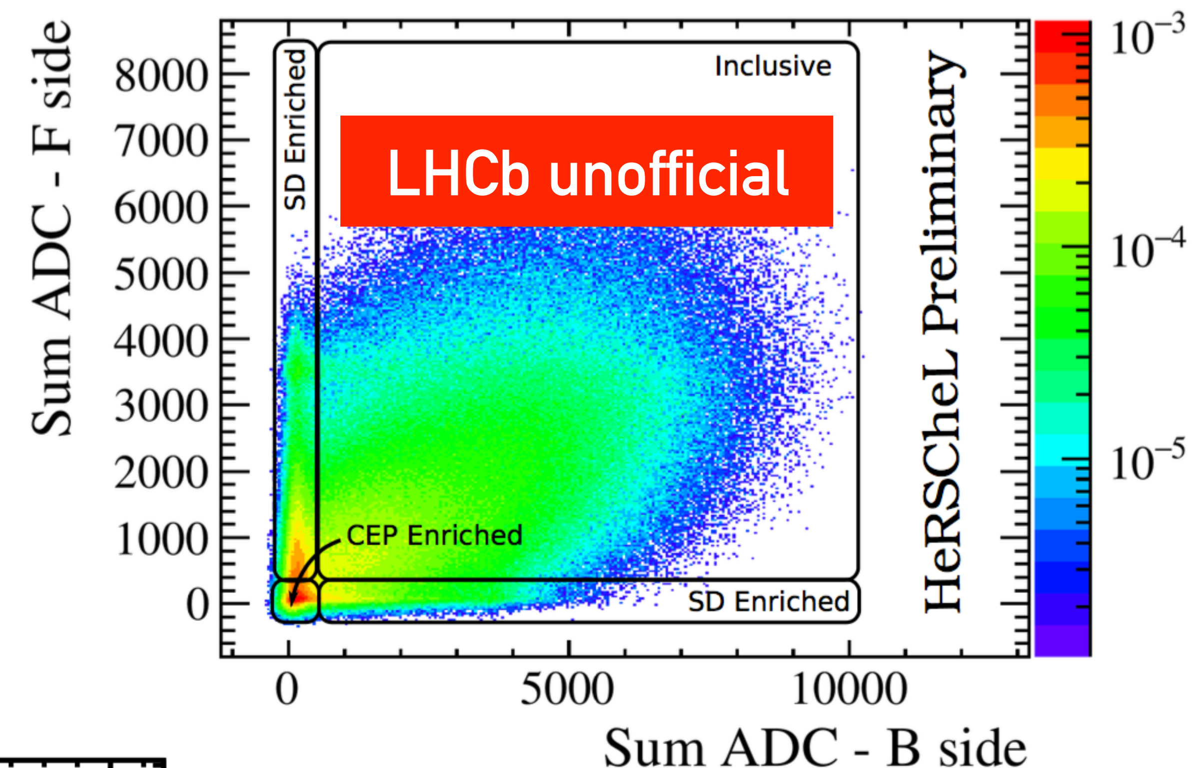


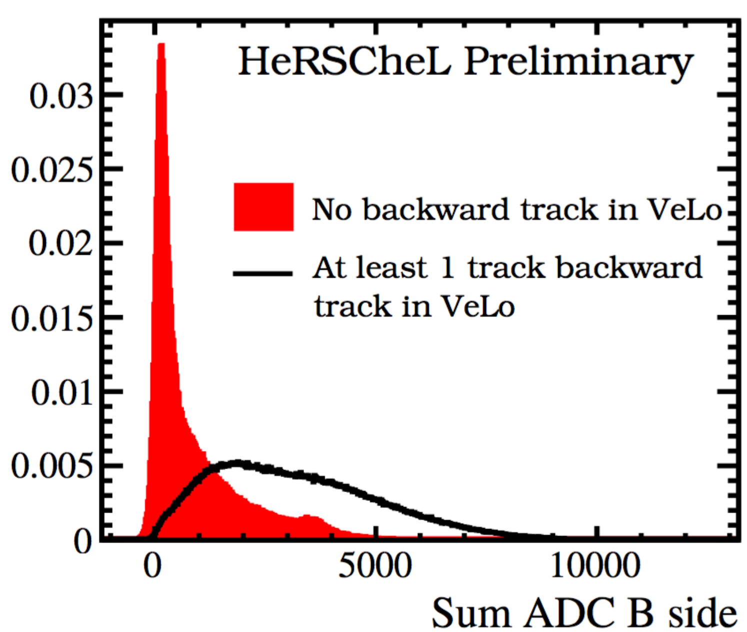
Random trigger on bb crossing

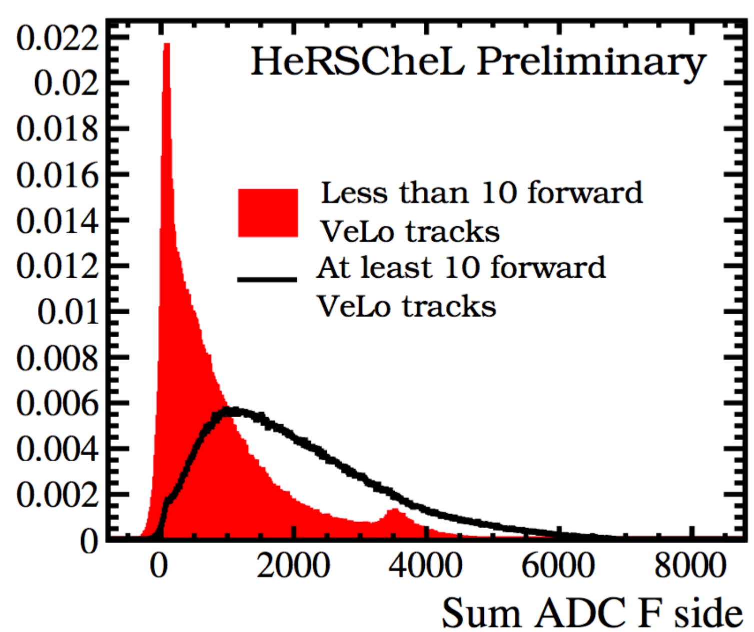
First empty crossing after a bb train



Correlations between B and F sides







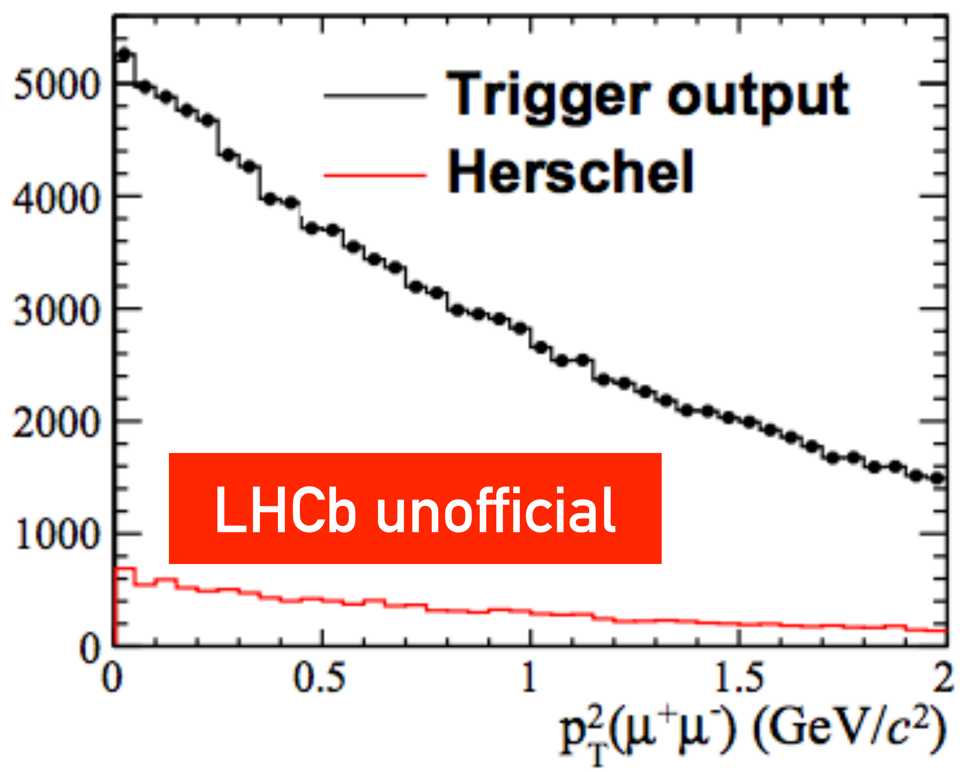
Correlations with the rest of LHCb

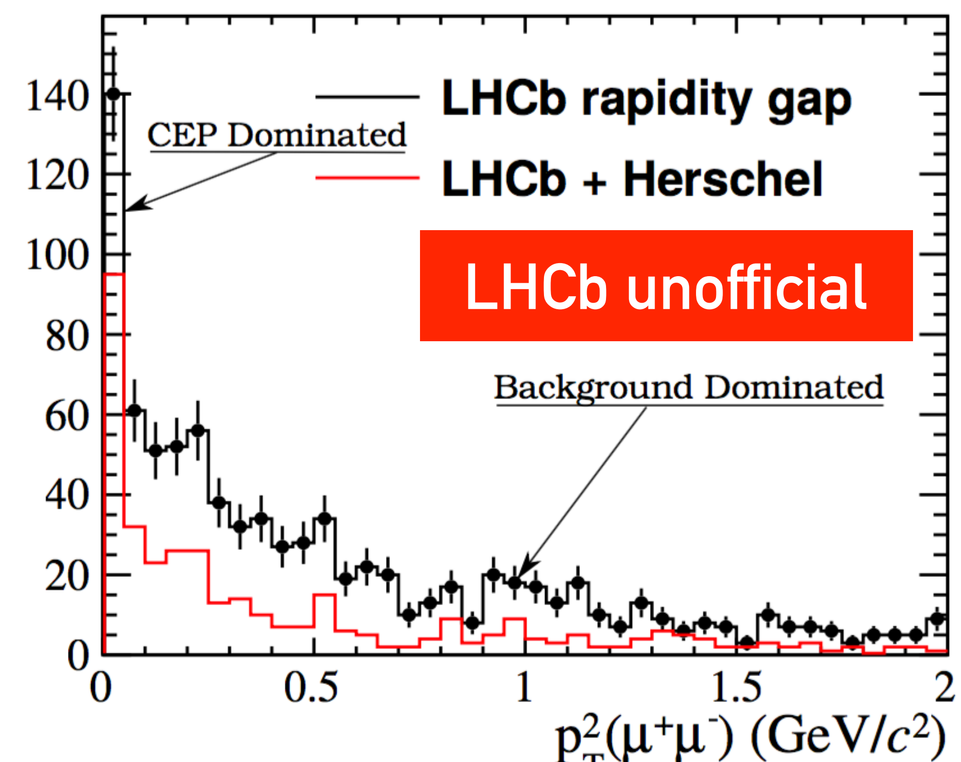
A BRIGHT FUTURE WITH HERSCHEL

*We infer **pomeron** exchange by searching for events with **large rapidity gaps***

***Consider exclusive process**: $pp \rightarrow p + \mu\mu + p$*

- *LHCb rapidity gap: 2 long and no other velo tracks*
- *LHCb+Herschel adds $N(ADC_{HRC}) < 3\sigma_{Pedestal}$ veto*





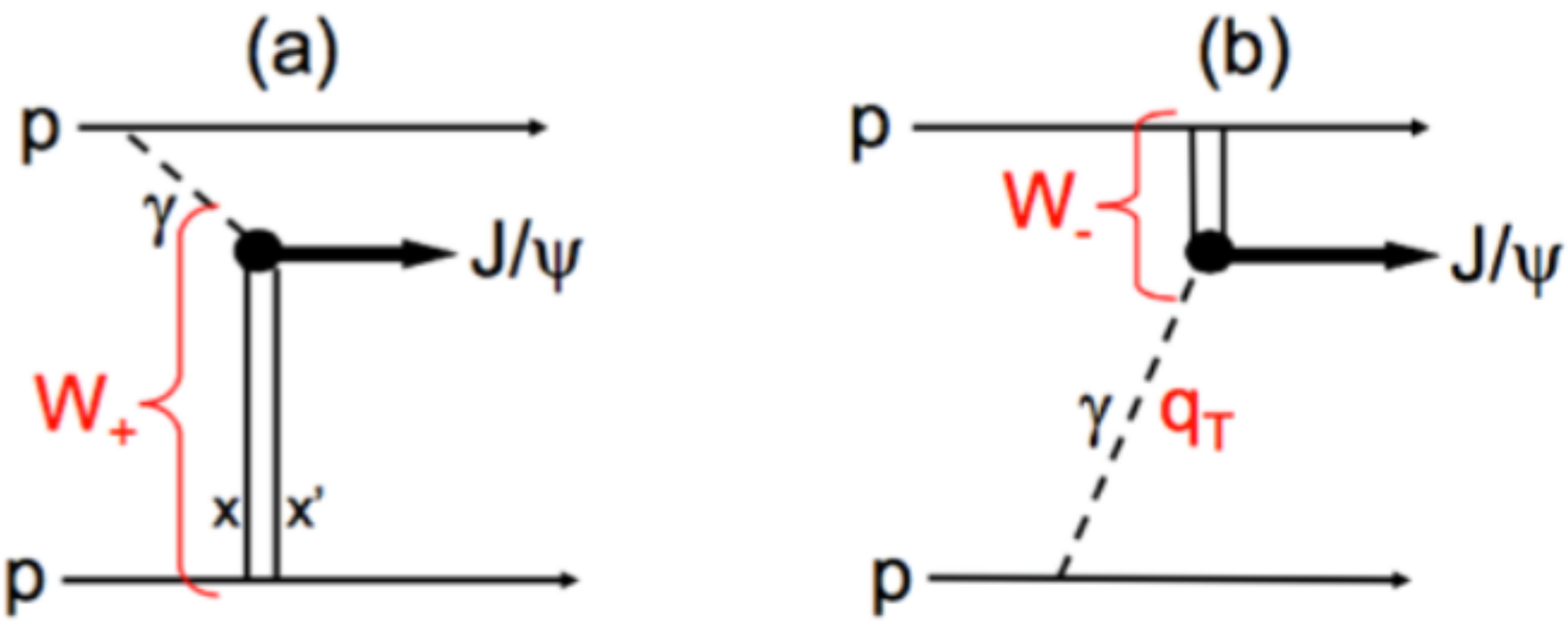
- *Top priority: integrate with L0; factor ~8 reduction in CEP L0 rate*
- *Exclusive J/ψ at 13 TeV (bg reduced by factor ~3 - 4) paper in preparation*
- *Herschel performance paper in preparation*

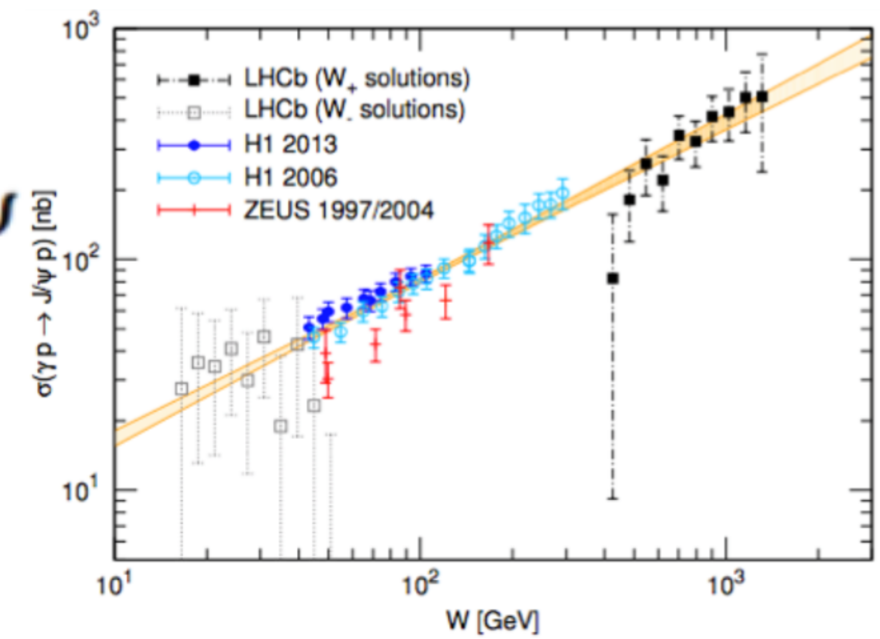
CONTINUING EXPLOITATION OF RUN 1 DATA

Analyses of interest using Run 1 data

1) *Exclusive quarkonium production in p-Pb data:*

- *Weizsacker-Williams photon flux enhanced by Z^2*
- *Photon emission ambiguity resolved*





2) *Exclusive exotica production in p-p data:*

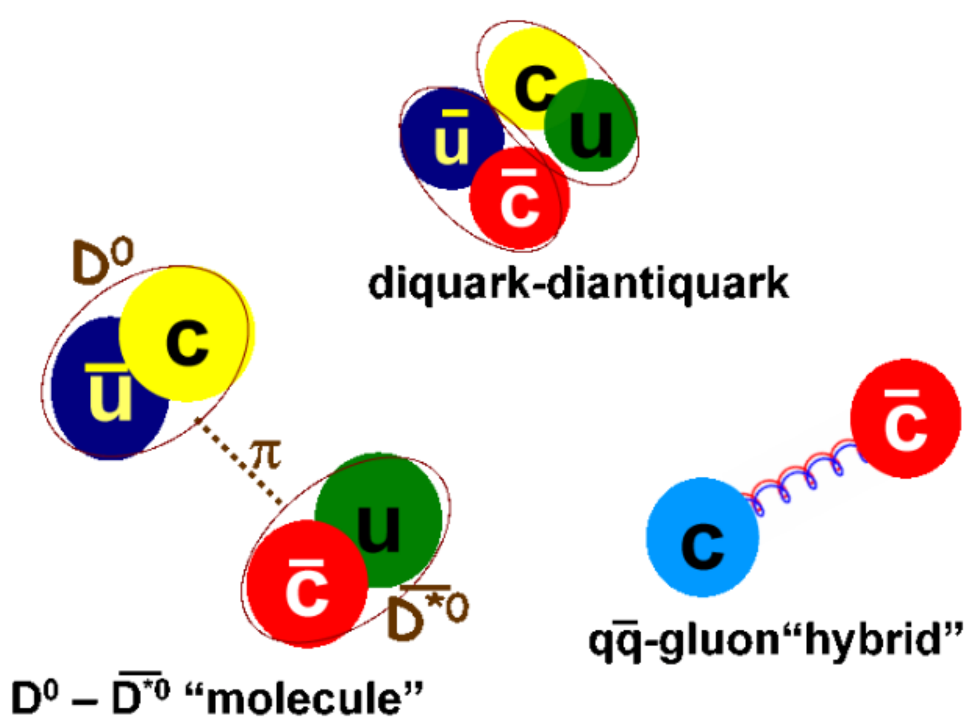
- *Pomeron exchange constrains quantum numbers of the CEP system*

CONTINUING EXPLOITATION OF RUN 1 DATA

Analyses of interest using Run 1 data

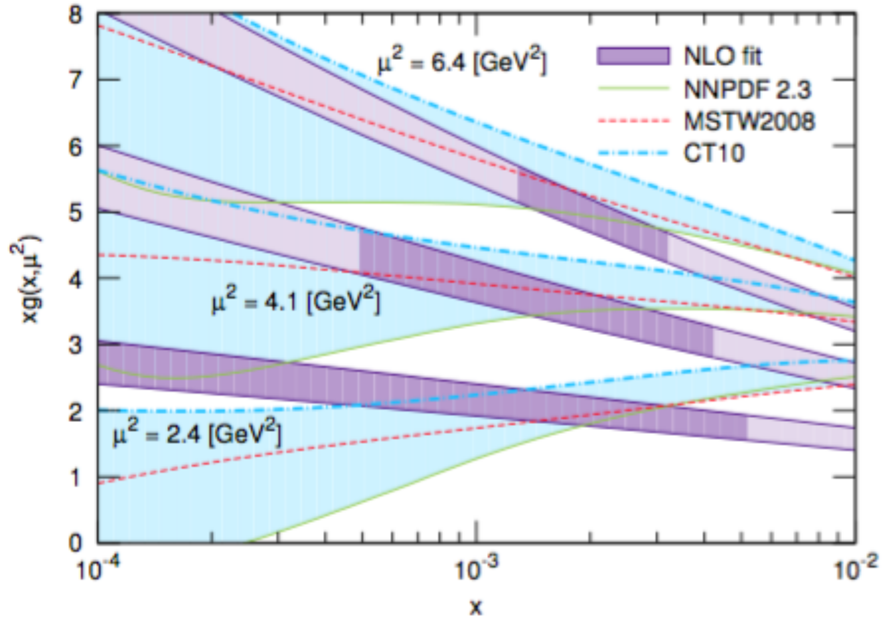
3) *Double open-charm production in p-p data:*

- *Many exotic candidates in inclusive $D^{(*)}D^{(*)}$ spectroscopy*
- *DD molecule, tetraquarks, ccg hybrids, conventional charmonium*
  - *Would not expect $X(3872) \to D^{*}D$ since hadronisation of the short-distance c anti-c pair to form loosely bound $D^{*}D$ state accompanied by other emission*
  - *If $X(3872)$ is conventional χ_{c1} then should be produced in CEP*

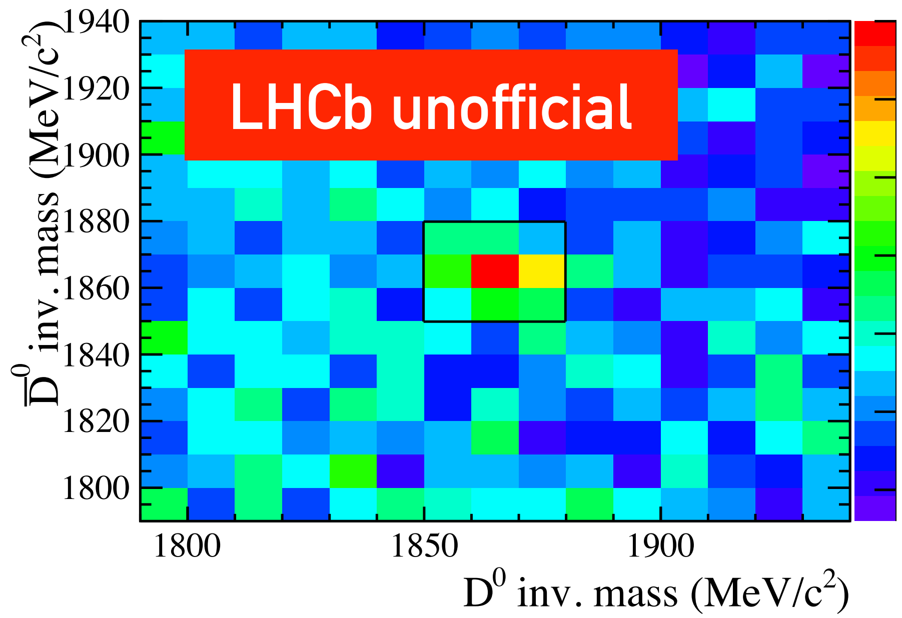


(URGENT!) CHALLENGES

1. ***It is essential to include CEP in PDF fits***
   - *CEP probes extremely low x; g(x) poorly known*
   - *Methods to include CEP with small systematic uncertainties are available*
   - *PDF fitting groups are cautious!*



2. ***Models of double open-charm production needed!***
   - *Measurement of prompt, correlated D^0D^0 production absent at LHC*
   - *No predictions or simulations exist*

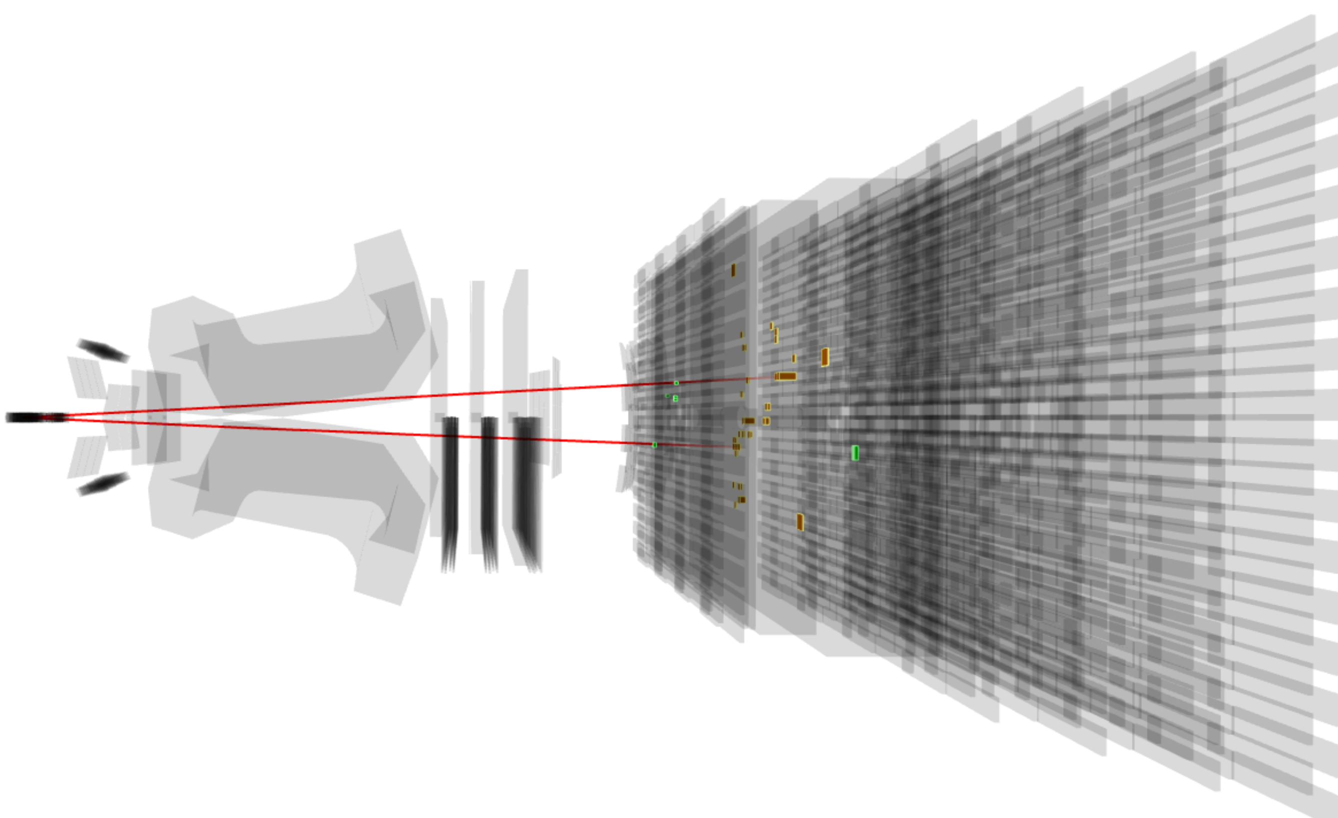


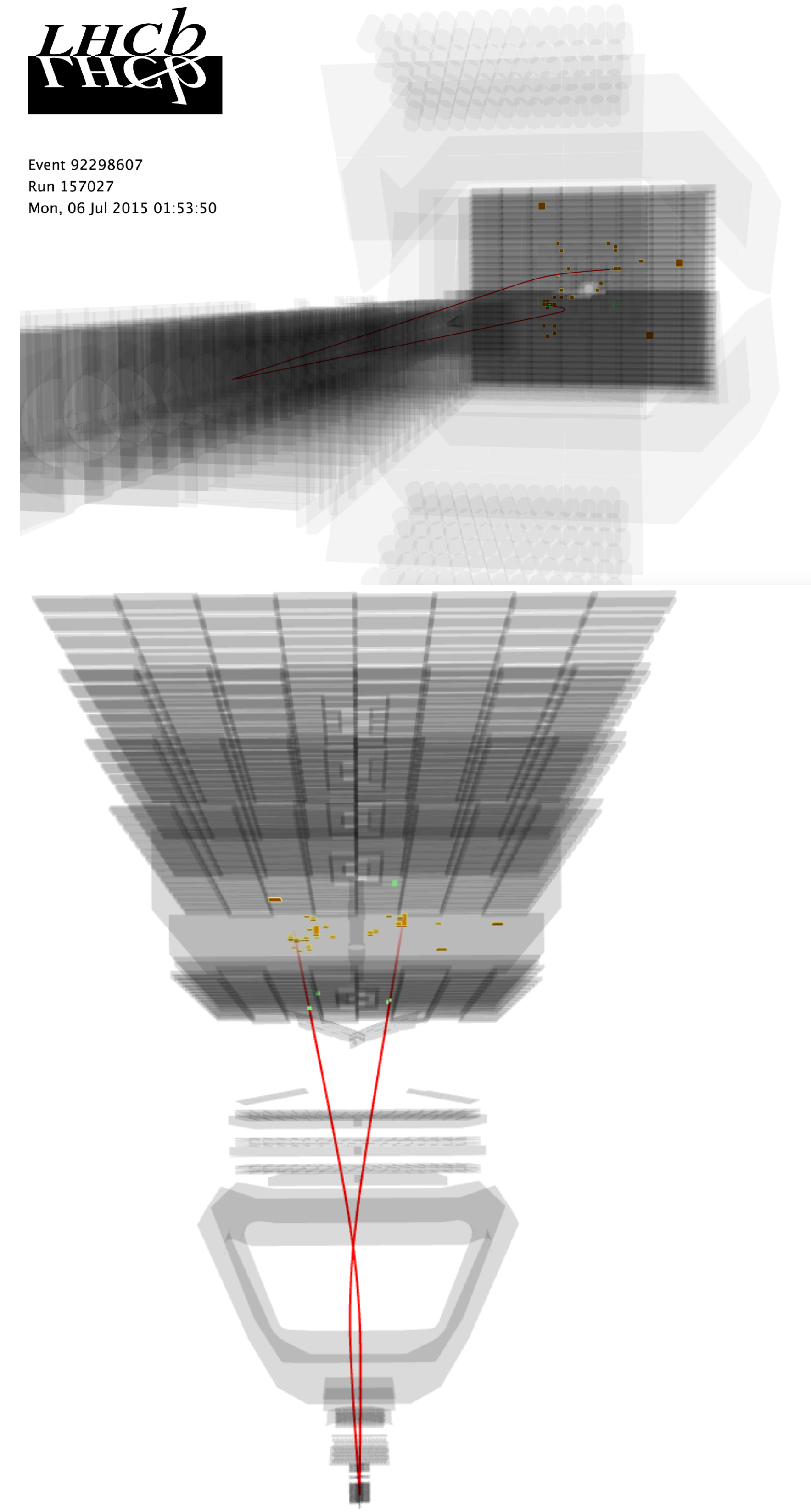
3. ***Enormous samples of exclusive continuum dimuon production are available***
   - *Simple, calculable QED process*
   - *Should be used to test predictions for soft-QCD survival factors & photon flux*

EARLY RUN 2 DATA

Early data shows promising signals:

- *Di-pion candidate in empty event*
- *Trigger tracking thresholds reduced to $p_T > 100$ MeV/c*
- *Can probe low-mass glueball candidates*

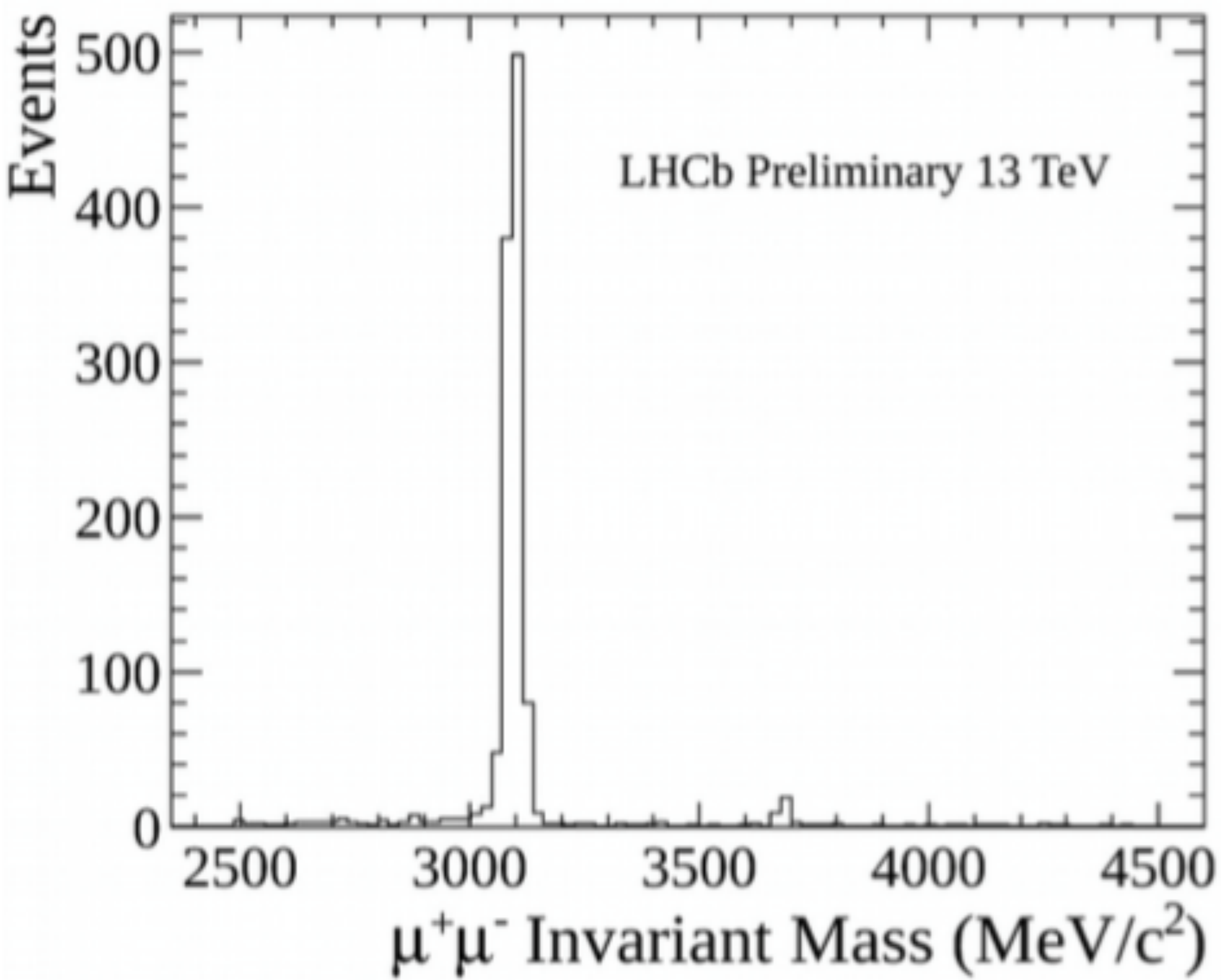




EARLY RUN 2 DATA

Early data shows promising signals:

- *J/ψ and ψ(2S) candidates in empty event*
- *Much greater handle on inelastic backgrounds*
  - *main source of Run 1 background and, often, systematic uncertainty*
- *Continue to probe gluon PDF at very low x*



SUMMARY

An exciting two years!

- *Diffractive physics demands greater study!*
- *CEP now a well-established field for LHCb*
  - *demonstrated via three Run 1 publications…*
  - *… and a number of exciting topics for Run 2*
- *The Herschel project is a game-changer for diffractive physics at LHC(b)*