Diffraction at the LHC

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EDS Blois
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Outline

- Diffraction a very wide subject, with much to cover, with lots of talks at this year's EDS on the topic: W. Schaefer, K. Goulianos, E. Gotsman, P. Lebiedowicz, M. Luszczak, J. Kaspar, R. Ciesielski, ATLAS, CMS/TOTEM, LHCb and ALICE talks on Tuesday, R. McNulty, M. Ruspa, A. Valkarova....

- Here, I will focus on two broad topics of relevance at the LHC:
  - Soft diffraction: models for soft elastic and inelastic scattering, information from the LHC...
  - Exclusive processes: topical 'hard diffractive' process, involving pQCD and soft effects. Outline theoretical approach and experimental status and outlook for some example processes.

Diffraction: definitions

M. L. GOOD AND W. D. WALKER
University of Wisconsin, Madison, Wisconsin
(Received May 26, 1960)

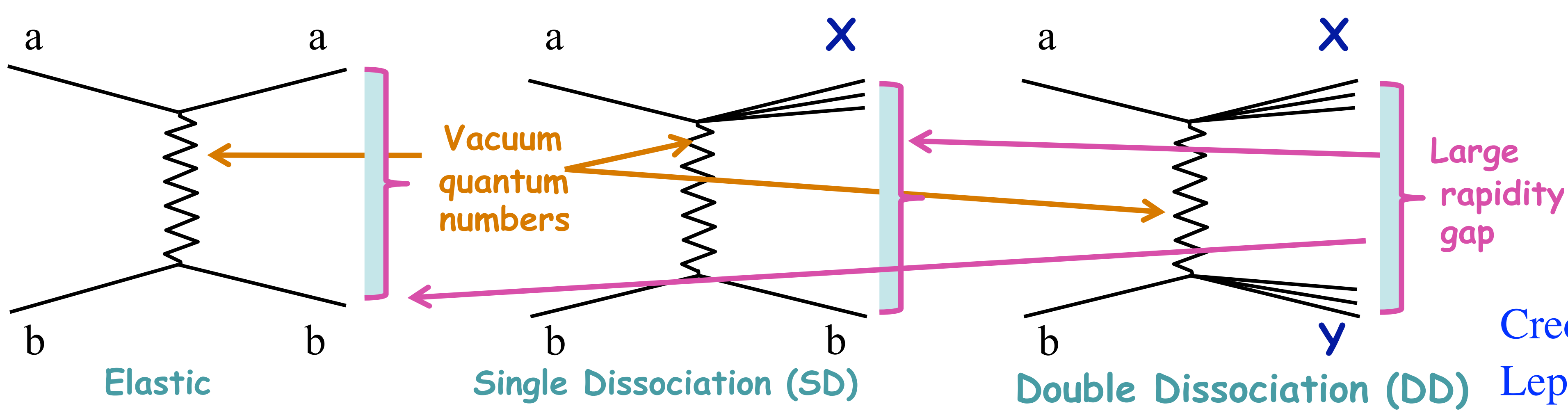
A phenomenon is predicted in which a high-energy particle beam undergoing diffraction scattering from a nucleus will acquire components corresponding to various products of the virtual dissociations of the incident particle, as $p \to \Lambda + K^+$ or $\pi^- \to \bar{p} + n$. These diffraction-produced systems would have a characteristic extremely narrow distribution in transverse momentum, and would have all the same quantum numbers as the initial particle; i.e., the same spin, isotopic spin, and parity. The process is related to that discussed

$\longrightarrow$ Vacuum quantum number exchange at high energies.

J. D. Bjorken
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 30 March 1992)

In hadron-hadron collisions, production of Higgs bosons and other color-singlet systems can occur via fusion of electroweak bosons, occasionally leaving a "rapidity gap" in the underlying-event structure.

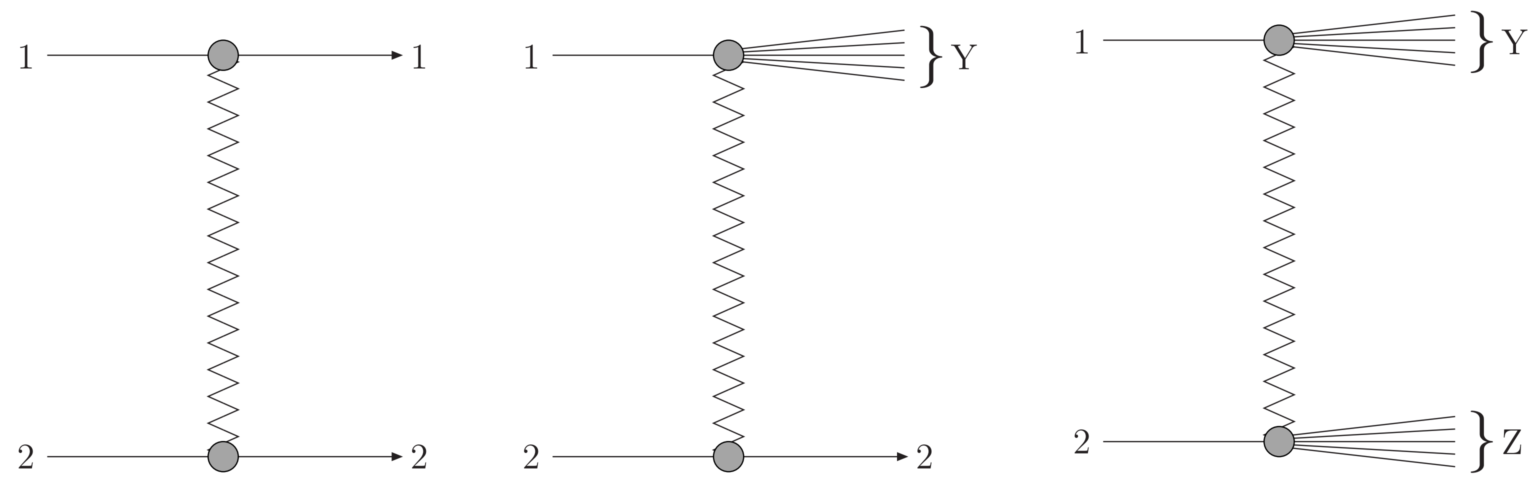
$\longrightarrow$ Large, non-exponentially suppressed rapidity gaps.



Credit: M. Ruspa, Lepton Photon 2009

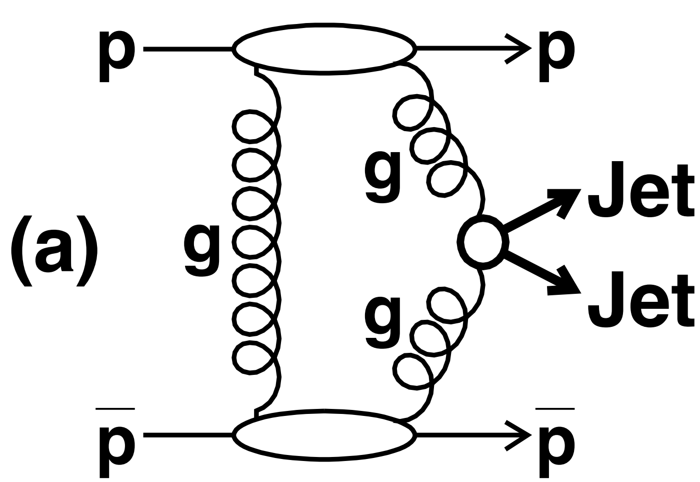
Diffractive processes

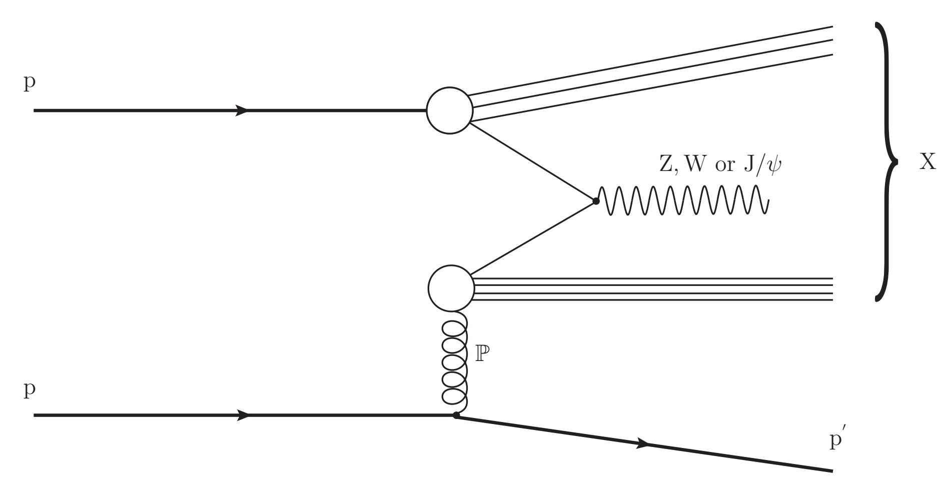
- Soft diffraction:



$\longrightarrow$ Non-perturbative approach needed. Typically use the well known tools of Regge theory/ general principles of unitarity etc but also depends sensitively on the model of structure of the proton.

- Hard diffraction:





$\longrightarrow$ Production of object with high mass/large momentum, requires ‘non-standard’ application of pQCD, as well as modeling of physics at soft scales.

Diffraction at the LHC

- The LHC has allowed measurement of diffraction to be made out to unprecedented collider energies, with broad rapidity coverage and proton tagging.
- Already measurements of the elastic, total and diffractive cross sections in Run I have thrown up some interesting 'surprises' and a hard diffraction program is developing.

$\longrightarrow$ Run II has a lot to offer: discussed in detail in upcoming yellow report...

CERN/LHCC 2013-021
February 28 2015

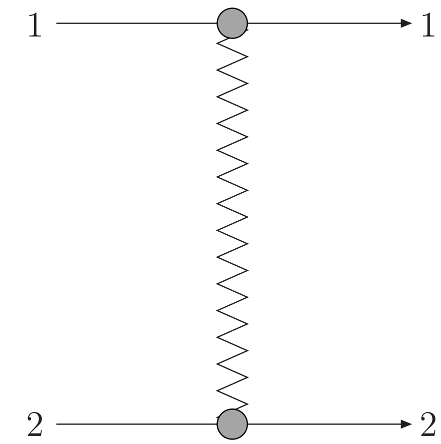
LHC Forward Physics

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

http://www-d0.fnal.gov/Run2Physics/qcd/loi_atlas/fpwg_yellow_report.pdf

Soft Diffraction

Soft diffraction- theory recap



- Simple (t-channel) approach- elastic scattering due to single pomeron exchange:

elastic amplitude

$$A(s,t) \sim \beta(t) \left(\frac{s}{s_0}\right)^{\alpha_{I\!P}(t)}$$

optical theorem

$$\sigma_{\text{tot}}(s) = 2\,\text{Im}\,A(s,0) \sim \left(\frac{s}{s_0}\right)^{\alpha_{I\!P}(0)-1}$$

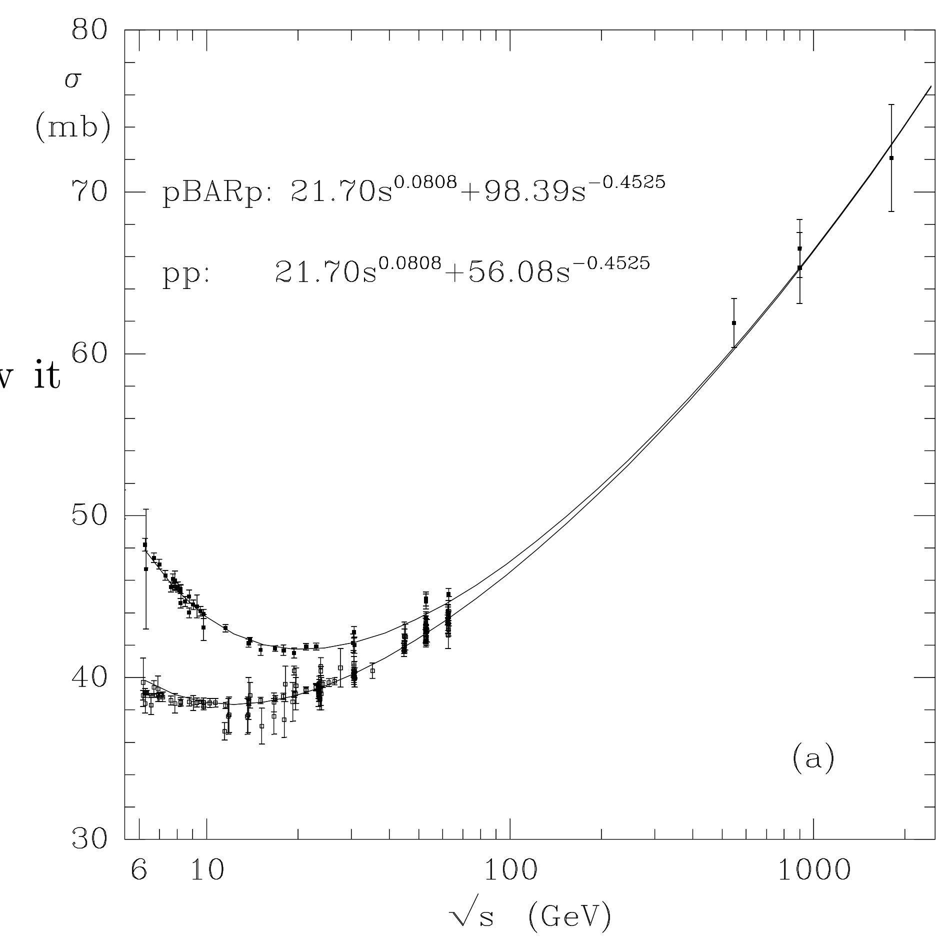
- Donnachie-Landshoff fit:

A. Donnachie, P.V. Landshoff,
Phys. Lett. B296 (1992) 227-232

$$\alpha_{I\!P}(t) = 1.08 + 0.25\,\text{GeV}^{-2}t$$

Conclusions

Regge theory remains one of the great truths of particle physics. We have shown how it provides an extremely simple and economical parametrisation of all total cross sections.



- However such a simple single pomeron exchange picture cannot account for the entire diffractive sector. Unitarizing effects due to multi-Pomeron exchange and internal structure of protons must be accounted for.

$\longrightarrow$ s-channel 'Regge Field Theory' (RFT) approach, including Good-Walker decomposition of protons.

s-channel approach

- Write in terms of impact parameter b.

$\sigma_{\rm inel} \equiv \int {\rm d}^2 b_t\, G_{\rm inel}(s, b_t)$

$\sigma_{\rm tot} = \sigma_{\rm el} + \sigma_{\rm inel}$ absorption prob.

Elastic unitarity: $2{\rm Im}\, T_{\rm el}(s,b) = |T_{\rm el}(s,b)|^2 + G_{\rm inel}(s,b)$,

solved for $T_{\rm el}(s,b) = i\left(1 - e^{-\Omega(s,b)/2}\right)$

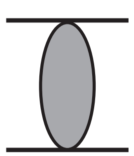
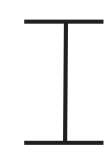
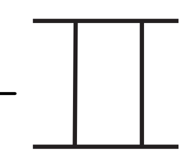
$\Omega(s,b)$: proton opacity

$e^{-\Omega(s,b)}$: prob. of no inelastic scattering

$$\begin{aligned}
\frac{d\sigma_{\rm tot}}{d^2b} &= 2{\rm Im}T_{\rm el}(s,b) = 2(1-{\rm e}^{-\Omega/2})\\
\frac{d\sigma_{\rm el}}{d^2b} &= |T_{\rm el}(s,b)|^2 = (1-{\rm e}^{-\Omega/2})^2,\\
\frac{d\sigma_{\rm inel}}{d^2b} &= 2{\rm Im}T_{\rm el}(s,b) - |T_{\rm el}(s,b)|^2 = 1-{\rm e}^{-\Omega}
\end{aligned}$$

- Can interpret in terms of pomeron exchange picture, but with:

$$\Omega(s,b) = \frac{-i}{s}\int \frac{d^2 q_t}{4\pi^2}\, e^{i\boldsymbol{q}_t\cdot\boldsymbol{b}}\, A(s, t=-q_t^2)$$

$\mathrm{Im}\, T_{\rm el} =$  $= 1 - e^{-\Omega/2} = \frac{\Omega}{2} - \frac{1}{2}\left(\frac{\Omega}{2}\right)^2 + \cdots =$  $+$  $+ \cdots$

i.e. $\Omega(s,b)$ related to Fourier transform of single pomeron exchange amplitude, and full elastic amplitude $T_{\rm el}(s,b)$ given by summing over all exchanges.

$\longrightarrow$ multi-pomeron/screening effects.

Diffractive dissociation

$p \to N^*$

- Low mass dissociation- proton may be excited into heavier mass state.

- Need to account for internal structure of proton: decompose into different 'Good-Walker' eigenstates, each of which undergoes elastic scattering.

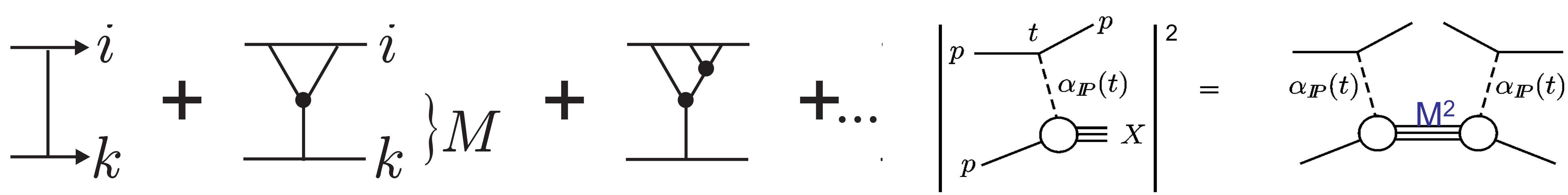
$$|p\rangle = \sum_i a_i |\phi_i\rangle \qquad\qquad \langle \phi_j | T | \phi_k \rangle = T_i \delta_{ij}$$

- If these have different interaction probabilities then outgoing superposition of states will be different from the incoming.

If T_i indep. of i then $= 0$

$$\longrightarrow \text{ Inelastic diffraction} \qquad \frac{\mathrm{d}\sigma_{\mathrm{SD}}}{\mathrm{d}^2 b} = \sum_i |a_i|^2 T_i^2 - \left(\sum_i |a_i|^2 T_i \right)^2$$

- Valid for low mass diffraction. For high mass diffraction can use triple Regge:



Models/MCs

• Some well developed models based on the basic approach described above are available. However, much room for differences in the implementation. Some examples:

- V. A. Khoze, A. D. Martin and M.G. Ryskin (KMR). MC implementation: SHRiMPS module of Sherpa.
  Eur. Phys. J. C71 (2011) 1617, 73 (2013) 2503...
- E. Gotsman, E. Levin, U. Maor (GLM).
  Eur. Phys. J. C71 (2011) 1553, Int. J. Mod. Phys. A30 (2015) 08, 1542005...
- Kaidalov & Poghosyan
  arXiv:0909.5156
- Ostapchenko/QGSJET MC
  S. Ostapchenko, AIP Conf. Proc. 928 (2007) 118, Phys. Rev. D 81, 11402 (2010)
- EPOS MC
  T. Pierog et al., arxiv:1306.0121, K. Werner, F.M Liu and T. Pierog, Phys Rev. C74 (2006) 044902
- MBR model
  R. Ciesielki and K. Goulianos, arXiv:1205.1446

Not all- PYTHIA, PHOJET....

Lessons from LHC run I - total cross section

- TOTEM and ALFA measurements of total cross sections at $\sqrt{s} = 7\,\mathrm{TeV}$:

TOTEM, EPL, 96 (2011) 21002

$$\sigma_{\rm tot} = \left(98.3 \pm 0.2^{\rm stat} \begin{array}{c} +2.8 \\ -2.7 \end{array}^{\rm syst}\right) \text{mb.}$$

ALFA, Nucl. Phys. B 889 (2014) 486-548

$$\sigma_{\rm tot}(pp \to X) = 95.35 \pm 0.38\ (\text{stat.}) \pm 1.25\ (\text{exp.}) \pm 0.37\ (\text{extr.})\ \text{mb},$$

- D-L would predict something lower $\sigma_{\rm tot} = 21.7\,\text{mb} \cdot 7000^{\overbrace{0.0162}^{2(\alpha_{I\!P}(0)-1)}} = 90.7\,\text{mb}$

Disagreement perhaps unsurprising for his simple approach. DL exceeds black disk limit at LHC. $\frac{\sigma_{\rm tot}}{8\pi B_{\rm el}} > 1$

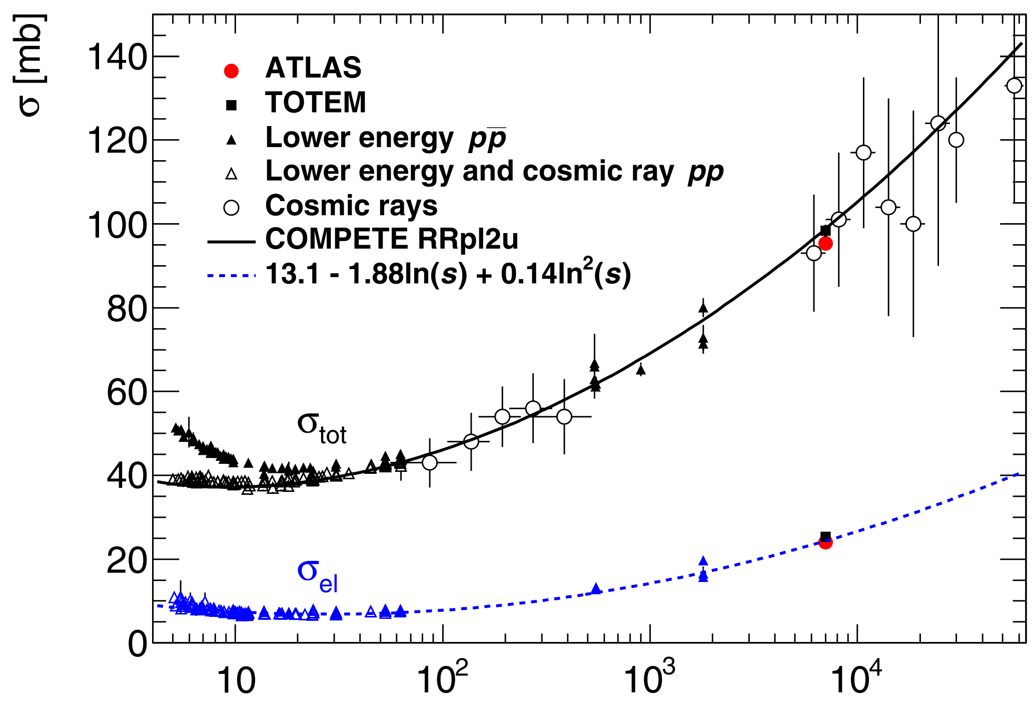
$\longrightarrow$ Screening/unitarizing effects important. But we would expect these to damp the DL prediction, not the other way round. More complex models also failed to predict these data, e.g.:

GLM, Eur. Phys. J. C71 (2011) 1553

GLM: $\sigma_{\rm tot} = 91.3\,\text{mb}$

KMR, Eur. Phys. J. C71 (2011) 1617

KMR: $\sigma_{\rm tot} = 88\,\text{mb}$



Lessons from LHC run I - elastic slope

- TOTEM and ALFA measurements of elastic slope: $$\frac{d\sigma_{el}}{dt} = \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} e^{-B|t|}$$

ALFA, Nucl. Phys. B 889 (2014) 486-548

$$B = 19.73 \pm 0.14\ (\text{stat.}) \pm 0.26\ (\text{syst.})\ \text{GeV}^{-2}.$$

TOTEM EPL, 95 (2013) 21002

$$B = (19.9 \pm 0.3)\ \text{GeV}^{-2}$$

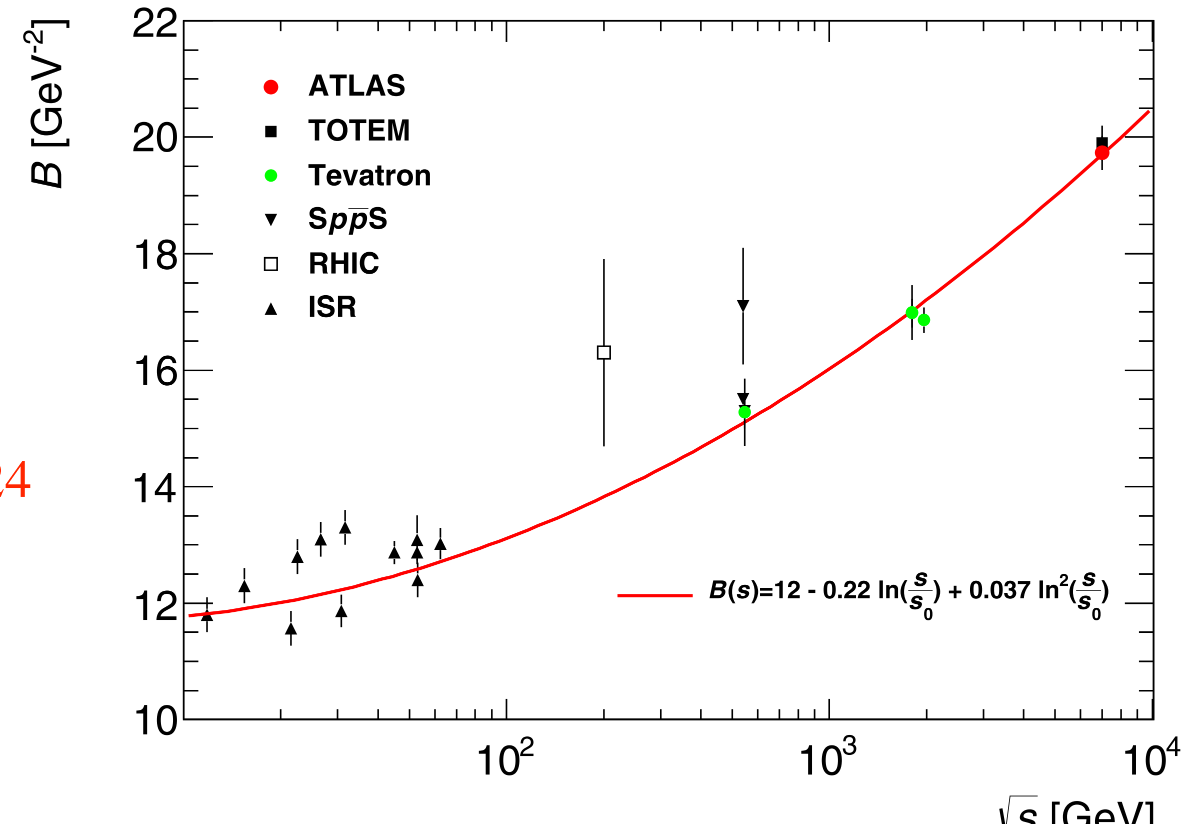
- Even taking higher CDF value at 1.8 TeV and $\alpha' = 0.25\,\text{GeV}^{-2}$ DL predicts:

$$B_{\text{el}} = 16.98 + 4 \times 0.25 \times \ln(7/1.8) = 18.34\ \text{GeV}^{-2}$$

$\longrightarrow$ Simple linear Regge scaling ruled out: $$B_{\text{el}} \neq 2b_0 + \alpha' \ln\left(\frac{s}{s_0}\right)$$

- Energy dependence fit well by second--order polyn. May be expected from ladder structure of pomeron exchange.

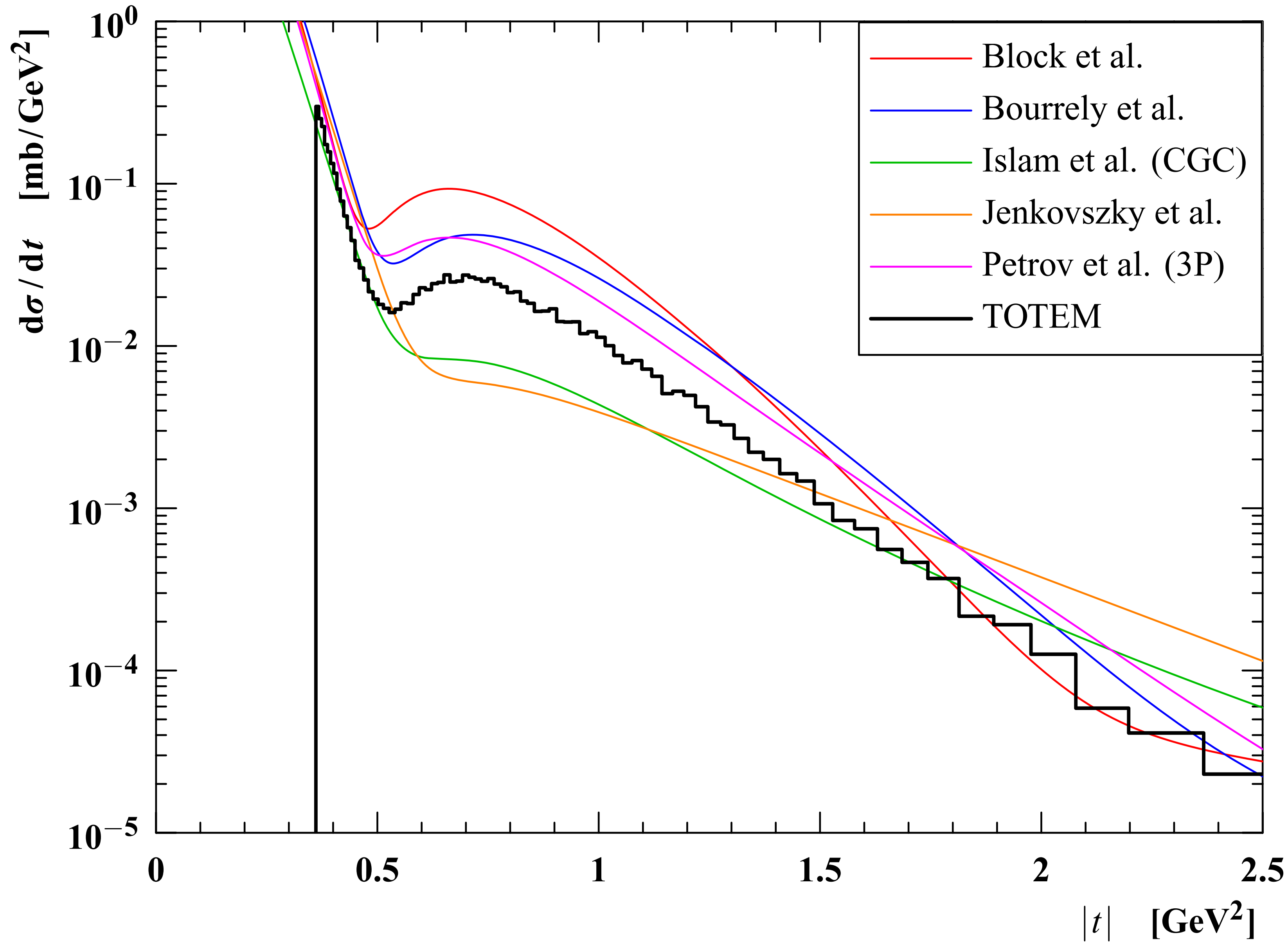
V. A. Schegelsky, M.G. Ryskin, Phys. Rev. D85 (2012) 094024



Lessons from LHC run I - elastic cross section

- TOTEM 7 TeV measurement of differential elastic cross section. No models predict data completely:

TOTEM EPL, 95 (2011) 41001



Lessons from LHC run I - low mass diffraction

TOTEM EPL, 101 (2013) 21003

- TOTEM give direct measurement of low mass diff. at 7 TeV:

$$\sigma_{\rm tot}^{\rm RP} - \sigma_{\rm el}^{\rm RP} - \sigma_{{\rm inel},|\eta|<6.5}^{\rm T2} = 2.62 \pm 2.17\,{\rm mb} \qquad M_X < 3.4\,{\rm GeV}$$

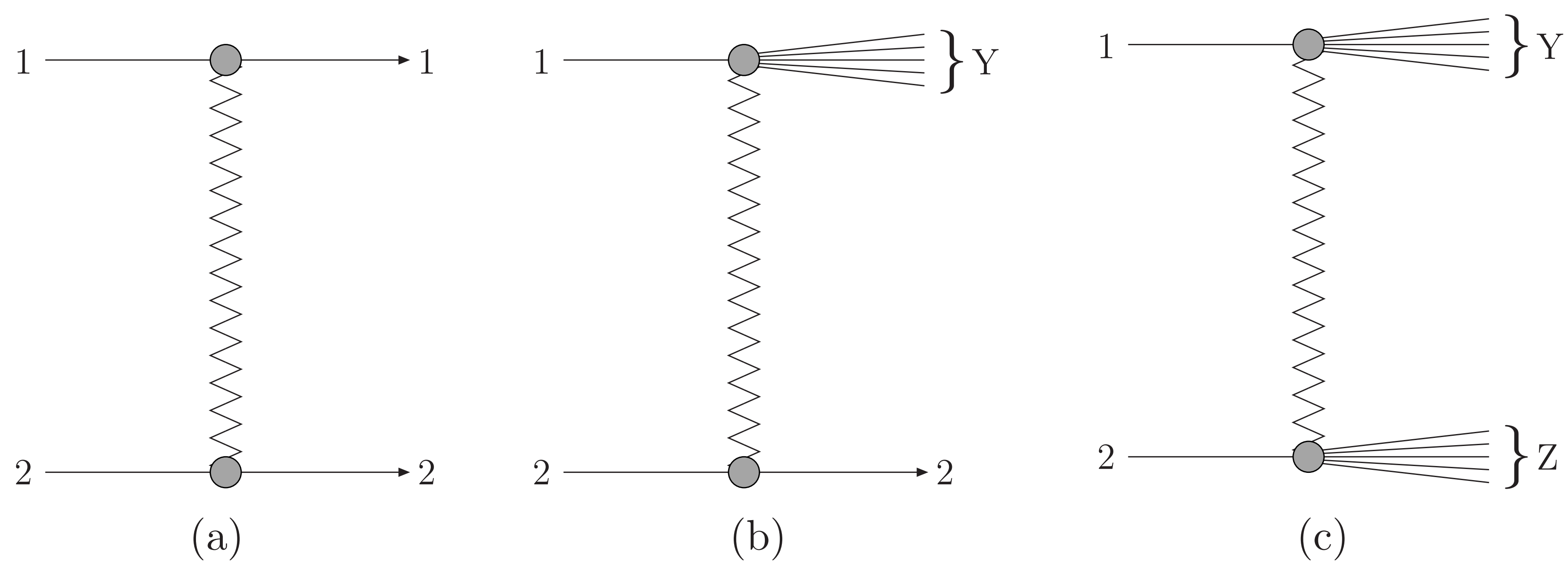
compare to lower energy measurements:

Other inelastic measurements: ATLAS, Eur. Phys. J C72 (2012) 1926, CMS-PAS-FSQ-12-005, ALICE, Eur. Phys. J C73 (2013) 2456

CERN-ISR: 31-62.5 GeV | UA4: 516 GeV | TOTEM: 7 TeV

$$\frac{\sigma_{\rm D}^{\rm lowM}}{\sigma_{\rm el}} = \frac{2-3}{7}, \qquad \frac{3}{12}, \qquad \frac{2.6}{25},$$

$\longrightarrow$ Ratio decreases with energy. Naively, driven by (the same) Pomeron exchange, expect to be ~ constant, i.e. one pomeron exchange overestimates data.



Lessons from LHC run I - high mass diffraction

• Range of results from ALICE, ATLAS, CMS and TOTEM on high mass inelastic diffraction.

TOTEM prelim., M. Berreti, talk at Diffraction 2014, ATLAS, Eur. Phys. J C72 (2012) 1926, CMS-PAS-FSQ-12-005, ALICE, Eur. Phys. J C73 (2013) 2456

• Appears to be some tension between TOTEM and ATLAS/CMS data, even accounting for model dependence in their extraction.

• S. Ostapchenko (Phys. Rev. D89 (2014) 7, 074009) : two models SD+ and SD-, for better agreement with ATLAS/CMS and TOTEM, respectively.

• Give quite different results for primary cosmic ray composition:

$E_0 = 10^{18} - 10^{20}$ eV

- SD- : consistent with almost pure proton.
- SD+ : requires substantial heavy nuclei frac.

	$d_p(1)$	$d_p(100)$	χ^2/d.o.f.
QGSJET-II-04	0.79	0.77	35.6/33
option SD+	0.77	0.75	41.4/33
option SD-	0.84	0.85	31.8/33

$\longrightarrow$ Consequence for astrophysical interpretation of cosmic ray data!

Post Run I- status of models

- No pre-LHC model successfully describe the Run I diffractive data. Wide range of data and trends in elastic, total and dissociative cross sections give much information for model improvements.

- Subsequently good description of LHC data claimed by:

  - KMR: now take $\phi_i - I\!P$ coupling $\gamma_i \propto 1/(k_i^2 + k_{I\!P}^2)$ where $k_{I\!P}(k_i)$ is characteristic mom. in pomeron (diff. eigenstate), with $k_{I\!P}^2 = k_0^2 s^{0.28}$. Then as $s \to \infty$, $\gamma_i \sim 1/k_{I\!P}^2$, indep. of i , and $\sigma_{\rm SD}^{\rm low\ M}/\sigma_{\rm el} \to 0$. Also leads to less absorption and thus faster rise in $\sigma_{\rm tot}(s)$.

  - GLM: new approach, matching the pomeron in N=4 SYM ($\leftrightarrow$ BFKL pomeron) to pQCD. see E. Gotsman talk on Tuesday.

  - EPOS/QGSJET: post-LHC tunes and updates developed

  - MBR: see K. Goulianos talk on Tuesday.

Another handle- rapidity gap survival

- For processes where exclusive final-states/rapidity gaps are demanded, must include the probability that additional soft particles are not produced: the soft survival factor, S^2.

- Relevant for diffractive jets, W/Z+gaps, exclusive photoproduction, central exclusive production (including semi-exclusive, with proton diss.)...

- 'Eikonal' survival factor due to proton-proton interactions, and `enhanced' due to proton-parton interactions. Typically $\langle S^2_{\rm eik}\rangle \ll \langle S^2_{\rm enh}\rangle$.

- Can write down the average $\langle S^2_{\rm eik}\rangle$ within particular model:

$$S^2_{\rm eik}(\mathbf{b}) \;=\; \frac{\left|\sum_{i,k}|a_i|^2\;|a_k|^2\;\mathcal{M}_{ik}(\mathbf{b})\;\;\exp(-\Omega^{\rm tot}_{ik}(s,\mathbf{b})/2)\right|^2}{\left|\sum_{i,k}|a_i|^2\;|a_k|^2\;\mathcal{M}_{ik}(\mathbf{b})\right|^2}\,.$$

$\longrightarrow$ Can provide additional test of model of soft diffraction.

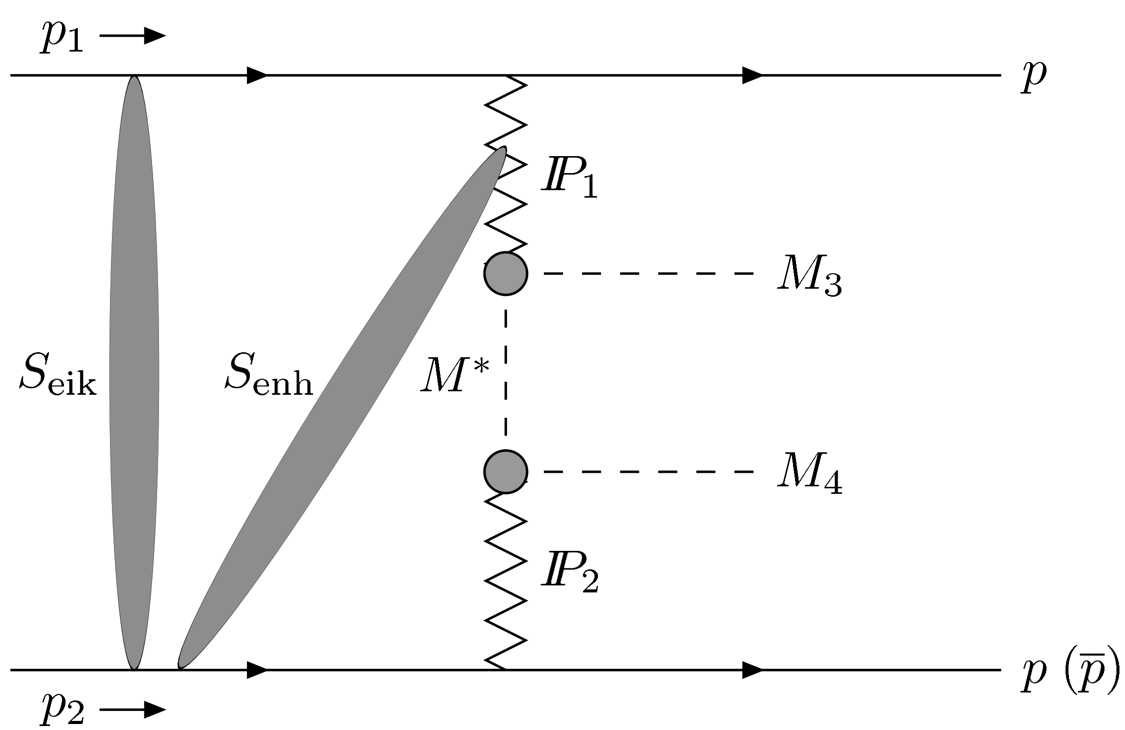
Rapidity gap survival - proton distributions

- The average $\langle S^2 \rangle$ can often get lost in other model uncertainties.

$\longrightarrow$ Look to more differential tests.

- Consider e.g. the central exclusive production of meson pairs, e.g.

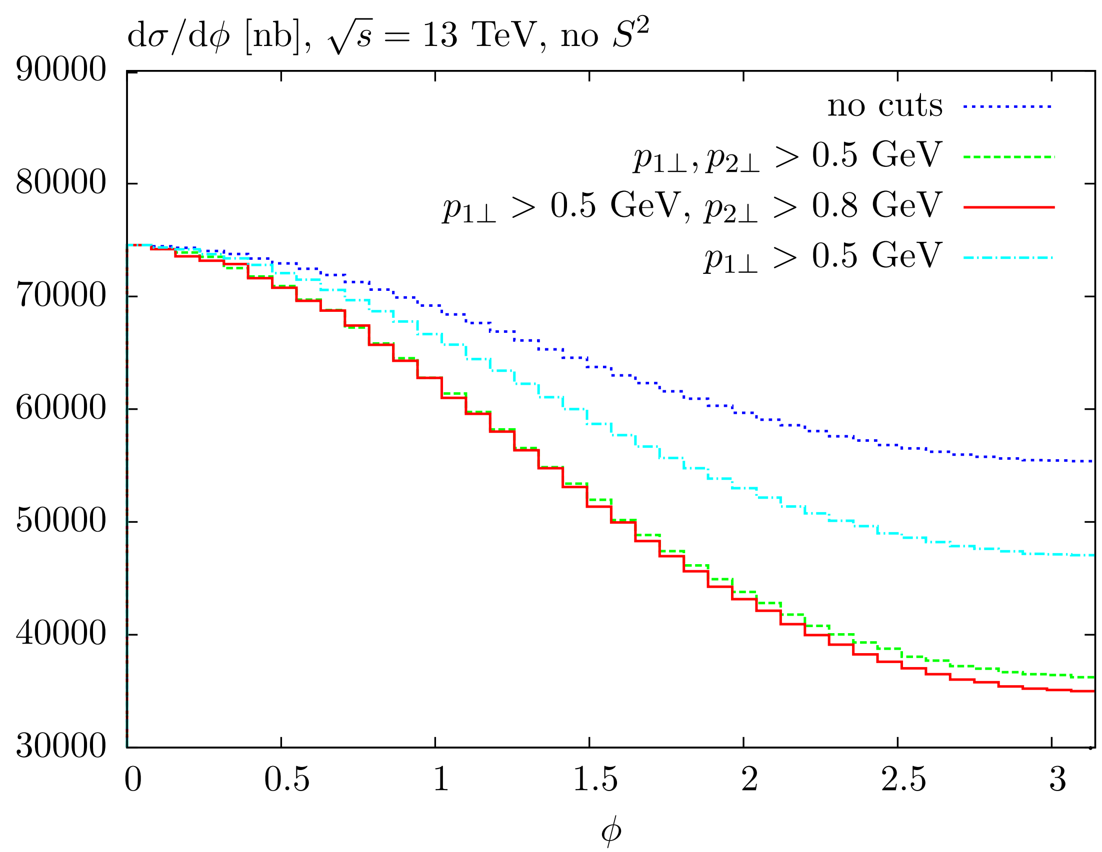
$$pp \to p + \pi^+\pi^- + p$$



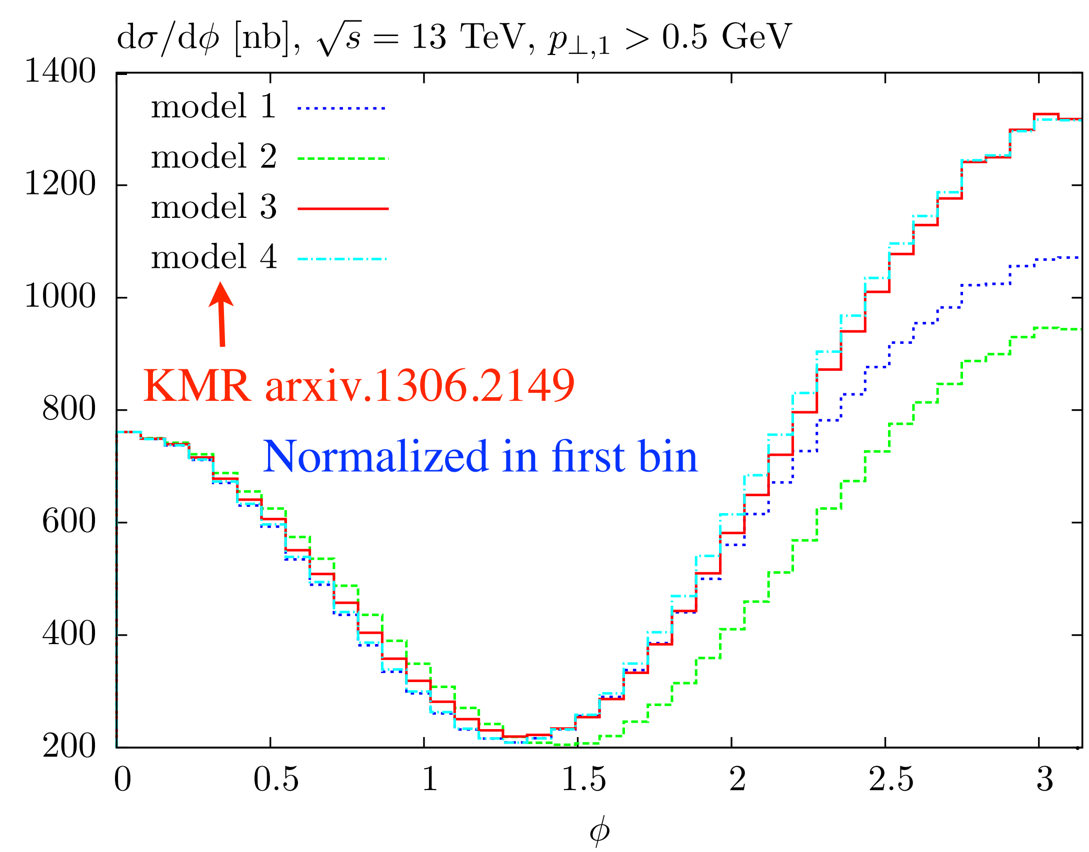
- Measured by CDF and ALICE, CMS by vetoing on additional activity, but without tagging protons. Realistic proposal to measure with tagged protons by ATLAS+ALFA and CMS+TOTEM in Run II.

• The observation of such a process with tagged protons also provides additional information about survival factors...

S^2 off



S^2 on



LHL, V.A. Khoze and M.G. Ryskin, arXiv:1312.4553

• Distribution in angle ϕ between outgoing protons strongly effected, in model dependent way.

• In particular true when larger values of proton $p_\perp$ are selected. Cancellation between screened and unscreened amplitudes leads to characteristic ‘diffractive dip’ structure

• Largely independent of production subprocess in central region.

V. A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0203122
LHL, V.A. Khoze, M.G. Ryskin and W.J. Stirling, arXiv:1011.0

Rapidity gap survival - differential measurements

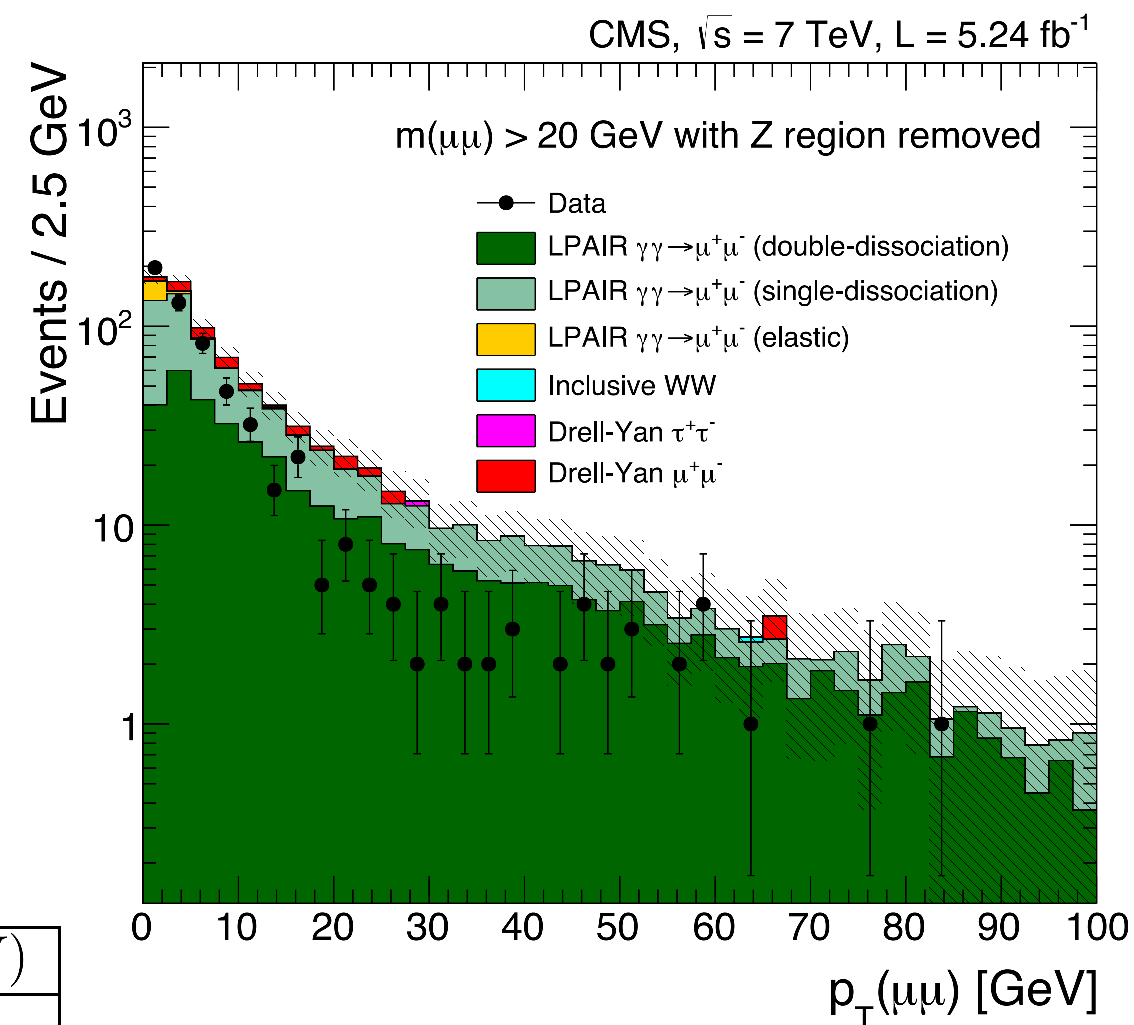
- Another possibility: central diffractive lepton pair production.
- In pure exclusive case $\langle S^2 \rangle \sim 1$, but for proton dissociation have larger $p_\perp$ transfer and therefore smaller $\langle S^2 \rangle$.

JHEP 1307 (2013) 116

- CMS $\mu^+\mu^-$ measurement: compare $p_\perp$ of $\mu^+\mu^-$ system against LPAIR. Overestimates data at higher $p_\perp$, due to survival factor.

$\longrightarrow$ Measurement sensitive to $\langle S^2(p_\perp^{\mu\mu}) \rangle$.

$$pp \to Y + l^+ l^- + Z$$



Not most up to date numbers, but give qualitative picture

Single	Low $M_{Y,Z}$ ($\lesssim 2.5$ GeV)	High $M_{Y,Z}$ ($\gtrsim 2.5$ GeV)	
S^2	0.86 ± 0.03	0.81 ± 0.03	
Double	(Low M_Y, Low M_Z)	(Low M_Y, High M_Z)	(High M_Y, High M_Z)
S^2	$0.3 - 0.45$	$0.2 - 0.28$	$0.08 - 0.16$

LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, Eur. Phys. J. C72 (2012) 2110

Exclusive Processes

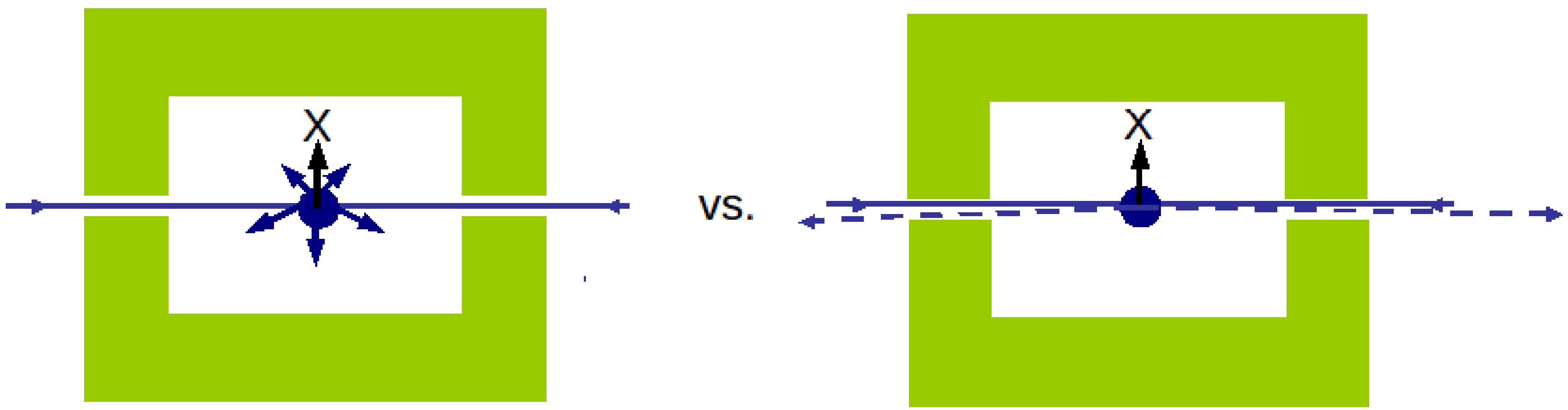
Central Exclusive Production

$$pp \to p + X + p$$

• Protons remain intact after collision. Only object of interest X is produced ($X =$ jets, $J/\psi, \pi^+\pi^-, W^+W^-$...).

• Generally interested in case where M_X is sufficiently high that a pQCD based approach may be taken.

$\longrightarrow$ Diffractive (colour singlet, rapidity gaps) but perturbative.



Also: Odderon

Can (principally) occur through $I\!\!P I\!\!P$, $I\!\!P\gamma$ and $\gamma\gamma$ interactions

(QCD mediated)

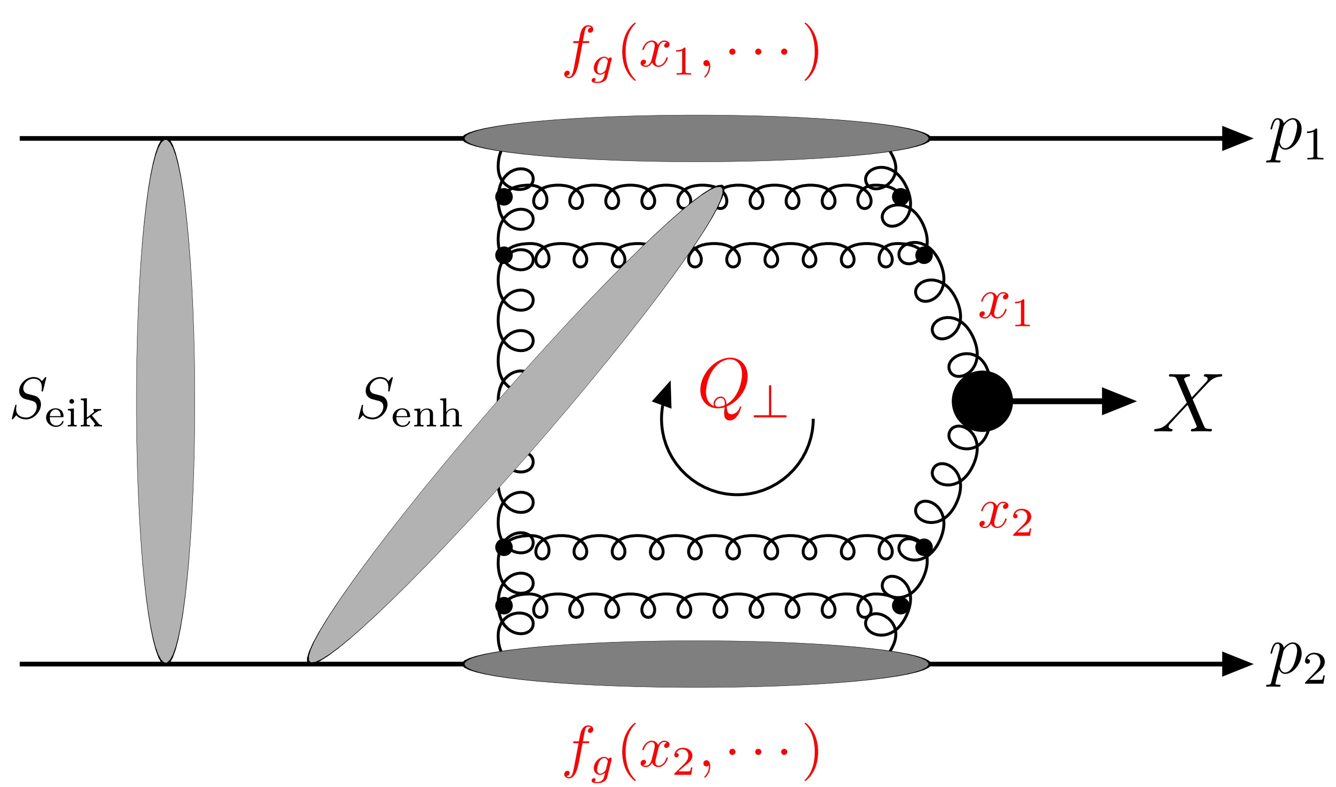
'Durham Model' of Central Exclusive Production

• Model via diagram shown: two gluons exchange in the t-channel. Use of pQCD justified by hard scale $\sim M_X$. IR stable result due to Sudakov factor: probability of no additional hard radiation.

• However must also include probability of no additional soft secondary particle production, independent of hard process: the soft survival factor S^2, discussed before.

$\longrightarrow$ Both soft and hard QCD must be included.

• $J_z^{PC} = 0^{++}$ selection rule: these quantum numbers are dominantly preferred, i.e. only certain $gg \to X$ helicity amplitudes contribute, not the usual inclusive sum.



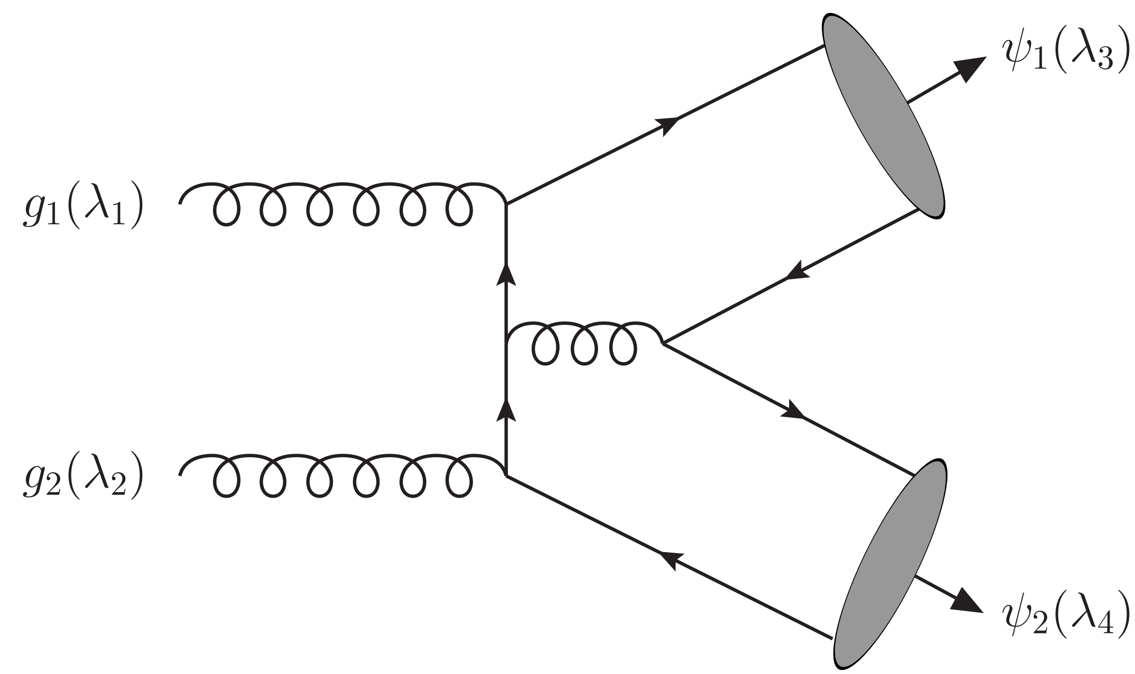
See my talk tomorrow for details of new 'superchic 2' MC implementation.

LHL, V.A. Khoze, M.G. Ryskin, J. Phys. G42 (2015) 5, 055001

Example: exclusive $J/\psi J/\psi$ production

• Heavy quark mass ensures this is perturbative. Highly topical as a probe of (inclusive) double parton scattering, as well as tetraquark decays...

• Generically we write the CEP process in terms of the $gg \to X$ helicity amplitudes, in this case $gg \to J/\psi J/\psi$.



• In high subprocess energy ($\hat{s} \gg M_\psi^2$) limit find that amplitudes with initial-state gluons in $J_z = 0$ config. vanish, while numerically suppressed away from this limit.

$\longrightarrow$ Expect $J/\psi J/\psi$ CEP cross section to be suppressed below naive estimates. Specific result of exclusive channel, relies upon selection rule.

Recently LHCb have released the first exclusive measurement:

Observation of charmonium pairs produced exclusively in pp collisions

J. Phys. G41 (2014) 11, 115002

The LHCb collaboration†

Abstract

A search is performed for the central exclusive production of pairs of charmonia produced in proton-proton collisions. Using data corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$ collected at centre-of-mass energies of 7 and 8 TeV, $J/\psi J/\psi$ and $J/\psi\psi(2S)$ pairs are observed, which have been produced in the absence of any other activity inside the LHCb acceptance that is sensitive to charged particles in the pseudorapidity ranges $(-3.5, -1.5)$ and $(1.5, 5.0)$. Searches are also performed for pairs of P-wave charmonia and limits are set on their production. The cross-sections for these processes, where the dimeson system has a rapidity between 2.0 and 4.5, are measured to be

$$\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},\\
\sigma^{J/\psi\, \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}$$

where the upper limits are set at the 90% confidence level. The measured $J/\psi\, J/\psi$ and $J/\psi\, \psi(2S)$ cross-sections are consistent with theoretical expectations.

LHL, V.A. Khoze, M.G. Ryskin, J. Phys. G42 (2015) 5, 055001

- We find, for the LHCb kinematics:

	MSTW08LO		CTEQ6L		GJR08LO	
	model 1	model 4	model 2	model 3	model 1	model 4
$\sqrt{s} = 8$ TeV	5.8	6.7	2.5	1.5	4.6	5.3
$\sqrt{s} = 14$ TeV	11.8	14.2	4.6	3.6	9.1	10.8

Table 2: Cross section, in pb, for the $J/\psi J/\psi$ CEP at $\sqrt{s} = 8$ and 14 TeV, using different models of the soft survival factor taken from [23], and with different PDF choices. The J/ψ pair is required to lie in the the forward rapidity region $2 < Y_X < 4.5$.

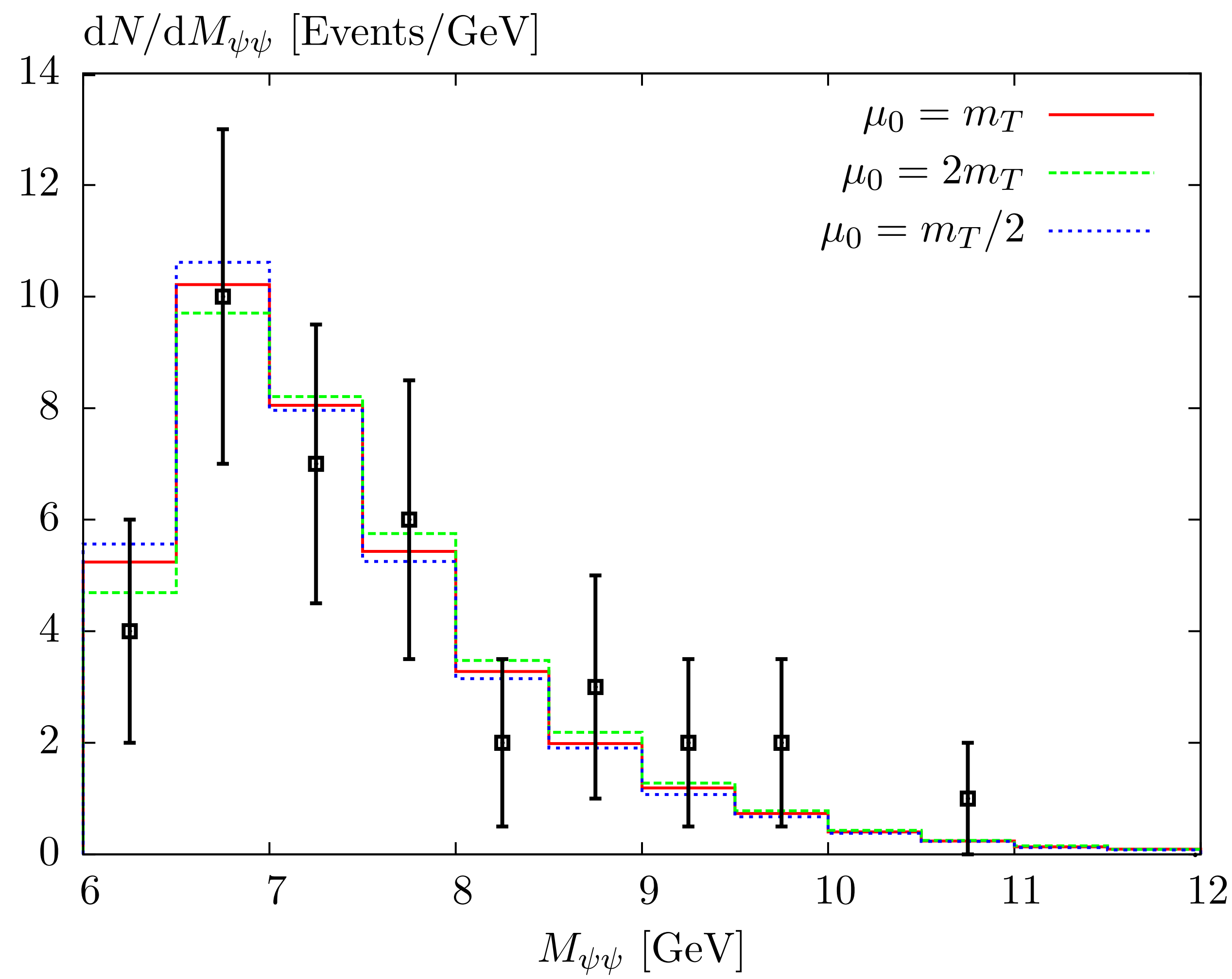
- After correcting for non-exclusive contamination, LHCb report an exclusive $J/\psi J/\psi$ cross section of $24 \pm 9\,\text{pb}$,

$\longrightarrow$ Larger (MSTW/GJR) cross sections in fair agreement, within (reasonably large) theoretical and experimental uncertainties, but interesting possibility that predicted cross section are a little low.

- Worth recalling that this level of agreement requires getting the perturbative Sudakov suppression (no extra hard radiation), soft survival factor (no extra soft radiation) and dynamics of process ($J_z = 0$ selection rule) right. Plenty of physics going on...

• Can compare $J/\psi J/\psi$ invariant mass distribution to LHCb measurement

Normalized
to data



$\longrightarrow$ Encouraging agreement, within experimental uncertainties. But absolute cross section perhaps a bit higher in data.

• Outlook: during Run II we can anticipate (hope for) further, higher statistics, measurements of this from LHCb (defocused beams + HERSCHEL): $J/\psi J/\psi, \psi(2S)\psi(2S), \chi_c\chi_c(?)\cdots$

Other processes: jet production

- Large cross sections, expect strong gg dominance, i.e. isolated gluon jets at the LHC. $\longrightarrow$ possible clean probe of properties of gluon jets.
- 3-jet events: expect enhancement in 'Mercedes' configurations in $q\bar{q}g$ case and potential for (first) observation of QCD 'radiation zeros' in $ggg/q\bar{q}g$ channels.

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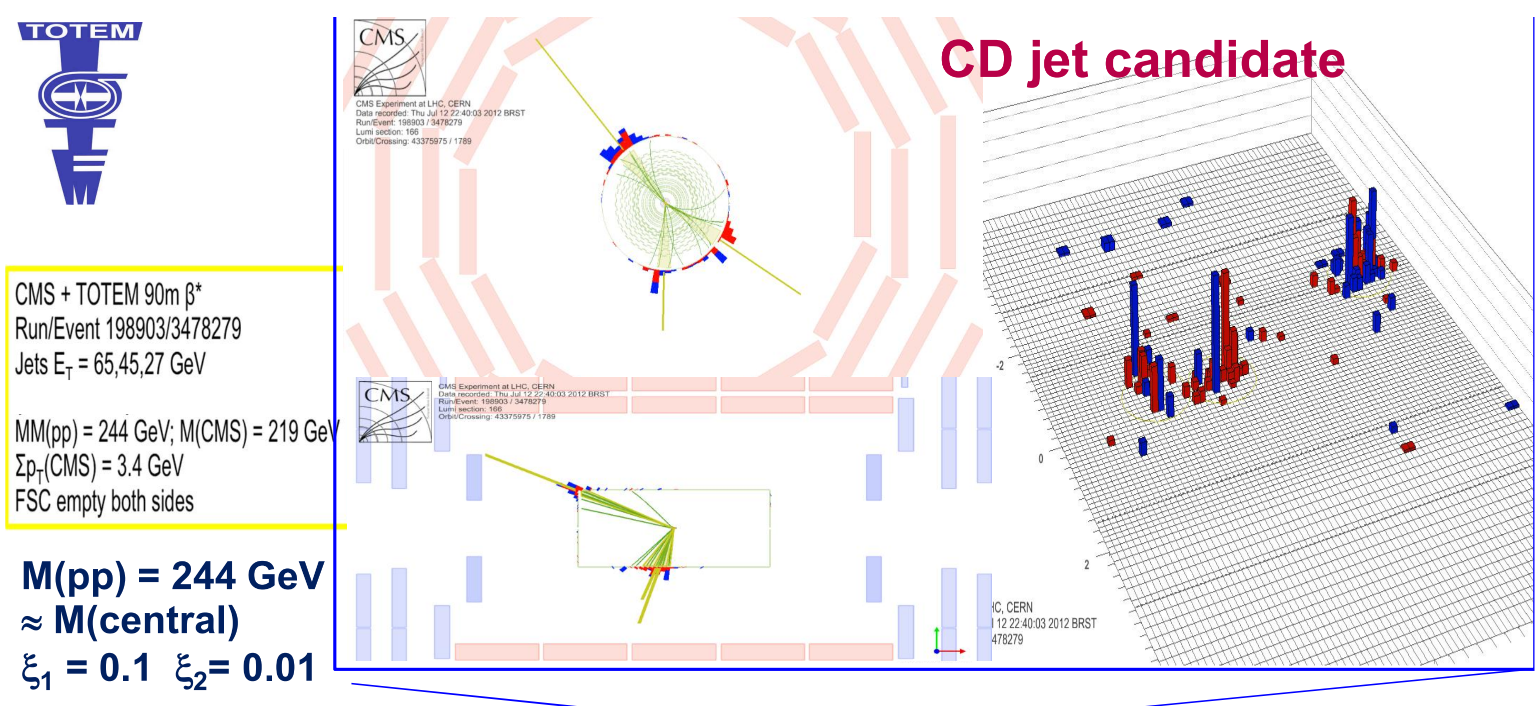
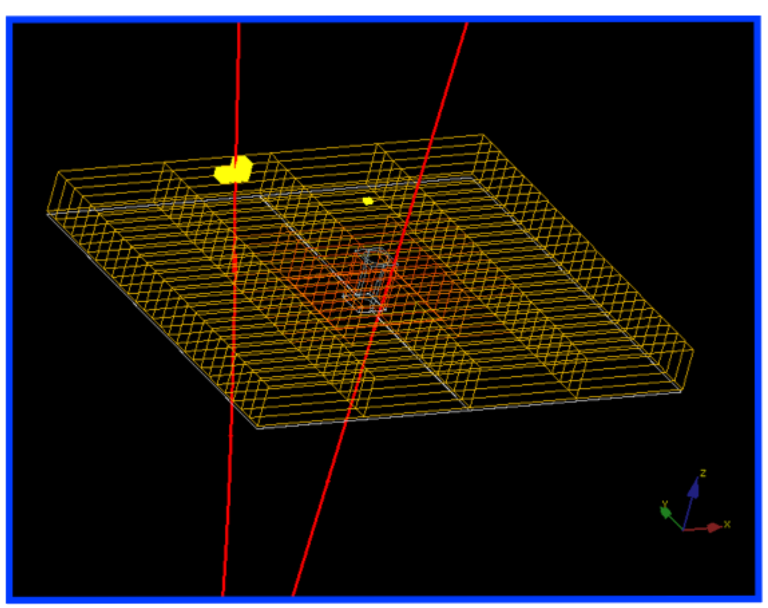
- Proposals for measurements during Run II with tagged protons, both during low lumi. running with CMS-TOTEM, ATLAS+ALFA (can expect ~ 10000 events for $100\,\mathrm{pb}^{-1}$) and during normal running with CT-PPS and AFP (detailed studies have been performed and S/B found to be viable).

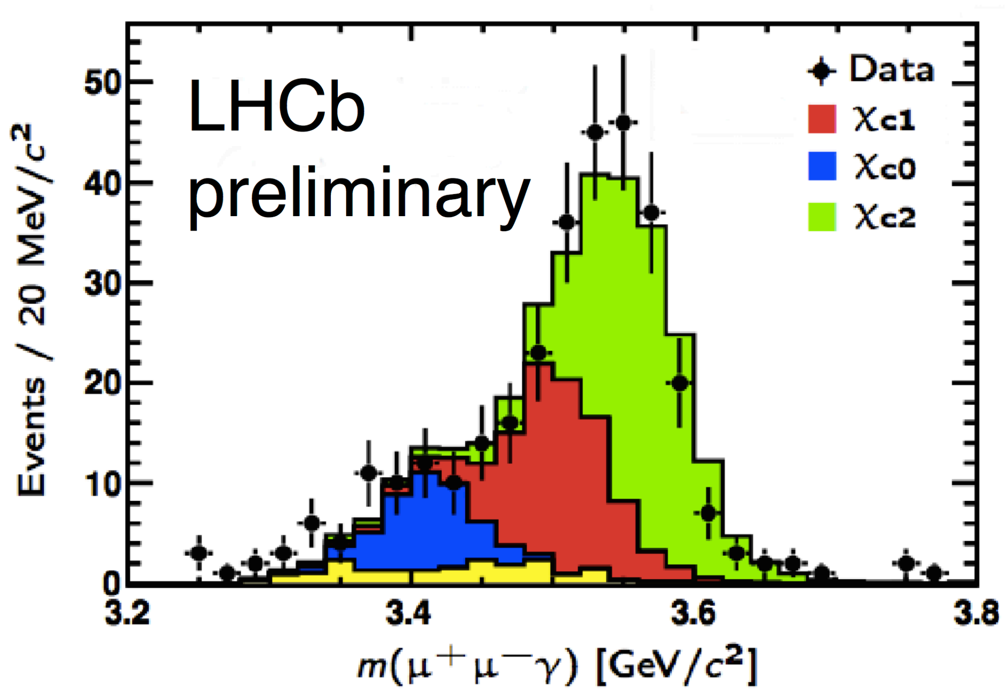


Other processes: heavy quarkonia

- Conventional quarkonia: χ_c CEP observed by CDF and LHCb. Expect hierarchy in cross sections ($\sigma(\chi_{c0}) \gg \sigma(\chi_{c1,2})$) unique to exclusive mode and expected/observed inclusively. The higher mass χ_b a useful possibility for the future. Measurements by LHCb and CMS-TOTEM during Run II proposed.

- Exotic quarkonia: for example, the very topical $X(3872)$. Quantum numbers known but assignment as e.g. a $D\overline{D}$ molecular state or a conventional $\chi_{c0}(2P)$ (or admixture of two) still undetermined. If dominantly $D\overline{D}$ then expect extra particles to be produced $\longrightarrow$ exclusive mode can distinguish between interpretations.





Run II measurements of interest

- Soft diffraction
  - Measurement of $\sigma_{\rm tot}$ and elastic slope $B_{\rm el}$ at 13 TeV (in particular to confirm rise of effective $\alpha'_{I\!P}$).

    c.f. ‘tensions’ in inelastic diffraction data
  - Accurate determination of $\sigma_{\rm SD}$ in different mass intervals: TOTEM-CMS (w/ FSCs), ATLAS+ALFA, and prospects at LHCb (HERSCHEL installed).
  - Detailed comparison of ${\rm d}\sigma_{\rm el}/{\rm d}t$ over wide t interval with different models.
  - CEP ‘interferometry’: e.g. correlations in proton distributions sensitive to soft survival factor.

    sensitive to proton opacity
- CEP processes:
  - Wide program of experimental studies proposed and possible during Run II, many not mentioned in this talk. Studies of jets, heavy quarkonia, exotic quarkonia, Higgs, two--photon induced processes photoproduction etc all of interest. The extensive rapidity coverage and proton tagging capabilities make the LHC ideal for these measurements.

See yellow report for further details!

Summary

- Diffraction very broad topic, covering soft and hard QCD physics.

- Soft diffraction: many models/MCs available, have been put to the test by the Run I LHC data at unprecedented collider energies, and often found to fall short. Testing our understanding of QCD, as well as having consequences for e.g. cosmic ray physics.

- Central exclusive production: 'hard diffractive' process, requiring non-trivial combination of soft and hard QCD. Can produce in principle any object that couples to gluons $\longrightarrow$ wide menu of processes to study

- LHC Run II has the potential to greatly increase our understanding of these processes. Please see the Forward Physics and Diffraction yellow report for status and prospects!