Working Group 2

Low x and diffraction

Summary

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KU

DIS 2017, 25th International Workshop on Deep Inelastic Scattering and Related Topics
April 7 2017, University of Birmingham

Working Group 2: Low x and Diffraction

9 sessions, 42 talks, 18 experiment, 24 theory/phenomenology

Speakers:

Marcin Guzik
Laurent Forthomme
Alexander Bylinkin
Bartłomiej Rachwał
Jesus G. Contreras Nuno
Frigyes Janos Nemes
Grzegorz Gach
Peter John Bussey
John Dainton
Karel Cerny
Kay Graham
Martin Hentschinski
Jan Cepila
Heikki Mantysaari
Radek Zlebcik
Renaud Boussarie
Yoshitaka Hatta
Oleg Kuprash
Benoit Roland
Gilvan Augusto Alves

Merijn van de Klundert
Jamal Jalilian-Marian
Mirko Serino
Oldrich Kepka
Grigorios Chachamis
Krzysztof Kutak
Agustin Sabio Vera
Victor Fadin
Sergey Bondarenko
Giovanni Antonio Chirilli
Guillaume Beuf
Tibor Zenis
Nestor Armesto Perez
Stephane Munier
Leszek Motyka
Bertrand Ducloue
Ian Balitsky
Elena Petreska
Aleksander Kusina

Main topics

Exclusive and diffractive processes in DIS and ultraperipheral collisions
Total and elastic cross sections

New theory developments:
Higher orders
New observables for low x
TMDs and low x

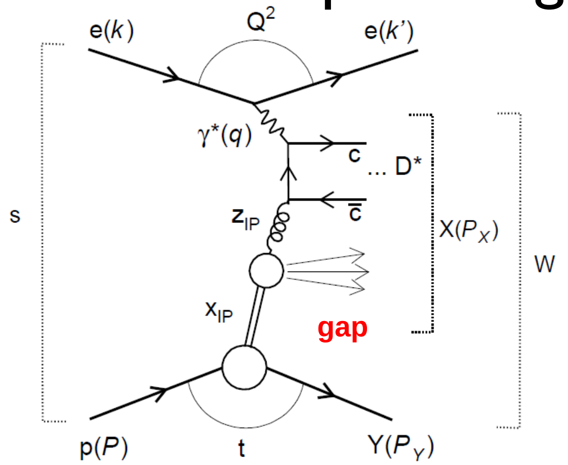
Multi-jets and forward jets
Multi-parton interactions

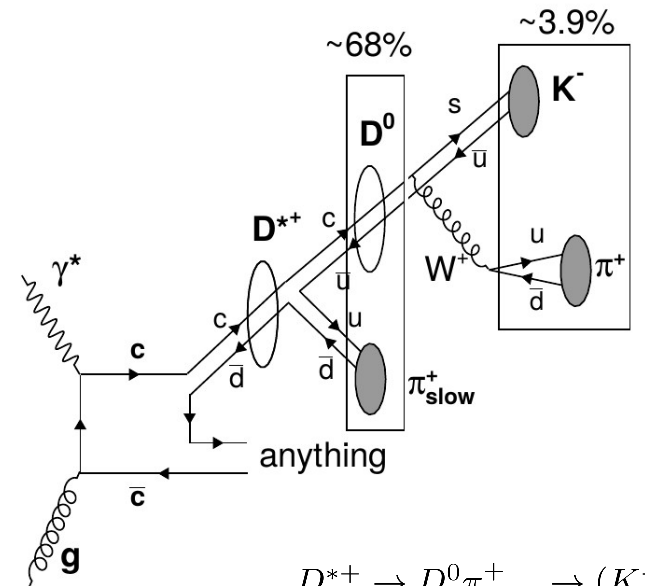
Fluctuations and correlations at low x

D^* diffractive production in DIS

Karel Cerny
H1

Charm production from photon gluon fusion





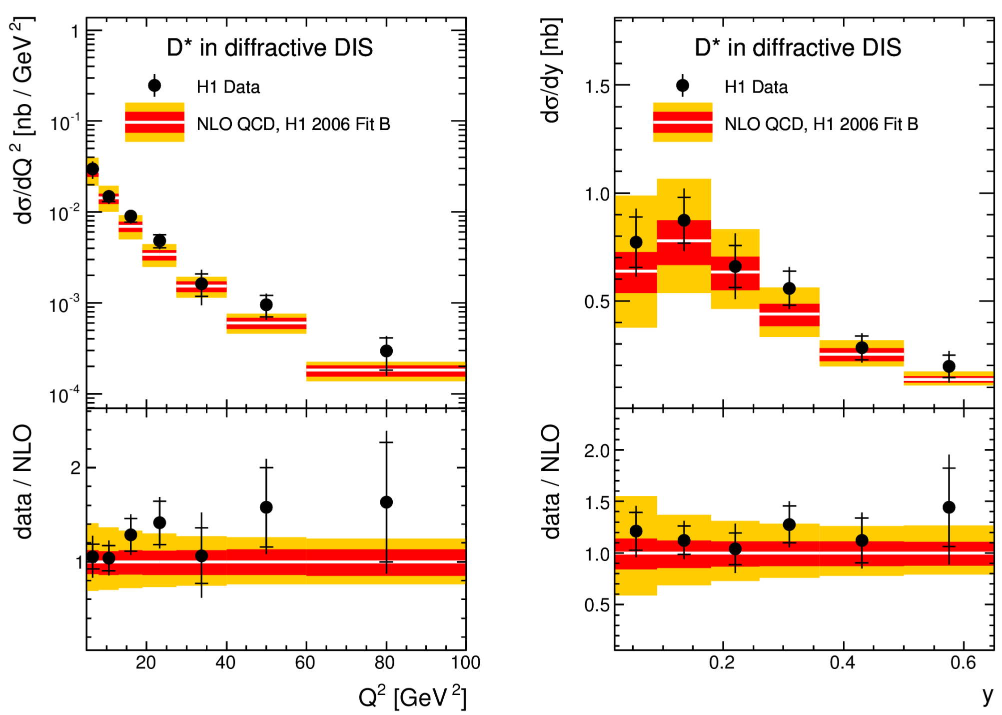
charm fragmentation

into D*(2010) $m_{D^*}^{\rm PDG} = 2010.26 \pm 0.05$ GeV

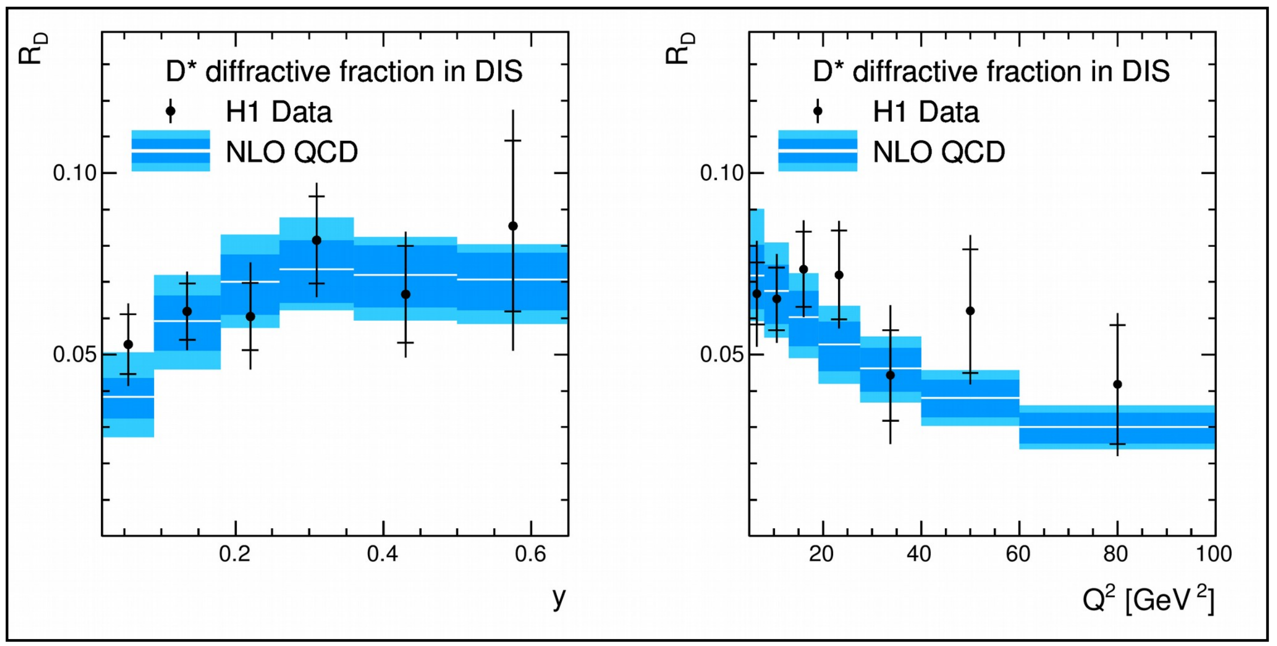
D* kinematics reconstructed fully from tracks in golden decay channel

$$D^{*+} \to D^0\pi^+_{slow} \to (K^-\pi^+)\pi^+_{slow}(+C.C.)$$

Differential cross section



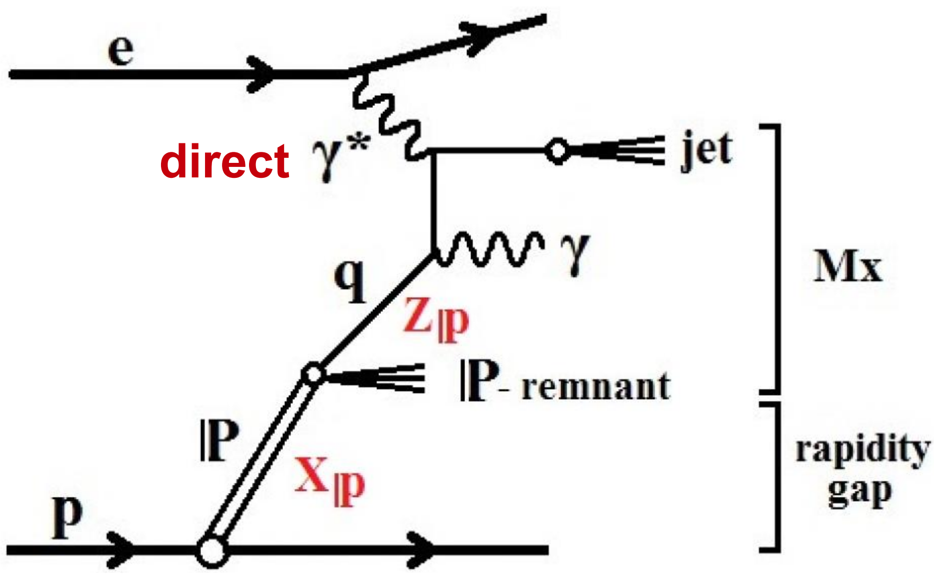
Diffractive ratio

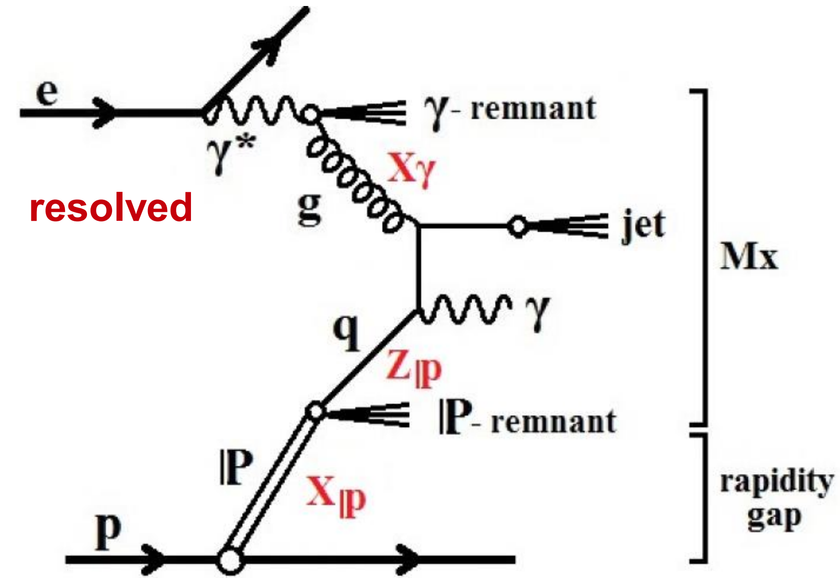


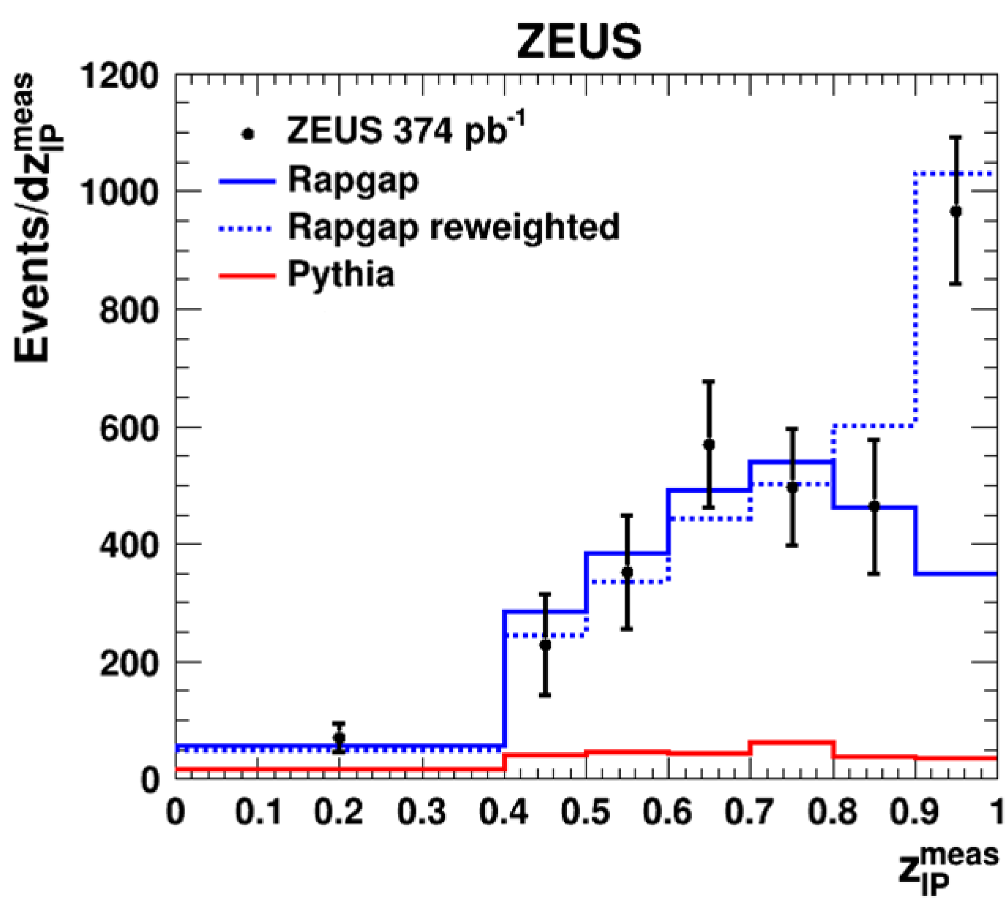
Results compatible with previous measurements
Shape and normalization reproduced well by NLO QCD with fit H1B 2006
Support for collinear factorization in diffractive DIS

Diffractive production of prompt photons in photoproduction

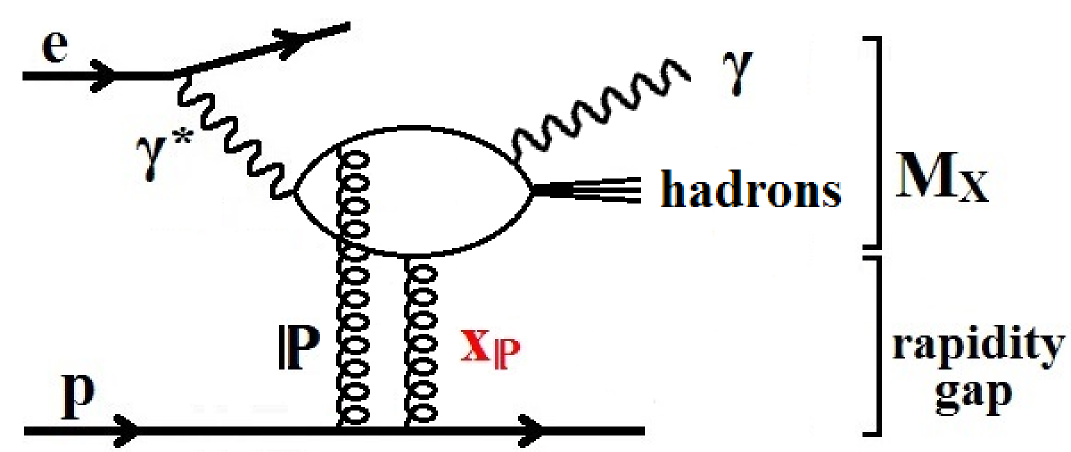
Peter J. Bussey
ZEUS







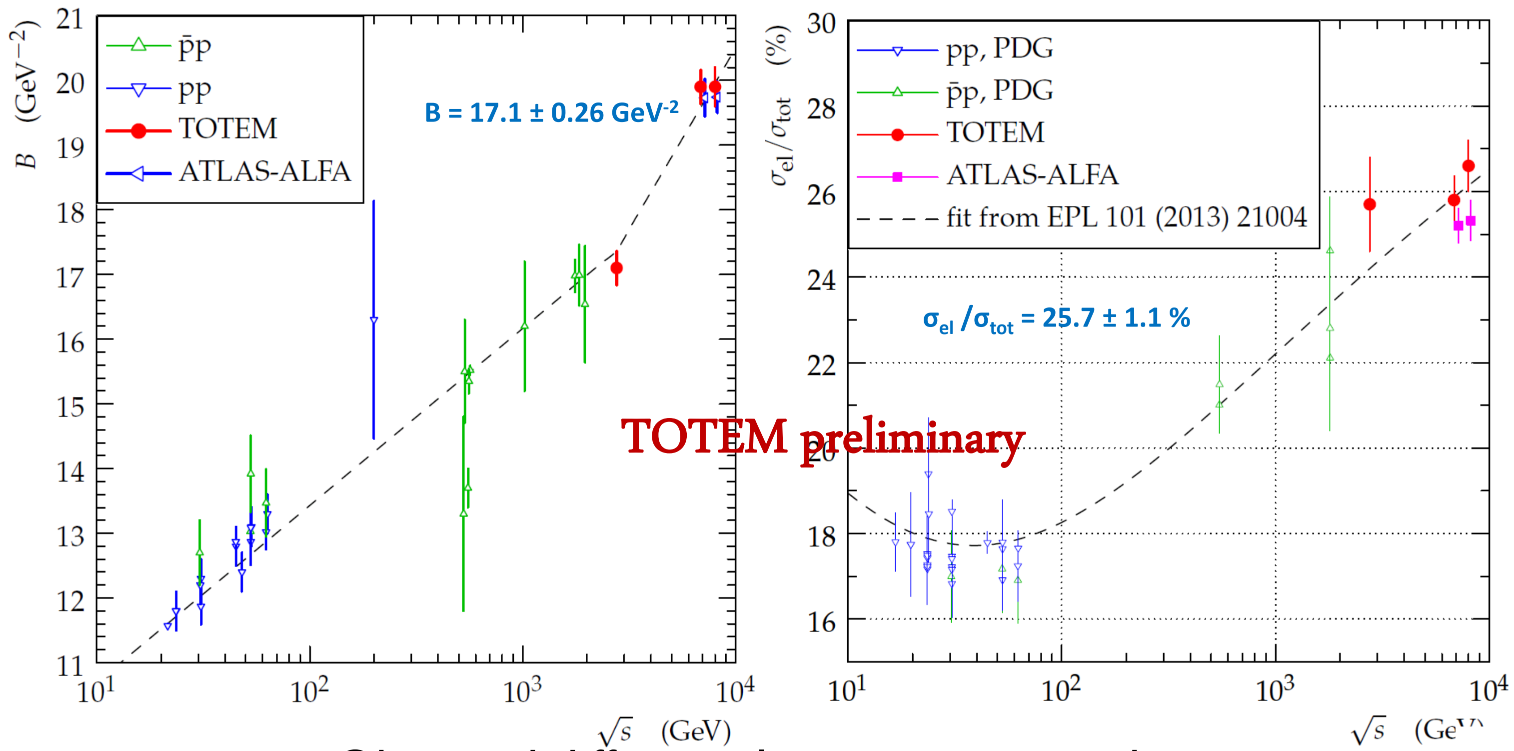
Distribution well described by RAPGAP with standard sets of DPDFs determined from DDIS.
Deviations only in the last bin.
Evidence for direct Pomeron interactions?



Elastic and total cross-section

Frigyes Nemes
TOTEM

The nuclear slope B and the σ_{el}/σ_{tot} ratio at √s = 2.76 TeV

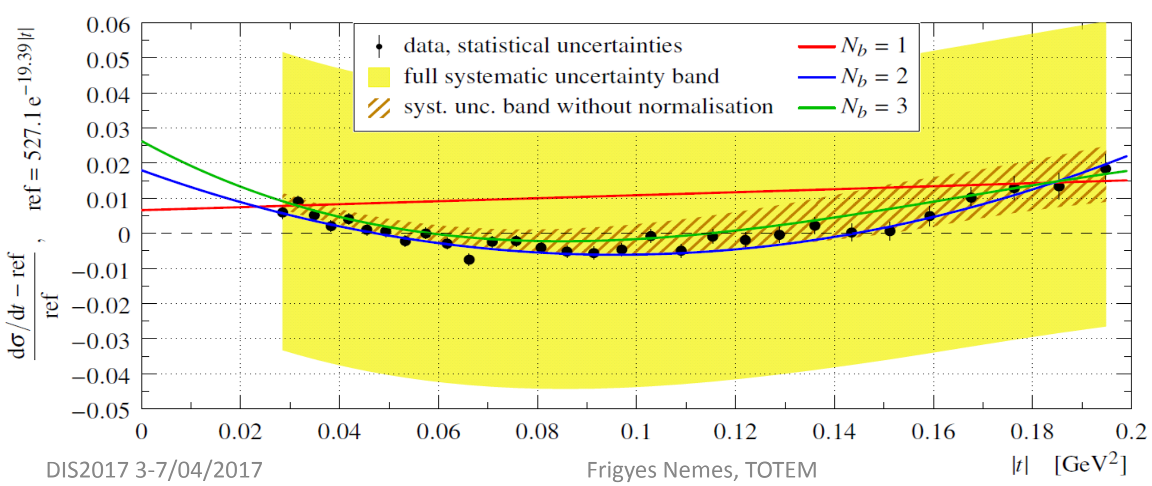


Result for B at 2.76 TeV consistent with previous trend observed at Tevatron and lower energies: linear in $\sqrt{s}$

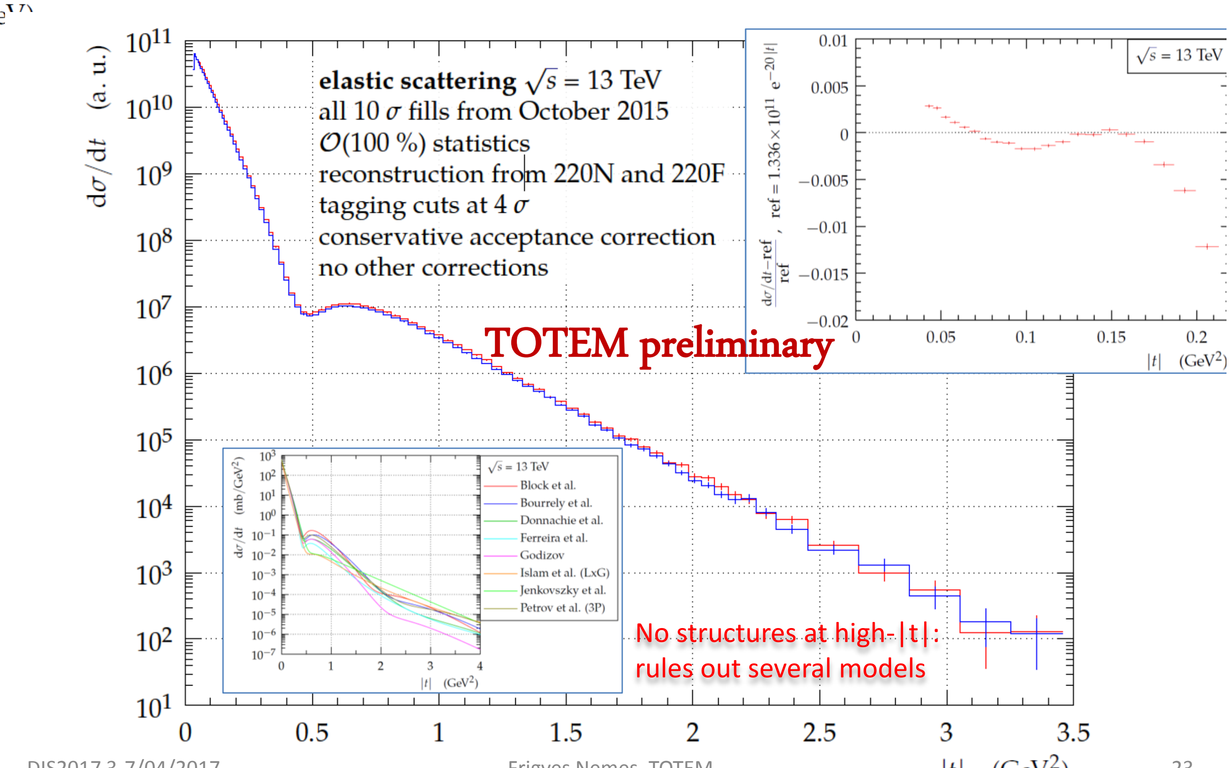
Visible change in energy dependence: quadratic in $\sqrt{s}$??

What is the origin: multi-Pomeron exchanges …?

Observed differential cross section with respect to pure exponential (8 TeV)



Pure exponential excluded with more than **7σ** significance

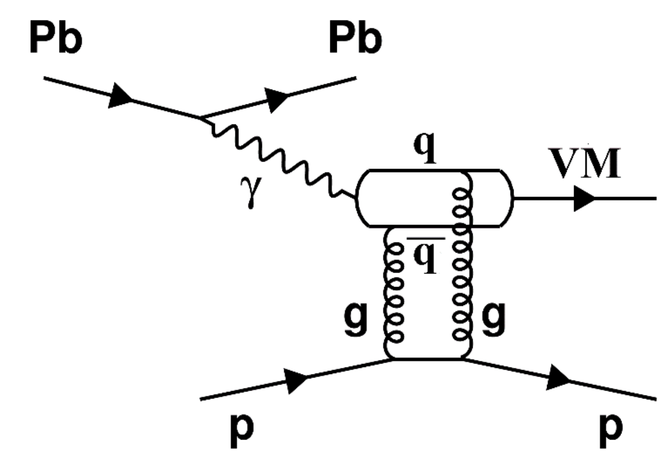


Preliminary results at 13TeV
No structure at high |t|

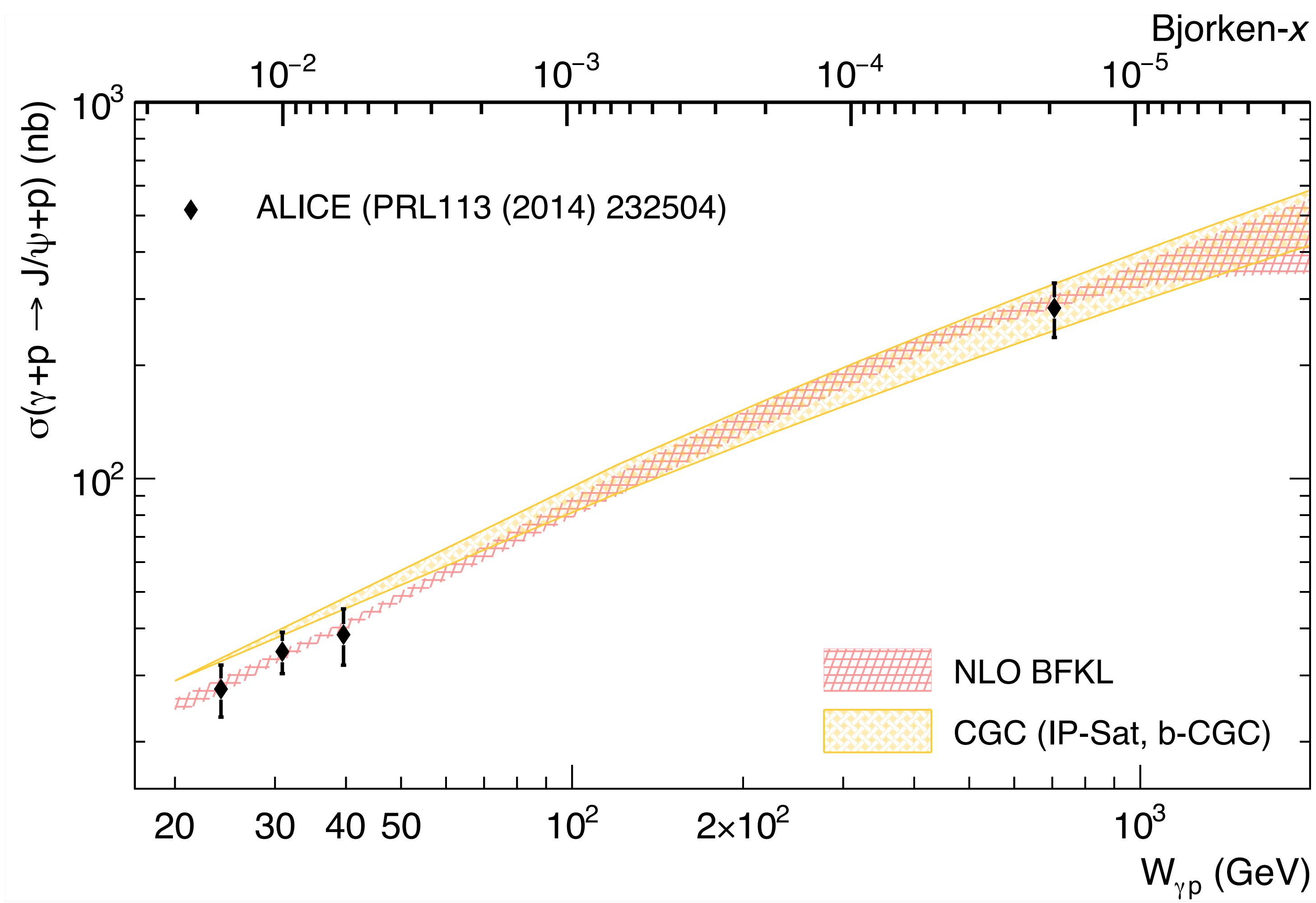
Exclusive production of J/ψ and ψ(2S) in p+Pb

Jesus G. Contreras
ALICE

Offers sensitivity to the gluon density (GPD)
Low scales open the window to test gluon saturation
t-dependence provides access to investigating shape of the proton

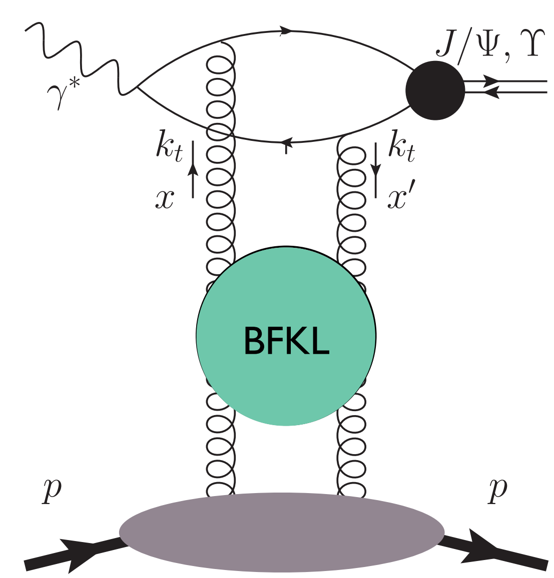


In pPb in ALICE, $W_{\gamma p}$ from 20 GeV to 1.5 TeV



Martin Hentschinski

NLL BFKL calculation - no saturation
Very good description of the data
Approaches with saturation work well too..



WG2: Low x and Diffraction

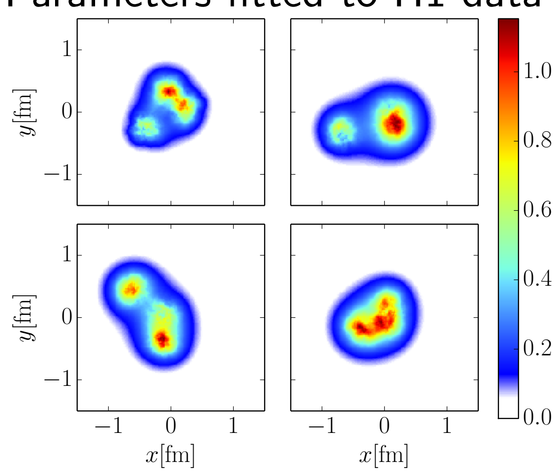
VM exclusive and dissociative production

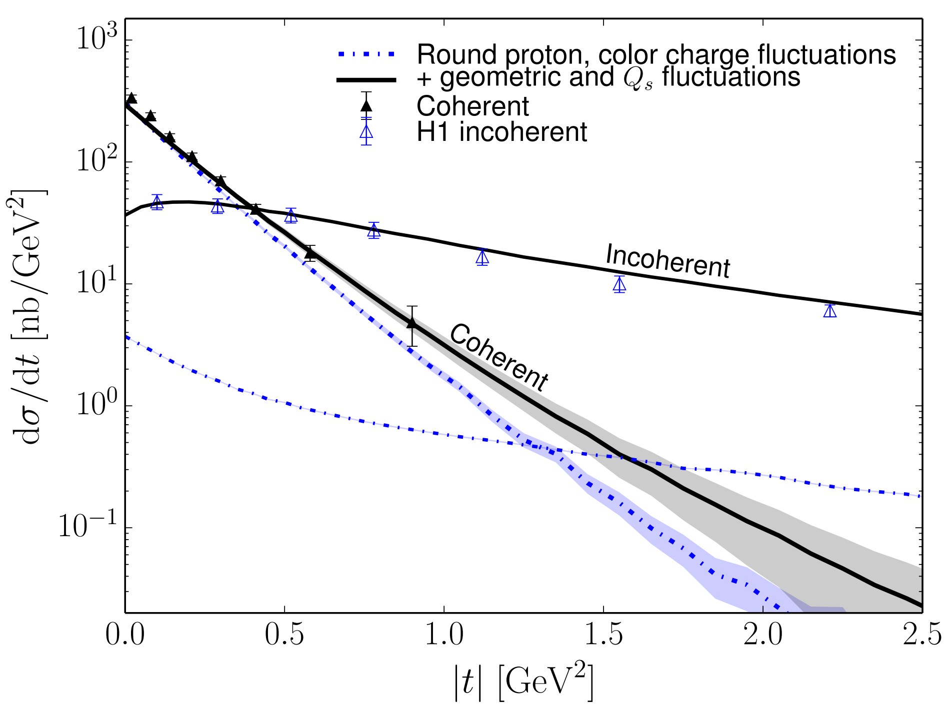
...so we do not know if gluon density *saturates* (yet), but maybe it *fluctuates*?

Heikki Mantysaari

Model the geometric fluctuations of density inside the proton

Parameters fitted to H1 data





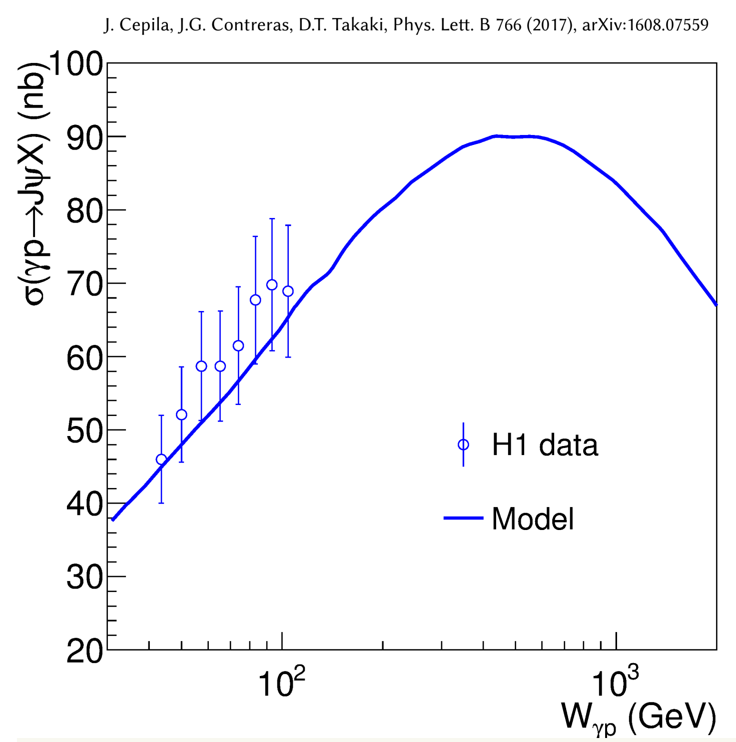
Coherent VM production: target stays intact

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}(x, Q^2, t)\rangle|^2$$

Incoherent VM diffraction: target breaks up.

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}(x, Q^2, t)|^2\rangle - |\langle \mathcal{A}(x, Q^2, t)\rangle|^2$$

Jan Cepila



At high energies the incoherent cross section decreases with energy, due to increase and overlap of hotspots

WG2: Low x and Diffraction

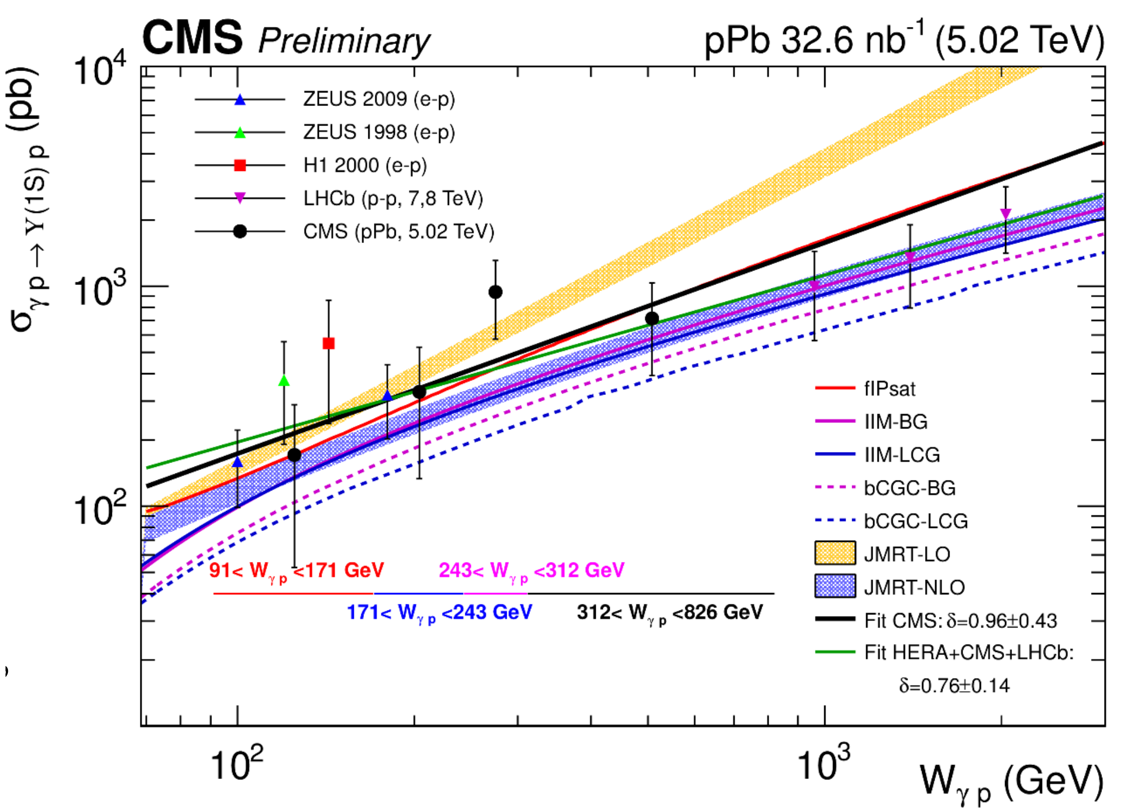
Exclusive production of ψ(2s) and ϒ

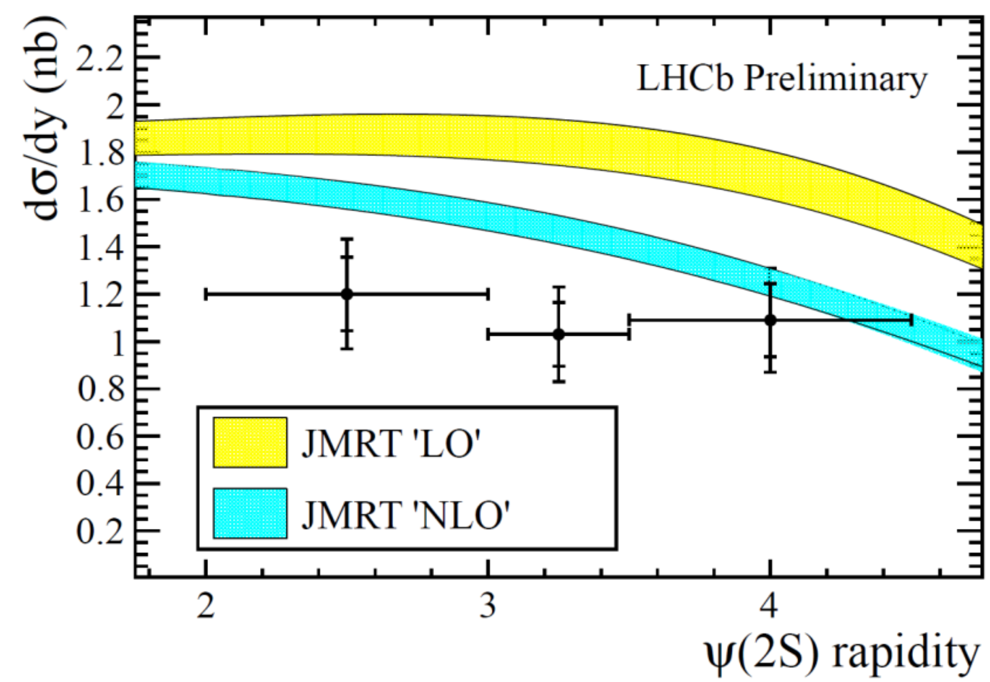
Bartłomiej Rachwał
LHCb

Exclusive production ψ(2s) at 13 TeV

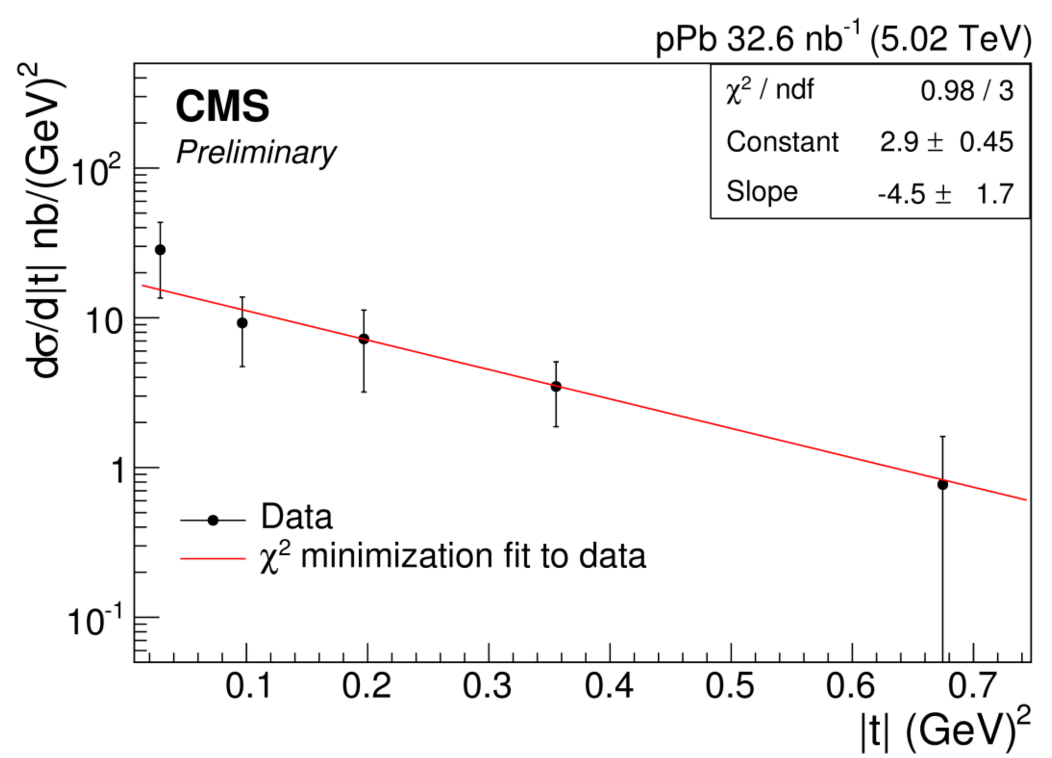
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < \eta(\mu^\pm) < 4.5) = 9.4 \pm 1.3(stat) \pm 0.5(sys) \pm 0.4\text{pb}$$

Alexander Bylinkin
CMS





A fit with power-law **A X (W/400)$^{\delta}$** to the CMS data
δ = (0.96 ± 0.43) , A = 655 ± 196
Data compatible with power-law dependence of σ($W_{\gamma p}$), disfavours LO pQCD predictions

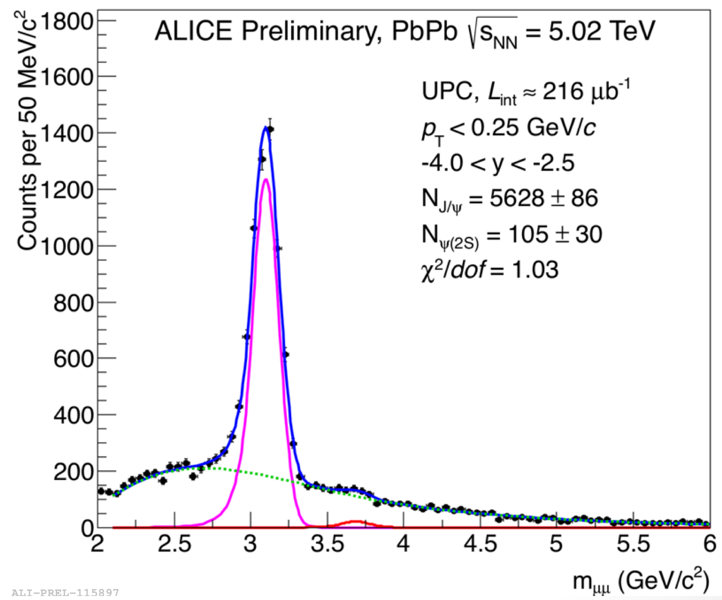


Still missing: energy dependence of t distribution for vector meson

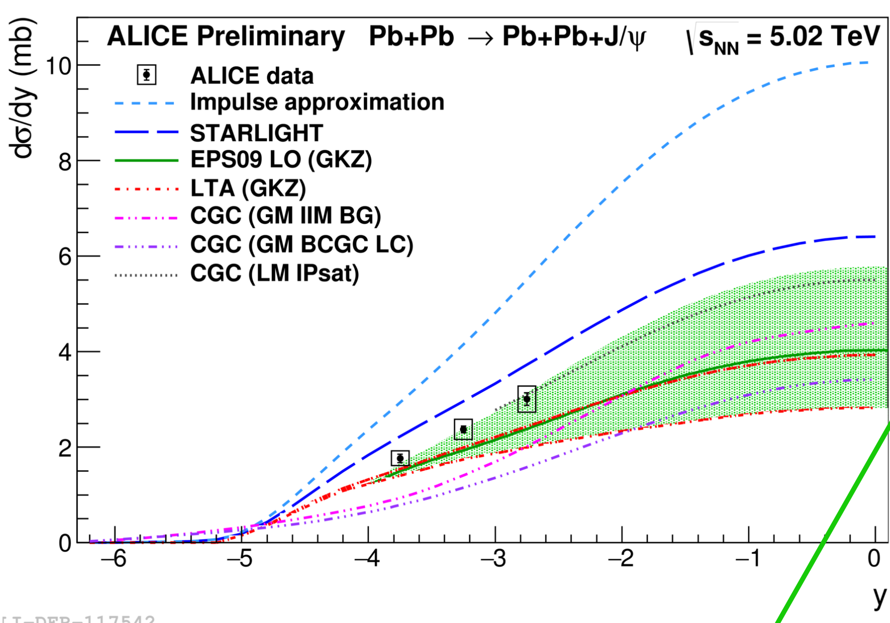
Exclusive production of J/ψ and ψ(2S) in Pb+Pb

Kay Graham
ALICE

Run 2 data

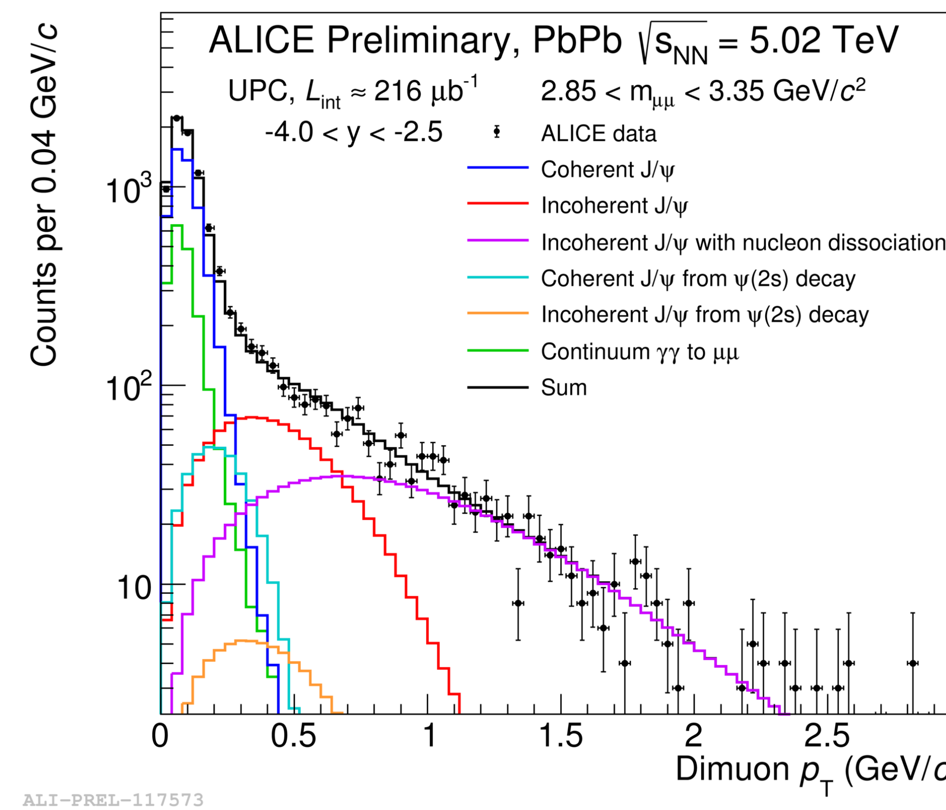


σ(ψ(2s))/σ(J/ψ) ≈0.166 ± 0.011 fits well with H1 data: 0.166 ± 0.007 (stat) ± 0.008 (syst) ± 0.007 (BR) [Phys.Lett.B541:251-264,2002]



- Impulse approximation: no nuclear effects
- STARLIGHT: VDM + Glauber (Klein, Nystrand *et al* Comput. Phys. Commun. 212 (2017) 258)
- EPS09 L0: EPS09 shadowing (Guzey, Kryshen, Zhalov, PRC93 (2016) 055206)
- LTA: Leading Twist Approximation (Guzey, Kryshen, Zhalov, PRC93 (2016) 055206)
- CGC GM: color dipole model + IIM/BCGC (Goncalves, Machado *et al*, PRC 90 (2014) 015203, JPG 42 (2015) 105001)
- CGC LM: Color dipole model + IPSat (Lappi, H. Mäntysaari, PRC 83 (2011) 065202; 87 (2013) 032201)

Cross section consistent with moderate nuclear gluon shadowing



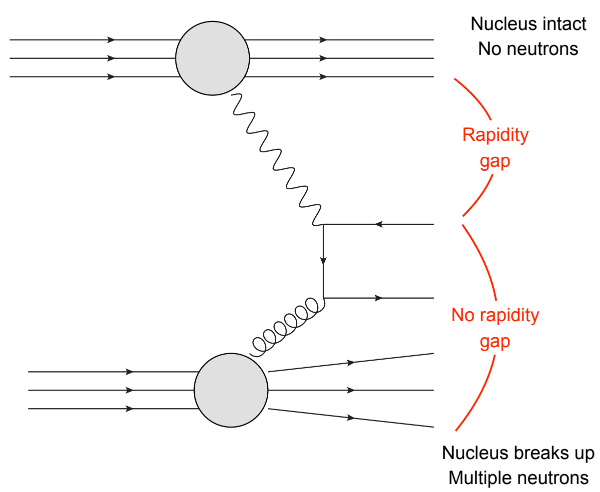
Both nucleon dissociation and incoherent production are needed to describe the data.

Multi-jet production in UPC in Pb+Pb

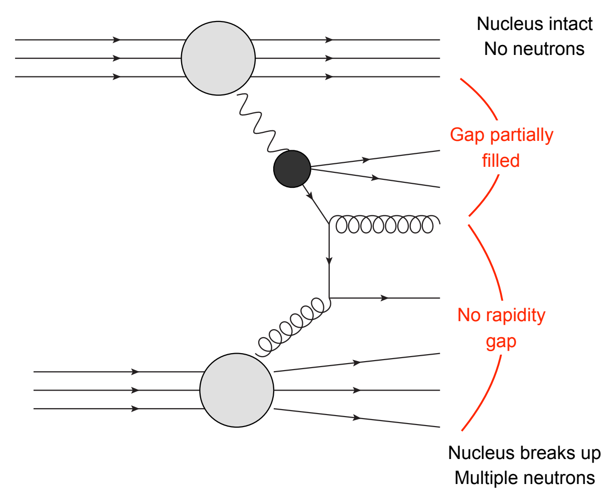
Oldrich Kepka
ATLAS

First study of photo-nuclear jets in Pb+Pb ultraperipheral collisions
Potential for constraining nuclear PDFs in extended kinematics

Direct



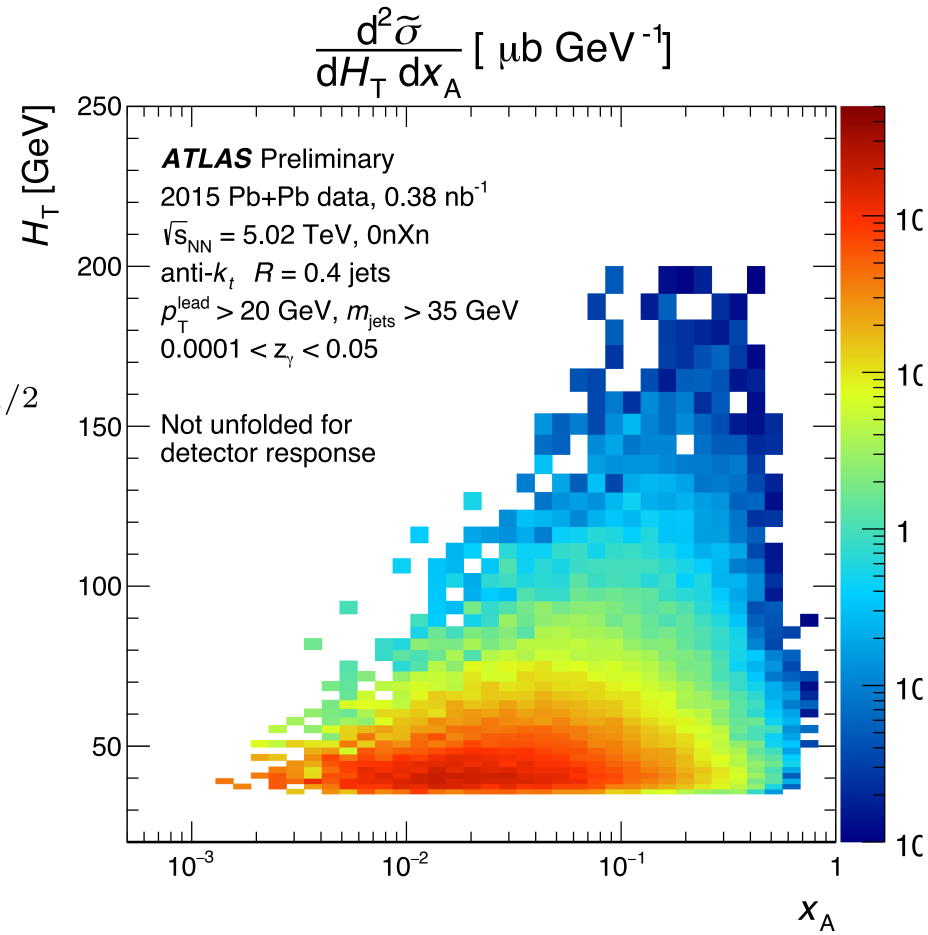
Resolved

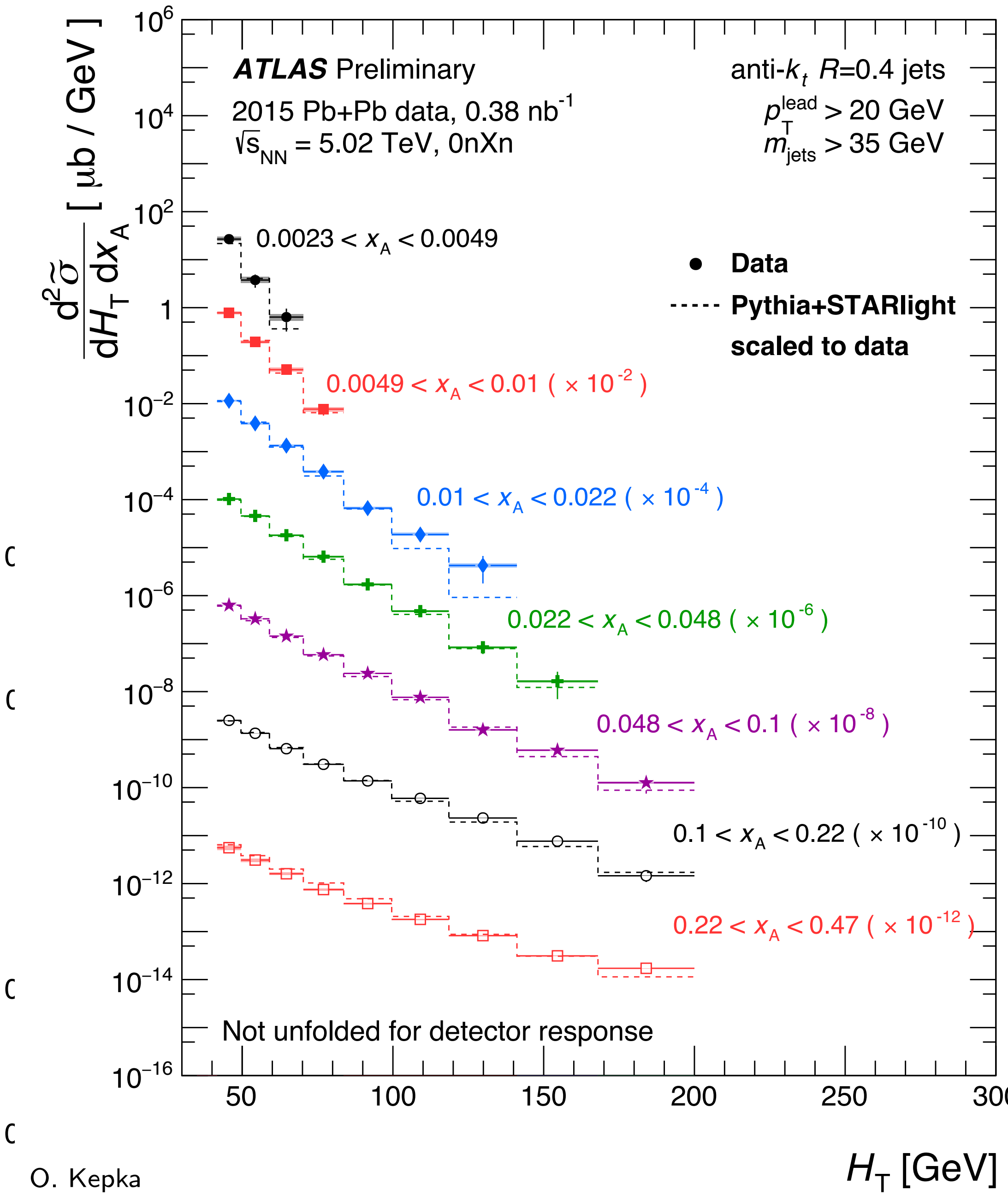


$$x_A = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$$

$$H_{\text{T}} \equiv \sum_{\text{jets}} p_{\text{T}i}$$

$$m_{\text{jets}} = \left(\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2 \right)^{1/2}$$





O. Kepka

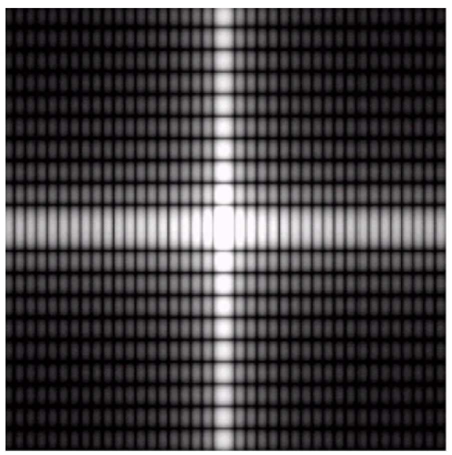
WG2: Low x and Diffraction

Diffractive dijets in DIS and UPC

Diffractive VM production, especially t - dependence, can provide with the valuable information about the spatial distribution of the target.

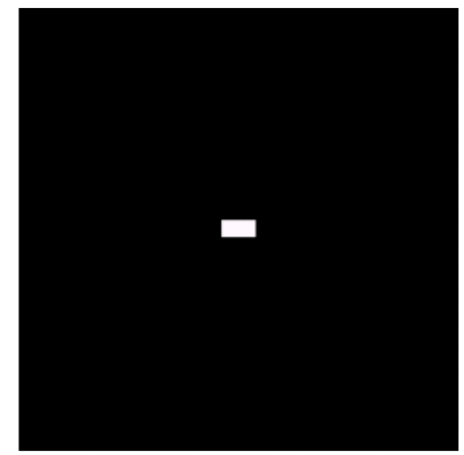
It is similar to image processing:

Fourier image

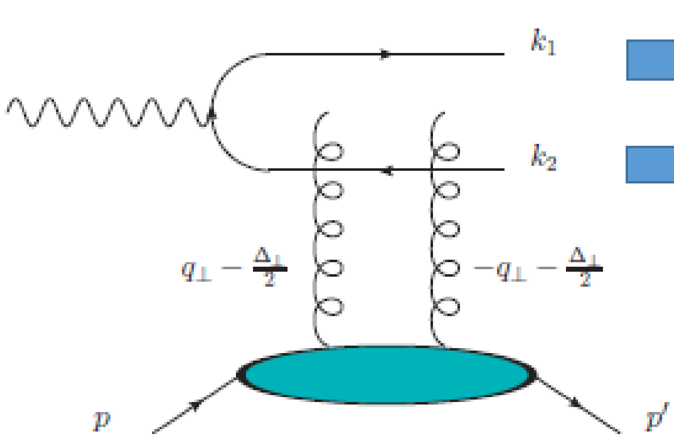


inverse 2-dim FT transform

Real space



Yoshitaka Hatta



Jet 1

Jet 2

$$\vec{\Delta}_\perp = -(\vec{k}_{1\perp} + \vec{k}_{2\perp})$$

Proton recoil momentum

$$\vec{P}_\perp = \frac{1}{2}(\vec{k}_{2\perp} - \vec{k}_{1\perp})$$

Dijet relative momentum

Diffractive dijets provide access to Wigner distribution or Generalized Transverse Momentum Distribution

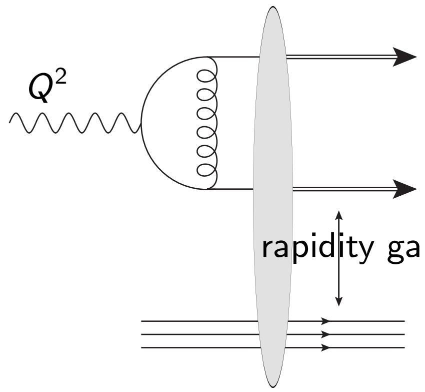
$$W(x, \vec{k}, \vec{\Delta})$$

Diffractive dijets: higher order calculations

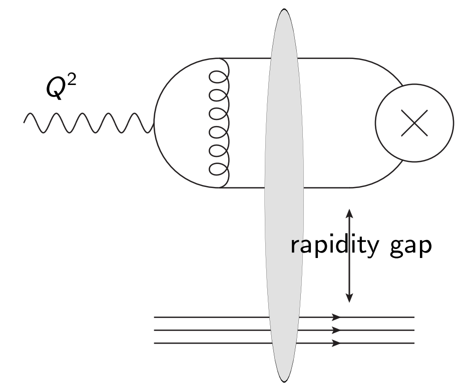
Higher order corrections to diffractive dijets

Renaud Boussarie

Diffractive dijet in CGC formalism at NLO



Diffractive VM production in CGC formalism at NLO

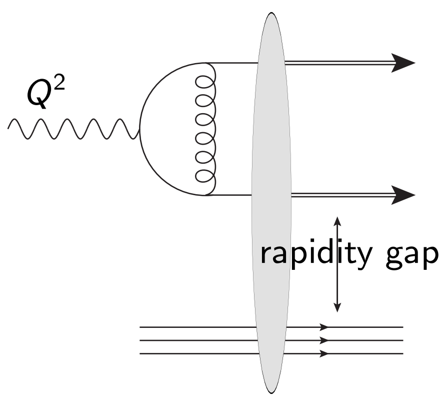


Diffractive dijets: higher order calculations

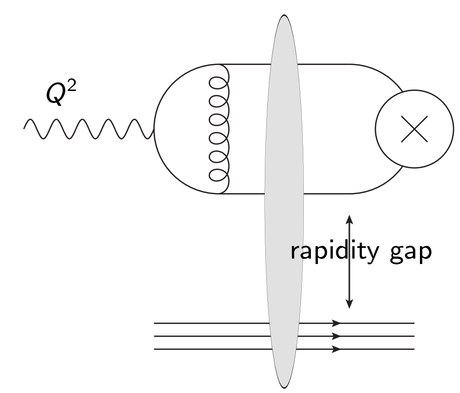
Higher order corrections to diffractive dijets

Renaud Boussarie

Diffractive dijet in CGC formalism at NLO



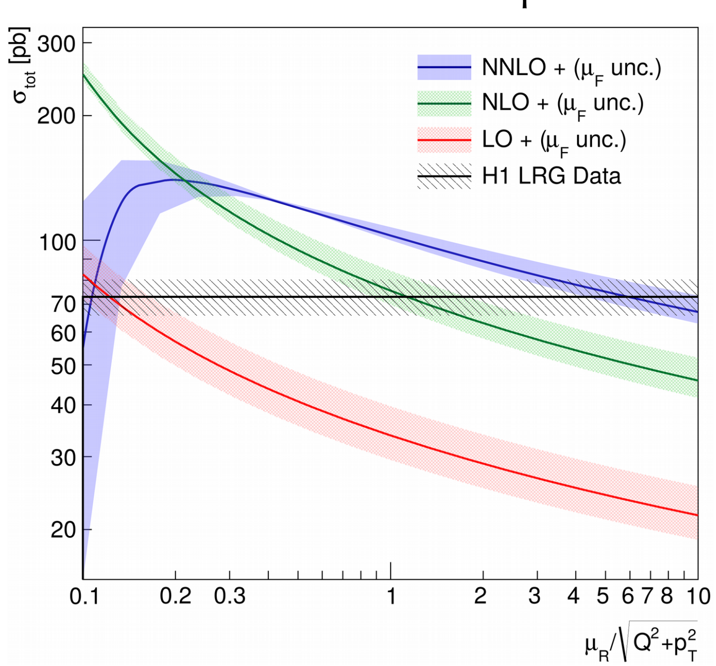
Diffractive VM production in CGC formalism at NLO



Radek Zlebcik

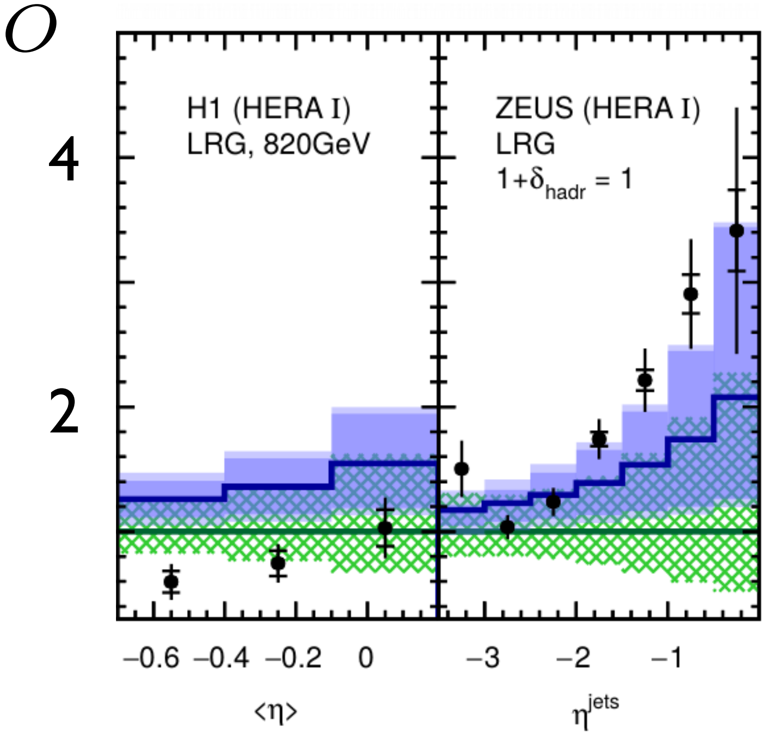
First study of diffractive dijets in collinear formalism at NNLO!

Renormalization scale dependence



Reduction of the renormalization (and factorization) scale dependence at NNLO

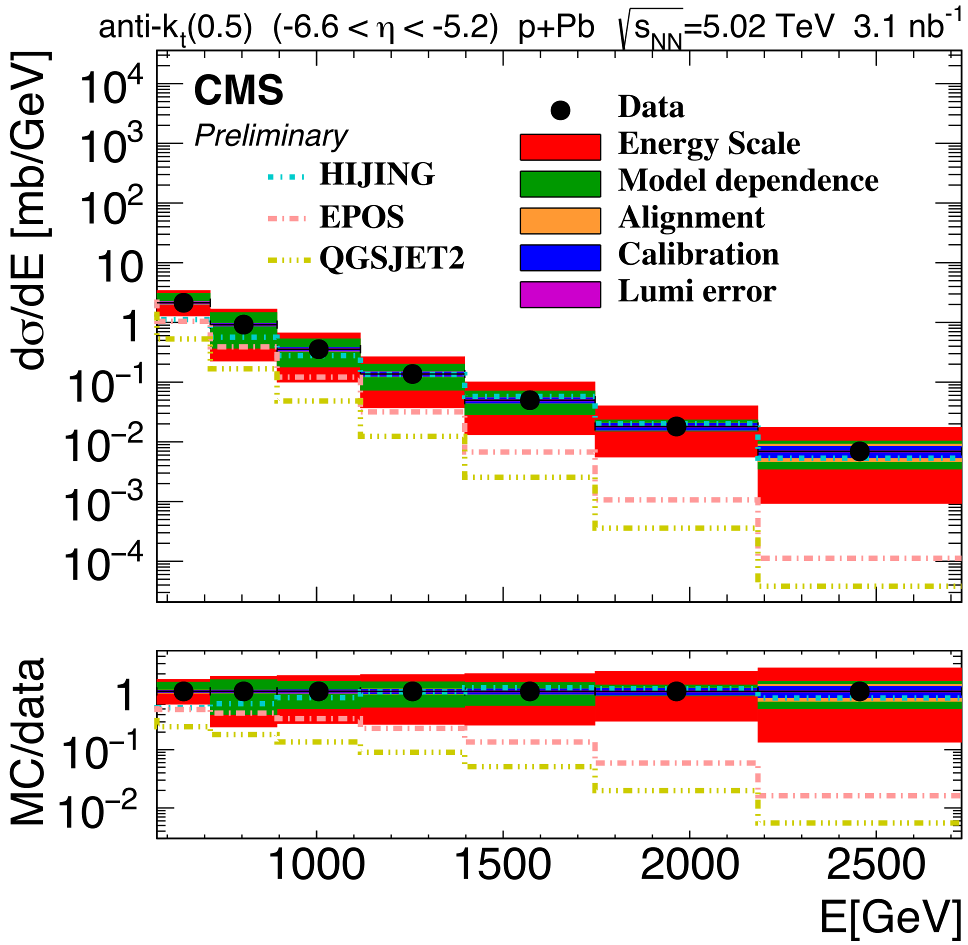
σ/σ_{NLO}

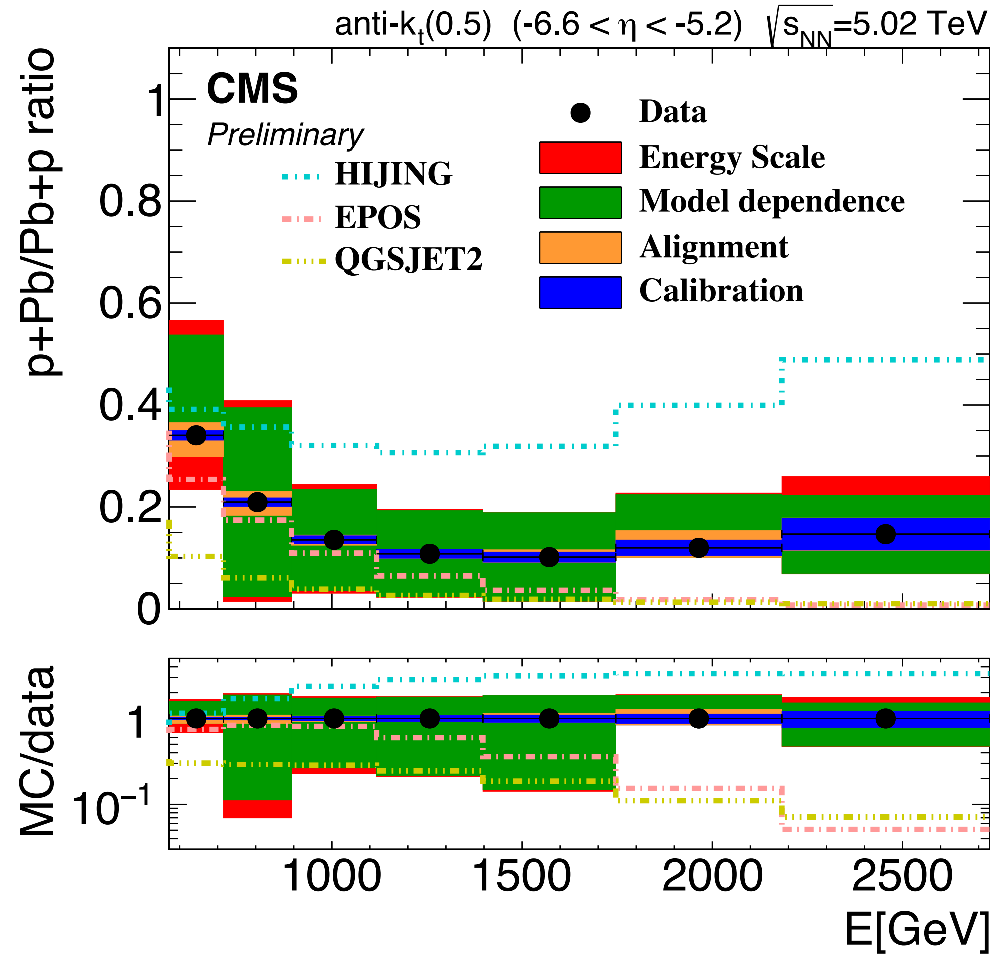


Higher order corrections are large: NNLO substantially higher than NLO for some distributions.
Need more detailed study, NNLO DPDFs?

Very forward jets in p+Pb and Pb+p with CASTOR

Merijn van de Klundert
CMS

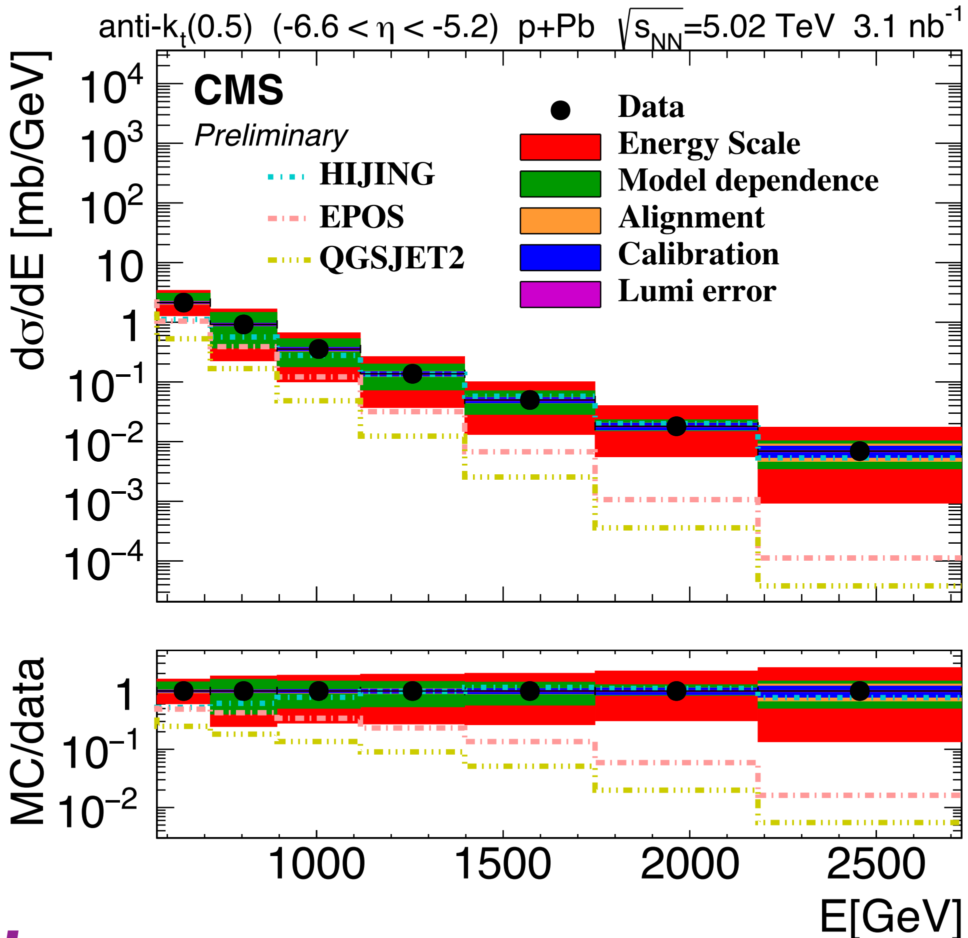


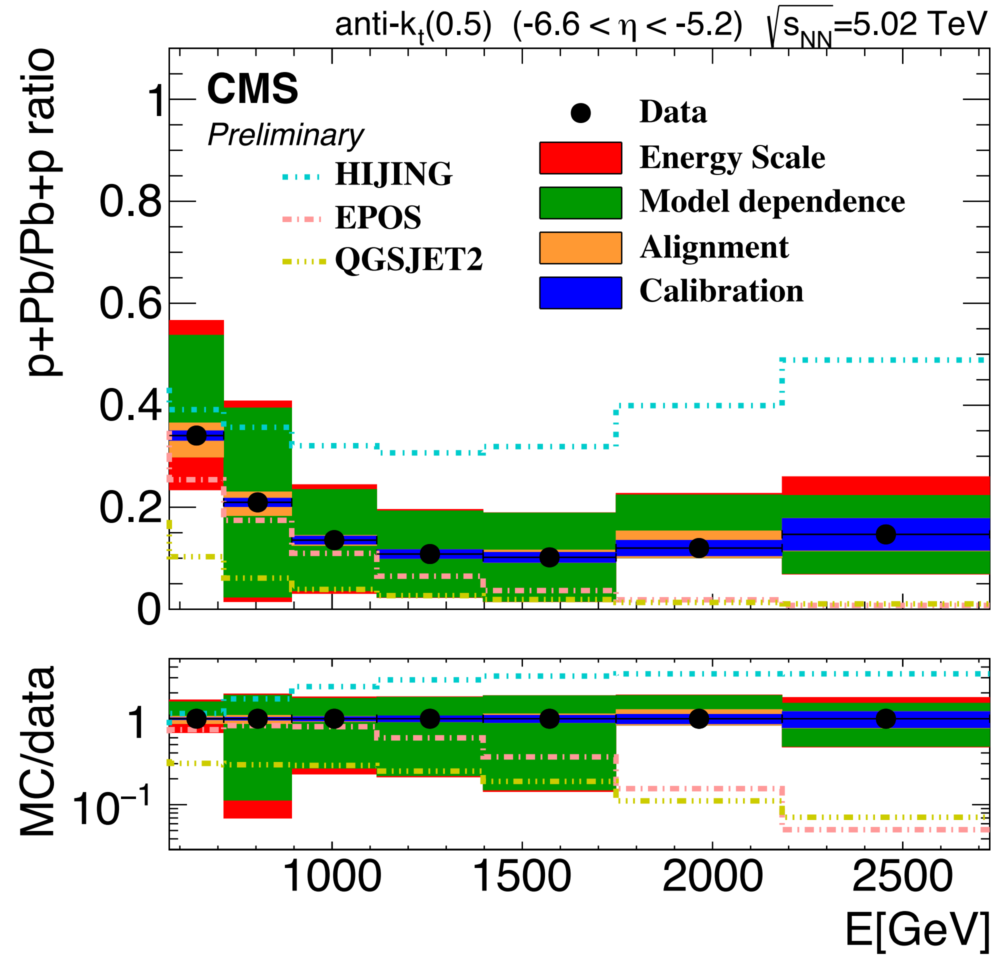


Very strong suppression of the p+Pb/Pb+p ratio
Caveat: compromised by boost of center of mass frame

Very forward jets in p+Pb and Pb+p with CASTOR

Merijn van de Klundert CMS

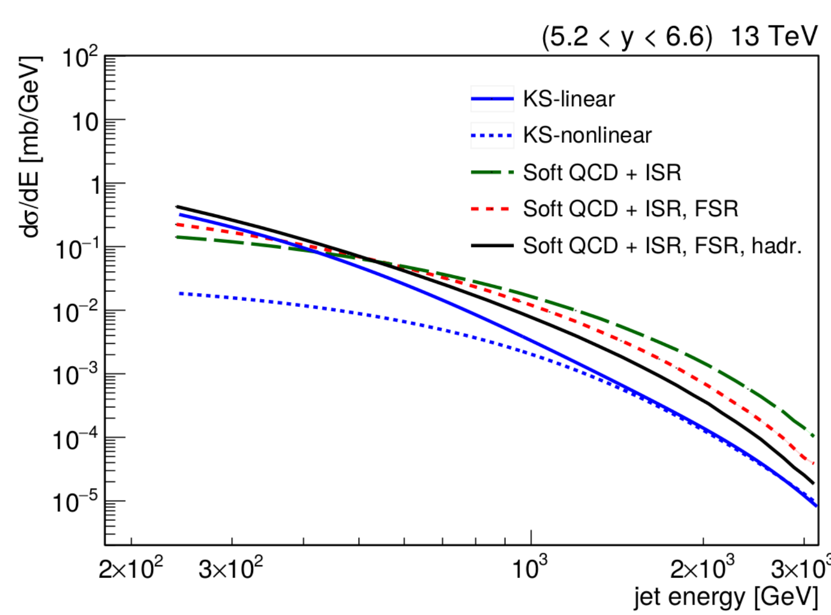




Krzysztof Kutak

Calculation of very forward inclusive jet in pp using formalism of hybrid factorization for CASTOR kinematics. Comparison of calculations with and without the gluon saturation. Strong suppression expected at low transverse momenta even in the proton - proton case.

Very strong suppression of the p+Pb/Pb+p ratio
Caveat: compromised by boost of center of mass frame

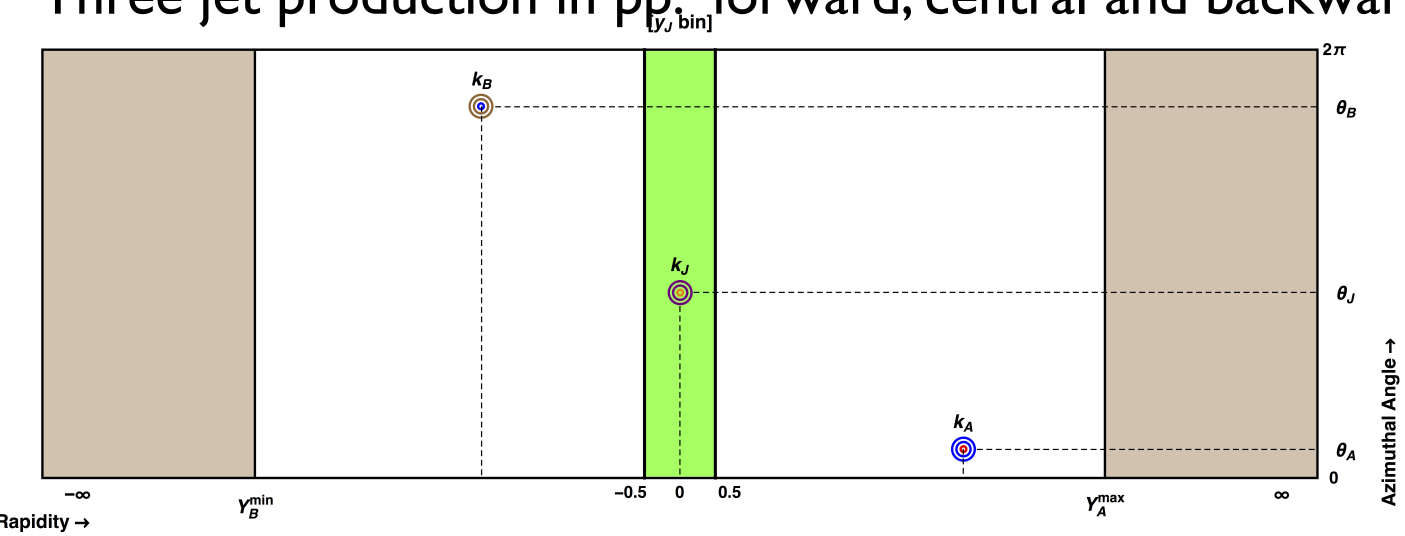


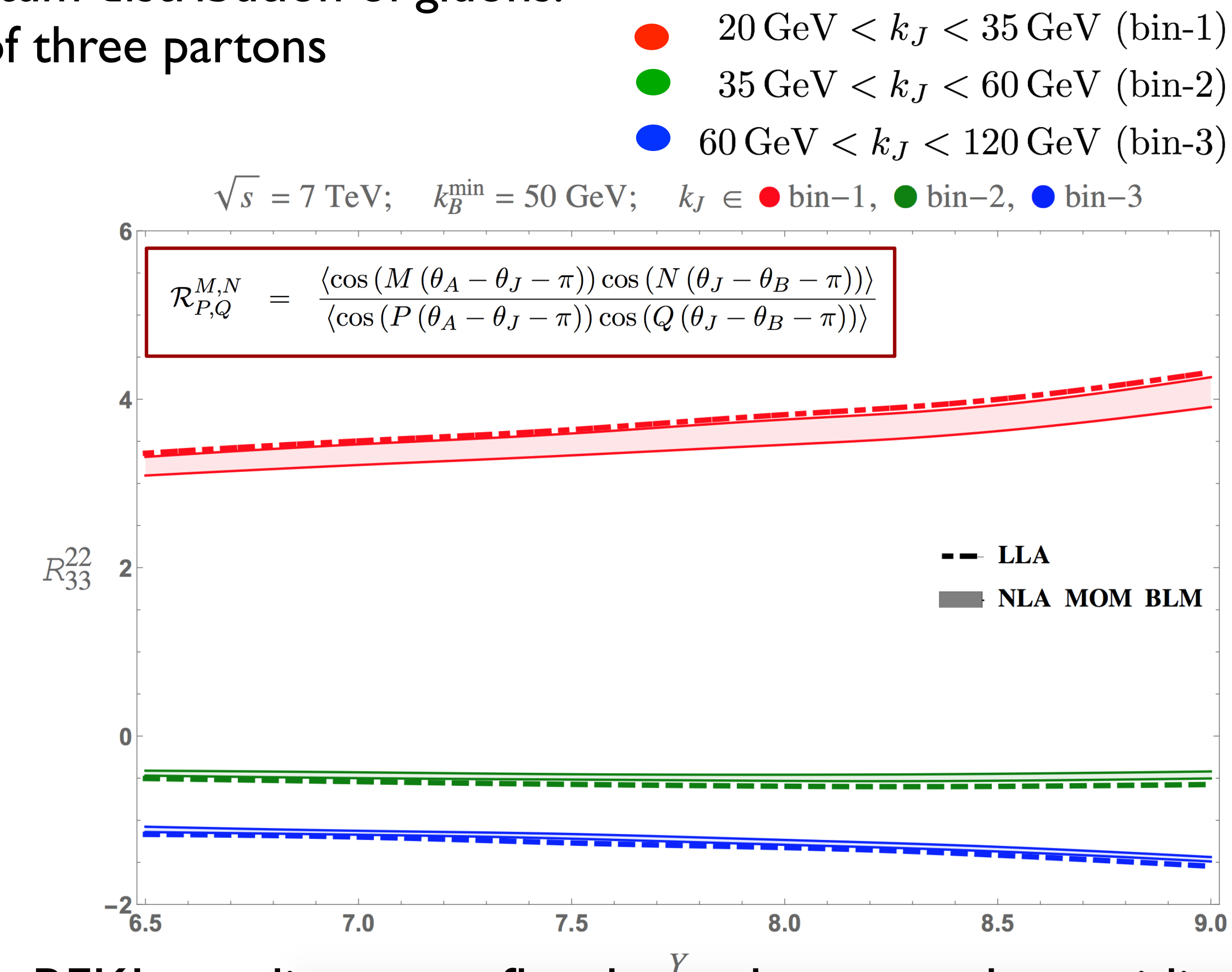
Low x and angular dependence

Low x dynamics, BFKL or saturation affects transverse momentum distribution of gluons.
This can be tested by studying angular dependence of three partons

Grigorios Chachamis

Three jet production in pp: forward, central and backward





BFKL predicts very flat dependence on the rapidity difference between forward and backward jets

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Grigorios Chachamis

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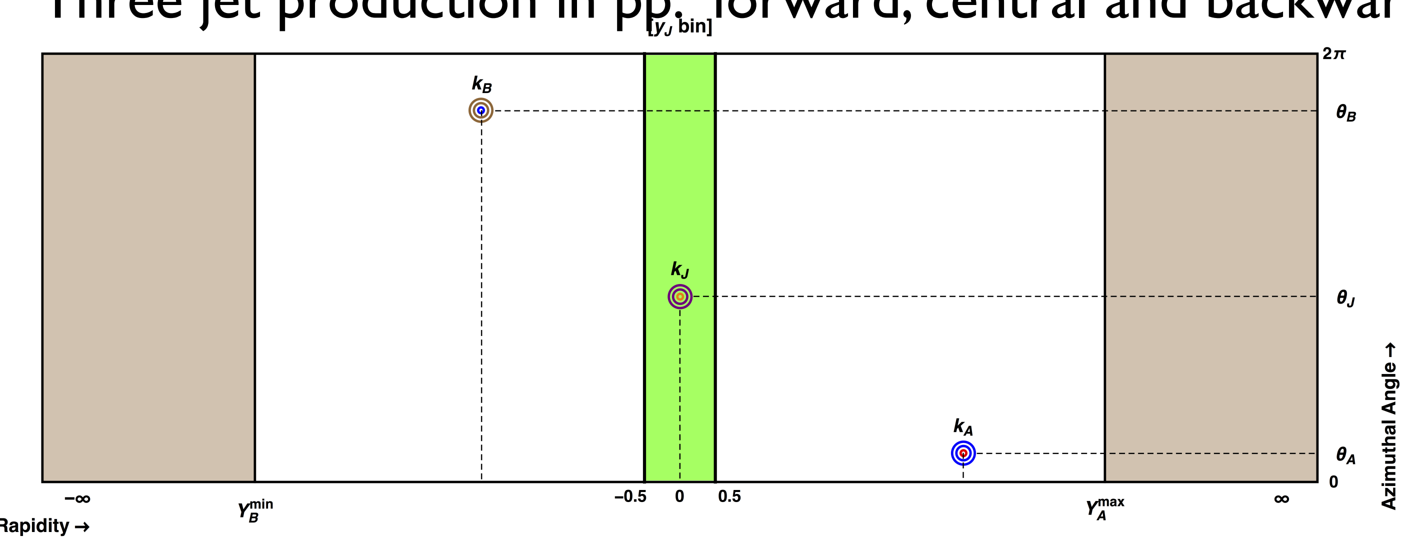
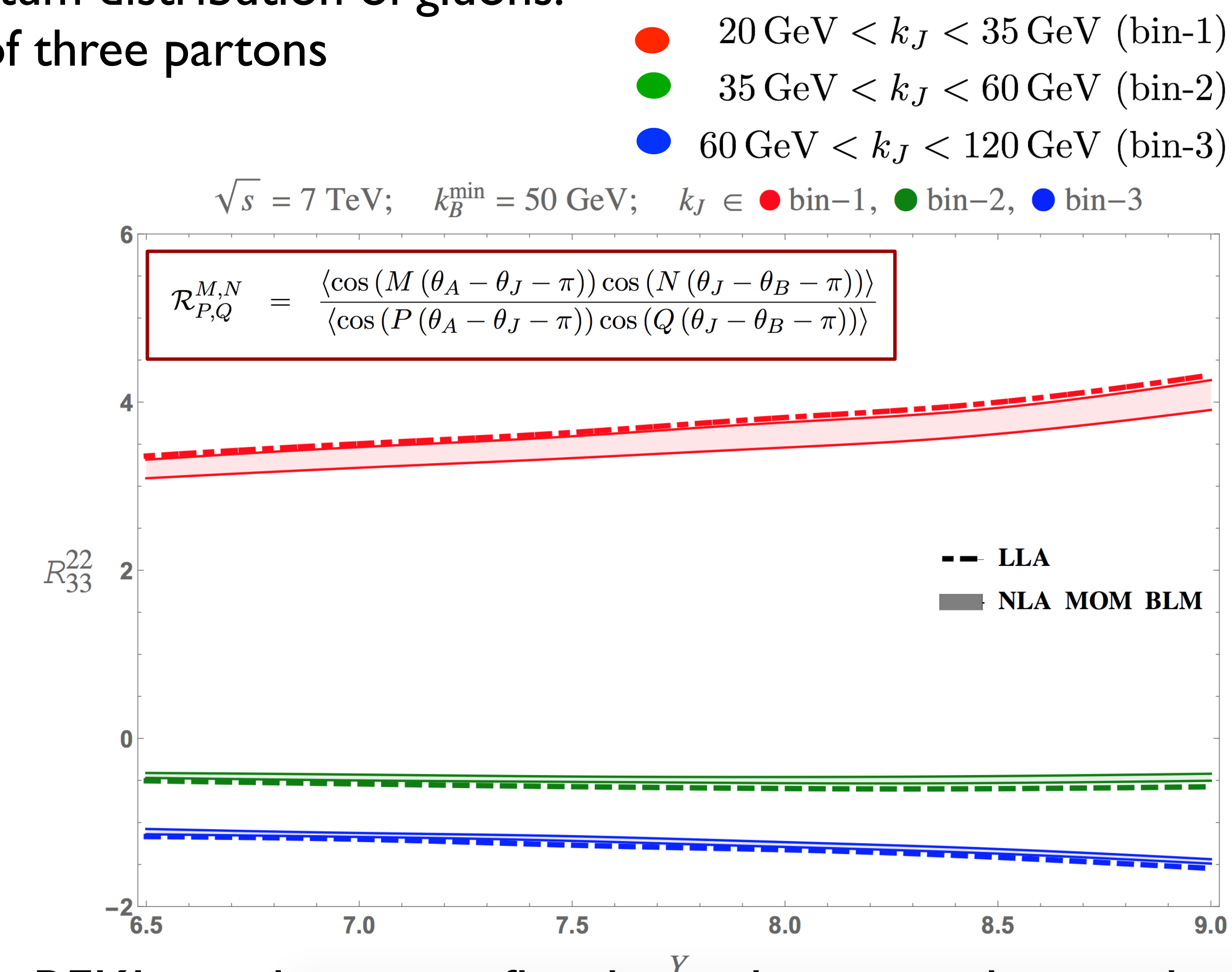
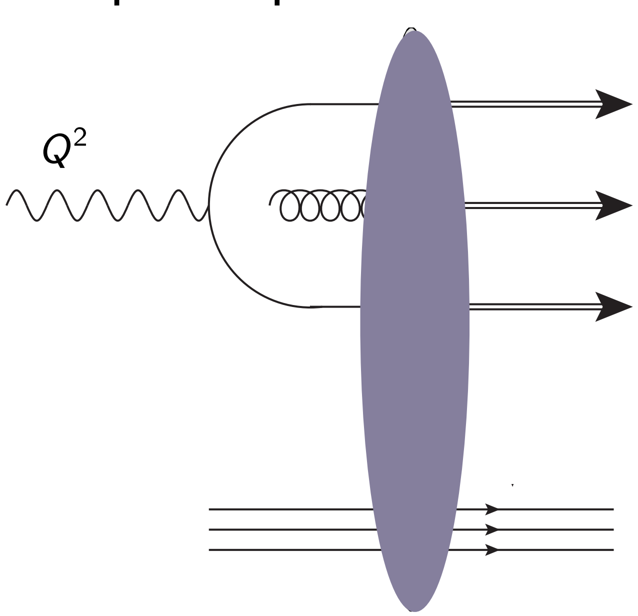




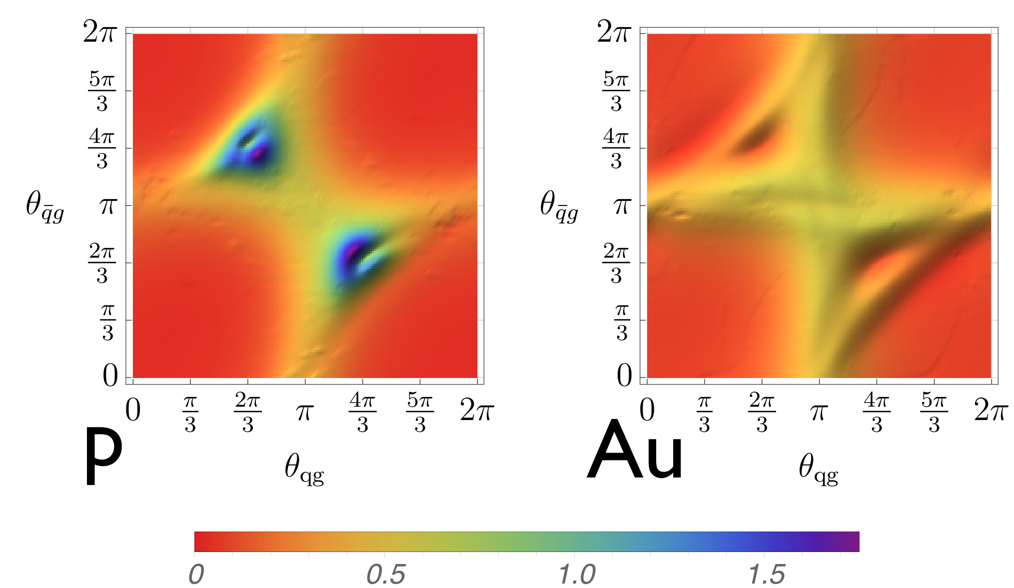
Jamal Jalilian-Marian

Three parton production in DIS within Color Glass Condensate



BFKL predicts very flat dependence on the rapidity difference between forward and backward jets

Dependence of the normalized cross section on the angular differences between gluon and quark/antiquark



WG2: Low x and Diffraction

Low x and angular dependence

Leszek Motyka

Low x dynamics can be also tested in Drell - Yan process by studying lepton angular distribution.

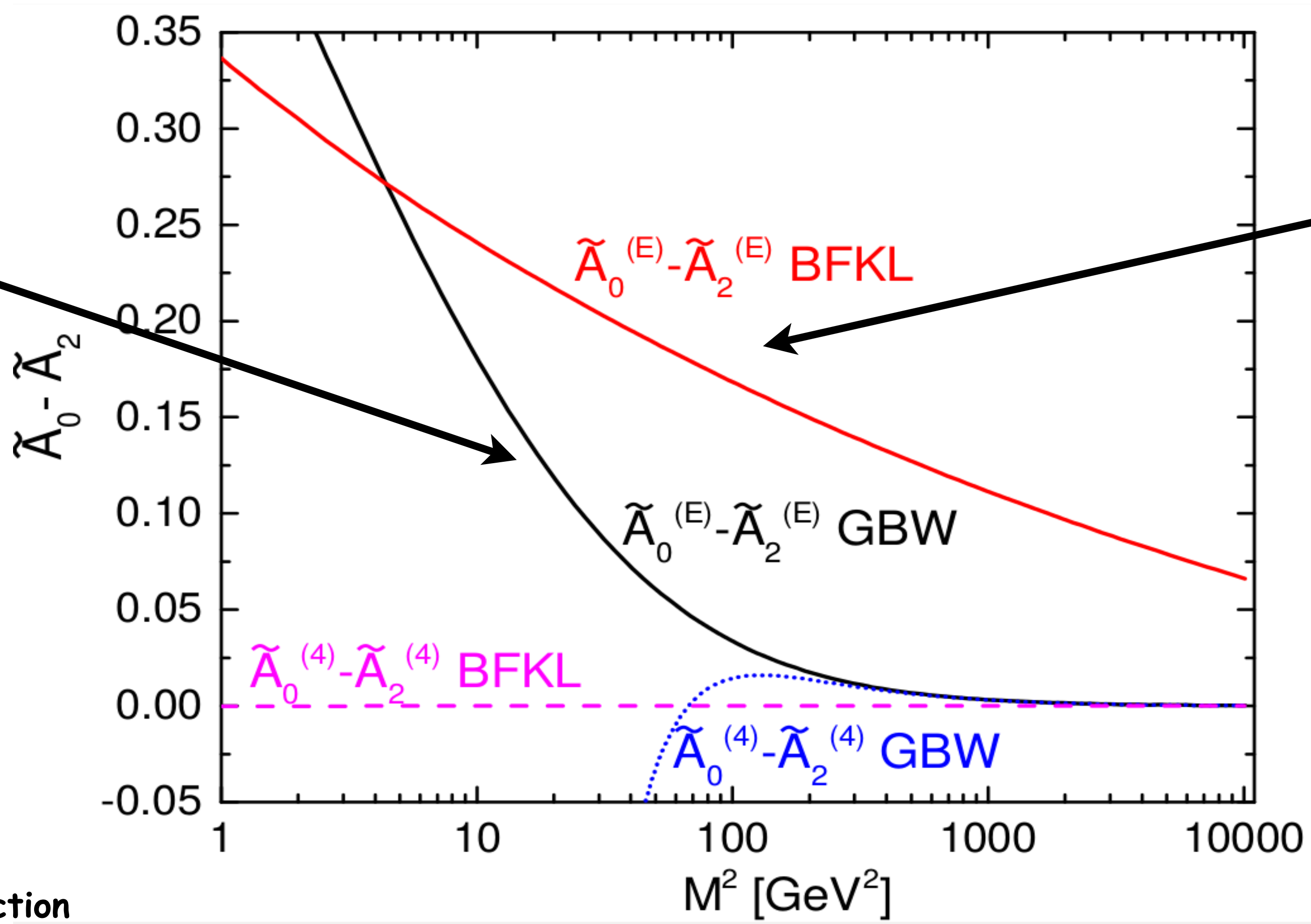
Lam-Tung relation holds up to NNLO in collinear approx.
Can be violated by k_T and/or higher twist effects.

$$W_L - 2W_{TT} = 0$$

$$\frac{d\sigma}{dx_F dM^2 d\Omega d^2 q_T} = \frac{\alpha_{\rm em}^2}{2(2\pi)^4 M^4} \left[(1-\cos^2\theta) W_L + (1+\cos^2\theta) W_T + (\sin^2\theta\cos 2\phi) W_{TT} + (\sin 2\theta \cos\phi) W_{LT} \right]$$

higher twist effects

k_T effects



Lam-Tung relation

$$\tilde{A}_0 - \tilde{A}_2 = 0$$

Transverse momentum distributions (TMD)

Ian Balitsky
Aleksander Kusina
Elena Petreska
Radek Zlebcik

A lot of theoretical effort to further develop TMD formalism

The main task is to understand the connection between the TMD and the low dynamics

Transverse momentum distributions (TMD)

Ian Balitsky
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Elena Petreska
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A lot of theoretical effort to further develop TMD formalism

The main task is to understand the connection between the TMD and the low dynamics

Ian Balitsky

New evolution equation that interpolates between DGLAP at moderate x and nonlinear Balitsky-Kovchegov equation at small values of x

Lipatov vertex at arbitrary momenta:

$$L^{ab}_{\mu i}(k, y_\perp, x_B)^{\mathrm{light-like}}$$

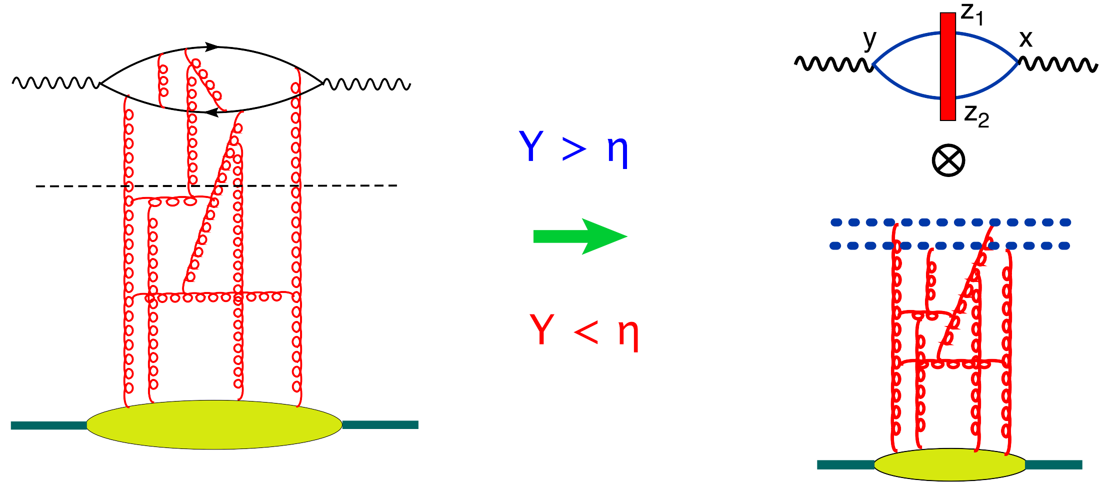
$$= g(k_\perp|\mathcal{F}^j\Big(x_B + \frac{k_\perp^2}{\alpha s}\Big)\Big\{\frac{\alpha x_B s g_{\mu i} - 2k^\perp_\mu k_i}{\alpha x_B s + k_\perp^2}(k_j U + U p_j)\frac{1}{\alpha x_B s + p_\perp^2}U^\dagger$$

$$- 2k^\perp_\mu U\frac{g_{ij}}{\alpha x_B s + p_\perp^2}U^\dagger - 2g_{\mu j}U\frac{p_i}{\alpha x_B s + p_\perp^2}U^\dagger + \frac{2k^\perp_\mu}{k_\perp^2}g_{ij}\Big\}|y_\perp)^{ab} + O(p_{2\mu})$$

NLO calculations of impact factor in DIS

Giovanni Chirilli
Guillaume Beuf

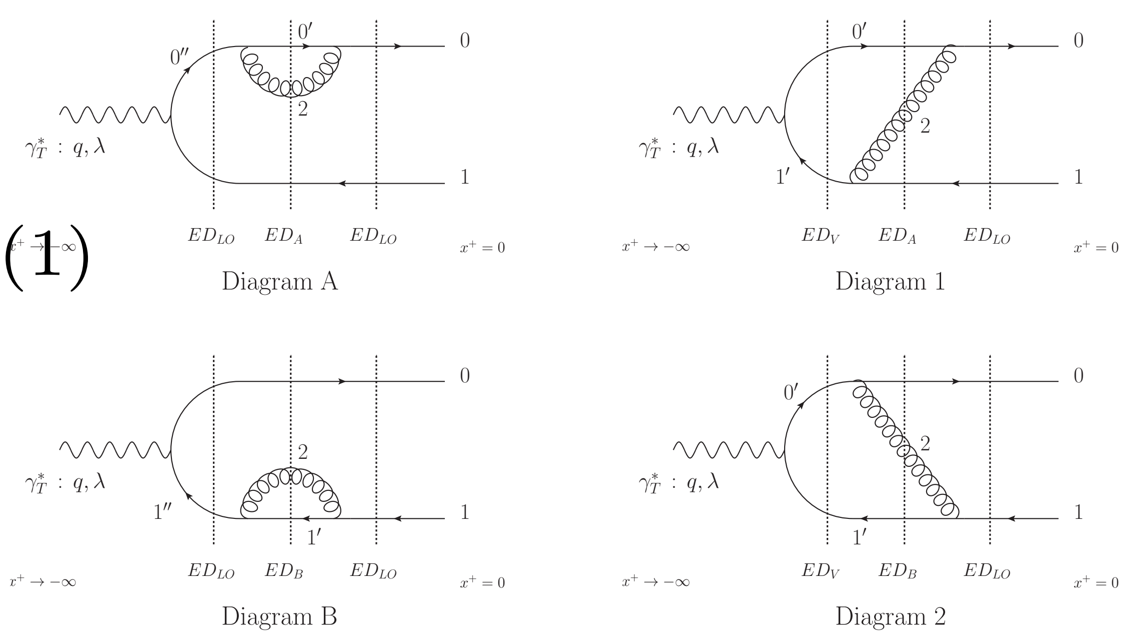
DIS amplitude is factorized in rapidity: η



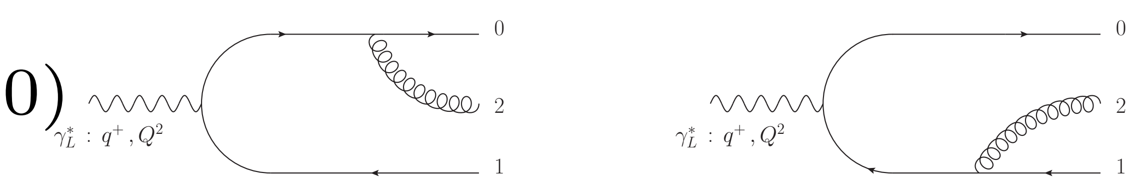
γ*g impact factor

Virtual and real corrections to the photon impact factor in light-front perturbation theory

$|q\bar{q}\rangle^{(1)}$



$|q\bar{q}g\rangle^{(0)}$



Next steps: phenomenology to NLO accuracy in DIS

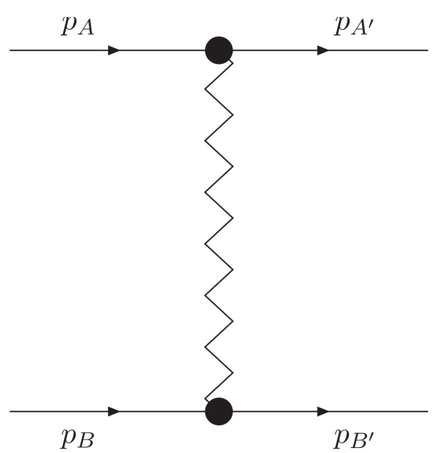
WG2: Low x and Diffraction

Violation of Regge factorization at NNLL

Victor Fadin

Regge limit: $s \to \infty$ $-t$ fixed

Property of QCD in the Regge limit: gluon Reggeization
Allows to express (many) amplitudes in terms of effective vertices and gluon trajectory
Valid at LL and NLL in powers of ln s

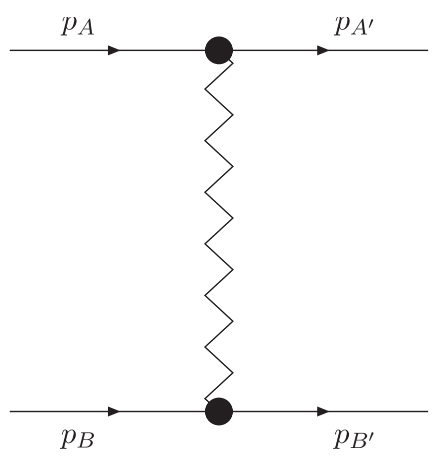


$$\mathcal{A}_{AB}^{A'B'} = \Gamma_{A'A}^{c} \left[\left(\frac{-s}{-t} \right)^{j(t)} - \left(\frac{s}{-t} \right)^{J(t)} \right] \Gamma_{B'B}^{c}$$

Violation of Regge factorization at NNLL

Victor Fadin

Regge limit: $s \to \infty$ $\quad -t$ fixed



Property of QCD in the Regge limit: gluon Reggeization
Allows to express (many) amplitudes in terms of effective vertices and gluon trajectory
Valid at LL and NLL in powers of ln s

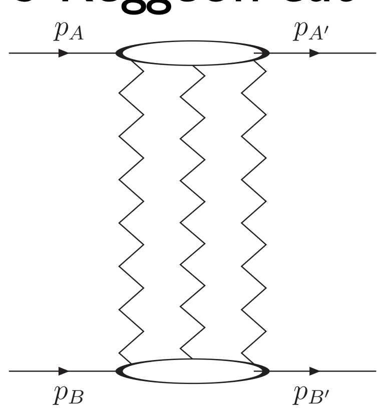
Violation of Regge factorization at NNLL
New structures appear

$$\mathcal{A}_{AB}^{A'B'} = \Gamma^{c}_{A'A}\left[\left(\frac{-s}{-t}\right)^{j(t)} - \left(\frac{s}{-t}\right)^{j(t)}\right]\Gamma^{c}_{B'B}$$

$$\mathcal{M}^{[8]}_{\rm rs}\left(\frac{s}{\mu^2},\frac{t}{\mu^2},\alpha_s\right) = 2\pi\alpha_s H^{(0),[8]}_{\rm rs}$$
$$\times\left\{C_{\rm r}\left(\frac{t}{\mu^2},\alpha_s\right)\left[A_+\left(\frac{s}{t},\alpha_s\right)+\kappa_{\rm rs}A_-\left(\frac{s}{t},\alpha_s\right)\right]C_{\rm s}\left(\frac{t}{\mu^2},\alpha_s\right)\right.$$
$$\left.+\mathcal{R}^{[8]}_{\rm rs}\left(\frac{s}{\mu^2},\frac{t}{\mu^2},\alpha_s\right)\right\},\quad \kappa_{gg}=\kappa_{qg}=0,\quad \kappa_{qq}=(4-N_c^2)/N_c^2$$

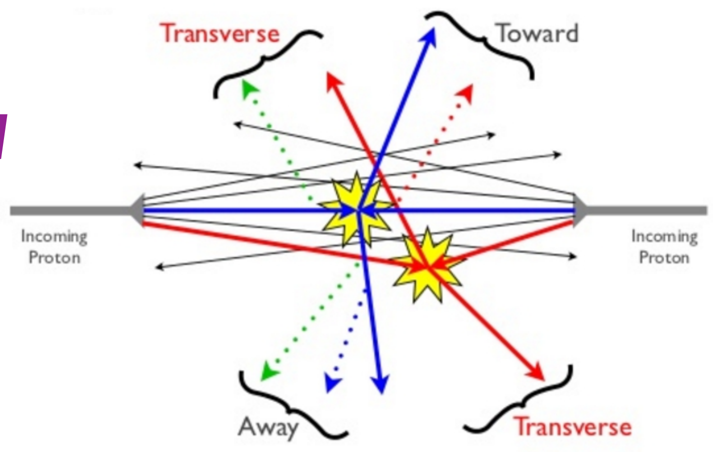
Non-factorizing remainder

Source of violation:
3 Reggeon cut



Underlying event studies

Oleg Kuprash
ATLAS
Benoit Roland
CMS



- **Refers to anything that accompanies the main hard scattering process:**
  - Beam remnants
  - Multiple Parton Interactions (MPI)
  - Initial and Final State QCD Radiation

Underlying event studies

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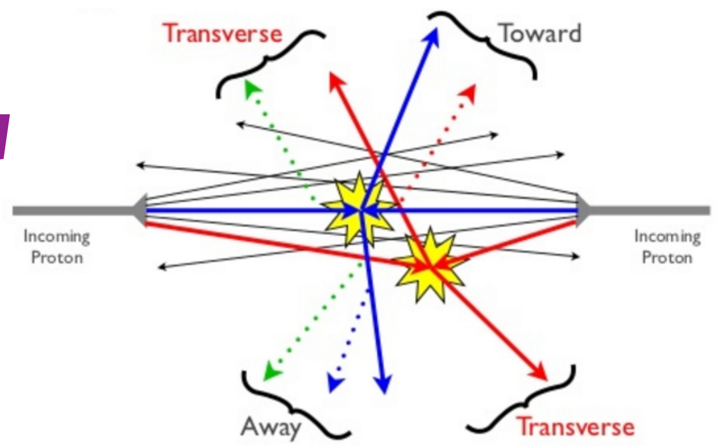

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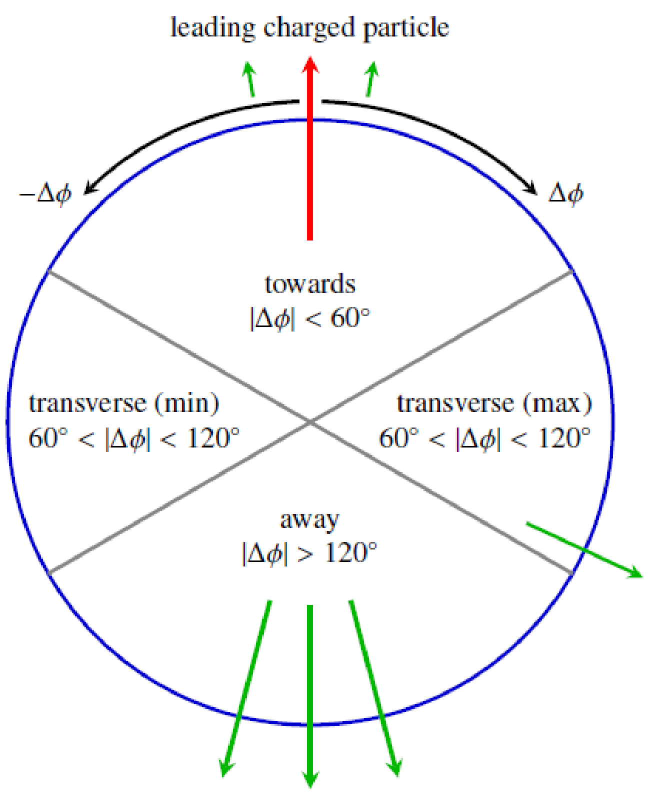
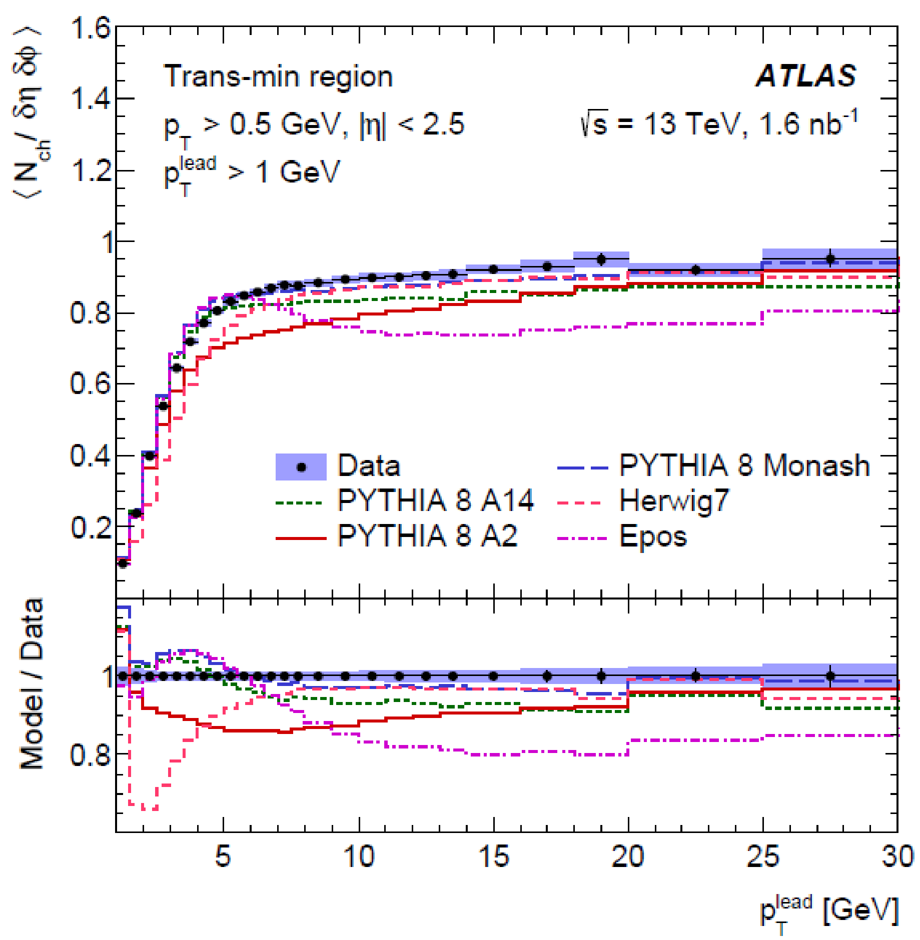
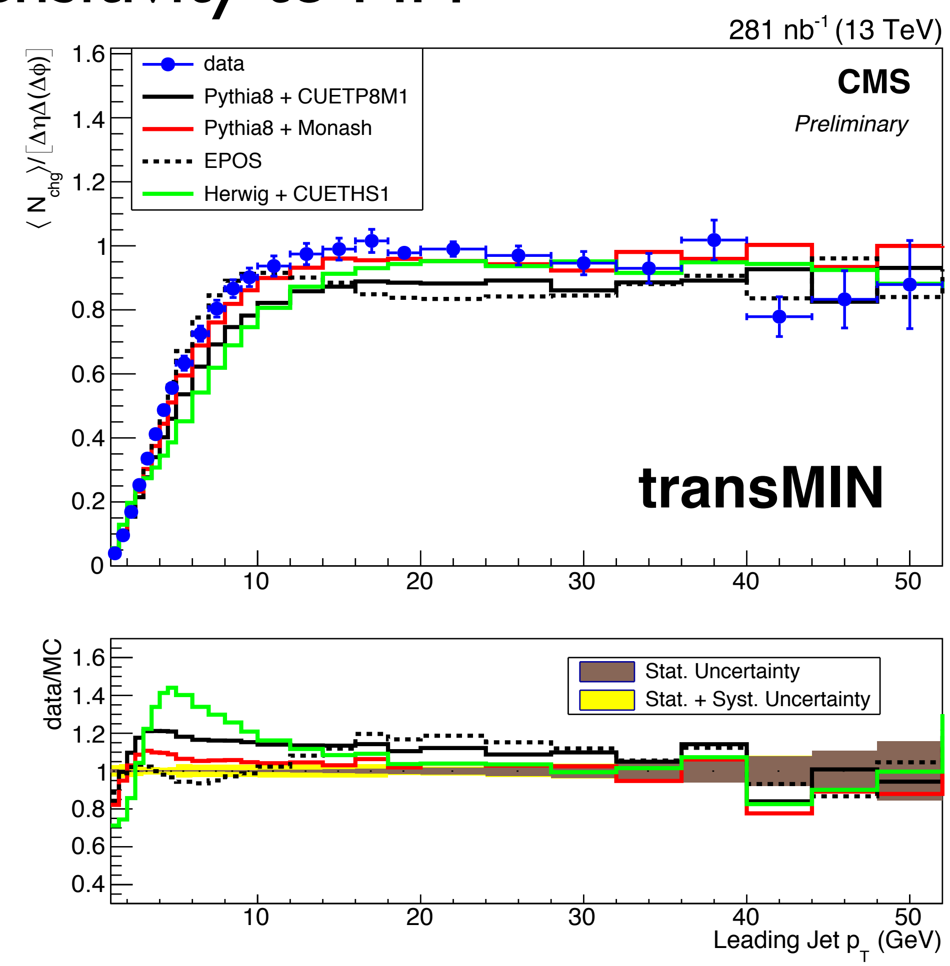


Transmin: region with most sensitivity to MPI



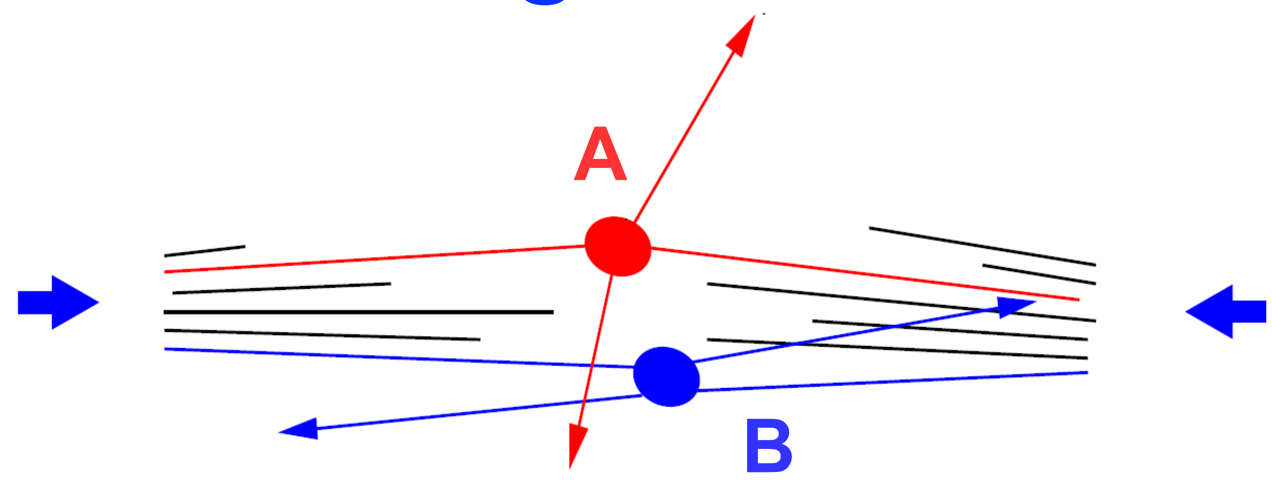


Large discrepancy between MC models in the low p_T region.

Double parton scattering

Oleg Kuprash
ATLAS
Gilvan Alves
CMS

- Two hard parton interactions occur in the same hadron-hadron interaction



→ **Pocket formula:**

$$\sigma^{AB}_{DPS} = \frac{m}{2}\frac{\sigma^{A}_{SPS}\,\sigma^{B}_{SPS}}{\sigma_{eff}} \quad \Rightarrow$$

ATLAS

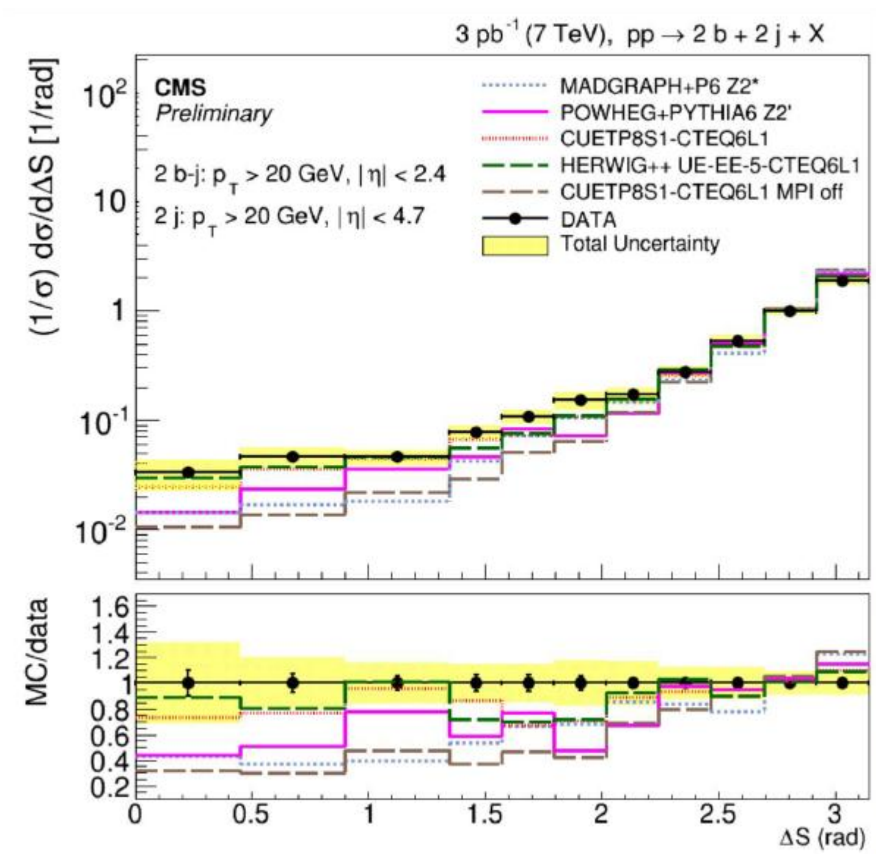
Effective cross section consistent with the previous measurements using jets

$$\sigma_{\text{eff}} = 14.9\,^{+1.2}_{-1.0}\ (\text{stat.})\ ^{+5.1}_{-3.8}\ (\text{syst.})\ \text{mb}$$

- f_{DPS}: fraction of DPS events in the inclusive 4-jet data sample

$$f_{\text{DPS}} = 0.092\,^{+0.005}_{-0.011}\ (\text{stat.})\ ^{+0.033}_{-0.037}\ (\text{syst.})$$

2b jets + 2 light jets



$$\Delta S = \arccos\left(\frac{\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}}) \cdot \vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})}{|\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}})| \cdot |\vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})|}\right)$$

$$\vec{p}_T(j_i, j_k) \equiv p_{T,i} + p_{T,j}$$

Need better implementation of DPS to describe the small ΔS region

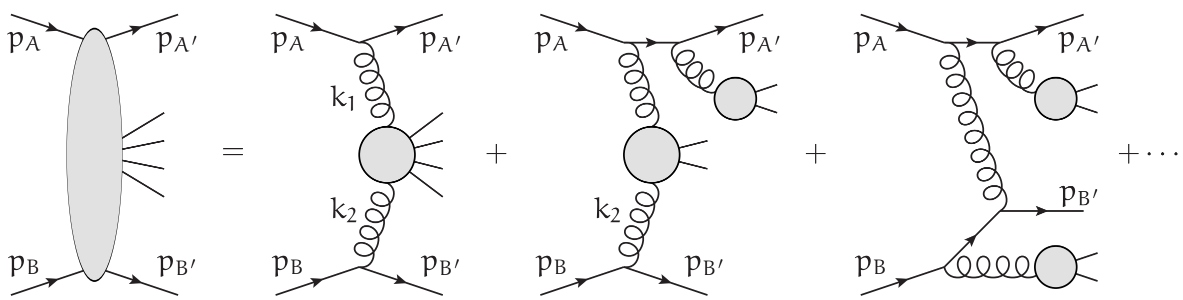
Multi-jet production and DPS

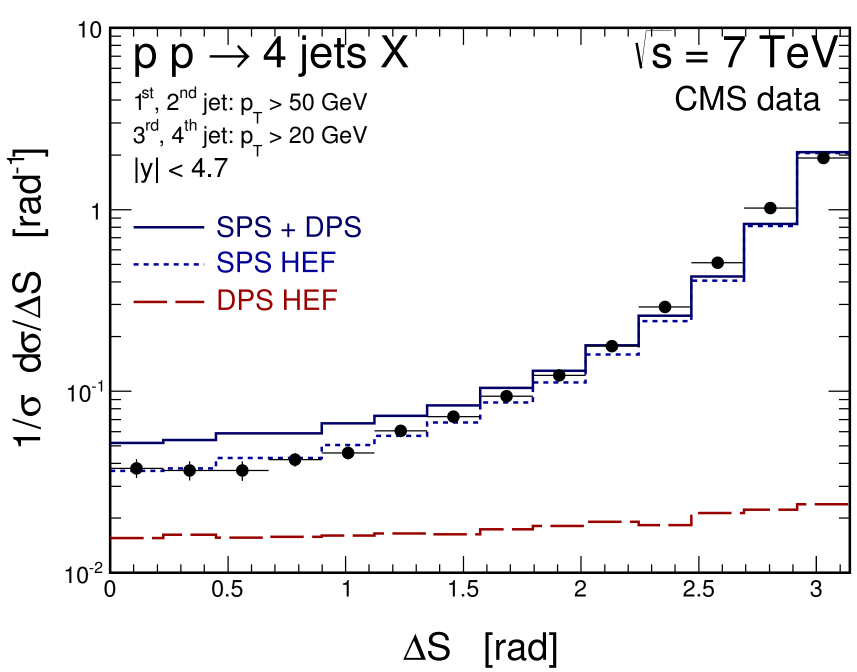
Mirko Serino

Description of multi-jet production within k_T (high-energy) factorization:

$$\sigma_{h_1,h_2\to q\bar{q}} = \int d^2k_{1\perp}\, d^2k_{2\perp}\, \frac{dx_1}{x_1}\, \frac{dx_2}{x_2}\, f_g(x_1,k_{1\perp})\, f_g(x_2,k_{2\perp})\, \hat{\sigma}_{gg}(m,x_1,x_2,s,k_{1\perp},k_{2\perp})$$

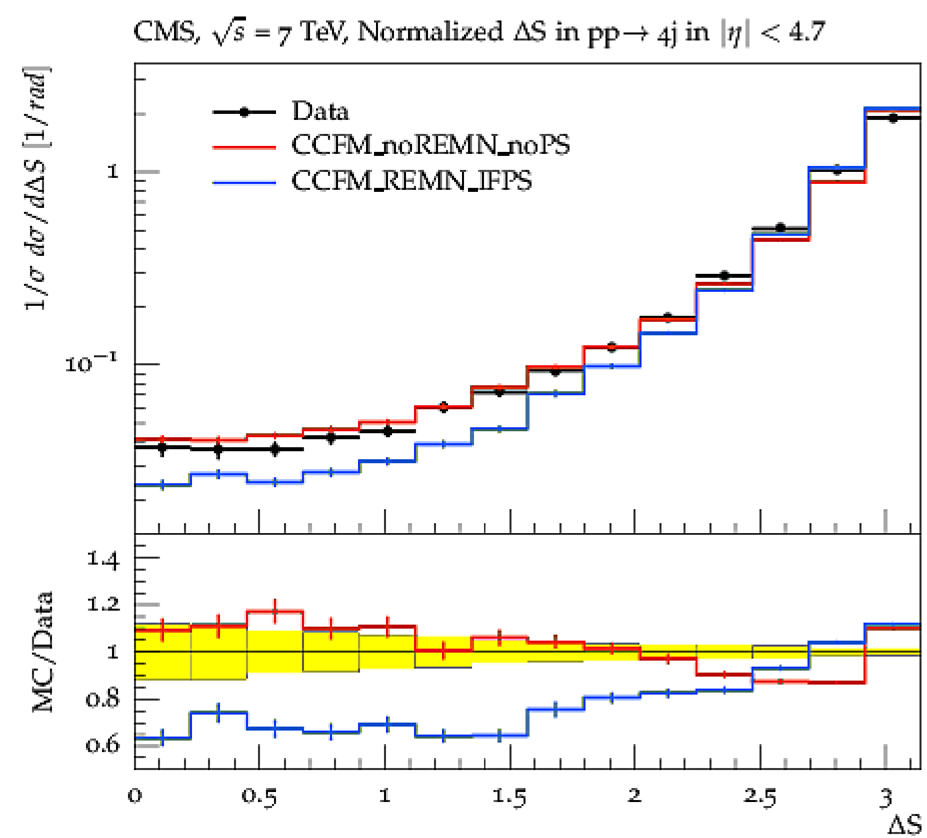
Off-shell gauge invariant amplitudes, constructed by embedding them into processes involving on-shell states





High energy factorization with DPS overshoots the data.

Include parton shower and perform matching to off-shell matrix elements



Now HEF without DPS consistently undershoots the data at small ΔS.

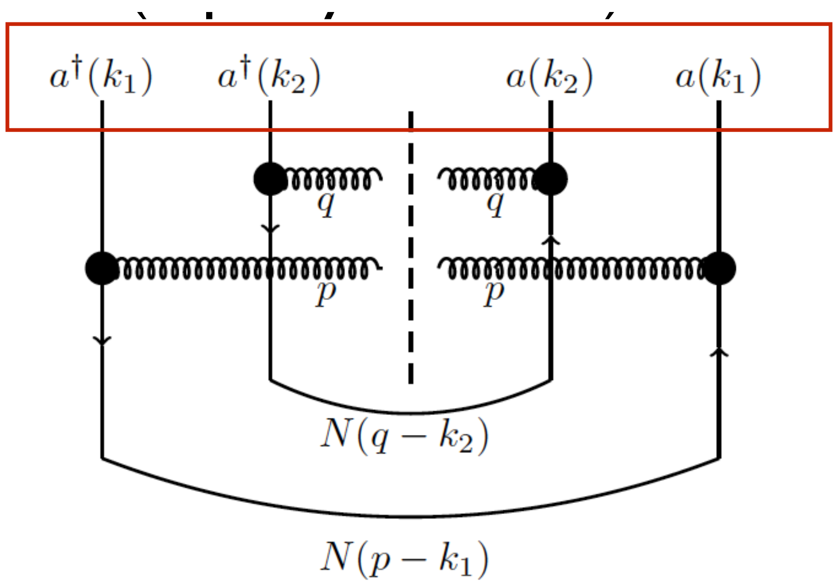
Suggest the need for DPS in 4jet production.

Quark correlations in Color Glass Condensate

Nestor Armesto

One of the most striking observations at LHC is the ridge: long range correlation in rapidity. Long range two-particle correlations appear in pp and pA, and show features which were previously thought to be present in AA only.

Within Color Glass Condensate (one of) the explanations is the Bose enhancement of the gluons in the wave function:



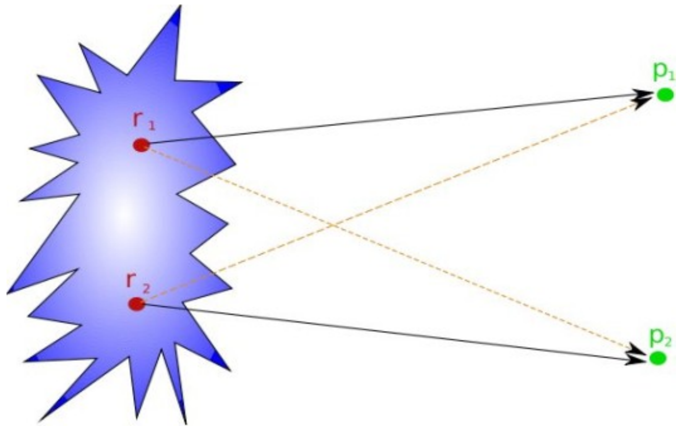
$$[a_a^i(k), a_b^{\dagger j}(p)] = (2\pi)^2 \delta_{ab} \delta^{ij} \delta^{(2)}(k-p)$$

$$a_a^i(k) \equiv \frac{1}{\sqrt{Y}} \int_{|\eta<Y/2|} \frac{d\eta}{2\pi} \, a_a^i(\eta, k)$$

Calculation of the quark correlations in the CGC framework
Quarks are fermions so should experience Pauli blocking
Calculations give negative correlations: Pauli blocking present in CGC
Short range correlation: peaked for $\Delta\eta \sim 2$

Measurement of Bose - Einstein correlations

Tibor Zenis
ATLAS



- Bose-Einstein correlations (BEC) represent a unique probe of the space-time geometry of the hadronization region and allow the determination of the size and shape of the source from which particles are emitted.
- BEC effect corresponds to an enhancement in two identical boson correlation function when the two particles are near in momentum space. It is a consequence of their wave function symmetry.

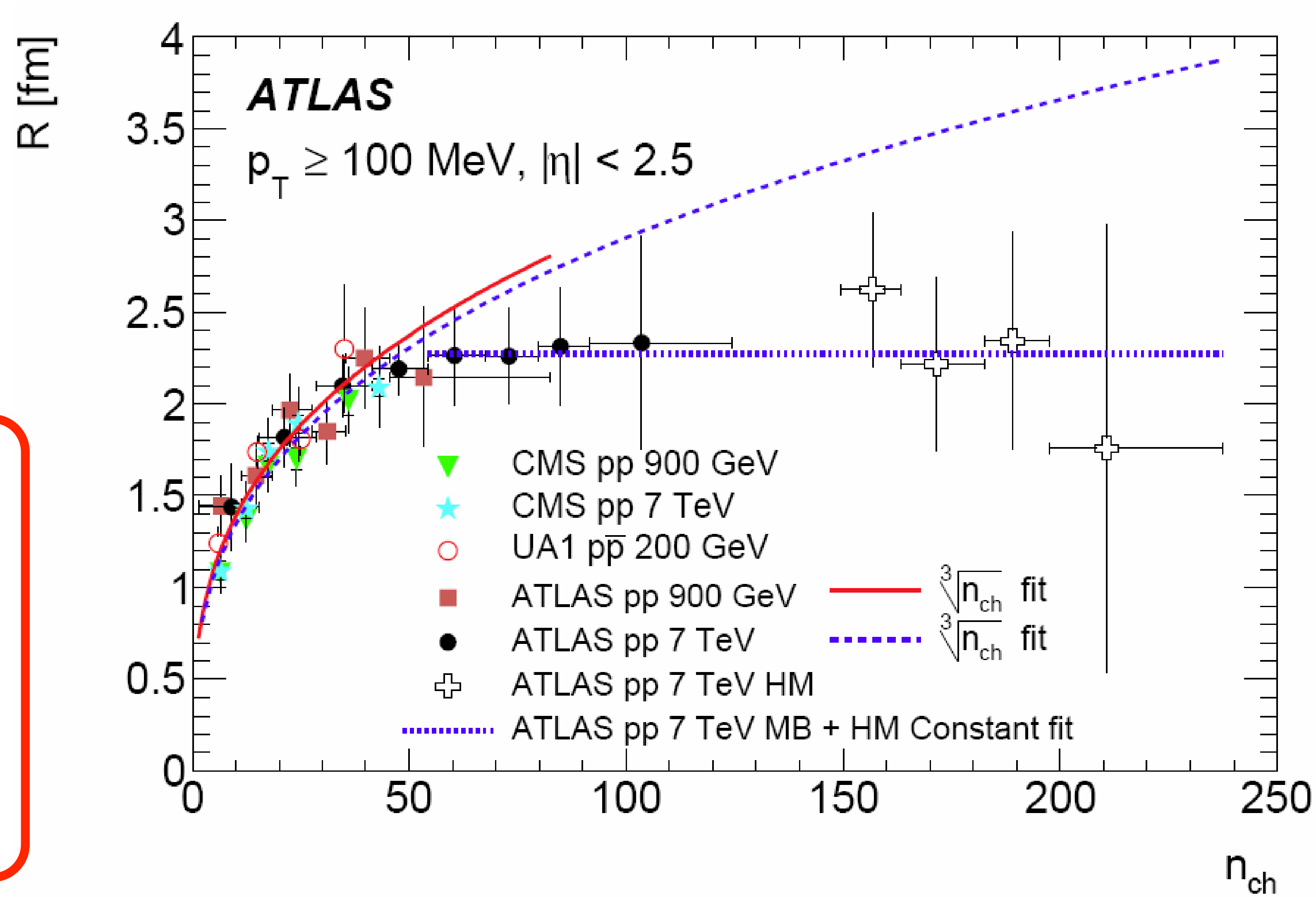
Correlation function

$$C_2(Q) = \frac{P(\boldsymbol{p}_1, \boldsymbol{p}_2)}{P(\boldsymbol{p}_1)\cdot P(\boldsymbol{p}_2)}$$

Parametrized using different models.
Basic parameter: source radius R

Saturation of the BEC radius observed at high multiplicity

$$R = 2.28 \pm 0.32\,\mathrm{fm}$$



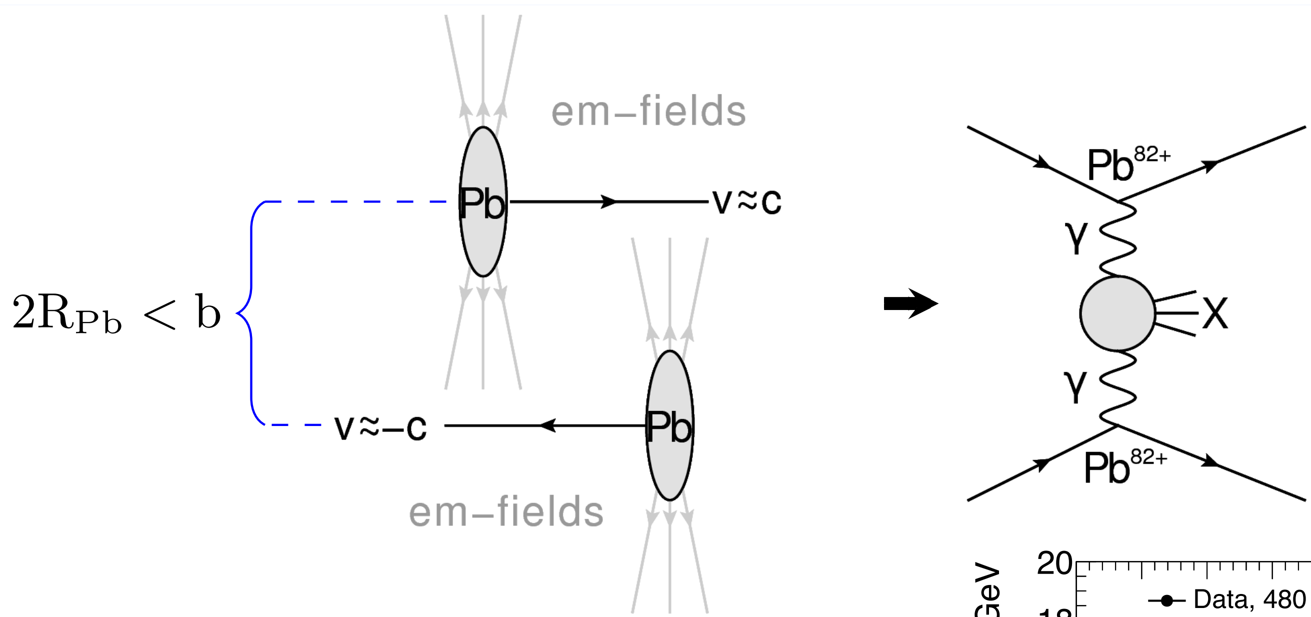
Final remarks

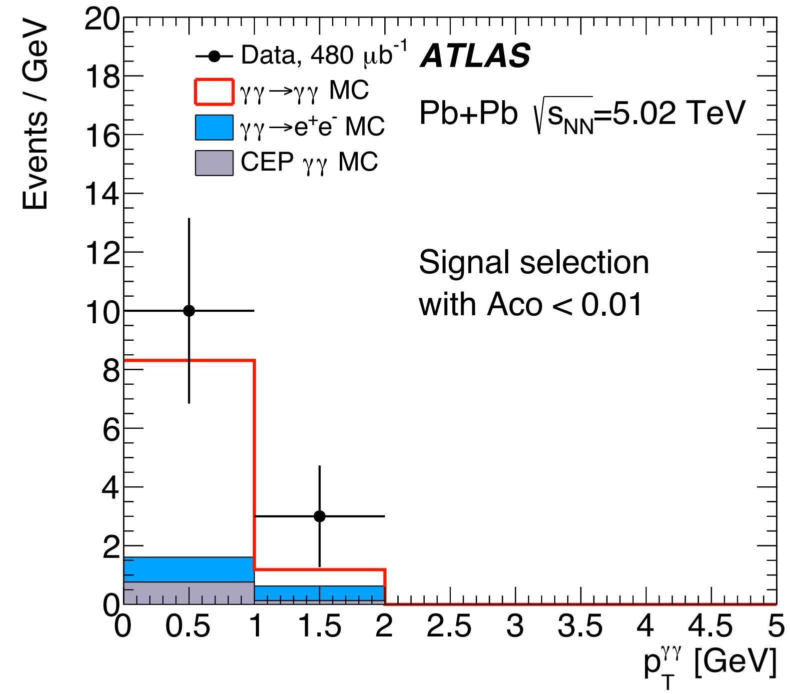
- Apologies to speakers whose talks were omitted in the summary.
- Many new results from experiments: exclusive production, (mostly from UPC), diffraction, jets, multi-parton interactions.
- Theoretical developments: new observables, higher order calculations in low x physics, building connection between low x formalism and other approaches, lots of new phenomenology.
- Finally, we would like to thank all the speakers in Working Group 2 for their excellent presentations. We would also like to thank all the participants who attended our session: we had great attendance and very lively discussions!

backup

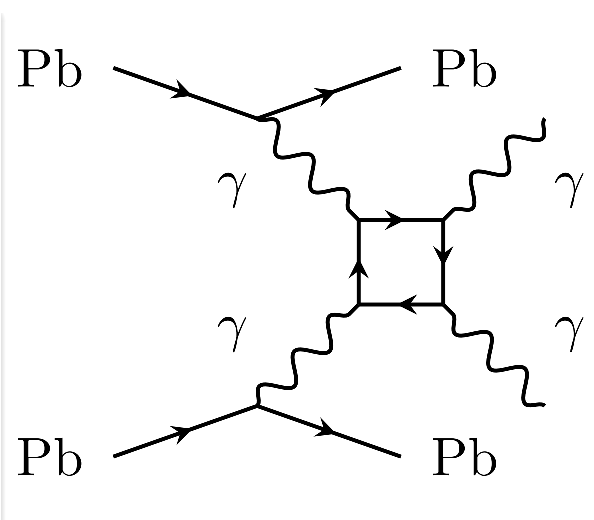
Ultraperipheral Pb+Pb collisions

Marcin Guzik
ATLAS





Light-by-light scattering



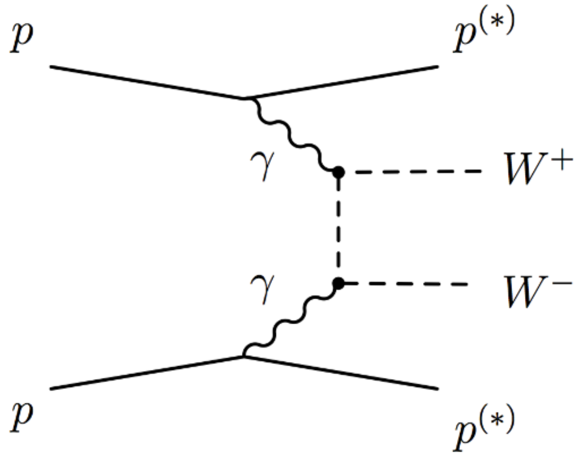
The first direct evidence for $\gamma\gamma \to \gamma\gamma$ scattering with significance of 4.4σ has been reported.

x-sec measured in fiducial region of $p_T^{\gamma} > 3\,\mathrm{GeV}$, $|\eta^{\gamma}| < 2.4$, $m_{\gamma\gamma} > 6\,\mathrm{GeV}$, $p_T^{\gamma\gamma} < 2\,\mathrm{GeV}$, Aco < 0.01
$\sigma = 70 \pm 20\,(\mathrm{stat.}) \pm 17\,(\mathrm{syst.})\,\mathrm{nb}$

Ultraperipheral and exclusive production

Alexander Bylinkin
CMS

Exclusive production of W pairs in proton proton collisions



- The exclusive production of W pairs is sensitive to anomalous quartic gauge couplings (aQGC)
- **The electroweak sector of Standard Model predicts QGC**
- **Any deviation from SM expectations can reveal a sign of new physics**

Ultraperipheral and exclusive production

Alexander Bylinkin
CMS

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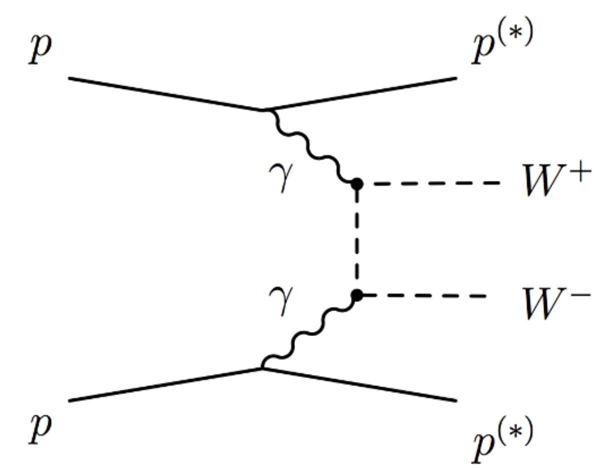

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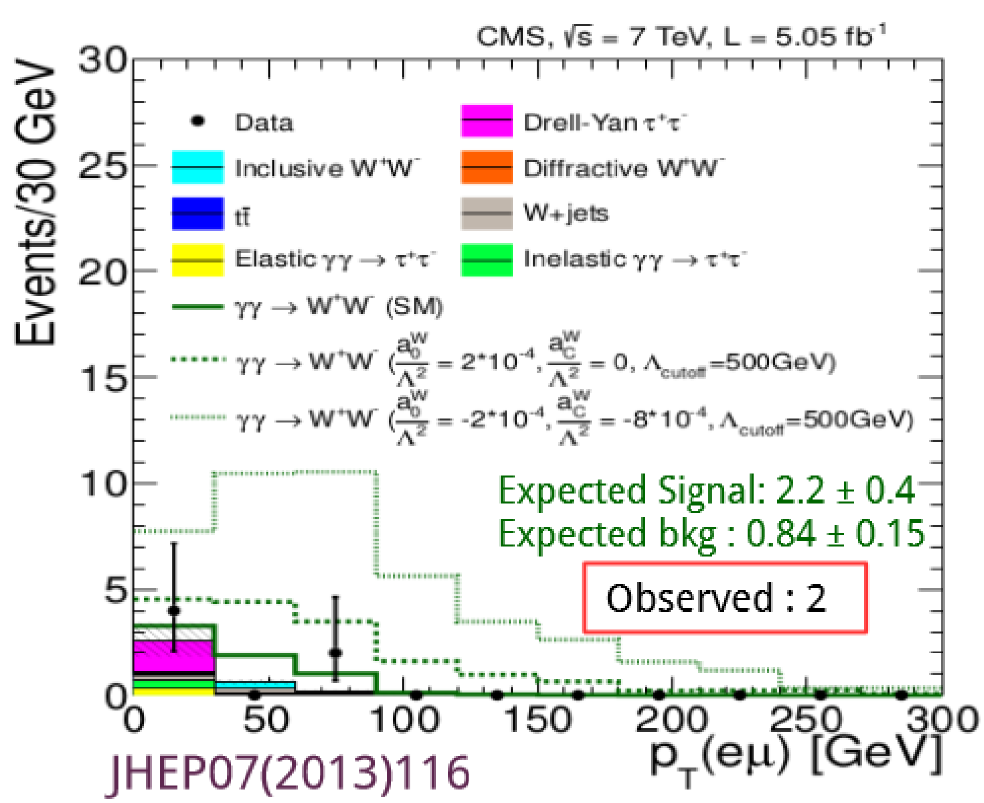

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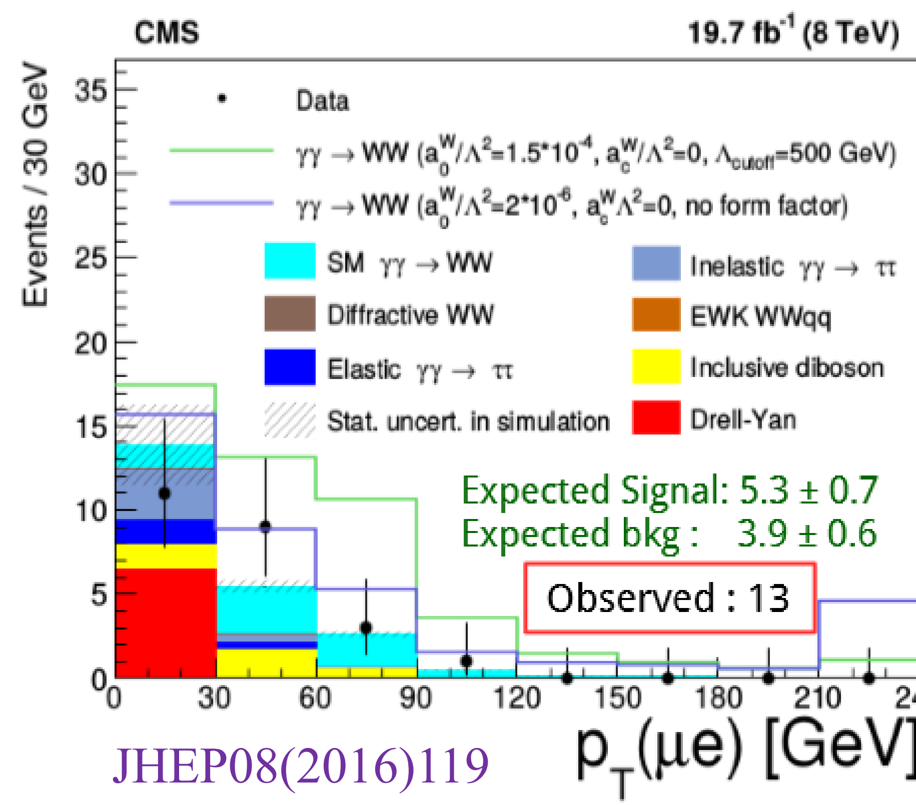

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Cross section times branching fraction

$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.2^{+3.3}_{-2.0}\,\text{fb}$

$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 10.8^{+5.1}_{-4.1}\,\text{fb}$

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Alexander Bylinkin
CMS

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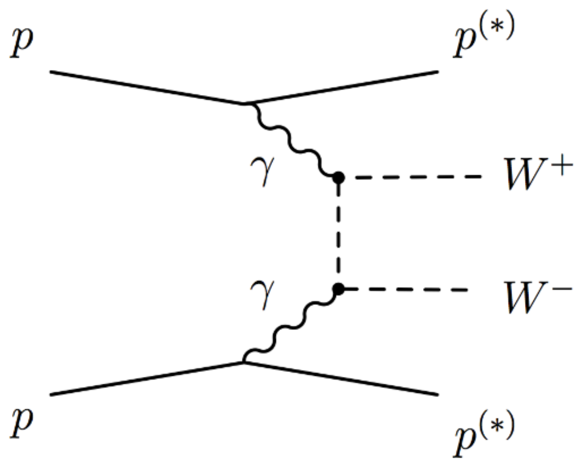

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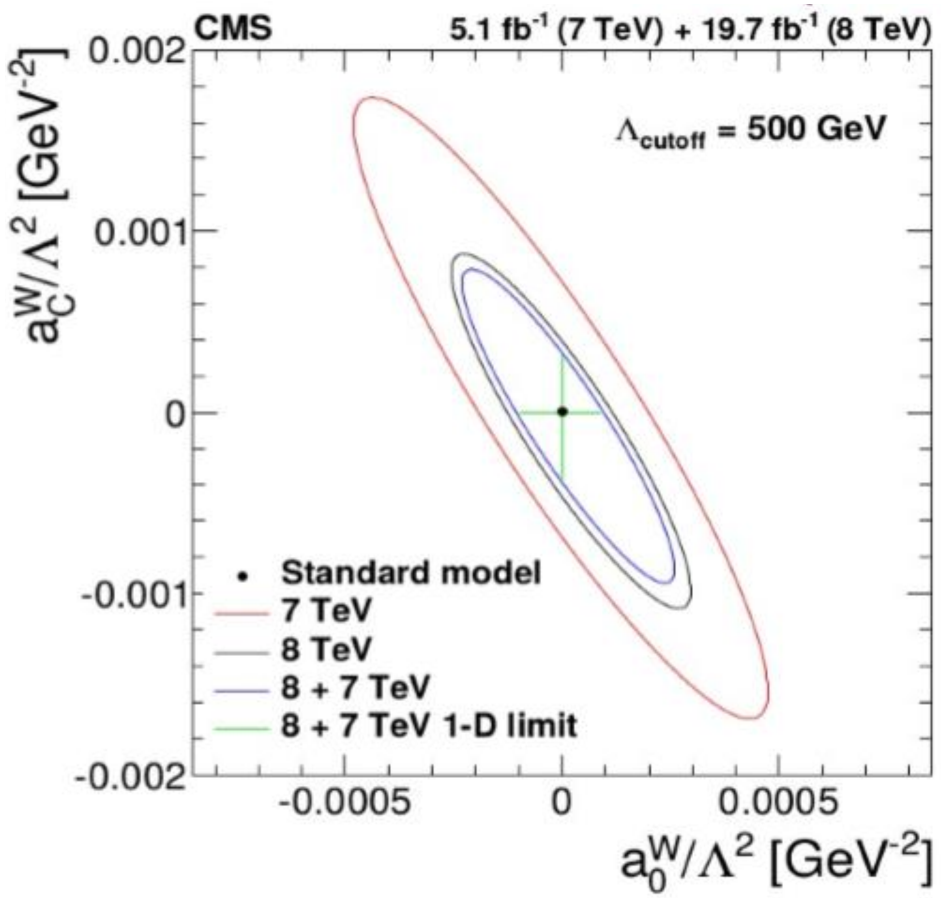

- **The most stringent limit so far, two orders of magnitude more stringent than LEP**