TESTING THE STANDARD MODEL IN THE FORWARD REGION AT THE LHC

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Irish Quantum Foundations,
Castletown House, 3,4th May 2013

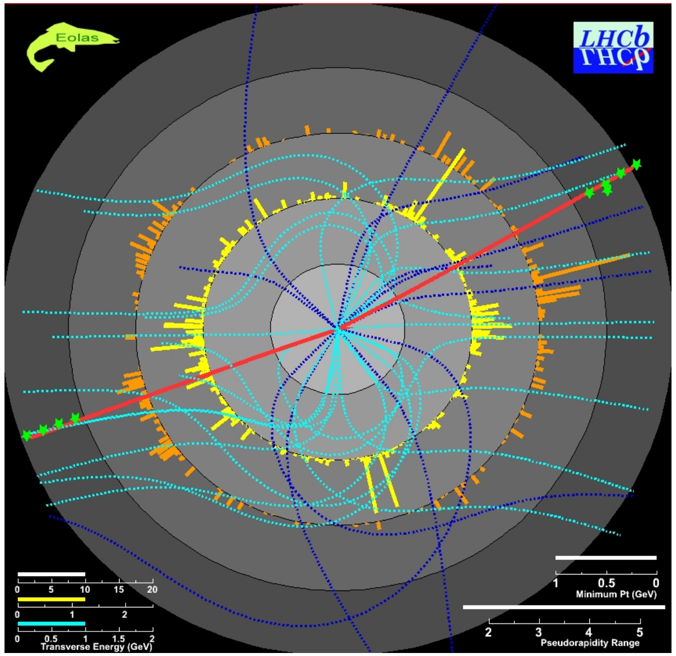
Outline

- **Theory**: The Standard Model
- **Experiment**: LHCb detector

① Electroweak tests using $W \rightarrow \mu\nu$, $Z \rightarrow \mu\mu$; probing the proton structure

② Electroweak tests using $Z \rightarrow \tau\tau$; sensitivity to Higgs

③ Test EM & QCD with exclusive production of dimuons, J/ψ and χ_c.



Analysis	Paper	Luminosity
$W \rightarrow \mu\nu$	JHEP 06 (2012) 058	$37pb^{-1}$
$\rightarrow \mu\mu$	CERN-LHCb-CONF-2013-007	$1fb^{-1}$
$\rightarrow \tau\tau$	JHEP 1301 (2013) 111.	$1fb^{-1}$
iggs	arXiv:1304.2591	$1fb^{-1}$
xclusive J/ψ	JPG 40 (2013) 045001	$37pb^{-1}$
Exclusive χ_c	CERN-LHCb-CONF-2011-022	$37pb^{-1}$

This is what we want to test....

$$
\begin{aligned}
\mathcal{L} \quad &= \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
&+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5)\Psi_f Z_\mu + \\
&- \frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \\
&-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 + \\
&- \frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \\
&- \frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 + \\
&+ \frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta \\
&- g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a
\end{aligned}
$$

fermion mass

$$
\begin{aligned}
\mathcal{L} \quad &= \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
&+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5) \Psi_f Z_\mu + \\
&- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \\
&\quad -ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 + \\
&\quad -\frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \\
&- \frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 + \\
&\quad + \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta \\
&\quad - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a
\end{aligned}
$$

Higgs mass

W mass

Z mass

fermion propagator

fermion mass

$$\mathcal{L} = \sum_f \boxed{(\bar{\Psi}_f(i\gamma^\mu\partial_\mu} - m_f)\Psi_f - eQ_f\bar{\Psi}_f\gamma^\mu\Psi_f A_\mu) +$$

$$+\frac{g}{\sqrt{2}}\sum_i(\bar{a}^i_L\gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L\gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w}\sum_f \bar{\Psi}_f\gamma^\mu(I^3_f - 2s^2_w Q_f - I^3_f\gamma_5)\Psi_f Z_\mu +$$

$$\boxed{-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu} - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \boxed{\frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu} +$$

W propagator

photon prop.

$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w(W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

Z propagator

$$\boxed{-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu} + ig' c_w(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

Higgs mass

$$-\frac{1}{2}M^2_\eta\eta^2 - \frac{gM^2_\eta}{8M_W}\eta^3 - \frac{g'^2 M^2_\eta}{32M_W}\eta^4 + |M_W W^+_\mu + \frac{g}{2}\eta W^+_\mu|^2 +$$

W mass

Higgs prop.

$$\boxed{+\frac{1}{2}|\partial_\mu\eta} + iM_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2}\frac{m_f}{M_W}\bar{\Psi}_f\Psi_f\eta$$

Z mass

$$-gG^a_\mu\psi_i\gamma^\mu T^a_{ij}\psi_j - \boxed{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}$$

gluon propagator

fermion propagator

fermion mass

QED vertex

$$\mathcal{L} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

W,Z vertex

$$+\frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5) \Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

W propagator

photon prop.

$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

W,Z,photon interactions

Z propagator

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

Higgs mass

$$-\frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 +$$

W mass

Higgs prop.

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

Higgs interactions with fermions and bosons

Z mass

$$- g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

QCD vertex

gluon propagator

fermion propagator

fermion mass

QED vertex

$$\mathcal{L}_G = \sum_f \left(\bar{\Psi}_f (i\gamma^\mu \partial_\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu\right) +$$

W,Z vertex

$$+\frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5) \Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

W propagator

photon prop.

$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

W,Z,photon interactions

Z propagator

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

Higgs mass

$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 +$$

W mass

Higgs prop.

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

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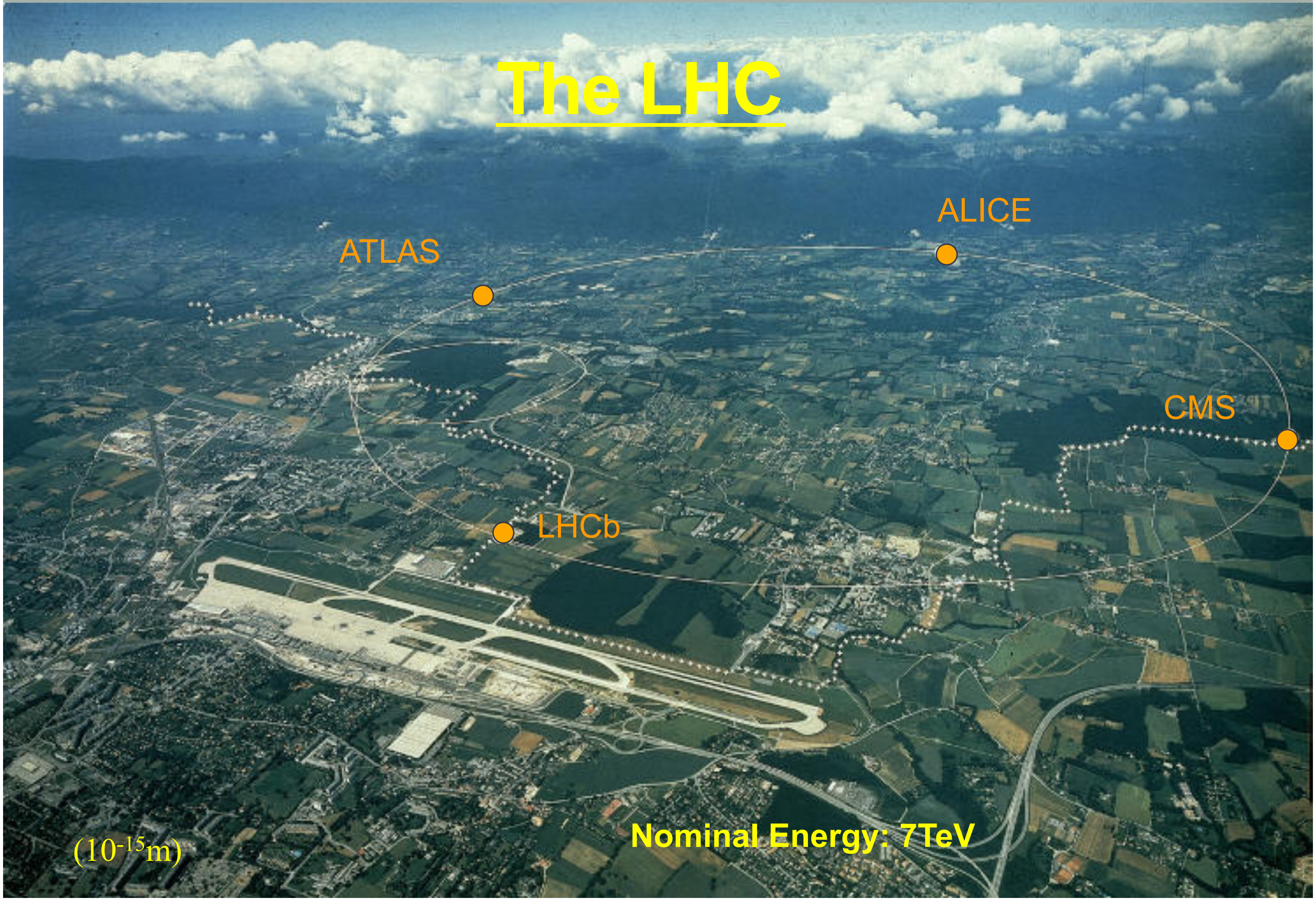
$$-g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

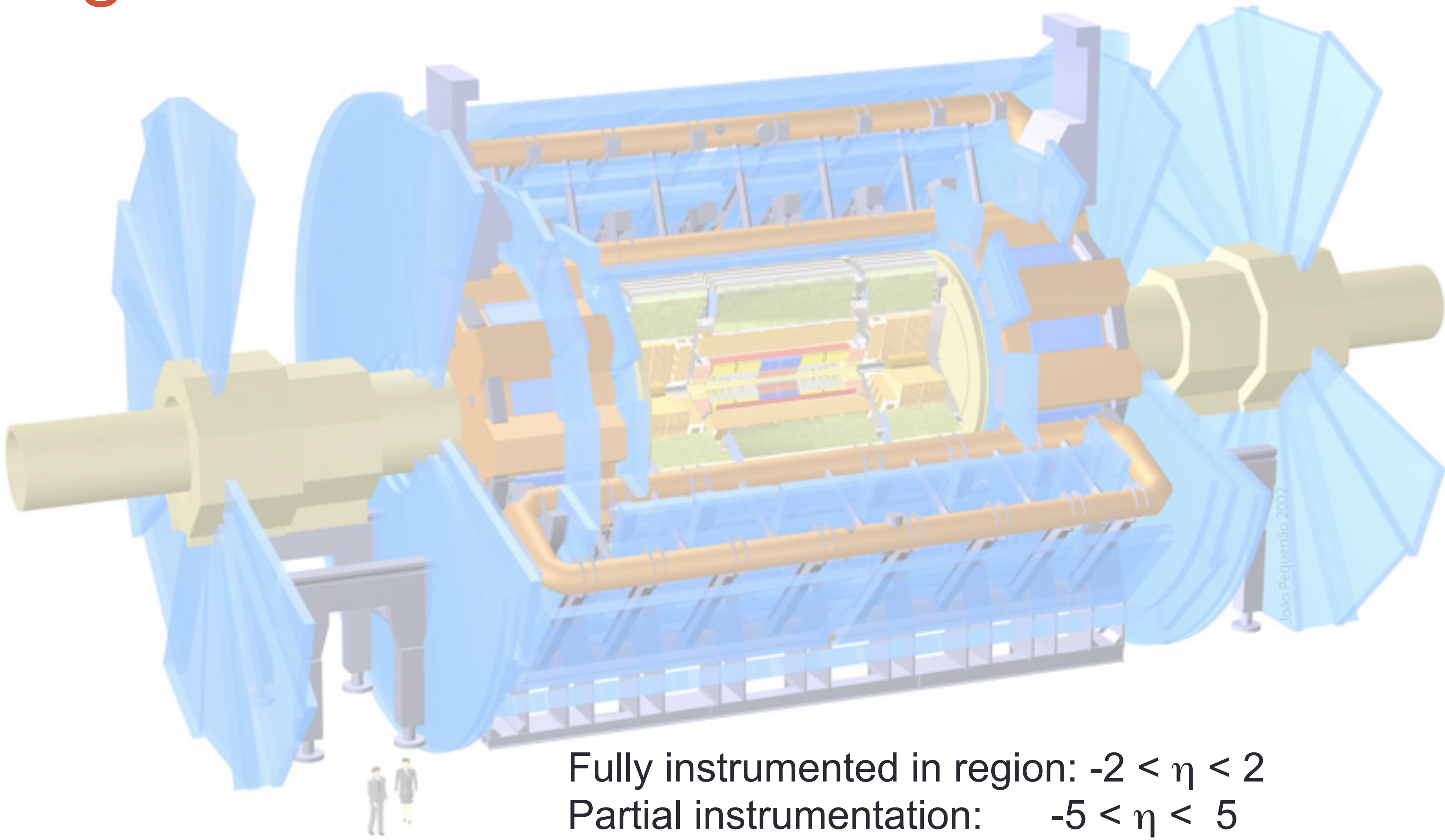
QCD vertex

gluon propagator

The LHC



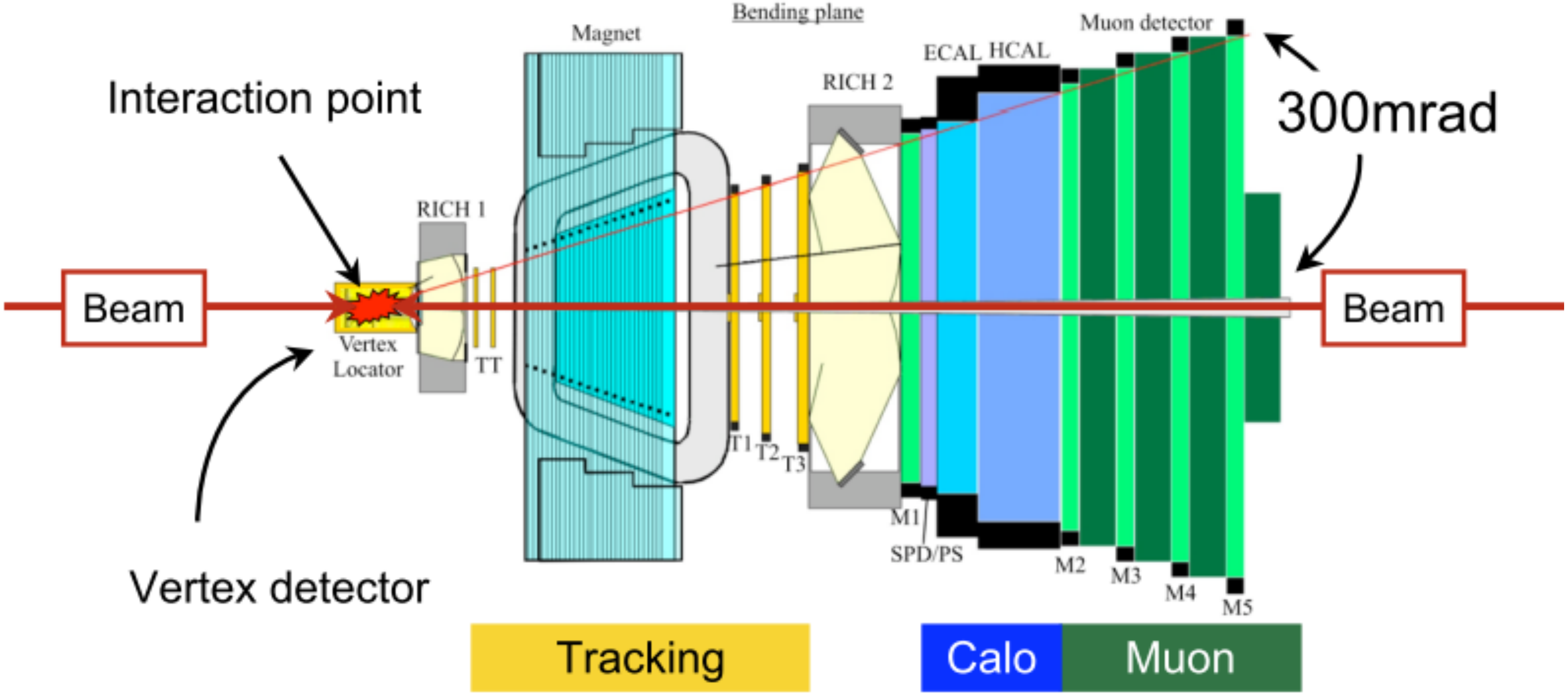
ATLAS and CMS surround the interaction region



Fully instrumented in region: $-2 < \eta < 2$

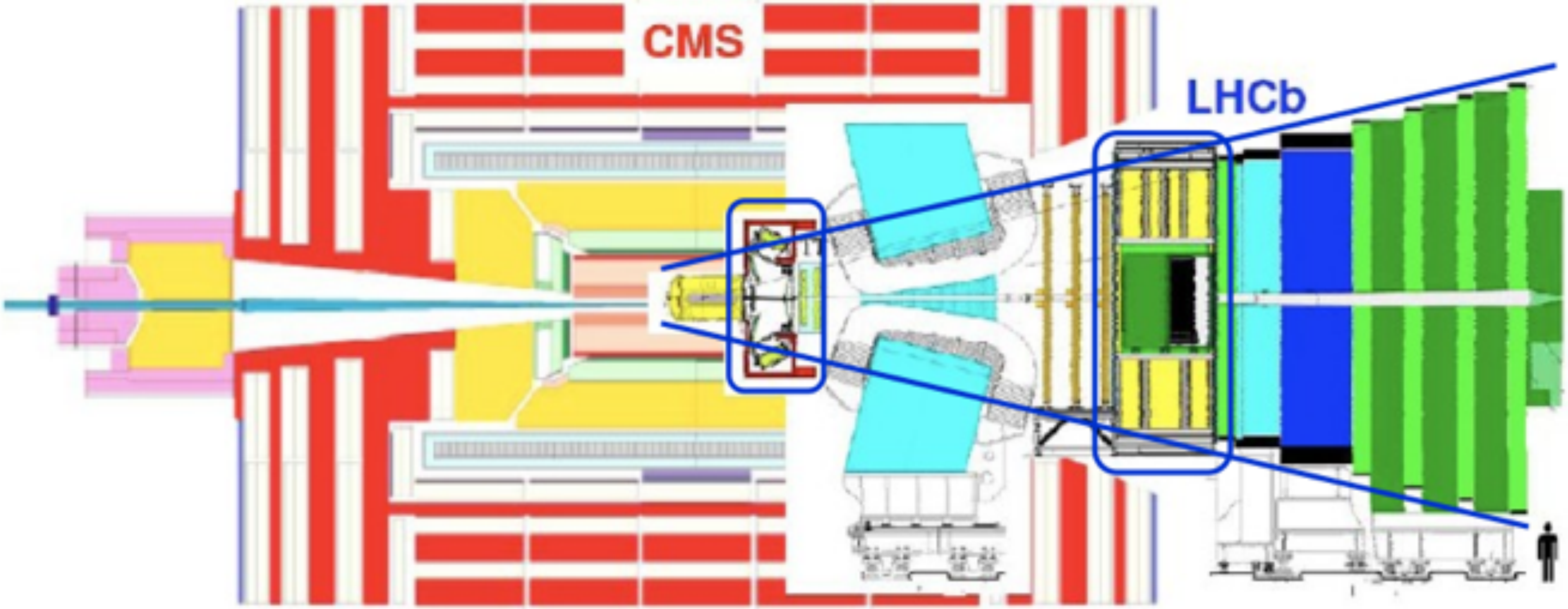
Partial instrumentation: $-5 < \eta < 5$

The LHCb detector

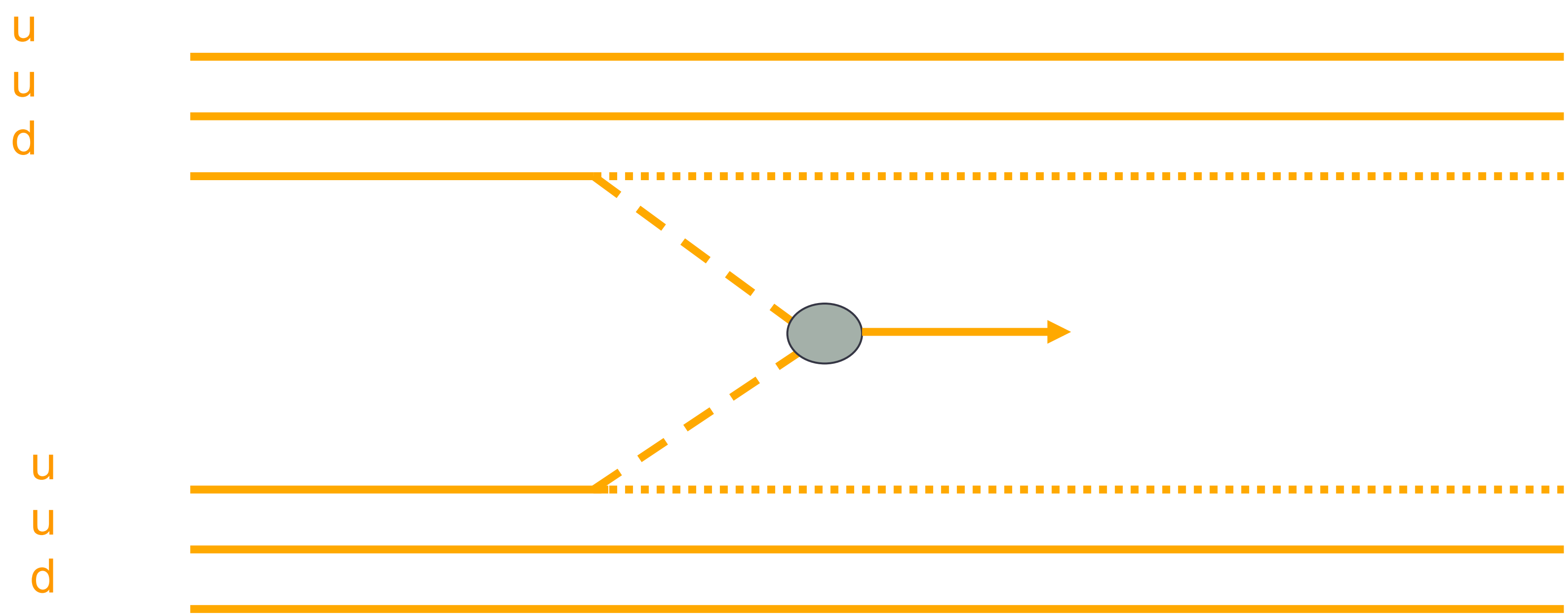


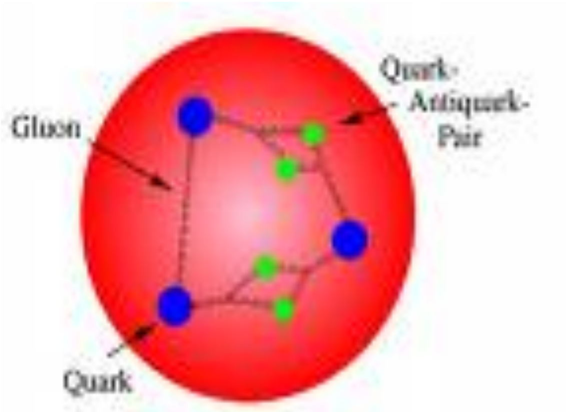
Fully instrumented within $1.9 \leq \eta \leq 4.9$

Complementarity of LHC detectors



1. Electroweak tests using $W \rightarrow \mu\nu$, $Z \rightarrow \mu\mu$; probing the proton structure



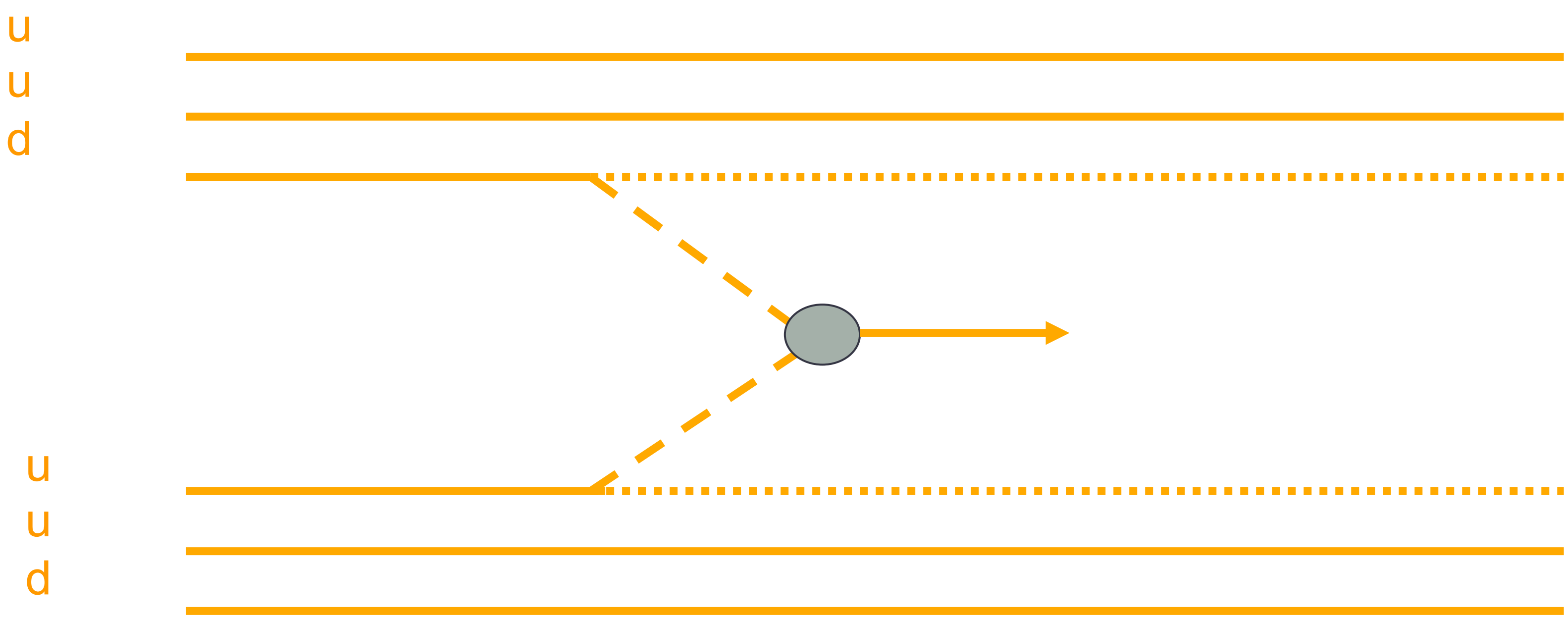


Parton Density Function (PDF): $f_q(x,Q^2)$

Probability that the proton contains this parton with this momentum fraction

Q = Invariant mass of parton interaction

x = $Qe^{\pm y}/\sqrt{s}$ [y is rapidity, √s c.o.m]



Theory v Experiment at the LHC

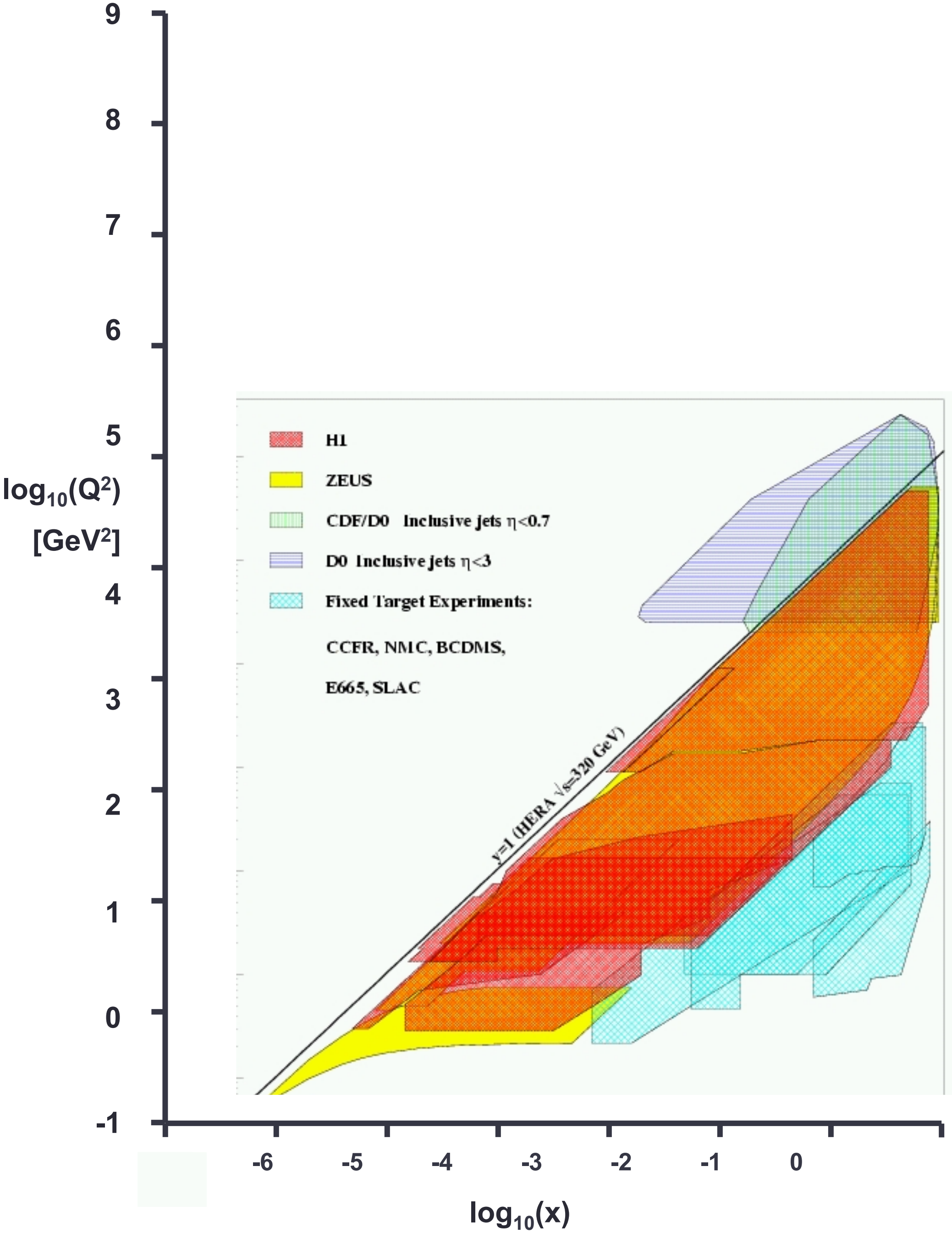
$$\sigma_X(Q^2) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, Q^2) f_2(x_2, Q^2) \hat{\sigma}_{ab\to X}(x_1, x_2, Q^2)$$

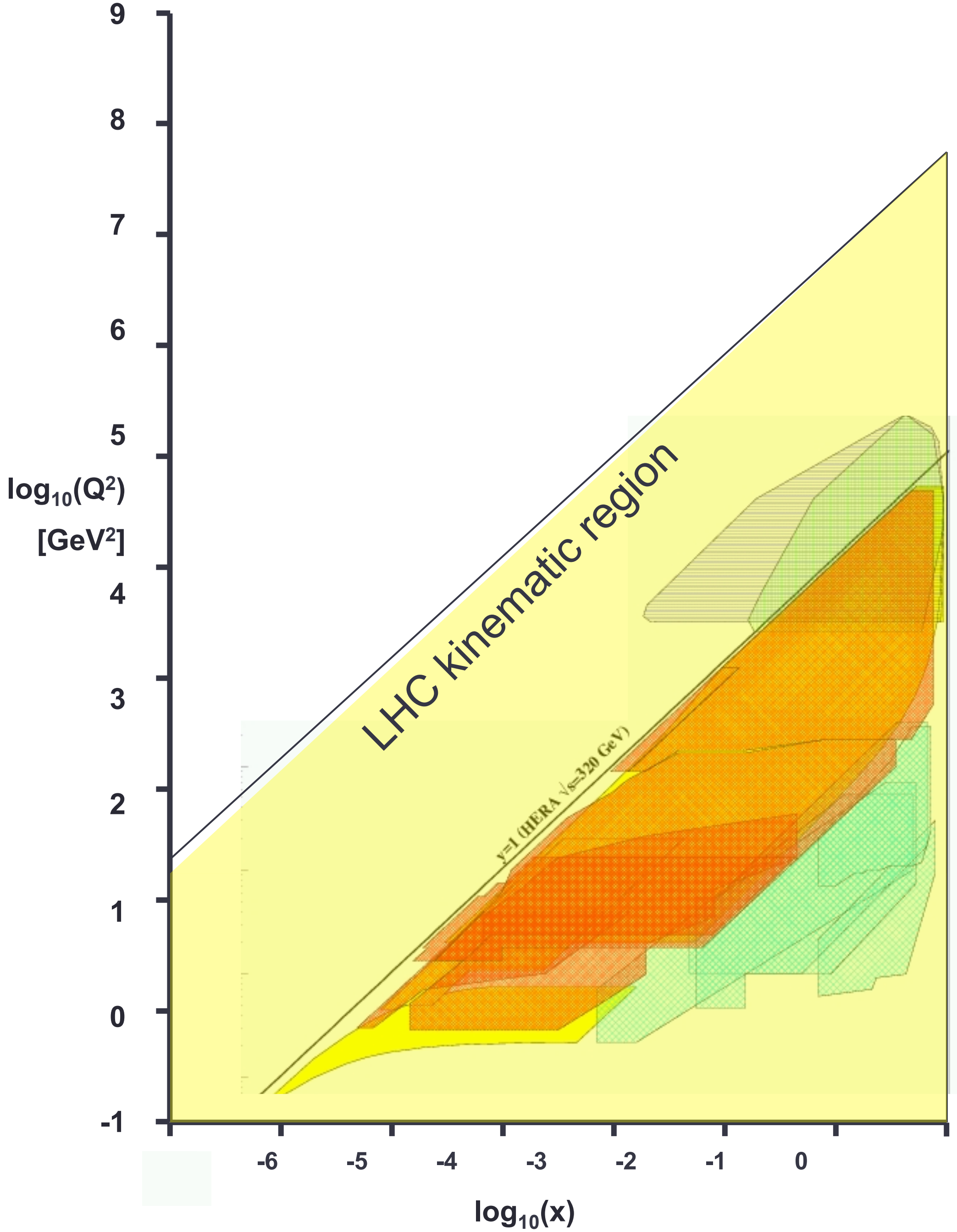
Hadronic Cross-section

PDFs

Partonic Cross-section

- Test the Standard Model at the highest energies. W/Z theory known to 1%
- Constrain parton distribution functions.
- Test QCD – of particular interest in regions with very soft gluons


H1
ZEUS
CDF/D0 Inclusive jets η<0.7
D0 Inclusive jets η<3
Fixed Target Experiments:
CCFR, NMC, BCDMS,
E665, SLAC
y=1 (HERA √s=320 GeV)
log10(Q2) [GeV2]
log10(x)
9
8
7
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0


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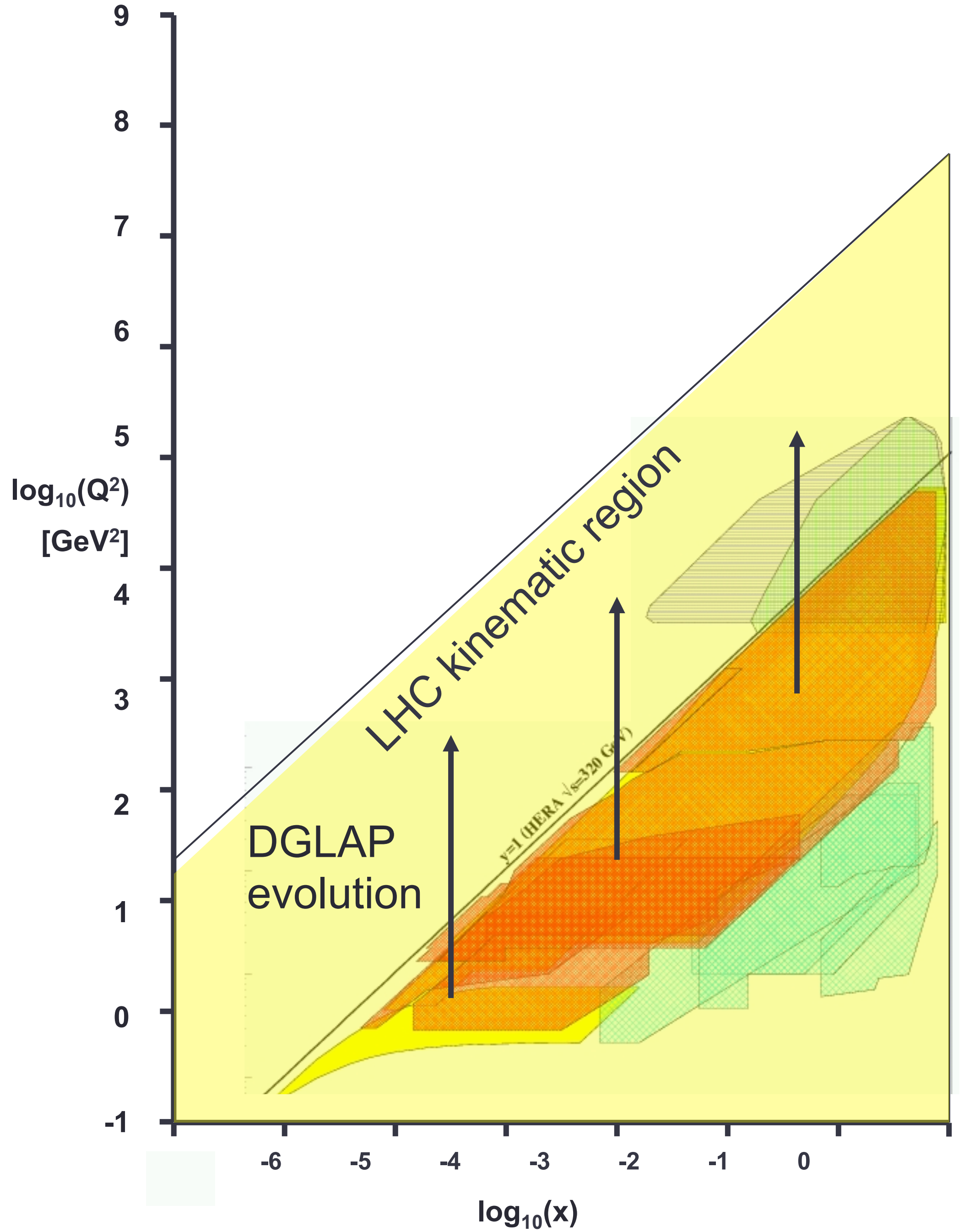
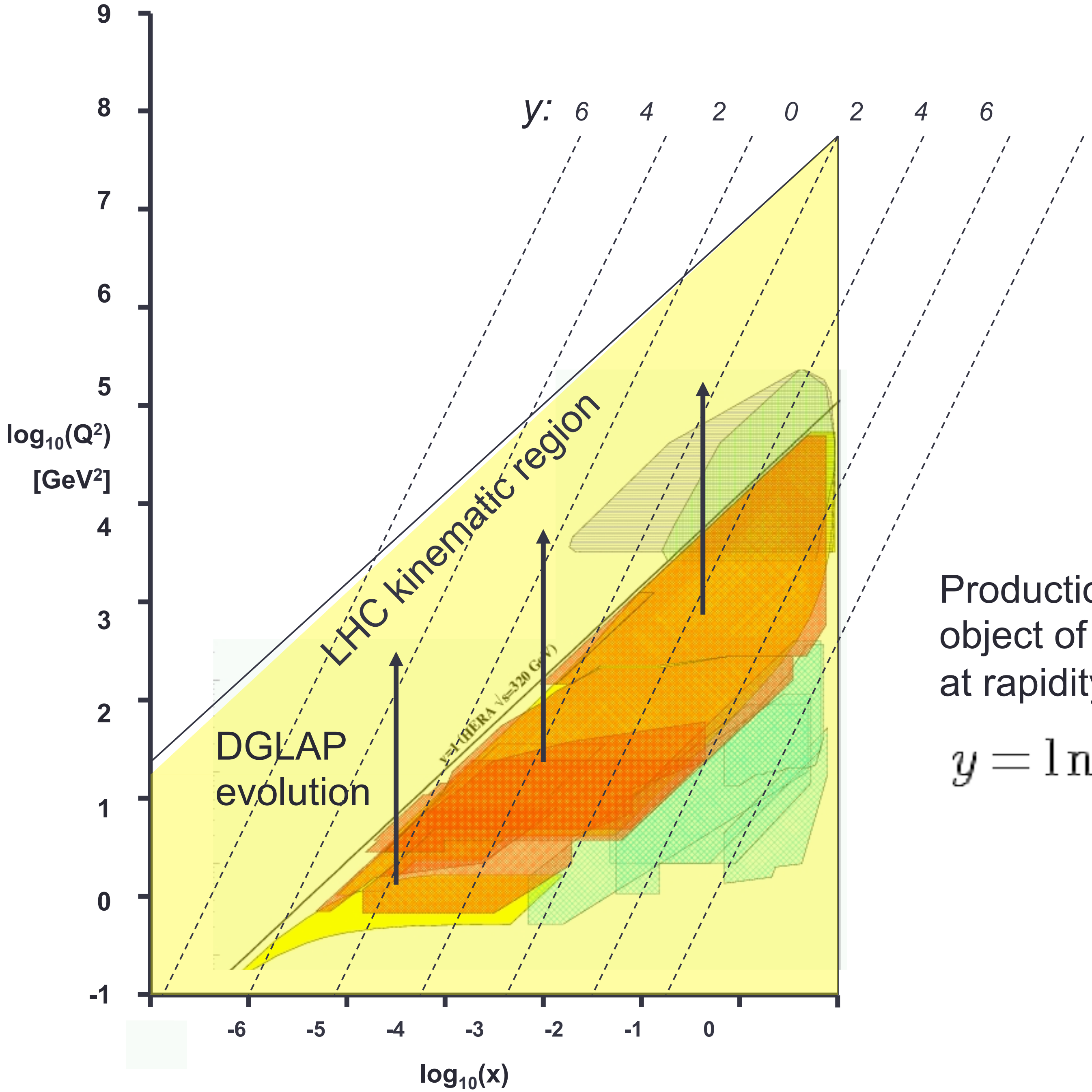
log10(x)
LHC kinematic region
y=1 (HERA √s=320 GeV)

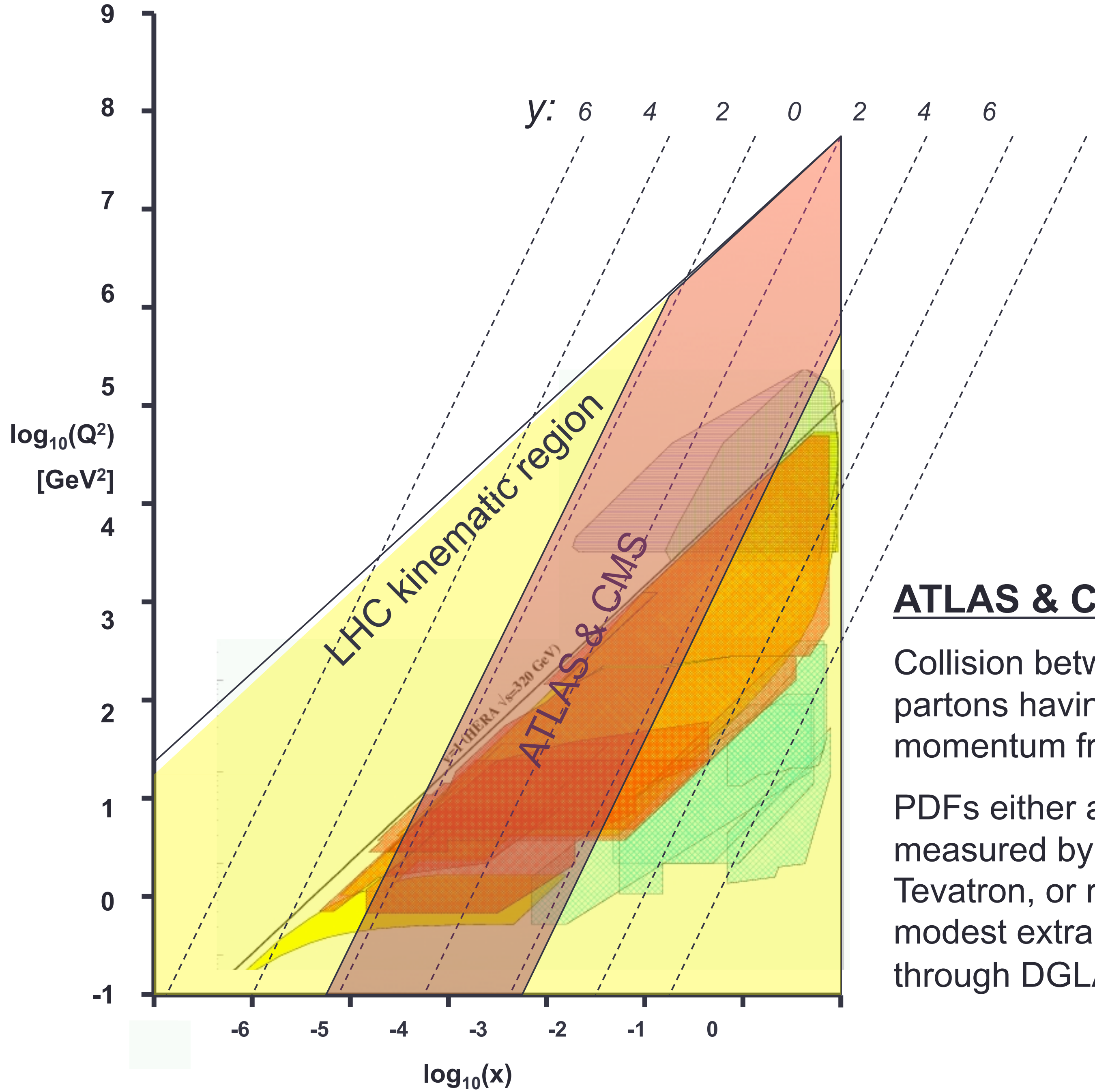


LHC kinematic region
DGLAP
evolution
y=1 (HERA √s=320 GeV)
log10(Q2)
[GeV2]
log10(x)
9
8
7
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0



Production of object of mass Q at rapidity

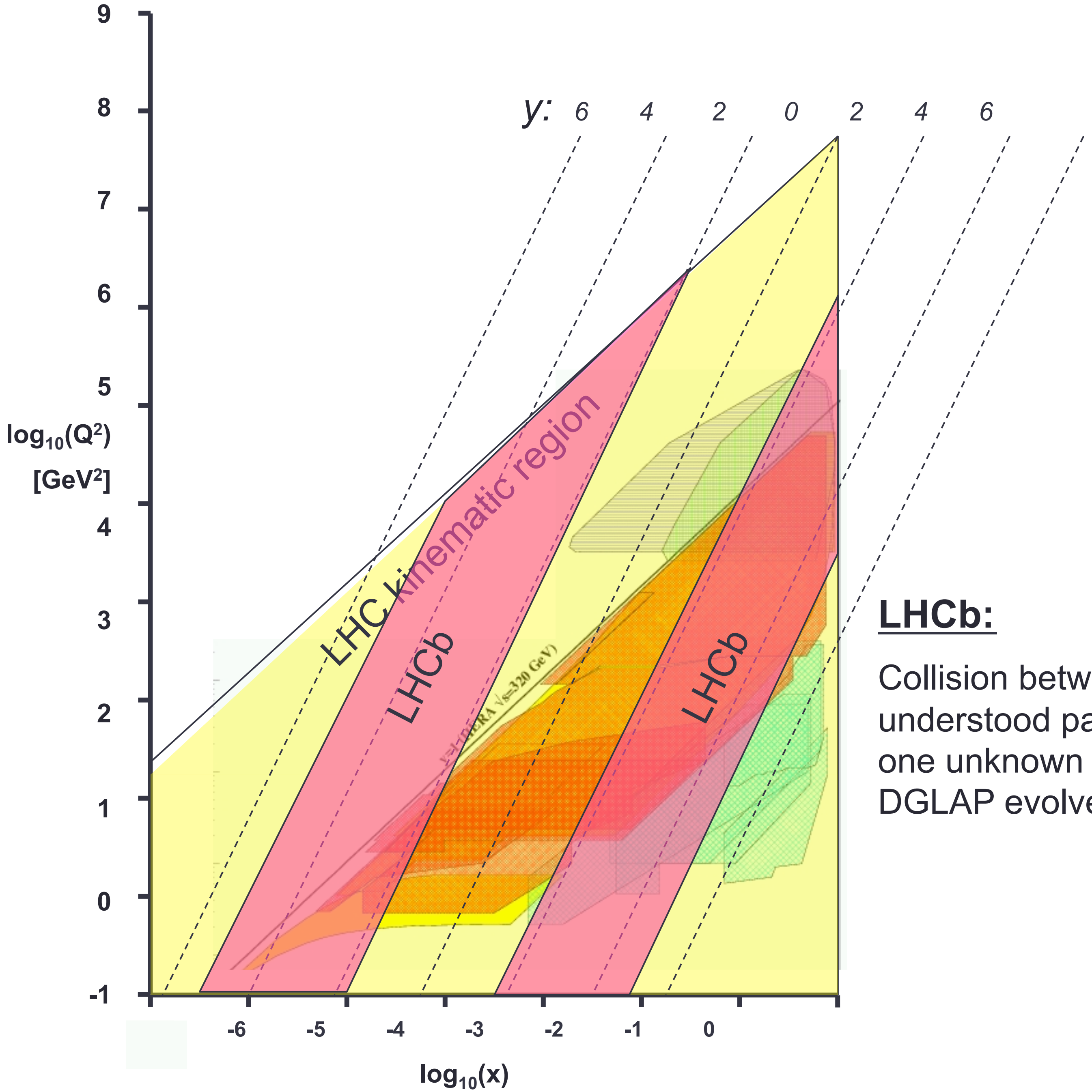
$$y = \ln\left(x\frac{\sqrt{S}}{Q}\right)$$



ATLAS & CMS:

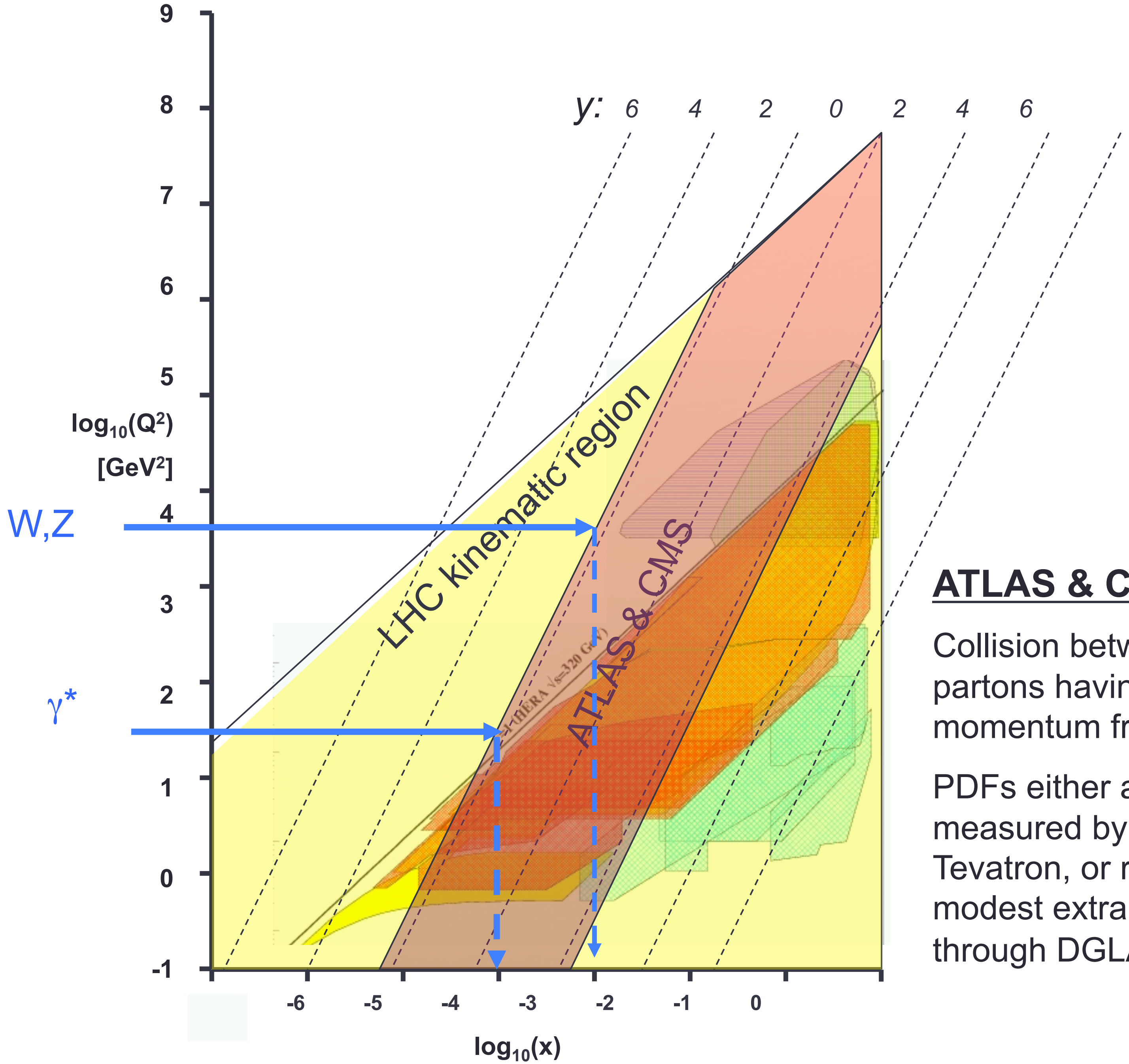
Collision between two partons having similar momentum fractions.

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.



ATLAS & CMS:

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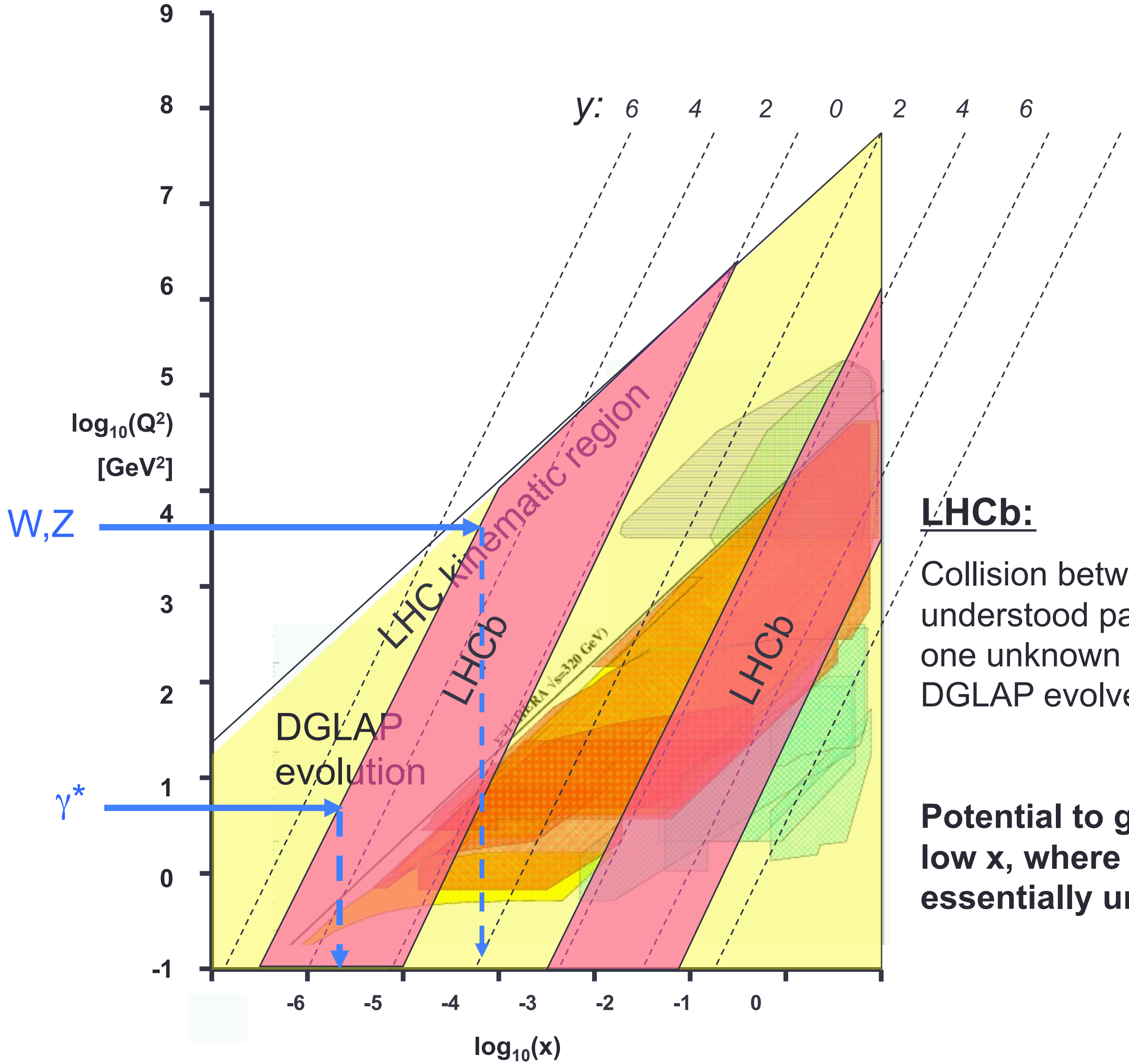
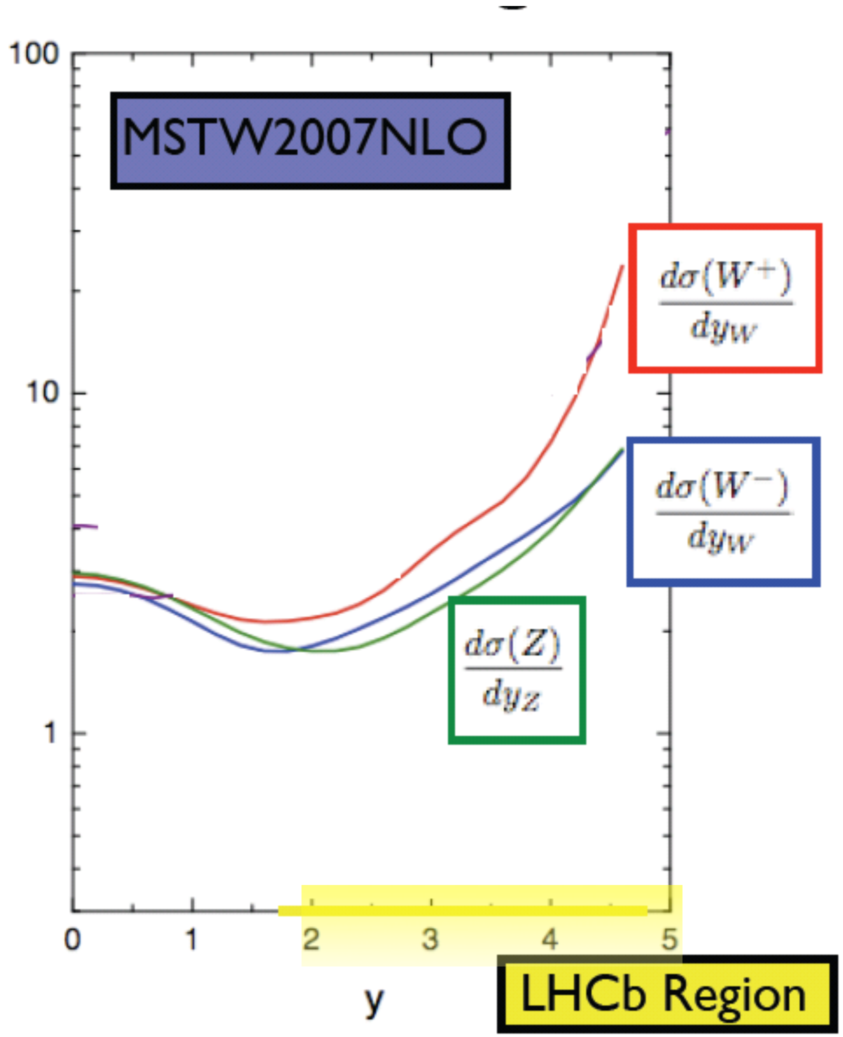


LHCb:

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

Potential to go to very low x, where PDFs essentially unknown

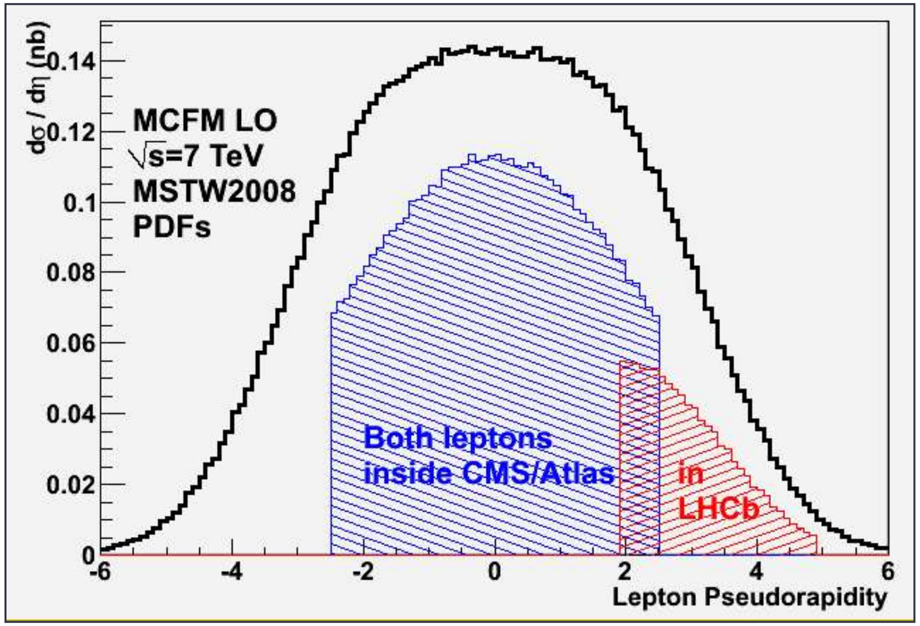
Pre-LHC precision on W,Z cross-sections

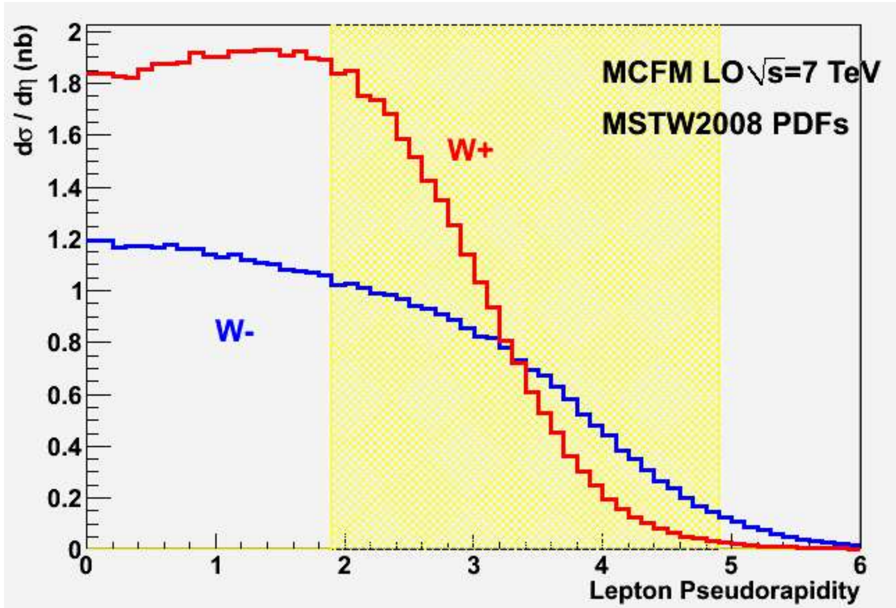


e.g. very roughly

$$\frac{W^+}{W^-} = \frac{u\bar{d}}{d\bar{u}} \approx \frac{u}{d}$$

W and Z production in the forward region

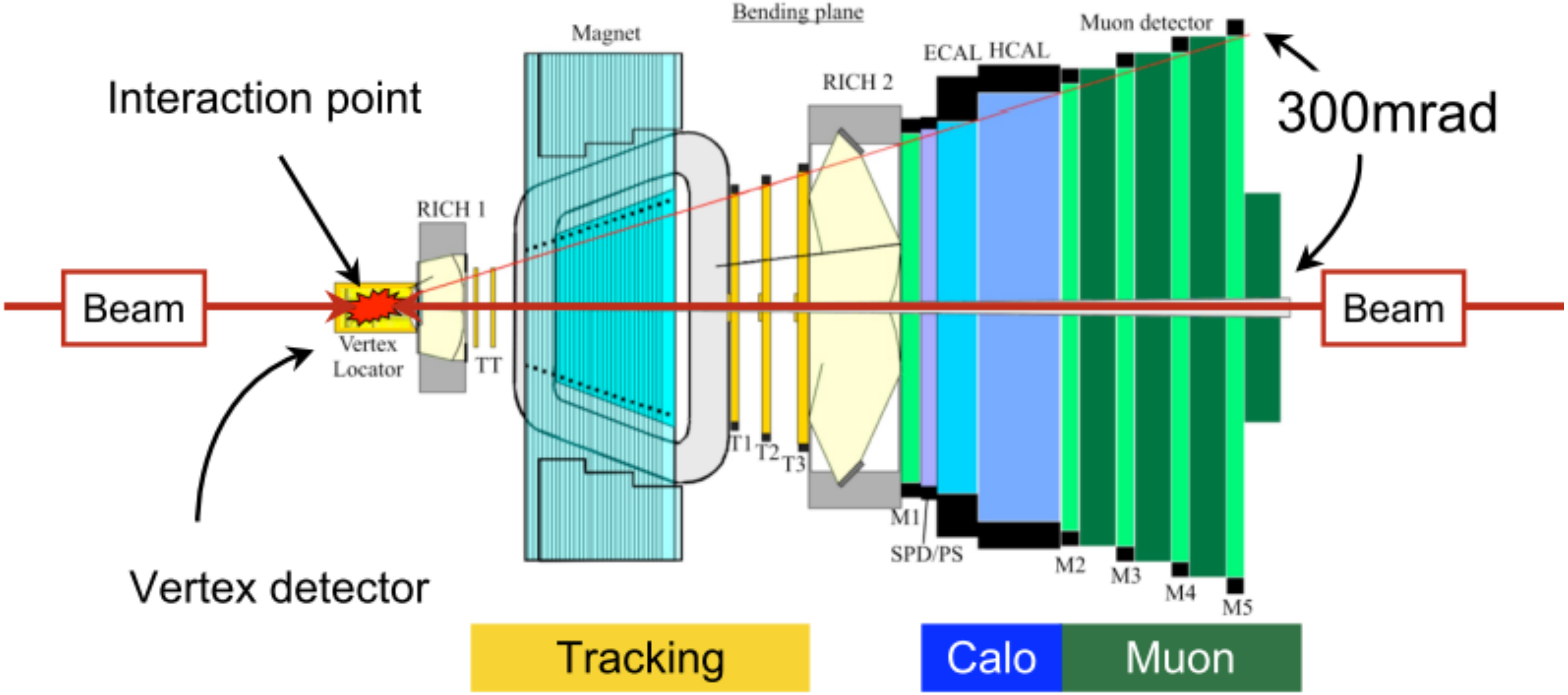




Experimentally: σ=N/L
Count number of events: Z→μμ, W→μν

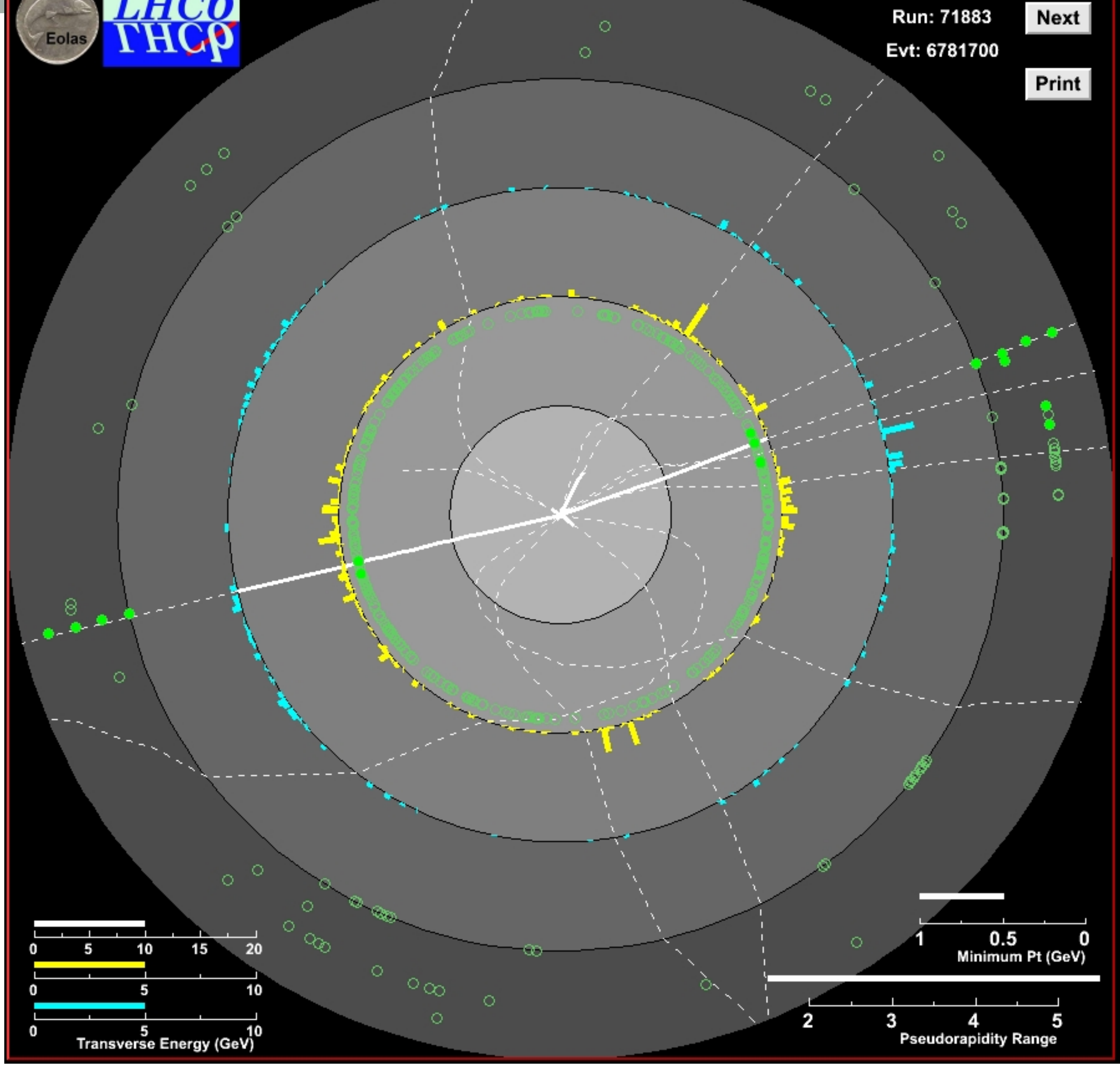
Master formula: $\boxed{\sigma = \frac{pN}{\varepsilon L}}$

The LHCb detector



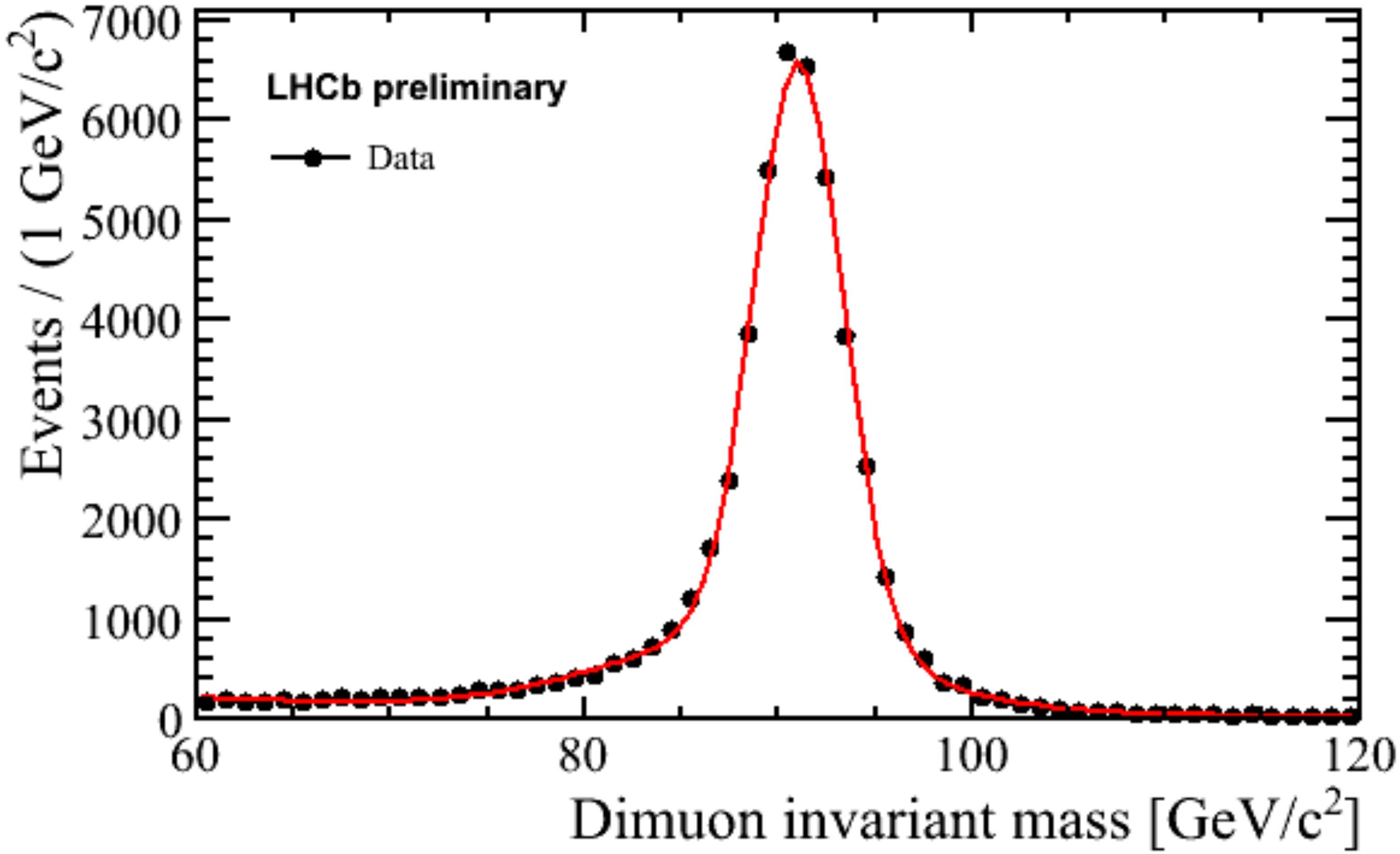
Fully instrumented within $1.9 \le \eta \le 4.9$

First Z candidate

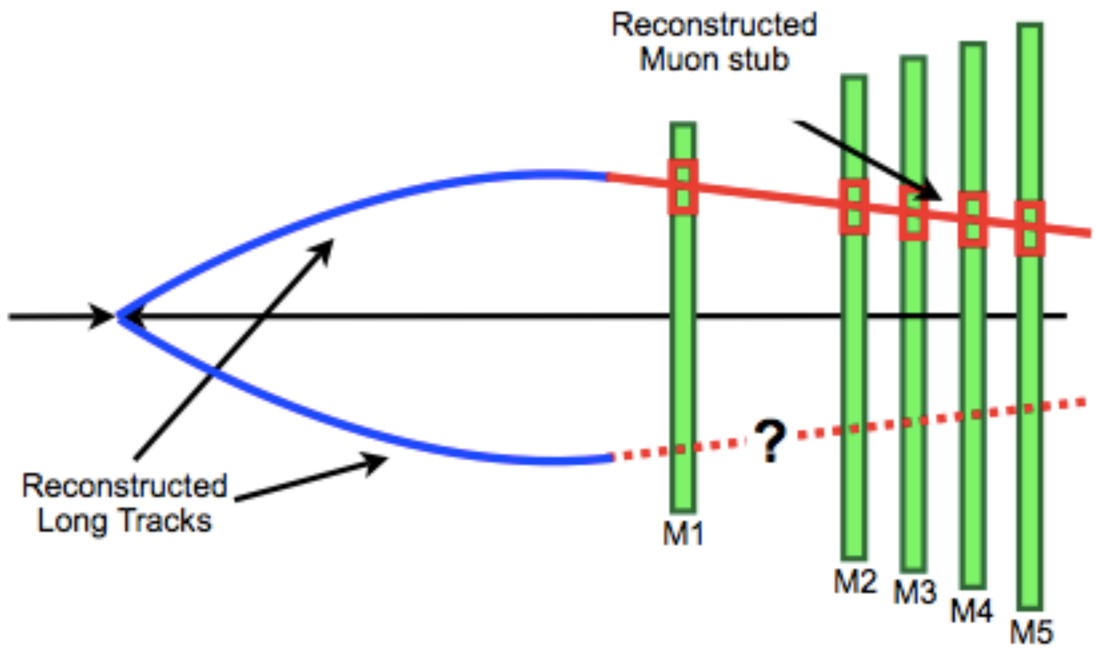


Z cross-section measurement

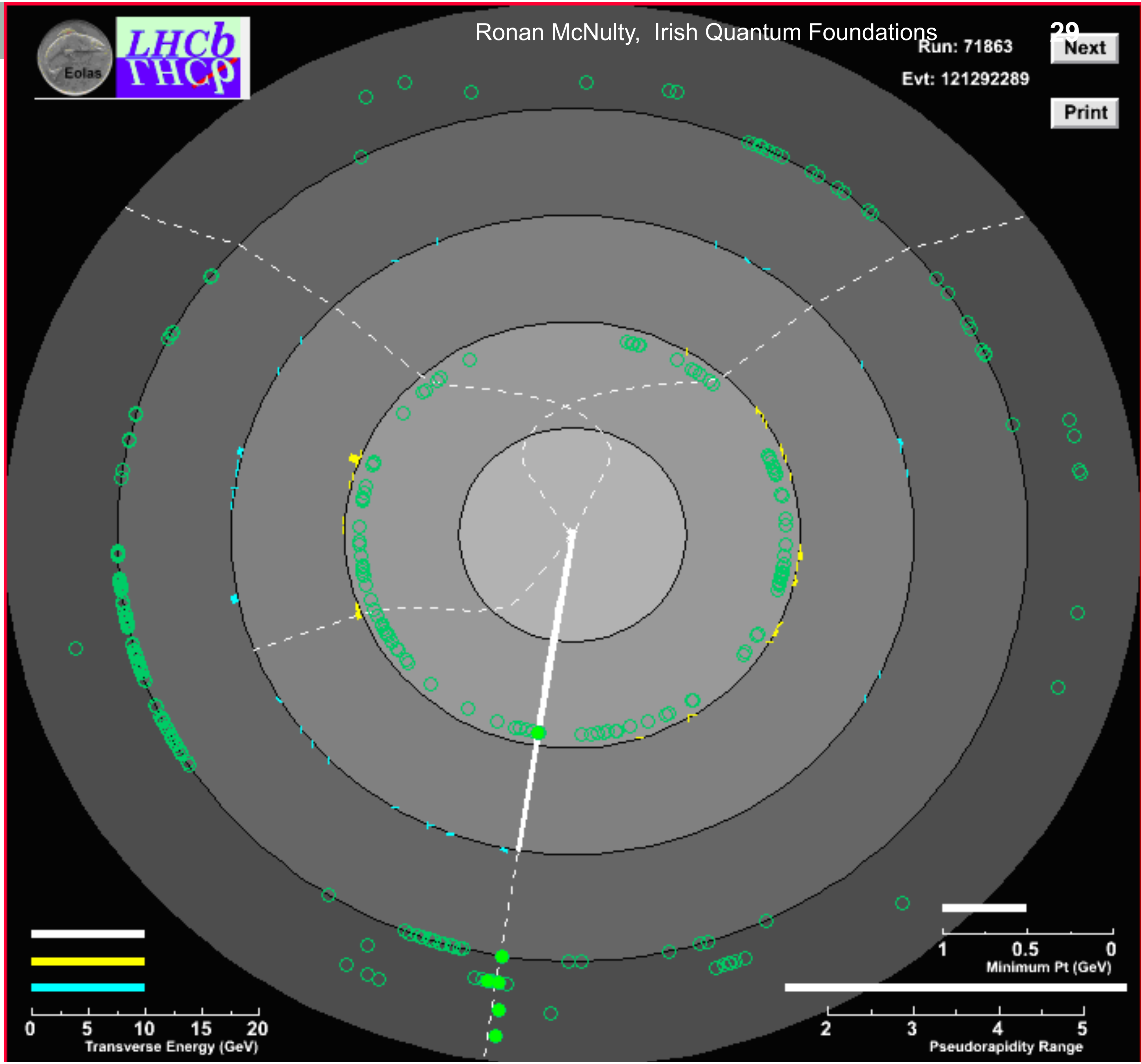
$$\sigma = \frac{pN}{\varepsilon L}$$



Efficiencies for W and Z analysis found from tag-and-probe

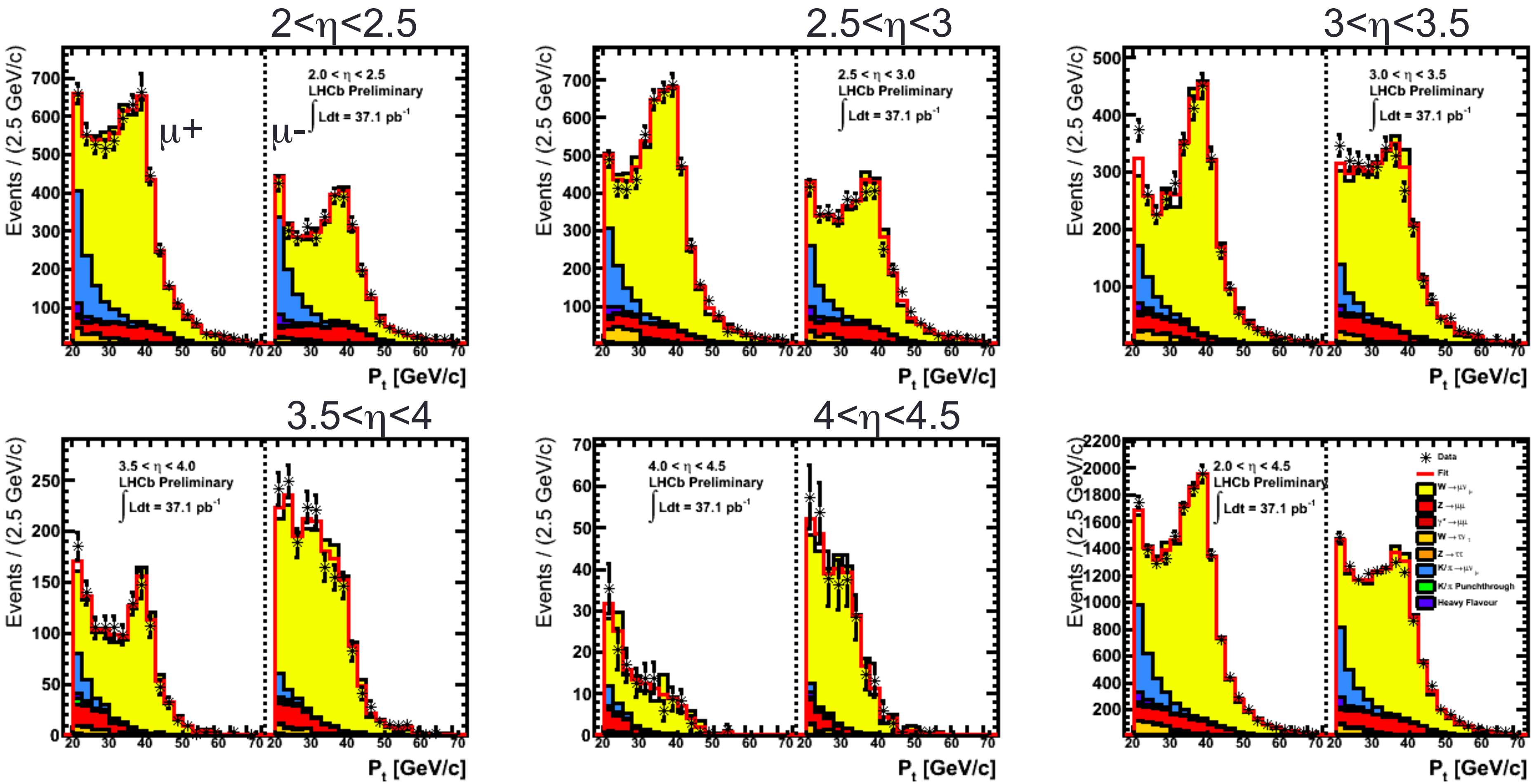


First W candidate

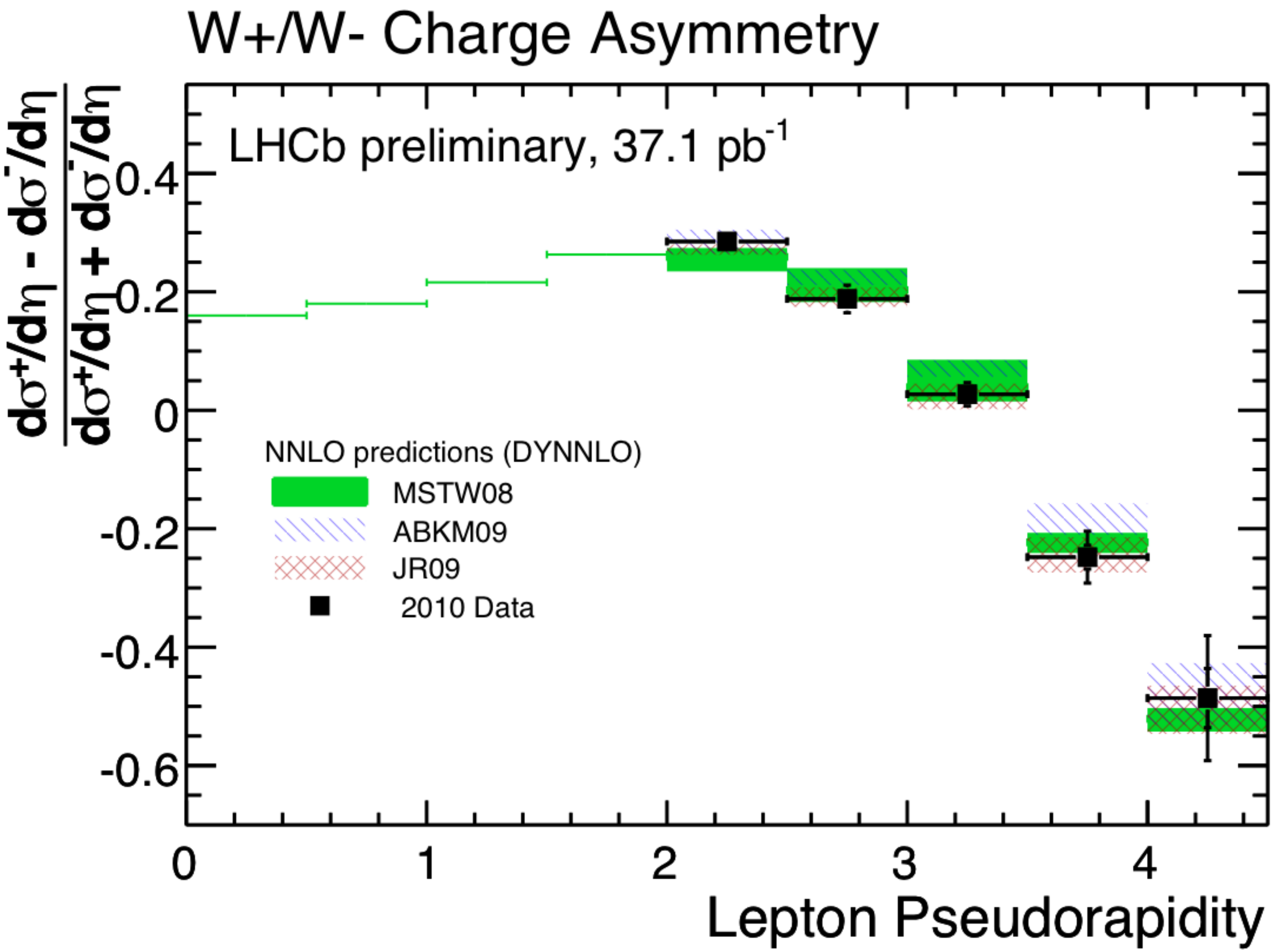


Purity of W selection

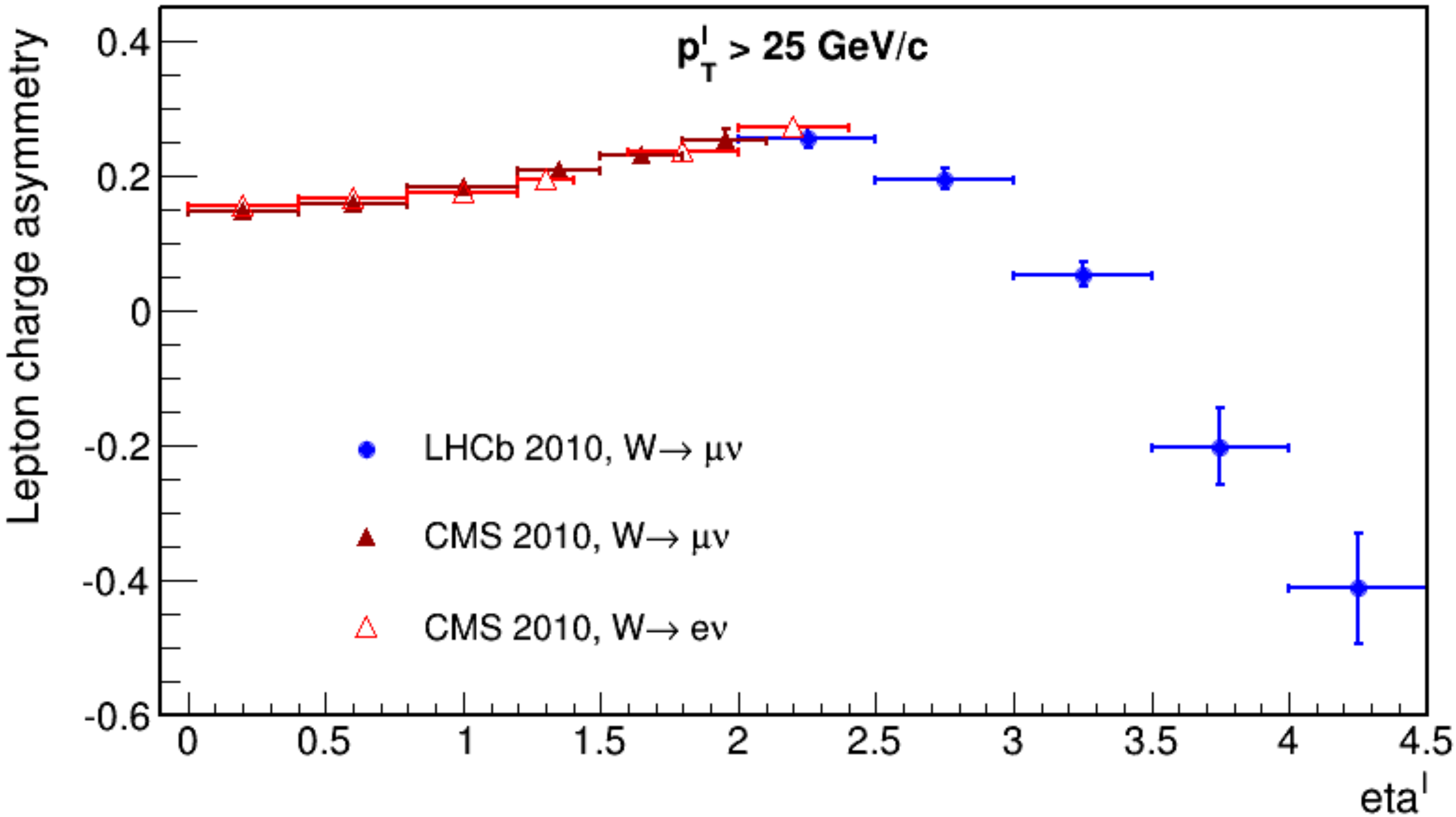
$$\sigma = \frac{pN}{\varepsilon L}$$



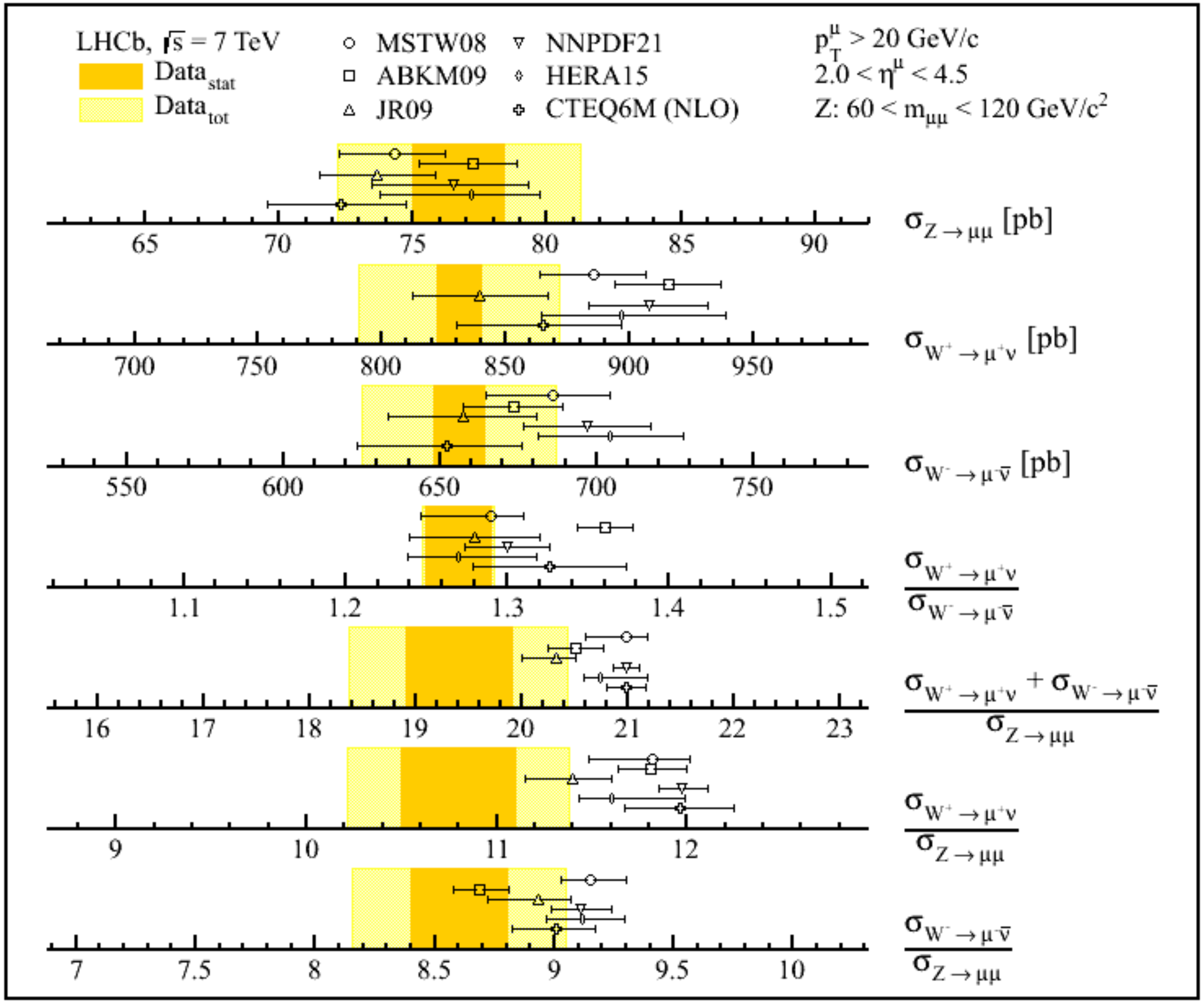
W charge asymmetry

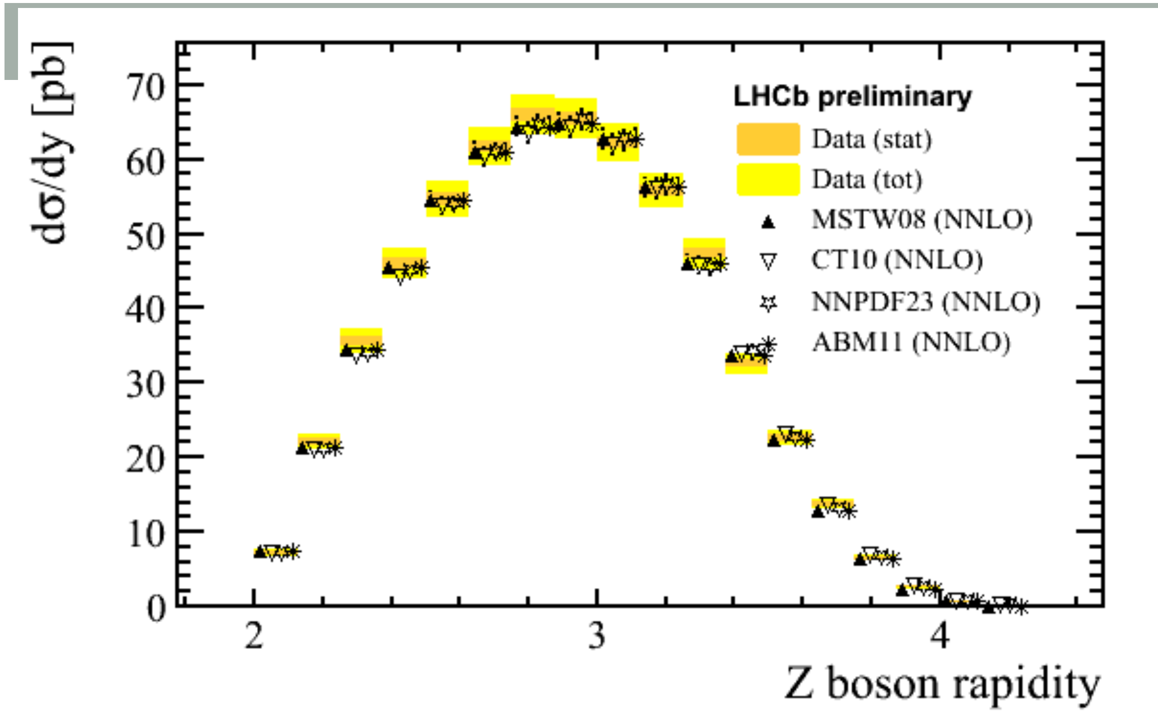


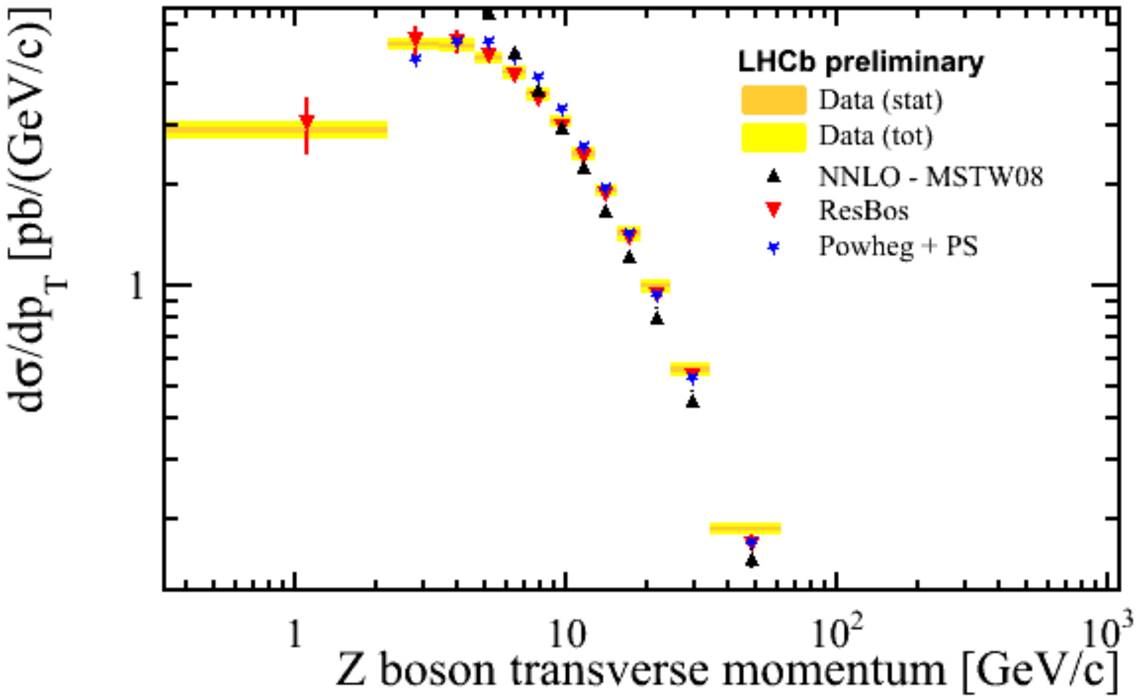
Comparison to CMS



Testing the theory







Z differential cross-section as fn of rapidity and transverse momentum

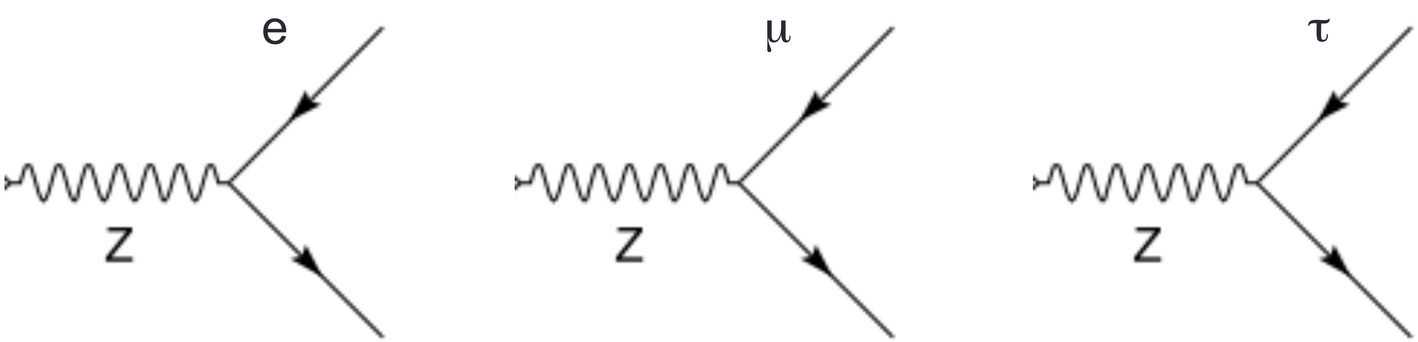
compared to various PDF sets and different generators

1. Summary

- Electroweak data from LHC is in good agreement with Standard Model Predictions.

- PDFs constrained and thus predict other processes (e.g. Higgs) with greater precision.

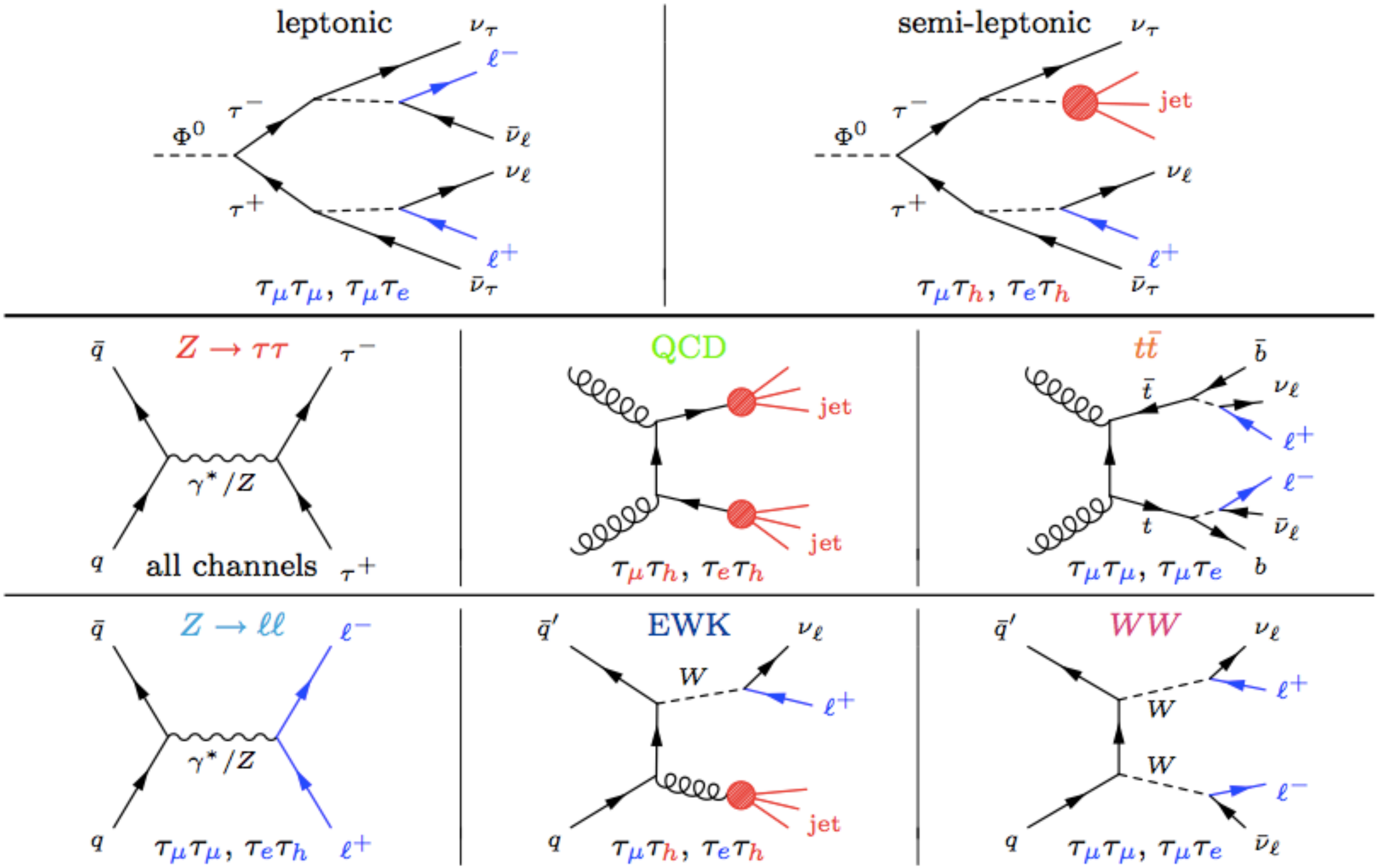
2. Electroweak tests using Z→ττ; sensitivity to Higgs



Are these couplings the same?

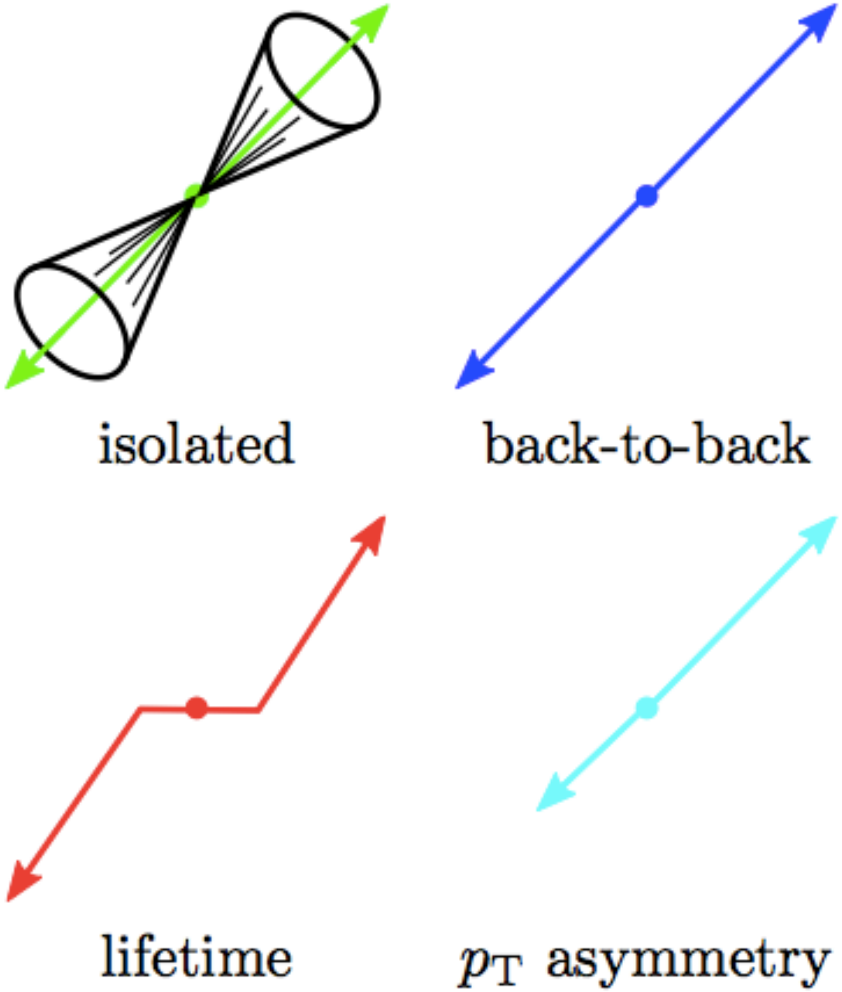
Could something else produce ττ?

Z->ττ signal and background



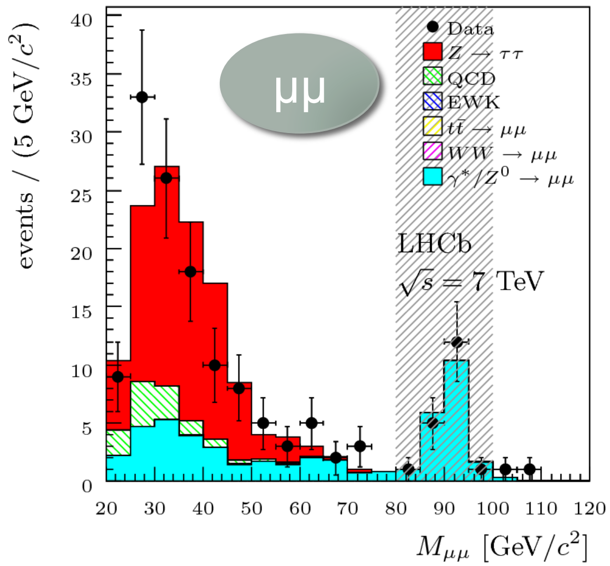
Trigger and selection

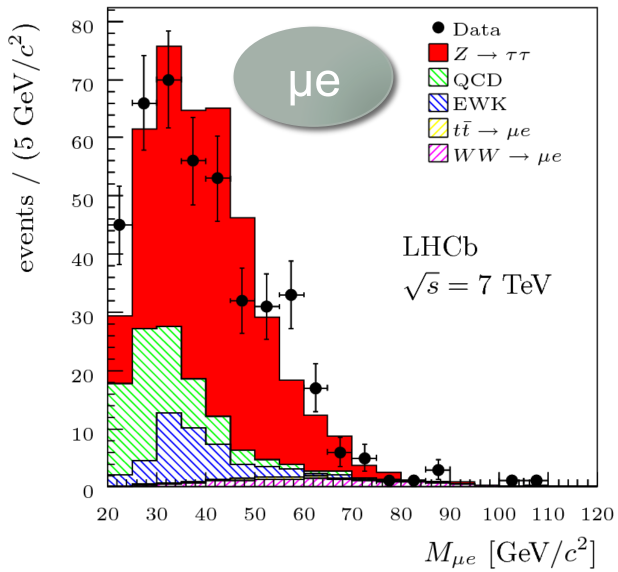
- triggers
  - muon ($p_T > 15$ GeV)
  - electron ($p_T > 10$ GeV)
- muon
  - muon track
- electron
  - large E_{ECAL}/p
  - small E_{HCAL}/p
- hadron (single-pronged)
  - small E_{ECAL}/p
  - large E_{HCAL}/p

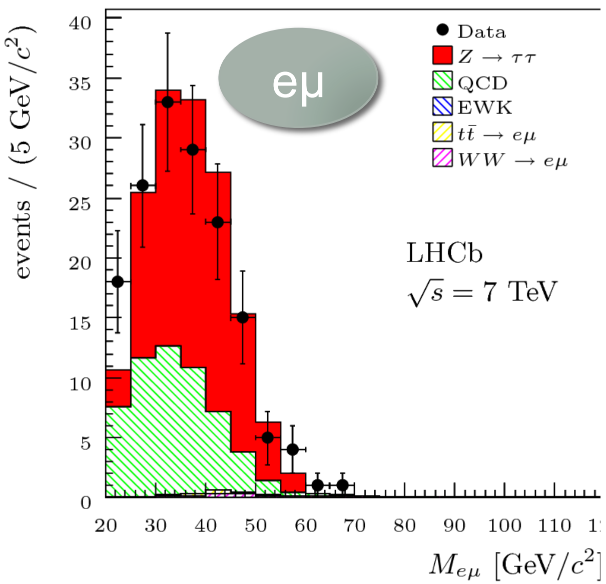


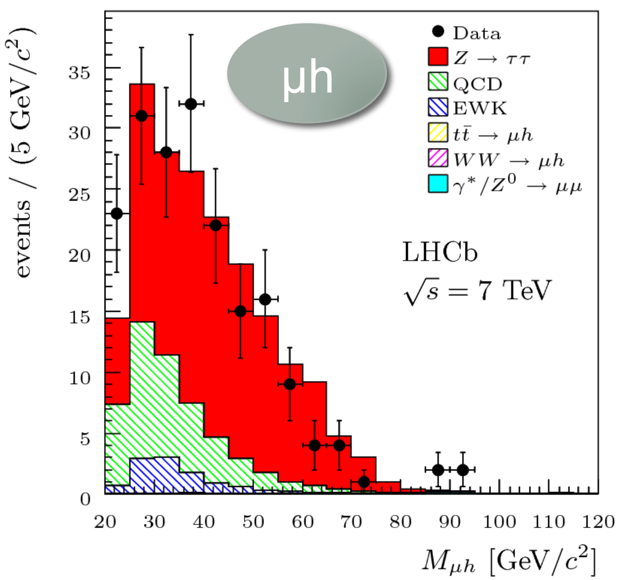
Estimated signal contributions

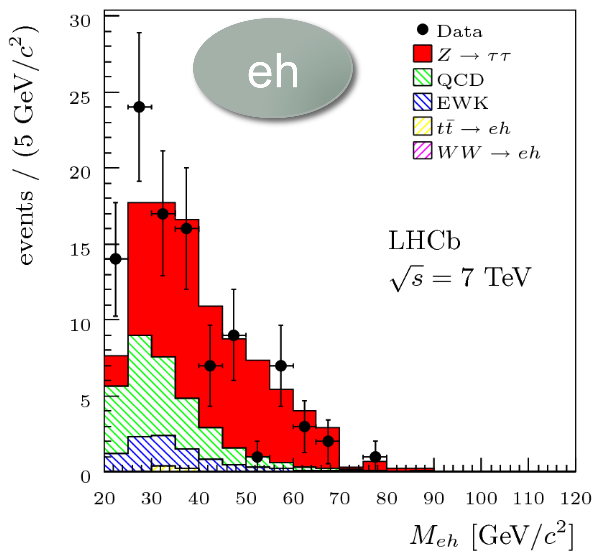
μμ



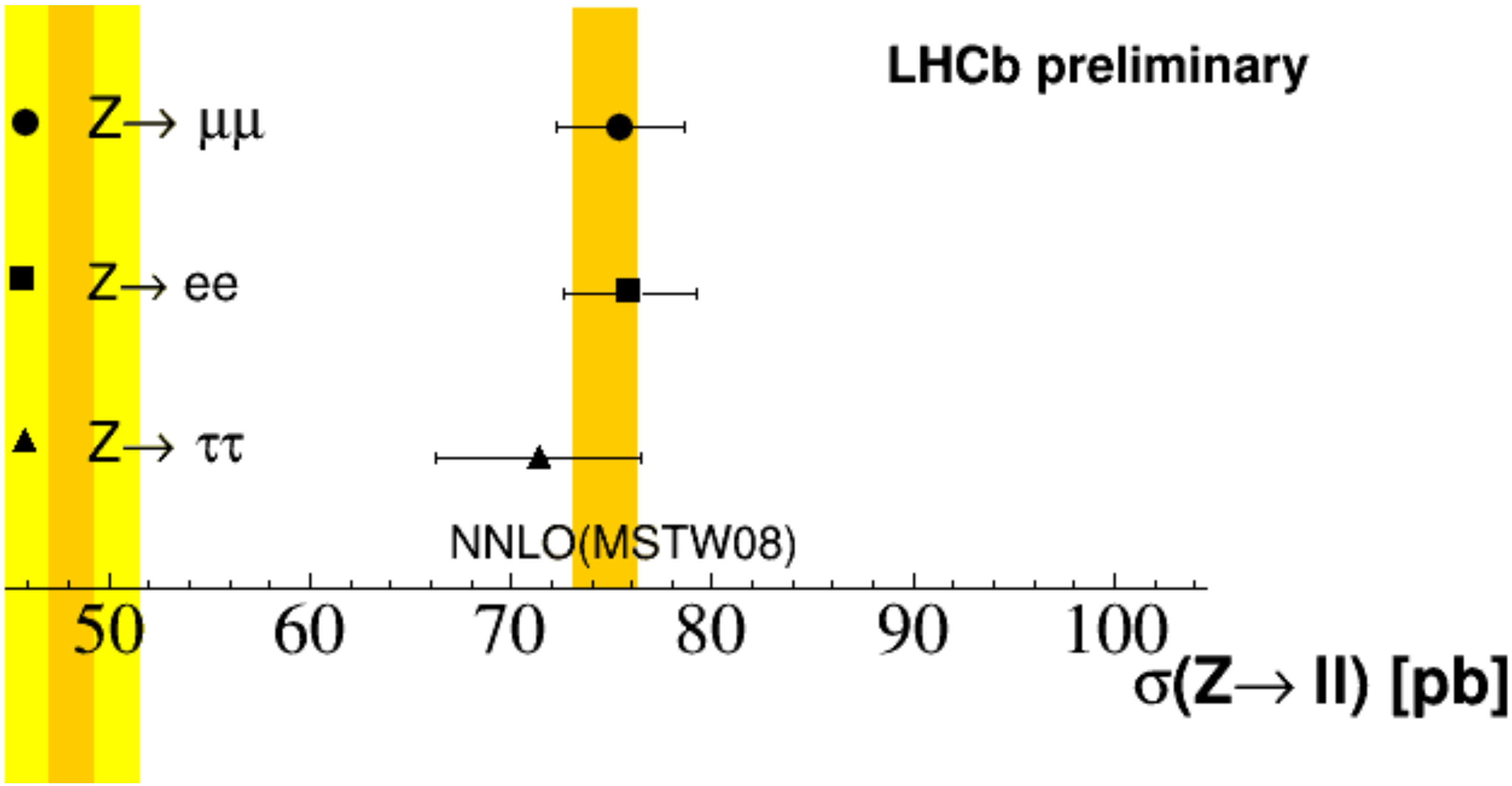




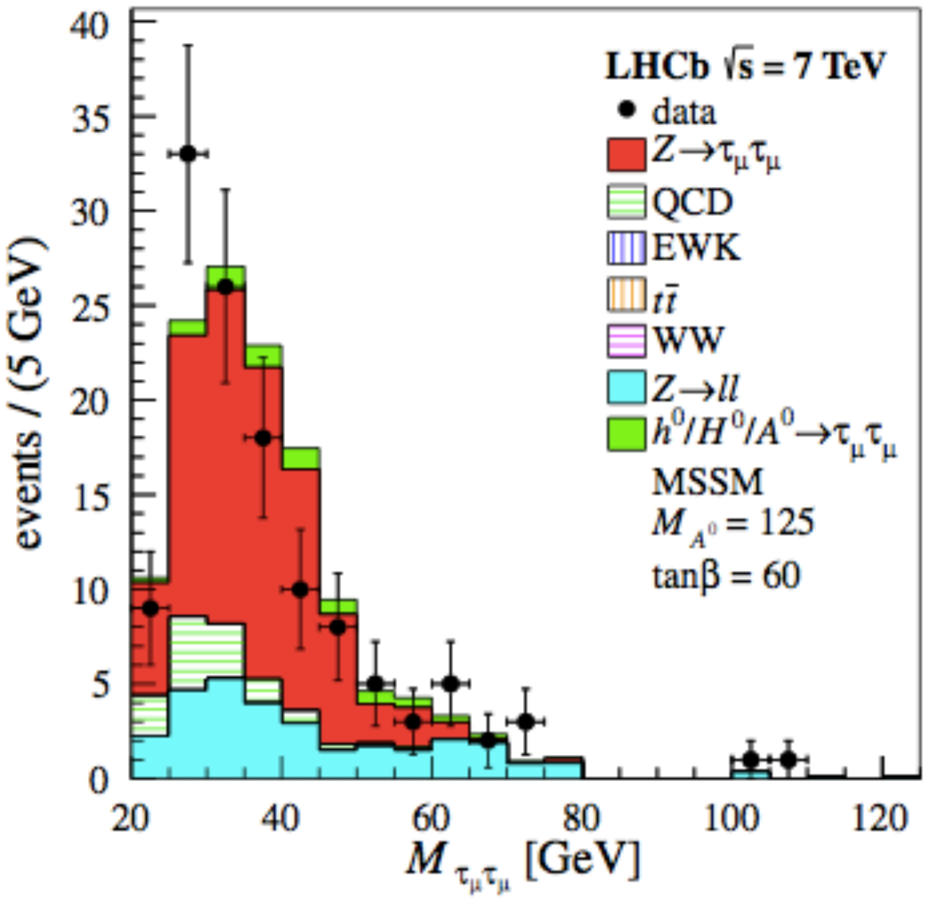




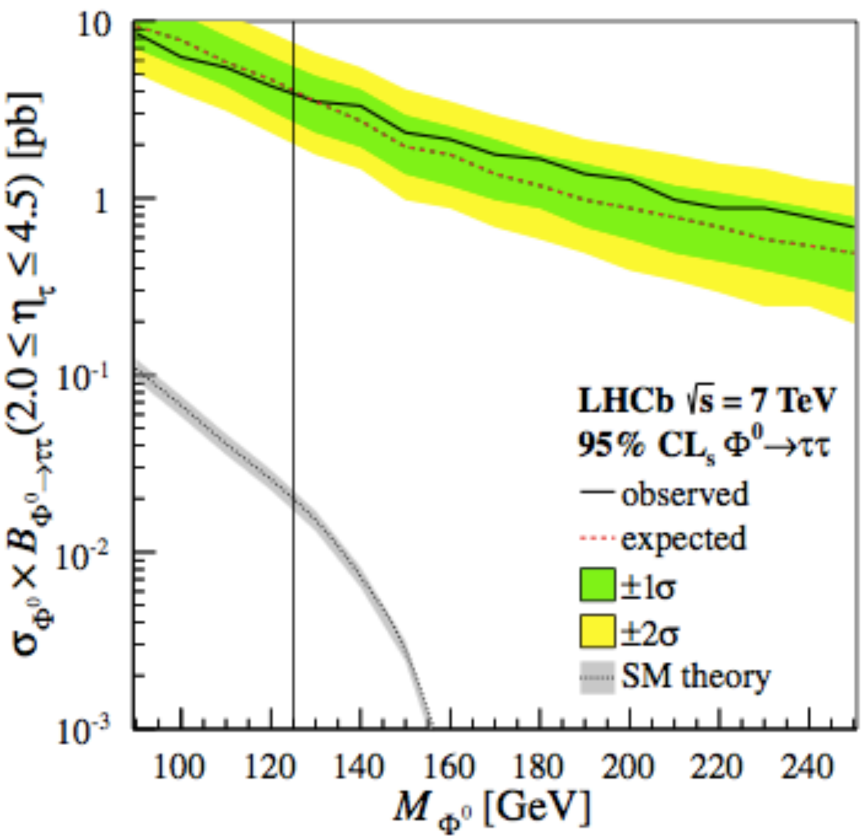
Comparison of Z->μμ and Z->ττ results



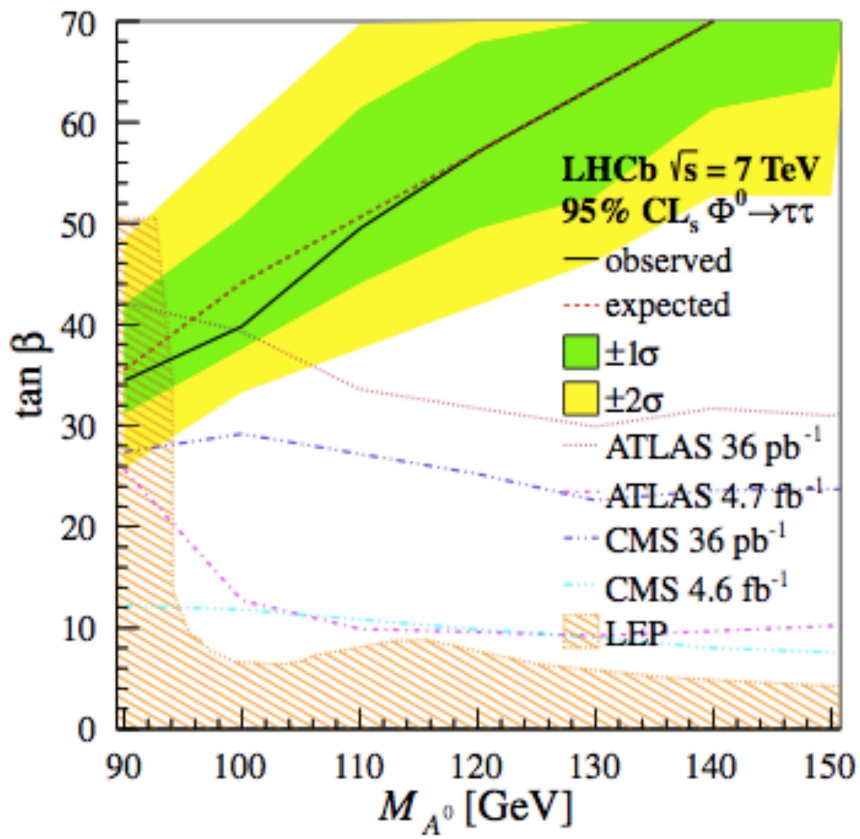
Reinterpretation in terms of Higgs



Higgs boson in the forward region



Model independent limits



SUSY limits (mhmax scenarios)

2. Summary

- Lepton universality holds
- SUSY parameter space severely constrained.
- With more statistics we are sensitive to Higgs production in the forward region.

3. Exclusive J/ψ and ψ(2S), χ_c and μμ

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IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

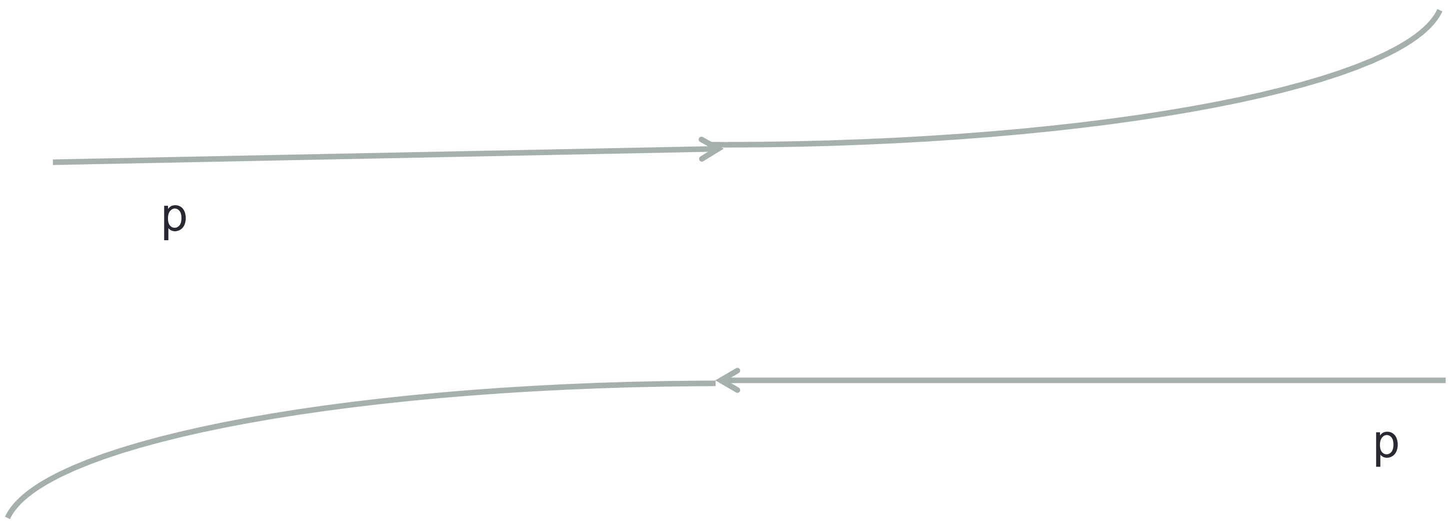
J. Phys. G: Nucl. Part. Phys. **40** (2013) 045001 (17pp) doi:10.1088/0954-3899/40/4/045001

Exclusive J/ψ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV

Results based on 37pb^{-1} of data taken in 2010

Physics of the Vacuum

Elastic

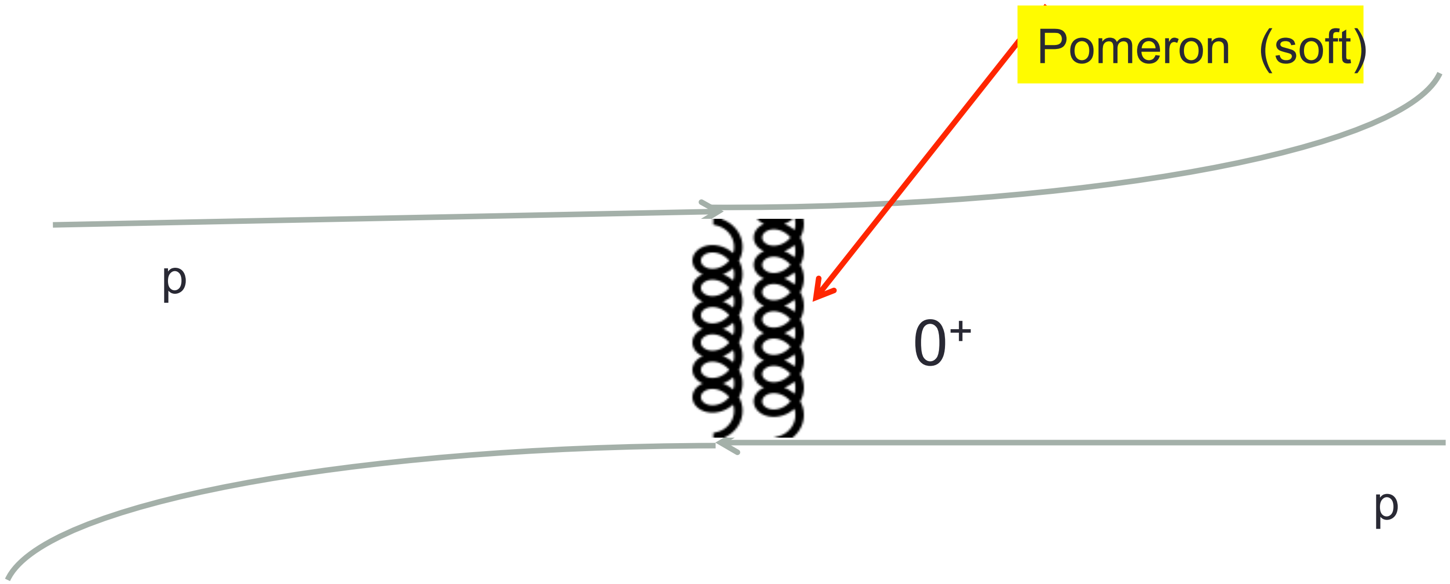


It's QCD – but not as we normally see it. It's colour-free

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

Physics of the Vacuum

Elastic



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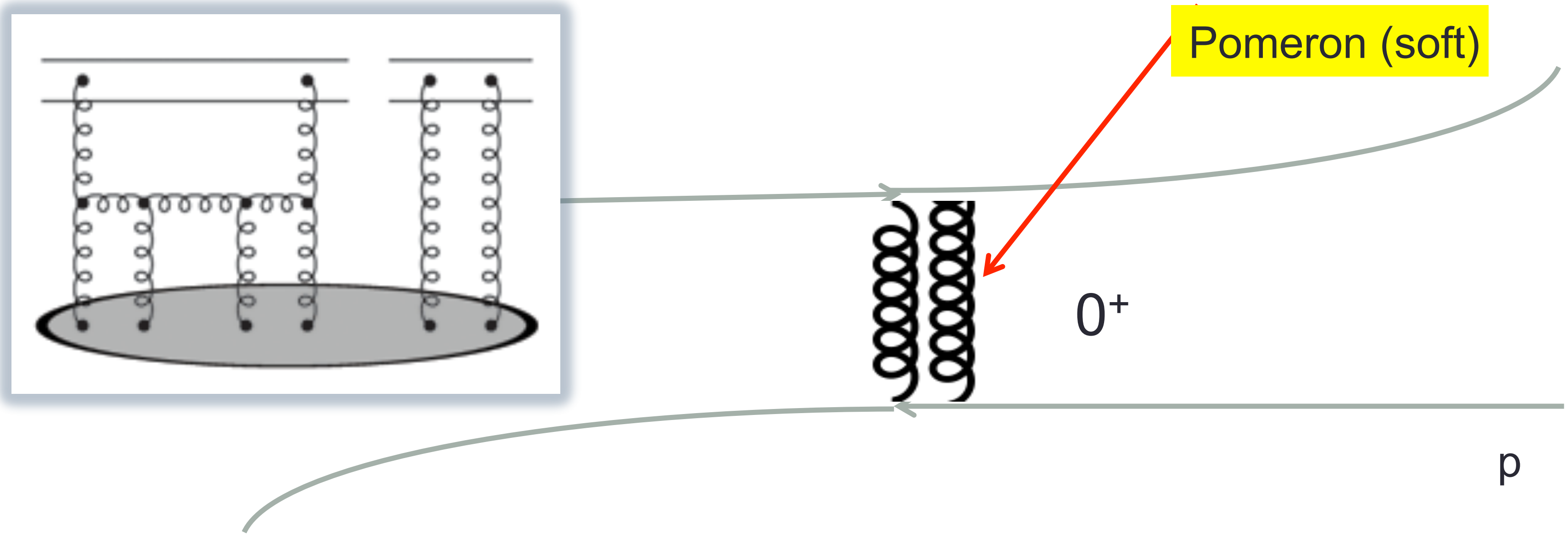

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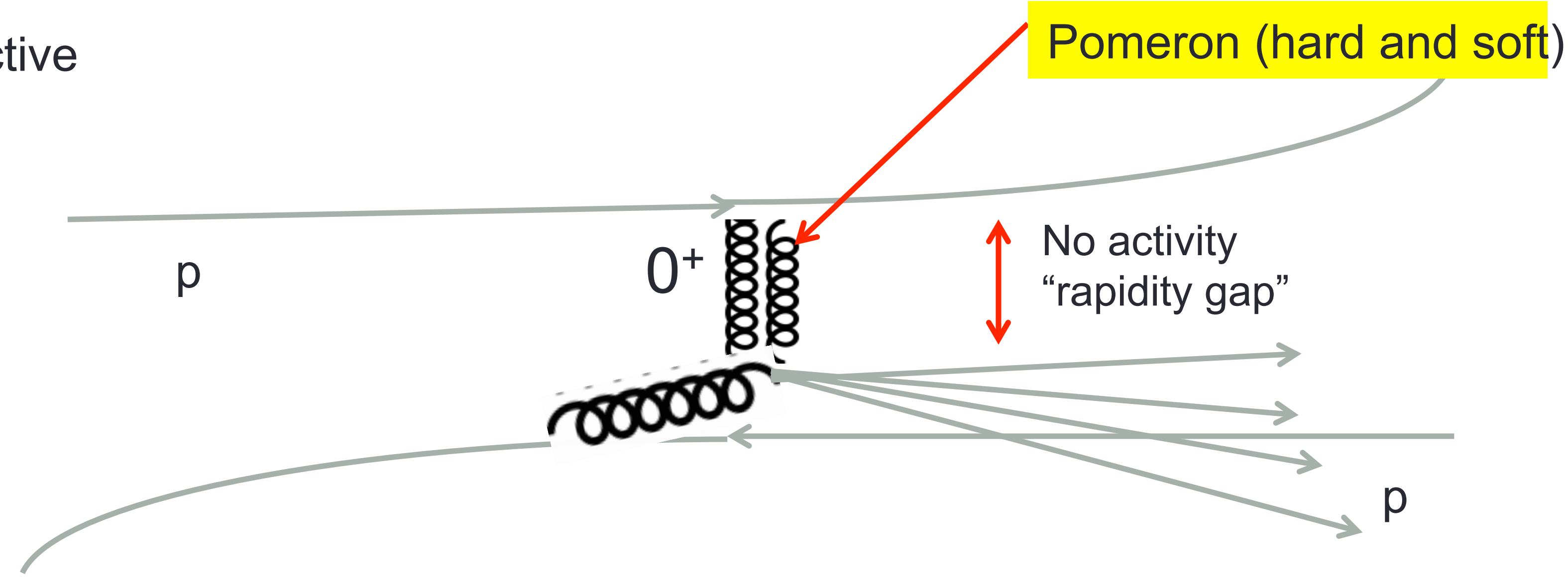
Physics of the Vacuum

Diffractive



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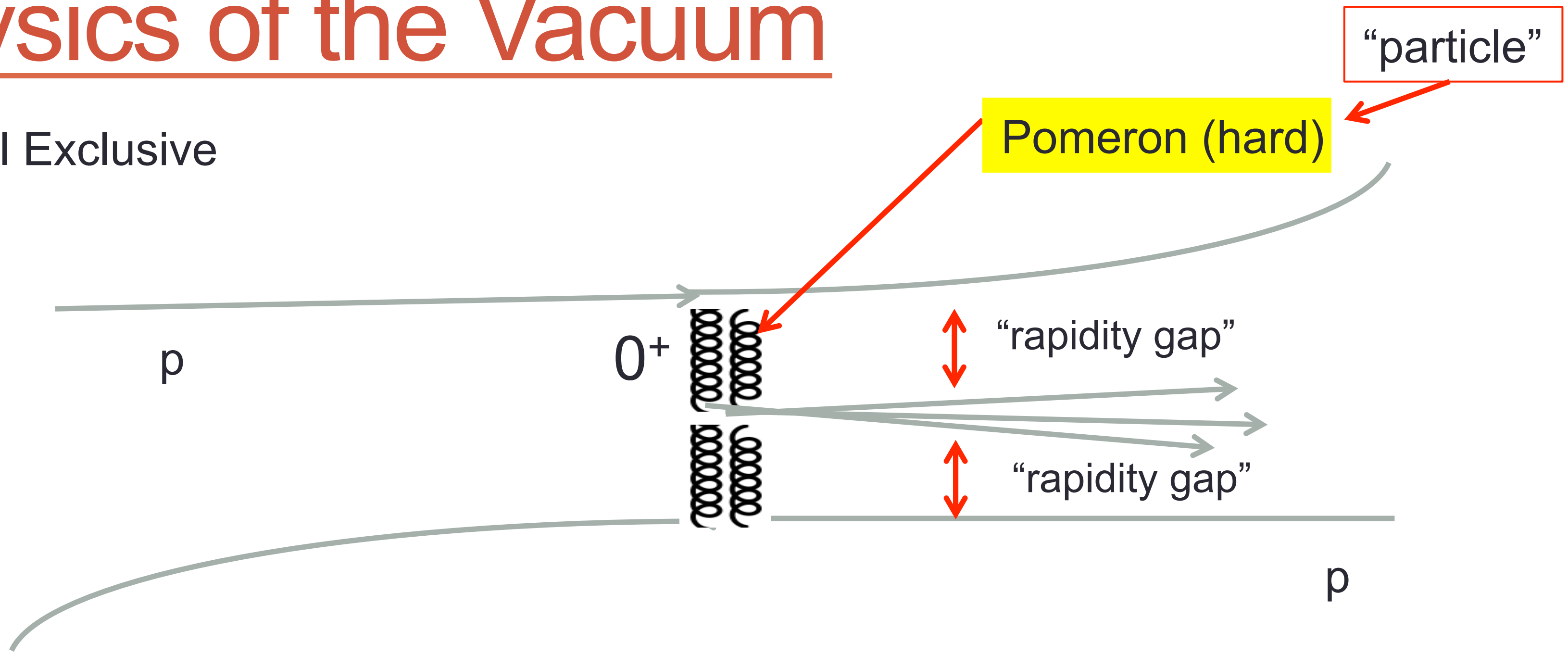
Physics of the Vacuum

Central Exclusive



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

$\sigma_{elastic} \approx 40\text{mb}$
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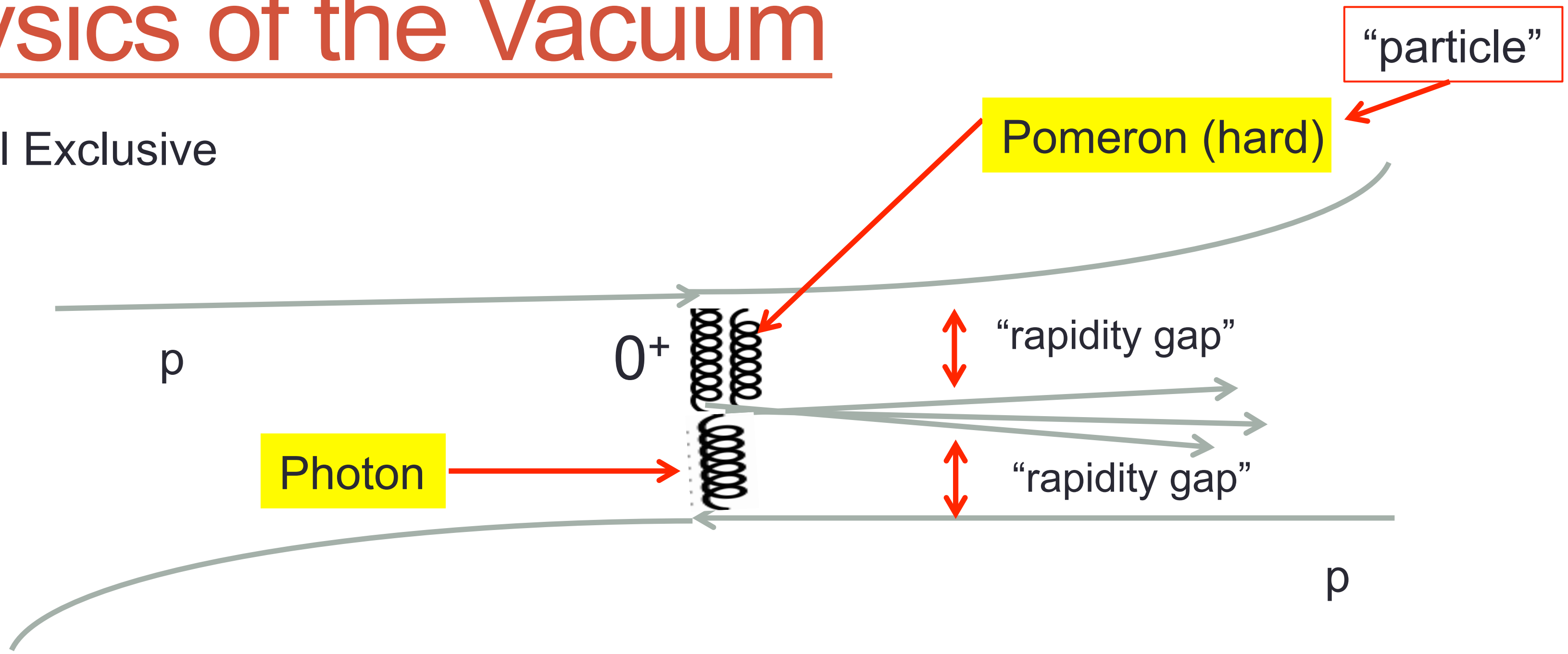
Physics of the Vacuum

Central Exclusive



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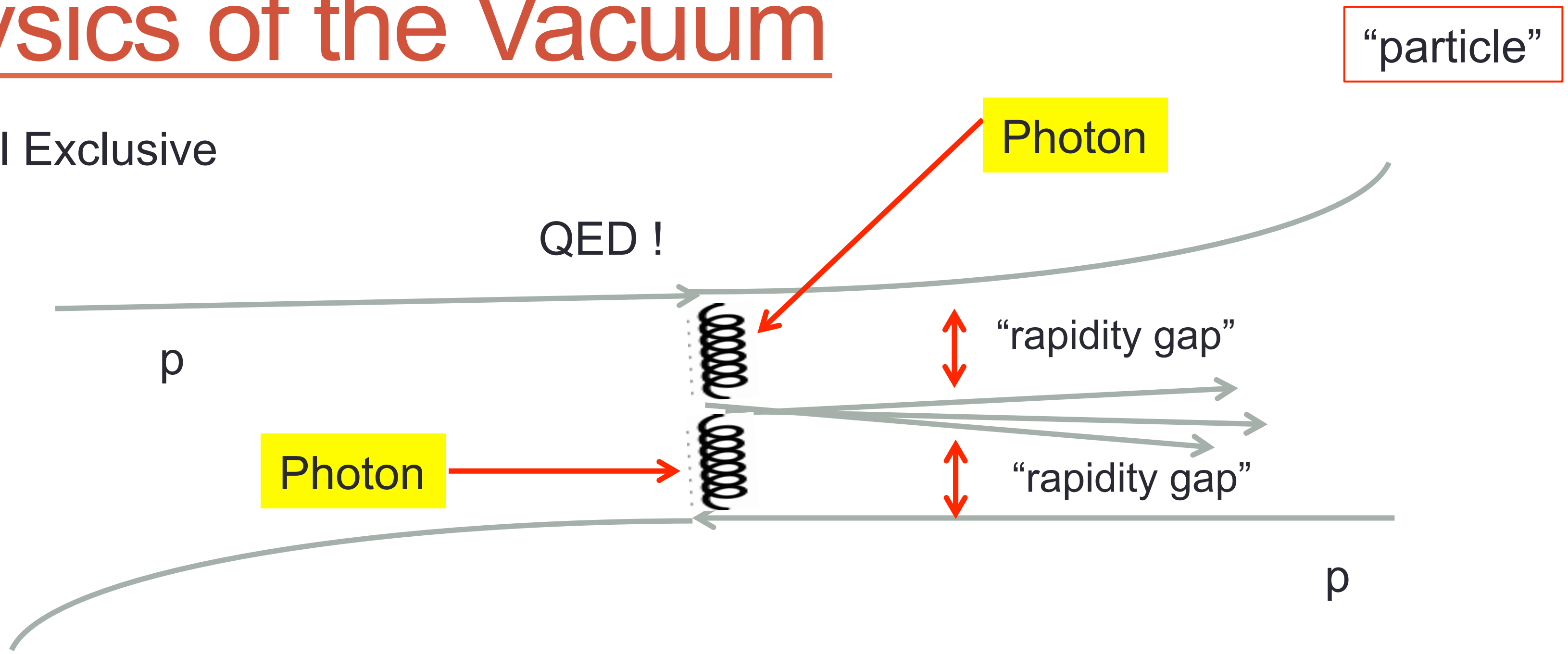
Physics of the Vacuum

Central Exclusive



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

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

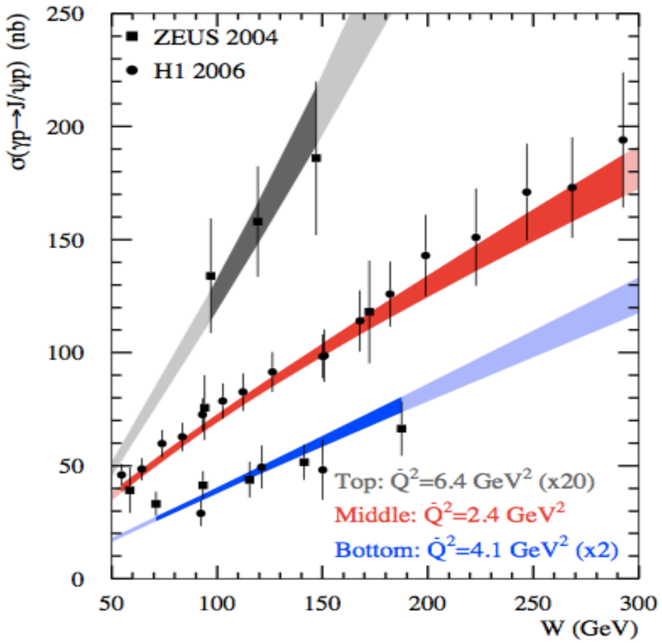
Sensitivity to gluon PDF

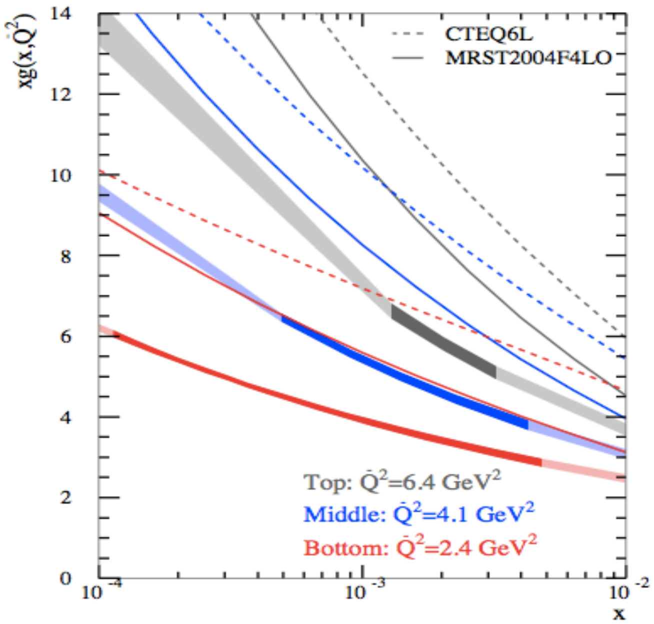
$xg \propto x^{-\lambda}$

Gluon PDF enters squared

Leading order cross-section

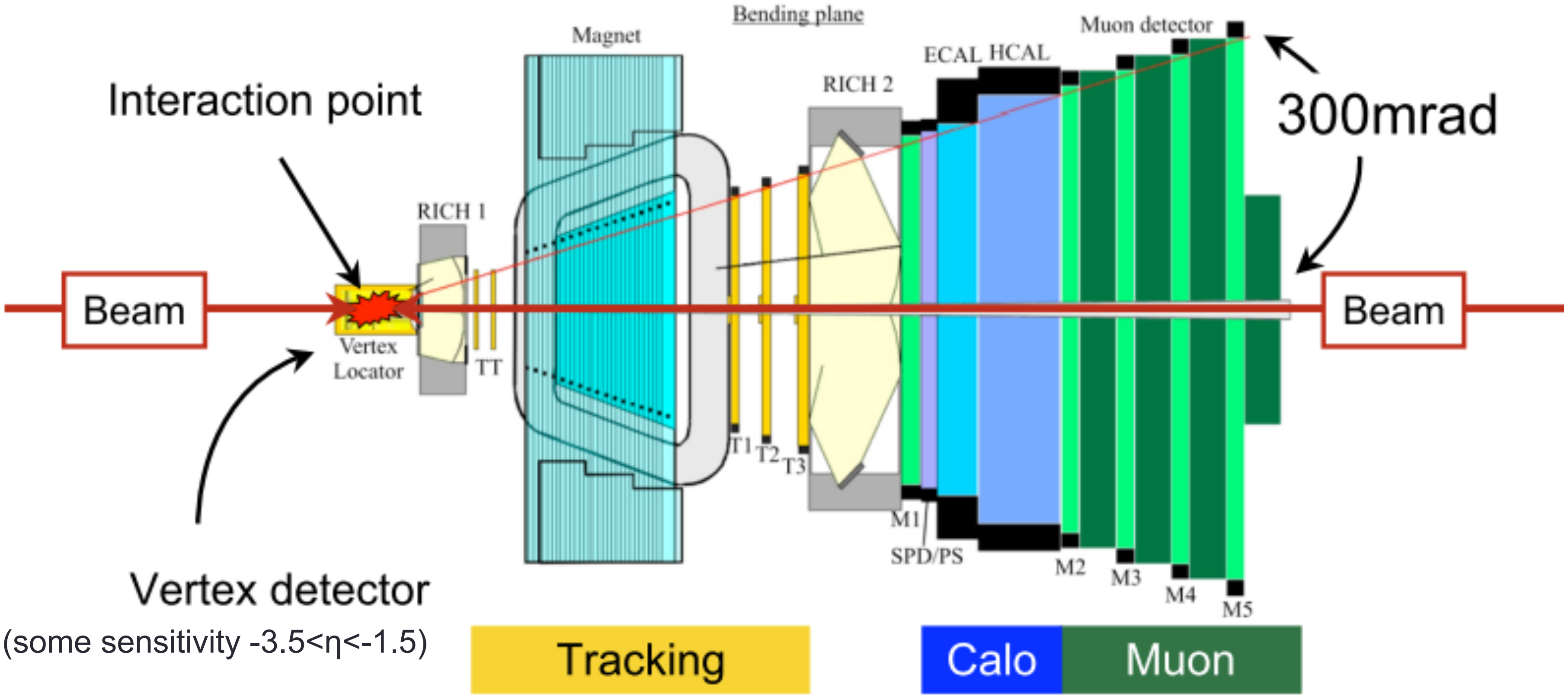
$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)$$





Examples of dependence of Jpsi cross-section on PDF (left) and extraction of gluon PDF (right) from Martin, Nockles, Ryskin, Teubner, arXiv:0709.4406v1

The LHCb detector

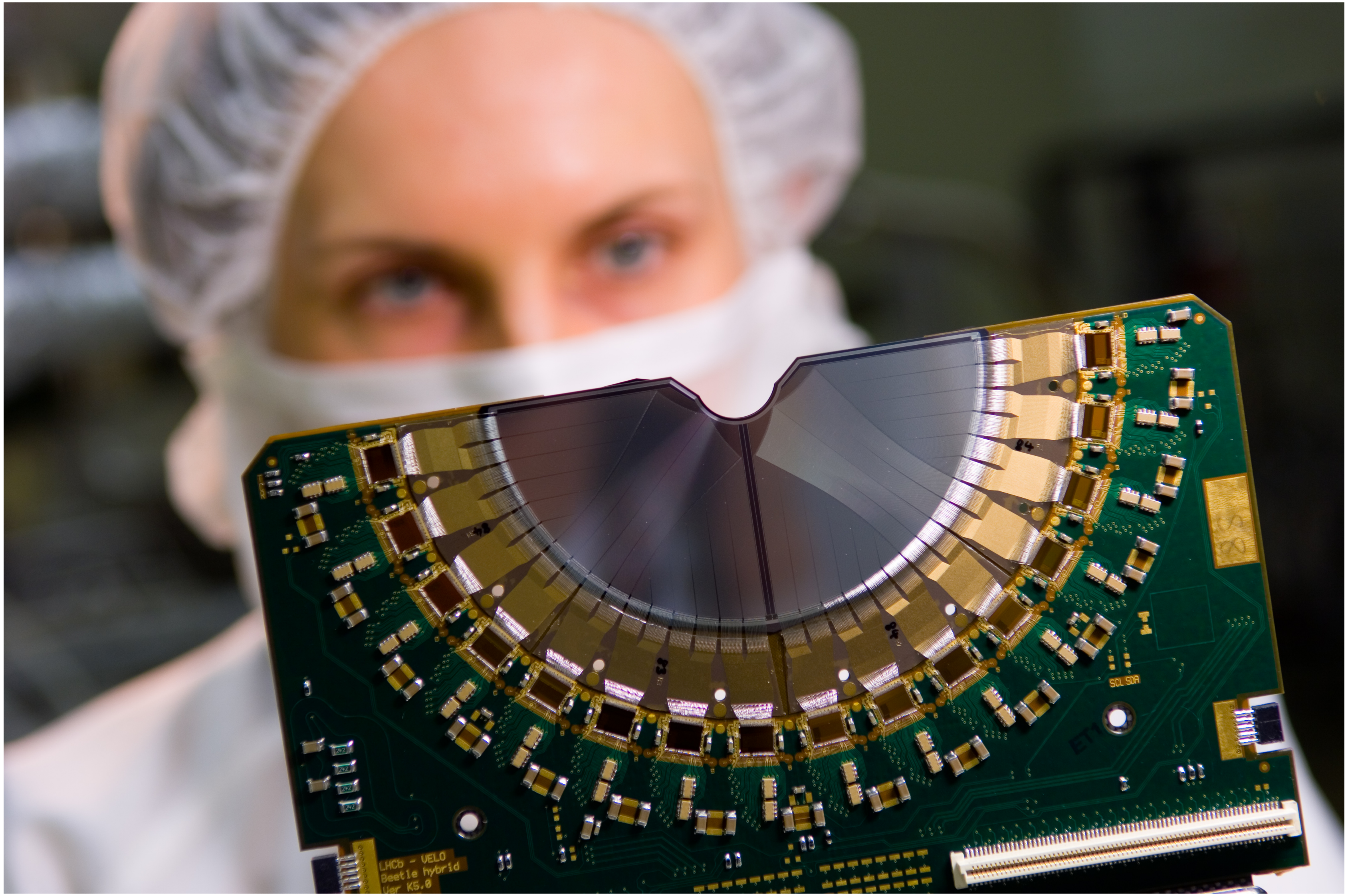


Fully instrumented within $1.9 \le \eta \le 4.9$

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

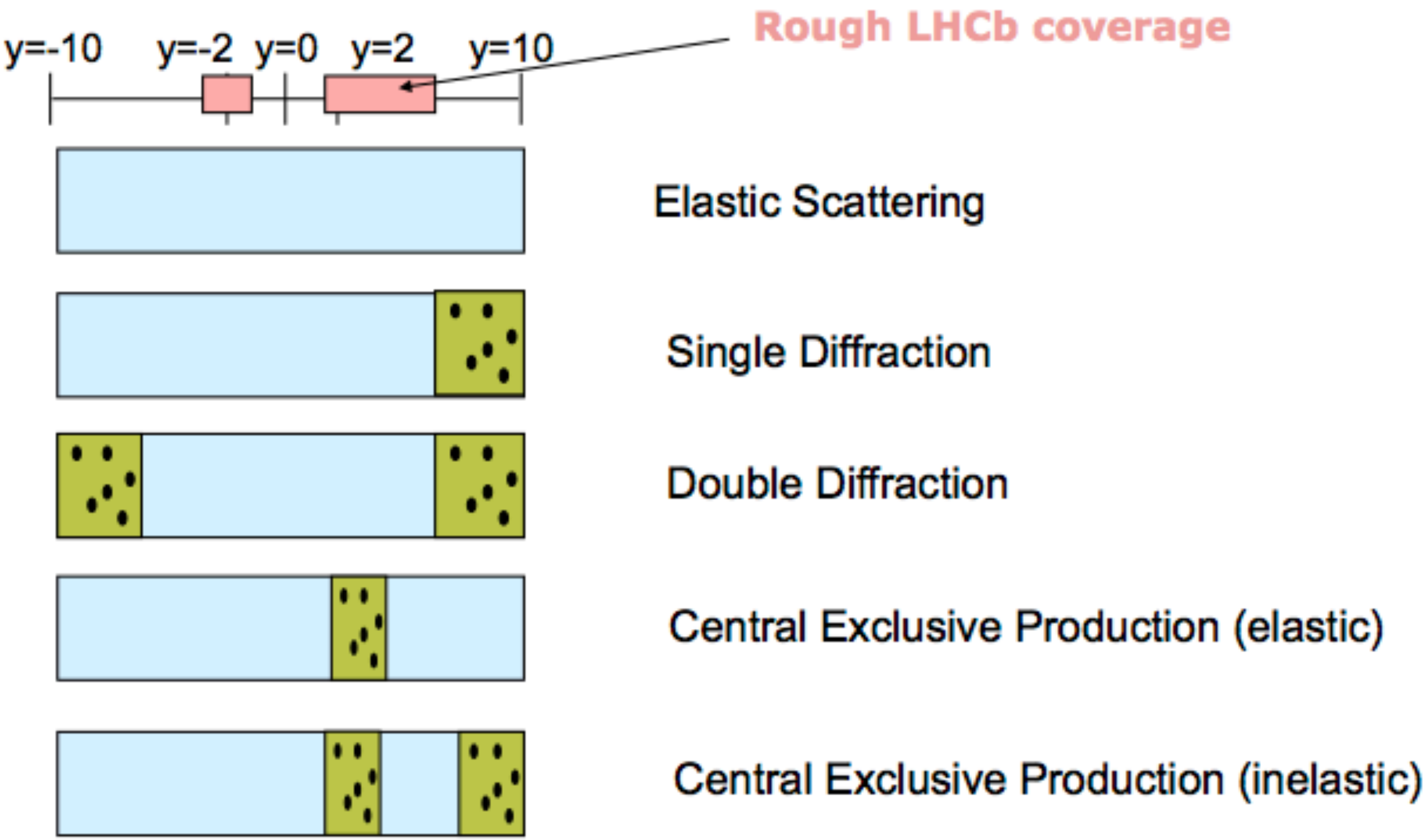
Low multiplicity required. Restricts to single-interaction collisions

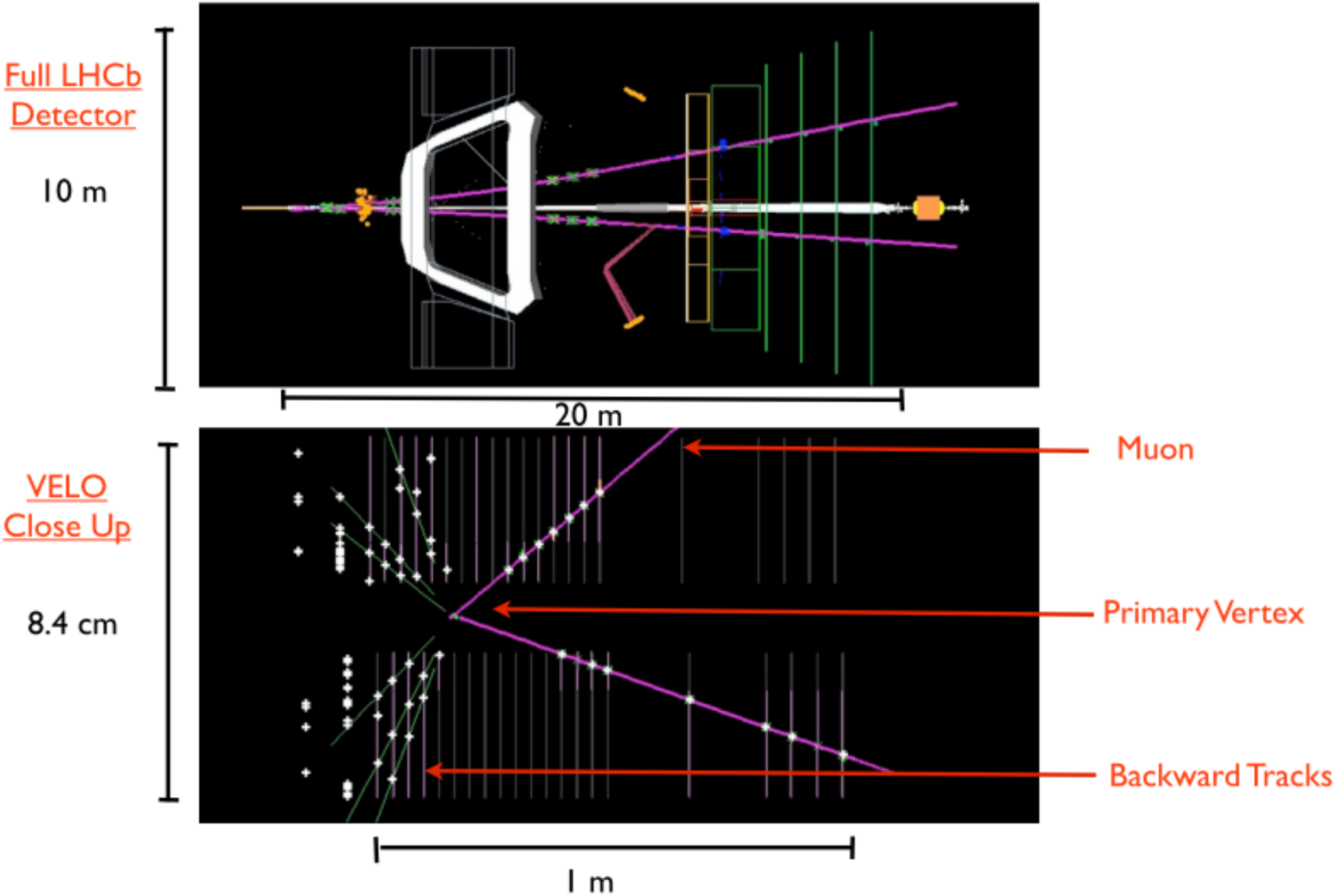
VELO sub-detector measures particle positions to 5um



UCD helped build, commission and operate the VELO

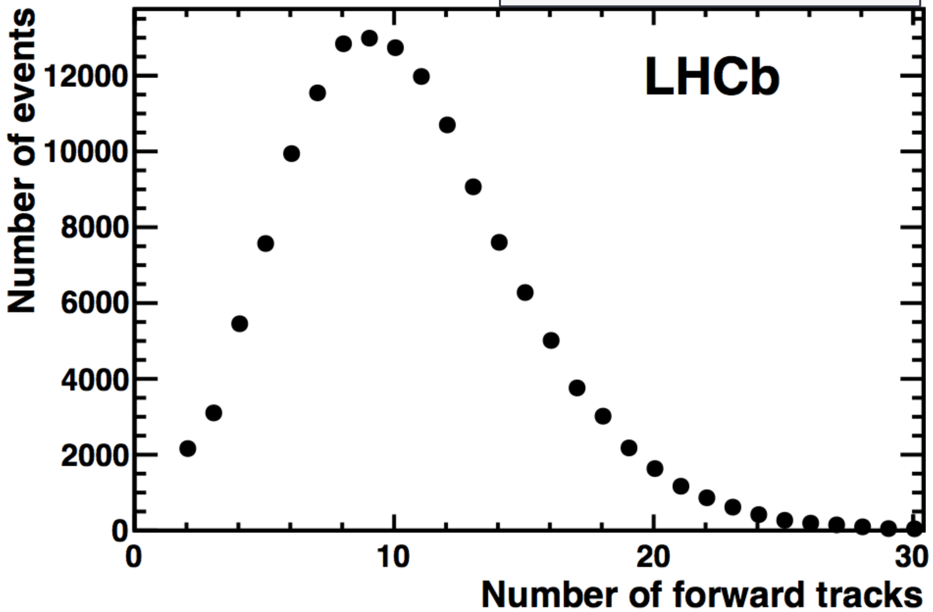
Graphical Representation




Full LHCb Detector
10 m
20 m
VELO Close Up
8.4 cm
1 m
Muon
Primary Vertex
Backward Tracks

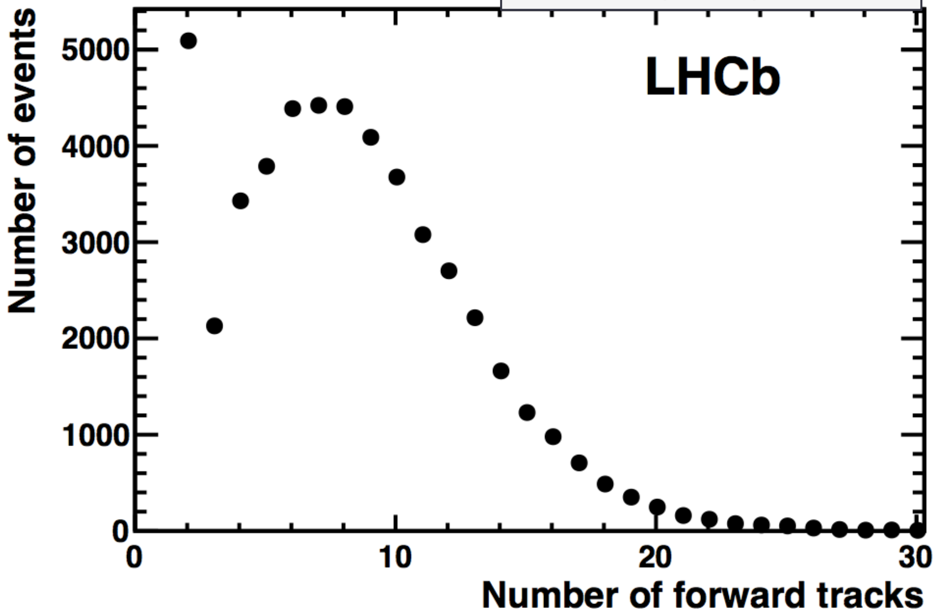
Effect of rapidity gap requirement on muon triggered events

JPG 40 (2013) 045001



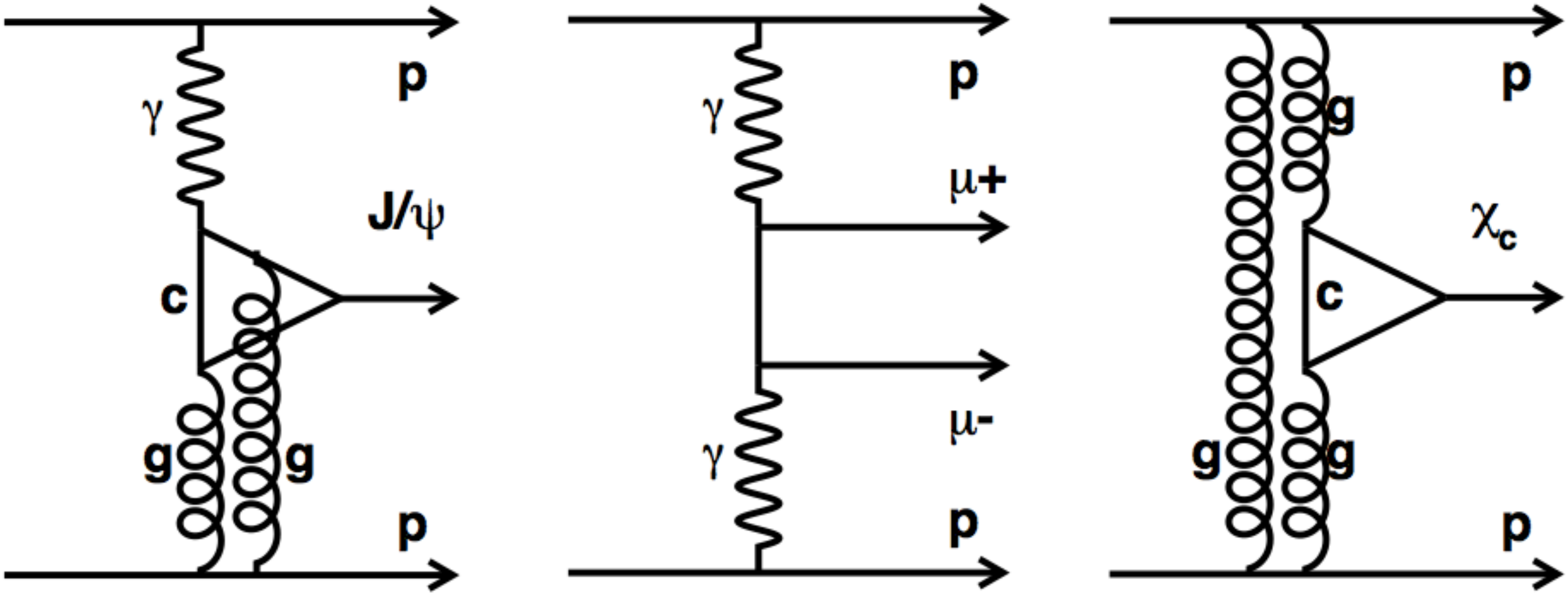
All triggered events

JPG 40 (2013) 045001



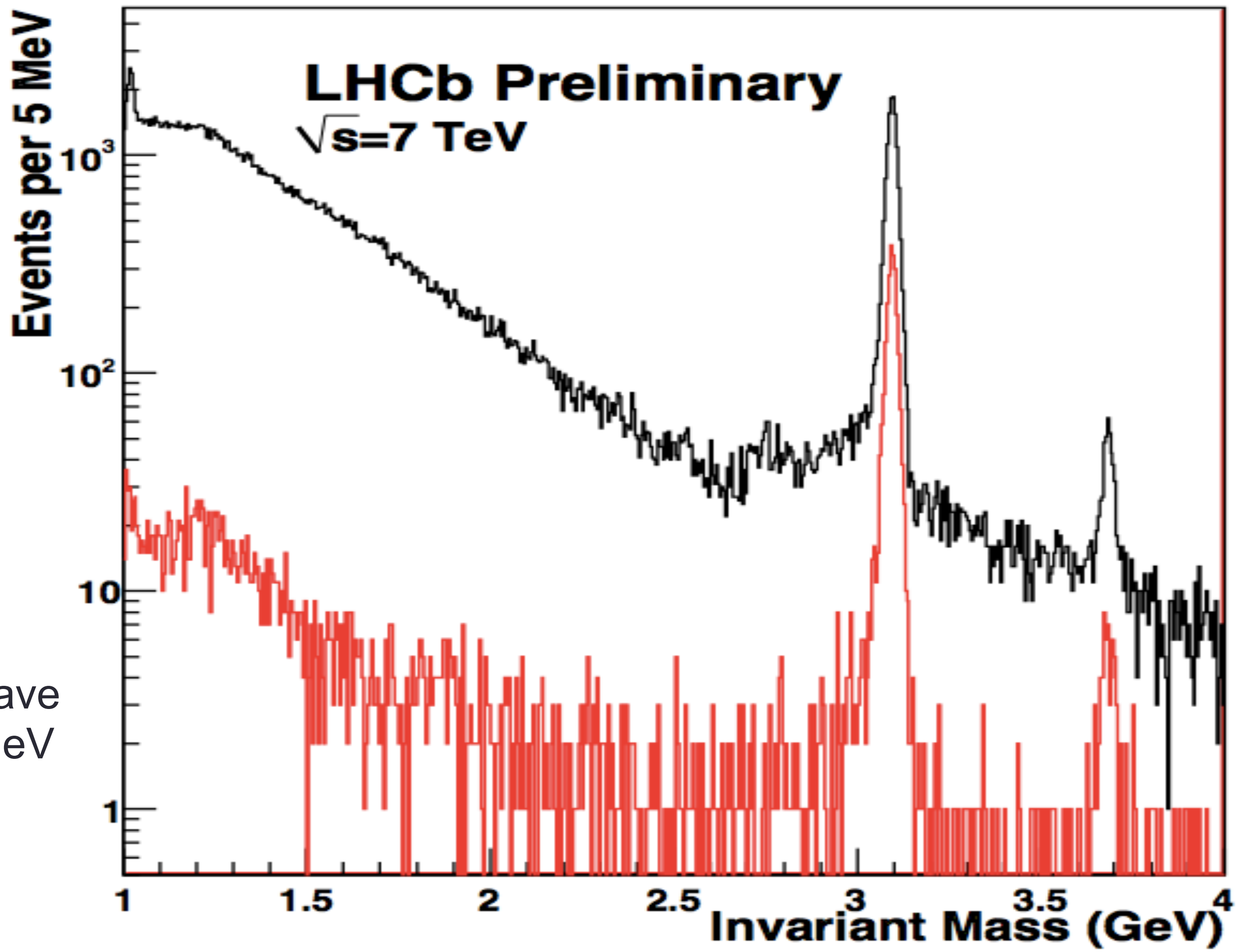
With veto on backward tracks

Central exclusive di-muon signals



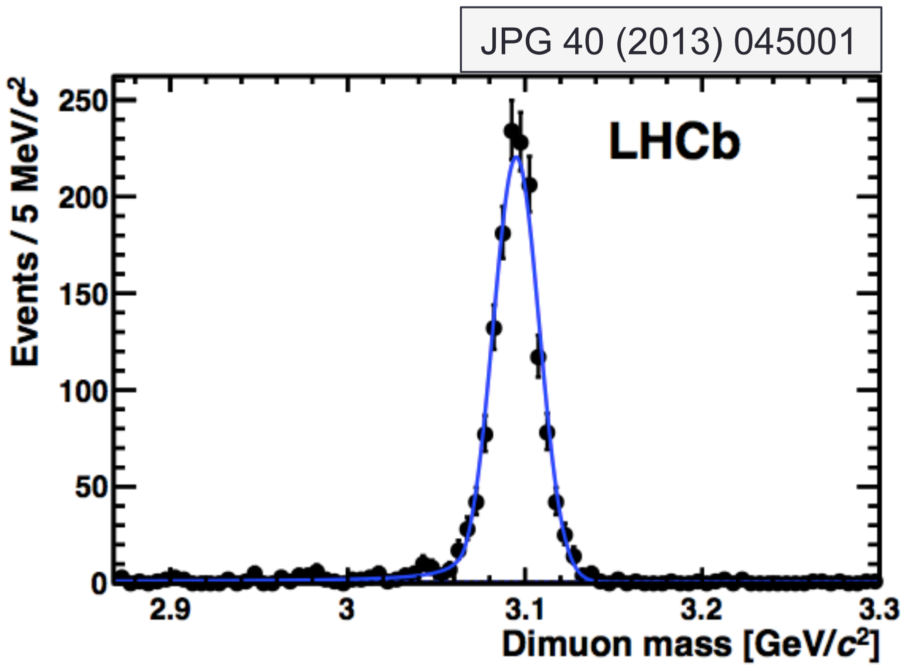
SuperChic: L. Harland-Lang, V. Khoze, M. Ryskin, W. Stirling, EPJ.C65 (2010) 433-448
Starlight: S.R. Klein & J. Nystrand, PRL 92 (2004) 142003.

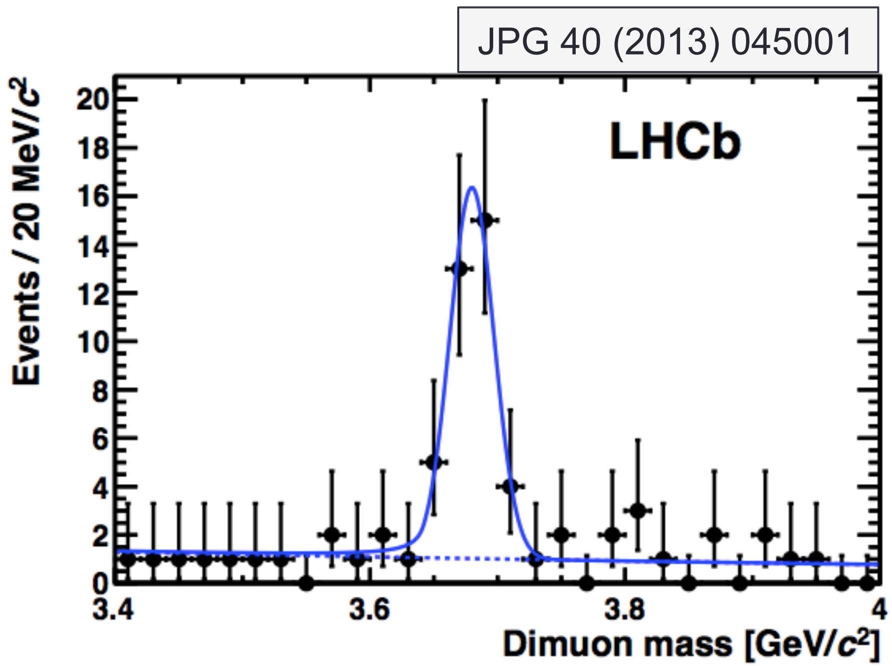
Before and after requiring precisely two tracks



Tracks have
p_T>400MeV
2<η<5

Non-resonant background very small





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

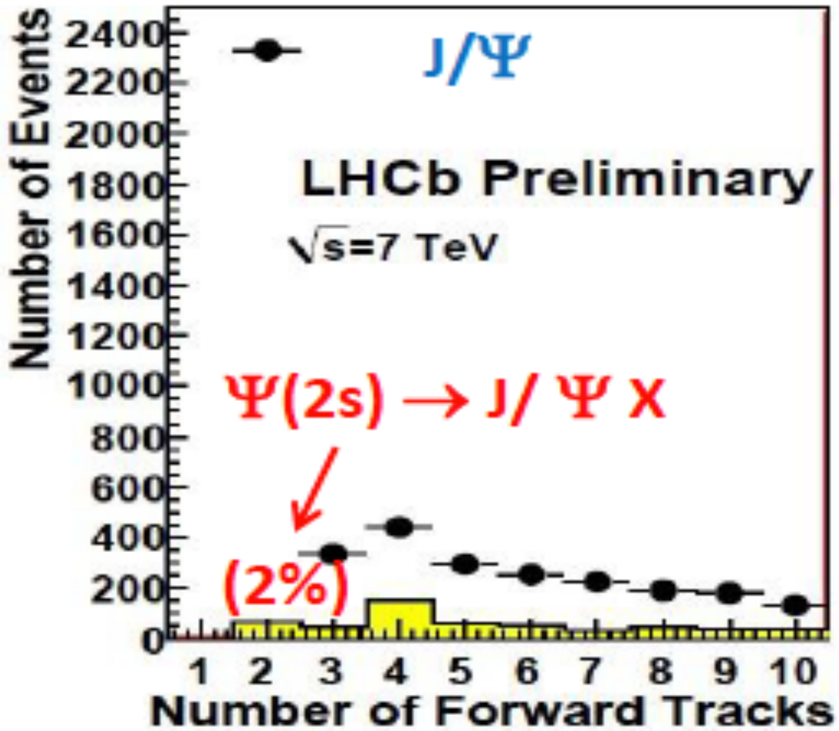
$$\sigma = \frac{pN}{\varepsilon L}$$

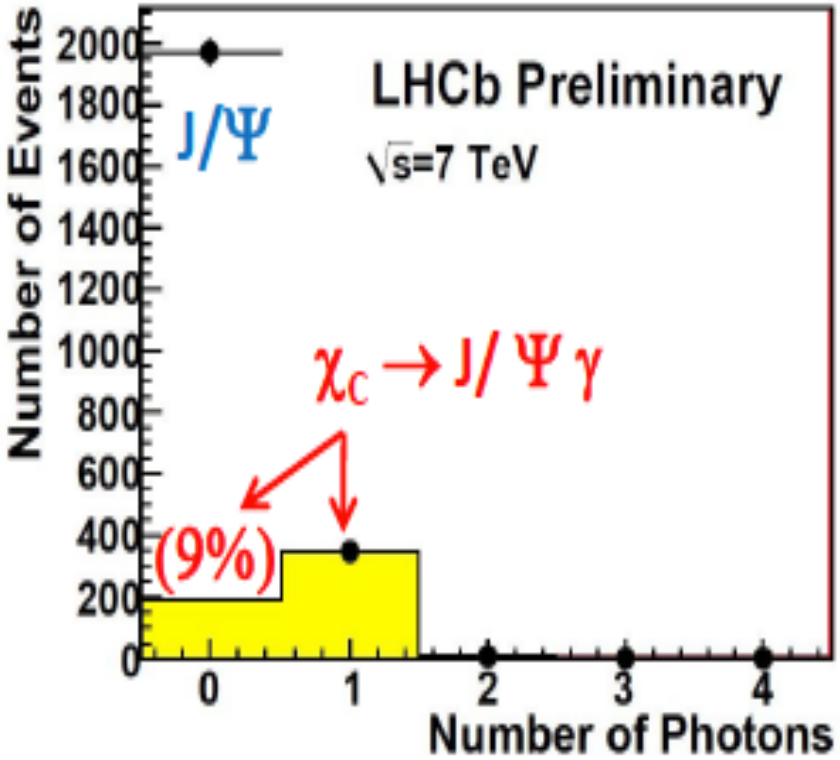
Luminosity

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

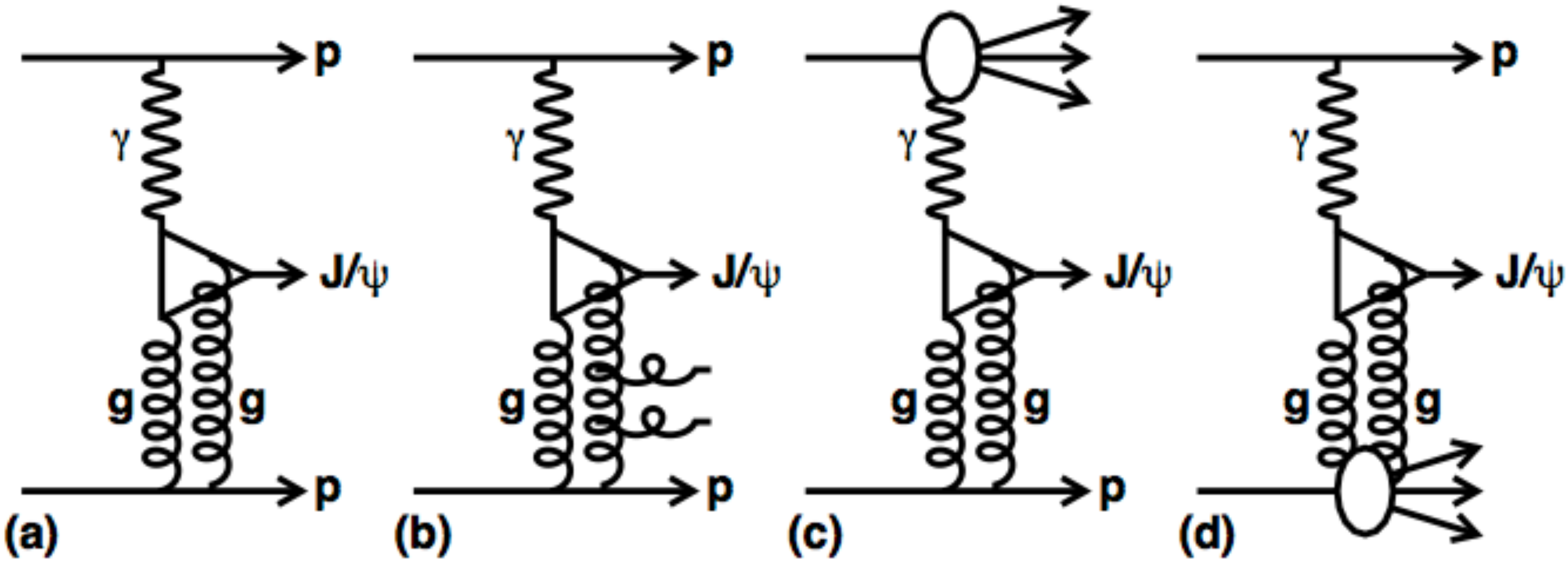
$$P(n) = \mu^n e^{-\mu} / n!$$

Feed-down backgrounds





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 data. Extrapolate to LHCb energies to get b= 6.1 +/- 0.3 GeV^{-2}

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

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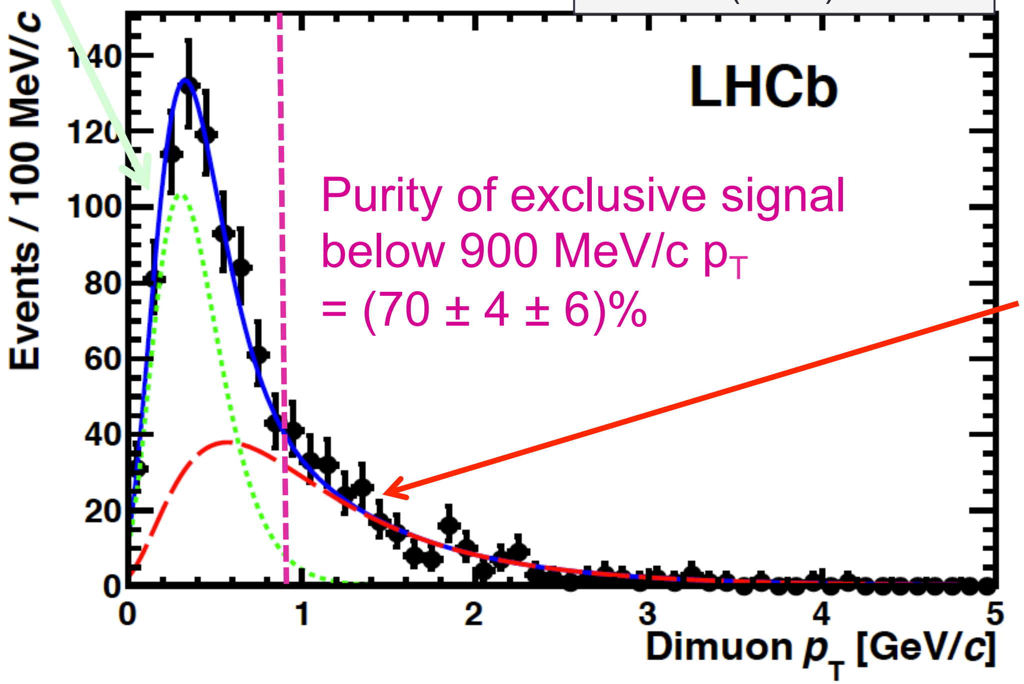


Inelastic background shape

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

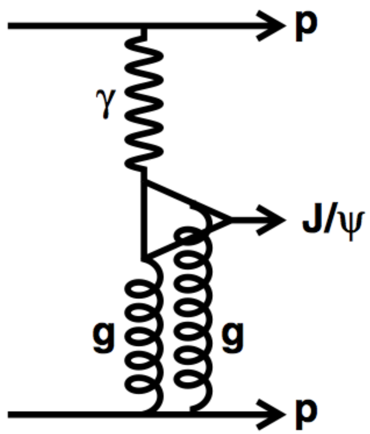
This approach works for QED production of dimuons, tested using LPAIR simulation.
Also checked with PYTHIA simulation of diffractive events.

LHCb compared to theory & experiment

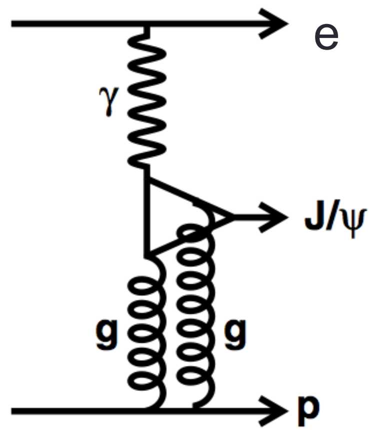
Predictions	$\sigma_{pp\to J/\psi\,(\to\mu^+\mu^-)}$	$\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}$
Gonçalves and Machado	275	
STARLIGHT	292	6.1
Motyka and Watt	334	
SUPERCHIC[a]	396	
Schäfer and Szczurek	710	17
LHCb measured value	$307 \pm 21 \pm 36$	$7.8 \pm 1.3 \pm 1.0$

[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.



LHCb compared to HERA



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

Twofold ambiguity

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

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

LHCb c/s is HERA c/s weighted by photon spectrum + gap survival factor (r)

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

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

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

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

LHCb

Power law results

$$a = 3nb$$
$$\delta = 0.72$$

HERA

LHCb compared to theory & experiment

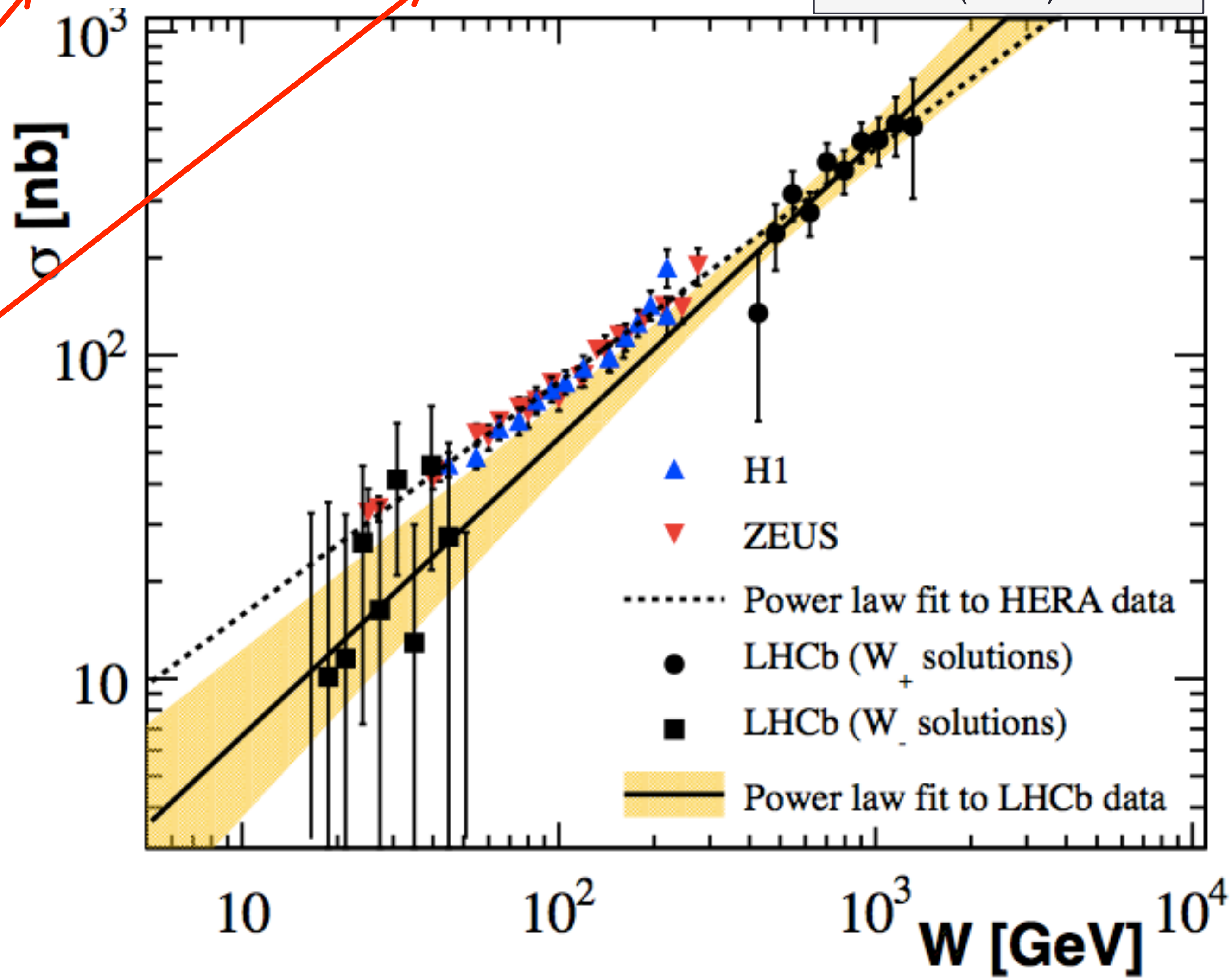
$$\frac{d\sigma}{dy}_{pp\to pVp} = r(y)\left[k_+\frac{dn}{dk_+}\sigma_{\gamma p\to Vp}(W_+) + k_-\frac{dn}{dk_-}\sigma_{\gamma p\to Vp}(W_-)\right]$$

JPG 40 (2013) 045001

measured

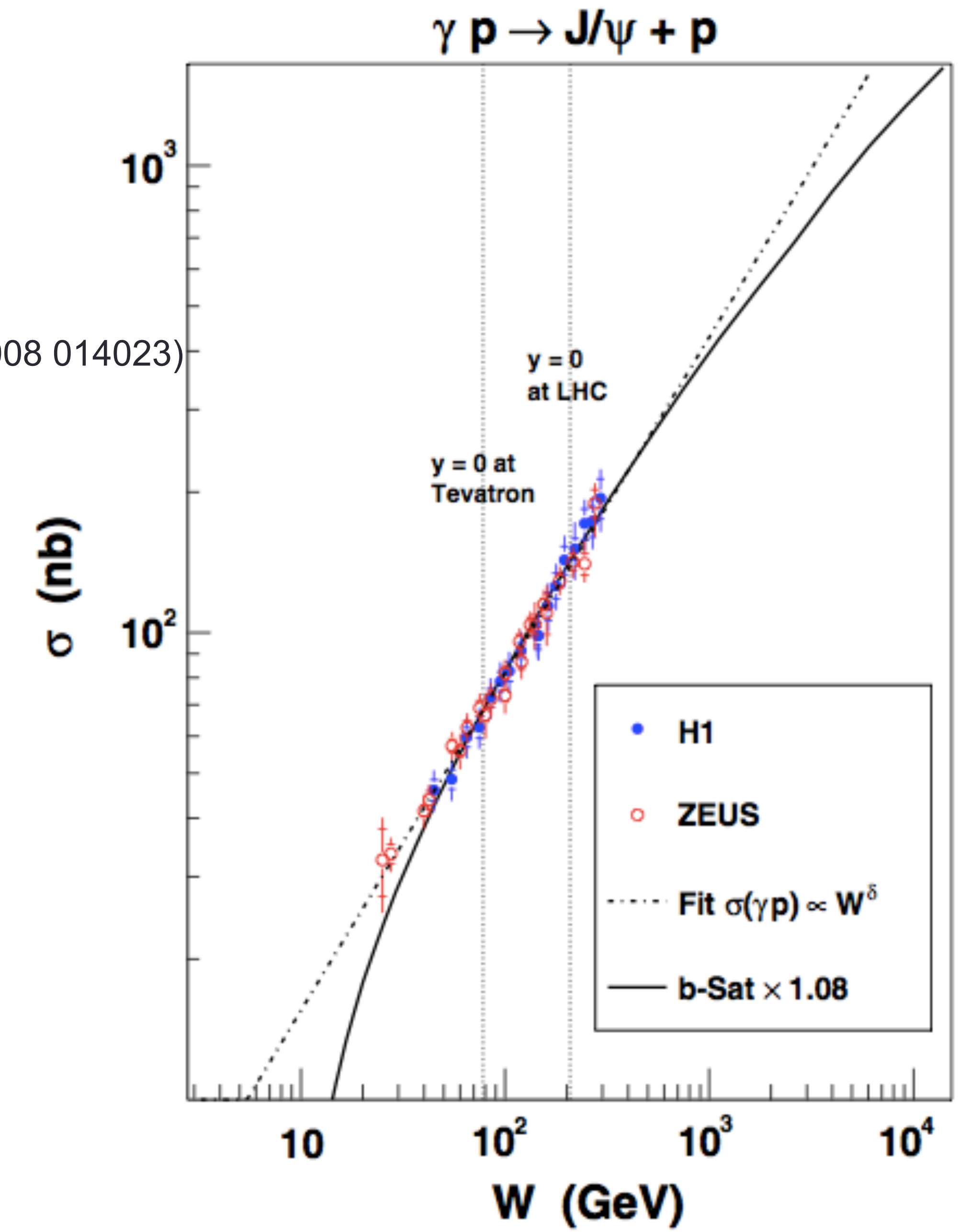
from fit

plotted

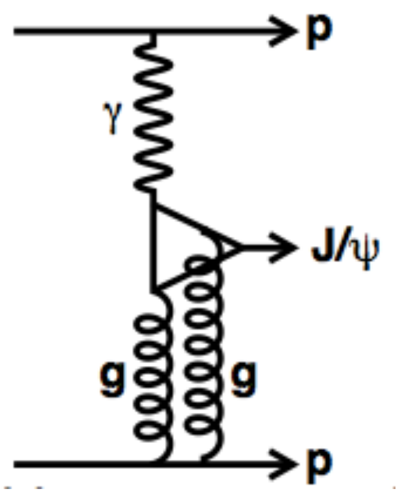


Deviations from power law

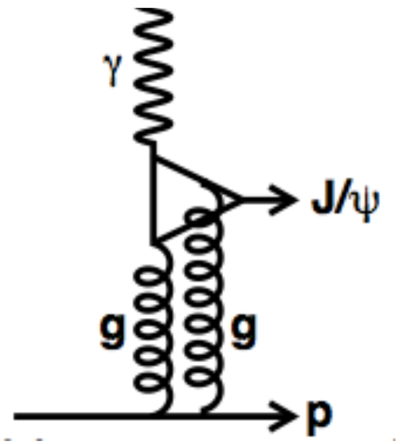
Saturation model (Motyka&Watt PRD 78 2008 014023) has deviation from pure power law.

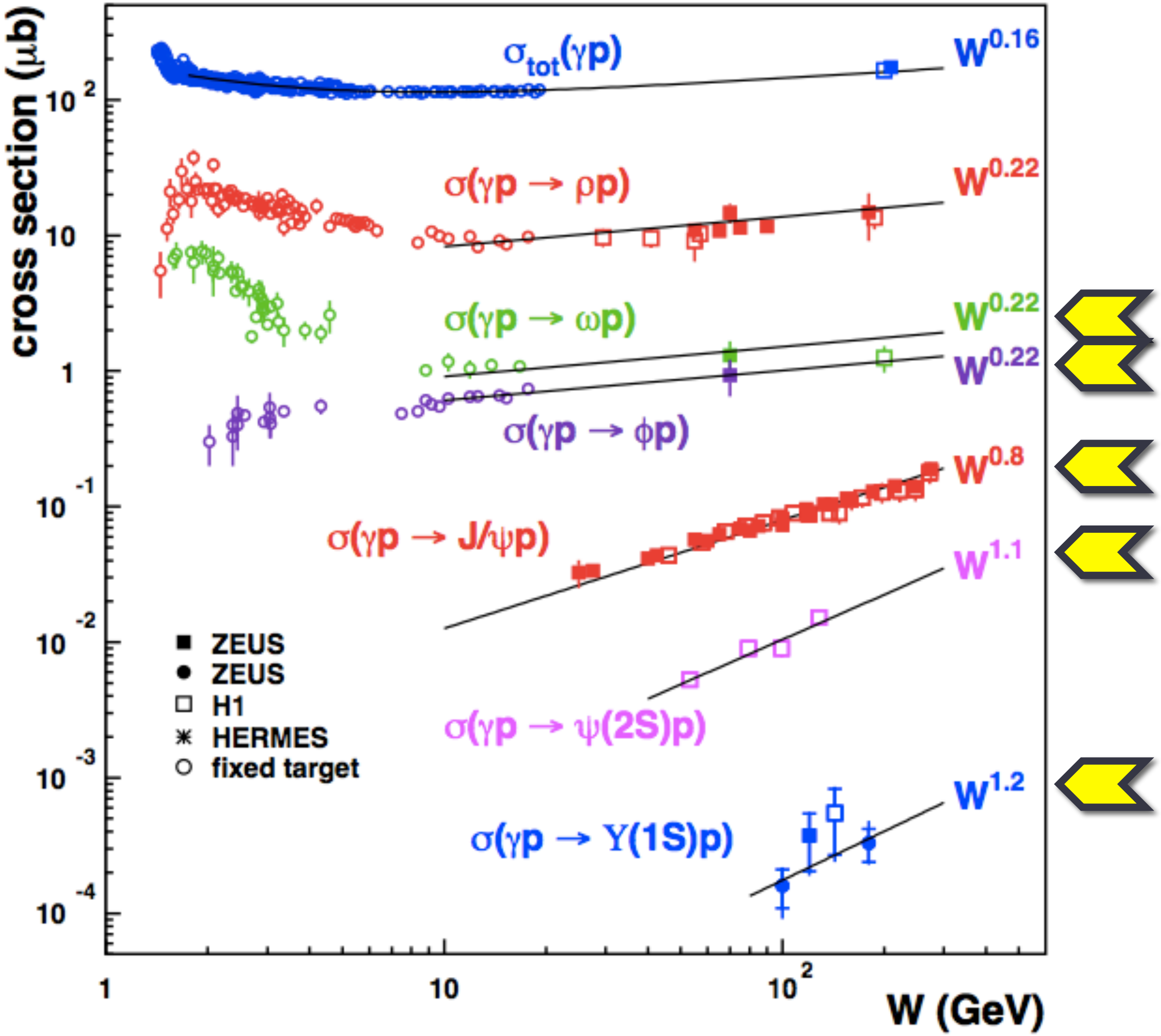


LHCb compared to theory & experiment



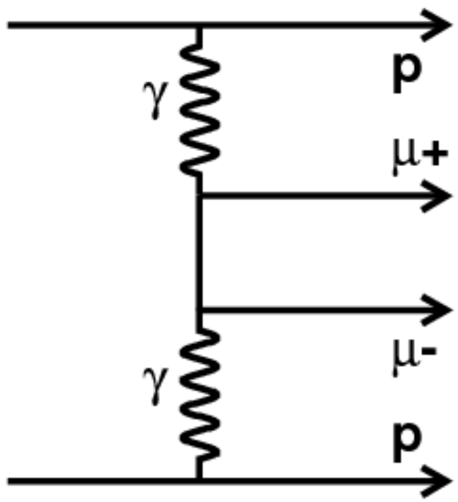
looks very like

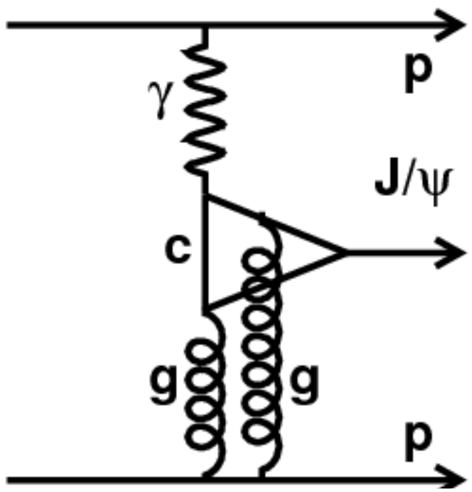


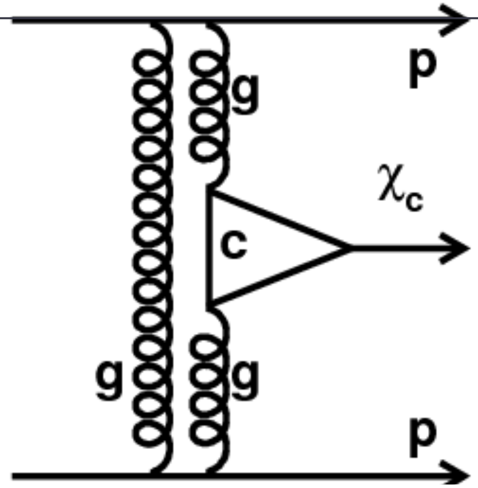


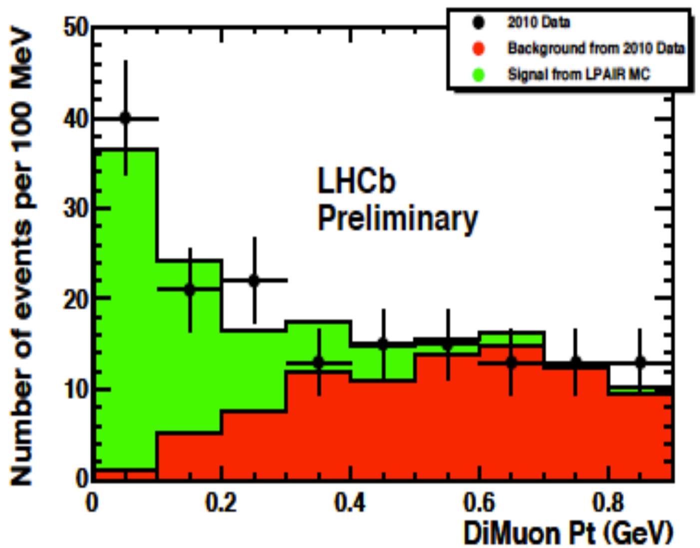
Other ways to fill the vacuum with muons

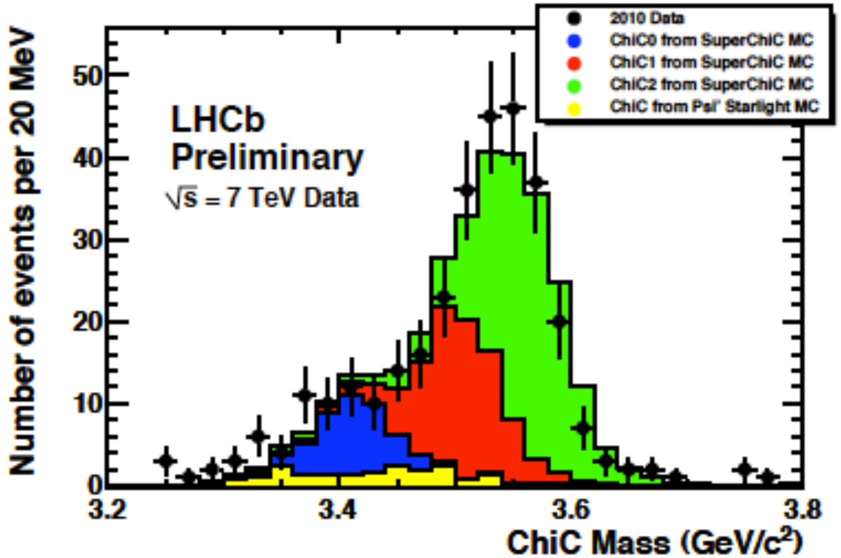
χ_c 0,1,2 decay to Jpsi+photon
Vacuum state should be 0











3. Summary

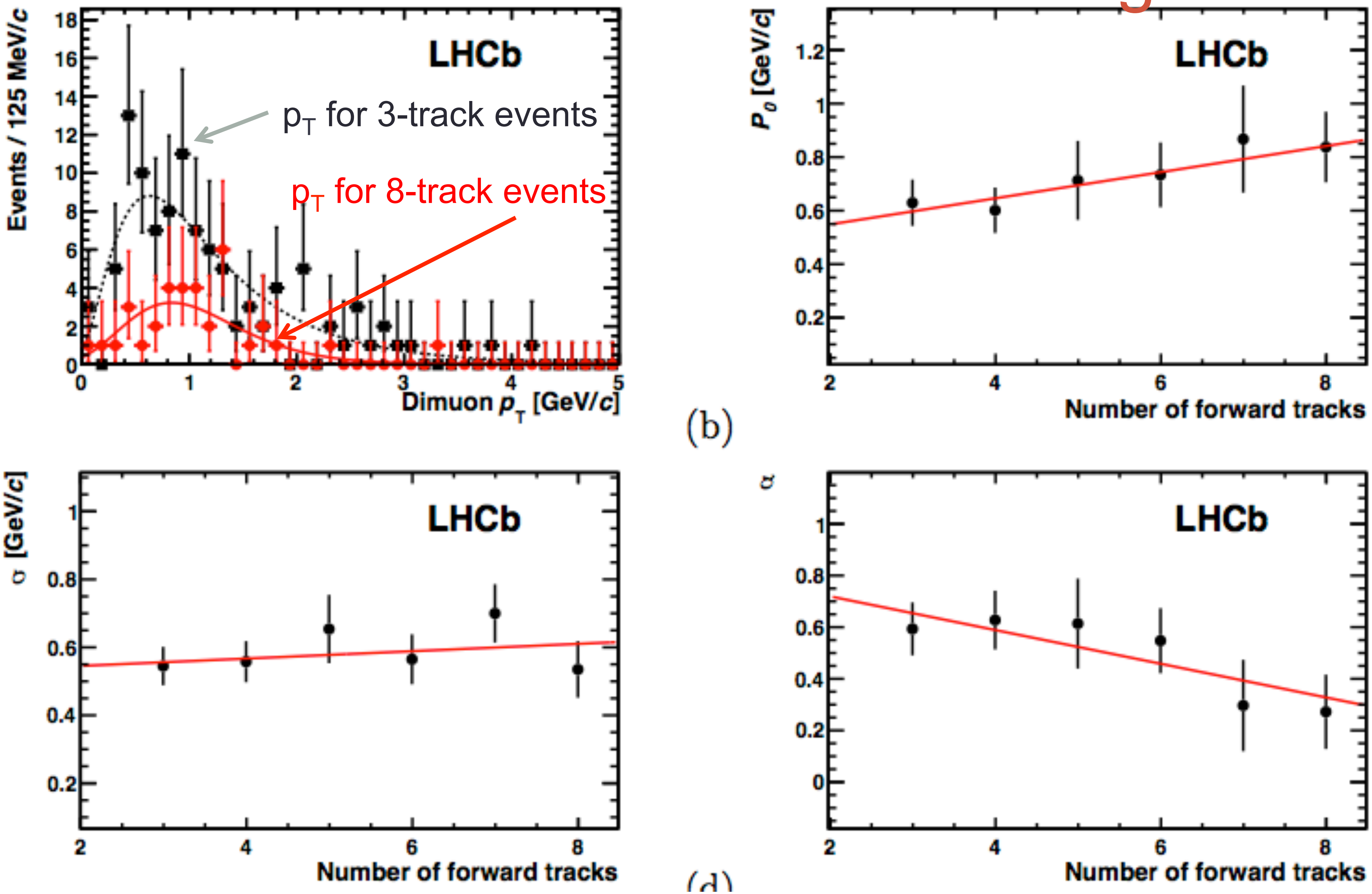
- Nature of the pomeron investigated
- Sensitive to gluon PDF
- Prospect for new phenomena in QCD
  - saturation
  - odderon (3-bound gluons)

Conclusions

- Rich variety of physics available from LHC
- Standard Model has so far resisted all our attempts to break it!
- Precision physics and new energy regimes are key to improved understanding
- Irish physics very much involved at the energy frontier.

Backup

Determination of non-resonant background



Exclusive pseudo-vector production

$\sigma_{\chi_{c0}\to\mu^+\mu^-\gamma}$ = 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

BR(χc0->J/ψγ)=1.2%
BR(χc1->J/ψγ)=34.4%
BR(χc2->J/ψγ)=19.5%

Dominance of Xc0 is confirmed.

Experimentally difficult to separate three resonances and determine non-resonant background for each.