W, Z and exclusive μμ at LHCb

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Workshop on Heavy Particles at the LHC
Pauli Centre, ETH, Zurich
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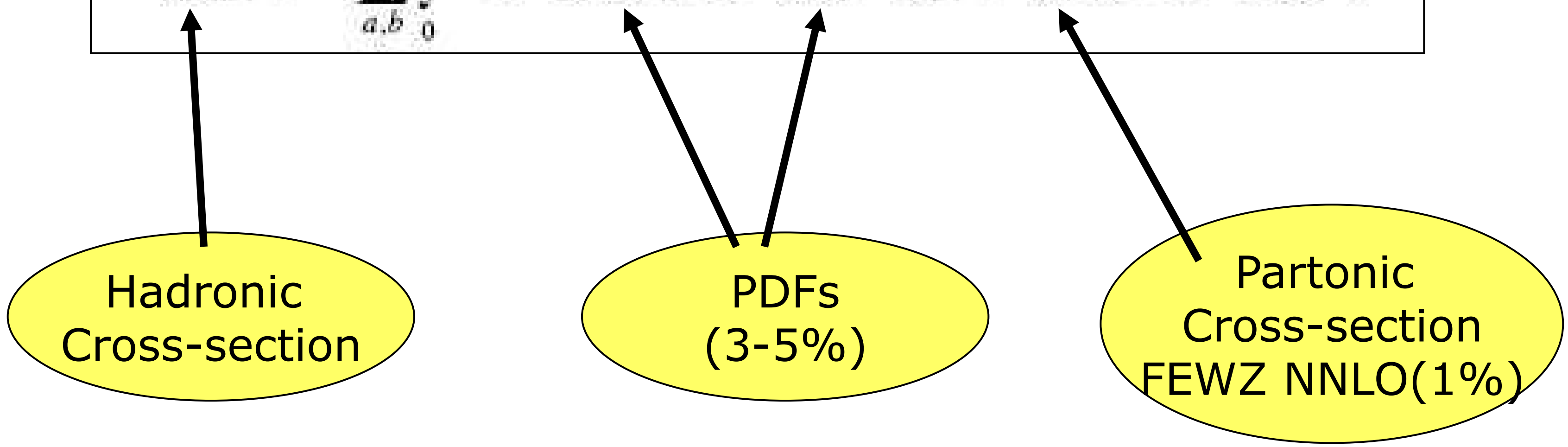
Outline

- Overview
- W,Z production (x~10^{-4})
- Sensitivity to PDFs
- Sensitivity to $\sin^2\theta_W$
- γ^* production (x~10^{-6})
- Exclusive processes

EW physics motivation

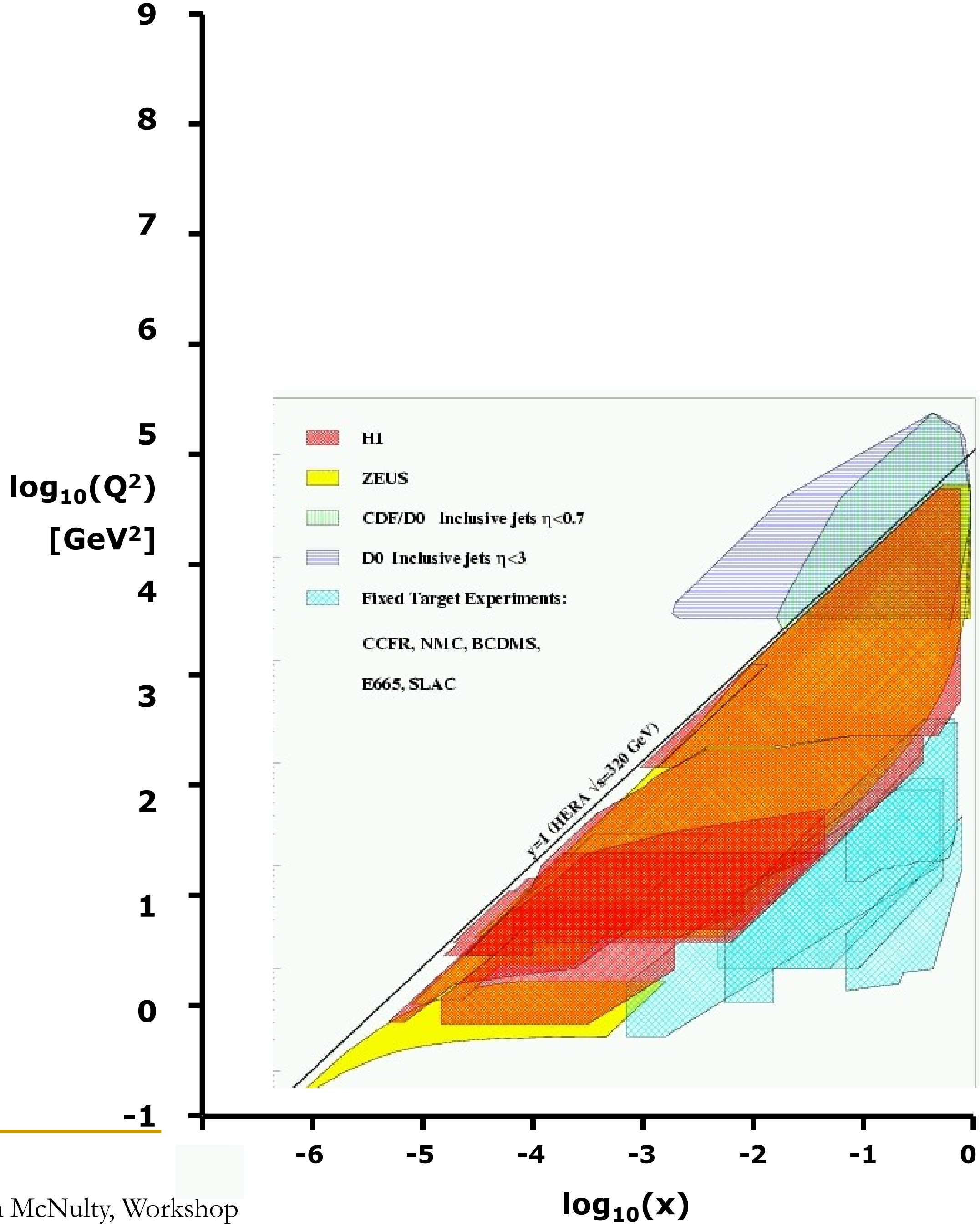
$$\sigma_X(Q^2) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, Q^2) f_2(x_2, Q^2) \hat{\sigma}_{ab \to X}(x_1, x_2, Q^2)$$



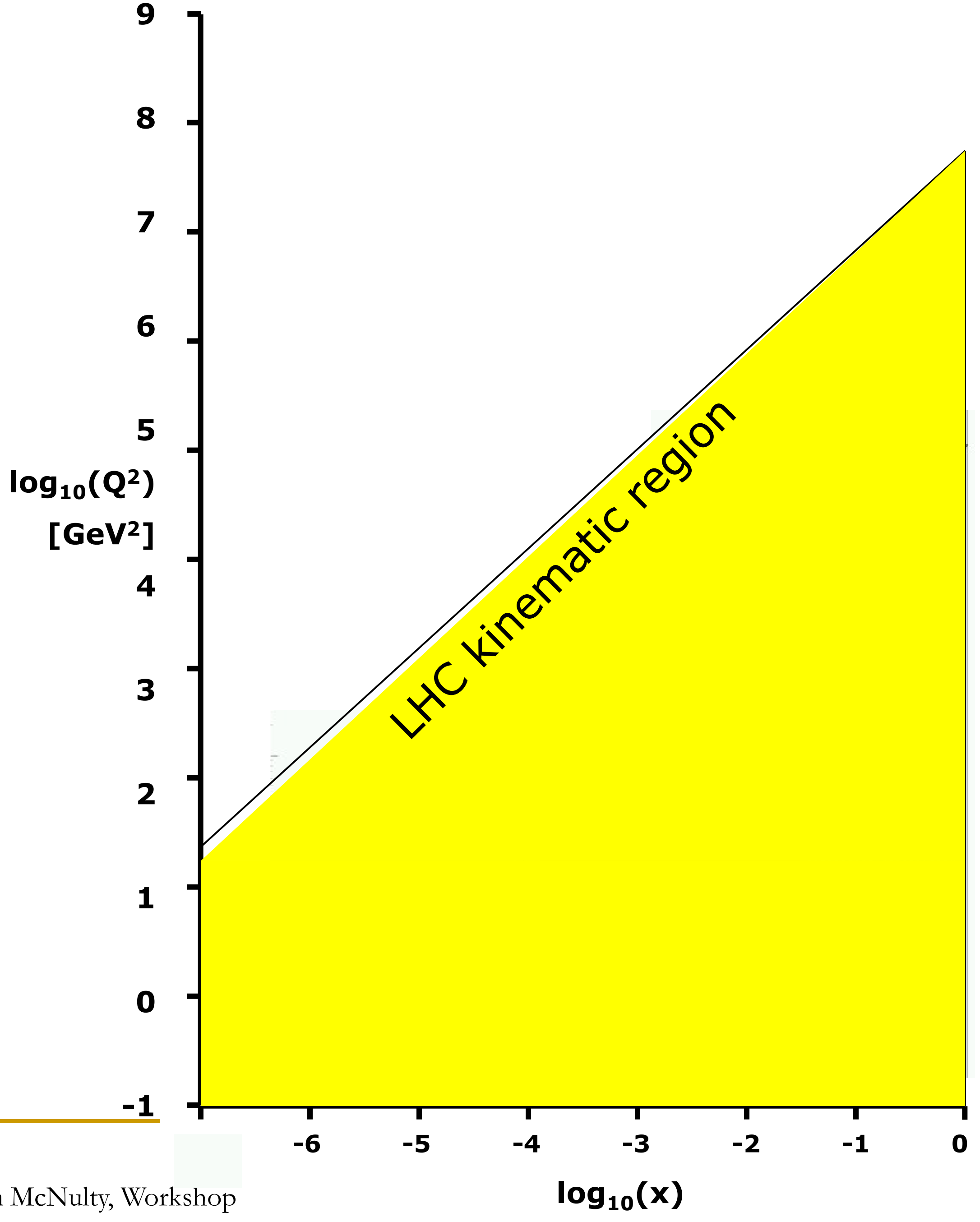
Test the SM at highest energies

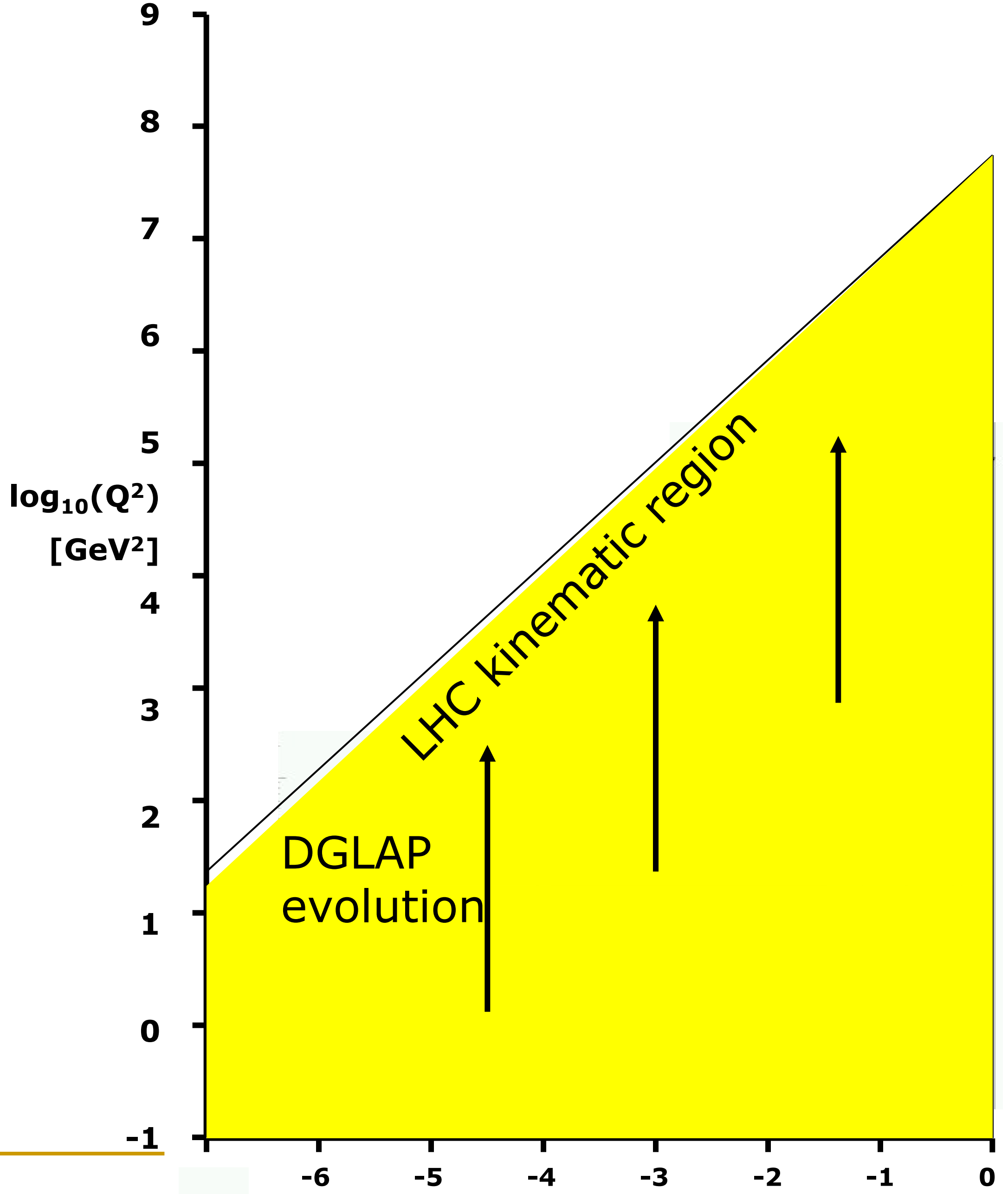
Check out that DGLAP evolution works (test QCD)

Push theory into interesting regions with very soft gluons

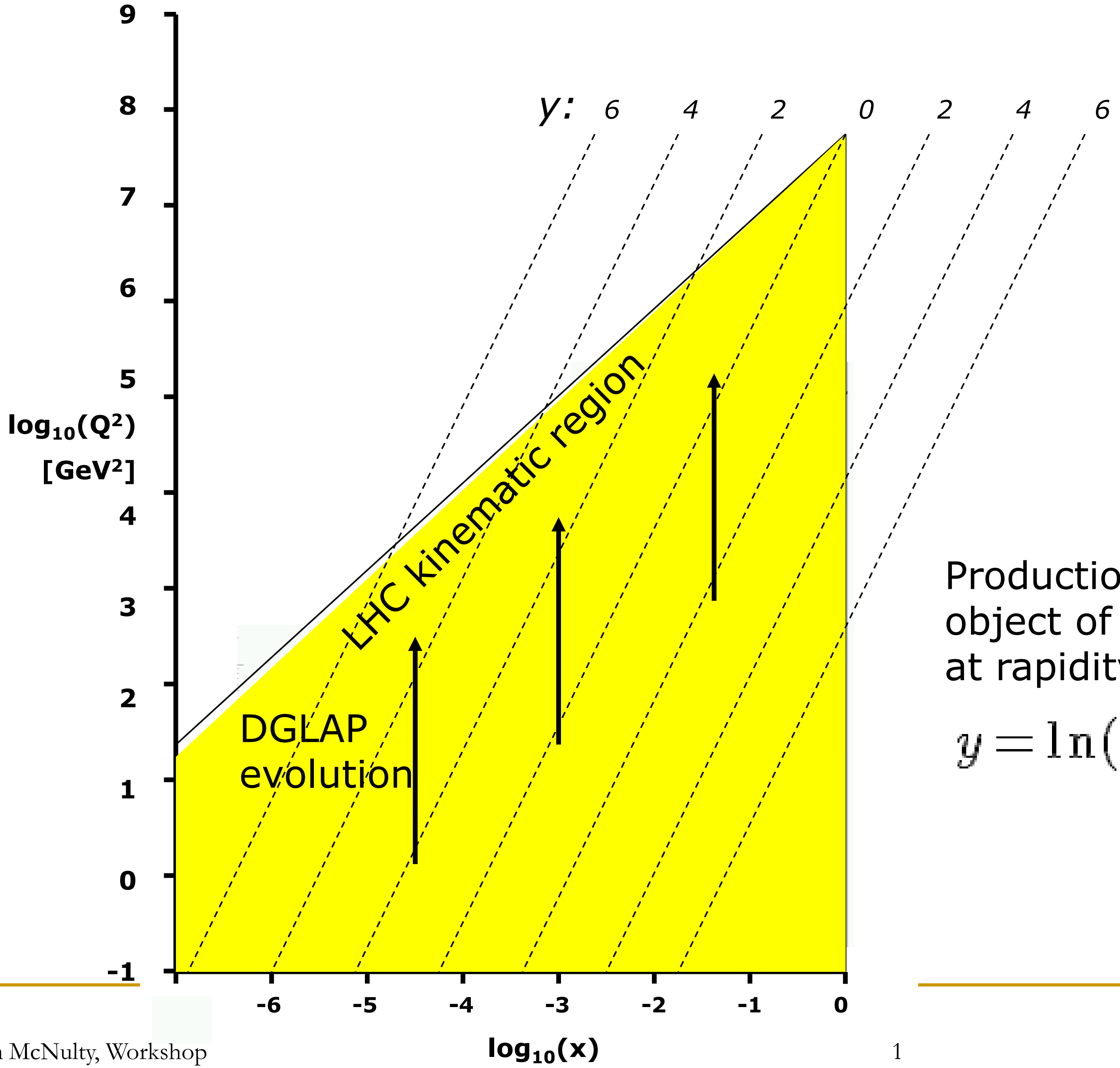


H1
ZEUS
CDF/D0 Inclusive jets η<0.7
D0 Inclusive jets η<3
Fixed Target Experiments:
CCFR, NMC, BCDMS,
E665, SLAC
y=1 (HERA √s=320 GeV)
log10(Q2) [GeV2]
log10(x)
9
8
7
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0


9
8
7
6
5
log10(Q2) [GeV2]
4
3
2
1
0
-1
LHC kinematic region
-6
-5
-4
-3
-2
-1
0
log10(x)

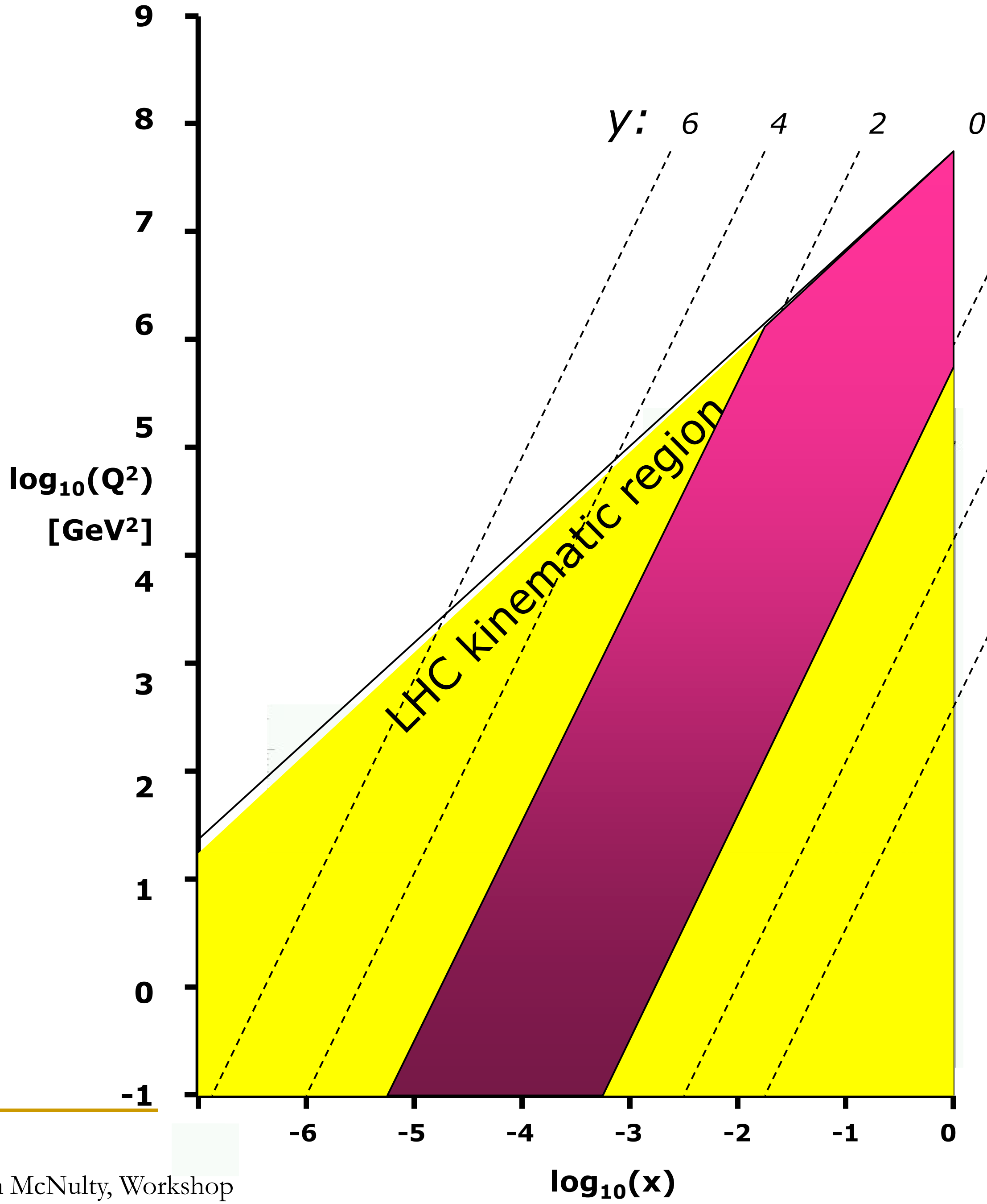


9
8
7
6
5
log10(Q2)
[GeV2]
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0
log10(x)
LHC kinematic region
DGLAP
evolution



Production of object of mass Q at rapidity

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

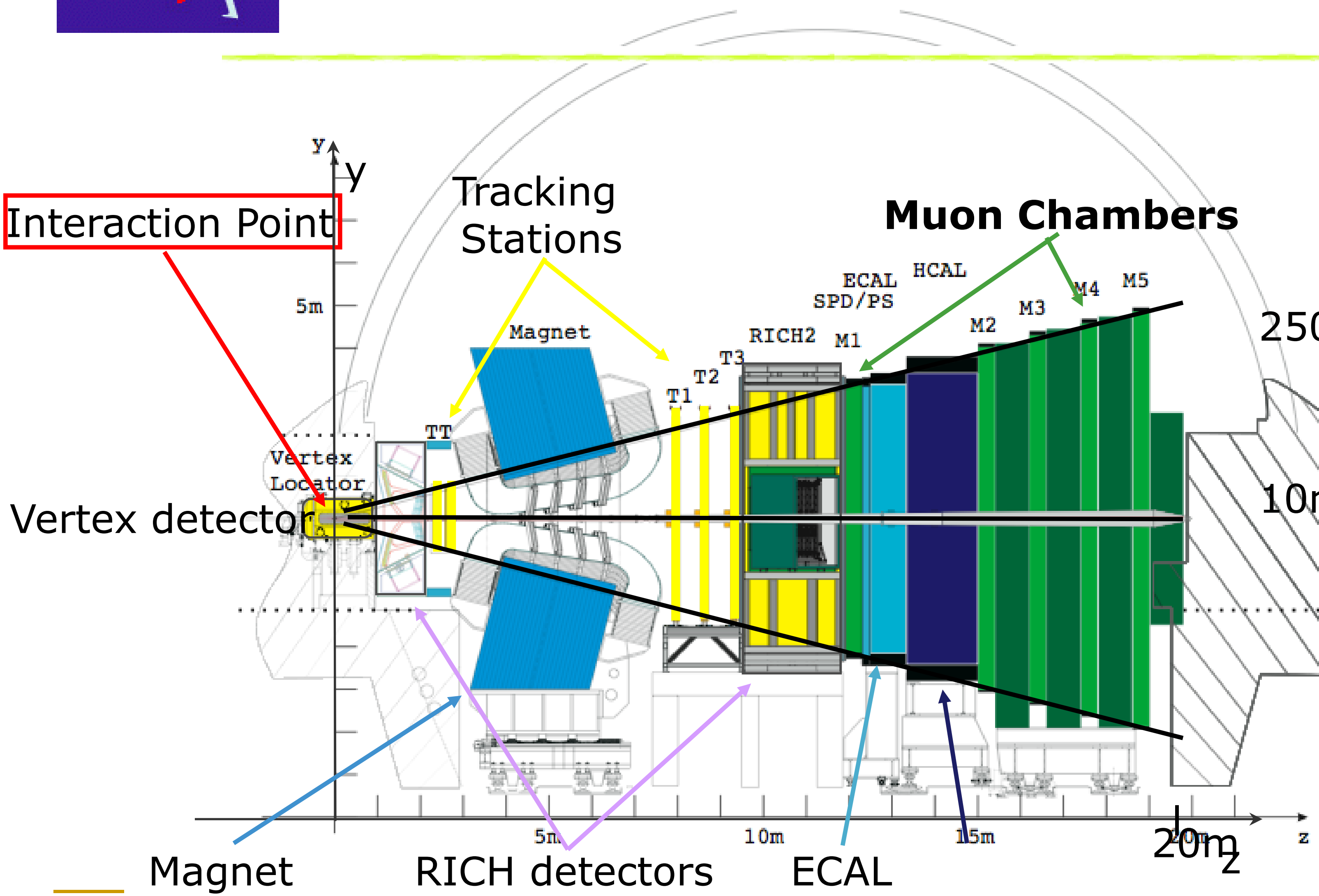


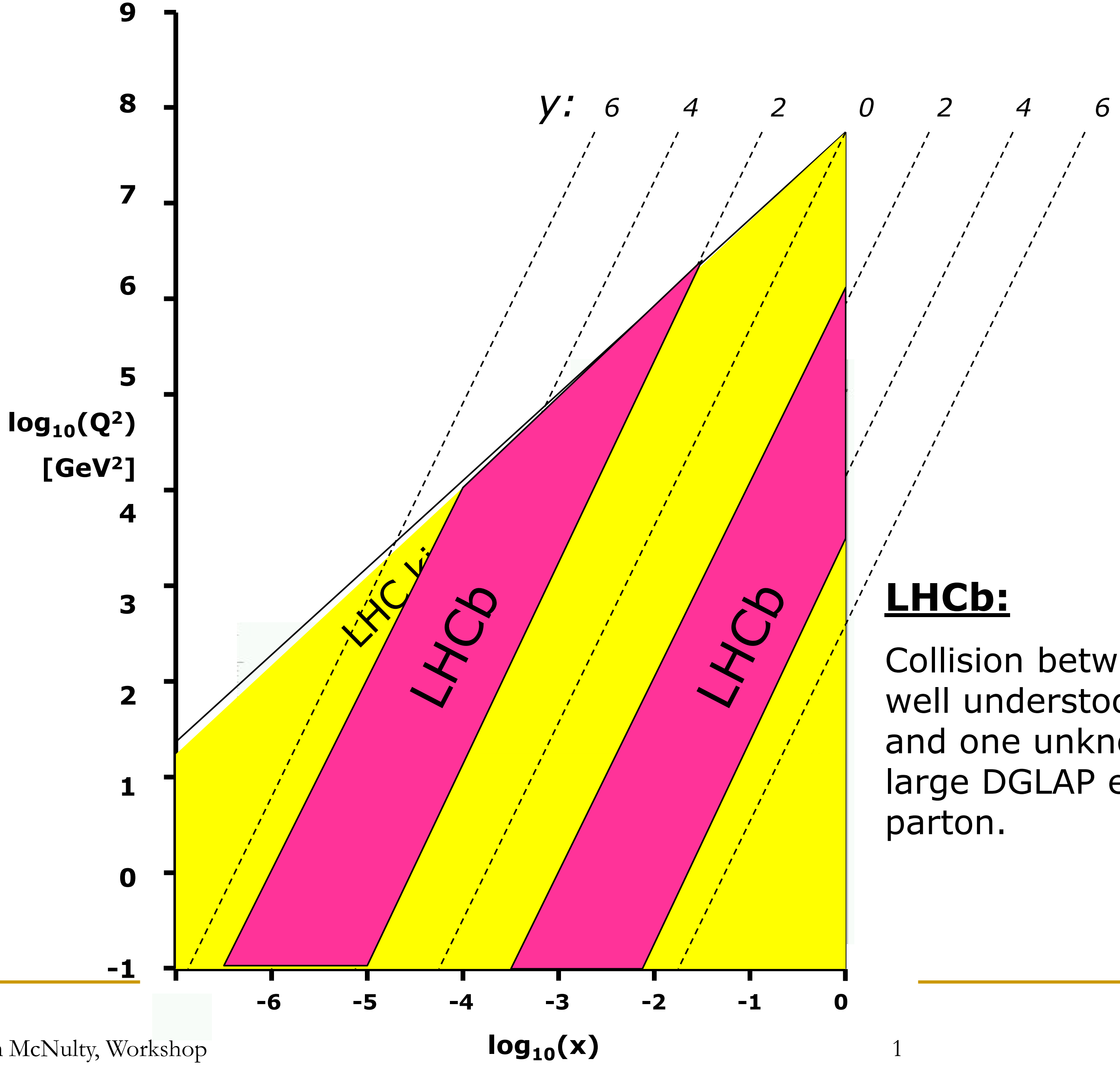
ATLAS & CMS:

Collision between two partons having similar momentum fractions.

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

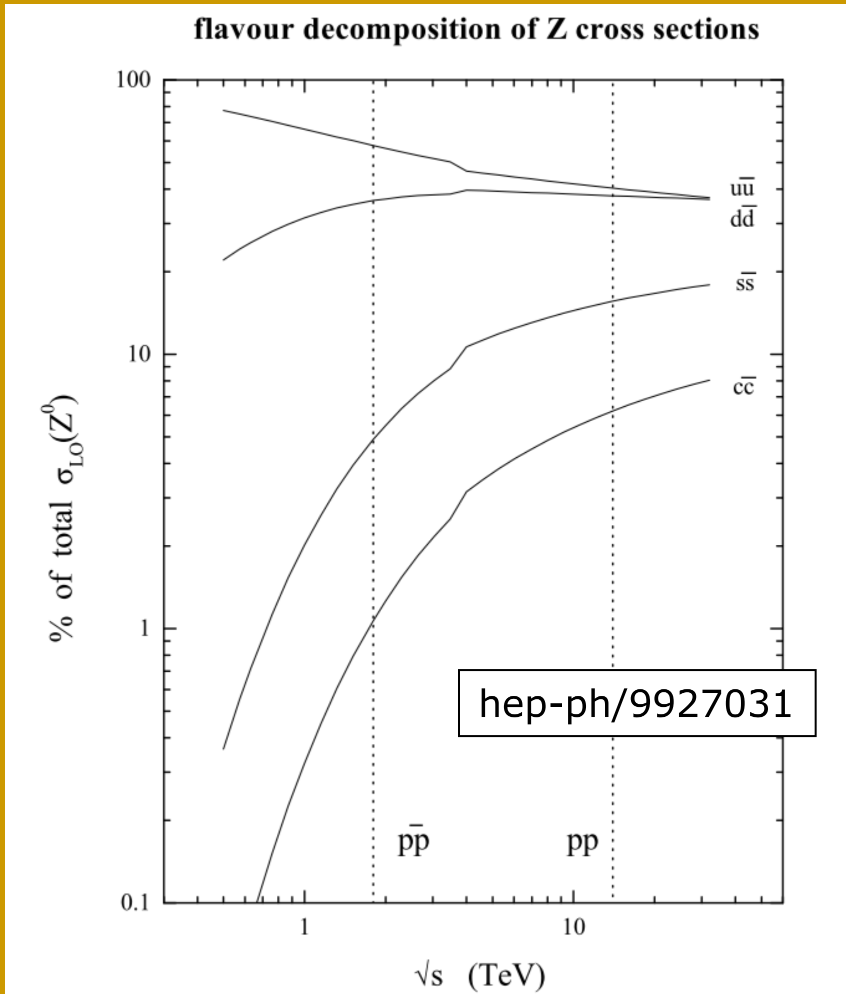
LHCb: a forward spectrometer

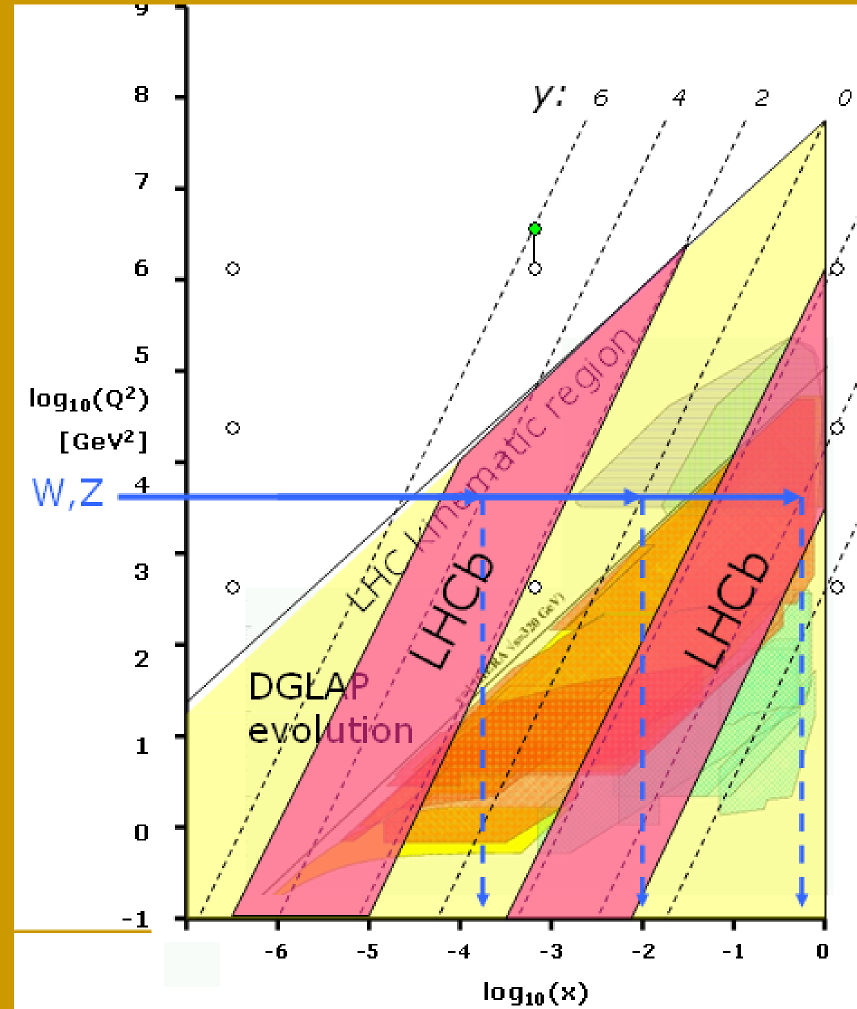




LHCb:

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

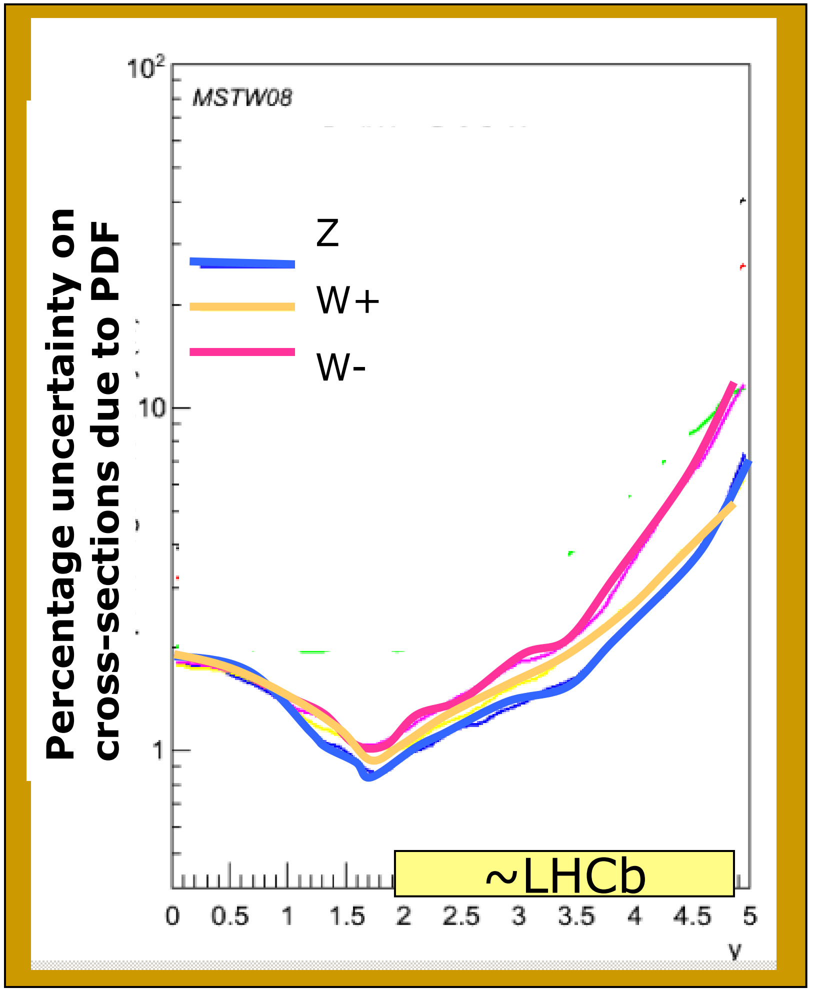

flavour decomposition of Z cross sections
% of total $\sigma_{LO}(Z^0)$
100
10
1
0.1
1
10
√s (TeV)
$u\bar{u}$
$d\bar{d}$
$s\bar{s}$
$c\bar{c}$
$p\bar{p}$
pp
hep-ph/9927031


y: 6 4 2 0
log10(Q2) [GeV2]
log10(x)
W,Z
LHC kinematic region
LHCb
LHCb
DGLAP evolution

Effect of PDF uncertainties on cross-sections

- Region where the most precise EW tests can be made.
- At highest rapidities, PDFs can be constrained.

- Experimental statistical error <<1%.
- Systematic error likely to be ~1%



But you can do better !

$$R_{\mp}(y_W) \equiv \frac{d\sigma/dy_W(W^-)}{d\sigma/dy_W(W^+)} \approx \frac{d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2)} = \frac{d(x_1)}{u(x_1)} \cdot \frac{\bar{u}(x_2)}{\bar{d}(x_2)} \approx \frac{d(x_1)}{u(x_1)}$$

So ratio of Ws is sensitive to d to u ratio. (For LHCb d_v/u_v)

$$A_{\pm}(y_W) = \frac{d\sigma/dy_W(W^+) - d\sigma/dy_W(W^-)}{d\sigma/dy_W(W^+) + d\sigma/dy_W(W^-)} \approx \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)} \approx \frac{u(x_1) - d(x_1)}{u(x_1) + d(x_1)}$$

W asymmetry is sensitive to difference in u and d. (For LHCb u_v-d_v)

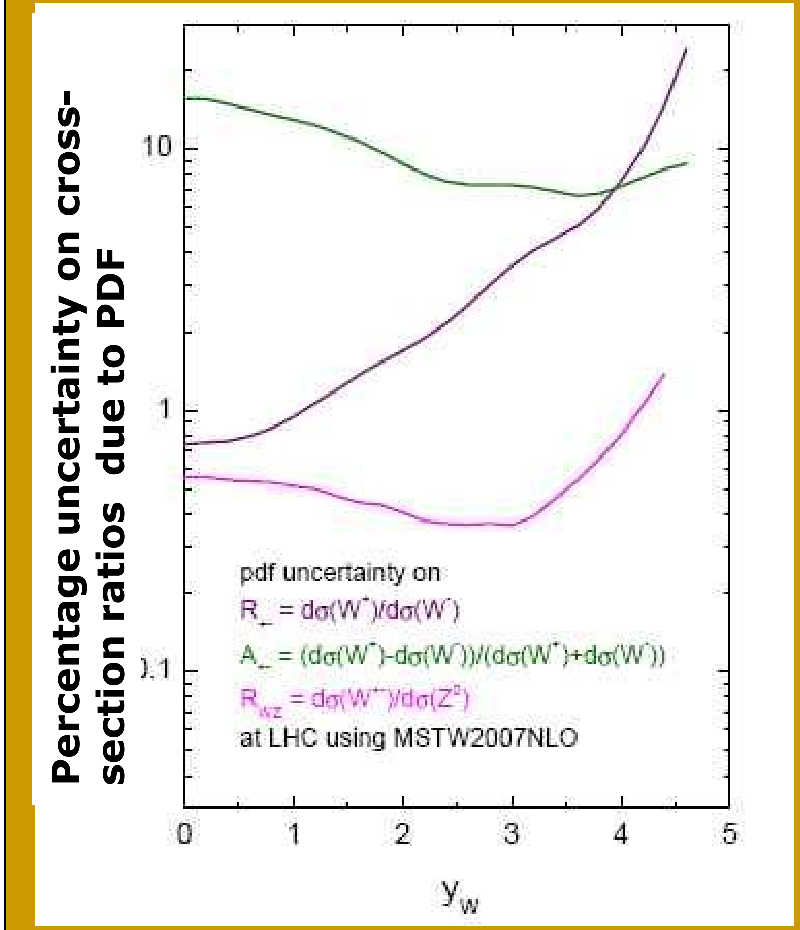
$$R_{Z/W}(y) \equiv \frac{d\sigma/dy(Z^0)}{d\sigma/dy(W^+) + d\sigma/dy(W^-)} \approx \frac{\kappa_u\, u(x_1')\bar{u}(x_2') + \kappa_d\, d(x_1')\bar{d}(x_2')}{|V_{ud}|^2 \left\{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)\right\}}$$

Ratio of Z to W is almost insensitive to PDFs!

Gold plated test of SM at the highest energies

Effect of PDF uncertainties on cross-sections

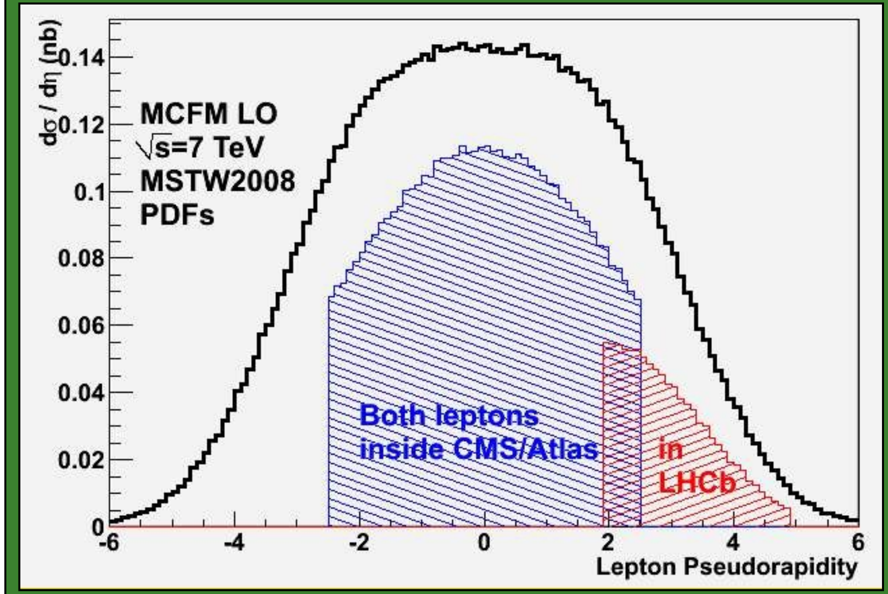
- R_{wz} precise test of SM everywhere.
- Difference in u and d quarks can be significantly improved by all experiments at the LHC.
- Going forward, you increasingly constrain the u-valence to d-valence ratio.

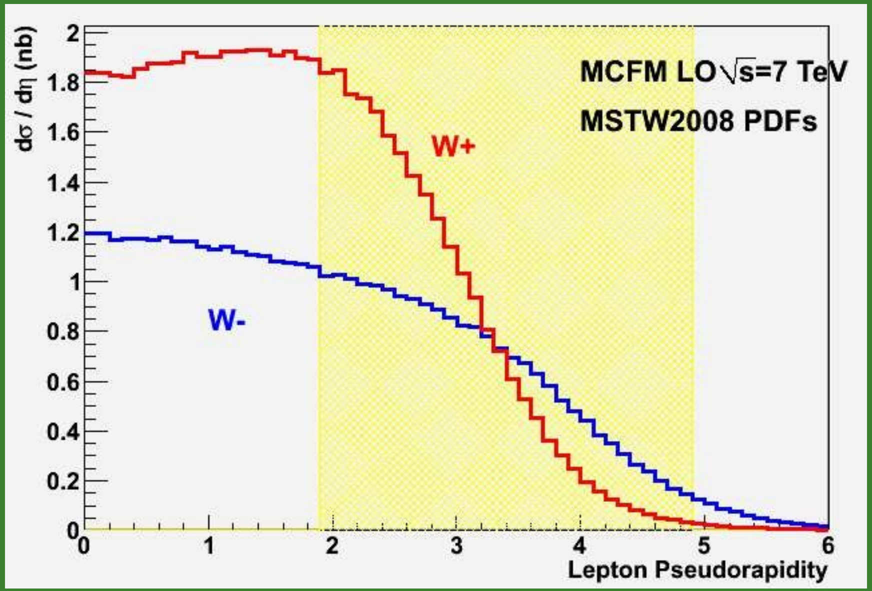


- Even nicer, most experimental systematics (especially luminosity) cancel in the ratio.

Z Cross-section Measurement at LHCb

$$\sigma(Z \to \mu\mu : 2 < \eta_{\mu} < 4.5, P_{T\mu} > 20\, GeV\ , 81 < M_{\mu\mu} < 101\, GeV\ )$$

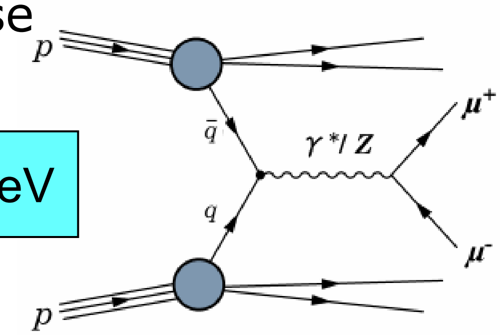




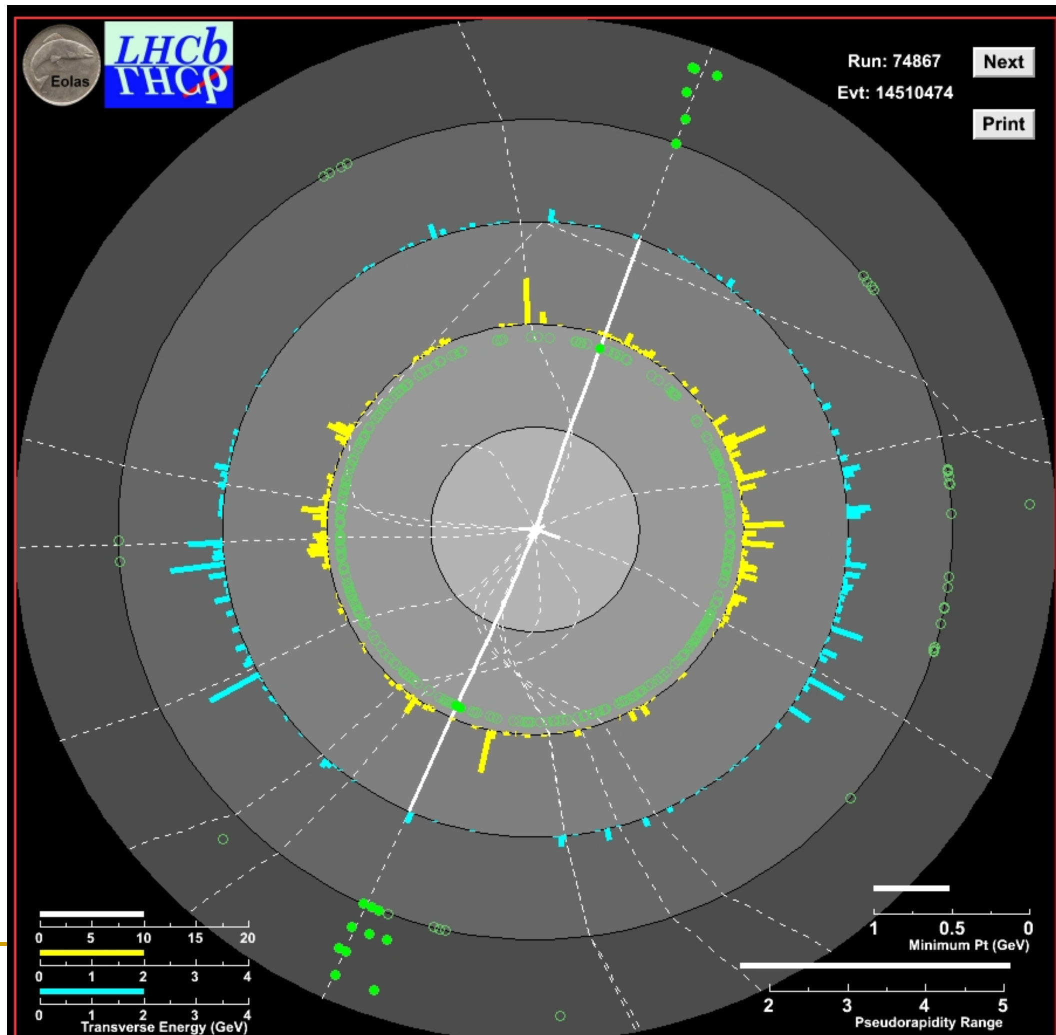
8% of Z within LHCb acceptance

17% (16%) of W^+ (W^-) within LHCb acceptance

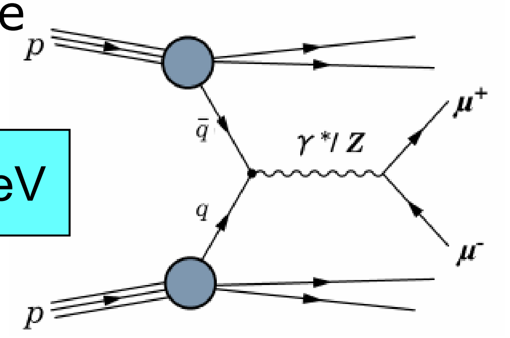
Z: Characteristic signature of two high transverse momentum muons with invariant mass m_Z



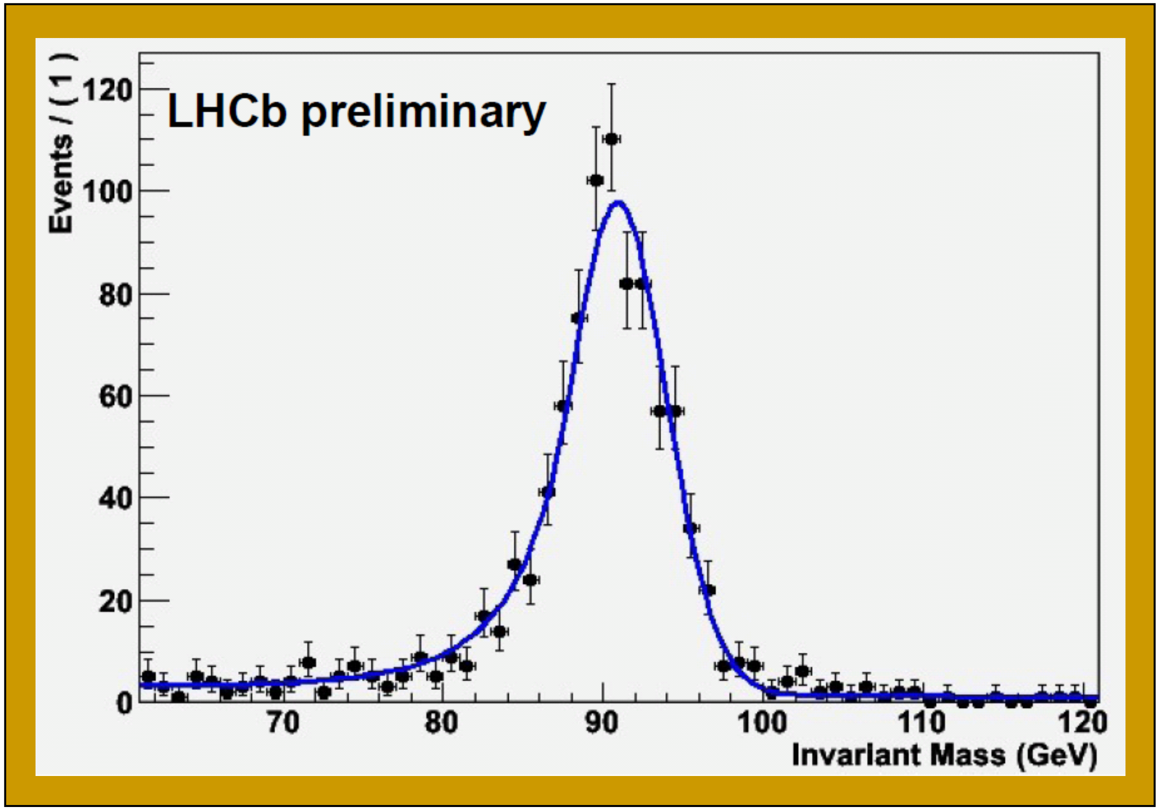
Require two muons: p_t>20GeV, 2<η<4.5. 81<$M_{\mu\mu}$<101 GeV



Z: Characteristic signature of two high transverse momentum muons with invariant mass m_Z



Require two muons: p_t>20GeV, 2<η<4.5. 81<$M_{\mu\mu}$<101 GeV



To turn into cross-section:

$$\sigma_{Z\rightarrow\mu\mu}(\Delta y) = \frac{N^Z_{tot} - N^Z_{bkg}}{\epsilon_Z L}$$

$$\epsilon_Z = A_z \epsilon_Z^{trig} \epsilon_Z^{track} \epsilon_Z^{muon} \epsilon_Z^{selection}$$

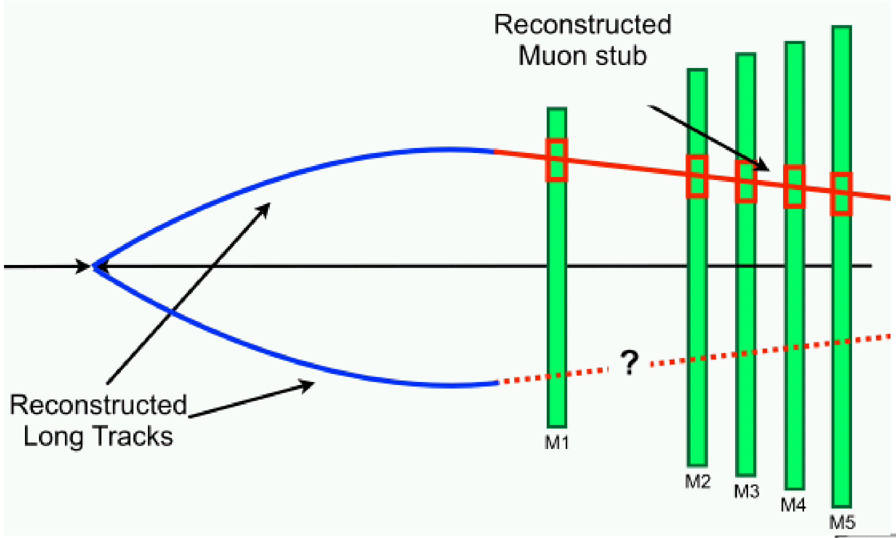
=1 =1

Insomuch as possible, take everything from data.

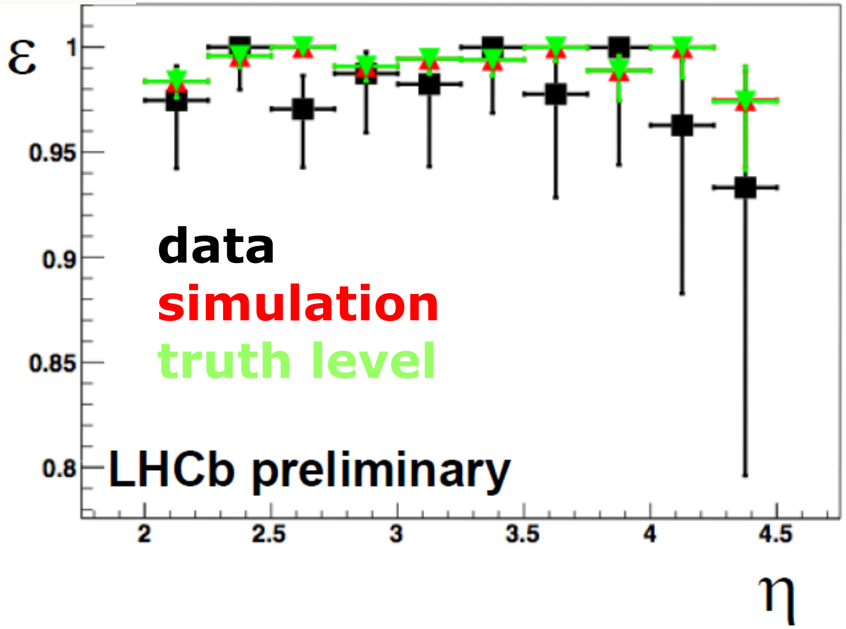
Muon identification efficiency

$\epsilon_Z = A_z \epsilon_Z^{trig} \epsilon_Z^{track} \epsilon_Z^{muon} \epsilon_Z^{selection}$

$\varepsilon_W = 98.2 \pm 0.5\%$
$\varepsilon_Z = 96.5 \pm 0.7\%$

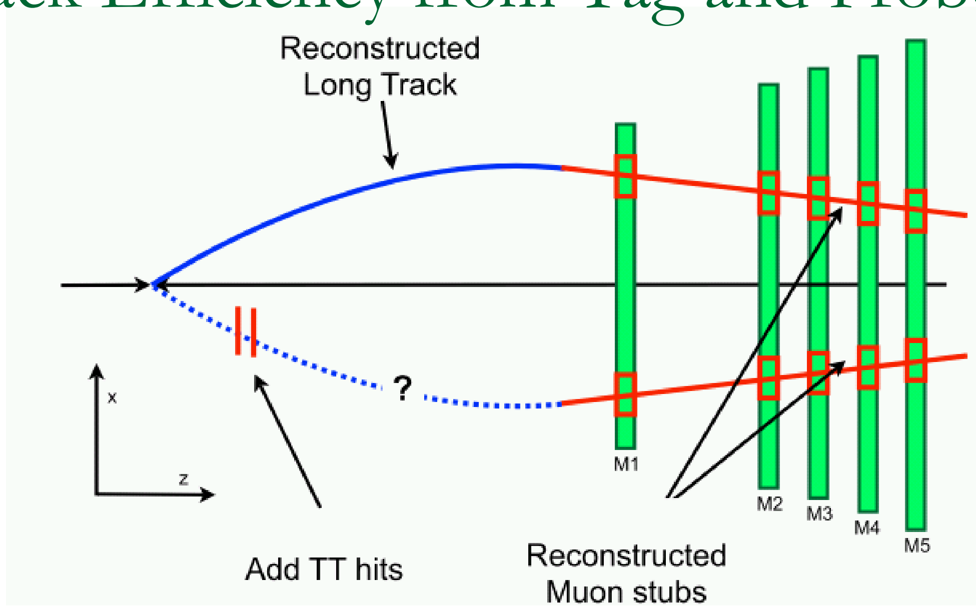


Efficiency flat in p_T, η, ϕ
No evidence for charge bias



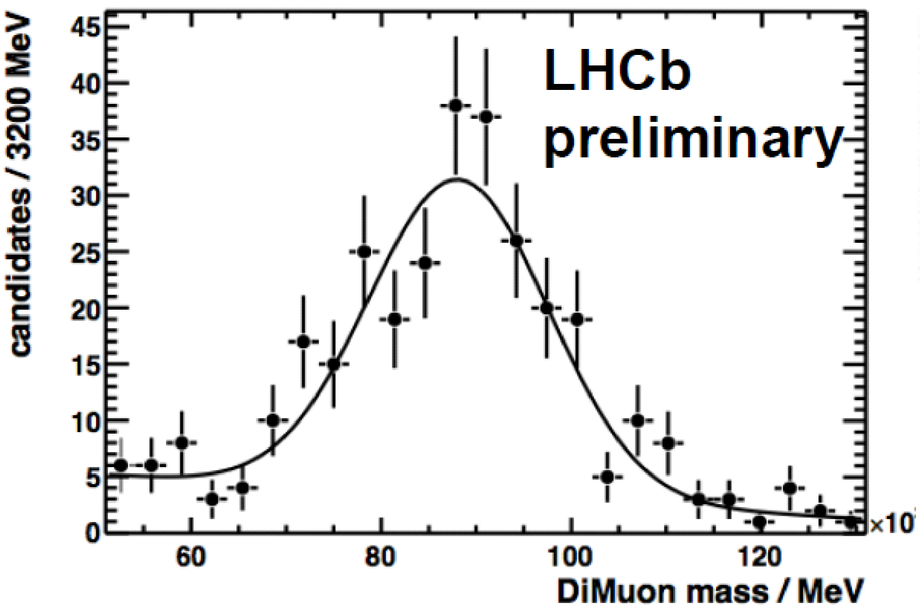
Track Efficiency from Tag and Probe

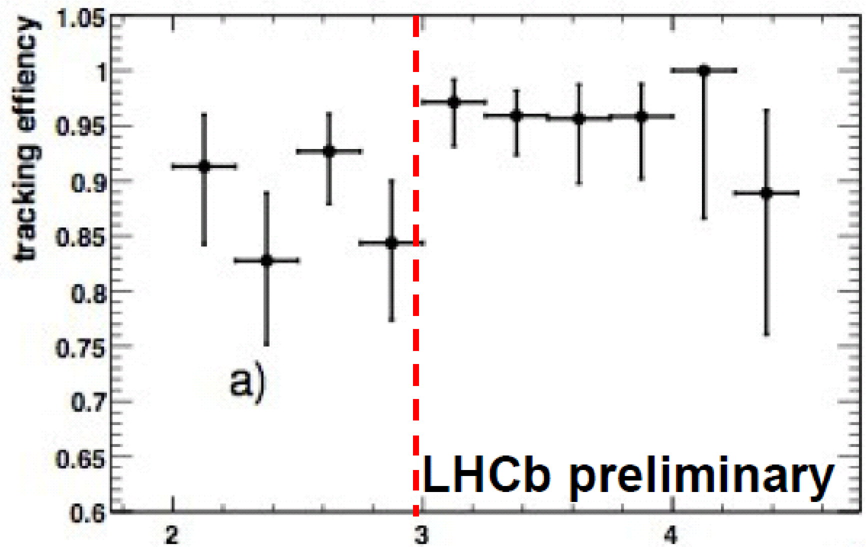
$$\epsilon_Z = A_z \epsilon_Z^{trig} \epsilon_Z^{track} \epsilon_Z^{muon} \epsilon_Z^{selection}$$



ε_{W+}=73 ± 3%
ε_{W-}= 78 ± 3%
ε_Z = 83 ± 3%

(W+/W- differ due to lepton η distribution)



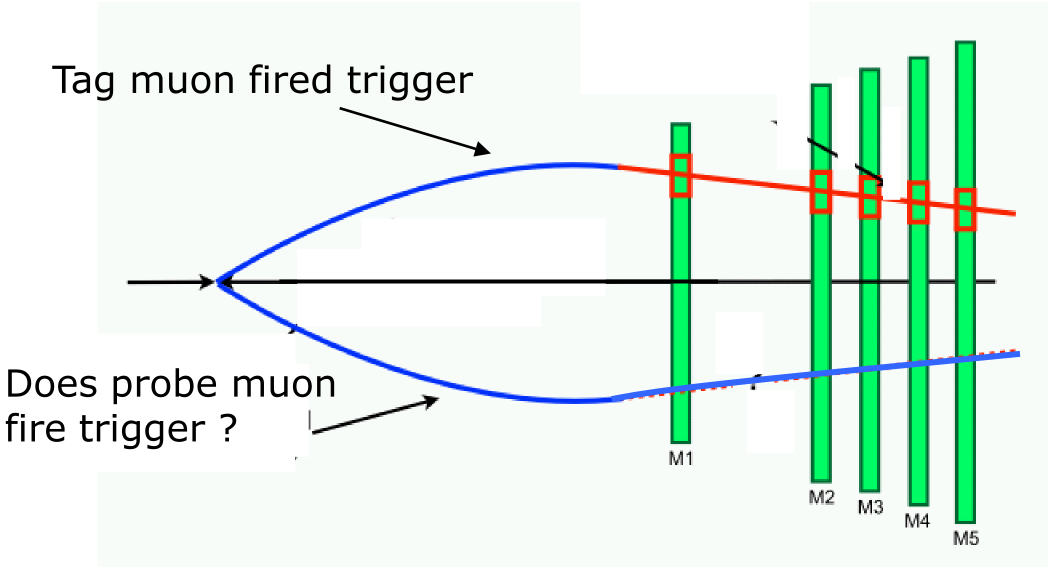


(flat in p_T and ϕ)

η

Trigger Efficiency from Tag and Probe

$$\epsilon_Z = A_Z \epsilon_Z^{trig} \epsilon_Z^{track} \epsilon_Z^{muon} \epsilon_Z^{selection}$$



$\varepsilon_W = 0.9*(80.5 \pm 1.4)\%$
$\varepsilon_Z = 0.9*(95.7 \pm 0.5)\%$

(Globel cuts:
Very large events
rejected by trigger)

Trigger path

LOMuonDecision_TOS (Muon stub with PT > 1.5 GeV/c)

Hlt1SingleMuonNoIPLOHighPTDecision_TOS (Long track Muon with PT > 10 GeV/c and no IP requirement)

Hlt2SingleHighPTMuonDecision_TOS

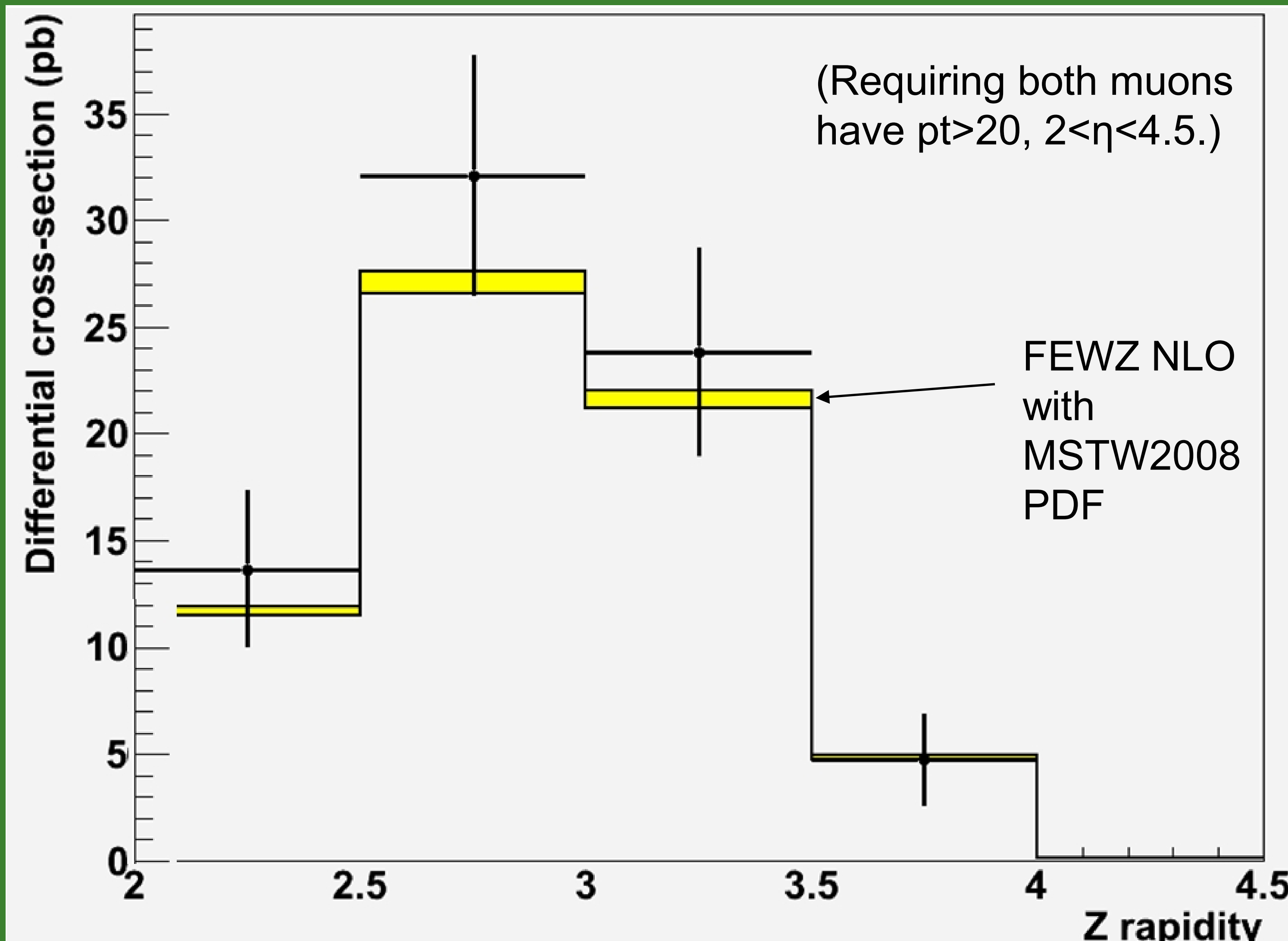
Z analysis

$$\sigma_{Z\to\mu\mu}(\Delta y) = \frac{N^Z_{tot} - N^Z_{bkg}}{\epsilon_Z L}$$

N_Z^{tot}	833
$Z \to \tau\tau$	0.2 ± 0.2
Heavy flavours	1 ± 1
Misidentified π/K	$<< 1$
N_Z^{bkg}	1.2 ± 1.2
ϵ^Z_{trig}	0.86 ± 0.01
ϵ^Z_{track}	0.83 ± 0.03
ϵ^Z_{muon}	0.97 ± 0.01
ϵ^Z_{sel}	1.
A^Z	1.
ϵ_Z	0.69 ± 0.03
L	$16.5 \pm 1.7 pb^{-1}$
$\sigma_Z(2. < \eta_1, \eta 2 < 4.5, 81 < m_Z < 101)$	$73 \pm 4 \pm 7$ pb.

↑ Phase space for measurement ↑

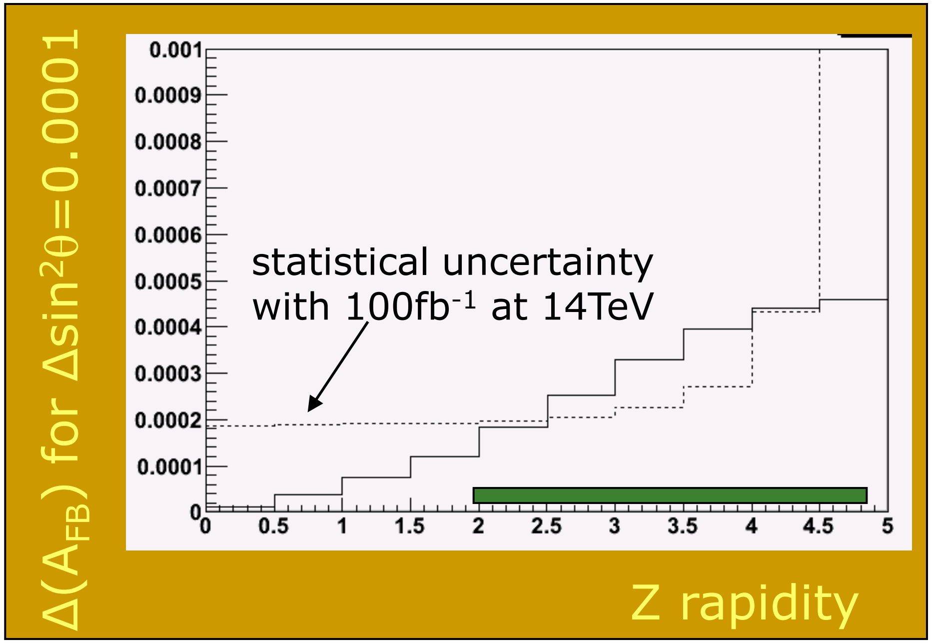
Differential distribution (Z)

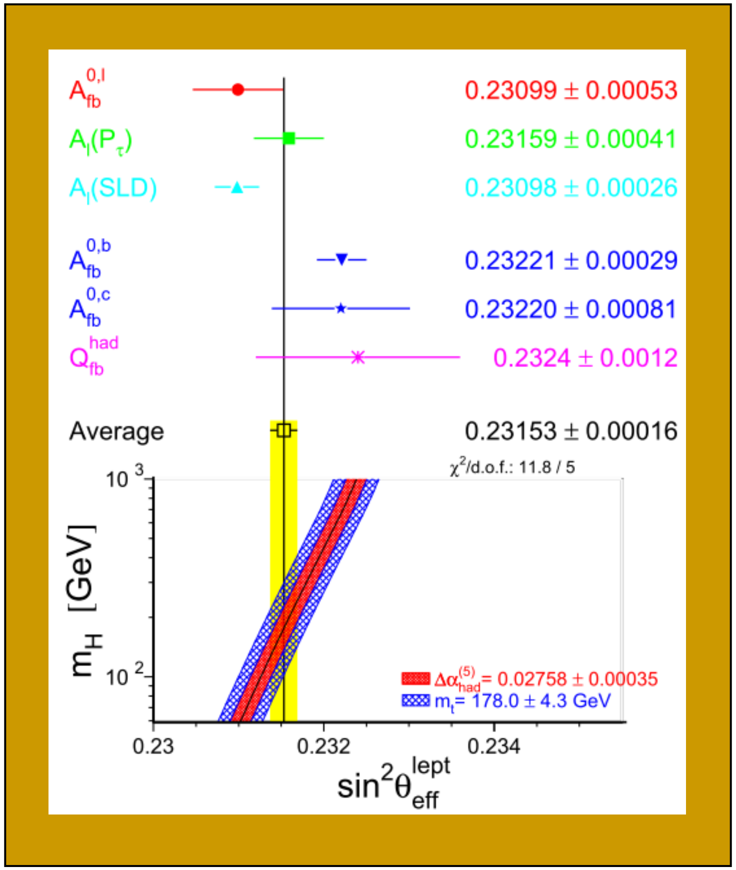


Measuring A_{FB} in pp->Z->μμ ?

$A^0_{FB}=3/4\, A_\mu(\, u\, A_u\; + d\, A_d + s\, A_s)$

LHC Problems: 1. PDF uncertainties
2. which is quark direction?





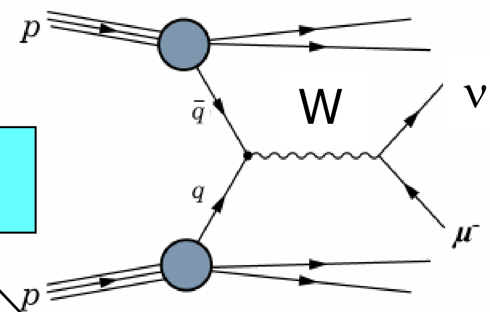
Statistically, a forward detector at high luminosity could measure A_{FB} with better precision than current WA.

How confident are we of theory? of PDF uncertainties? of detector systematics?

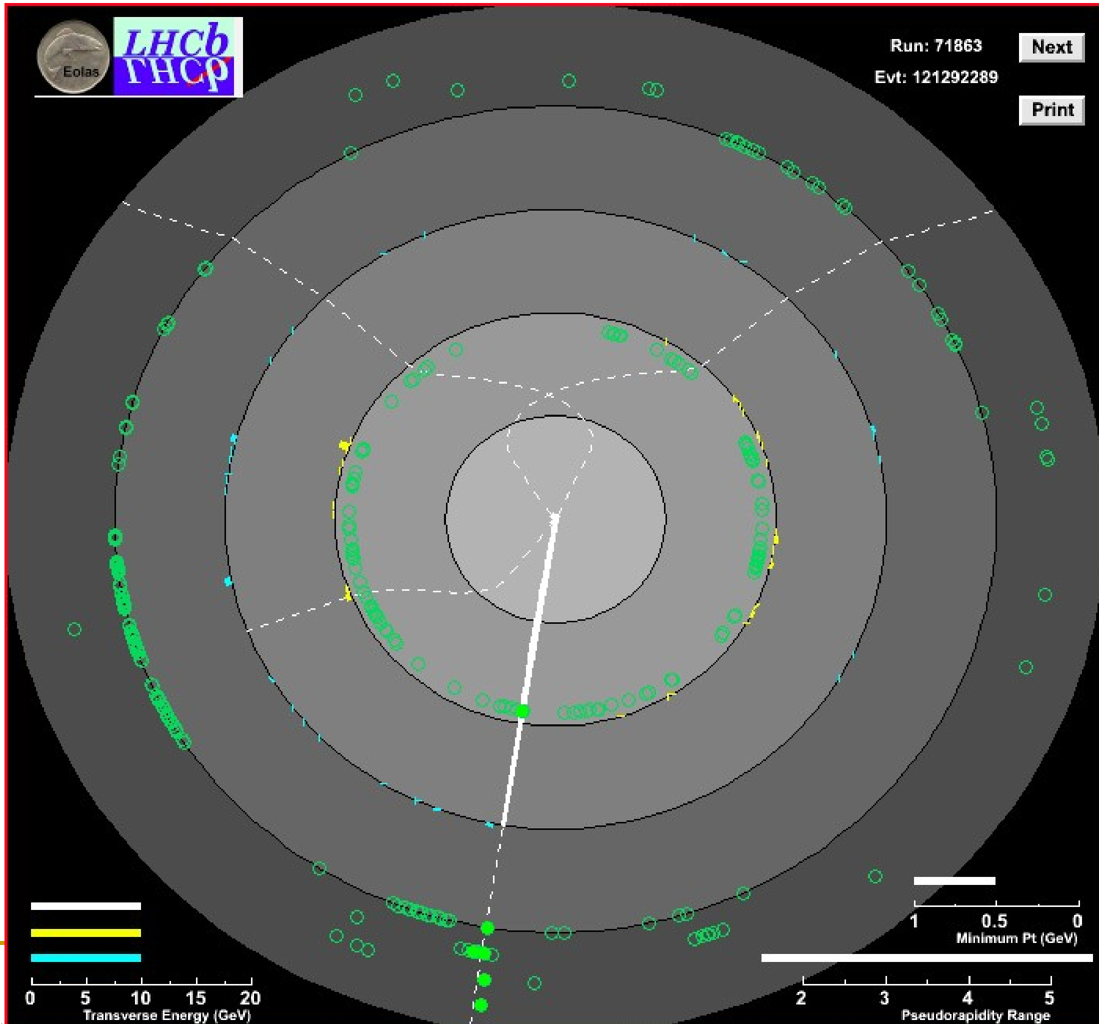
W Cross-section Measurement at LHCb

$$\sigma(W \rightarrow \mu\nu : 2 < \eta_{\mu} < 4.5, P_{T\mu} > 20\,GeV\ )$$

W: One high transverse momentum muon with little else. Background much larger than for Z



Require muon p_t>20GeV + little activity in 'rest of event'



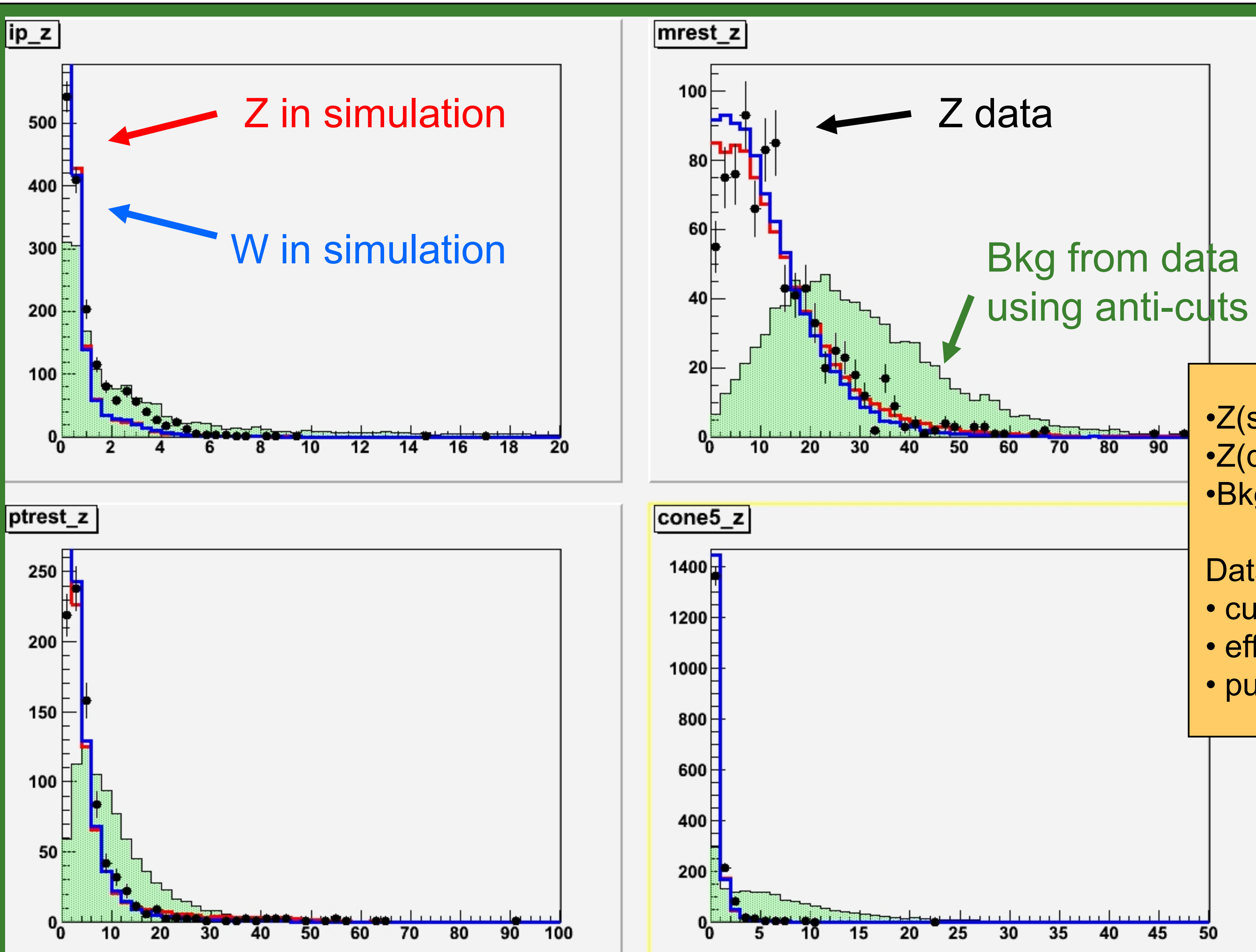
Can be found using Z events **in data**

Selecting W events

- pt of muon (>20GeV)

- ip significance of muon (<2)
- Mass of *rest of event* (<20 GeV)
- Pt of *rest of event* (<10 GeV)
- Charged transverse momentum in cone of 0.5 units of $\sqrt{(\Delta\eta)^2+(\Delta\Phi)^2}$ around muon. (<2 GeV)

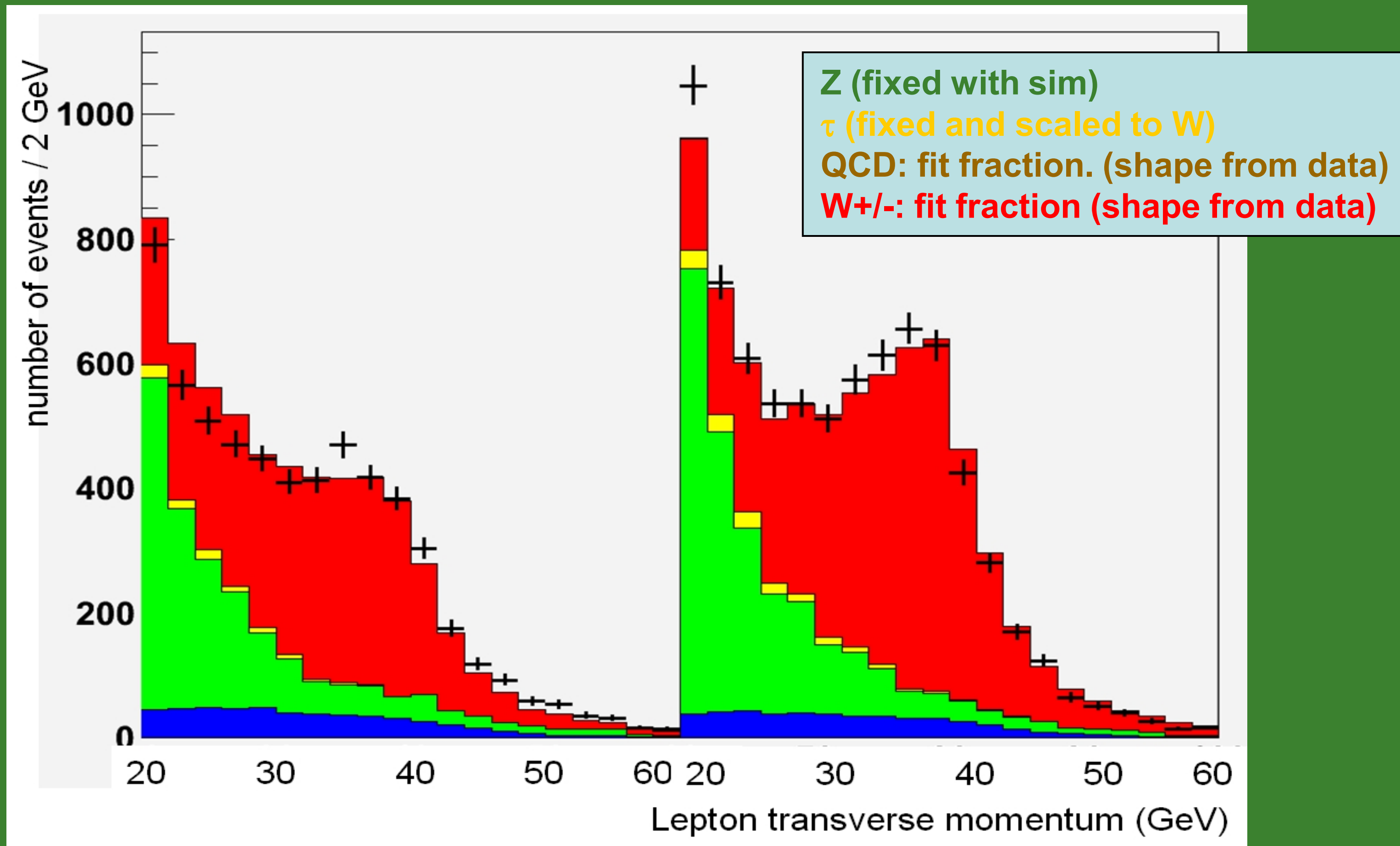
W analysis



- Z(sim) = W(sim)
- Z(data) ~ Z(sim)
- Bkg(data) != Z(data)

Data derived:
- cuts;
- efficiency;
- purity.

W analysis



$$\sigma_{W\to\mu\nu}(\Delta\eta) = \frac{N^W_{tot} - N^W_{bkg}}{\epsilon_W L} \rightarrow \frac{N^W_{tot}}{L}\left(\frac{p_W}{\epsilon_W}\right)$$

and all found from data.

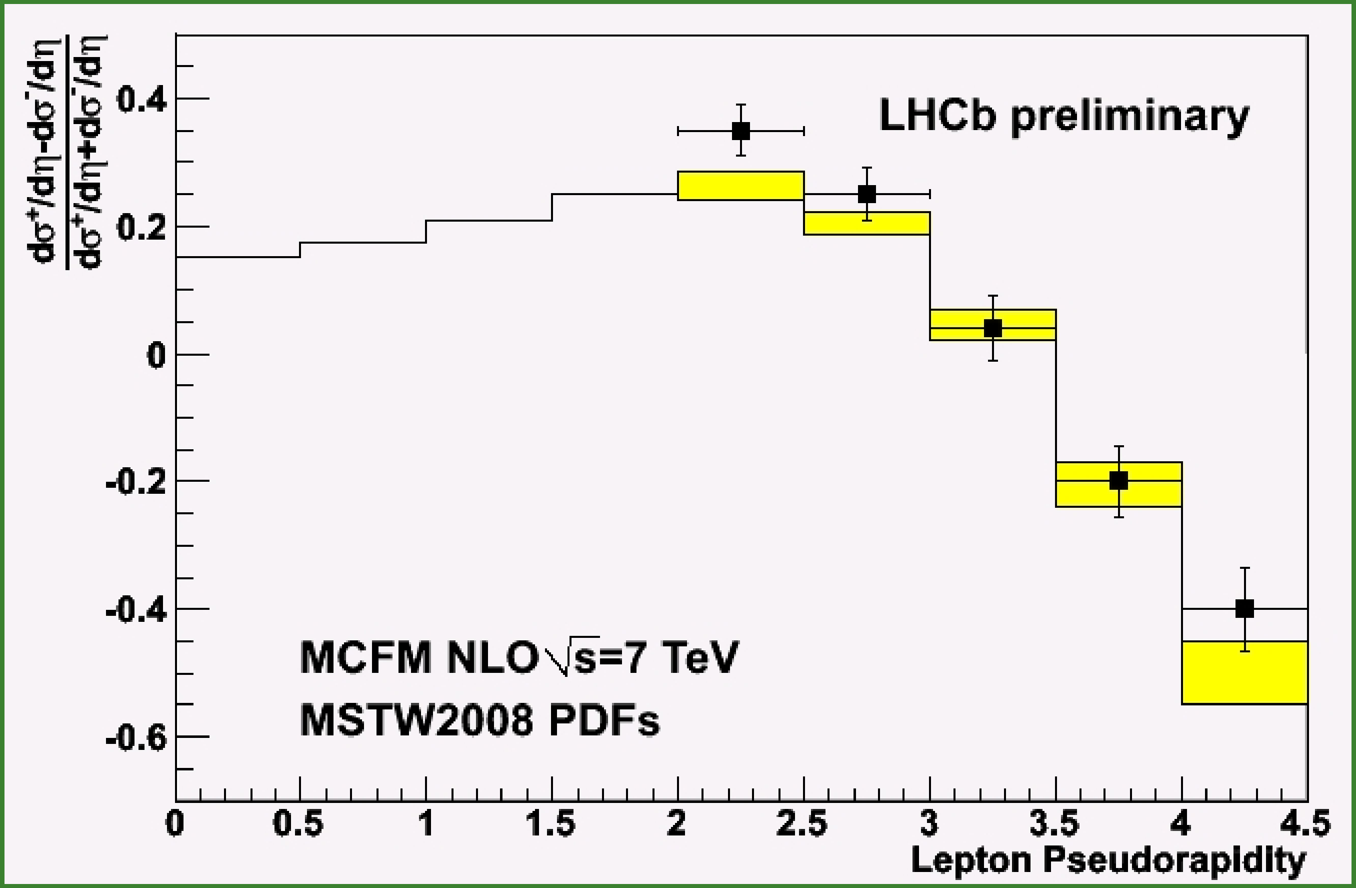
W analysis

$$\sigma_{W\to\mu\nu}(\Delta\eta) = \frac{N^W_{tot} - N^W_{bkg}}{\epsilon_W L}$$

	$W+$	$W-$
N_W^{tot}	7624	5732
$W \to \tau\nu$	151	90
$Z \to \tau\tau$	2	2
$Z \to \mu\mu$	460	506
QCD	2194 ± 150	1654 ± 150
N_W	4817 ± 165	3480 ± 161
ϵ^W_{trig}	0.725 ± 0.03	
ϵ^W_{track}	0.73 ± 0.03	0.78 ± 0.03
ϵ^W_{muon}	0.982 ± 0.005	
ϵ^W_{sel}	0.55 ± 0.01	
A^W	1	1
ϵ_W	0.29 ± 0.01	0.31 ± 0.01
N_W^{tot}	16610 ± 800	11226 ± 650
L	$16.5 \pm 1.7\ \mathrm{pb}^{-1}$	$16.5 \pm 1.7\mathrm{pb}^{-1}$
$\sigma_W(2.0 < y < 4.5)$	$1007 \pm 48 \pm 100$ pb	$682 \pm 40 \pm 68$ pb

(Measurement as function of lepton rapidity)

W asymmetry

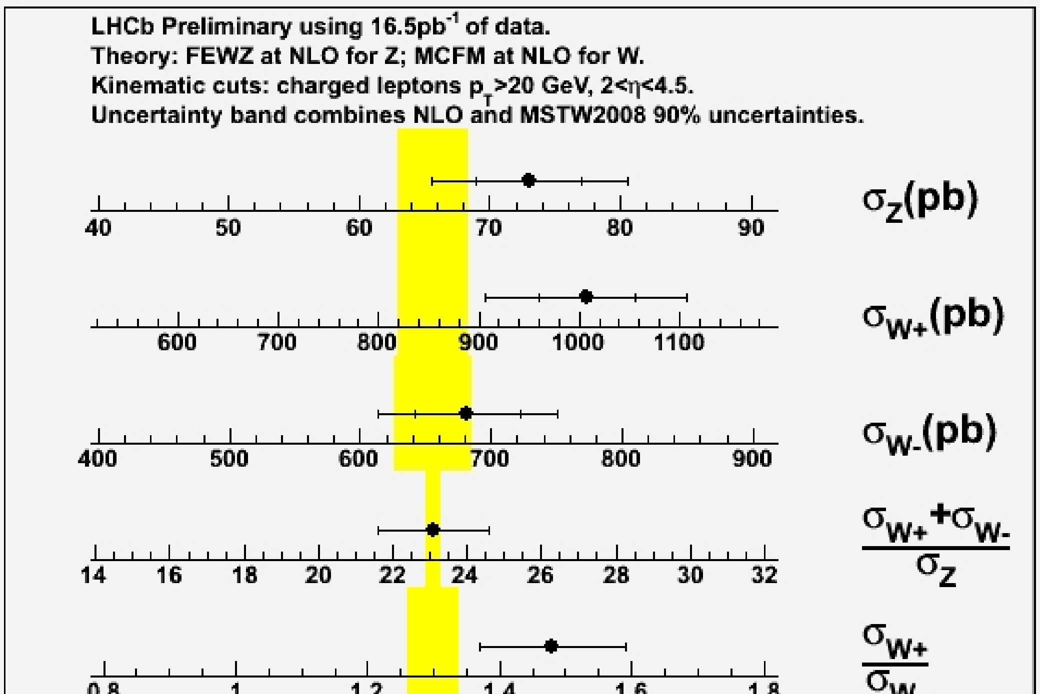


$\frac{d\sigma^+/d\eta - d\sigma^-/d\eta}{d\sigma^+/d\eta + d\sigma^-/d\eta}$
0.4
0.2
0
-0.2
-0.4
-0.6
LHCb preliminary
MCFM NLO $\sqrt{s}$=7 TeV
MSTW2008 PDFs
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Lepton Pseudorapidity

W,Z Summary

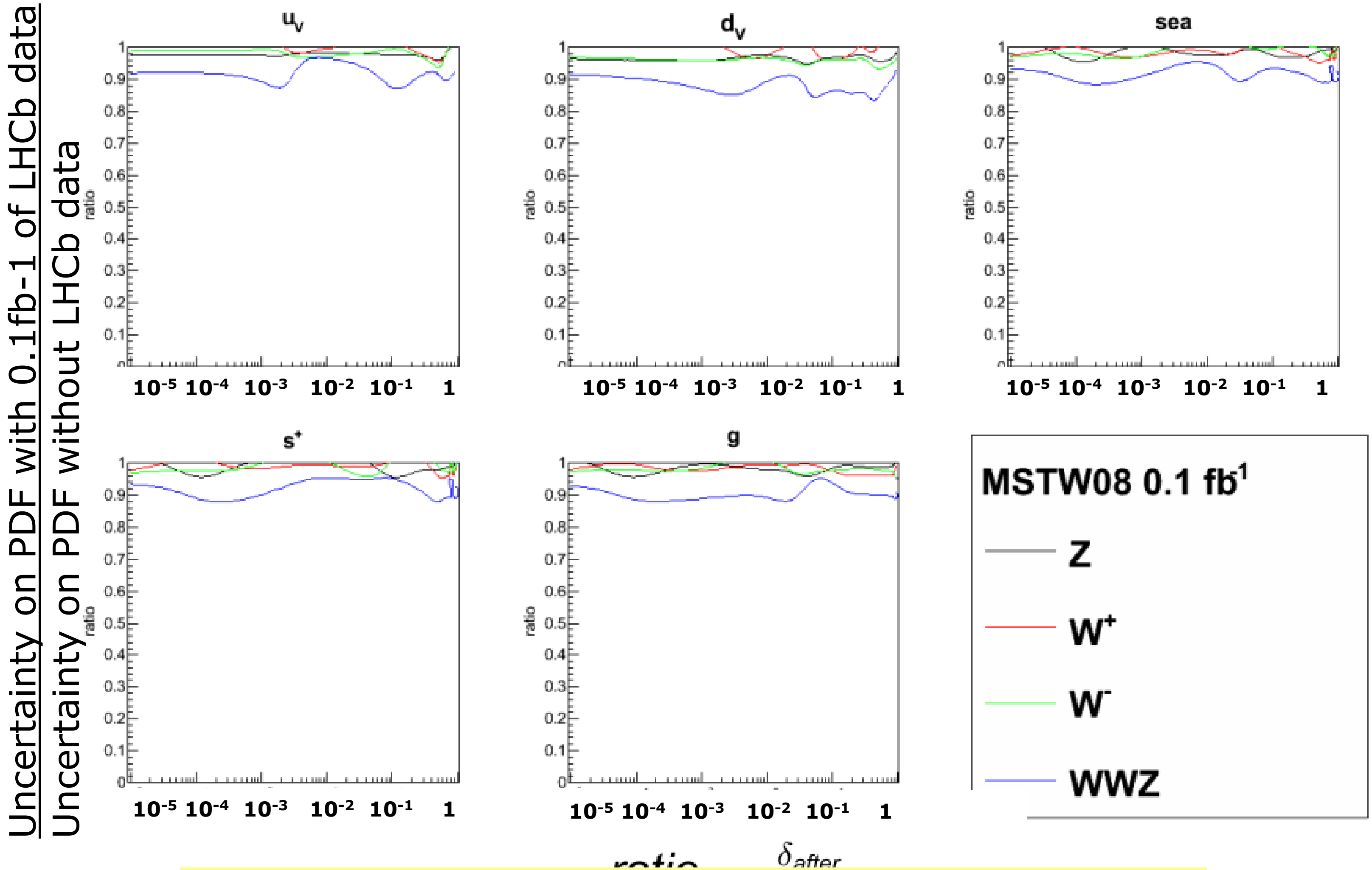
$$\frac{\sigma_{W+}(2.0<\eta_\mu<4.5)+\sigma_{W-}(2.0<\eta_\mu<4.5)}{\sigma_Z(2.0<y<4.5)}$$

Generator	Order	PDF Set	Z	$W+$	$W-$	$(W^+ + W^-)/Z$	W^+/W^-
FEWZ	NLO	MSTW08NLO CTEQ66NLO NNPDF2.0	$65.7^{+2.9}_{2.5}$				
MCFM		MSTW08NLO CTEQ66NLO NNPDF2.0	$65.5^{+2.8}_{-2.5}$	855 ± 43	656 ± 39	23.1 ± 0.1	1.30 ± 0.05
FEWZ	NNLO	MSTW08NNLO					
Data			$73 \pm 4 \pm 7.5$	$1007 \pm 48 \pm 101$	$682 \pm 40 \pm 68$	23.1 ± 1.5	1.48 ± 0.11



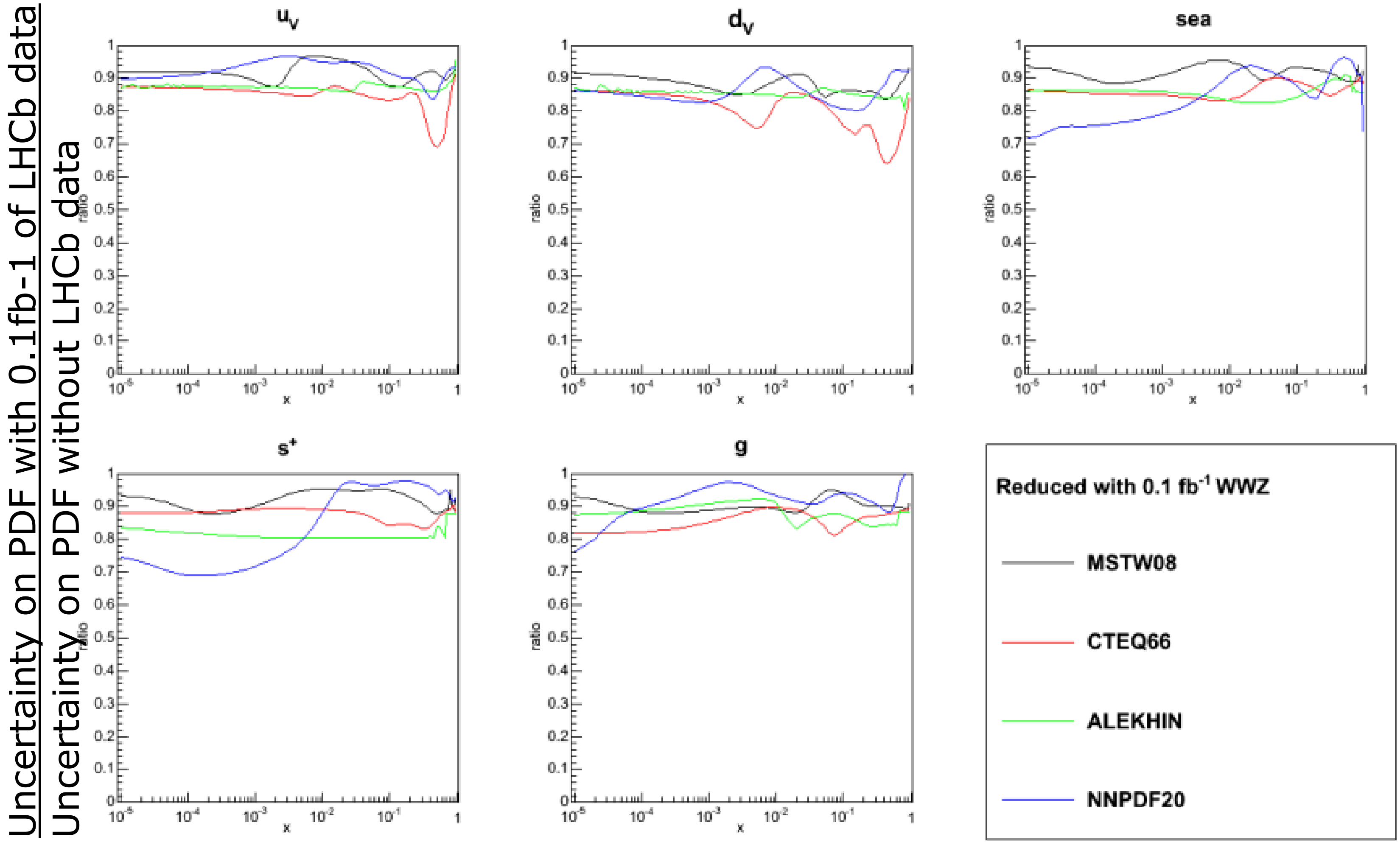
How well can W,Z measurements constrain the PDFs?

Improvement to **MSTW08 PDFs** with 0.1fb-1 of high mass vector bosons at 7TeV



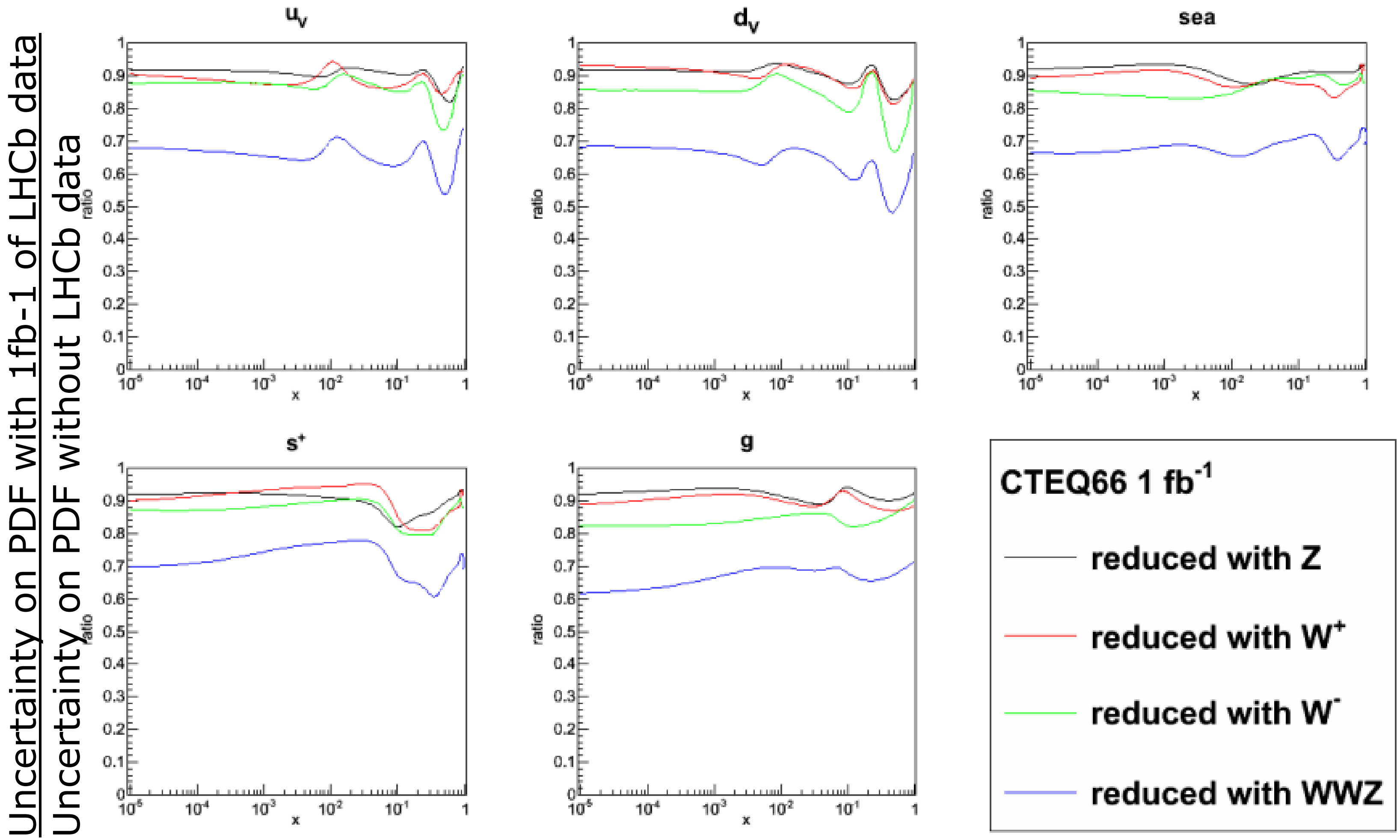
Modest improvement with small amount of data

Comparison with different PDFs using 0.1fb-1 of high mass vector bosons at 7TeV



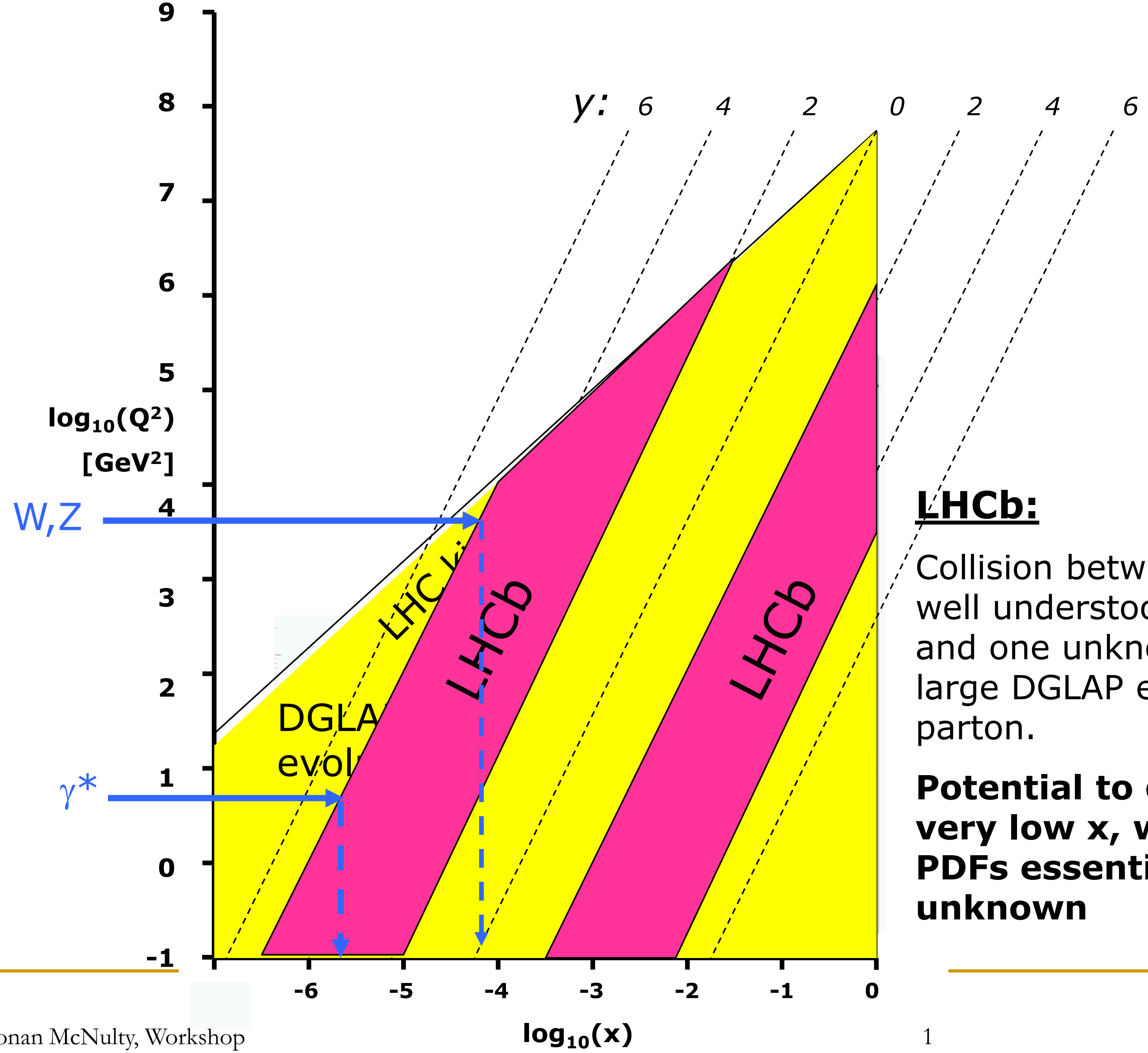
Similar sensitivity. Ability to distinguish models

Improvement to **CTEQ66 PDFs** with 1fb-1 of high mass vector bosons at 14 TeV



More data and higher energy lead to larger improvements.

Using γ^* to go to very low-x.

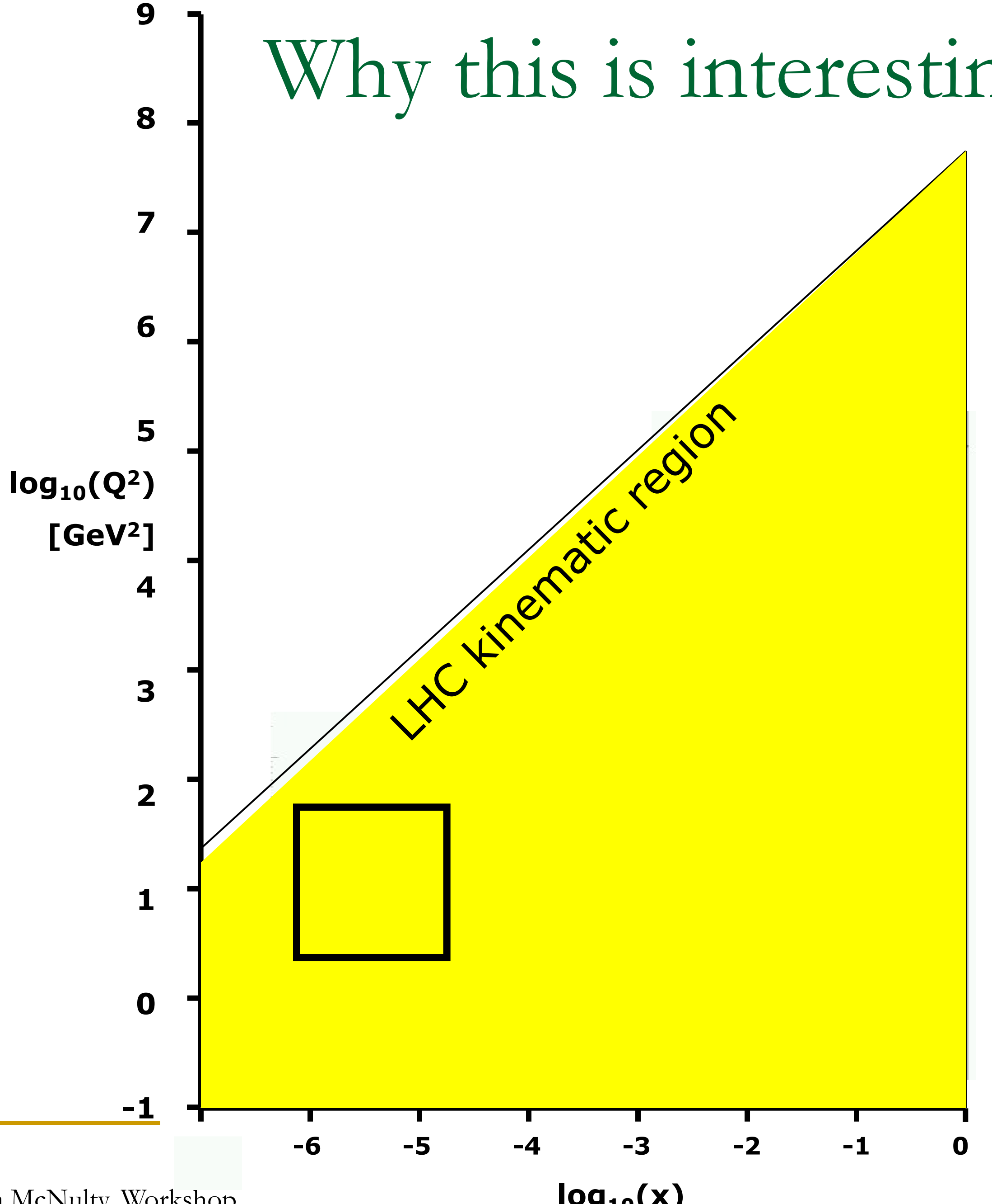


LHCb:

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

Why this is interesting…

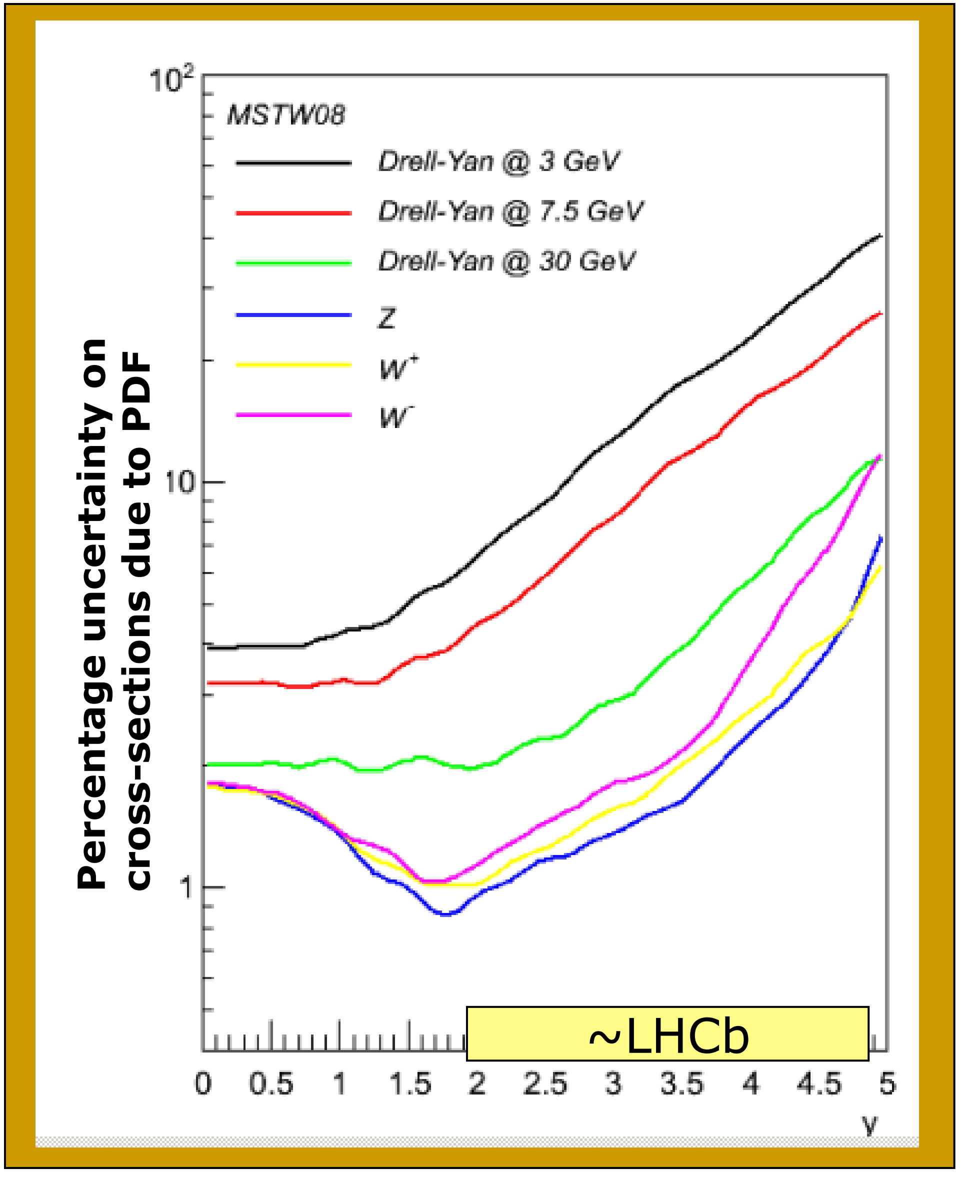


Unexplored region
Very little HERA data at this x

More theoretical work required to make predictions

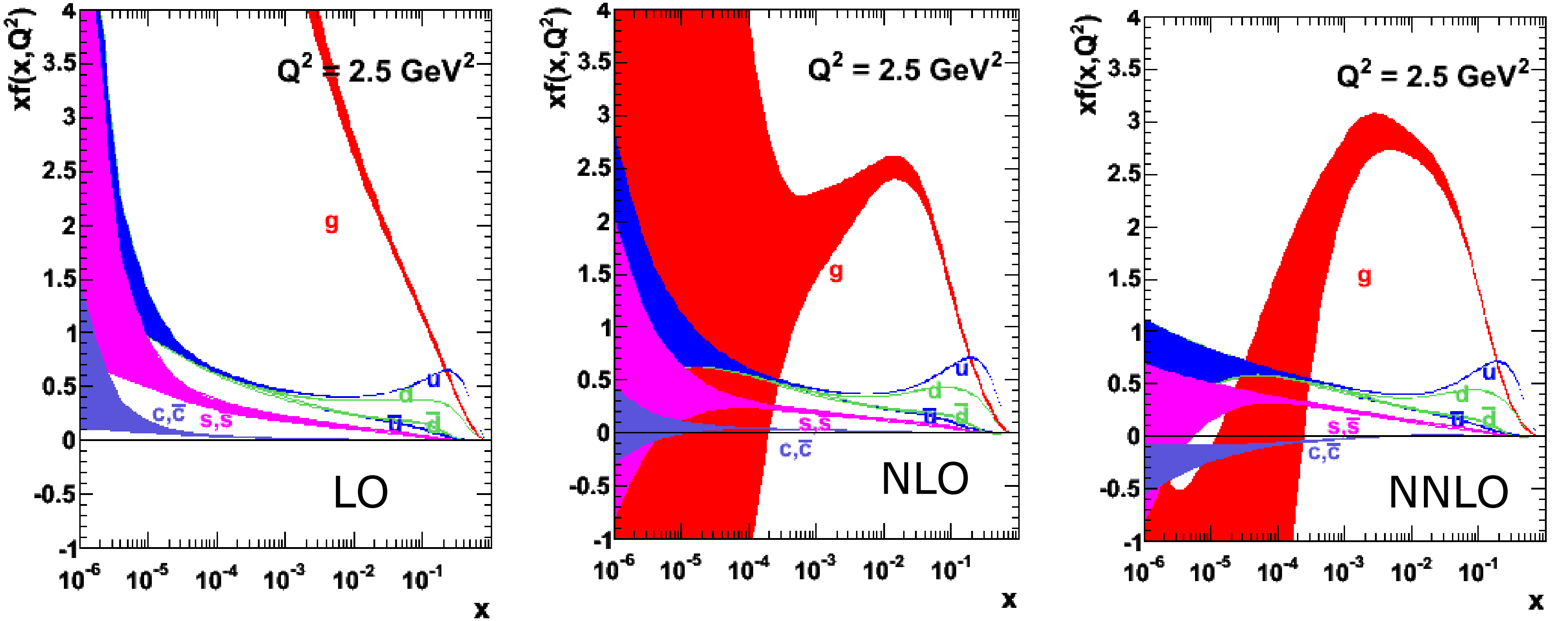
Sensitivity to saturation?

Effect of PDF uncertainties on cross-sections



PDF uncertainties at low-x, low-Q^2

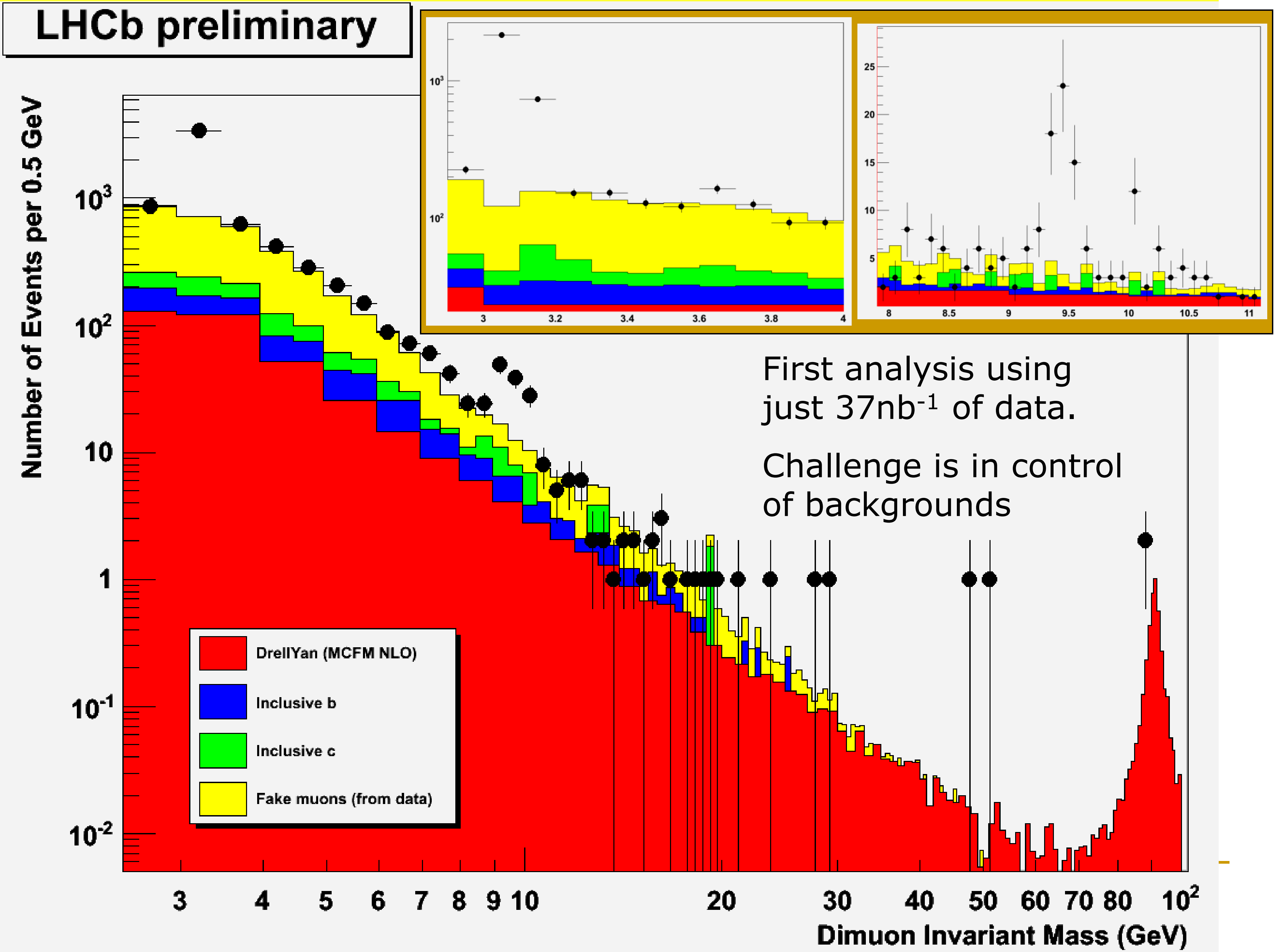
MSTW08. (Thanks to Graeme Watt)



Different behaviour and uncertainty with order of calculation.

Gluon essentially unconstrained by data below 10^{-4}

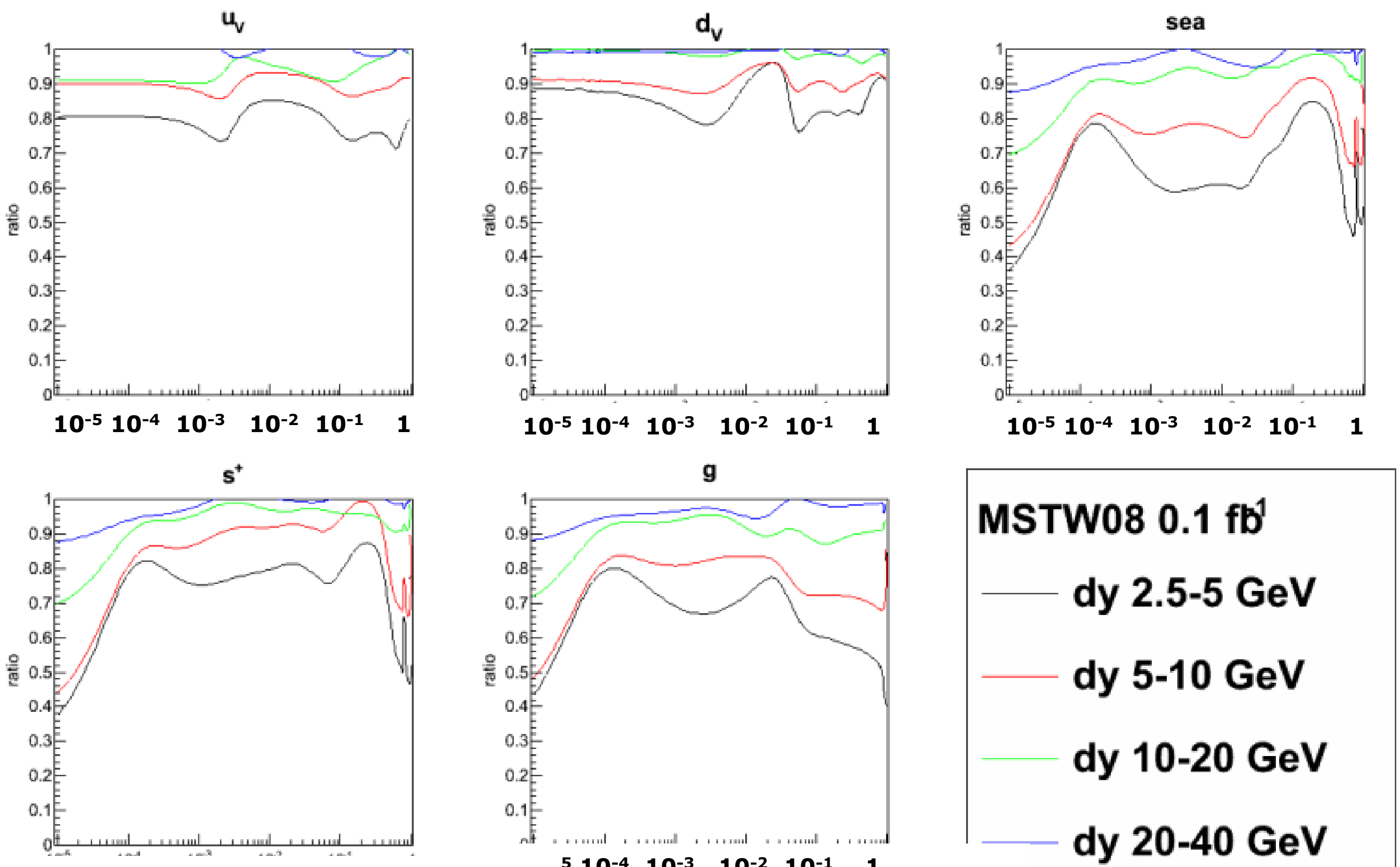
DGLAP evolution not trustworthy in this region. Gluon re-summation effects. Possibly entering saturation regime.



First analysis using just 37nb^{-1} of data.

Challenge is in control of backgrounds

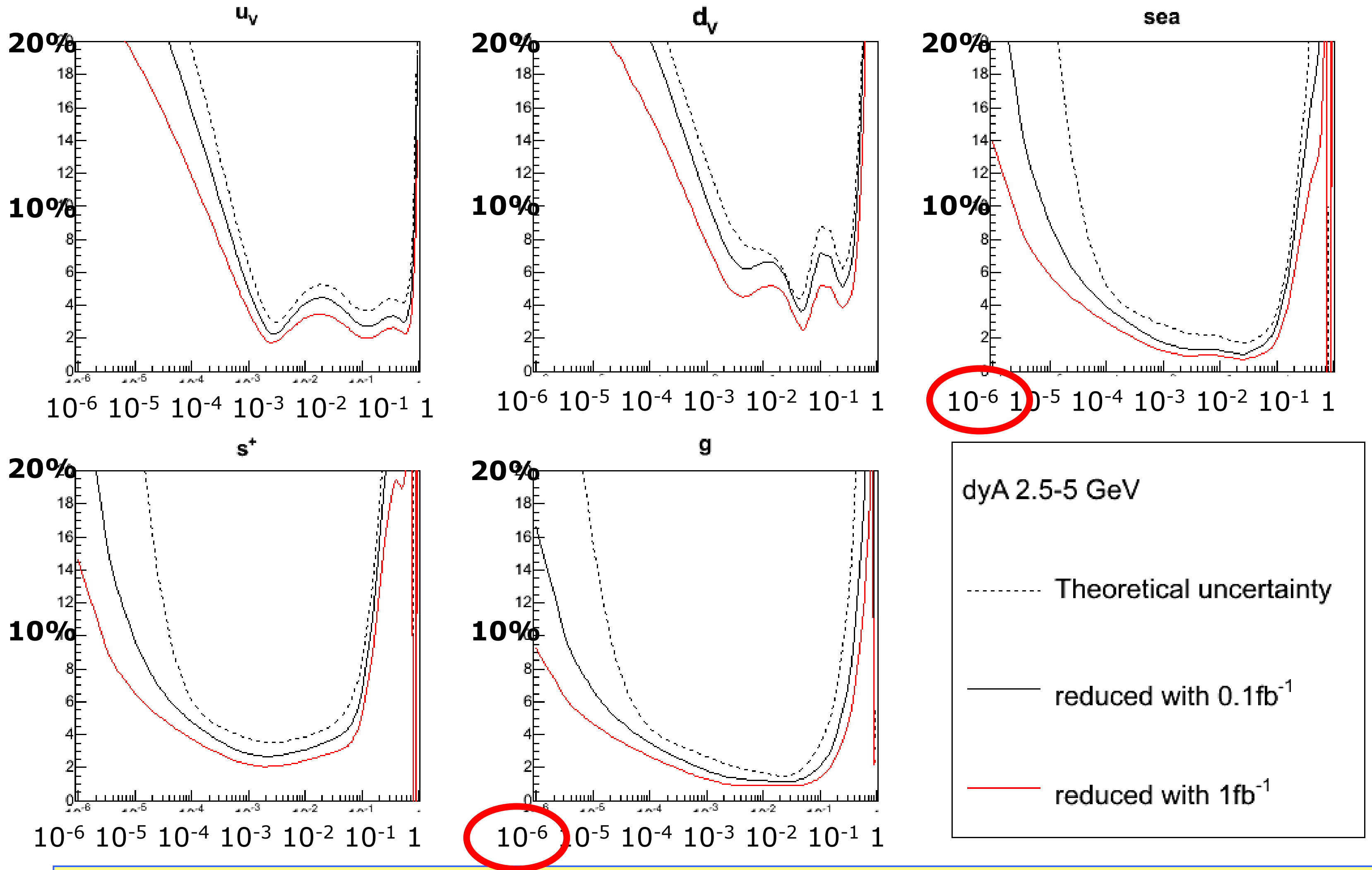
Improvement to **MSTW08 PDFs** with 0.1fb-1 of low mass vector bosons at 7TeV



Similar improvements to NNPDF, CTEQ and Alekhin PDFs.

Sensitivity exists to distinguish between models.

Current uncertainty on **MSTW08 PDFs** and projections with $0.1fb^{-1}$, $1fb^{-1}$ of very low invariant mass muons at 7TeV



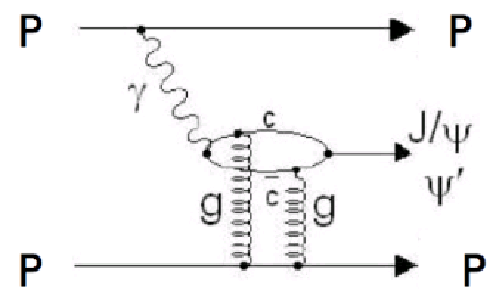
Significant improvements possible with modest amount of data

Exclusive dimuon final states

Exclusive particle production (2μ and nothing else)

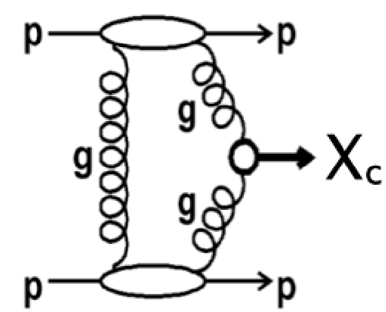
1

Exclusive JPsis, Psi' (-> $\mu^+\mu^-$)
Produced by photon pomeron fusion
Starlight: Models diphoton and photon pomeron fusion
(S.R.Klein and J.Nystrand, Phys. Rev. Lett. 92 (2004) 142003).



2

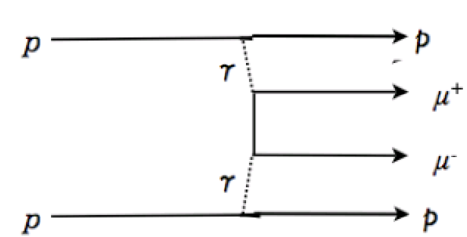
Exclusive ChiC (-> $\mu^+\mu^-$ + γ)
Produced by double pomeron exchange
SuperChiC: MC for central exclusive production
(L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, W.J. Stirling,
arXiv:0909.4748 [hep-ph].).



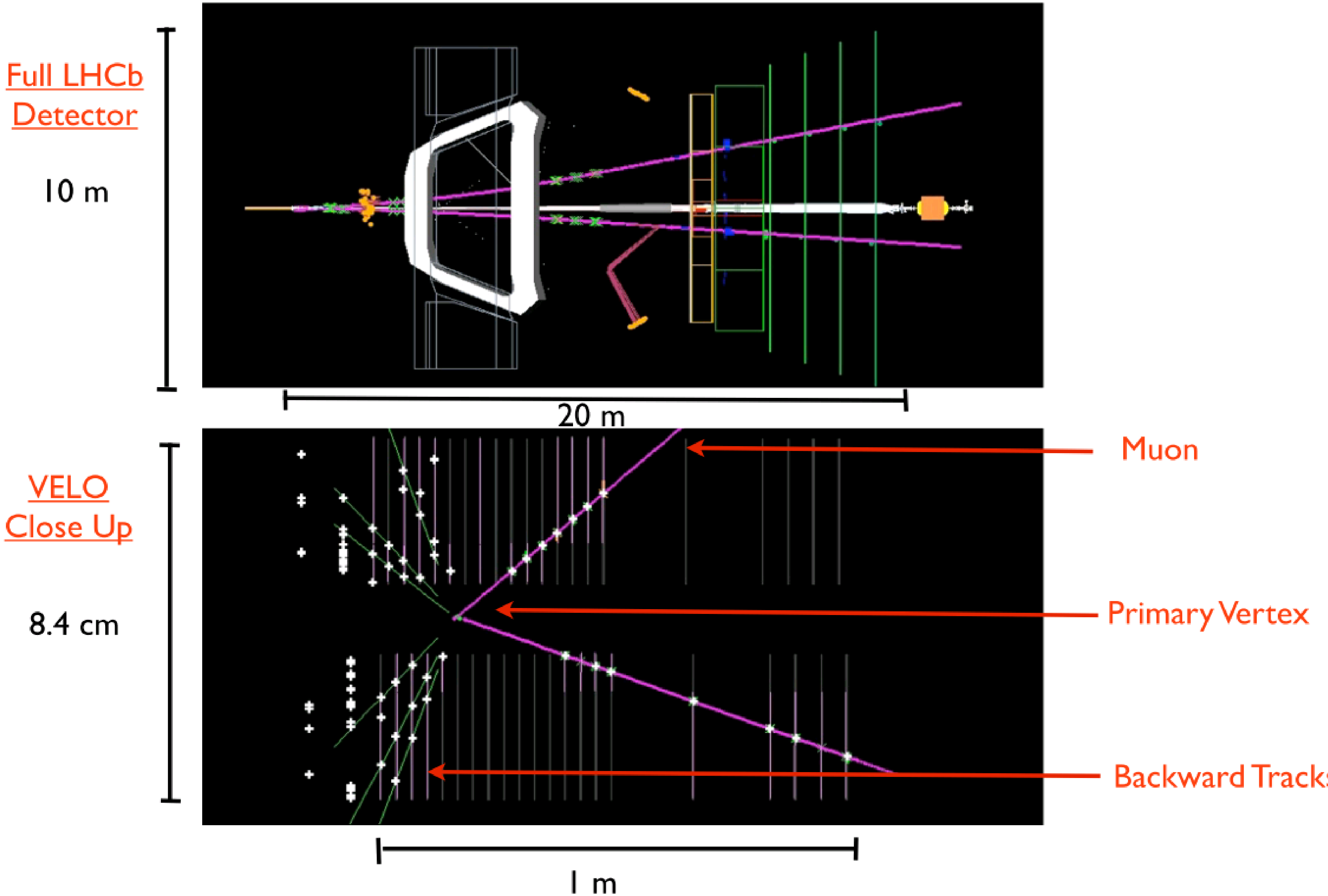
3

Exclusive diphoton dimuon
Produced by diphoton fusion
LPAIR: Models EM production of lepton pairs
(A.G.Shamov and V.I.Telnov, NIM A {\bf 494} (2002) 51).

For LHC Luminosity



But is it exclusive ?

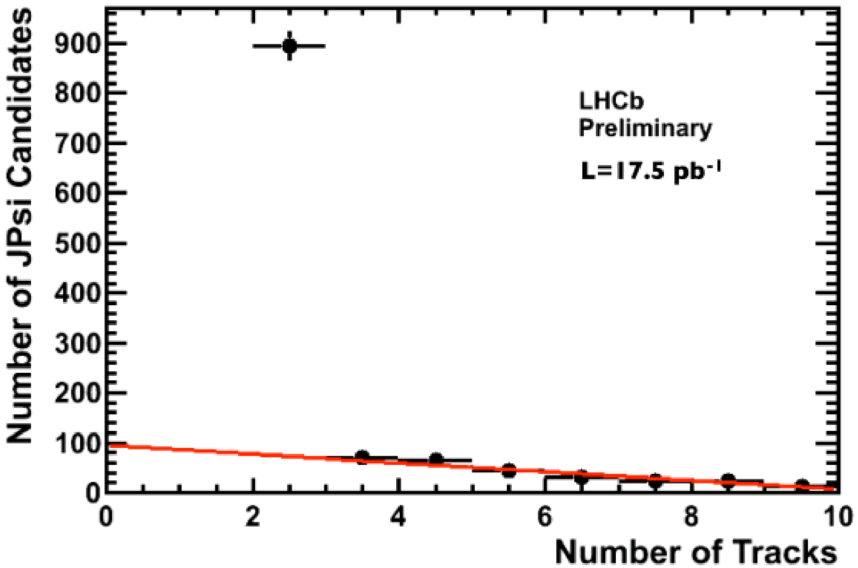


#J/Psi as Fn of #tracks

Assuming Linear background ?

Extrapolate Background to determine number of experimentally exclusive events

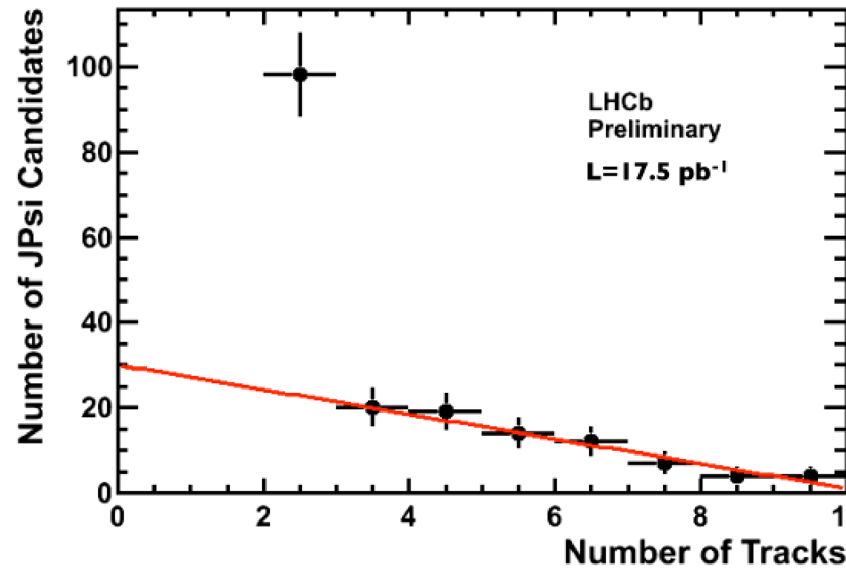
JPsi + No Photon



817 Exclusive JPsi candidates
77 Background Events

Purity of Events = 91%

JPsi + 1 Photon



76 Exclusive ChiC candidates
22 Background Events

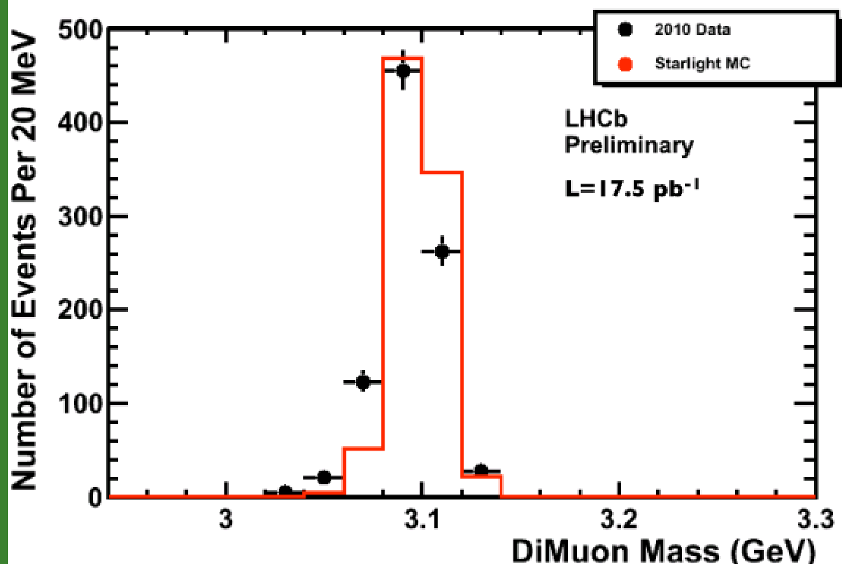
Purity of Events = 78%

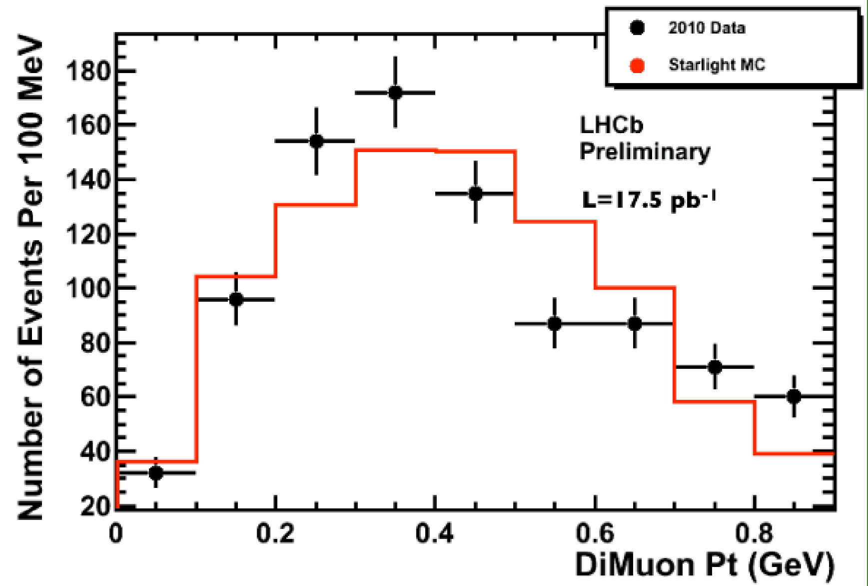
Exclusive J/Psi (compared to Starlight)

1

Require 2μ consistent with Jpsi + no other charged or neutral activity

Normalized to number of events





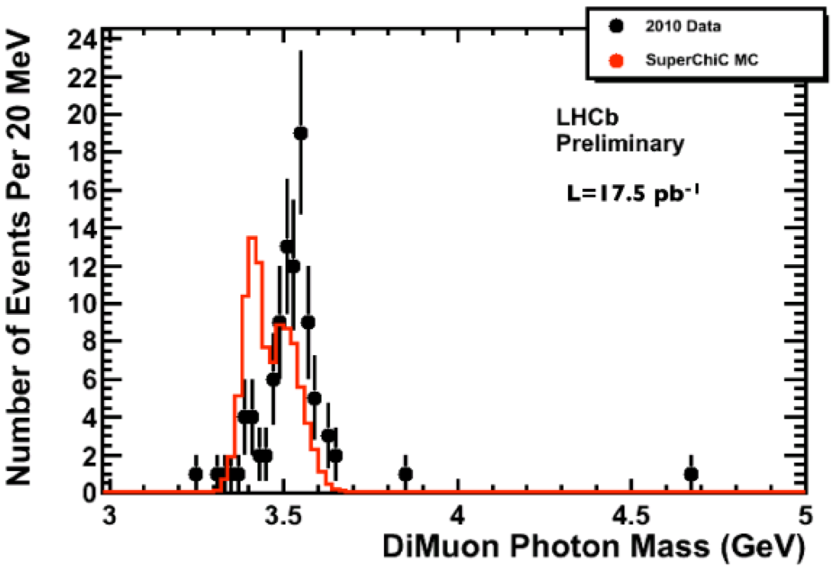
Number of exclusive candidates: 817 (Calculated from extrapolation)

Purity of Events = 91%

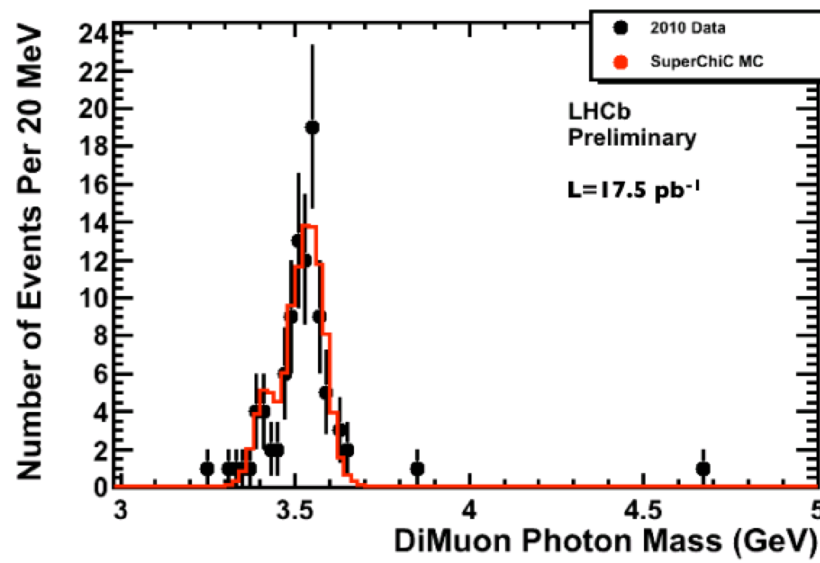
2 Exclusive Chi_c (compared to SuperCHIC)

Require 2m consistent with Jpsi, 1 photon, and nothing else

Normalised to number of events
ChiC0: 52%,ChiC1: 36%,ChiC2: 12%



Normalised to number of events
ChiC0: 12%,ChiC1: 36%,ChiC2: 52%

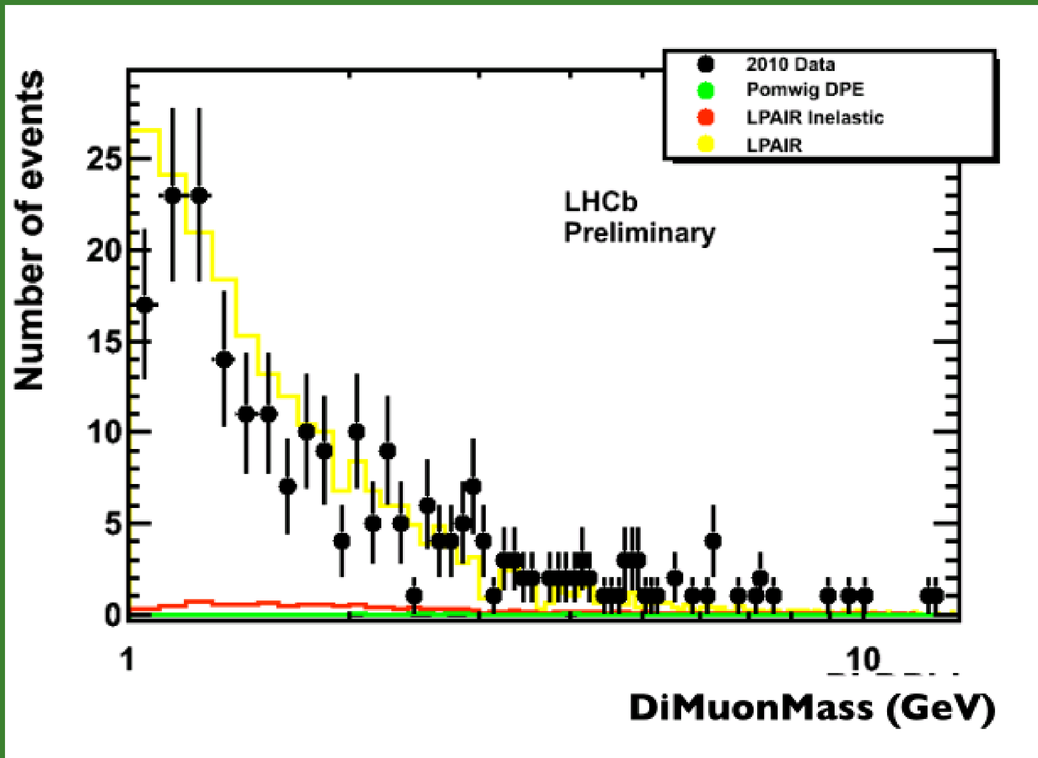


Number of exclusive candidates: 76 (Calculated from extrapolation)

Purity of Events = 78%

3 Diphoton fusion (compared to LPAIR)

Require 2 back-to-back muons and no other charged or neutral activity. Remove resonances.



As in other cases, feed-down from non-exclusive processes needs to be evaluated.

Precision on luminosity given by uncertainty on backgrounds and trigger efficiency.

Summary

- LHCb EW programme complementary to ATLAS/CMS
- Tests SM in different region with similar precision
- Possible future precision measurement of $\sin^2\theta_W$
- Constrain PDFs at low x for W,Z and very low x for γ^*.
- Potential for luminosity measurement at few % level.