Results on Diffractive Physics at LHCb

Ronan McNulty (UCD Dublin)
On behalf of the LHCb collaboration

Diffractive and electromagnetic processes at high energies,
WE-Heraeus-Summerschool, Heidelberg, Sept 2-6, 2013

Outline

- Theoretical background and motivation
  - Understanding the vacuum
  - Investigating the pomeron
  - Gluon PDF
  - New phenomena
- Experimental Signatures
- The LHCb experiment
- Analysis and Results
  - Central Exclusive J/ψ,ψ',χ_c, μμ
- Future plans
  - ϒ,Φ,χ,ηη,X,searches

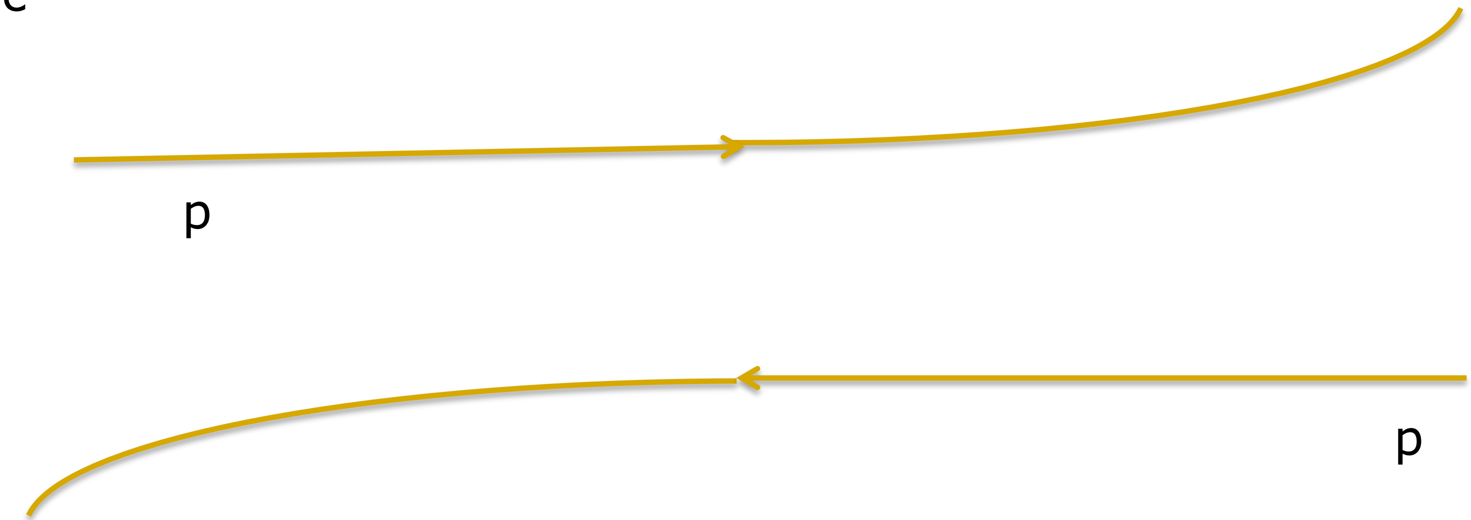
Theoretical background and motivation

Understanding QCD

- At hard scales
  - theory perturbative and thus predictive
  - well tested by experiment
  - non-abelian nature (colour / α_S running) confirmed
- At soft scales
  - difficult (impossible?) to predict
  - yet this is where most physics happens
  - describes bound hadrons and nature of vacuum
  - choose your experimental environment carefully and challenge theory
- Open questions
  - colourless objects (pomeron, reggeon, odderon)
  - glueballs
  - QCD must 'break down' at very soft scales (rise of gluon PDF violates unitarity) – there must be new phenomenology like saturation.

Physics of the Vacuum

Elastic

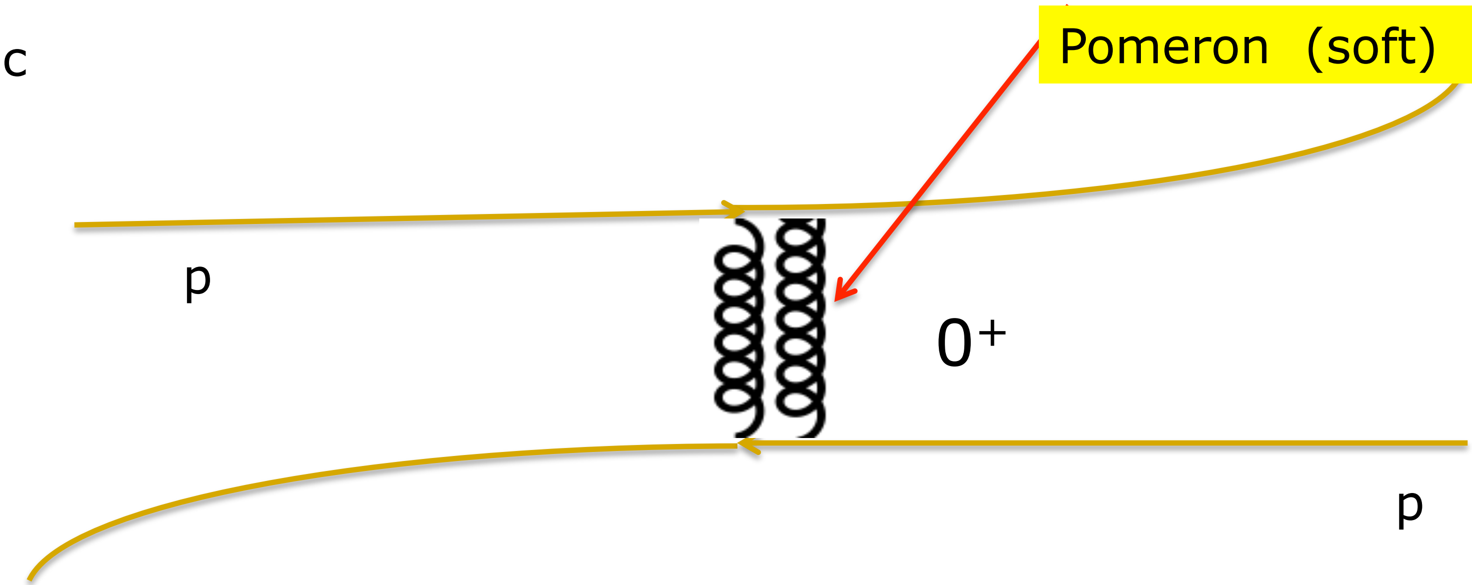


It's QCD – but not as we normally see it. It's colour-free

$\sigma_{elastic}$ ≈ 40mb
$\sigma_{diffractive}$ ≈ 10mb
$\sigma_{inelastic}$ ≈ 60mb

Physics of the Vacuum

Elastic



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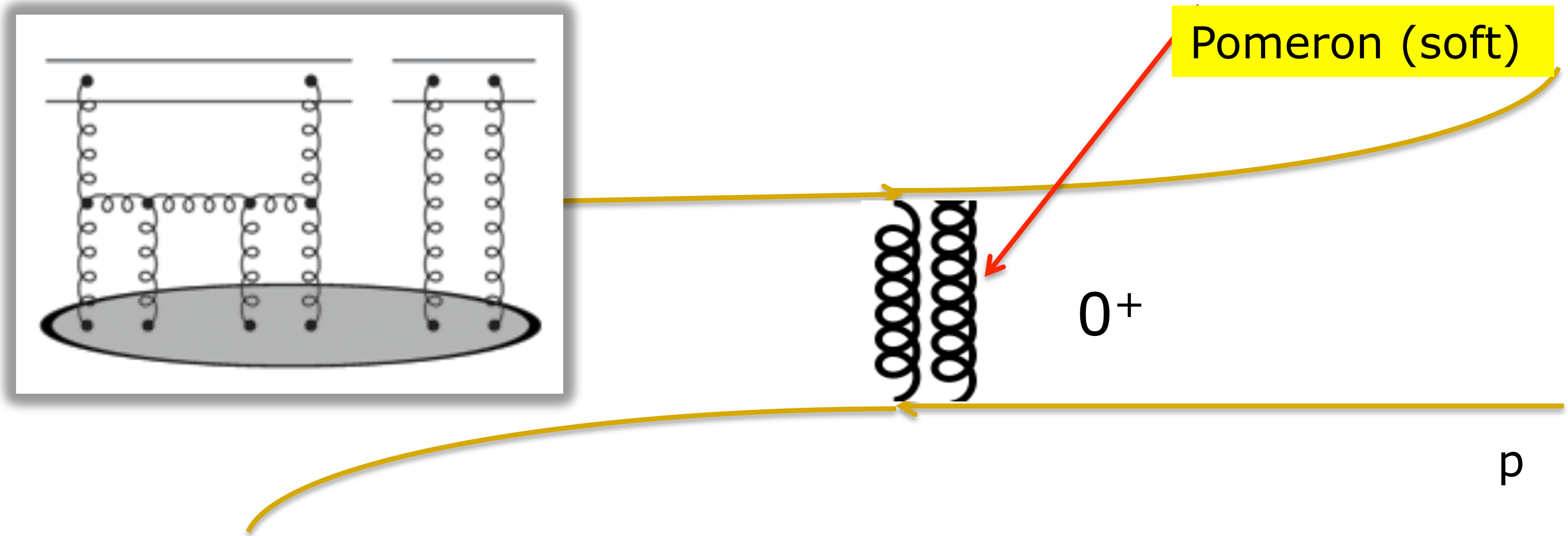

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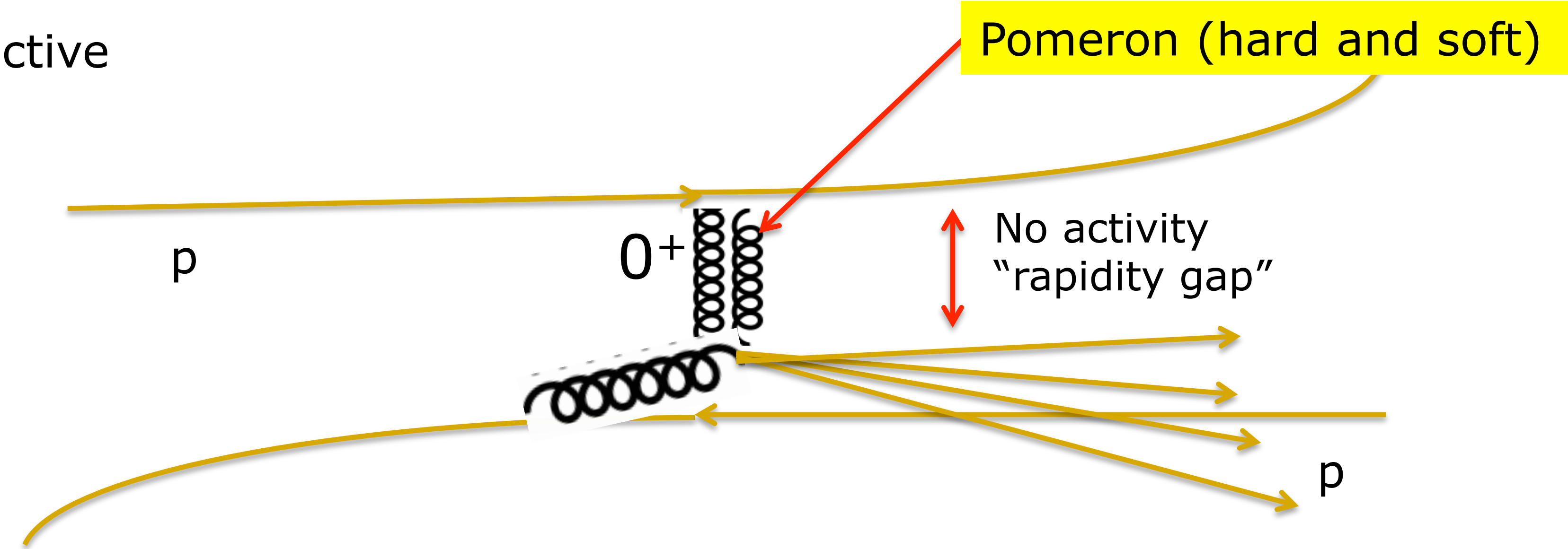
Physics of the Vacuum

Diffractive



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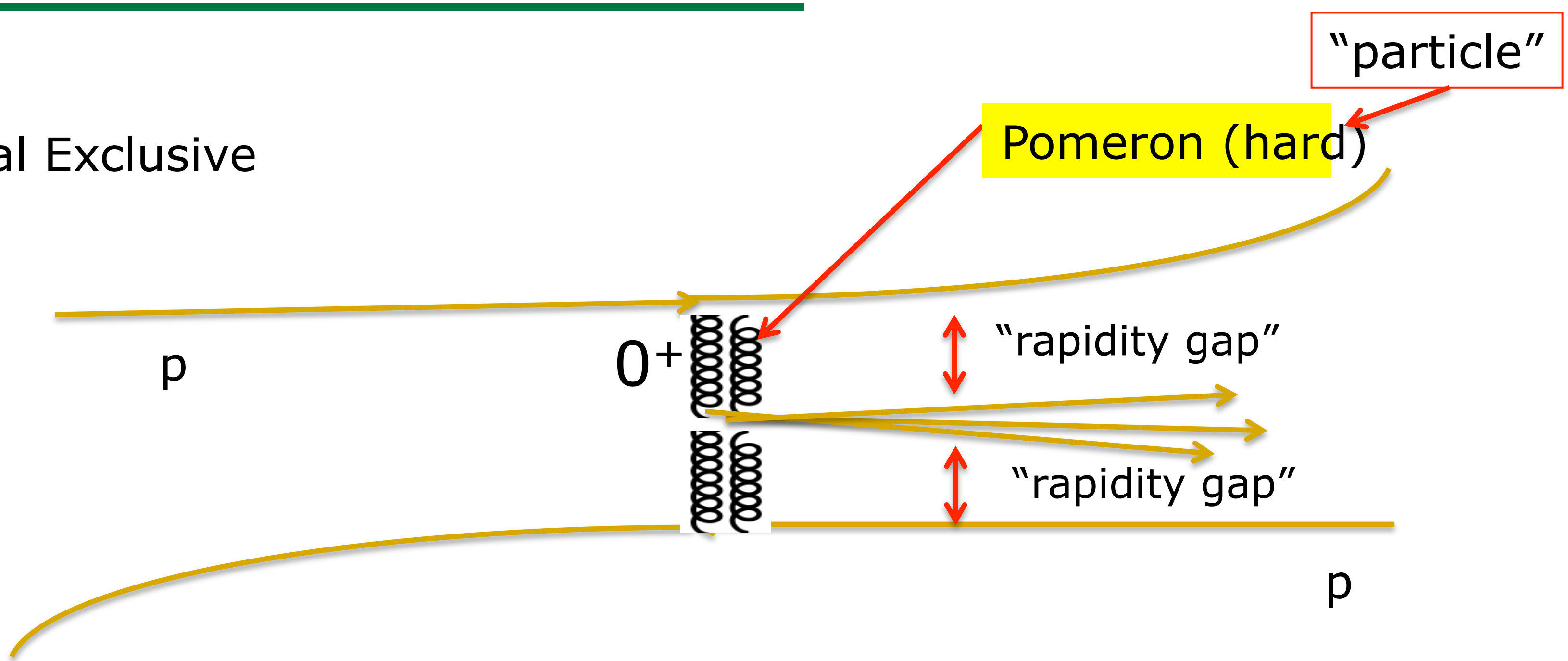
Physics of the Vacuum

Central Exclusive



Elastic diffractive: clean environment to study vacuum, and in particular, transition between soft and hard pomeron.

$\sigma_{elastic} \approx 40mb$
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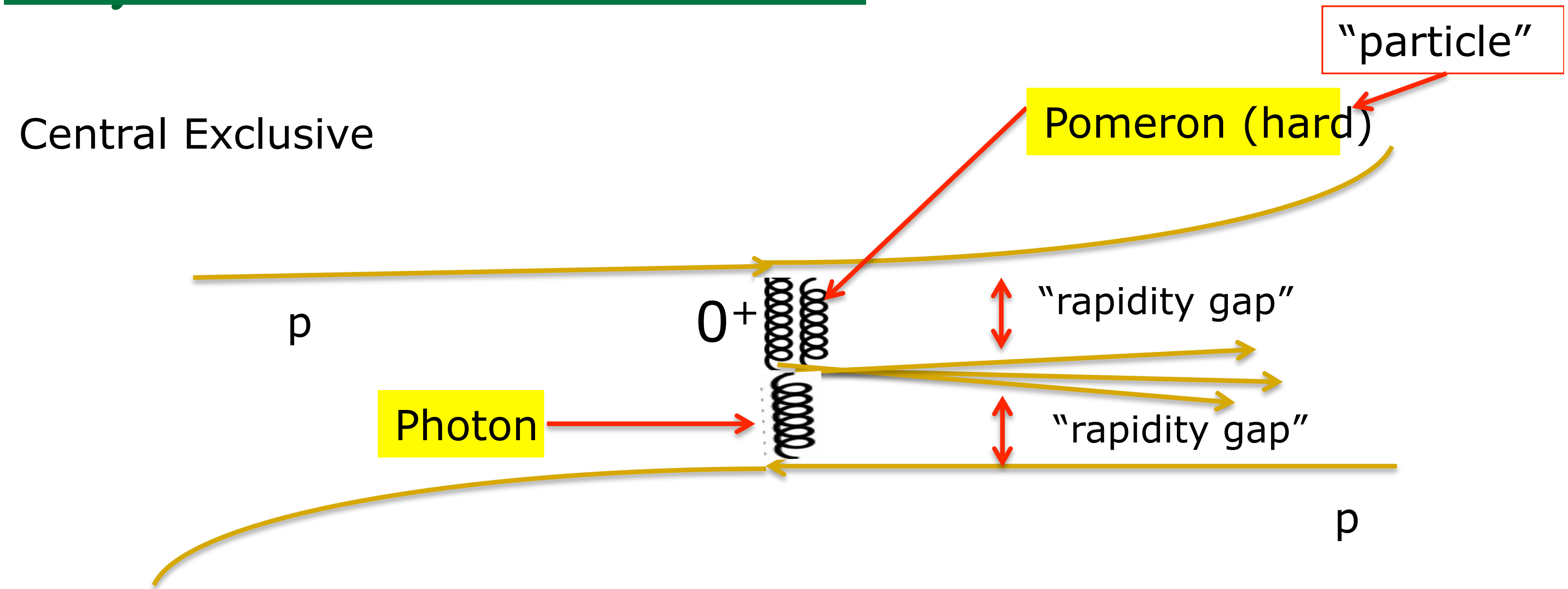
$\sigma_{inelastic} \approx 60mb$

Physics of the Vacuum



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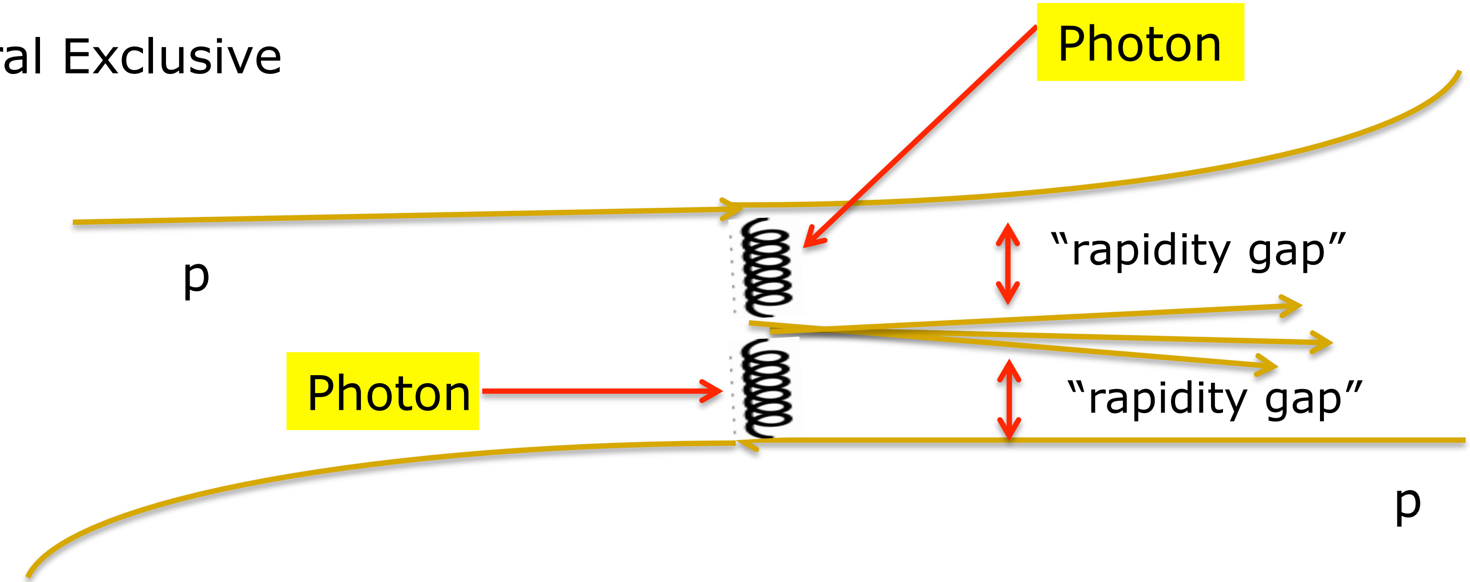
Physics of the Vacuum

Central Exclusive



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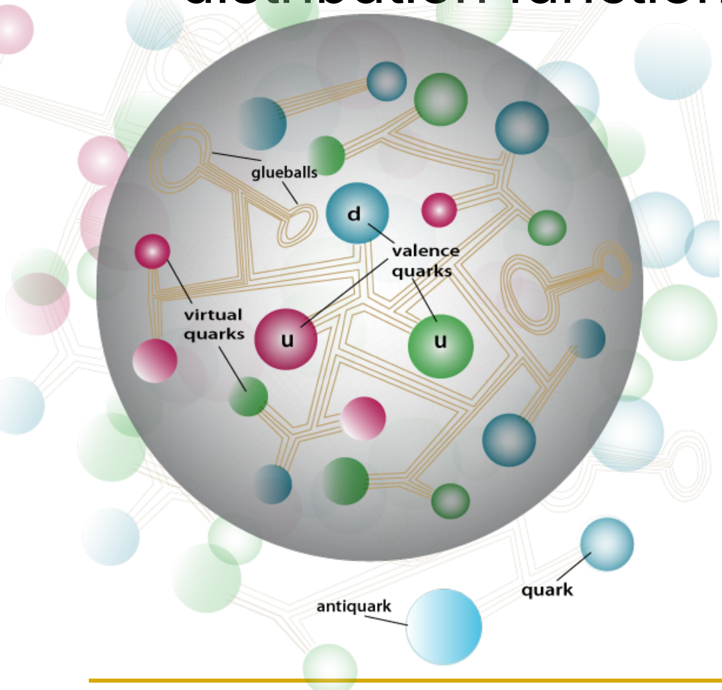
Pragmatic reasons to understand gluon

- If you want to describe gg->X, gg->H
- if you want to describe the underlying event

- content of proton described in terms of parton distribution functions

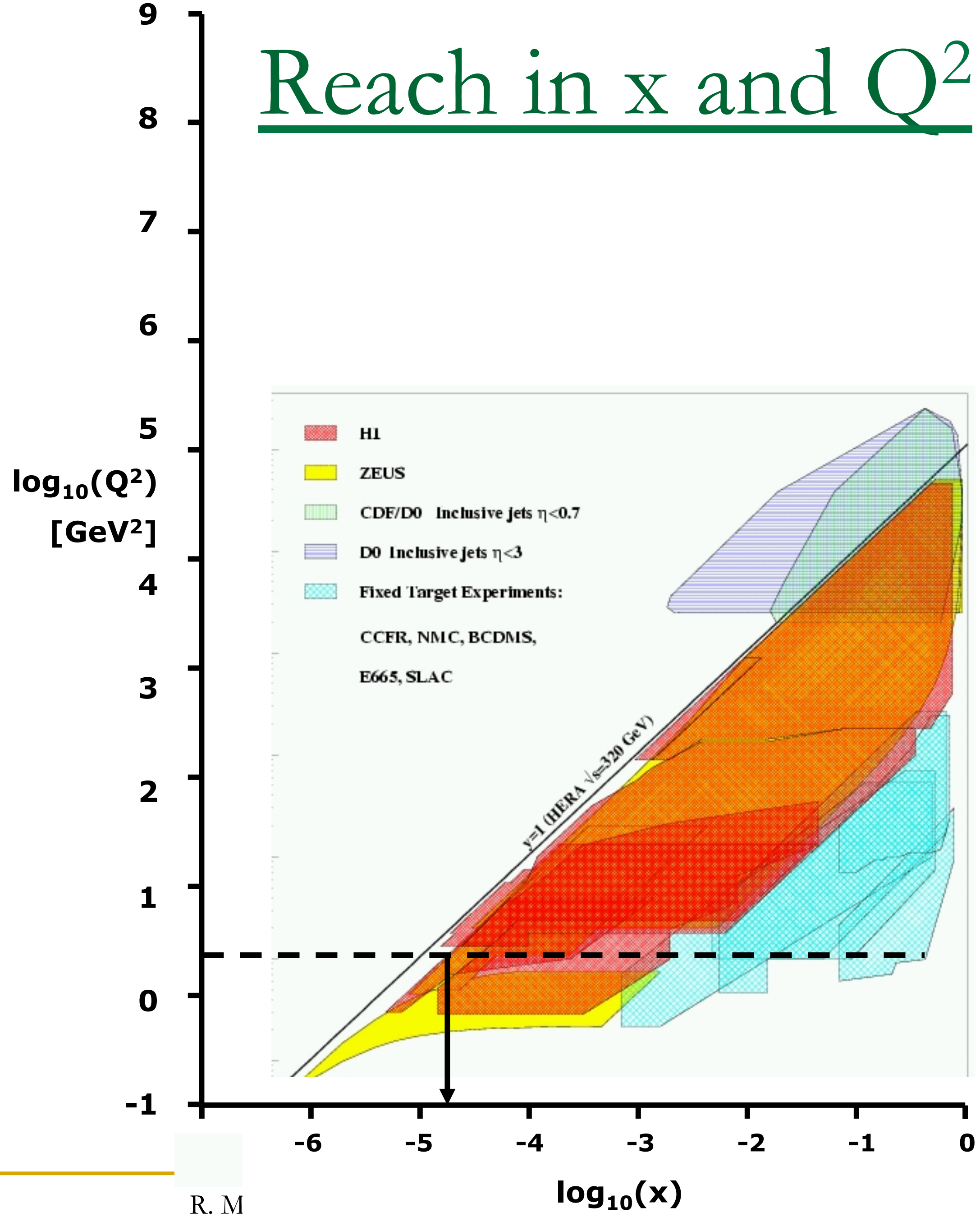


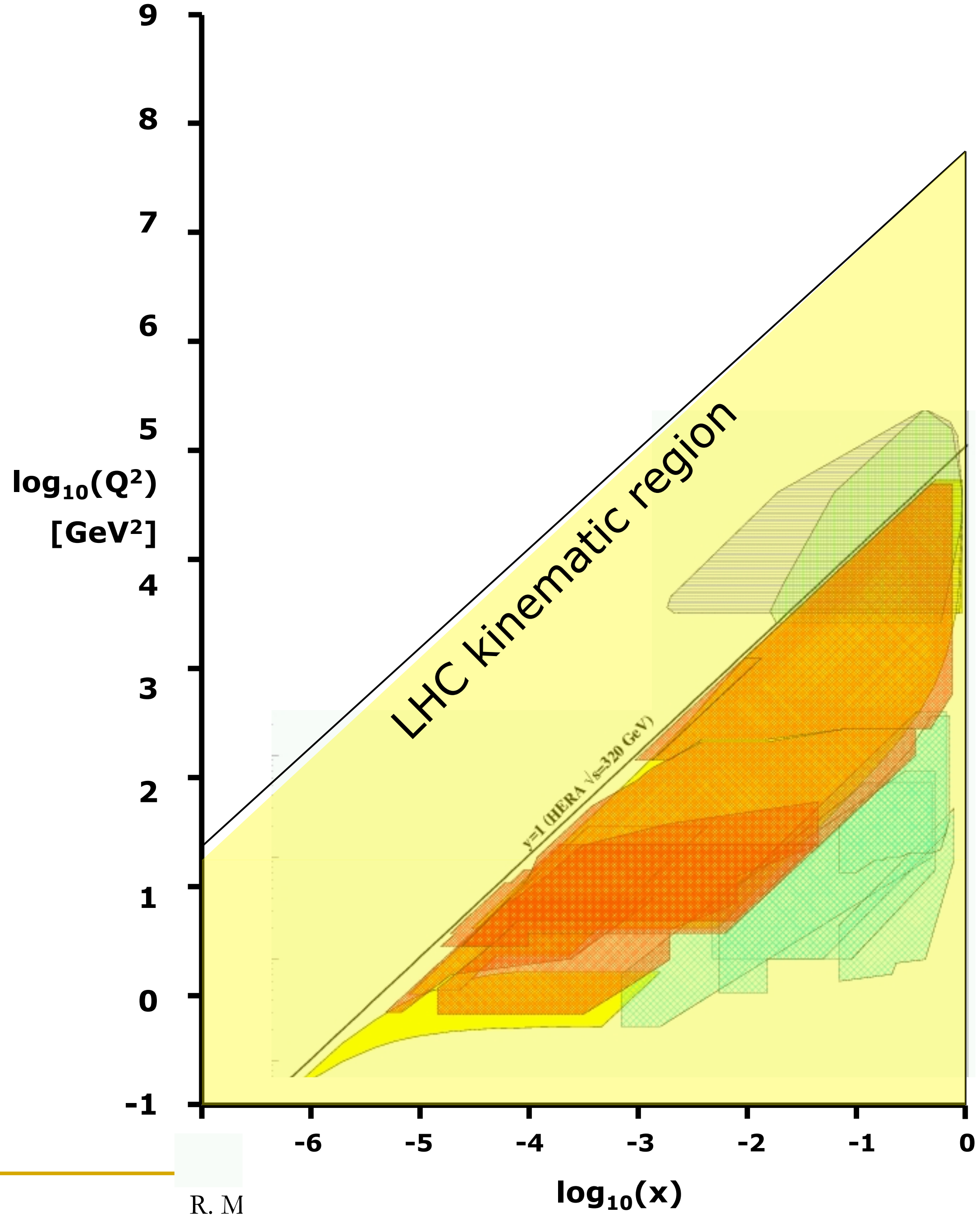
$\mathbf{f_q(x,Q^2)}$

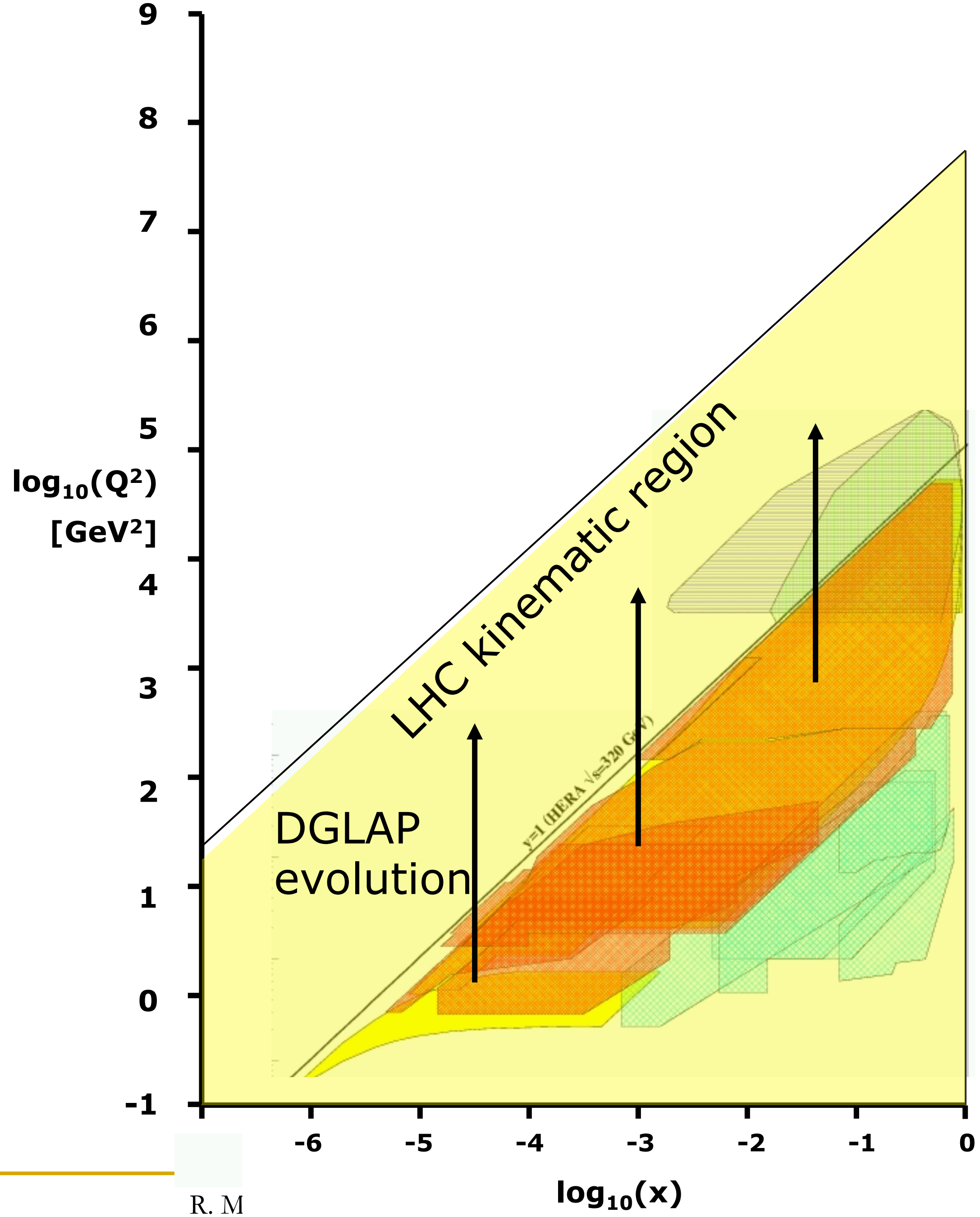
Probability that proton contains <u>this parton</u>
with <u>this momentum fraction</u>

Q = Invariant mass of parton interaction
x = $Qe^{\pm y}/\sqrt{s}$ [y is rapidity, √s c.o.m]

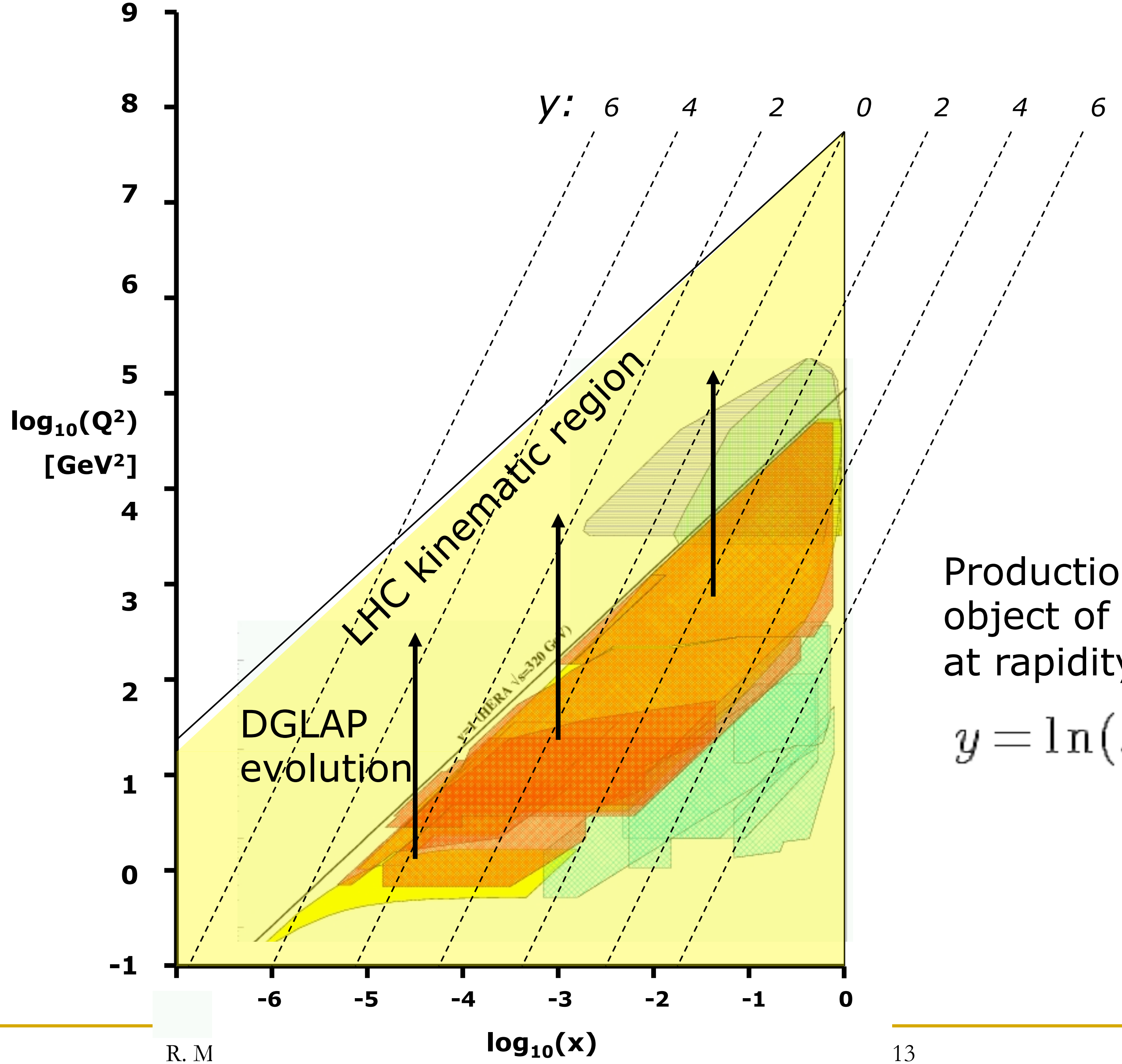
Reach in x and Q²




9
8
7
6
5
4
3
2
1
0
-1
log10(Q2) [GeV2]
LHC kinematic region
y=1 (HERA √s=320 GeV)
-6
-5
-4
-3
-2
-1
0
log10(x)

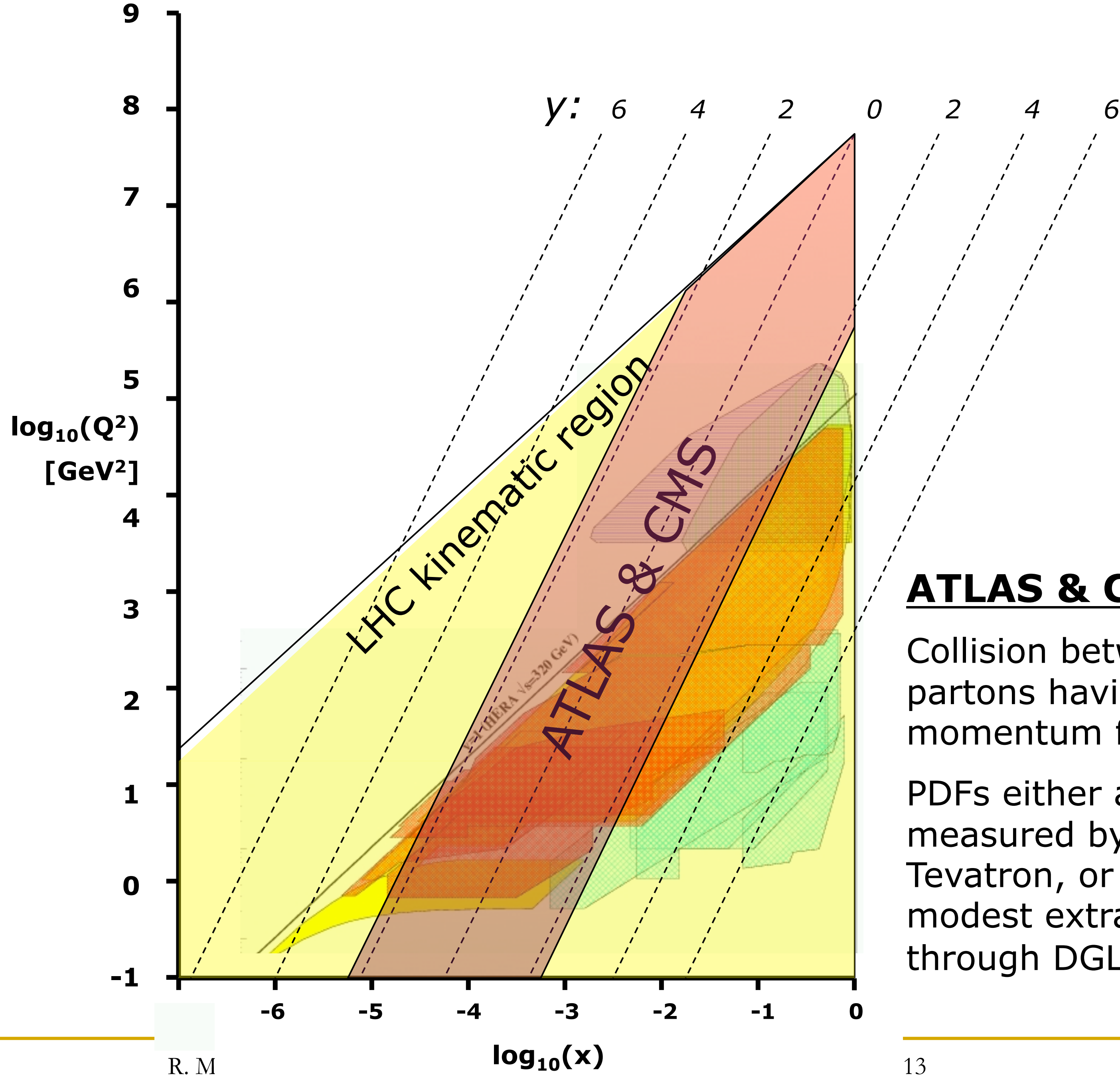


LHC kinematic region
DGLAP
evolution
log10(Q2) [GeV2]
log10(x)



Production of object of mass Q at rapidity

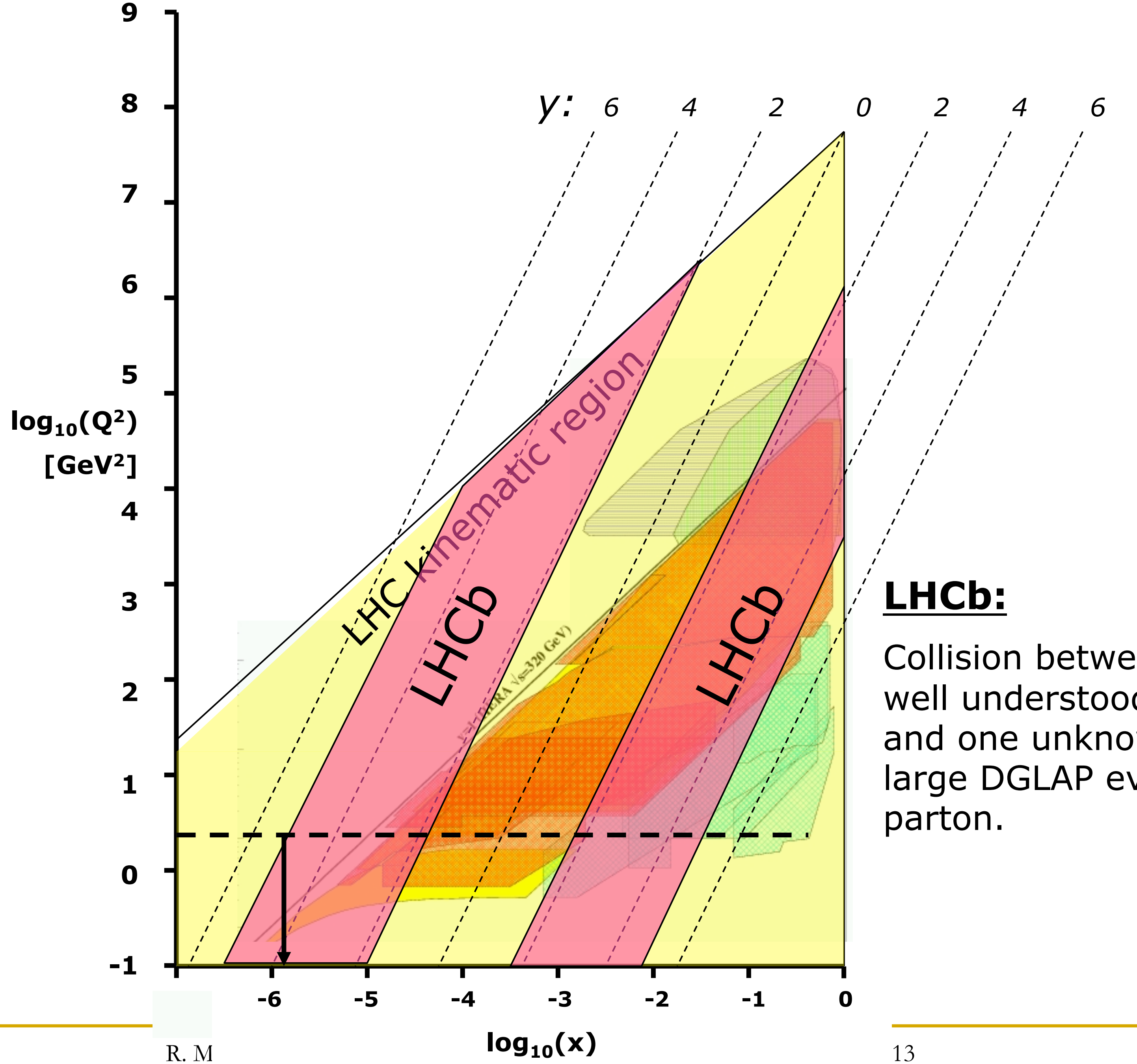
$$y = \ln\left(x\frac{\sqrt{S}}{Q}\right)$$



ATLAS & CMS:

Collision between two partons having similar momentum fractions.

PDFs either already measured by HERA or Tevatron, or requiring modest extrapolation through DGLAP.

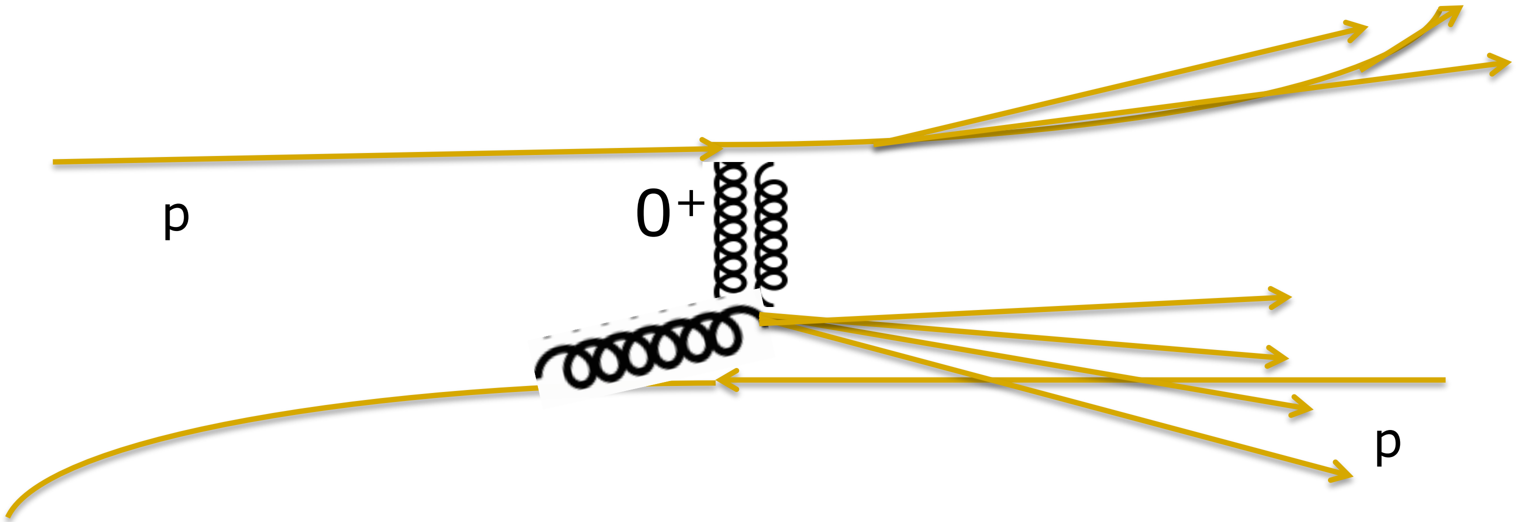


LHCb:

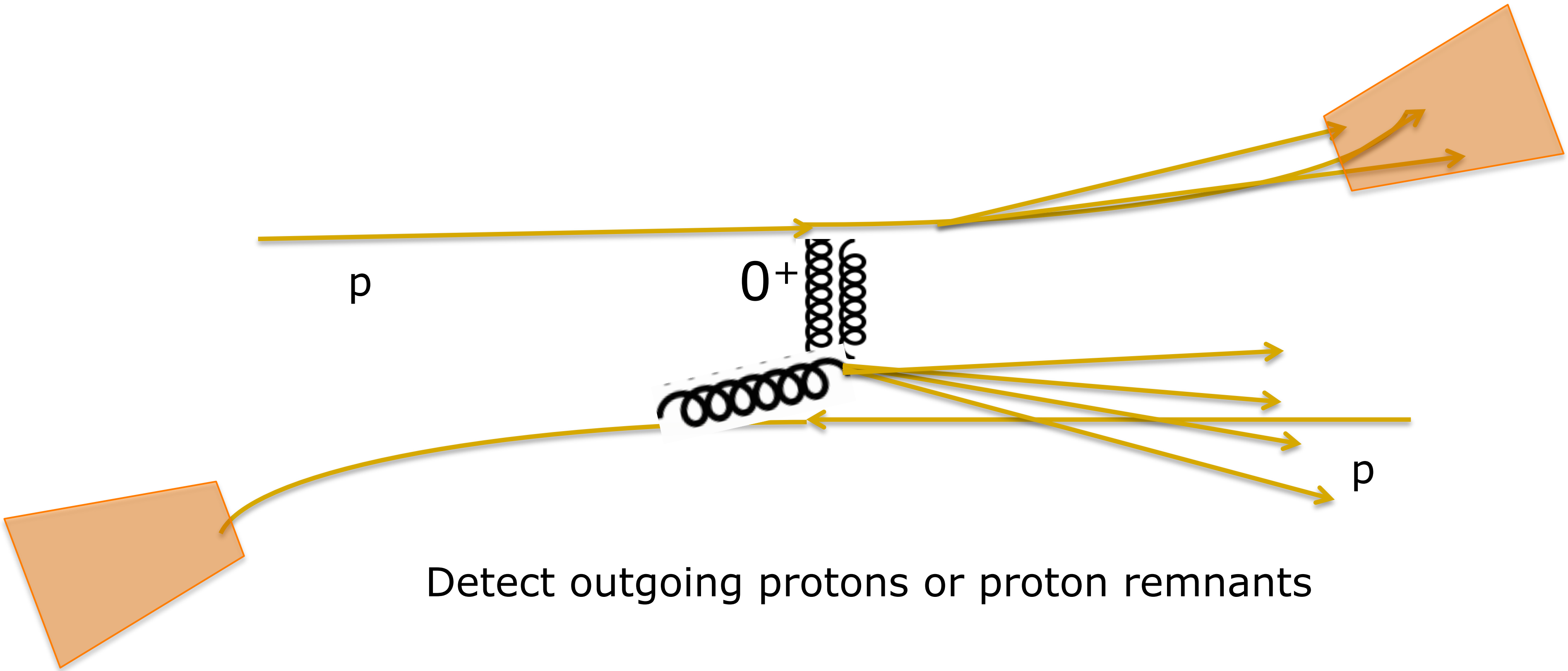
Collision between one well understood parton and one unknown or large DGLAP evolved parton.

Experimental Signatures

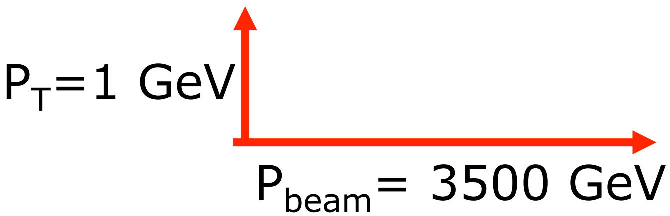
Experimental Signatures: How to distinguish diffractive events



How to distinguish diffractive events



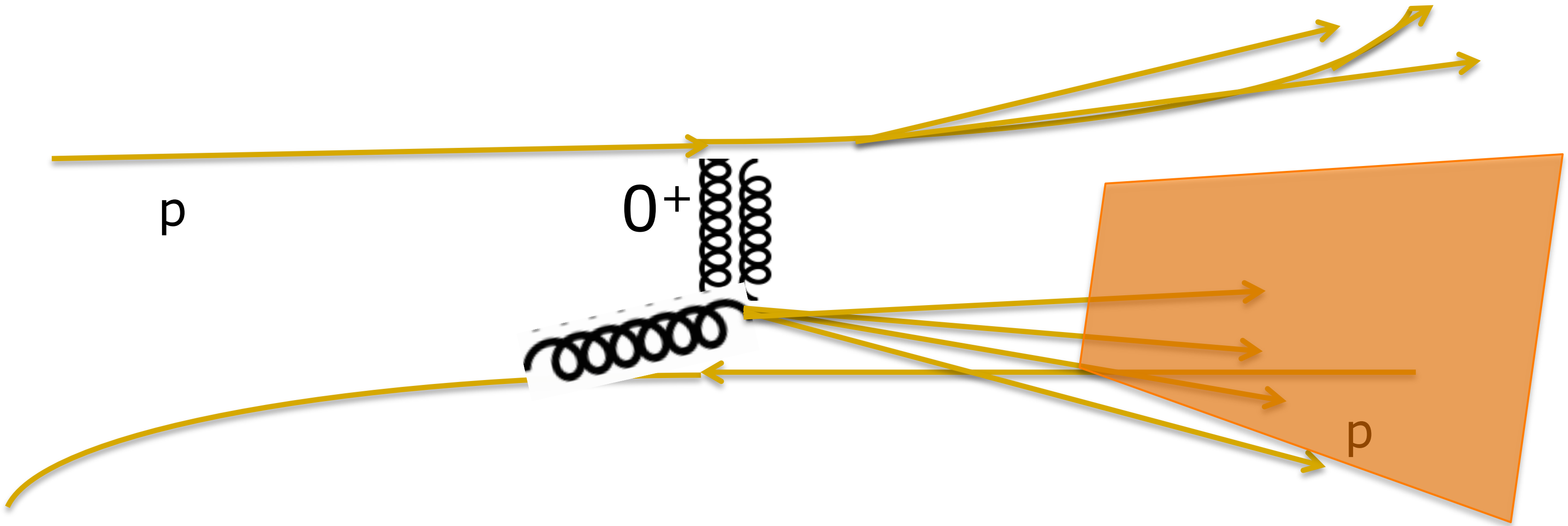
Detect outgoing protons or proton remnants



$y \sim \eta = -\log(\tan(\theta/2) = 9$

Requires detector that approaches the beamline

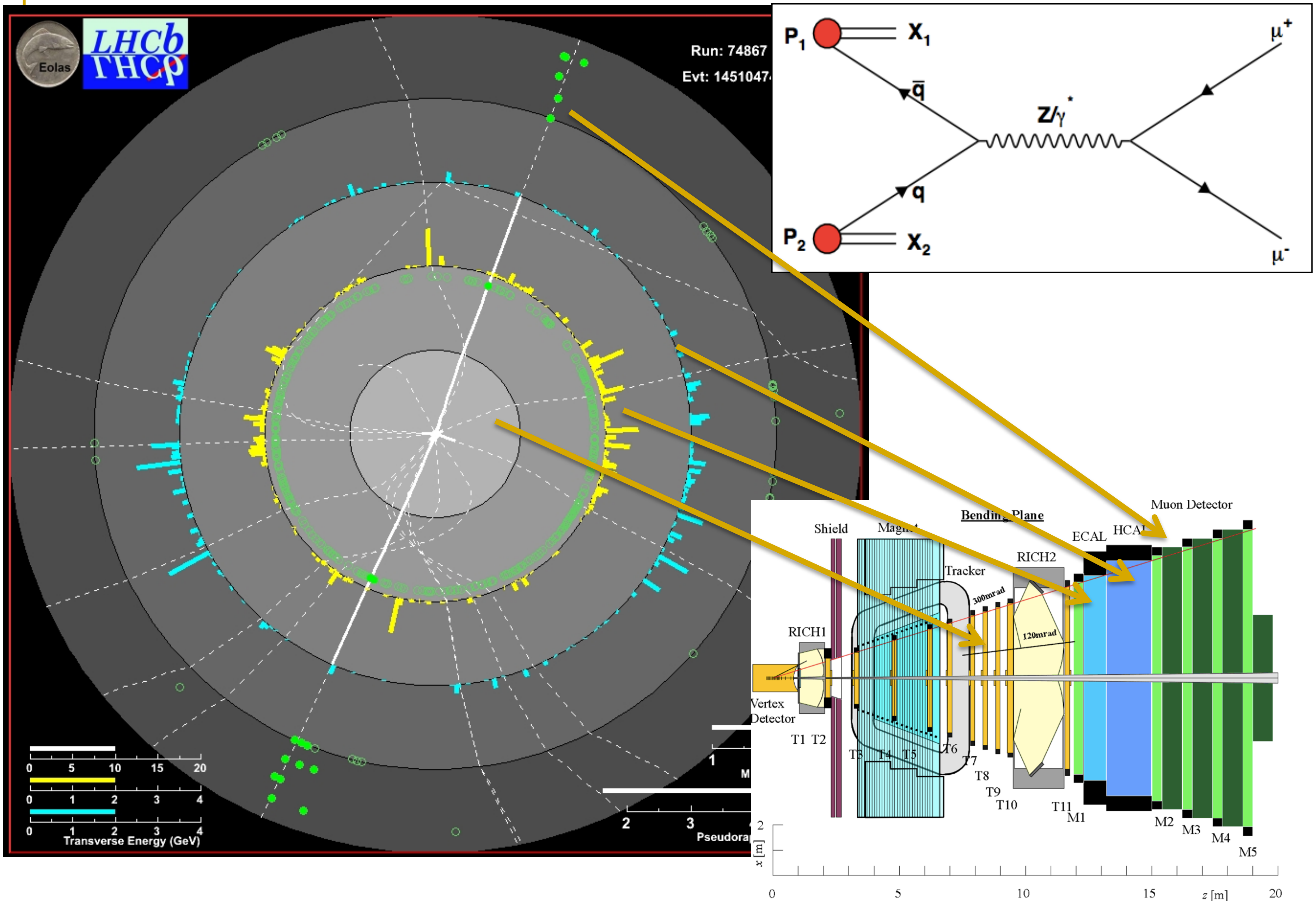
How to distinguish diffractive events

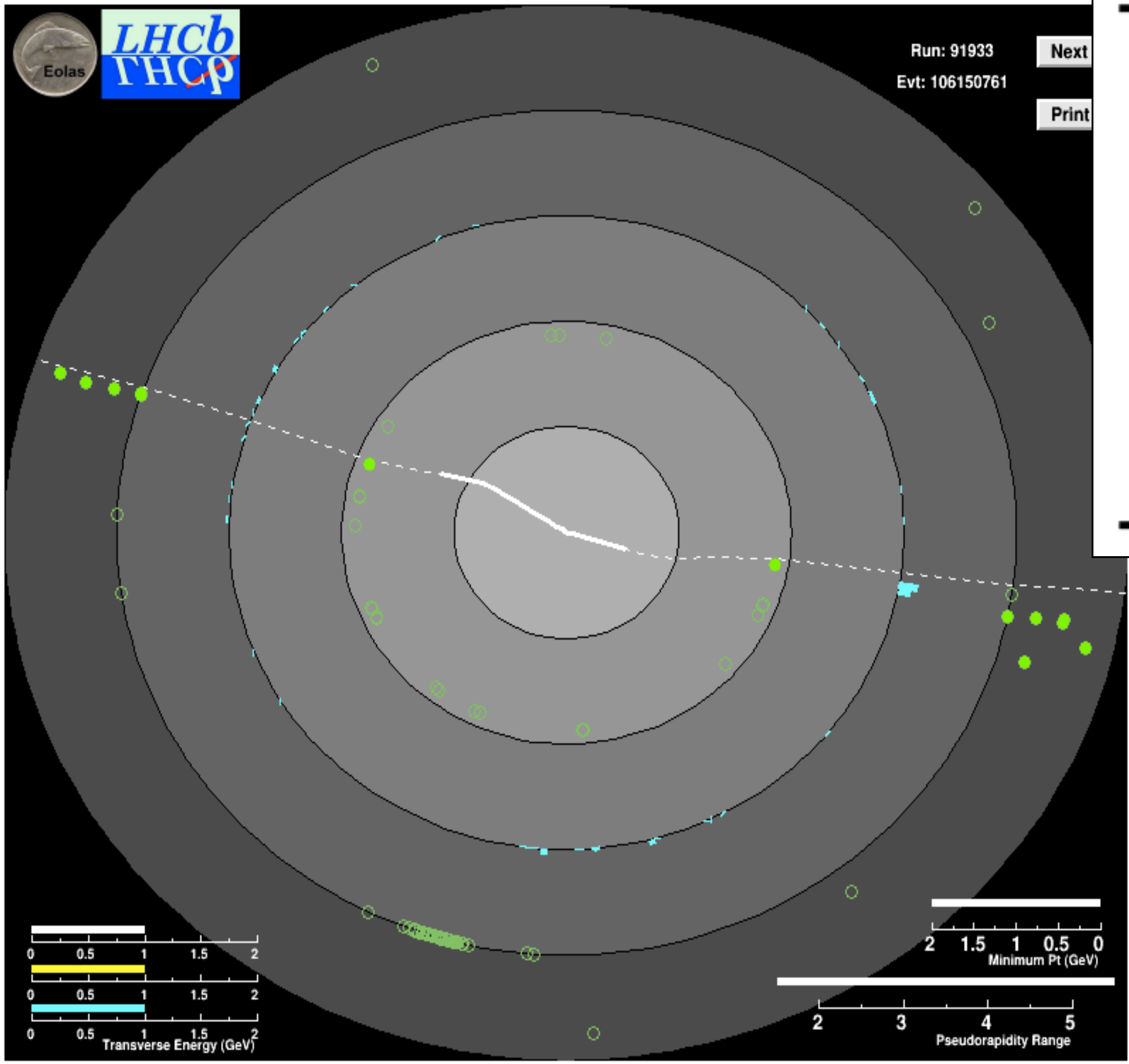


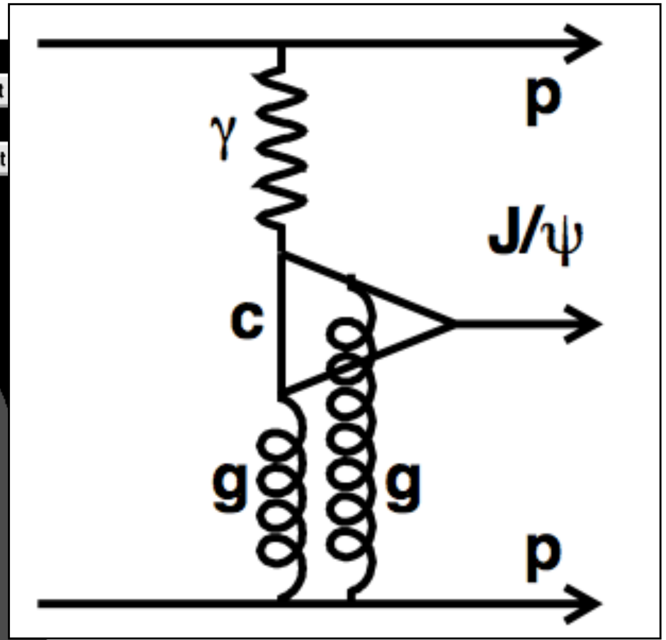
Detect 'central' system including presence of **rapidity gap**

All diffractive events will have a large rapidity gap (from the system down to the beam line) due to the colourless exchange

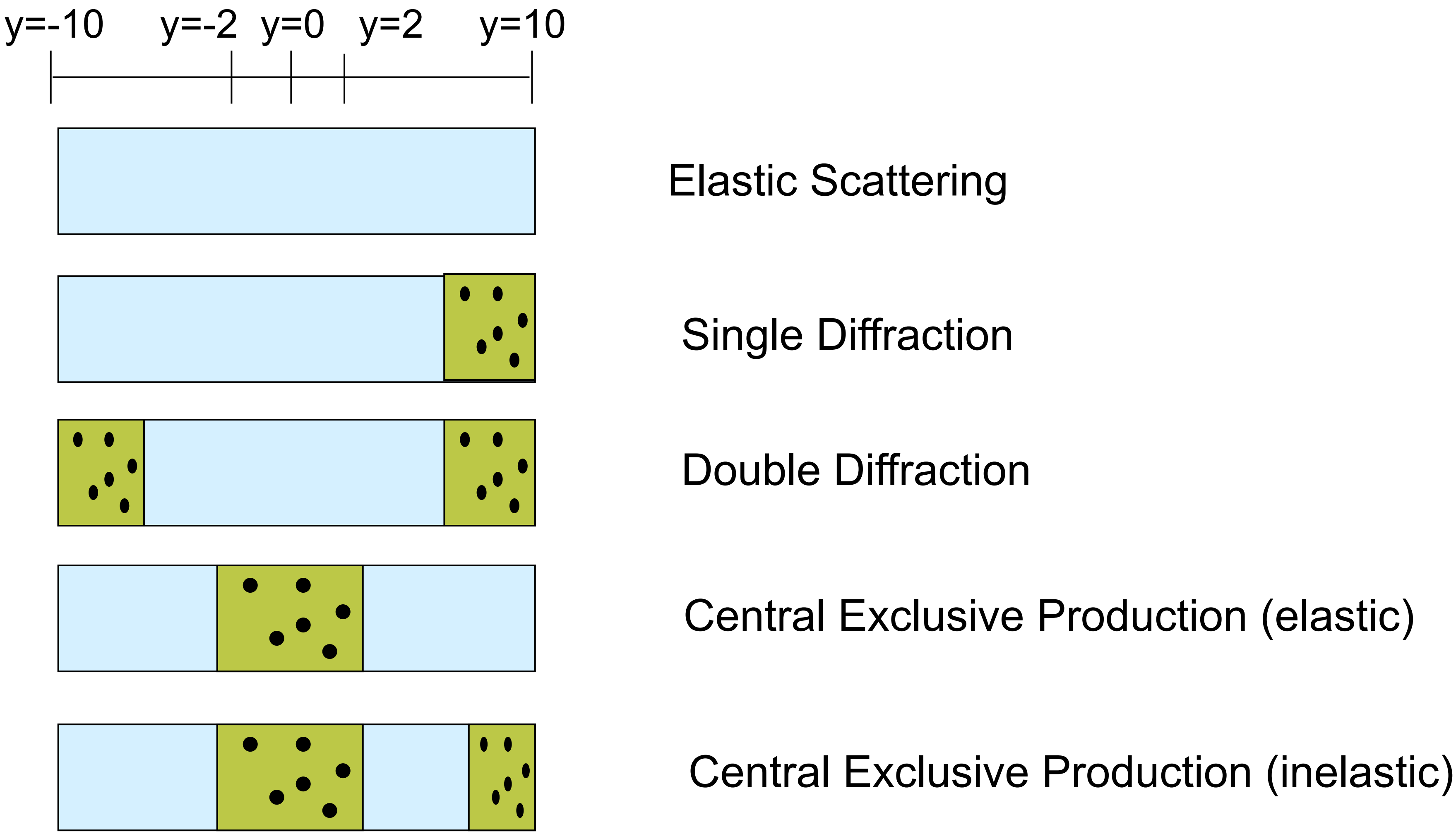
Most pp interactions distribute particles throughout 4π(collimated in jets but also with activity between jets)


Eolas
LHCb
Run: 74867
Transverse Energy (GeV)
P1
X1
P2
X2
q̄
q
Z/γ*
μ+
μ-
Muon Detector
Bending Plane
Shield
ECAL
HCAL
RICH2
Tracker
RICH1
Vertex Detector
300mrad
120mrad
T1 T2
T3 T4 T5 T6 T7 T8 T9 T10 T11
M1 M2 M3 M4 M5
x [m]
z [m]

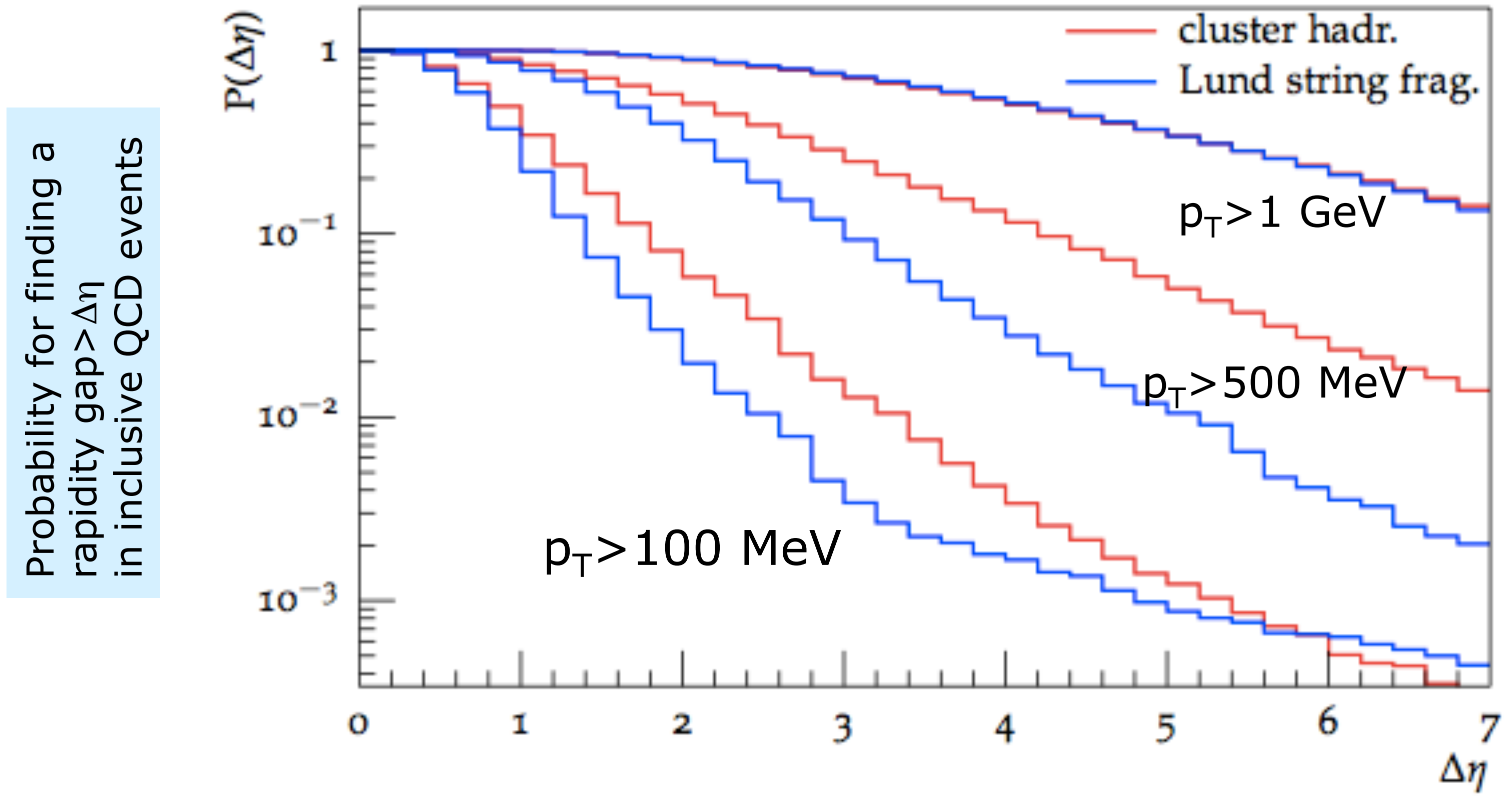

Eolas
LHCb
Run: 91933
Evt: 106150761
Next
Print
Minimum Pt (GeV)
Pseudorapidity Range
Transverse Energy (GeV)


p
γ
J/ψ
c
g
g
p

Graphical Representation



What's a large gap?



- Khoze, Kraus, Martin, Ryskin, Zapp, "Diffraction and correlations at the LHC: definitions and observables", arXiv:1005.4839v2
- Probability for inclusively produced J/psi to give two muons and nothing else inside LHCb is < 0.000005

Effect of beam pile-up

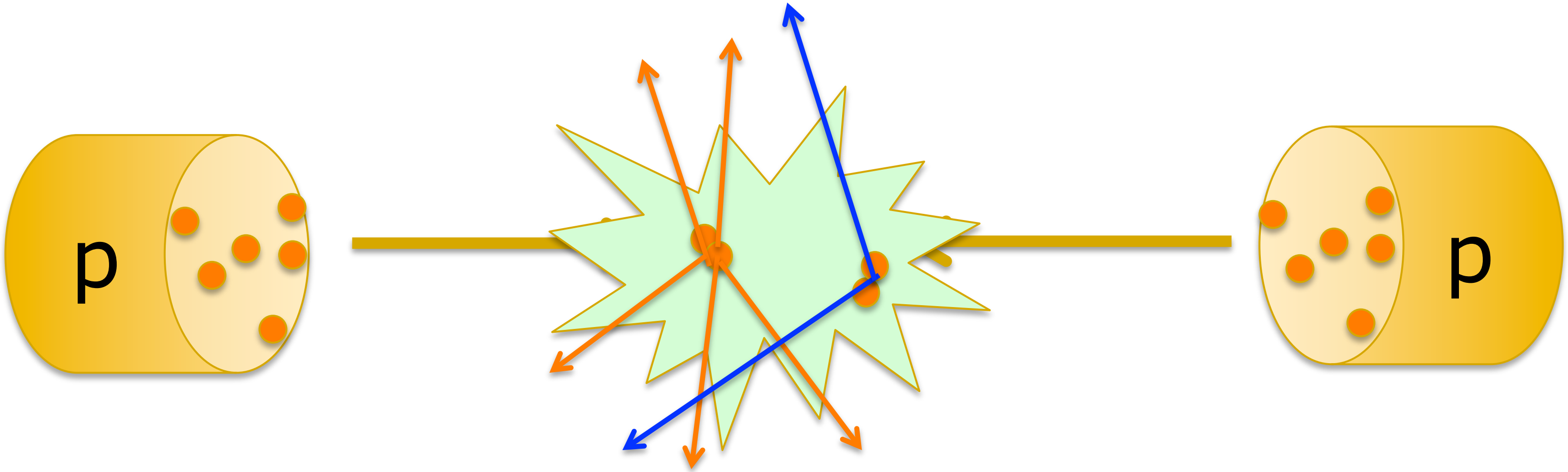
Detect empty event except for some isolated activity.

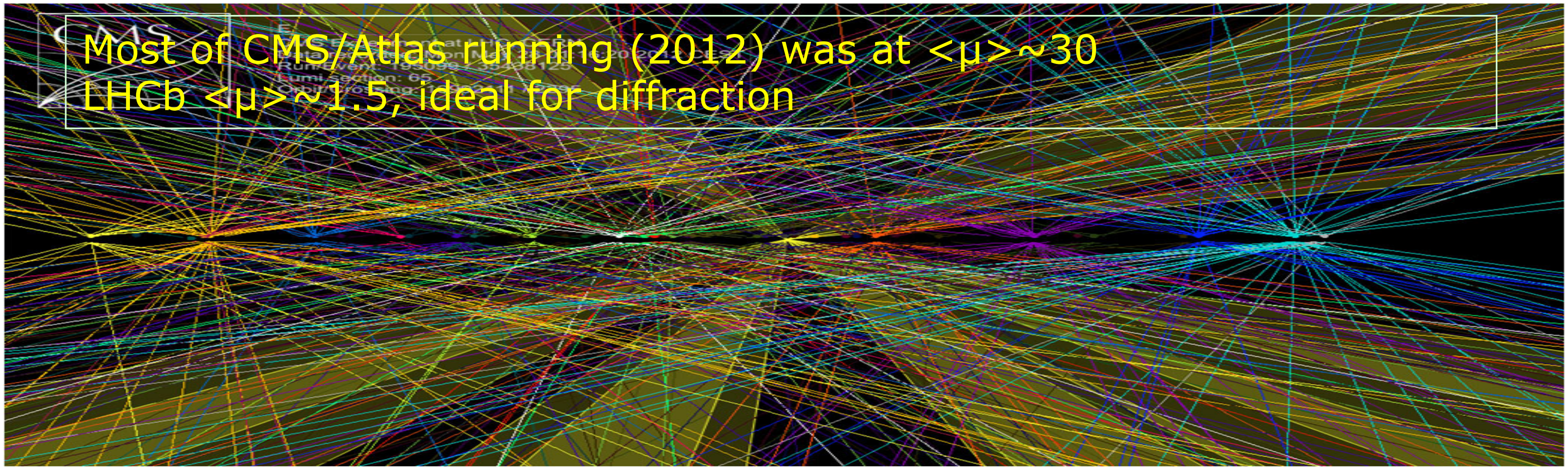
$N_X=\sigma_X L$ with L luminosity (number of protons per unit area)

High luminosity to increase probability for producing rare processes like Higgs (or SUSY)

Increases number of interactions <μ>.

Detect empty event except for some isolated activity.

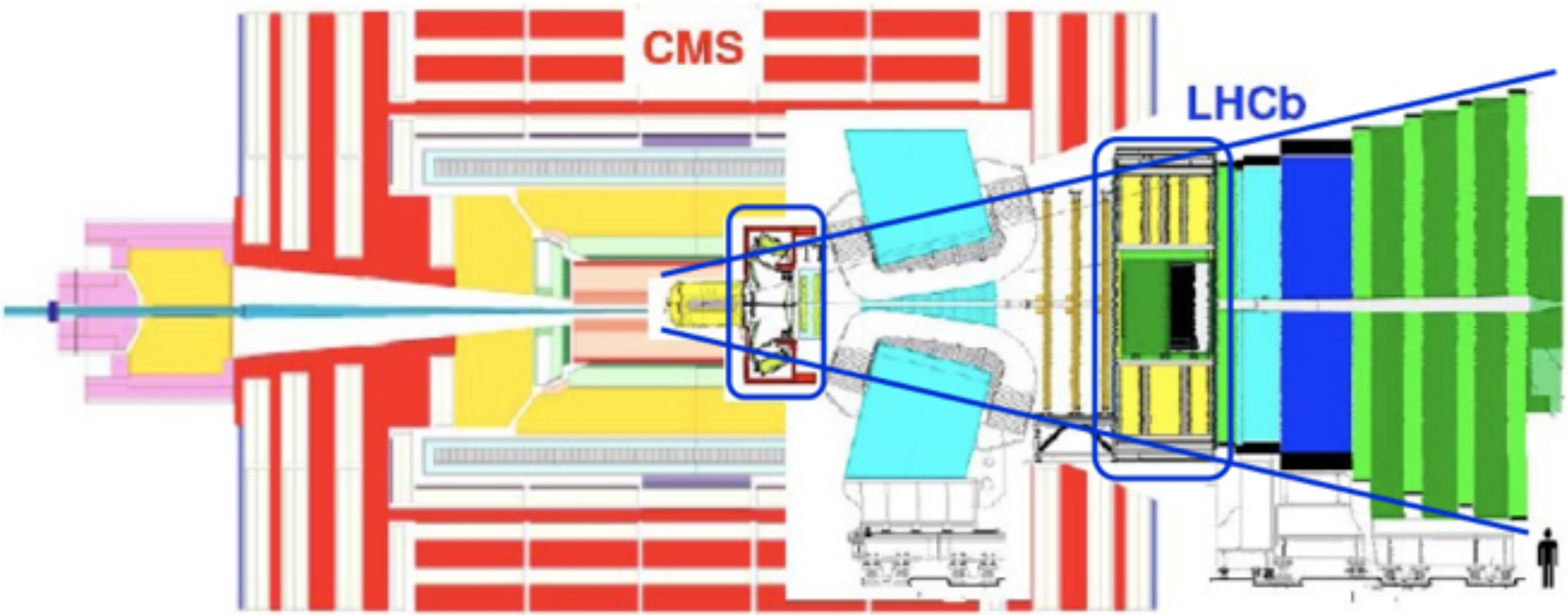




The LHCb experiment

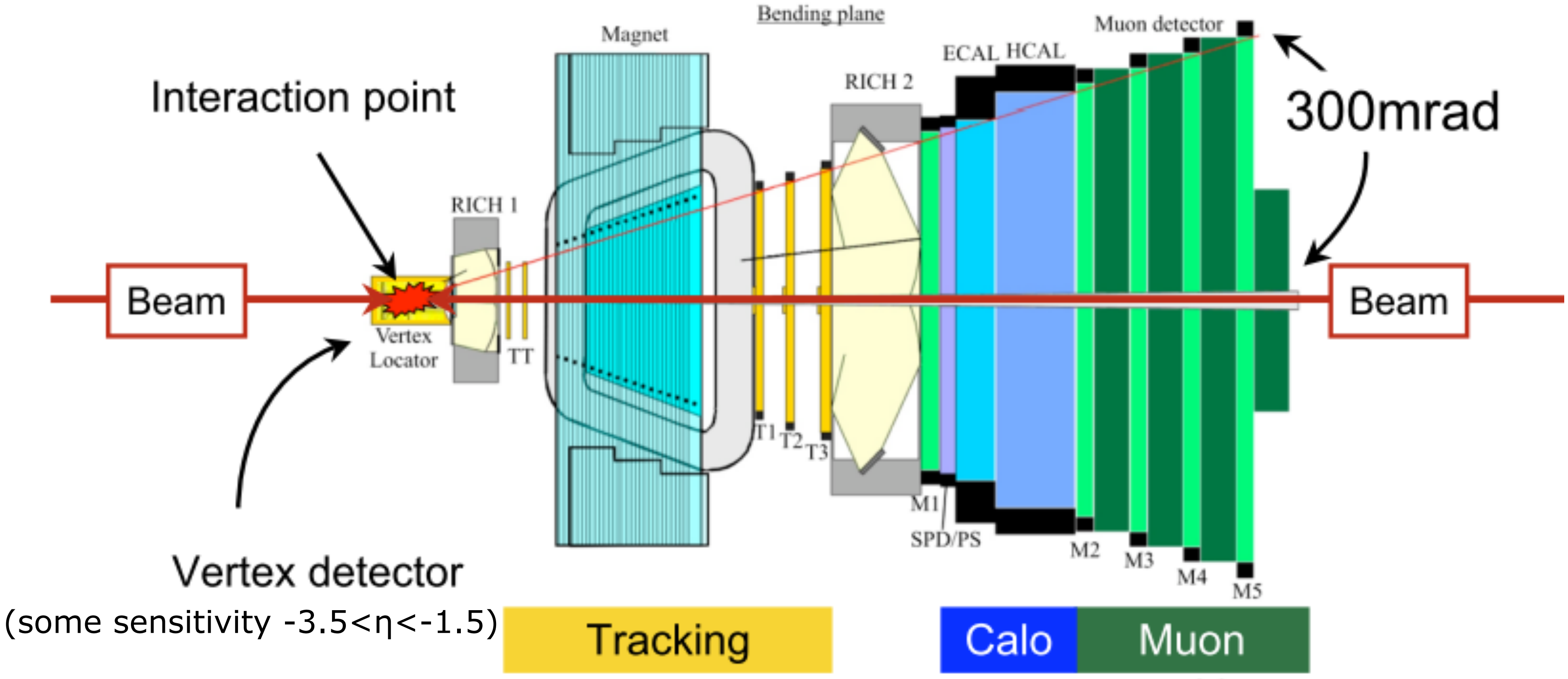

CMS+TOTEM
Alice
ATLAS
LHCb

LHCb: A forward detector



Fully instrumented in region: : $2 < \eta < 5$
Some detection: $-3.5 > \eta > -1.5$
Large enough acceptance to look for gaps
Can trigger on low transverse momentum objects

The LHCb detector

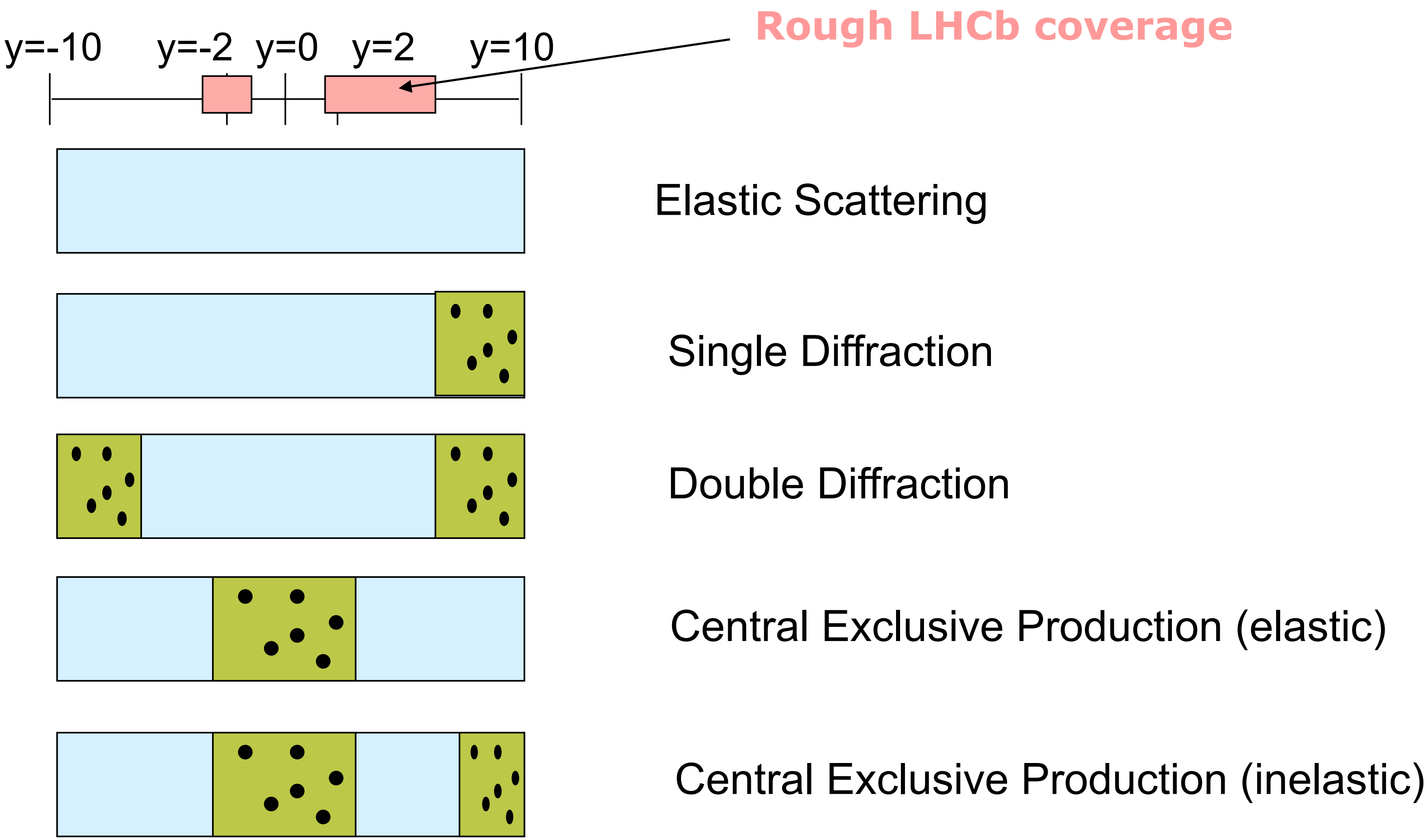


Fully instrumented within $2 < \eta < 5$

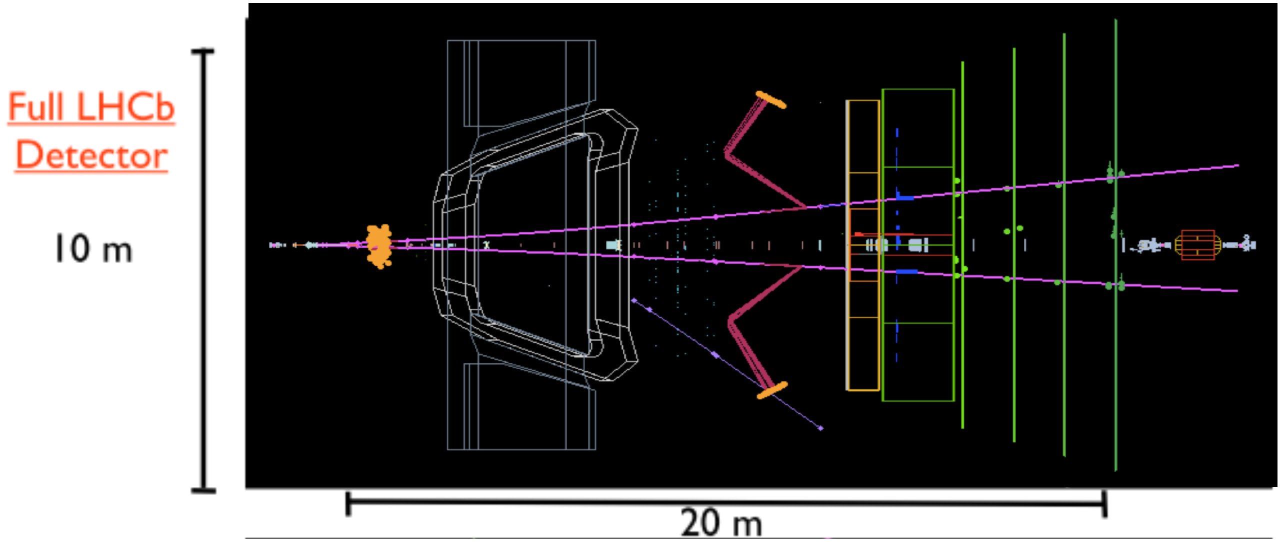
Trigger: $p_\mu > 3$ GeV, $pt_\mu > 0.4$ GeV, $m_{\mu\mu} > 2.5$ GeV

Low multiplicity required. Restricts to single-interaction collisions

Graphical Representation



Use of backwards tracks



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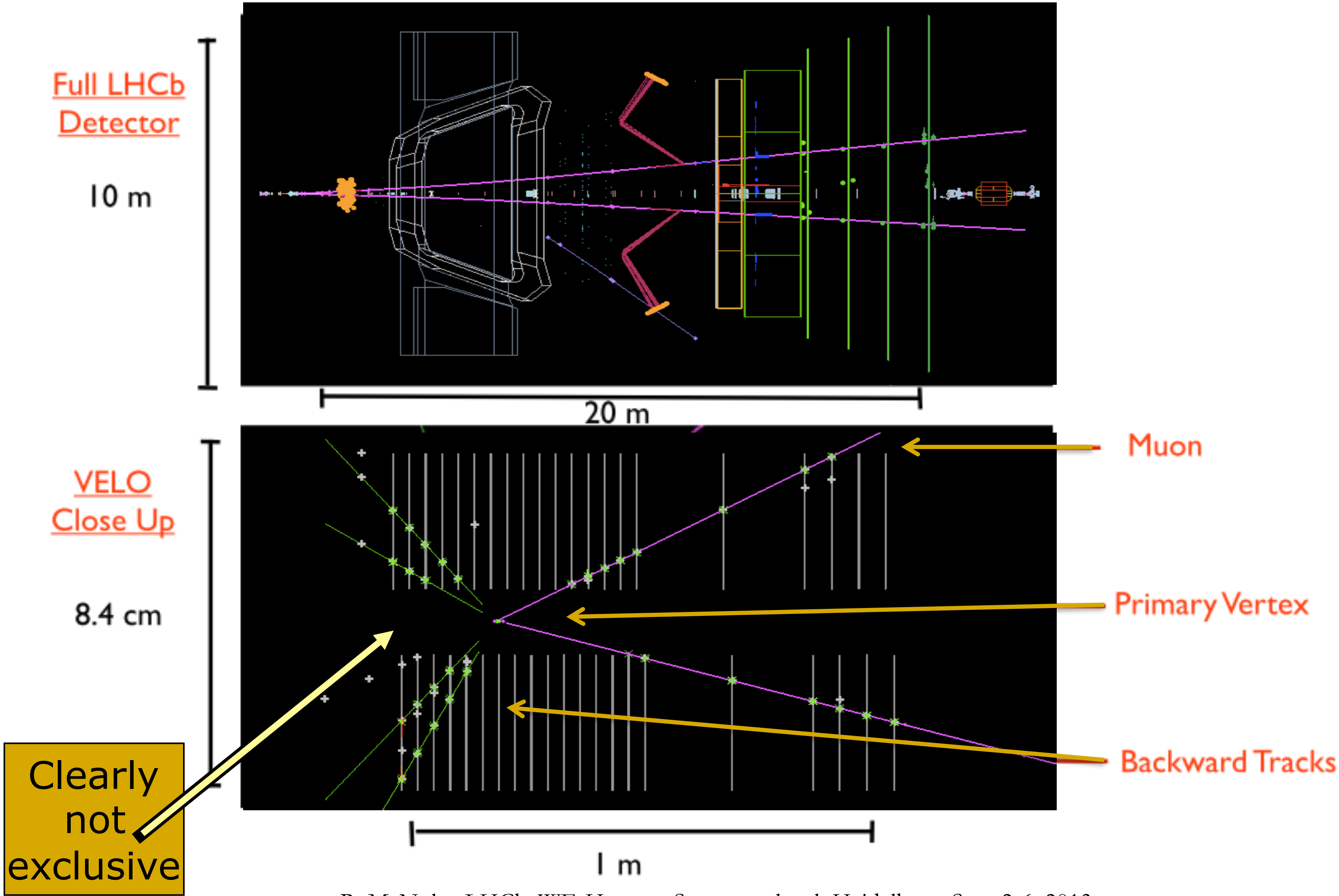
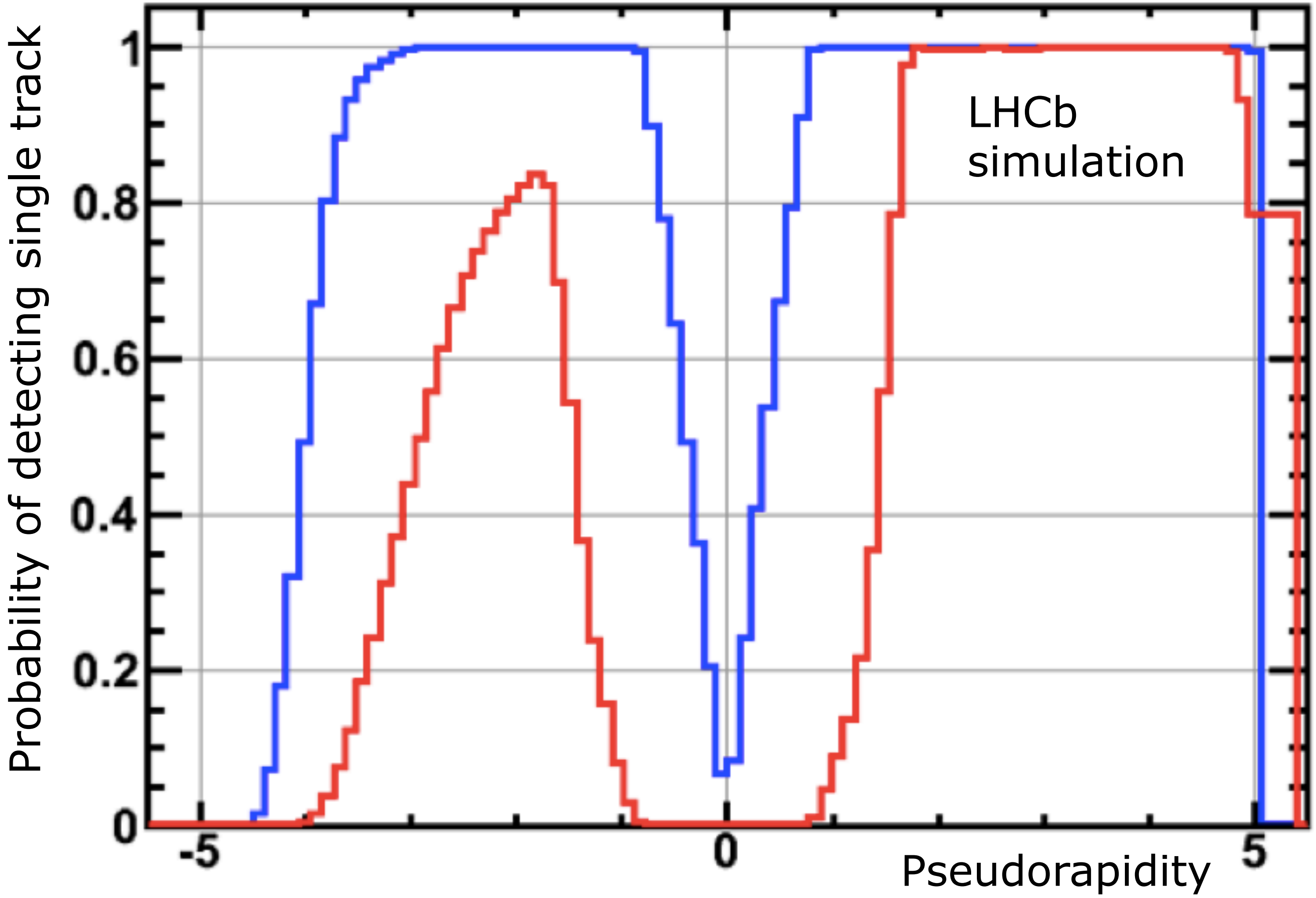
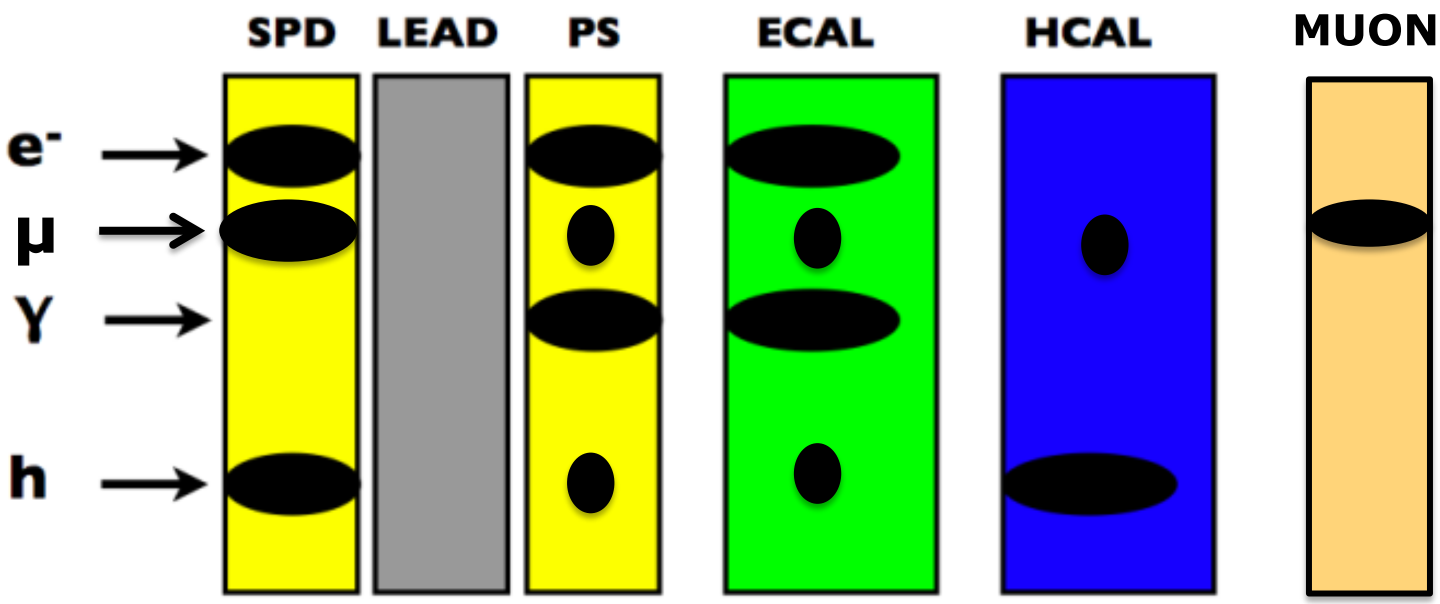




All results I show imply red region void, except for signal.

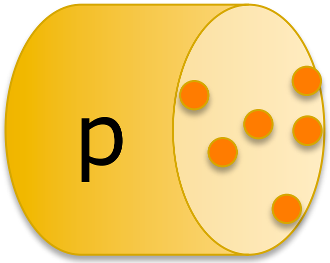
Calorimeter System in LHCb



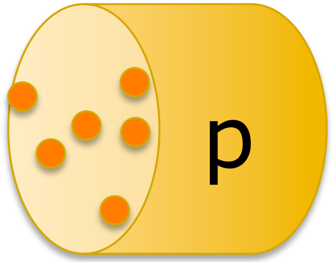
Scintillation Pad Detector.
If a charged particle goes through, we get a signal.
Rough count of number of charged particles.

Use in trigger to select **low multiplicity** events for CEP. >0,<20 hits

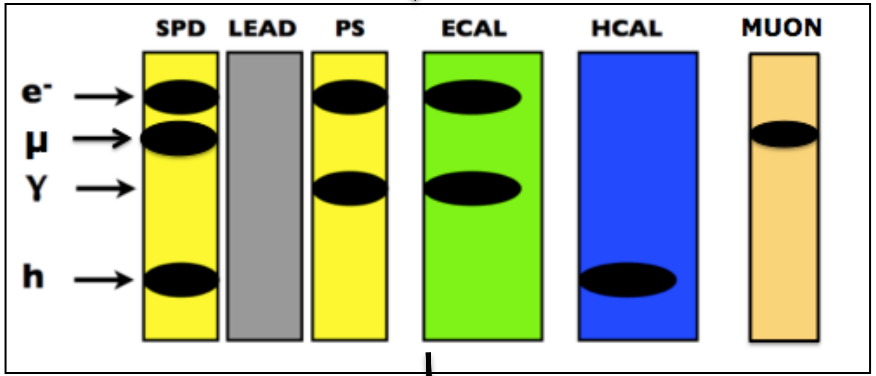
Triggering



40 MHz



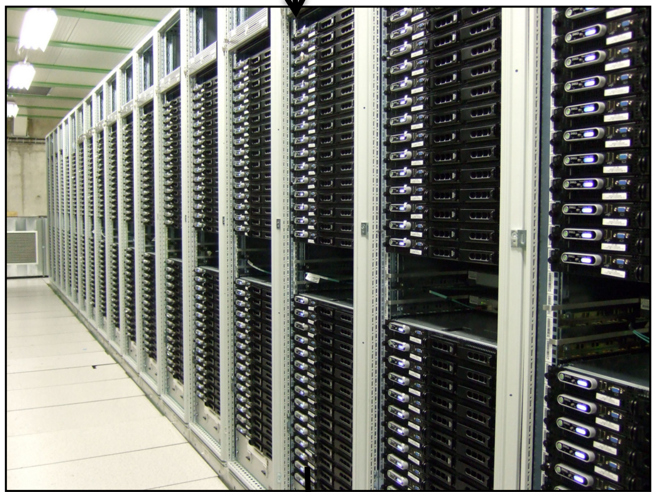
L0 Trigger:



Hardware:
Fast electronics

1 MHz

HLT Trigger:



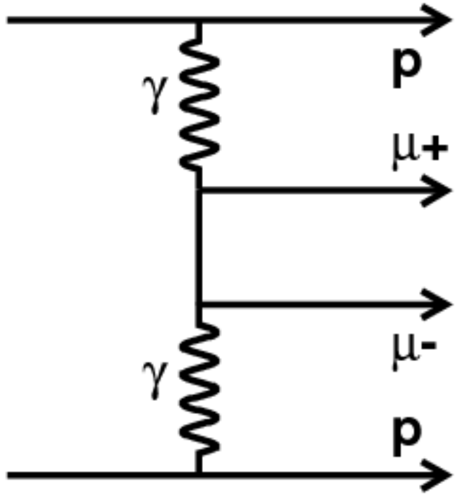
Software:
Parallel processing

2 kHz

Diffractive Physics with muons

Central Exclusive Production with Dimuon final states

Related phenomena where the colourless object creates a particle



QED

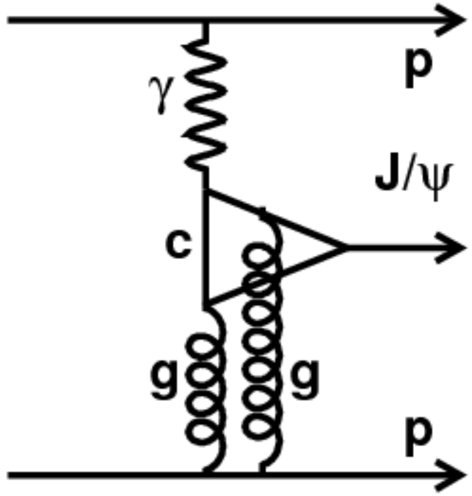
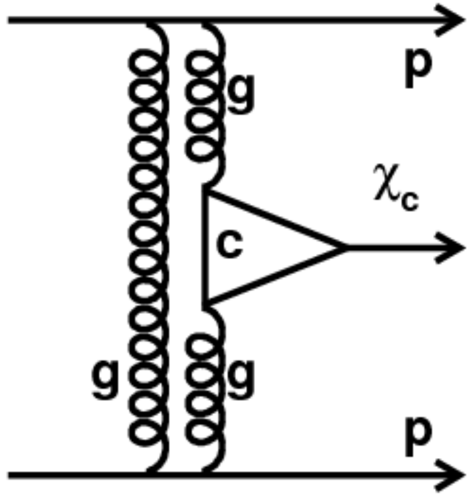


Photo production



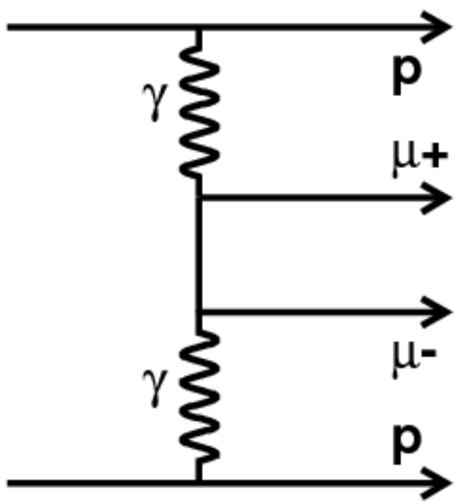
Double pomeron exchange

(Note: $J/\psi \rightarrow \mu\mu$ and $\chi_c \rightarrow J/\psi\gamma$)

Requiring dimuons significantly reduces inclusive QCD backgrounds

Motivation

Usually proton collisions produce very many final state particle because the gluon is a coloured object.
But if a **colourless** object is exchanged…..



QED

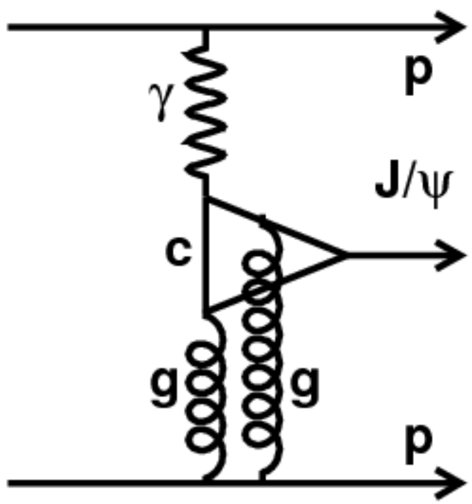
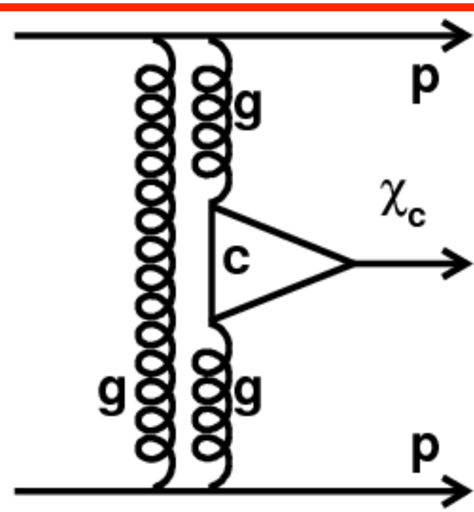


Photo production

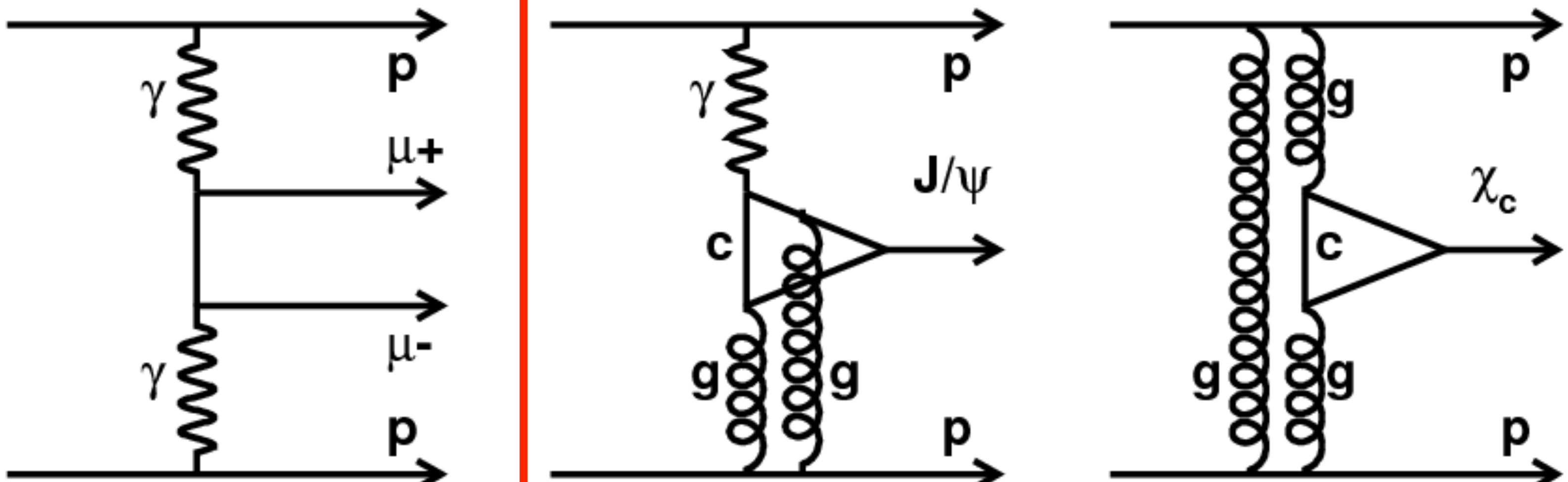


Double pomeron exchange

Unambiguous evidence for pomeron
Constrain diffractive PDF at very low x (10^{-6})
Sensitive to **saturation** effects
'Standard Candle' for other DPE processes, in particular, Higgs.

Motivation

Usually proton collisions produce very many final state particle because the gluon is a coloured object.
But if a **colourless** object is exchanged…..

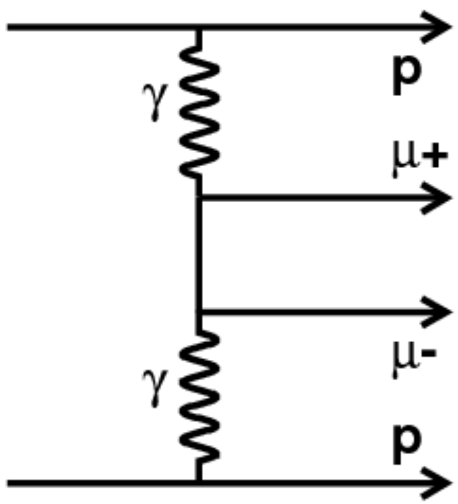


QED **Photo production** **Double pomeron exchange**

QED process. Can be predicted with high accuracy (<1%)
Candidate process for very precise luminosity determination at LHC

Motivation

Usually proton collisions produce very many final state particle because the gluon is a coloured object.
But if a **colourless** object is exchanged…..



QED

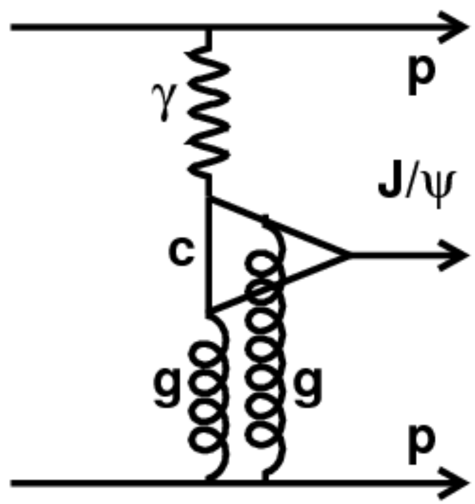
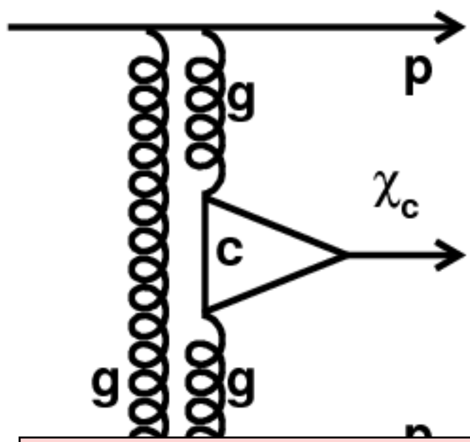
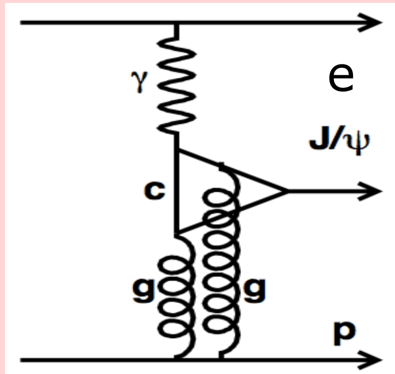


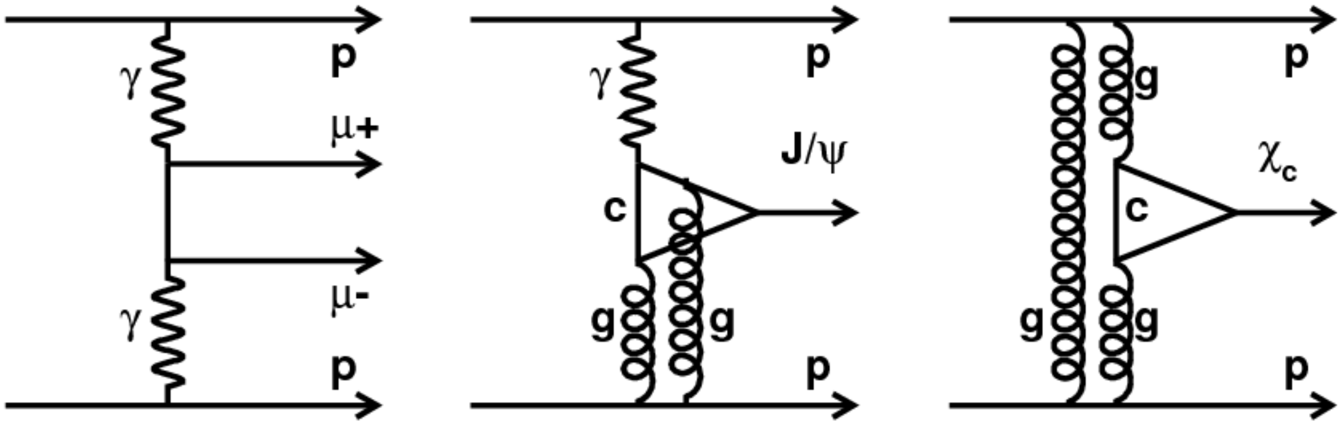
Photo production



Test of QCD and pomeron in clean environment
Measured at HERA/Tevatron but at different W
Sensitive to diffractive PDF at very low x (10^{-6})
Search for the odderon

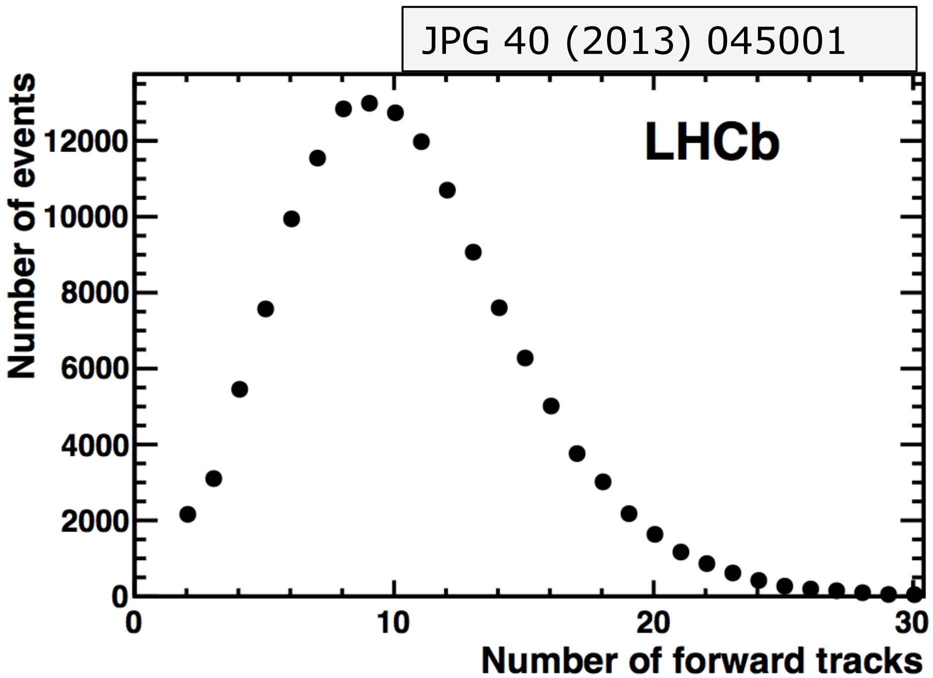


Simple Selection Criteria

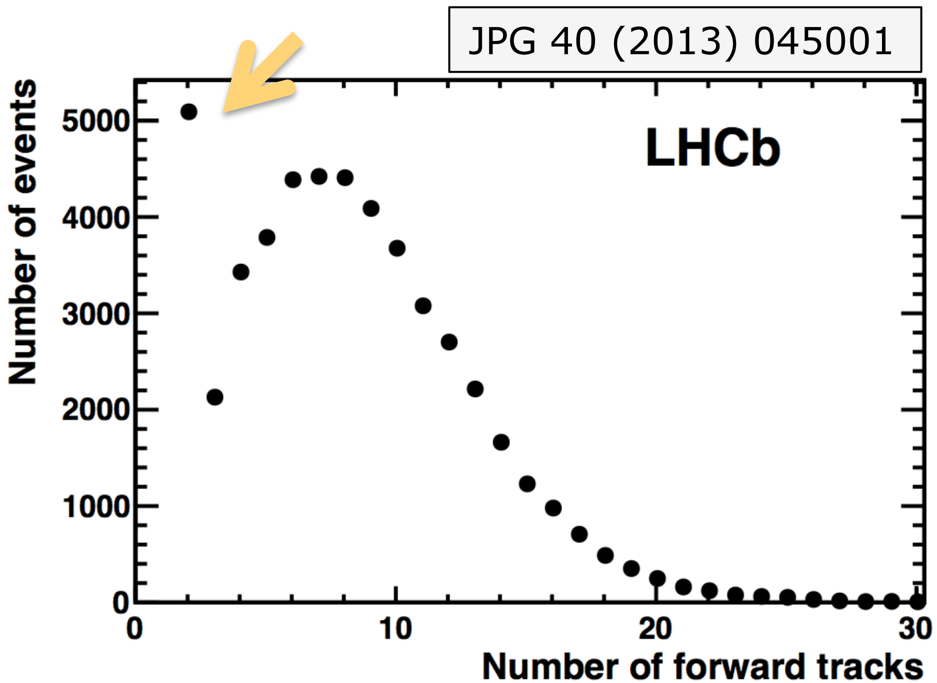


- **No backward tracks** **(2 gaps that sum to 3.5 units of rapidity)**
- **Precisely two forward muons**
- No photons (for J/psi and diphoton process)
- One photon (for ChiC analysis)
- p_T of dimuon <900 MeV (<100MeV for pμμp).

Effect of rapidity gap requirement on low multiplicity muon triggered events



All triggered events



With veto on backward tracks

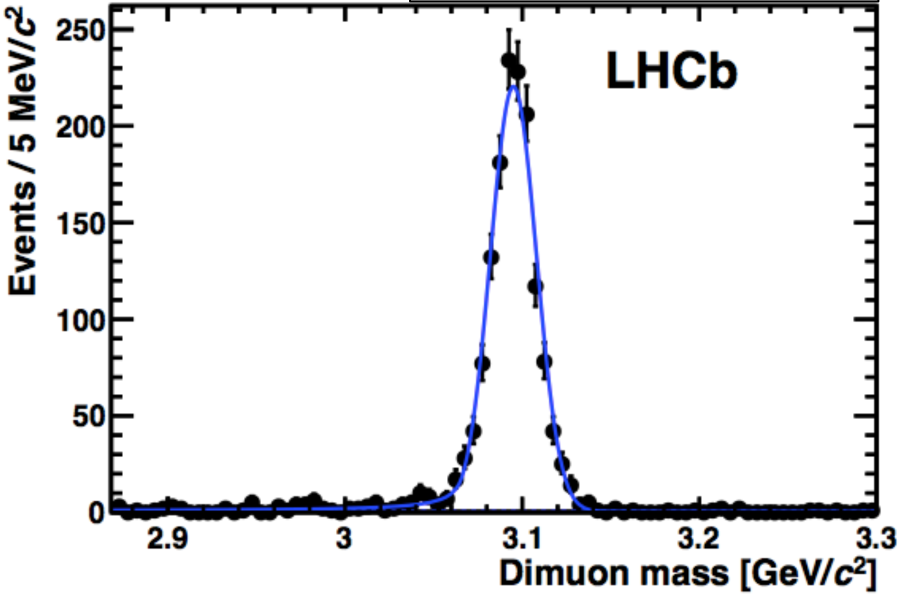
J/ψ and ψ'

- Results published in JPG 40 (2013) 045001
- Based on $37pb^{-1}$ (Full 2010 dataset)

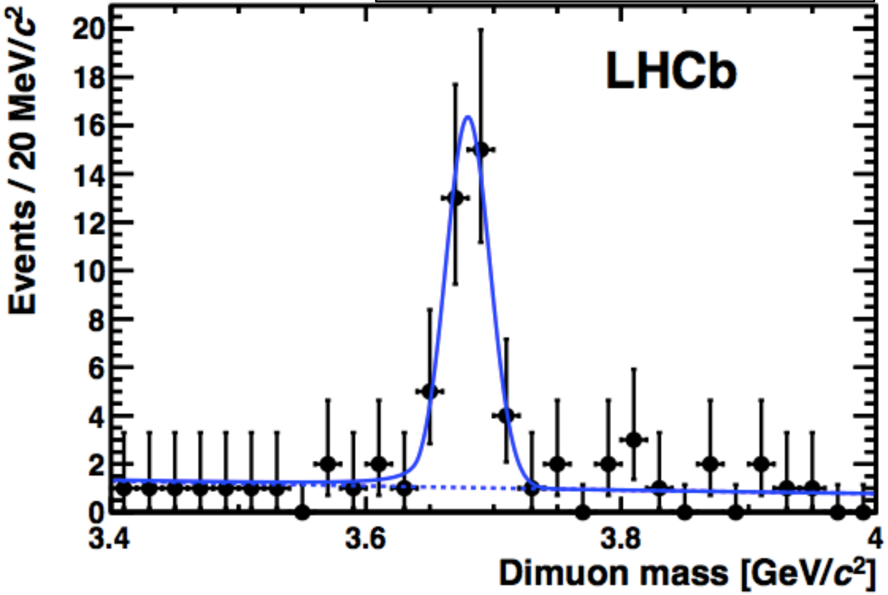
- No backward tracks
- Precisely two forward muons
- No photons

Non-resonant background very small

JPG 40 (2013) 045001



JPG 40 (2013) 045001



Distributions are not background-subtracted.
37pb-1 of data: 1492 J/ψ and 40 ψ(2s)

Cross-section measurement

Purity:
1. non-resonant bkg (1%)
2. Chi_c feeddown (9%)
3. Psi' feedown (2%)
4. Inelastic Jpsi production (30%)

Number of events observed

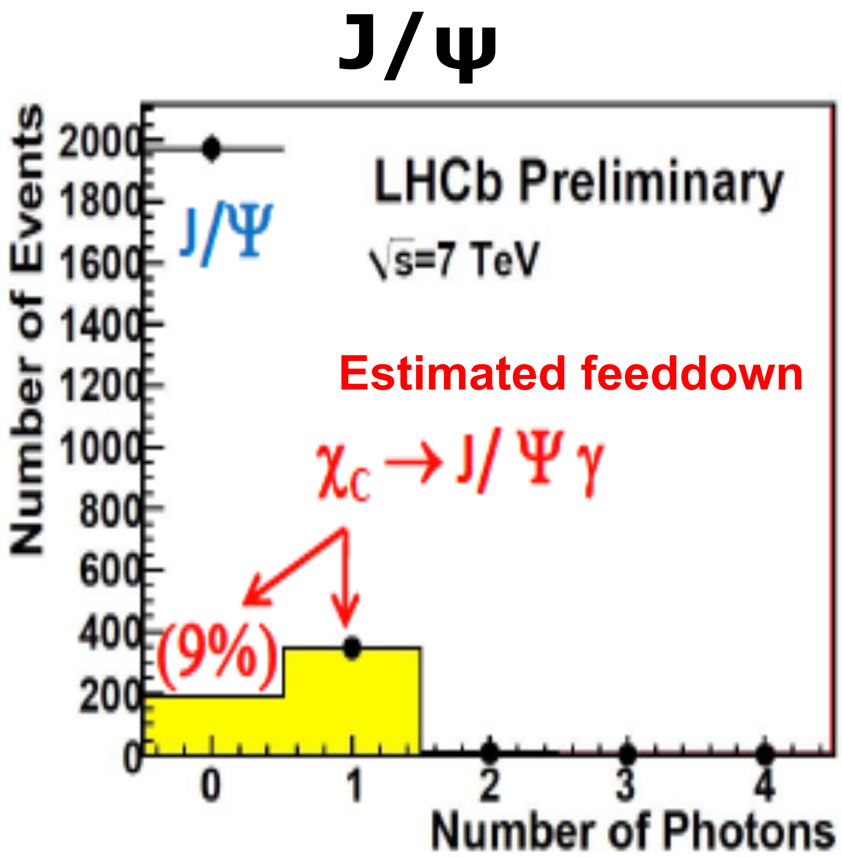
$$\sigma = \frac{pN}{\varepsilon L}$$

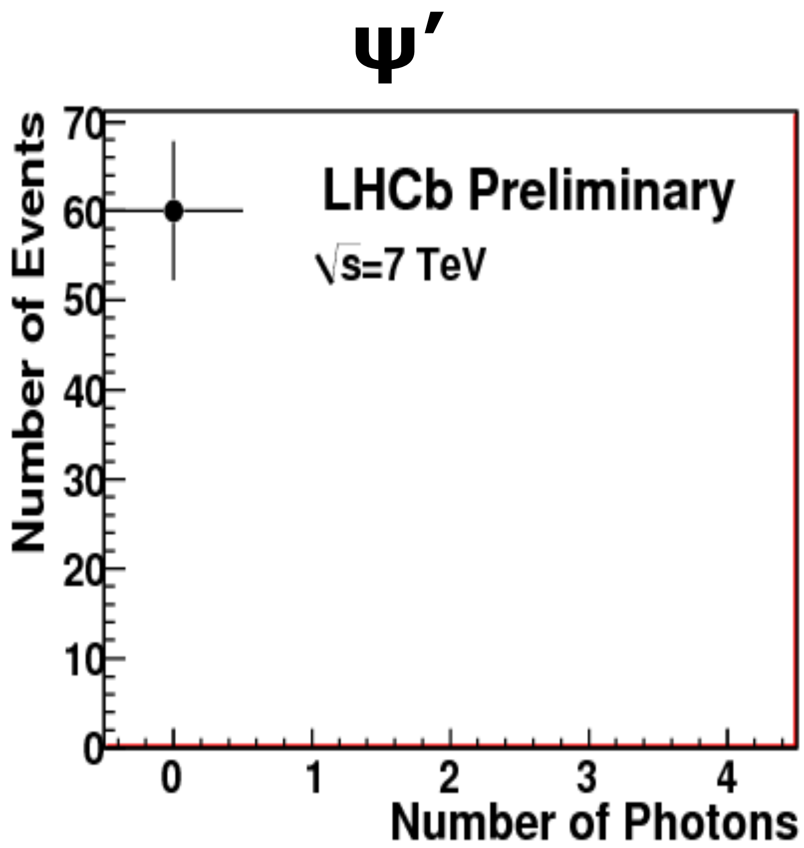
Luminosity

Efficiency:
1. Trigger
2. Tracking & muon id.
3. Single interaction beam-crossing

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

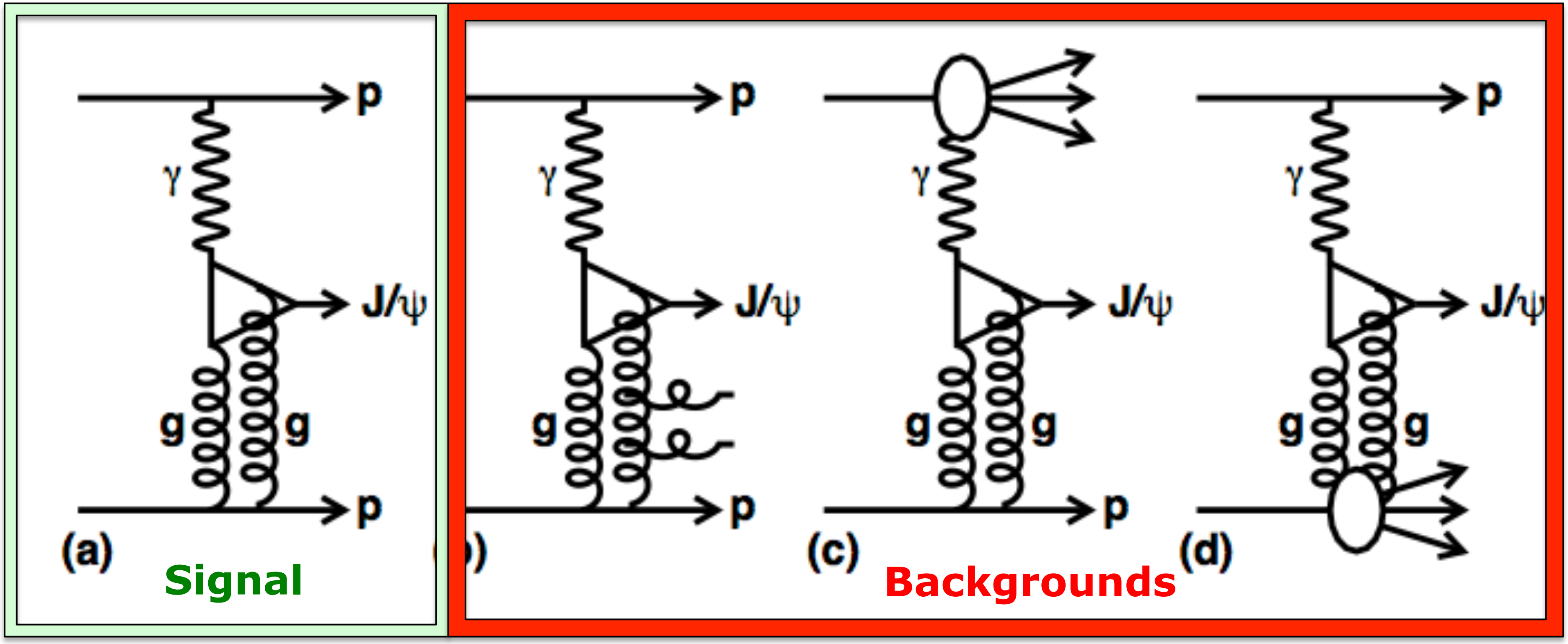
Feed-down background





(Note: $J/\psi \rightarrow \mu\mu$ and $\chi_c \rightarrow J/\psi\gamma$)

Inelastic background



Characterise p_T spectrum of background using shapes with 3-8 tracks and extrapolate to 2 track case.

Inelastic background

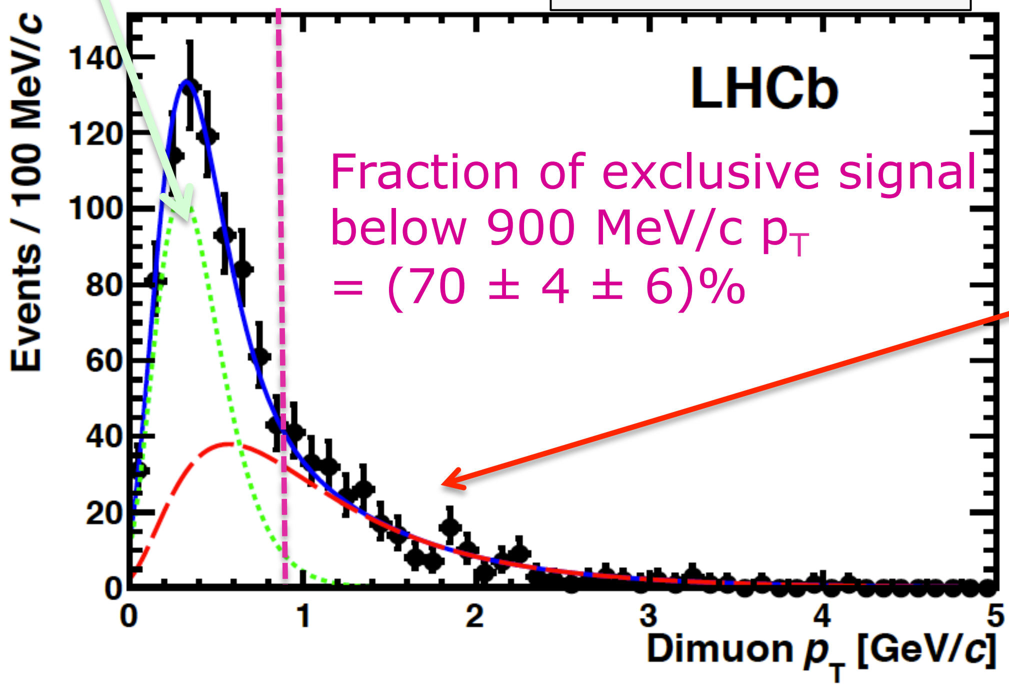
Signal shape

Estimated from Superchic using exp(- b p_T^2) (arXiv: 0909.4748)

Take b from HERA. Extrapolate to LHCb energy to get b= 6.1 +/- 0.3 GeV^{-2}

Crosscheck: Fit to spectrum below with b free gives b = 5.8 +/- 1 GeV^{-2}

JPG 40 (2013) 045001



Fraction of exclusive signal below 900 MeV/c p_T = (70 ± 4 ± 6)%

Inelastic background shape

Estimated from data.
Characterise shape for 3-8 tracks and extrapolate to 2 tracks.

.

LHCb compared to theory & experiment

Results (in pb) are for VM with two muons with 2<η<4.5

Predictions	$\sigma_{pp\to J/\psi\,(\to\mu^+\mu^-)}$	$\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}$
Gonçalves and Machado	275	
STARLIGHT	292	6.1
Motyka and Watt	334	
SUPERCHIC[a]	396	
Schäfer and Szczurek	710	17
LHCb measured value	$307 \pm 21 \pm 36$	$7.8 \pm 1.3 \pm 1.0$

[a] SUPERCHIC simulation does not include a gap survival factor.

All predictions (bar Schaefer&Szcaurek) have similar approach and give similar results and are consistent with our data.

See J. Figiel presentation at this school

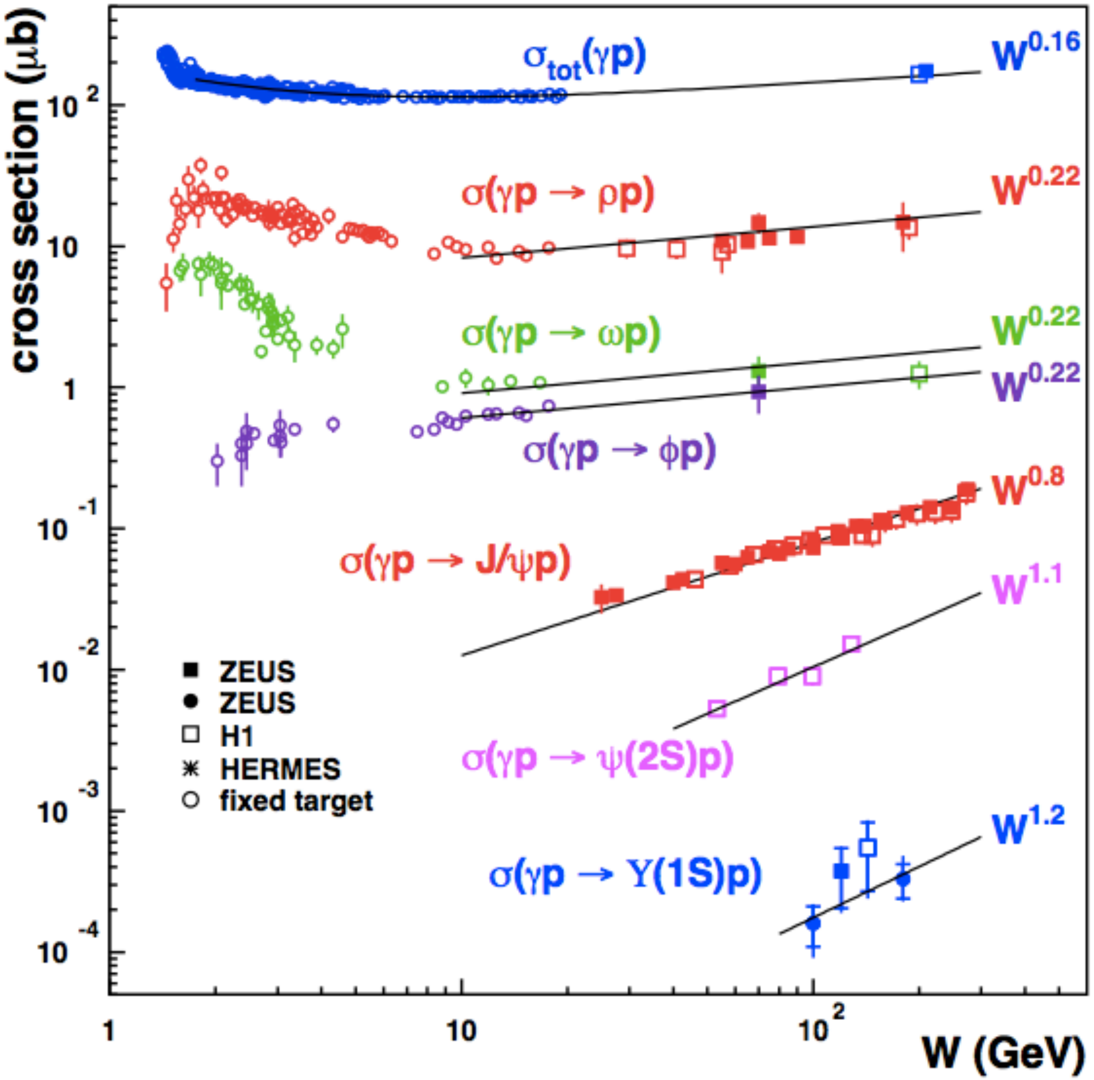
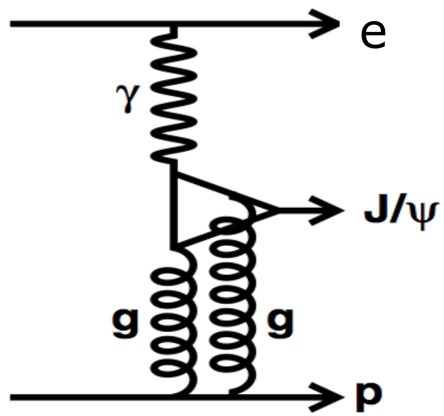


Photo-production cross-section



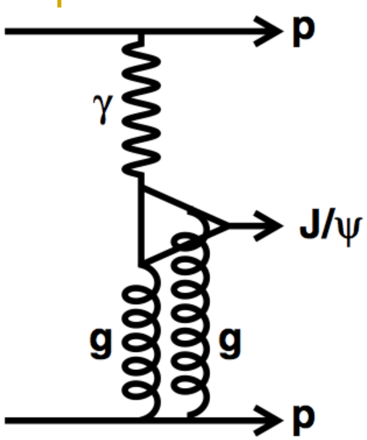
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

$$\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2 + M_{J/\psi}^2).$$

Cross-section proportional to gluon² $\sigma \sim (xg)^2$ and so $\sigma \sim x^{\lambda}$

[1] Martin A D, Nockles C, Ryskin M and Teubner T 2008 Small x gluon from exclusive J/ψ production *Phys. Lett.* B **662** 252 (arXiv:0709.4406)
[2] Ryskin M G 1993 J/ψ electroproduction in LLA QCD *Z. Phys.* C **57** 89
[3] Ryskin M G, Roberts R G, Martin A D and Levin E M 1997 Diffractive J/ψ photoproduction as a probe of the gluon density *Z. Phys.* C **76** 231 (arXiv:hep-ph/9511228)

LHCb compared to HERA

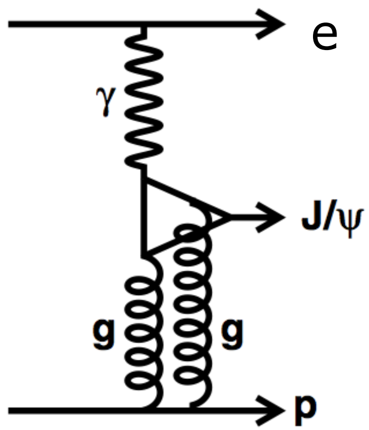


$$W^2 \equiv (q + p_2)^2 = x_\gamma s - Q^2 ,$$

$$x_\gamma = \frac{M_{\psi_\perp}}{\sqrt{s}} e^{y_\psi} ,$$

$$x = \frac{M_{\psi_\perp}}{\sqrt{s}} e^{-y_\psi} ,$$

Twofold ambiguity



LHCb c/s is HERA c/s + photon spectrum + gap survival factor (r~0.8)

$$\frac{d\sigma}{dy}_{pp\to pVp} = r(y)\left[k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to Vp}(W_+) + k_- \frac{dn}{dk_-}\sigma_{\gamma p\to Vp}(W_-)\right]$$

$$k_\pm \approx (m_V/2)\exp(\pm|y|),$$

LHCb differential data fitted assuming power law dependence $\sigma(W) = aW^\delta$

Power law results

LHCb	HERA
$a = 0.8^{+1.2}_{-0.5}\,nb$	$a = 3nb$
$\delta = 0.92 \pm 0.15$	$\delta = 0.72$

LHCb compared to theory & experiment

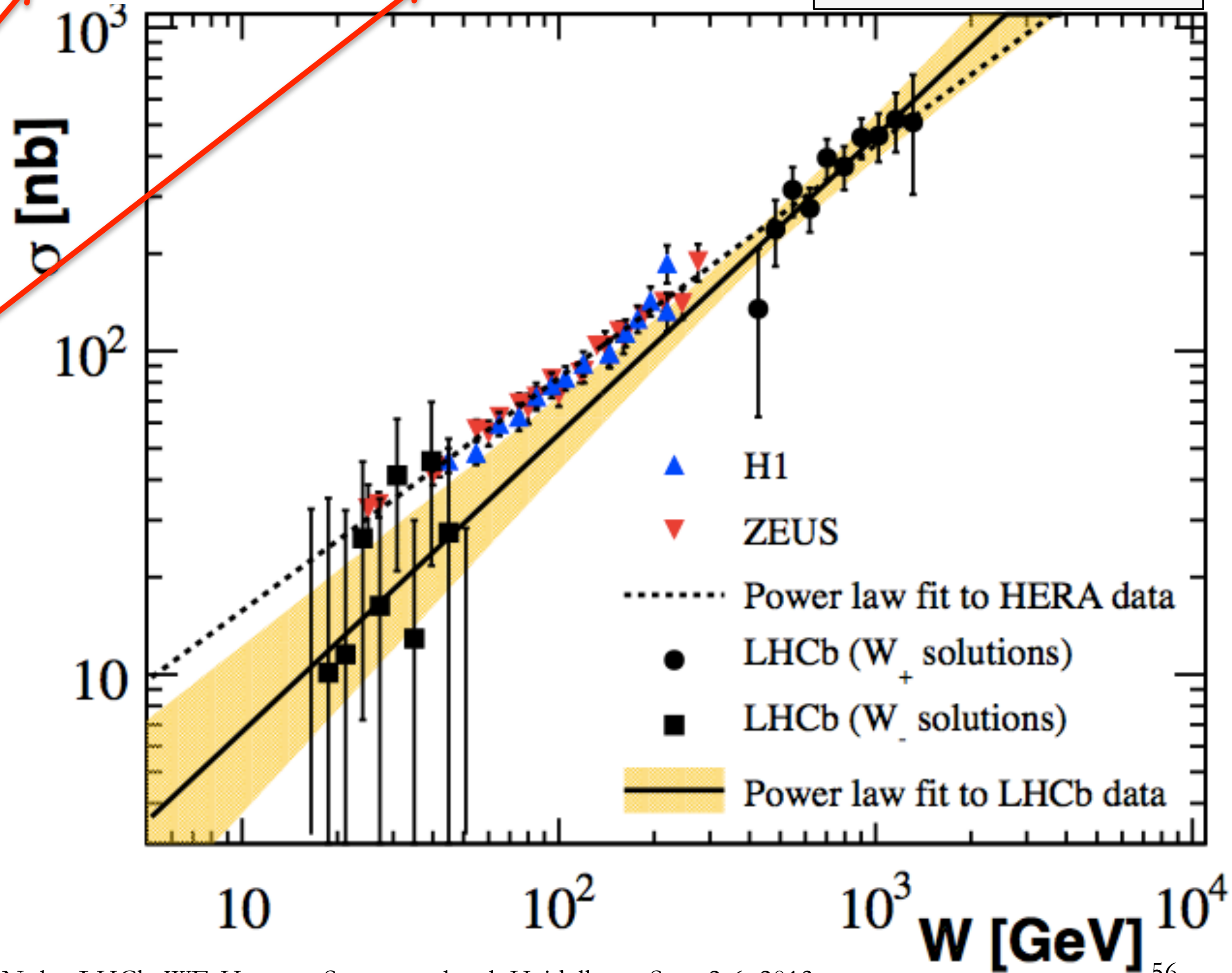
$$\left.\frac{d\sigma}{dy}\right|_{pp\to pVp} = r(y)\left[k_+\frac{dn}{dk_+}\sigma_{\gamma p\to Vp}(W_+) + k_-\frac{dn}{dk_-}\sigma_{\gamma p\to Vp}(W_-)\right]$$

measured

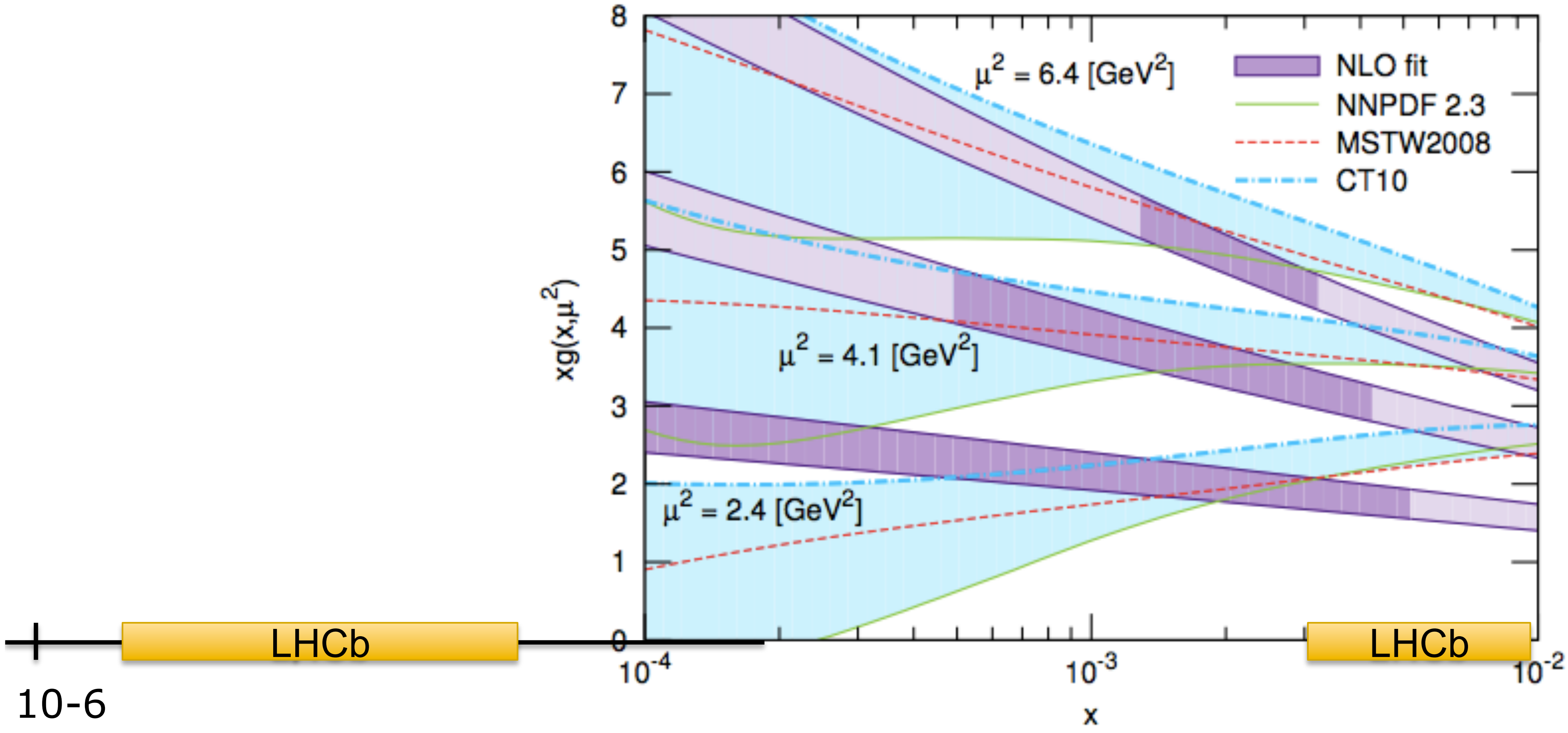
from fit

plotted

JPG 40 (2013) 045001

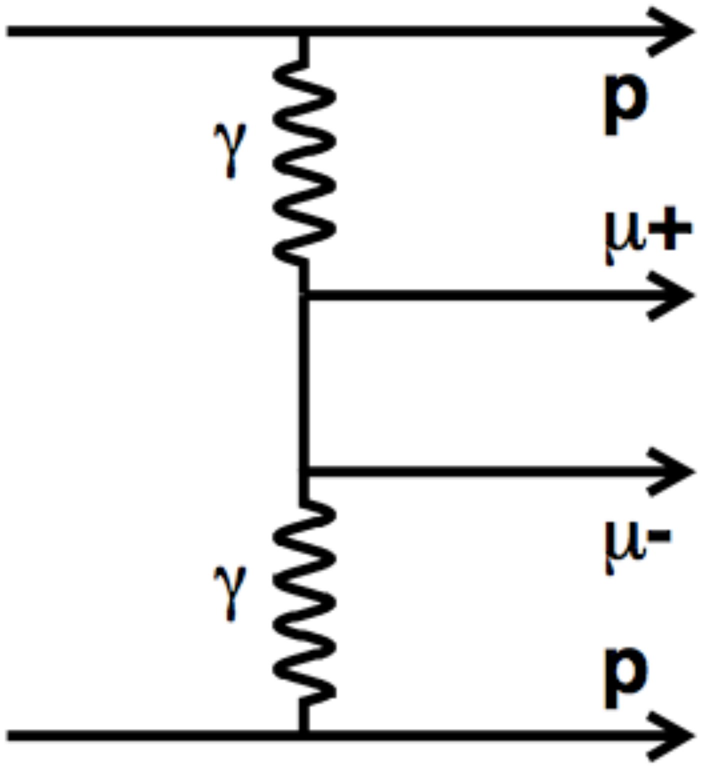


Sensitivity to gluon pdf (arXiv: 1307.7099)



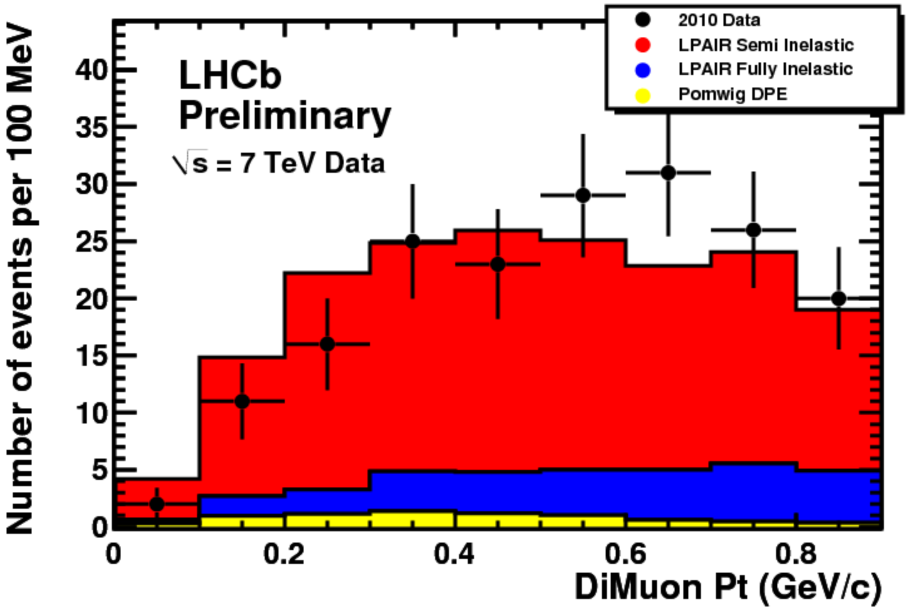
pp->pμμp

LHCb-CONF-2011-022



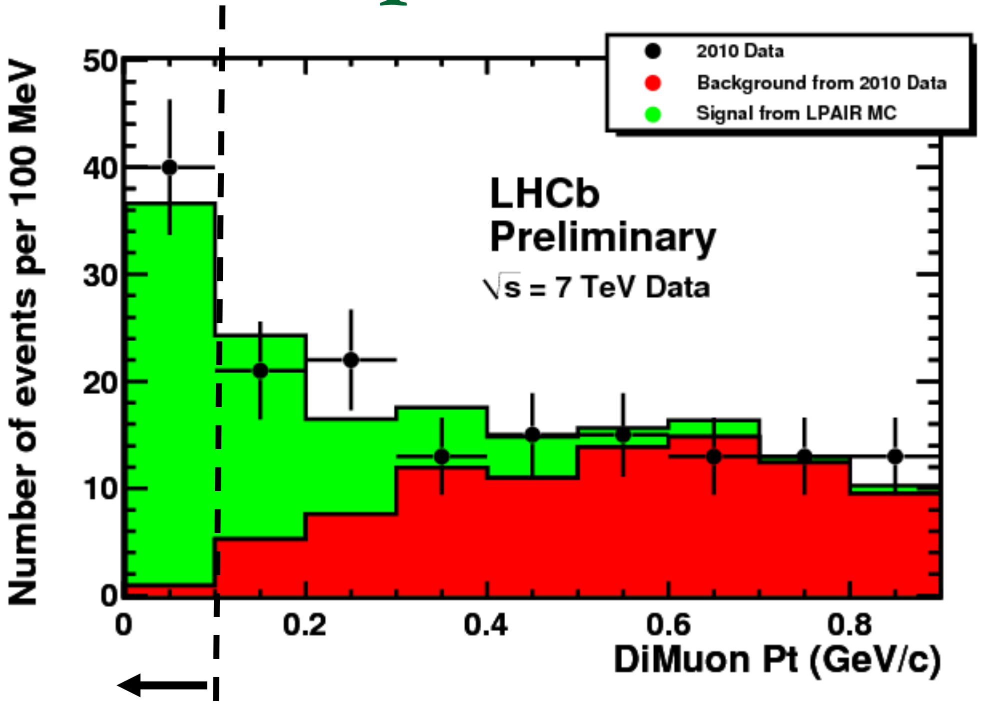
- No backward tracks
- Precisely two forward muons. $m_{\mu\mu}$>2.5 GeV
- No photons

Fit elastic and inelastic components



Shape for inelastic events

Note: this time we have simulation that predicts the shape for the three contributions.



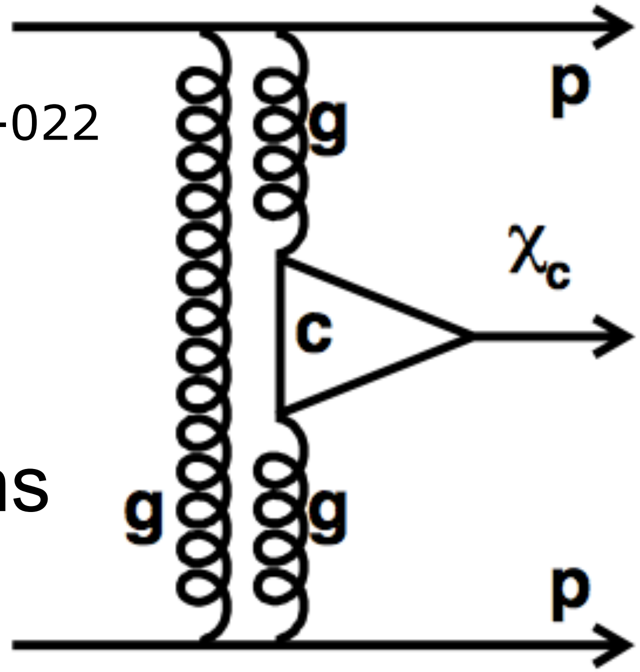
Fit to signal events

Background shape from data
Signal shape from simulation.

Measured cross-section pμμp: 67 +- 19 pb | LPAIR (J. Vermaseren) 42 pb

$\chi_{c0,c1,c2}$

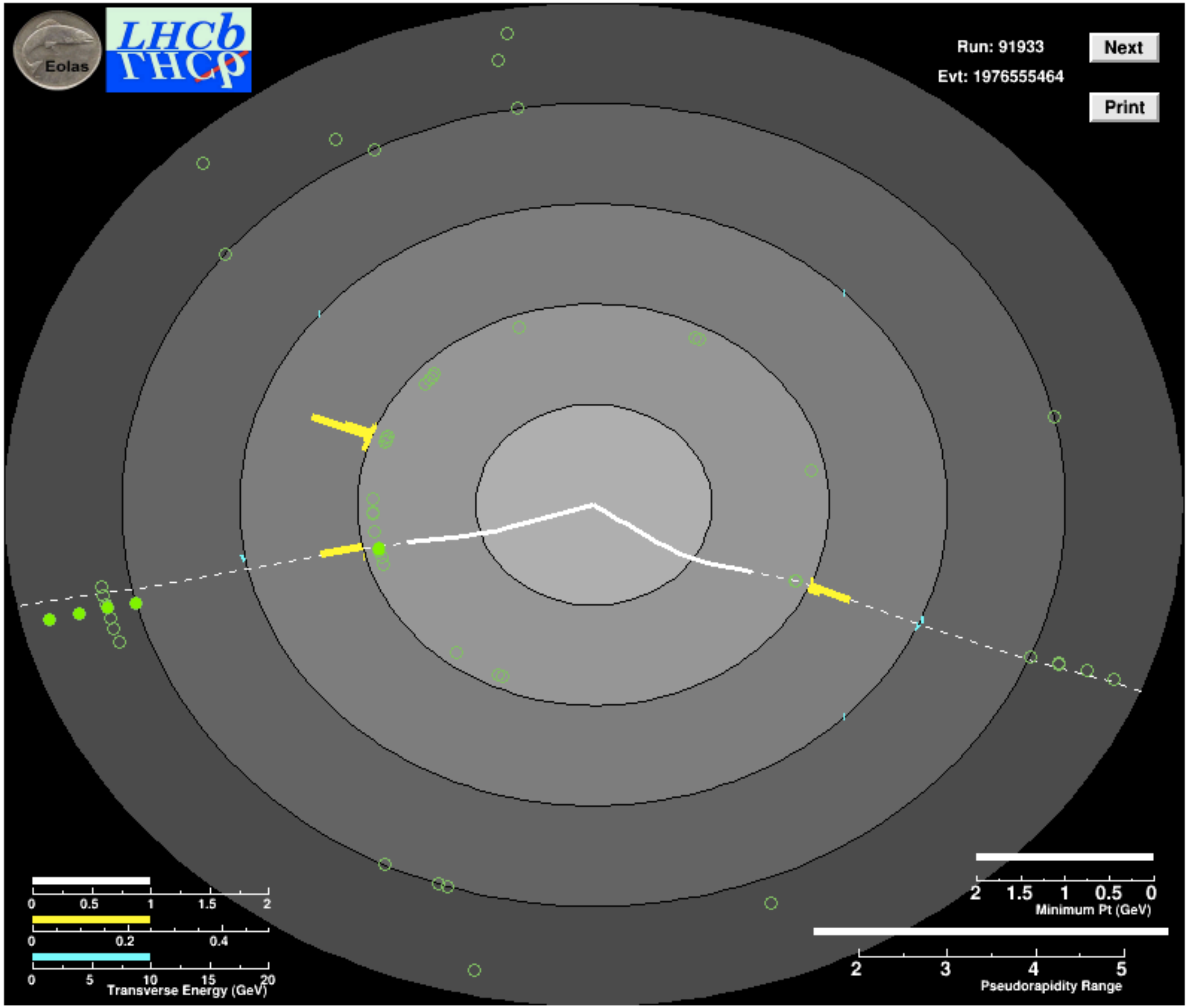
LHCb-CONF-2011-022



- No backward tracks
- Precisely two forward muons
- Precisely one photon

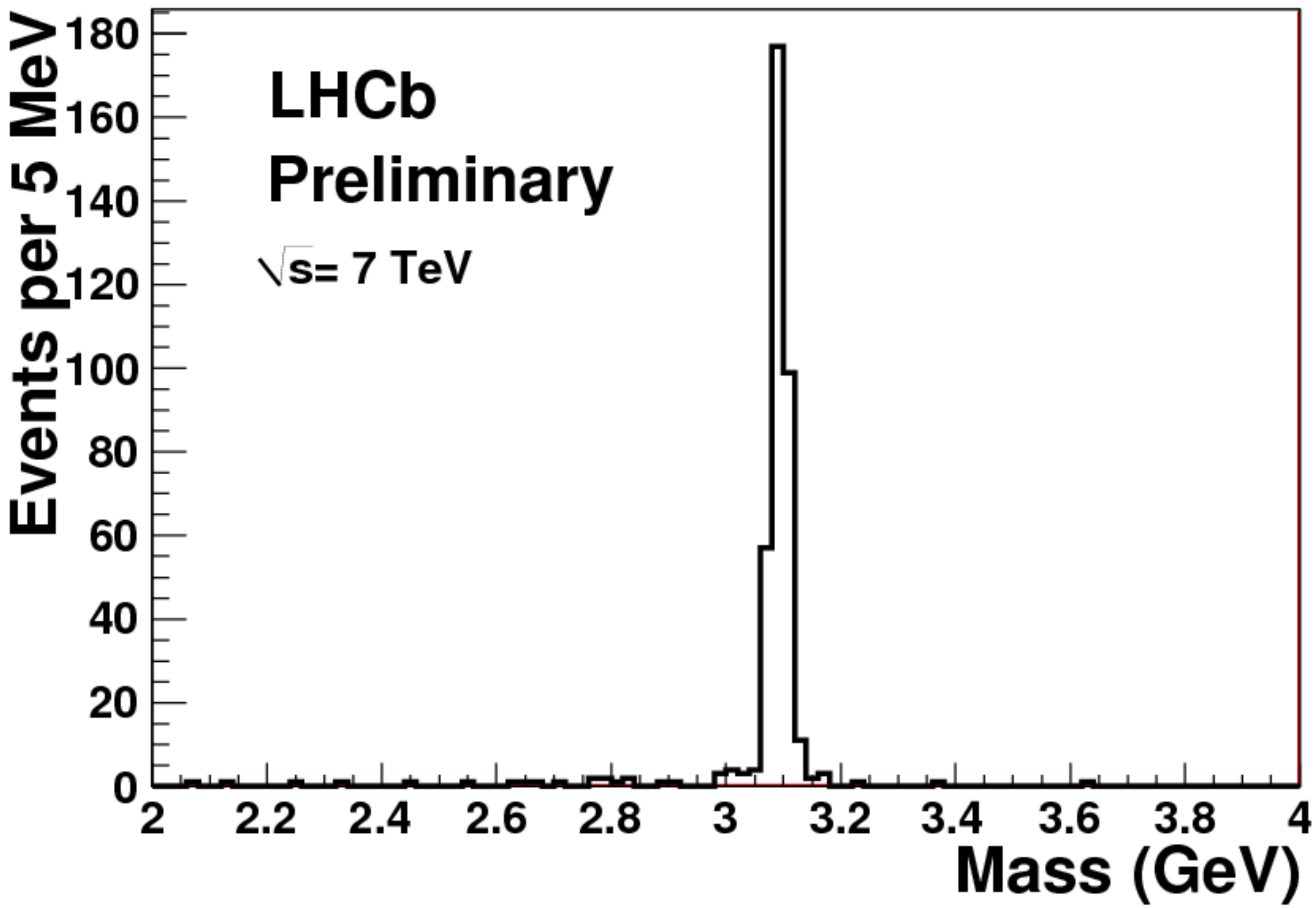
(Note: $\chi_c \to J/\psi\gamma$) and $J/\psi \to \mu\mu$

- Expect
  - χ_{c1} suppressed due to Landau-Yang theorem
  - χ_{c2} suppressed: can't have a bound state with J=2, J_z=0
  - χ_{c0} dominant (for small p_T)
  - This is different from inclusive chi production.



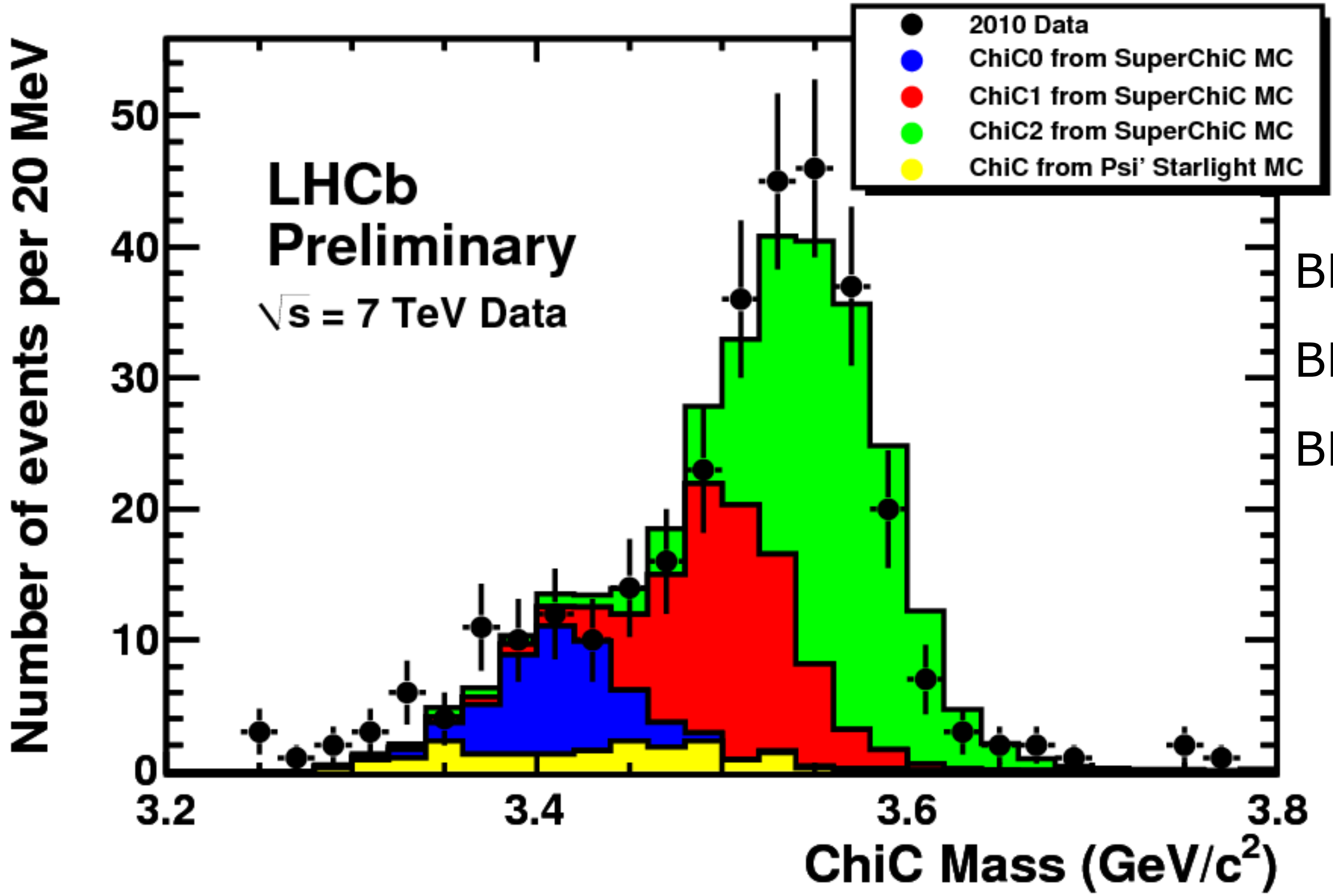
Eolas
LHCb
Run: 91933
Evt: 1976555464
Next
Print
0
0.5
1
1.5
2
0
0.2
0.4
0
5
10
15
20
Transverse Energy (GeV)
2
1.5
1
0.5
0
Minimum Pt (GeV)
2
3
4
5
Pseudorapidity Range

χ_c: DiMuon Invariant Mass



About half the background that was observed in the exclusive J/ψ analysis (since no continuum process).

χ_c: DiMuon+Photon Invariant Mass



BR(χc0->J/ψγ)=1.2%

BR(χc1->J/ψγ)=34.4%

BR(χc2->J/ψγ)=19.5%

Inelastic contribution appears to be much larger than for J/ψ.
In a first approximation it should be square of bkg in J/ψ process.

Theory v experiment

$\sigma_{\chi_{c0}\to\mu^+\mu^-\gamma}$ = 9.3 +/- 2.2 +/- 3.5 +/- 1.8 pb
$\sigma_{\chi_{c1}\to\mu^+\mu^-\gamma}$ = 16.4 +/- 5.3 +/- 5.8 +/- 3.2 pb
$\sigma_{\chi_{c2}\to\mu^+\mu^-\gamma}$ = 28.0 +/- 5.4 +/- 9.7 +/- 5.4 pb

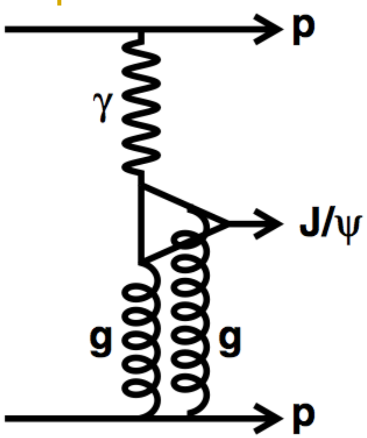
LHCb preliminary results with 2010 data

	χ_0: 9.3 +- 4.5 pb	χ_1: 16.4 +- 7.1 pb	χ_2: 28.0 +-12.3 pb
SuperChic:	14 pb	10 pb	3 pb

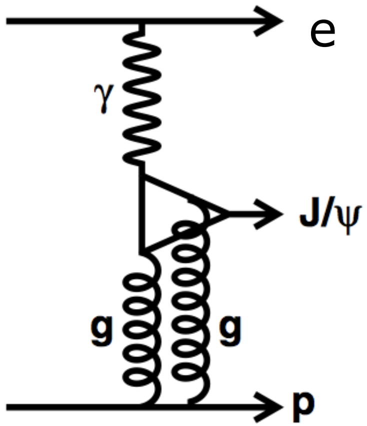
Large contribution due to X_{c0} is confirmed.

χ_{c2} larger than expected but note that non-elastic background has been assumed same for each resonance. More precise data required.

Future Prospects



LHCb compared to HERA

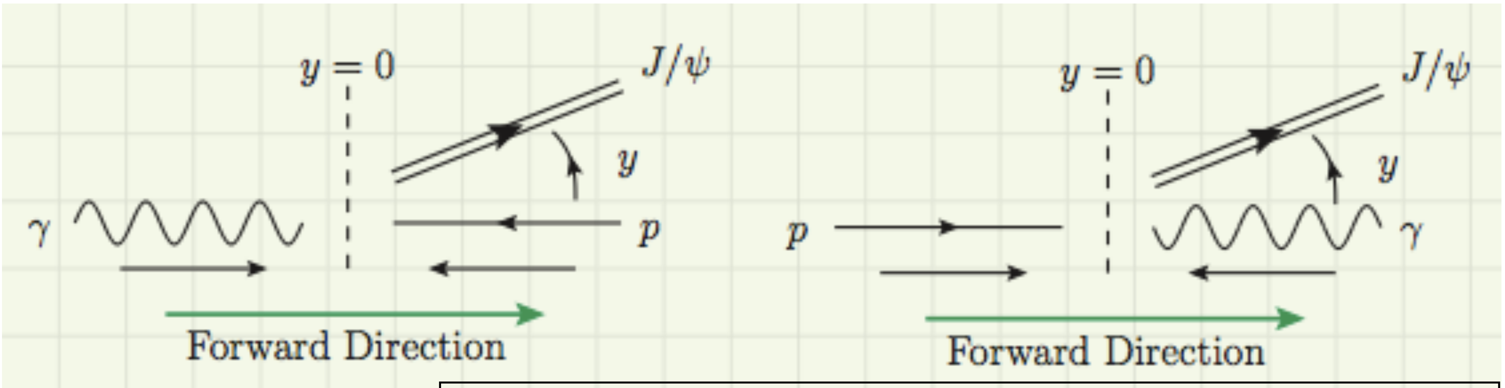


$$W^2 \equiv (q + p_2)^2 = x_\gamma s - Q^2 \ ,$$

Twofold ambiguity

$$x_\gamma = \frac{M_{\psi_\perp}}{\sqrt{s}} e^{y_\psi} \ ,$$

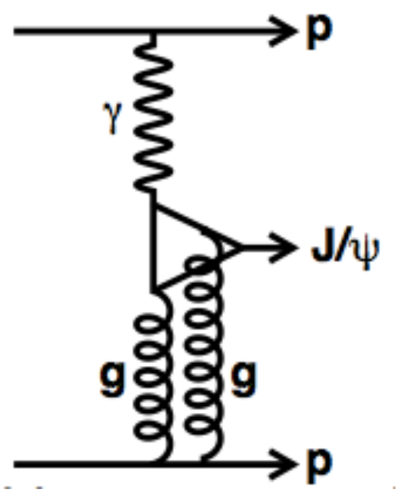
$$x = \frac{M_{\psi_\perp}}{\sqrt{s}} e^{-y_\psi} \ ,$$



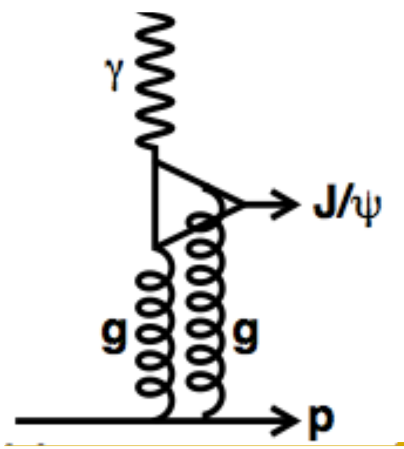
S. Jones, LHC Forward Physics WG , 27.8.2013

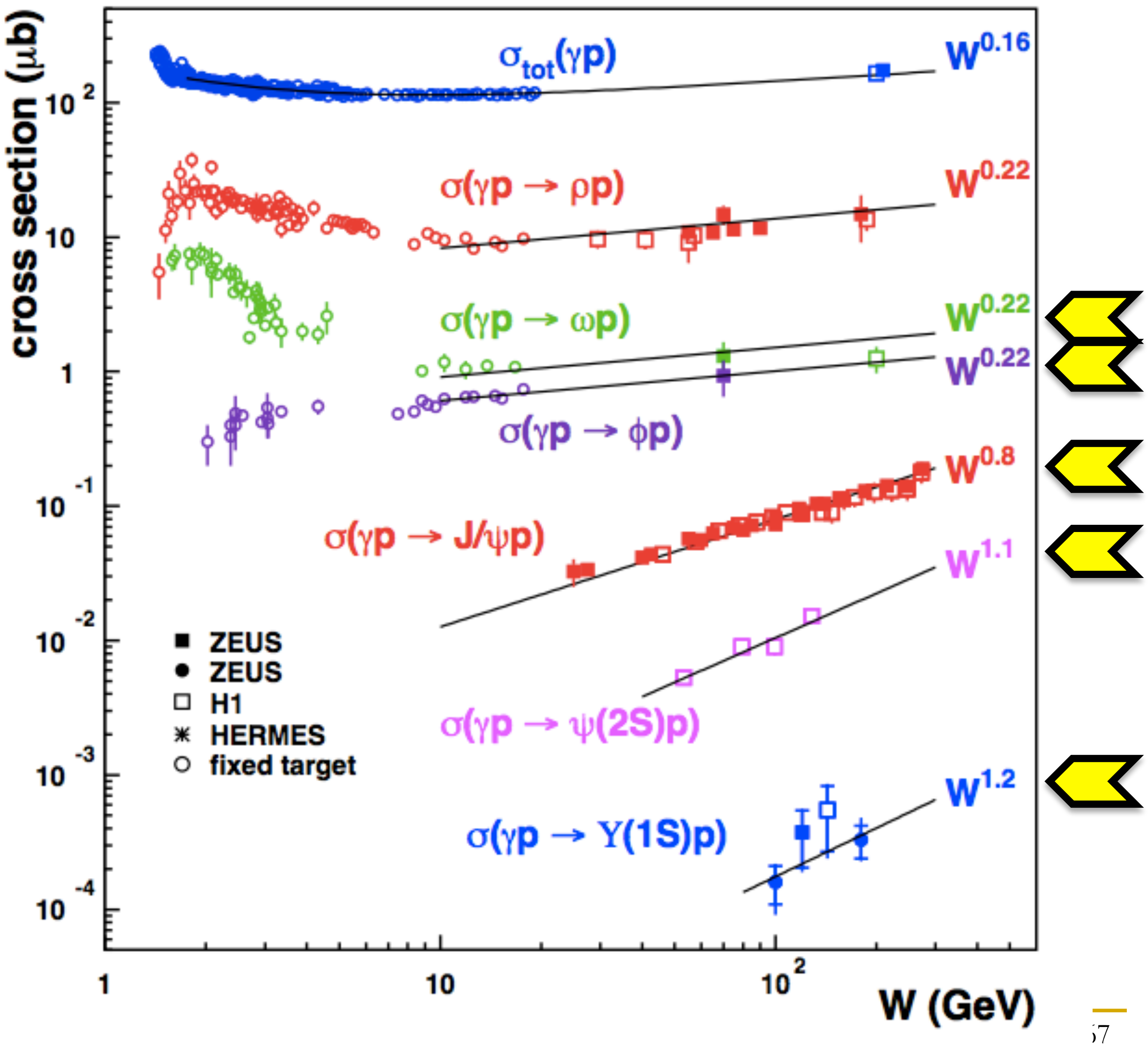
Repeat measurement with proton-lead collision data.
Photon nearly always comes from the lead nucleus (Z^2)
(J.Nystrand EPS2013, Stockholm)

LHCb compared to HERA

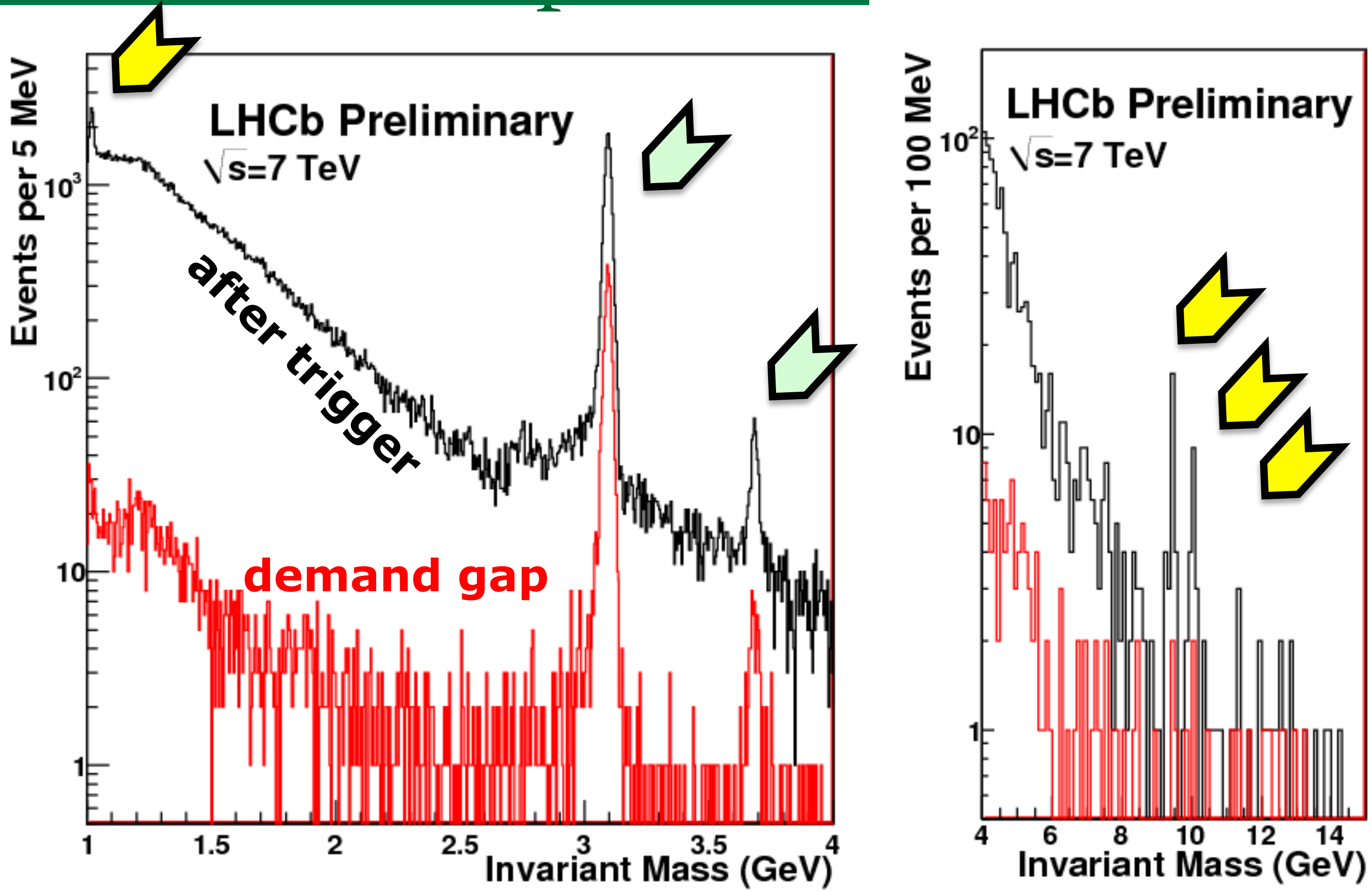


looks very like



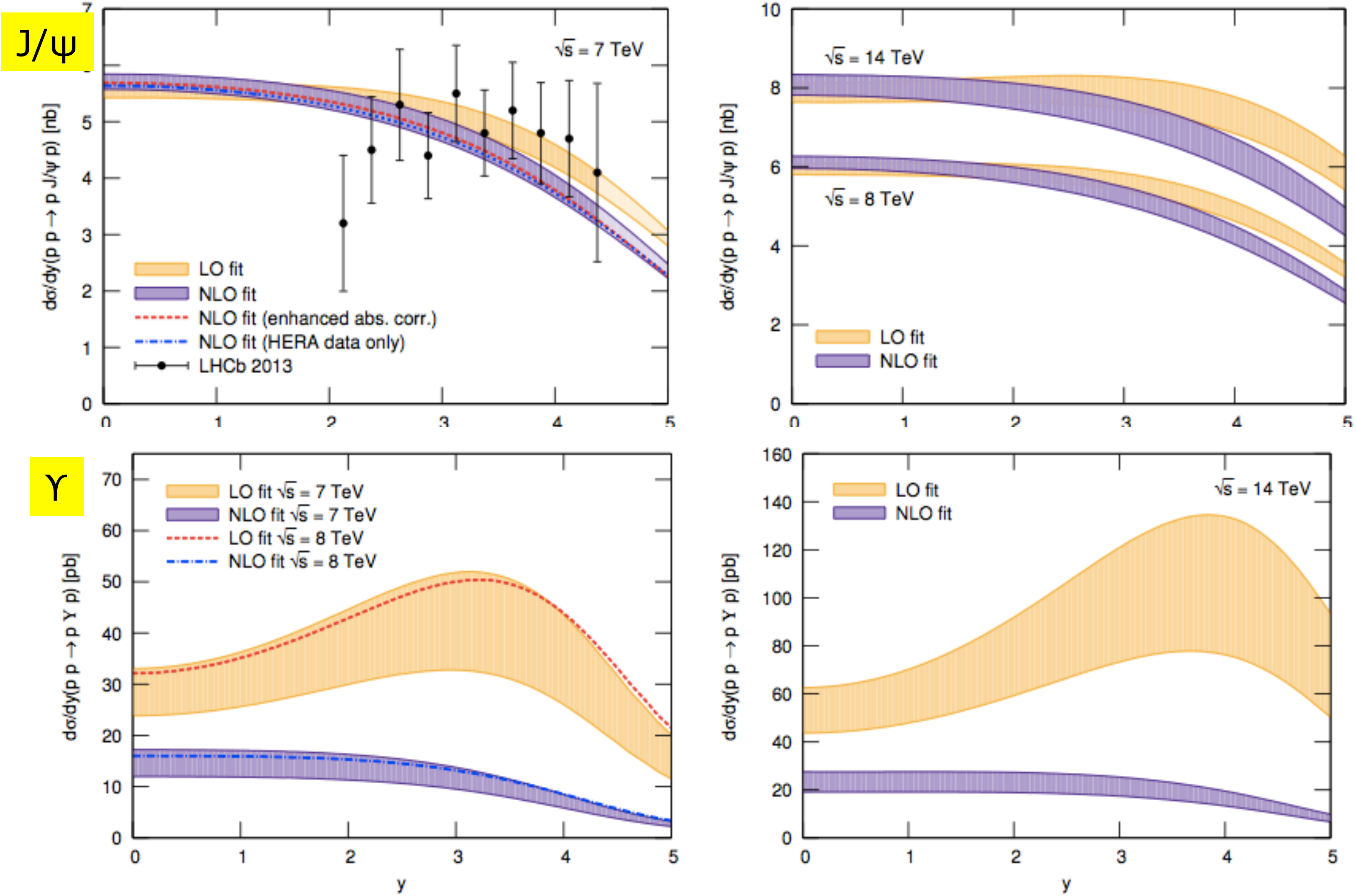


Dimuon Mass Spectrum

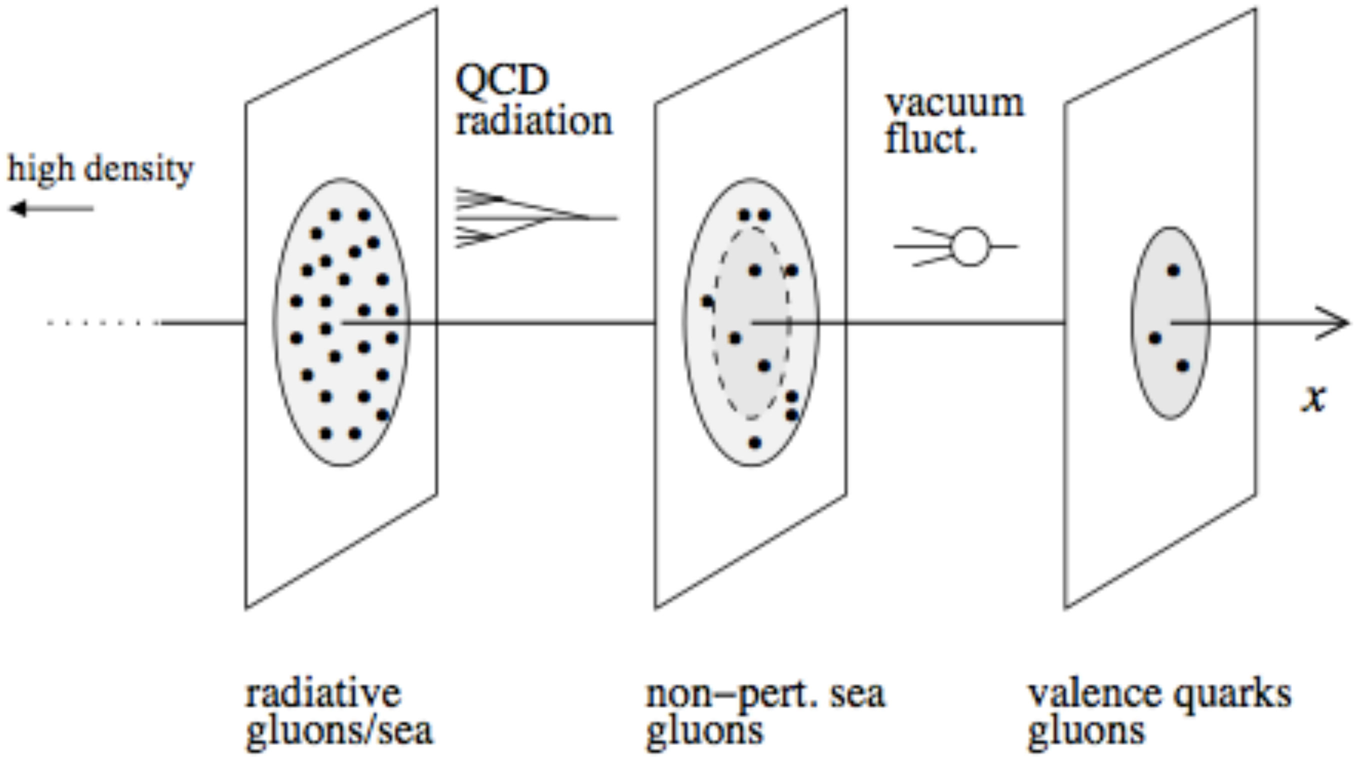


Factor ~ *100 data now available with 2011+2012 (~3fb^{-1})

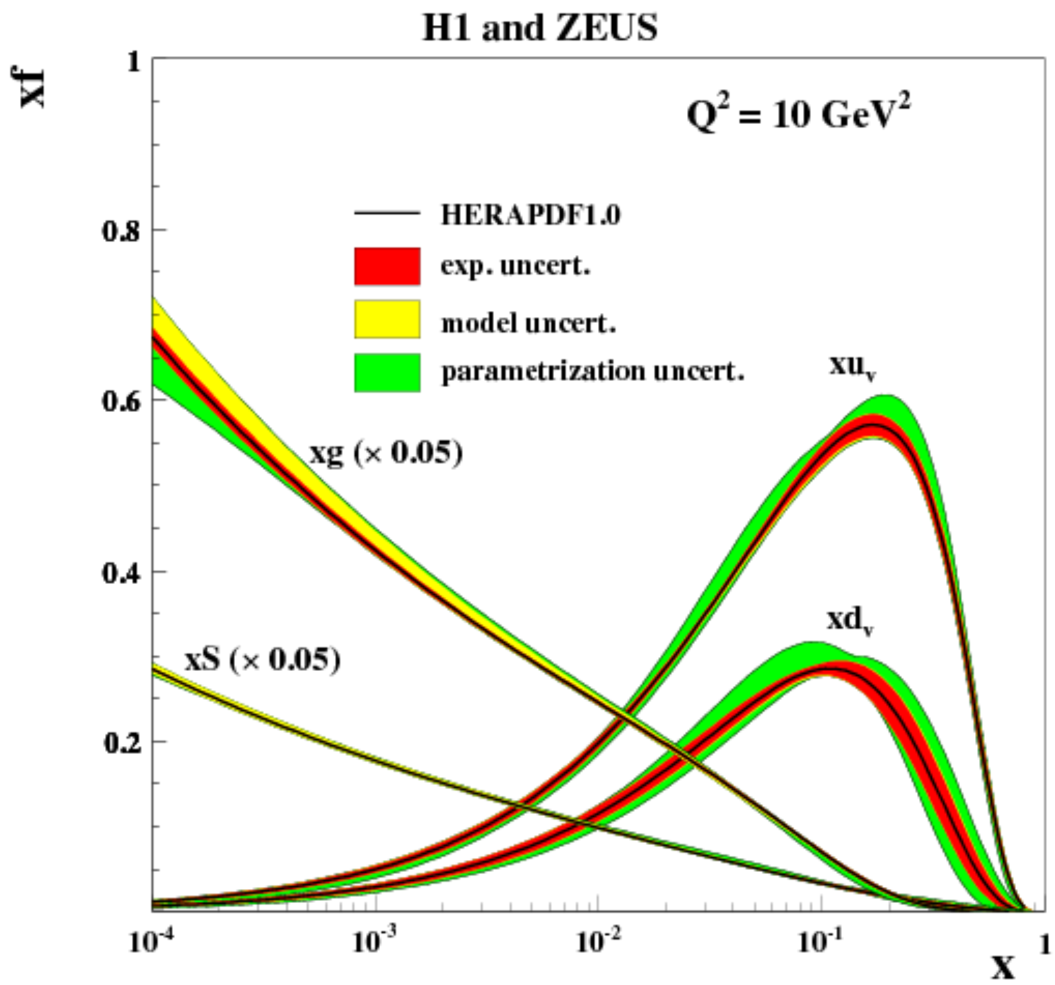
Predictions (arXiv: 1307.7099)



Sensitivity to saturation effects



Sensitivity to saturation effects

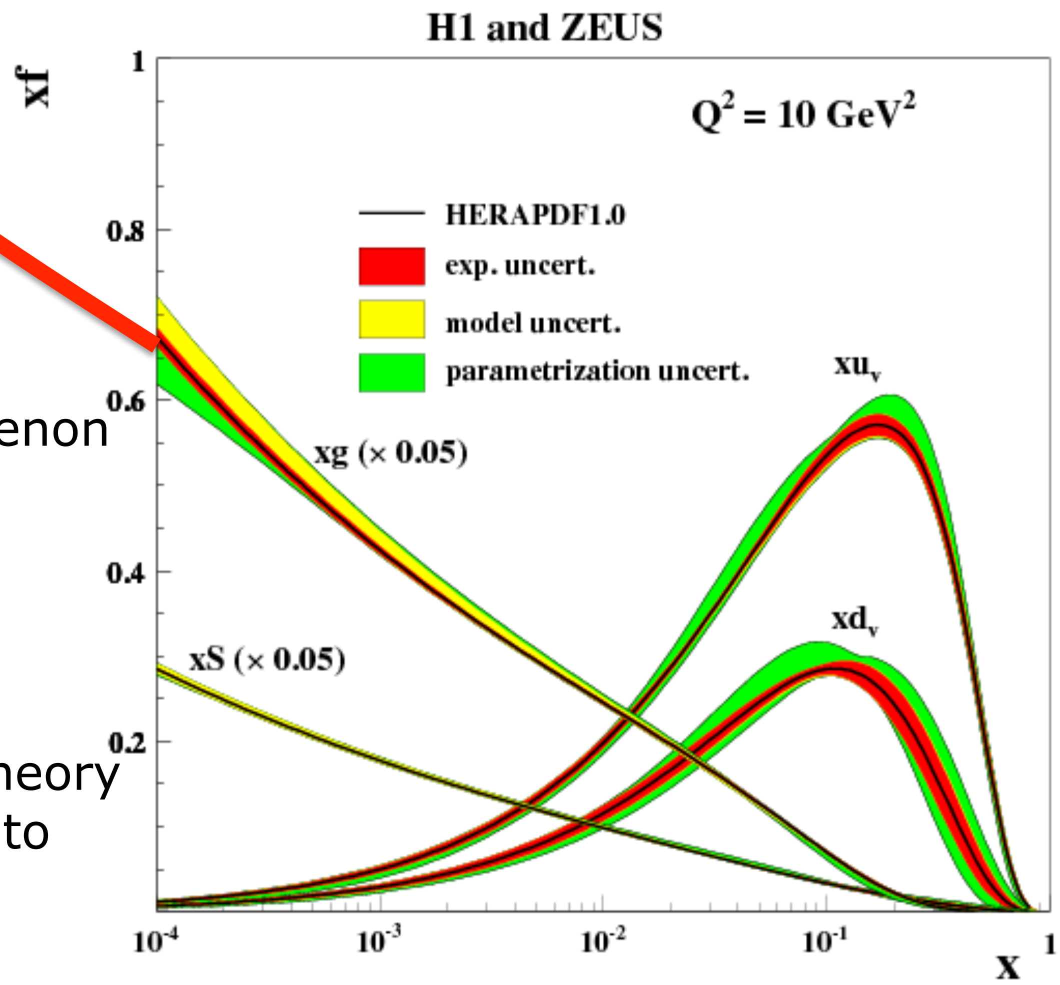


Sensitivity to saturation effects

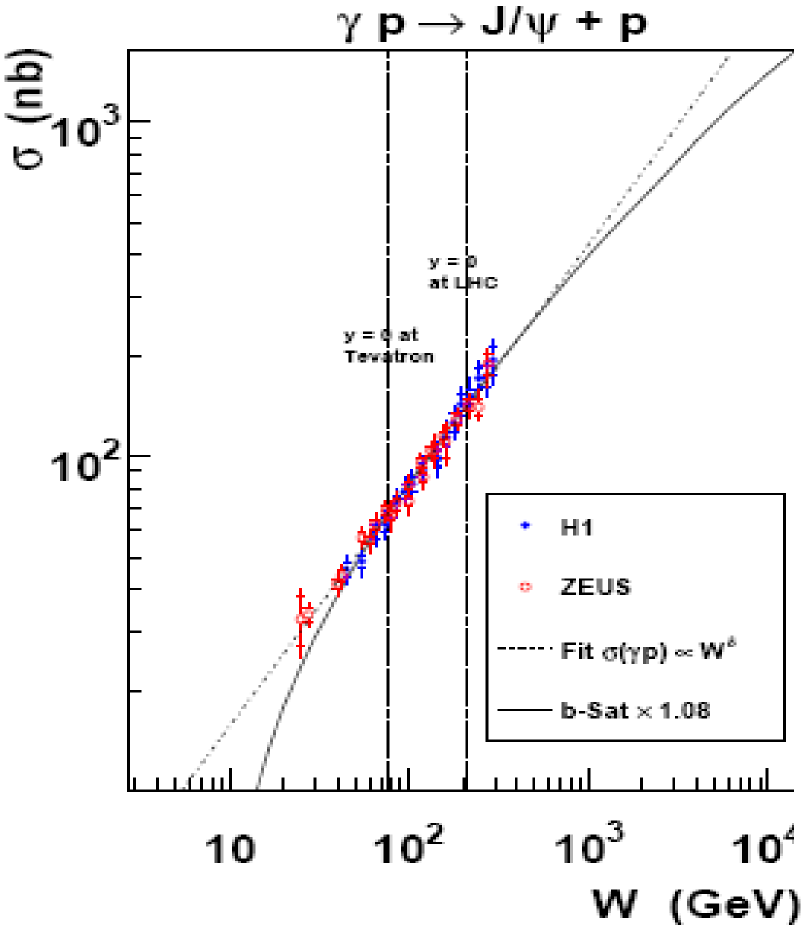
At some point a new phenomenon must come into play.

- perhaps a 'detail' of QCD
- perhaps a new particle

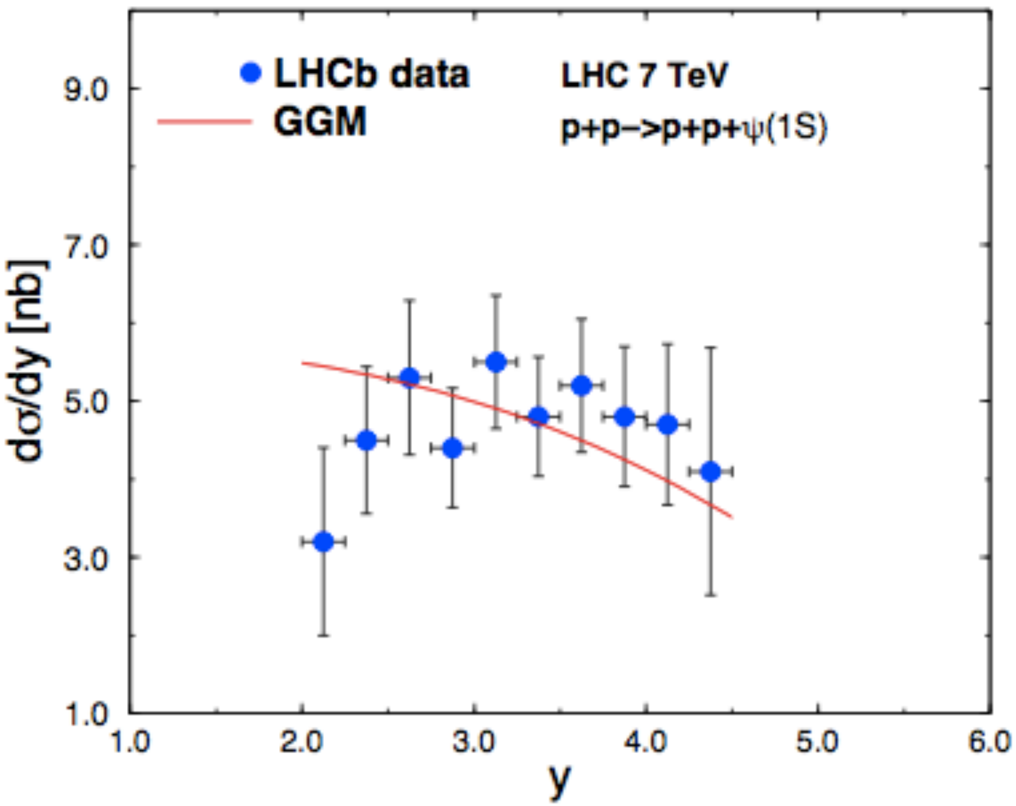
A region in which you know theory breaks down, is a good place to perform experiments.



Sensitivity to saturation effects



Motyka, Watt:
PRD 78, 014023 (2008)

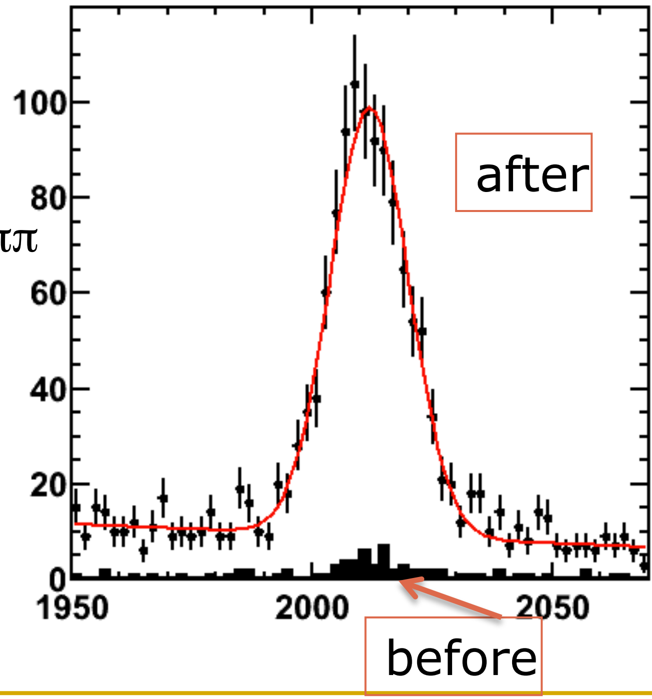


Gay Ducati et al., arXiv: 1305.4611

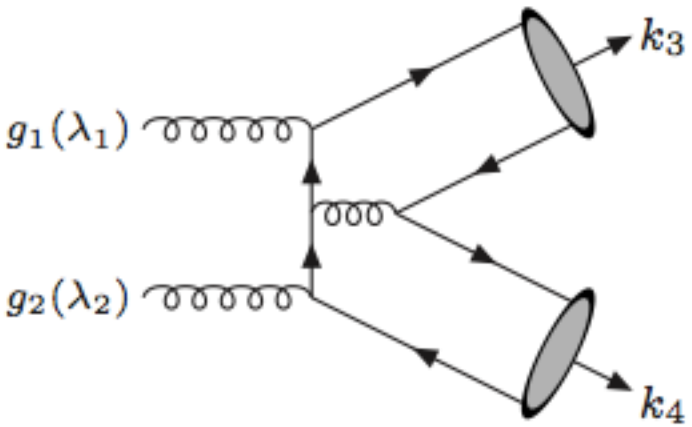
χ_c meson

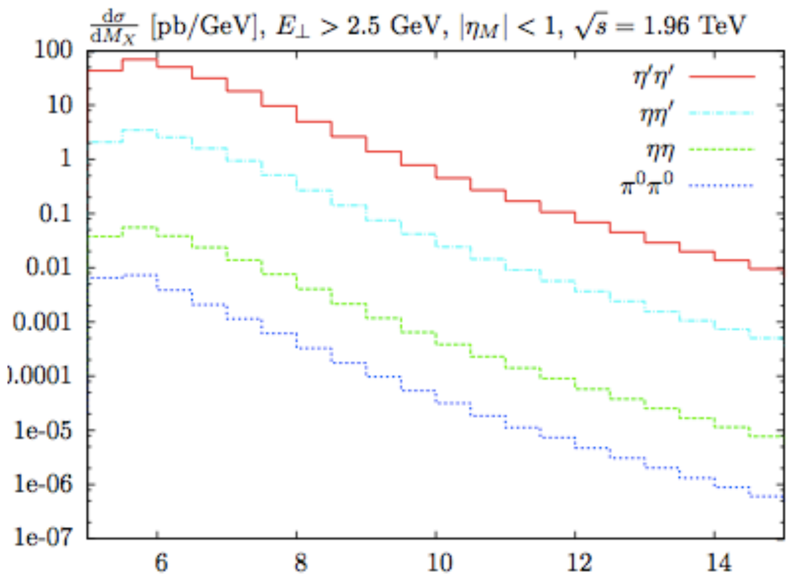
- To see χ_{c0}, choose more favourable decay:
  - χ_{c0}->ππ or KK ~1% while χ_{c2}->ππ or KK ~0.1%
  - Backgrounds? (Harland-Lang et al. arXiv: 1105.1626)
  - LHCb: RICH detectors + real-time analysis

Example of D*->Kππ reconstruction in low multiplicity events

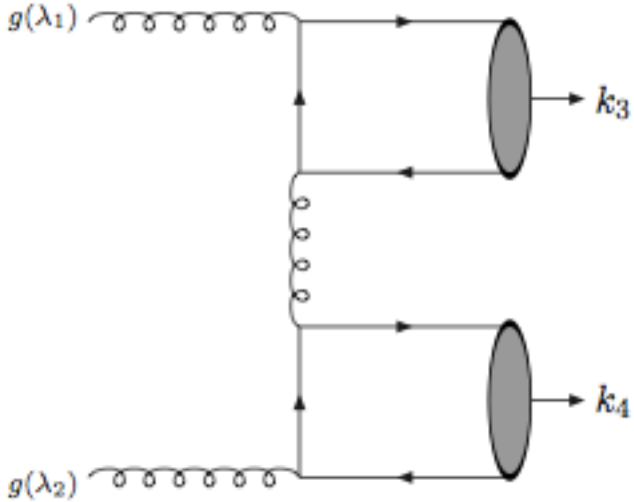


CEP meson-meson production arXiv:1105.1626

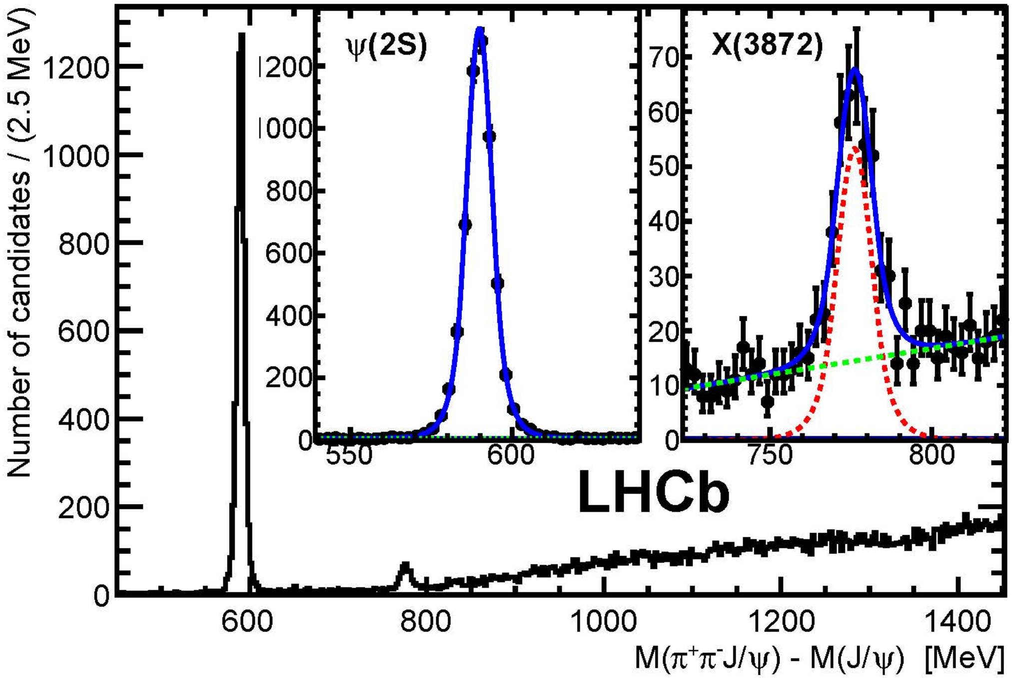




- Vanishing cs when gluons in J_z=0
- Flavour non-singlet mesons suppressed (thus ππ/KK small)
- Flavour singlet (e.g. η'η' production) can proceed via



Relevance for X(3872)



X(3872) observed inclusively. (arXiv:1112.5310) Could it be produced exclusively?

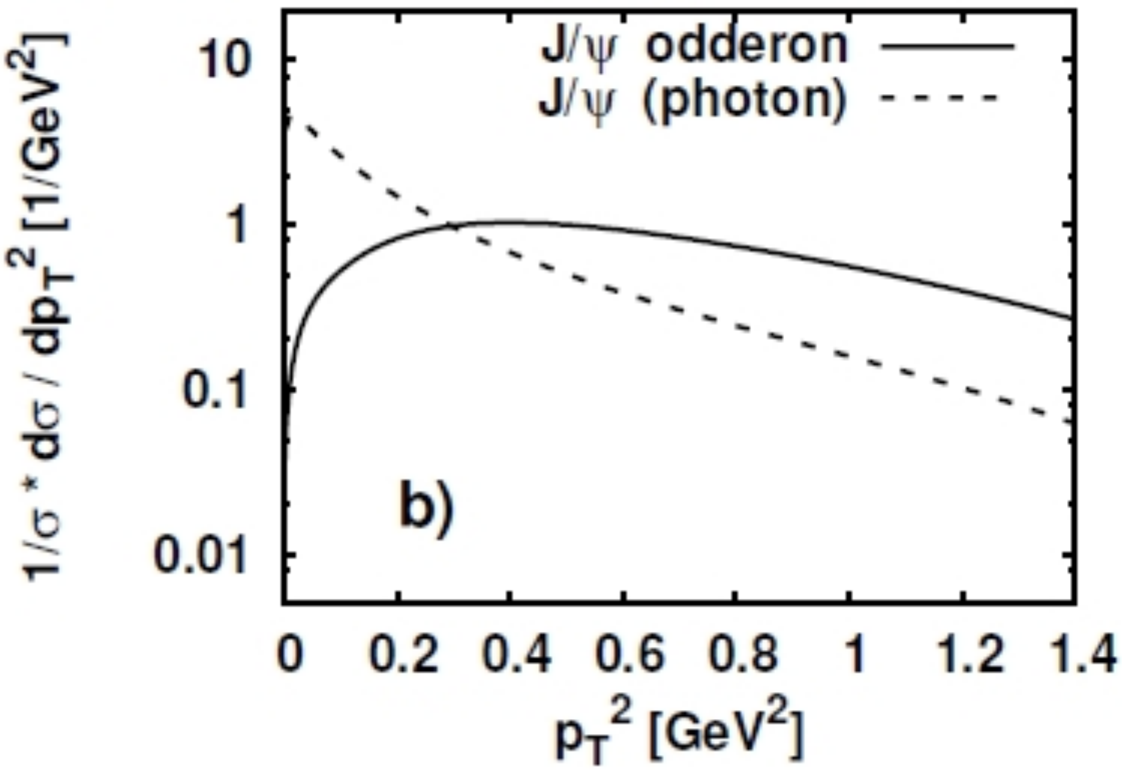
- J^{PC} of X(3872) shown by LHCb to be 1++ (arXiv:1302.6269)
- $\chi_{c(1++)}$ has been observed exclusively.
- If X(3872) is a bound cc state, might expect to observe it in central exclusive production – it decays in similar way as ψ(2S) and χ_c

Exotics

- CEP is rich in colour-neutral gluons
- Excellent laboratory to find two predicted QCD objects: **odderons** and **glueballs**
- Backgrounds from normal (colourful) QCD heavily suppressed.

Search for odderon

- Motyka, DIS 2008.



Glueballs

Machado & daSilva, arXiv: 1111.608

Meson	LHC ($\sqrt{s} = 5.5$ TeV)				ALICE ($\sqrt{s} = 2.76$ TeV)	
	$\Gamma_{\gamma\gamma}$ [eV]	Γ_{gg} [MeV]	$\sigma_{\gamma\gamma}$ [μb]	$\sigma_{I\!PI\!P}$ [mb]	$\sigma_{\gamma\gamma}$ [μb]	$\sigma_{I\!PI\!P}$ [mb]
$f_0(1500)$	0.77	69.8	1.30	1.07	0.78	0.99
$f_0(1710)$	7.03	70.2	8.60	0.68	4.10	0.64
$X(1835)$	0.02	70.3	0.02	0.54	0.01	0.50

- Glueball candidates may be copiously produced at LHC but obscured by coloured combinatoric background.
- Different sensitivities in pp and pA running.
- In DPE only resonances are produced and decay_mode + spin-parity analysis + bkg estimates may allow their observation.

Summary

- First Observation of CEP at LHC
- First separation of χ_c spin states in CEP
- Good agreement with theory predictions
- Consistency with HERA and CDF results for J/ψ and QED produced dimuons.

- Excellent testing ground for QCD and behaviour of gluon at low x.

- Potential to discover glueballs, saturation and other exotic phenomena

J/ψ, $\psi(2s)$, Υ

Data

Zeus collaboration, hep-ex/9704013
Zeus collaboration, hep-ex/0201043
H1 collaboration, hep-ex/0205107
H1 collaboration, arXiv:0510.016
CDF collaboration, arXiv:0902.1271
Zeus collaboration, arXiv:0903.4205
LHCb collaboration, arXiv:1301.7084
H1 collaboration, arXiv:1304.5162

Theory:

Ryskin, Z.Phys. C57 (1993) 89.
Ryskin, Roberts, Martin, Levin, hep-ph/9511228
Martin, Nockles, Ryskin, Teubner, hep-ph/0709.4406
Jones, Martin, Ryskin, Teubner, arXiv: 1307.7099
Khoze Martin Ryskin, hep-ph/0201301
Khoze, Martin, Ryskin, Stirling, hep-ph/0410020v2
Motyka, Watt: PRD 78, 014023 (2008)
Schaefer, Szczurek: PRD 76, 094014 (2007)
Klein, Nystrand, PRL92, 142003 (2004); PRD60 014903 (1999).
Goncalves, Machado, PRD77, 014037 (2008), arXiv:1305.4611.

Further references

- **Odderon:**
  - Leszek, Motyka, DIS2008
  - Bzdak, Motyka, Szymanowski, Cudell, PRD 75, 094023 (2007)
  - Khoze, Martin, Ryskin, hep-ph/0201301v2
  - Stein, Schafer, PLB 300 (1993) 400.
  - Schaefer, Mankiewicz, Nachtman, PLB272 (1991) 419.
  - Ewerz, hep-ph/0306137
- **Chi_c:**
  - Harland-Lang, Khoze, Ryskin, Stirling, arXiv:0909.4748, arXiv:1304.4262
  - Khoze, Martin, Ryskin, Stirling, Eur. Phys. J. C35 (2004) 211.
  - Pasechnik, Szczurek, hep-ph/0901.4187v2
  - Pasechnik, Szczurek, Teryaev, hep-ph/0909.4498v1
- **Di photon production**
  - J. Vermaseren, Nucl. Phys. B229 (1983) 347.
  - Boonekamp et al., hep-ph/1102.2531v1