WG2: Summary

Sylvester Joosten and Feng Yuan

*all mistakes or omissions in this summary come from Feng
** except for the ones made by Sylvester

A snapshot of WG2

- Total of 42 talks (19 exp+23 theory)
- Topics range from small-x to threshold J/psi production
- Theory talks
  - Small-x spin physics: helicity, orbital angular momentum, Sivers function, …
  - Precision on small-x saturation: forward pA, DIS, Diffractive DIS, vector meson
  - Collinear vs small-x CGC
- Experiment talks
  - Low-x physics, diffraction, and collectivity in small systems from LHC
  - Heavy quarkonium production from threshold to ultra-peripheral heavy ion collisions
  - Forward hadron productions in pA collisions
  - Baryon stopping in photonuclear reactions

Theory: overall summary

- Very active field, great progress in the last few years, and well represented in WG2 sessions
- Three major threads
  - Theory advances: spin structure at small-x, diffractive parton distributions, CGC vs collinear factorization, etc.
  - Precision computations in CGC: next-to-leading order for various small-x processes
  - Phenomenology to interpret the experimental data

Theory I: proton spin at small-x

- Phenomenology very important to understand proton spin sum rule: all collider experiments, including EIC, have limits on the kinematics, where theory guidance may help to finally solve the spin puzzle
- Bartels, Ermolaev, Ryskin (BER) 1996, double logarithmic resummation for helicity distributions
  - Boussarie, Hatta, Yuan 2019, extend to parton orbital angular momenta
- Kovchegov, Pitonyak, Sievert (KPS) 2016-2019 applied dipole formalism
  - See talks by OSU group, Florian Cougoulic, Brandon Manley, Daniel Adamiak, Jeremy Borden, Ming Li, M Gabriel Santiago

Proton spin at small-x: updates on helicity distributions

New approach from Kovchegov et al agrees with previous BER approach (almost)

A quick conclusion

- Small-x evolution equations for helicity distributions at DLA.
- Involve the new dipole G_2 operator.
- Numerical agreement with the intercept found by BER: $(1/x)^{3.66\sqrt{\alpha_s N_c/2\pi}}$

Florian Cougoulic

$$\Delta\Sigma(x,Q^2) \sim \Delta G(x,Q^2) \sim g_1(x,Q^2) \sim \left(\frac{1}{x}\right) \qquad \alpha_h \approx 3.66074\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

- A *very* small discrepancy compared to the prediction of BER: $\alpha_h^{BER} \approx 3.66394\sqrt{\frac{\alpha_s N_c}{2\pi}}$

We find a resummed small-*x* anomalous dimension

$$\Delta\gamma_{GG}(\omega) = \frac{\omega}{2}\left[1 - \sqrt{1 - \frac{16\bar{\alpha}_s}{\omega^2}\sqrt{1 - \frac{4\bar{\alpha}_s}{\omega^2}}}\right] = \frac{4\bar{\alpha}_s}{\omega} + \frac{8\bar{\alpha}_s^2}{\omega^3} + \frac{56\bar{\alpha}_s^3}{\omega^5} + \frac{496\bar{\alpha}_s^4}{\omega^7} + \mathcal{O}\left(\alpha_s^5\right)$$

- Comparison with BER again yields a very small discrepancy at $\mathcal{O}\left(\alpha_s^4\right)$

$$\Delta\gamma_{GG}^{BER}(\omega) = \frac{\omega}{2}\left[1 - \sqrt{1 - \frac{16\bar{\alpha}_s}{\omega^2}\frac{1 - \frac{3\bar{\alpha}_s}{\omega^2}}{1 - \frac{\bar{\alpha}_s}{\omega^2}}}\right] = \frac{4\bar{\alpha}_s}{\omega} + \frac{8\bar{\alpha}_s^2}{\omega^3} + \frac{56\bar{\alpha}_s^3}{\omega^5} + \frac{504\bar{\alpha}_s^4}{\omega^7} + \mathcal{O}\left(\alpha_s^5\right)$$

Jeremy Borden

Proton spin at small-x: other results

- Orbital angular momenta

$$L_{q+\bar{q}}(x,Q^2) \sim L_G(x,Q^2) \sim \Delta\Sigma(x,Q^2) \sim \Delta G(x,Q^2) \sim \left(\frac{1}{x}\right)^{3.66\sqrt{\frac{\alpha_s N_c}{2\pi}}}$$

Brandon Manley

See also, Boussarie, Hatta, Yuan 2019

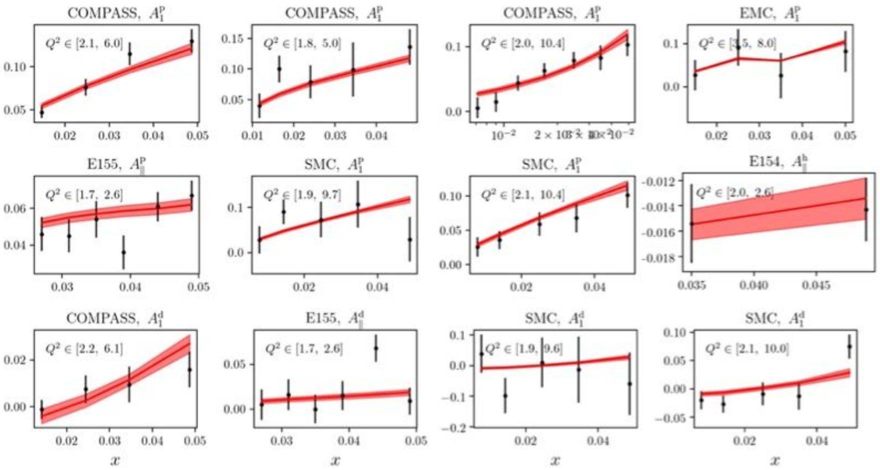
- Quark Sivers function

$$\boxed{f_{1T}^{\perp q}(x \ll 1, k_T^2) = \underbrace{C_O(k_T^2, x)\,\frac{1}{x}}_{\text{Odderon}} + \underbrace{C_1(k_T^2)\left(\frac{1}{x}\right)^{3.4\sqrt{\frac{\alpha_s N_c}{4\pi}}}}_{\text{Sub-eikonal Correction}} + \ldots}$$

M Gabriel Santiago

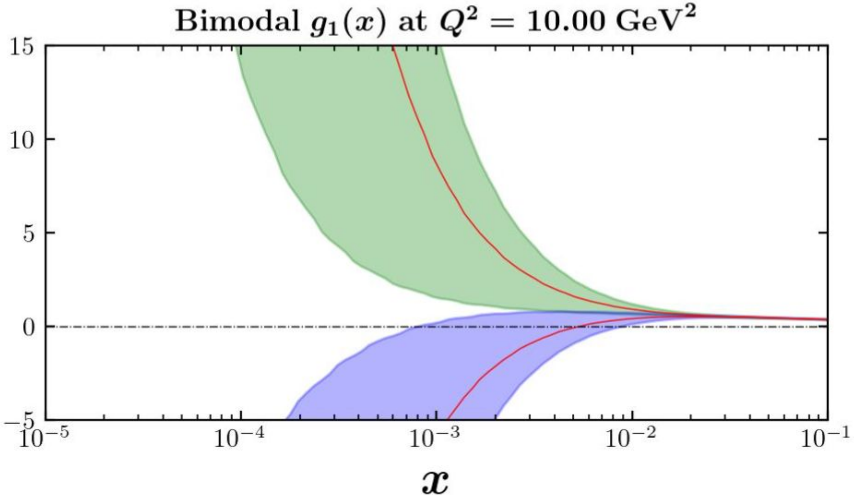
See also, Boer, Echevarria, Mulders, Zhou, 2016

Proton spin at small-x: phenomenology



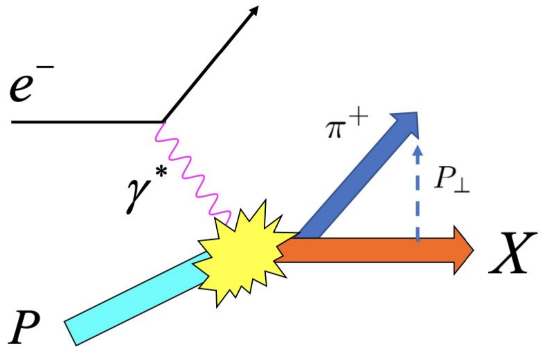
Daniel Adamiak

(Preliminary) Extraction of g_1^p

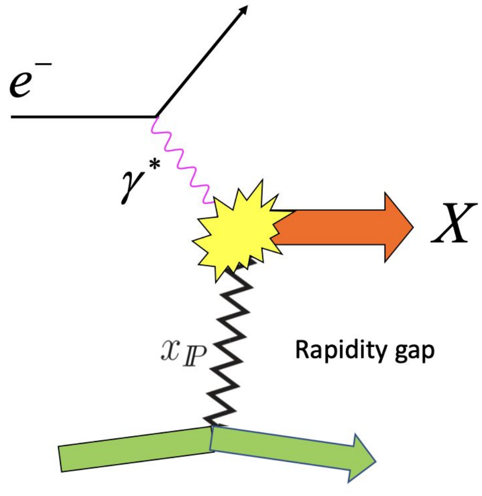


CGC Playground: diffractive DIS

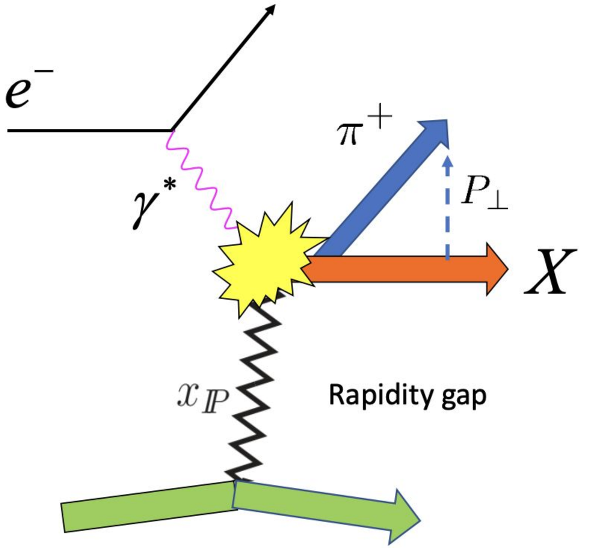
Yoshitaka Hatta



Semi-inclusive DIS



Diffractive DIS

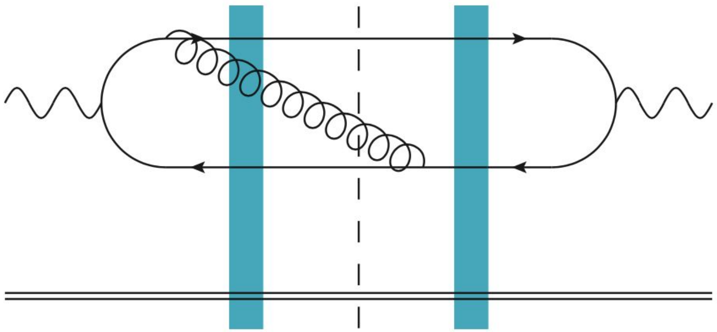


Semi-inclusive diffractive DIS

Iancu, Mueller, Triantafyllopoulos (2021)
Hatta, Xiao, Yuan (2022)

CGC Playground: diffractive DIS (NLO)

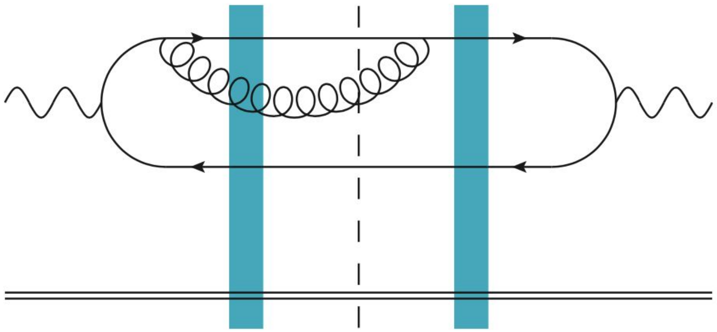
Jani Penttala
Henri Hänninen



Progress made toward a complete NLO calculations

We are completing the full NLO calculation

- Explicit cancellation of divergences
- One finite contribution still being calculated



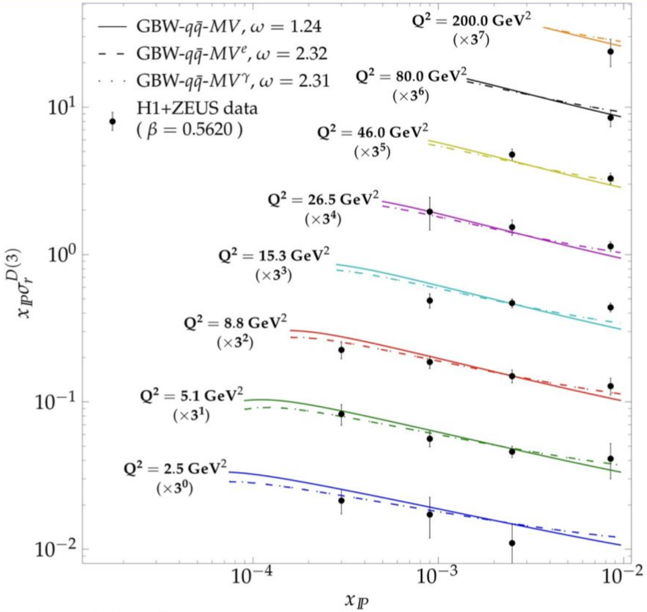
Future:

- Numerical implementation of the full NLO result
- Comparisons to the existing HERA data and predictions for the EIC

CGC Playground: Diffractive DIS (phenomenology)

Proton shape: Optimal steepness

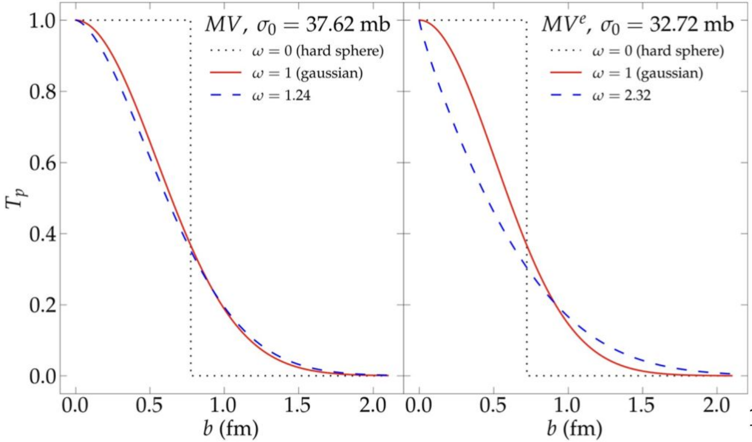
Anh-Dung Le



Combined data from
H1, ZEUS collaboration, EPJC 72, 2175 (2012)

$$T_p(\boldsymbol{b}) = \frac{\Gamma\left(\frac{1}{\omega}, \frac{2\pi b^2}{\sigma_0 \omega}\right)}{\Gamma\left(\frac{1}{\omega}\right)}$$

- **GBW-qq** result is fitted to diffractive HERA combined data for β>0.5 (24 data points) using the chosen proton shape.
- Optimal steepness:
  - ω = 1.24 (χ²/dof ≈ 1.87) for **MV**
  - ω = 2.32 (χ²/dof ≈ 1.08) for **MV^e**
  - ω = 2.31 (χ²/dof ≈ 1.09) for **MV^γ**

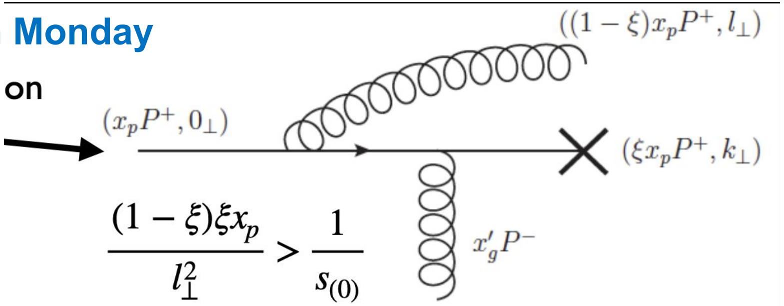


CGC Playground: single particle production in pA

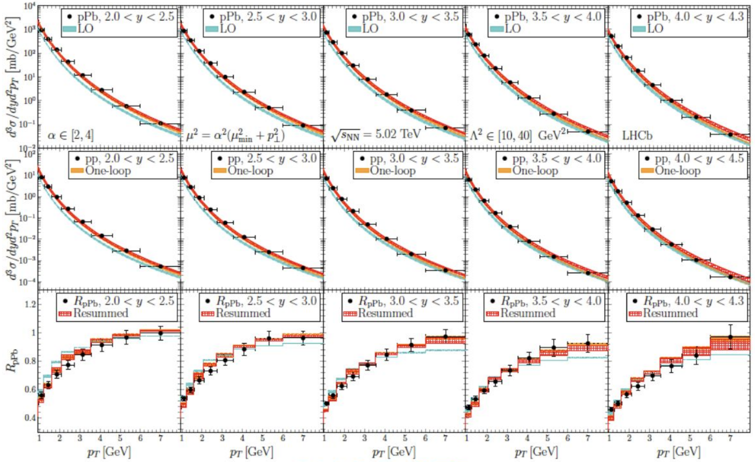
State of art, NLO+threshold resummation

Dumitru's talk on Monday

on



$$\frac{(1-\xi)\xi x_p}{l_\perp^2} > \frac{1}{s_{(0)}}$$

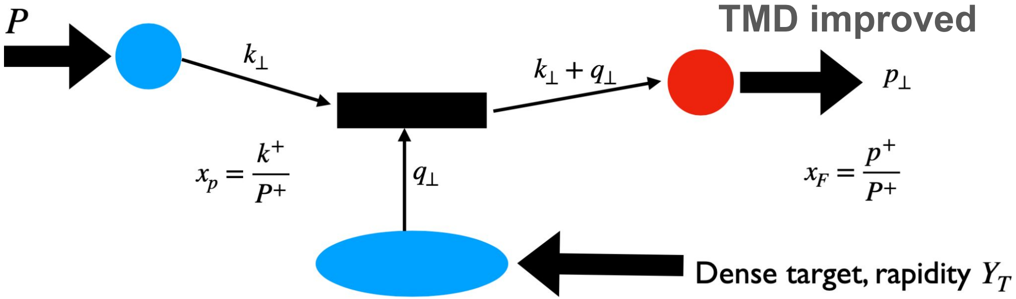


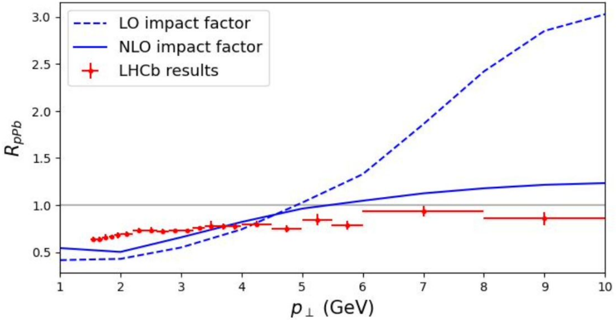
2112.06975

New developments

Néstor Armesto

TMD improved





π^0 R_{pPb} at y = 3, √s = 8.16 TeV (LHCb kinematics). Dipole evolved with KCBK. PDF and FF at NLO. Impact factor at LO/NLO. LHCb data are taken from [LHCb, 2108.13115].

Yossathorn Awabutr

dipole evolved with KCBK

CGC Playground: two particle correlations, great effort in the last few years!!

Back-to-back dijets at NLO

Farid Salazar

Complete small-x TMD factorization at NLO

$$d\sigma^{\gamma^*_\lambda + A \to \text{dijet}+X} = \mathcal{H}^{ij,\lambda}_{\text{NLO}}(Q, \boldsymbol{P}_\perp; \mu_F; R) \int \frac{d^2\boldsymbol{b}_\perp}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{b}_\perp} \alpha_s \widetilde{G}^{ij}_Y(\boldsymbol{b}_\perp) e^{-S_{\text{Sud}}(\boldsymbol{b}_\perp, \mu_F)} + \mathcal{O}(\alpha_s^2)$$

fully analytic result

$$d\sigma^{(0),\lambda=\text{L}} = \alpha_{\text{em}}\alpha_s e_f^2 \delta_z^{(2)} \mathcal{H}^{0,\lambda=\text{L}}_{\text{LO}} \left\{1 + \frac{\alpha_s(\mu_h)}{\pi}\left[\frac{N_c}{2}\tilde{f}_1^{\lambda=\text{L}}(\chi, z_f) + \frac{1}{2\pi N_c}\tilde{f}_2^{\lambda=\text{L}}(\chi)\right]\right\}$$
$$\times \int \frac{d^2\boldsymbol{r}_{bb'}}{(2\pi)^4} e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{r}_{bb'}} \hat{G}^0_{Y_f}(\boldsymbol{r}_{bb'}) \widetilde{S}(\mu_h^2, \boldsymbol{r}_{bb'}^2)$$
$$+ \alpha_{\text{em}}\alpha_s e_f^2 \delta_z^{(2)} \mathcal{H}^{0,\lambda=\text{L}}_{\text{LO}} \frac{\alpha_s(\mu_h)}{\pi} \left\{\frac{N_c}{2}\left[1 + \ln(R^2)\right] + \frac{1}{2N_c}\left[-\ln(z_1 z_2 R^2)\right]\right\}$$
$$\times \int \frac{d^2\boldsymbol{r}_{bb'}}{(2\pi)^4} e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{r}_{bb'}} \hat{h}^0_{Y_f}(\boldsymbol{r}_{bb'}) \widetilde{S}(\mu_h^2, \boldsymbol{r}_{bb'}^2)$$

Analogous expression for elliptic anisotropy $d\sigma^{(2),\lambda=L}$

$$f_1^{\lambda=\text{L}}(\chi, z_f) = 7 - \frac{3\pi^2}{2} - \frac{3}{2}\ln\left(\frac{z_1 z_2 R^2}{\chi^2}\right) - \ln(z_1)\ln(z_2) + 2\ln\left(\frac{(1+\chi^2)z_f}{z_1 z_2}\right)$$
$$- \ln(1+\chi^2)\ln\left(\frac{1+\chi^2}{z_1 z_2}\right) + \left\{\text{Li}_2\left(\frac{z_2 - z_1\chi^2}{z_2(1+\chi^2)}\right) - \frac{1}{4(z_2 - z_1\chi^2)}\right.$$
$$\left. + \frac{(1+\chi^2)(z_2(2z_2 - z_1) + z_1(2z_1 - z_2)\chi^2)}{4(z_2 - z_1\chi^2)^2}\ln\left(\frac{z_2(1+\chi^2)}{\chi^2}\right) + (1 \leftrightarrow 2)\right\}$$

$$\chi = \frac{\bar{Q}}{P_\perp}$$

Similar expression for f_2

The first proof of TMD factorization at NLO at small-x (modulo the non-linear evolution of the WW)

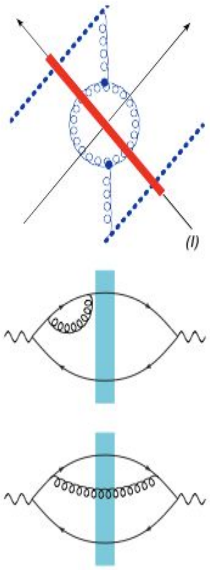
Next-to-Eikonal corrections

Guillaume Beuf

- One twist 2 term, interpreted as the first order expans phase from the gluon TMD definition
- Kinematical twist 3 terms
- Twist 3 gluon TMDs, with one $\mathcal{F}_i^{\ -}$ replaced by $\mathcal{F}^{+-}$
- Twist 3 correlators of 3 field strengths

CGC Playground: Impact Factors at NLO

Progress towards NLO



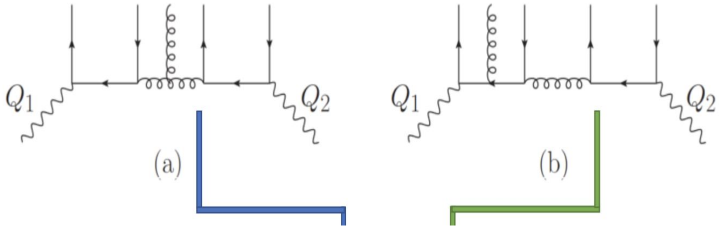
Full NLO accuracy ($\sim \alpha_s^2 \ln 1/x$) requires

- Evolution equation
  - NLO BK: Balitsky, Chirilli, 0710.4330
  - Resummation of transverse logs: Iancu, et al, 1502.05642, 1507.03651
  - Numerical solution: Lappi, H.M, 1601.06598
- Impact factor (γ^* wave function at NLO)
  - $m_q = 0$: Hänninen, Lappi, Paatelainen, 1711.08207; Beuf 1708.06557
  - With heavy quarks (mass renormalization in LCPT): Beuf, Lappi, Paatelainen 2103.14549 2112.03158, 2204.02486
  - Numerical implementation: Hänninen, H.M, Paatelainen, Penttala, 2211.03504
- Also many other processes, talks by Dumitru, Tawabutr, Mulian, Penttala, Salazar, Hänninen, . . .

Heikki Mantysaari

Small x resummation of photon impact factor and the $\gamma^*\gamma^*$ high energy scattering

Dimitri Colferai[1], Wanchen Li[2], and Anna M. Staśto[2]

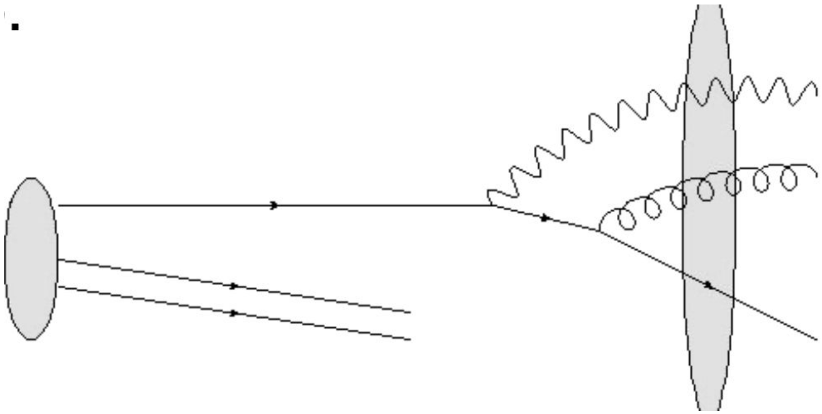


Wanchen Li

CGC Playground: Photon+Jet production in pA collisions

- Next to leading order computation in progress

  Yair Mulian



- Next-to-Eikonal corrections

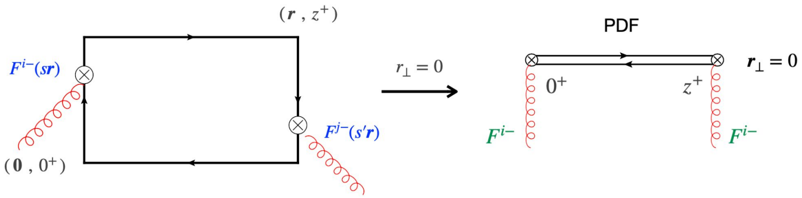
  Arantxa Tymowska

CGC vs Collinear factorization

3D gluon distribution

Boussarie, MT (2020-2021)

$$xG^{ij}(x,k_\perp) \equiv 2\int_{s,s'}\int \frac{dz^+ d\boldsymbol{r}}{(2\pi)^3 P^-} e^{ixP^-z^+ - i\boldsymbol{k}\cdot\boldsymbol{r}} \langle P|\,\mathrm{Tr}\,[0,z^+]_{\boldsymbol{r}} F^{j-}(z^+,s'\boldsymbol{r})\,[z^+,0]_{\boldsymbol{0}} F^{i-}(0,s\boldsymbol{r})\,|P\rangle$$

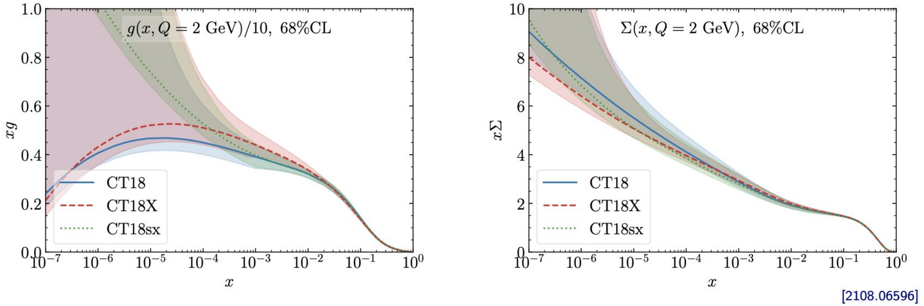


- Top down approach to collinear region of phase space at small x: Minimal correction to the semi-classical approach to small x to restore x dependence using a partial twist expansion
- In the case of inclusive DIS: while the hard part is unchanged a new (gauge invariant) 3D gluon distribution that interpolates between the dipole operator at small x and the gluon PDF at leading twist
- We also recover the NLO cross-section for DIS, DDVCS, DVCS and TCS
- Quantum evolution requires the introduction of an additional kinematic variable k^-
- Outlook: investigate relations to DGLAP and BK evolution in the non-linear regime

Yacine Mehtar-Tani

x-dependent scale, motivated by saturation physics, applied to collinear PDF global fit

Small-x resummation vs saturation scale

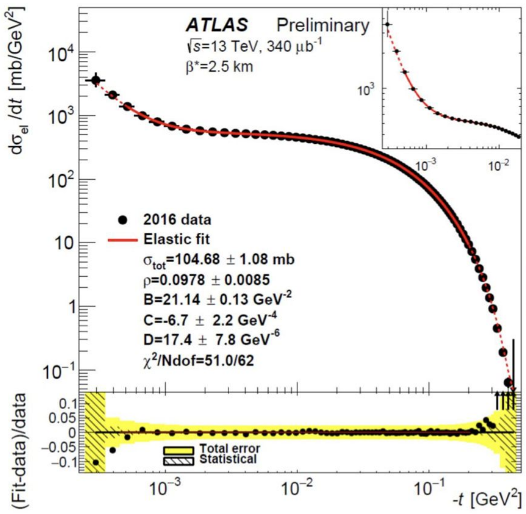


- We obtain the same level of agreement between data and theory
- Both approaches enhance (reduce) the gluon (singlet) PDF at small x and Q
- At a higher Q, the small-x effect disappear.

Keping Xie

Experiment

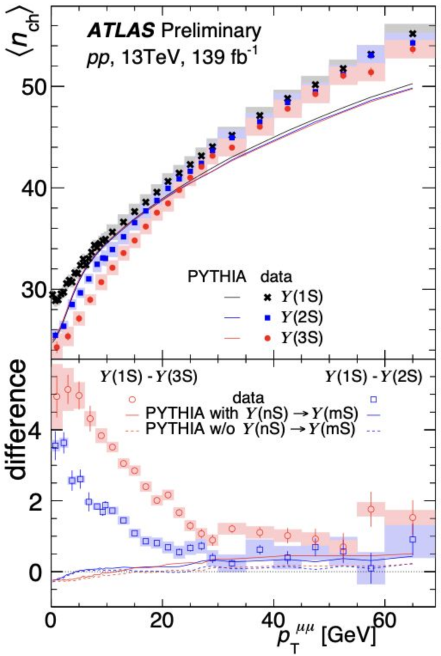
New results from ATLAS



$t \in [2.5 \cdot 10^{-4}, 4.6 \cdot 10^{-1}]$ GeV²

Differential elastic p-p cross section measured with ALFA

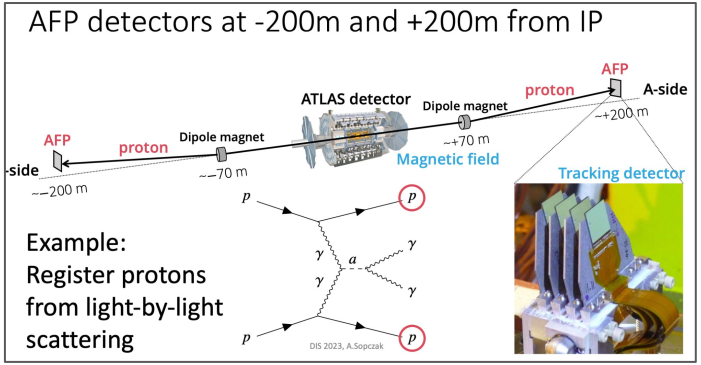
Tomas Sykora



Correlation of Y-meson production with the underlying event - substantial differences in particle multiplicities

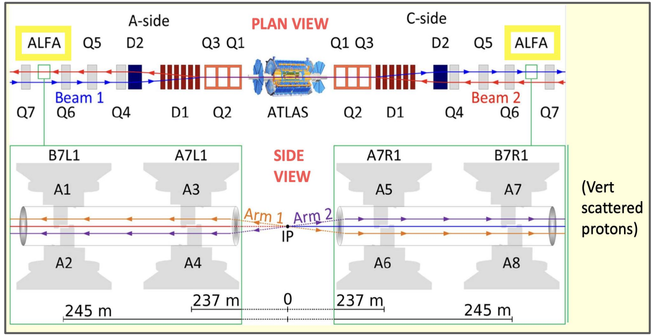
Claire Gwenlan

ATLAS forward proton detectors



Andre Spoczak

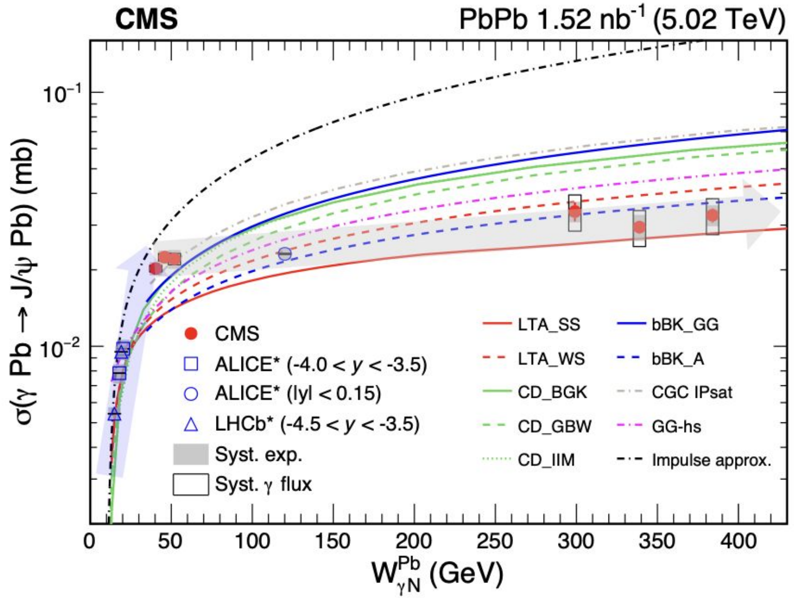
ATLAS ALFA detectors



Peter John Bussey

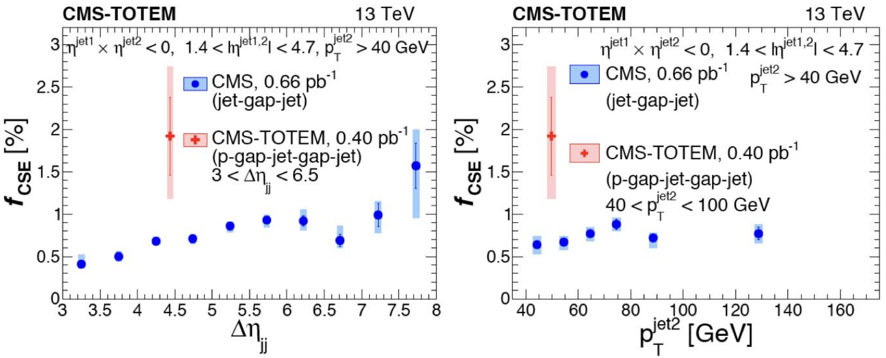
Results from CMS

Flattening in coherent J/Ψ production cross section for γ+Pb at high energies



- **σ(J/Ψ) vs. W** not predicted by state of the art models
  - **Gluon saturation?** or **black disk limit?** or **other physic effects?**

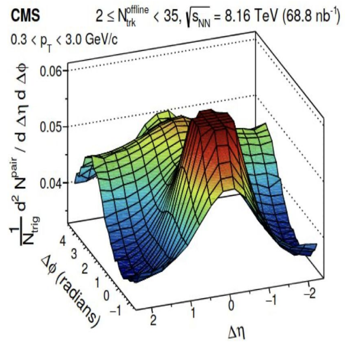
Zaochen Ye



- **Jet gap jet events were observed for the 1st time by CMS!** (Phys.Rev.D 104 (2021) 032009)

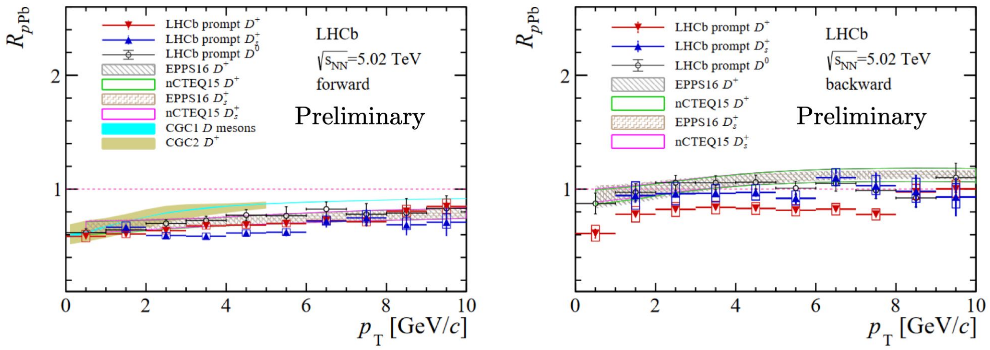
Christophe Royon

- **First CMS measurements of two particle correlations in γ-proton**
  - Significant v_2 values consistent with non-flow model
  - No evidence of ridge structure in near-side, long-range region
- It adds to the plethora of small systems in which collectivity is being studied
- arXiv:2204.13486



Moisés León Coello

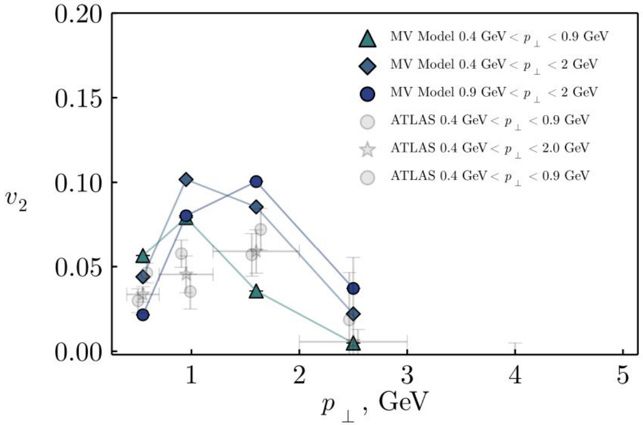
New results from LHCb



New measurement of $D^{\pm}$ R_{pPb} shows a backward deficit, while $D_s^{\pm}$ agrees with nPDF predictions.

Thomas Beuttcher

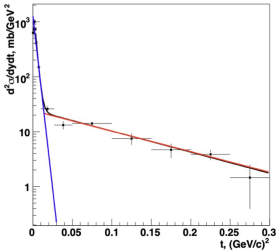
CGC calculation to describe Pb+Pb at LHC



Haowu Duan

Issues with the Good-Walker Approach

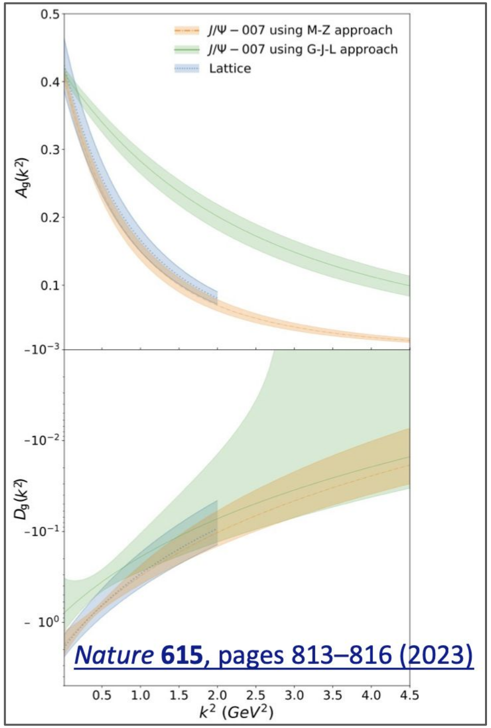
Spencer R. Klein

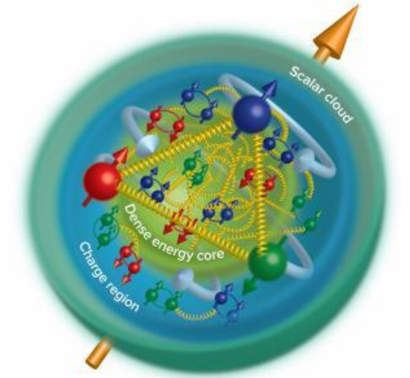


Many examples where coherent-photoproduction happens where Good-Walker predicts it should not occur. The formalism needs to be extended to account for more complicated/realistic reactions with additional particles.

Latest photoproduction results from Jefferson Lab

Gluon gravitational form factors and proton mass radius from J/ψ photoproduction in **Hall C**. Mass radius smaller than charge radius: the proton has a dense energetic core

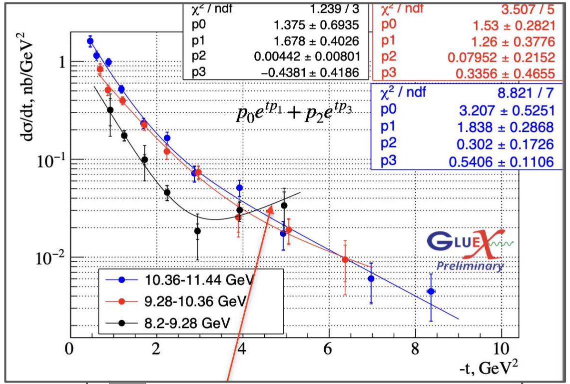


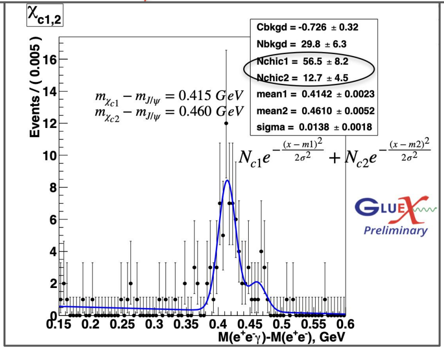


Theoretical approach	$\sqrt{\langle r_m^2 \rangle_g}$ (fm)
Holographic QCD	0.755+/-0.067
GPD	0.472+/-0.085
Lattice	0.746+/-0.055

Shivangi Prasad

Preliminary results on differential J/ψ cross section from **GlueX**, and first look at the χ_c near threshold

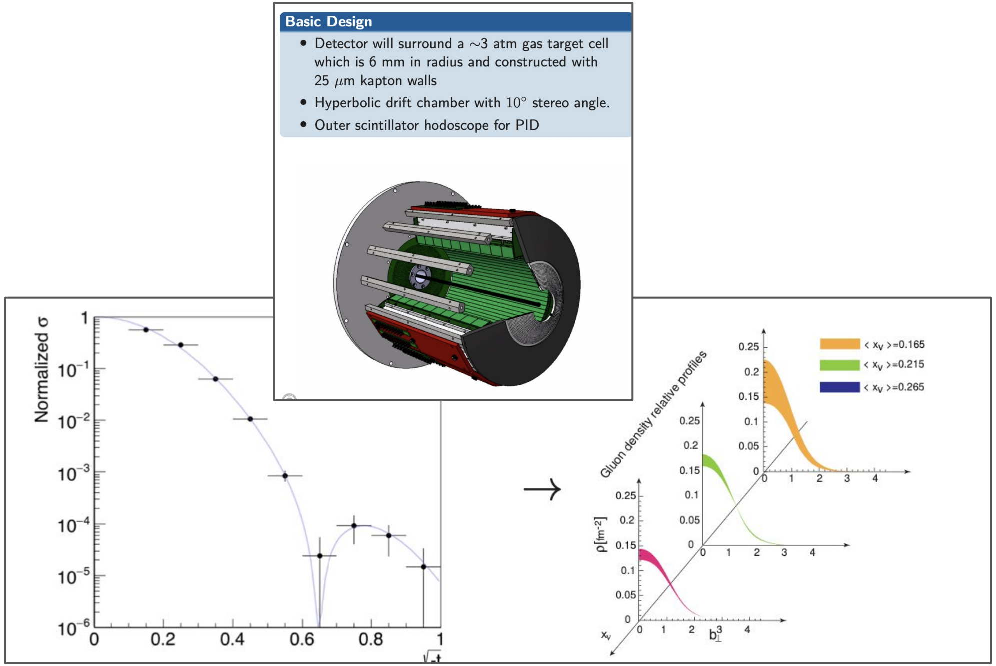




Lubomir Pentchev

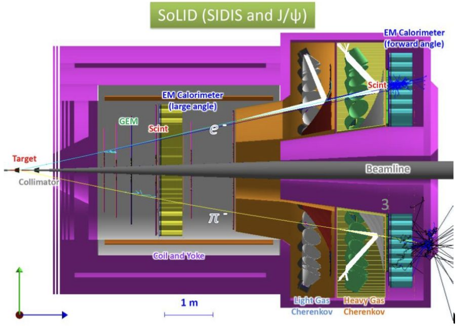
Future at Jefferson Lab

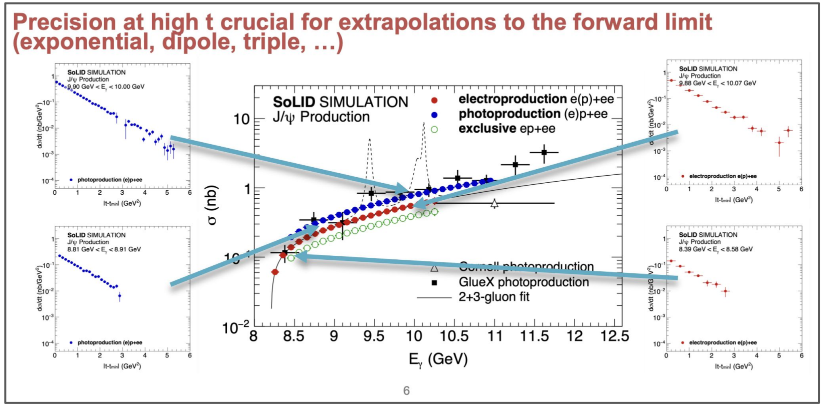
ALERT at Jefferson Lab (scheduled for summer 2024): access gluon GPD of ^{4}He through exclusive φ production at CLAS with new recoil detector



Whitney Armstrong

Precision near-threshold J/ψ and beyond (TCS, DDVCS, …) with SoLID - strongly endorsed by PAC, tentatively ~2029

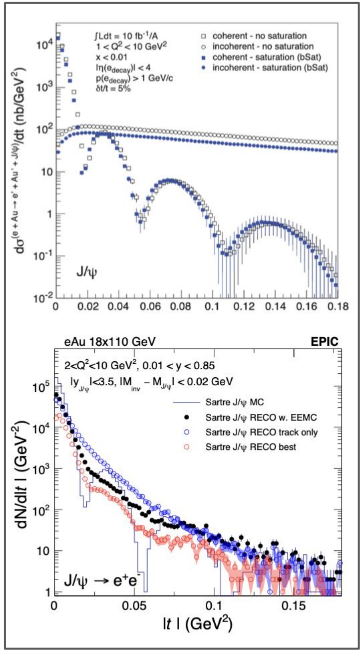




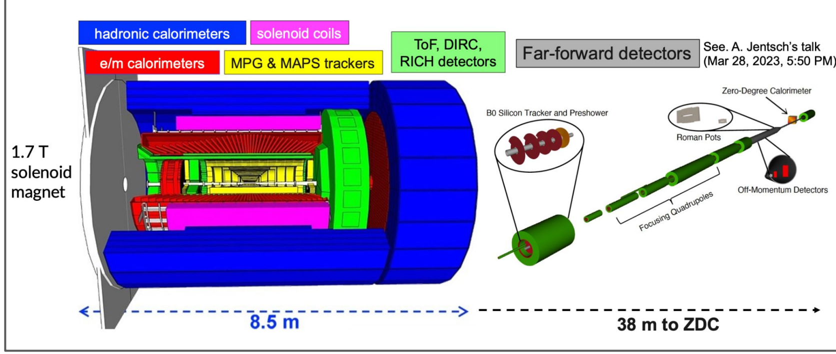
Zhiwen Zhao

Future at EIC

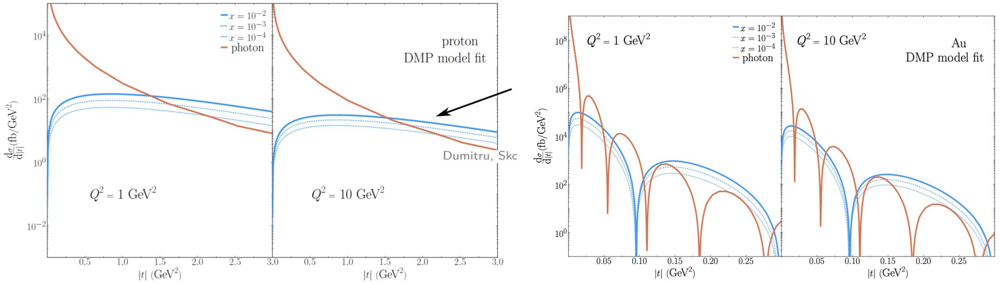
Diffractive vector meson production at ePIC to study the gluon spatial distribution in nuclei



Kong Tu



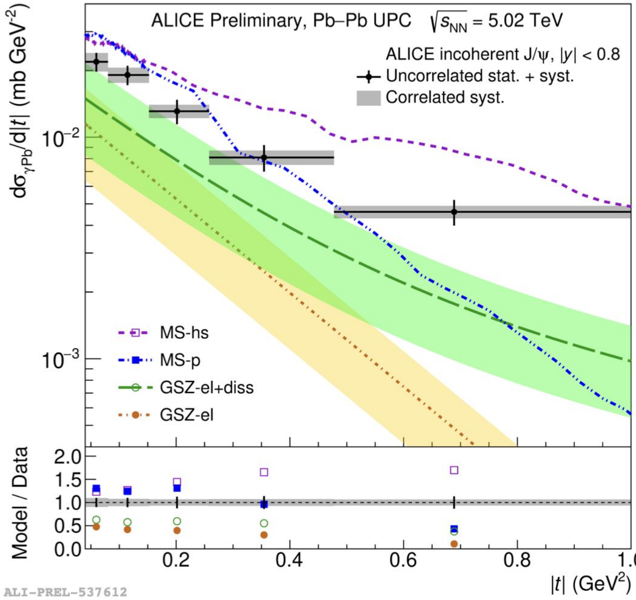
Projections for exclusive η_c and odderons - signature requires large-t for the proton but easier to see on nuclei



Sanjin Benić

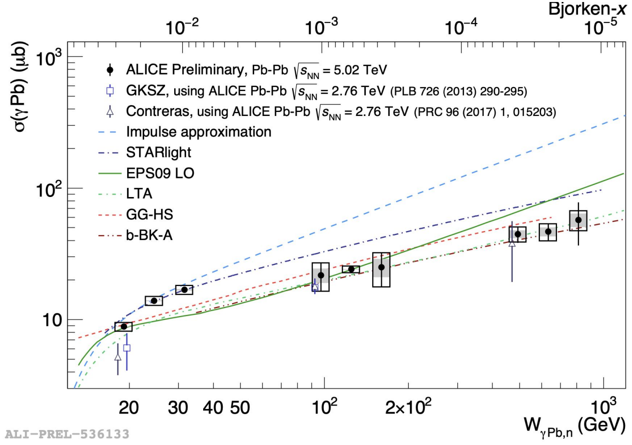
New UPC results from ALICE

New results for t-dependence for incoherent J/ψ cross section in γPb, data with sensitivity to “gluonic hot-spots”



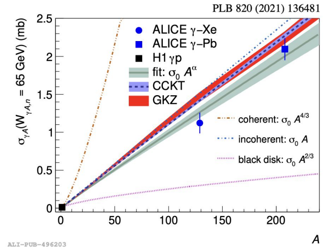
Daniel Tapia Takaki

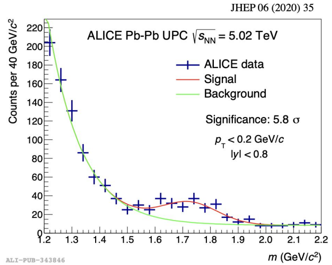
New results on J/ψ elastic photoproduction in γ-Pb



Valeri Pozdniakov

ρ^0 and di-kaon from UPC

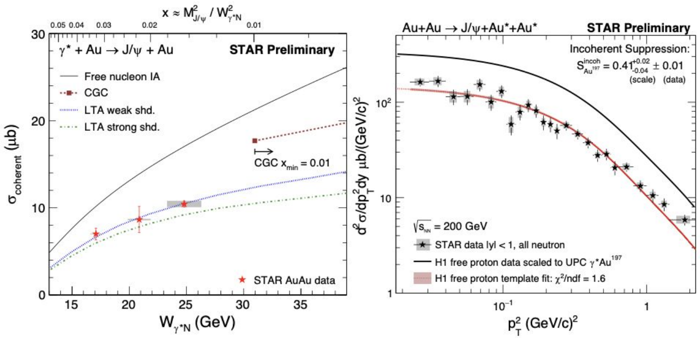




Abdennacer Hamdi

New results from STAR

J/ψ measurements in Au+Au UPC at RHIC. Strong suppression compared to H1 proton data.



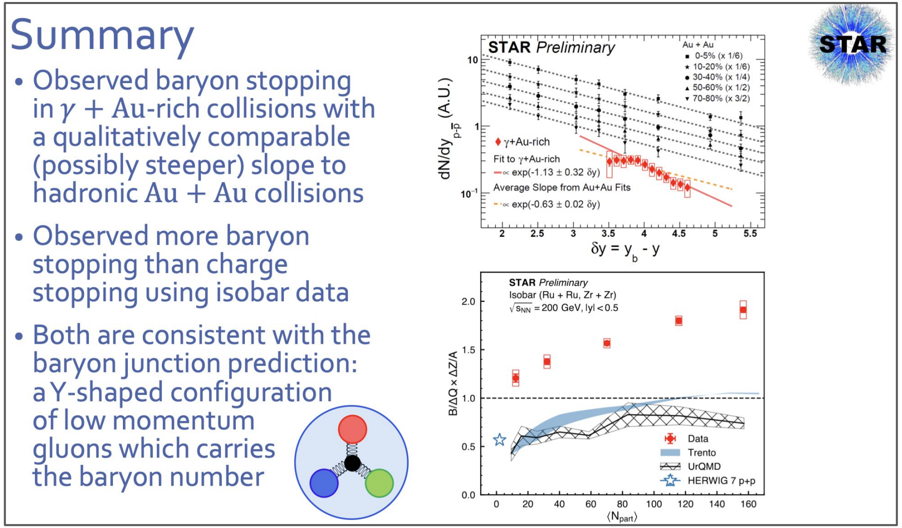
STAR has made many **first-time J/ψ** measurements in UPCs at RHIC:

✓ Strong **nuclear suppression** seen for both coherent (~ 40%) and incoherent (~60%) production

✓ **Bound** nucleon and **free** proton have similar shape in p_T^2 up to ~ 2 (GeV/c)^2

Kong Tu

Preliminary results on baryon stopping in γ+Au-rich collisions



Nicole Lewis

Thank you!!!