Ultra-peripheral collisions

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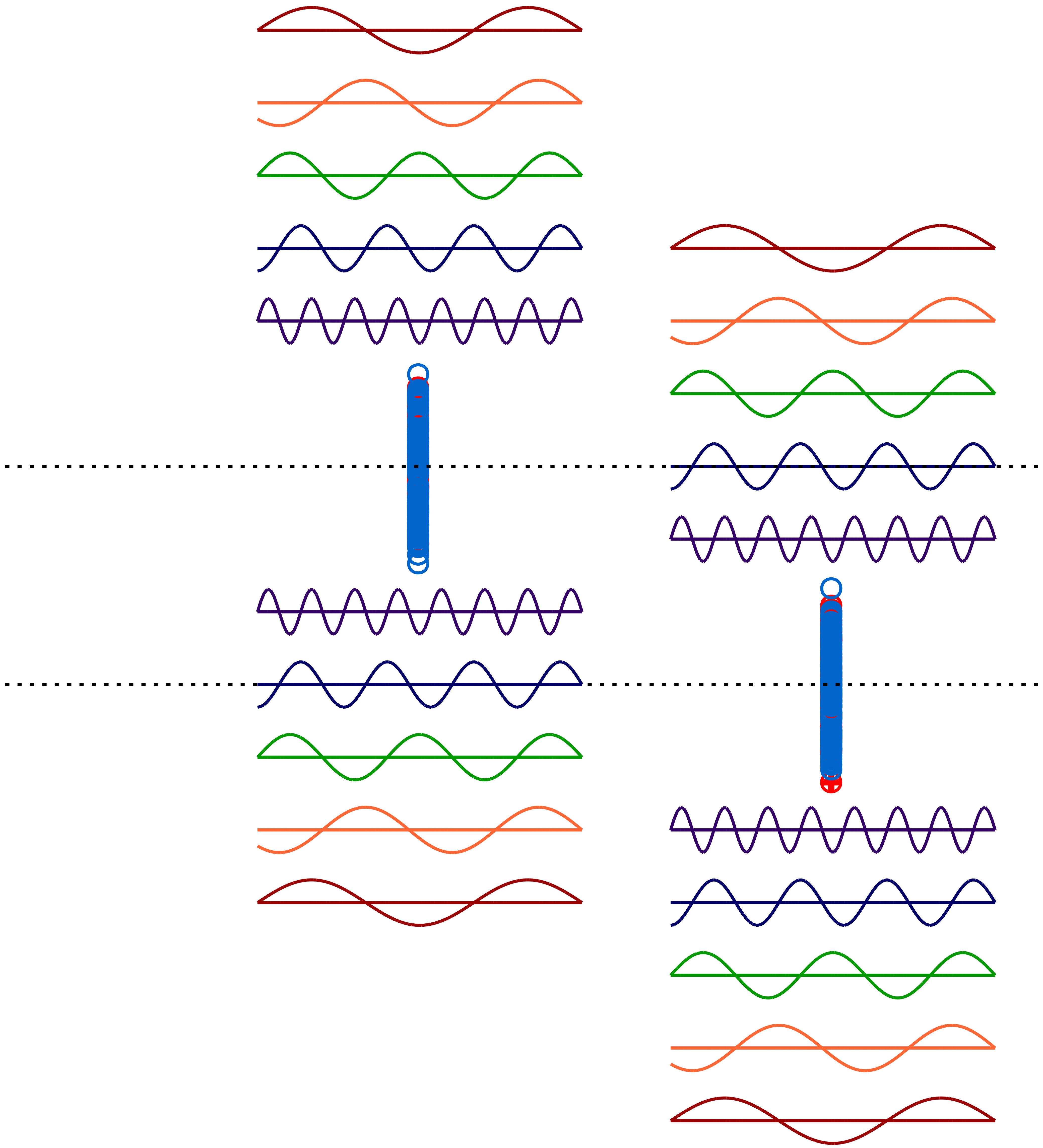
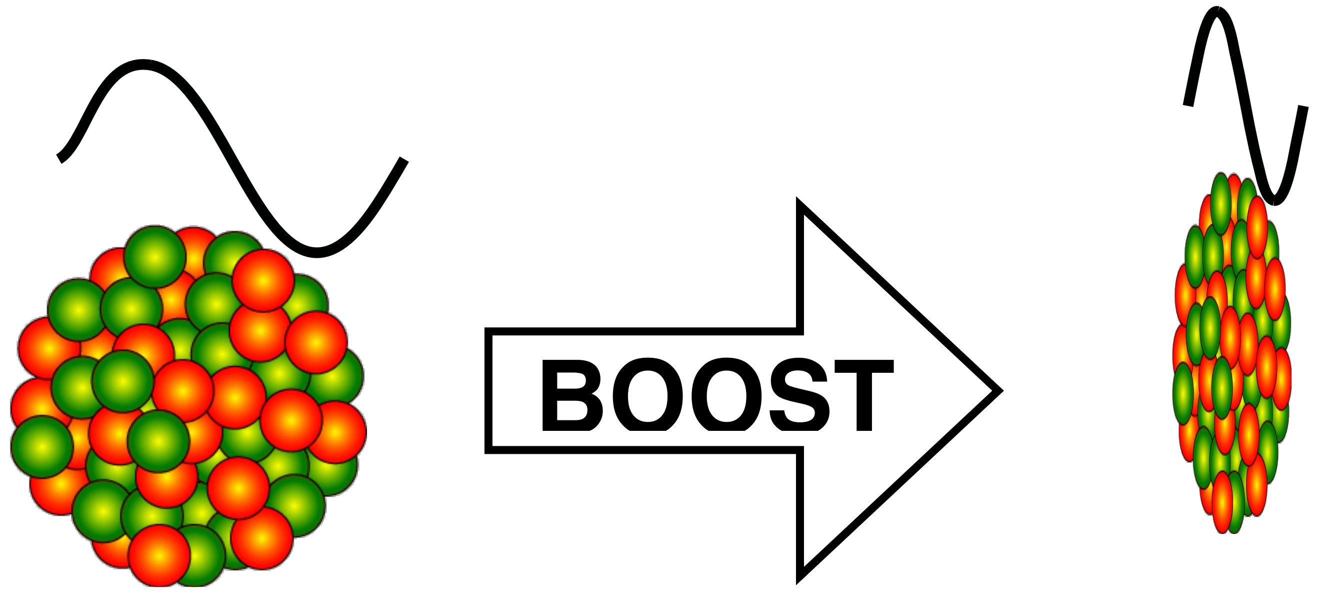
Ultra-peripheral collisions

- In HI collisions the large electromagnetic fields accompanying the nuclei can be expressed in terms of an equivalent photon flux
  - Leads to photon-photon and photon-nucleus collisions
- At large impact parameter ($b > 2\,R_N$) this is the dominant interaction mechanism in HI collisions: "ultra-peripheral collisions"



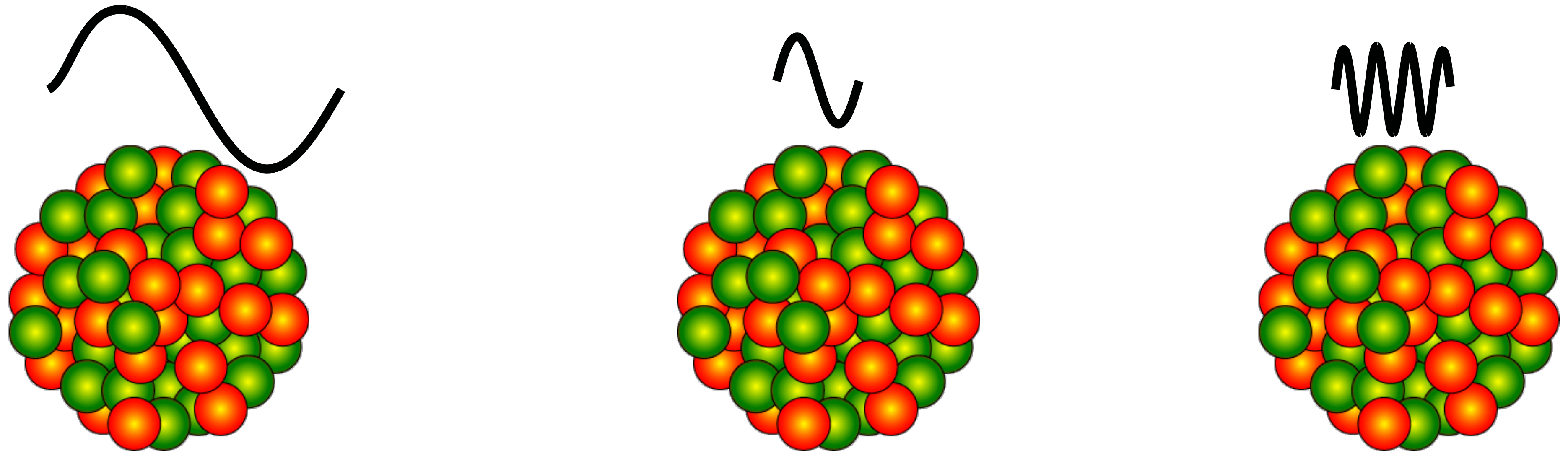
Ultra-peripheral collisions: scales

- For photons that can be emitted ***coherently*** by entire nucleus, flux is enhanced by Z^2
  - k_T, $|q| \lesssim \hbar c/2R_N \sim$ 15 MeV,
  - k_0, $k_z \lesssim \gamma\, \hbar c/2R_N \sim$ 80 GeV @ LHC



  - Flux drops rapidly with increasing E (and $|q|$)

Z^2 → Z → Z × Proton form factor

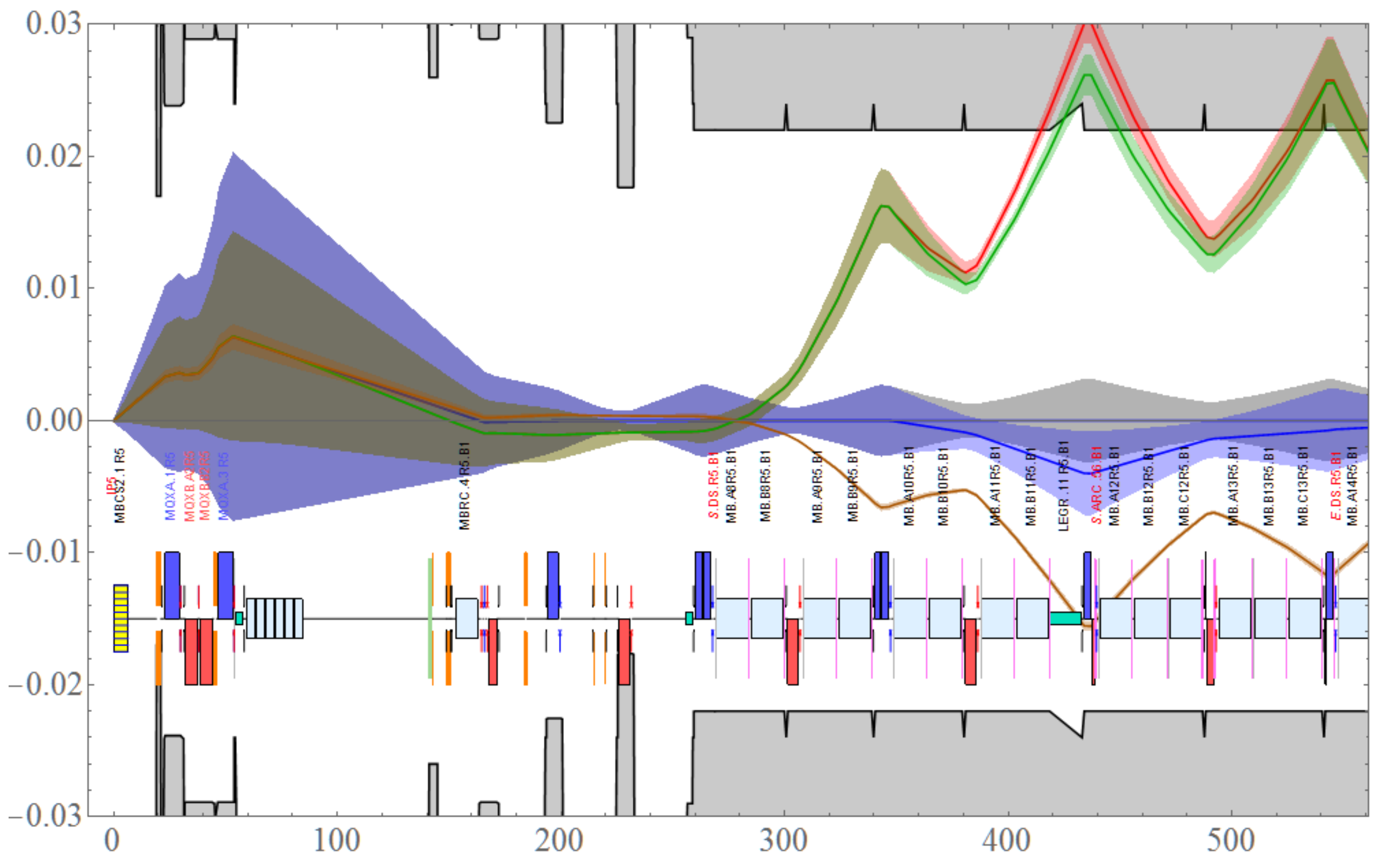


coherent incoherent

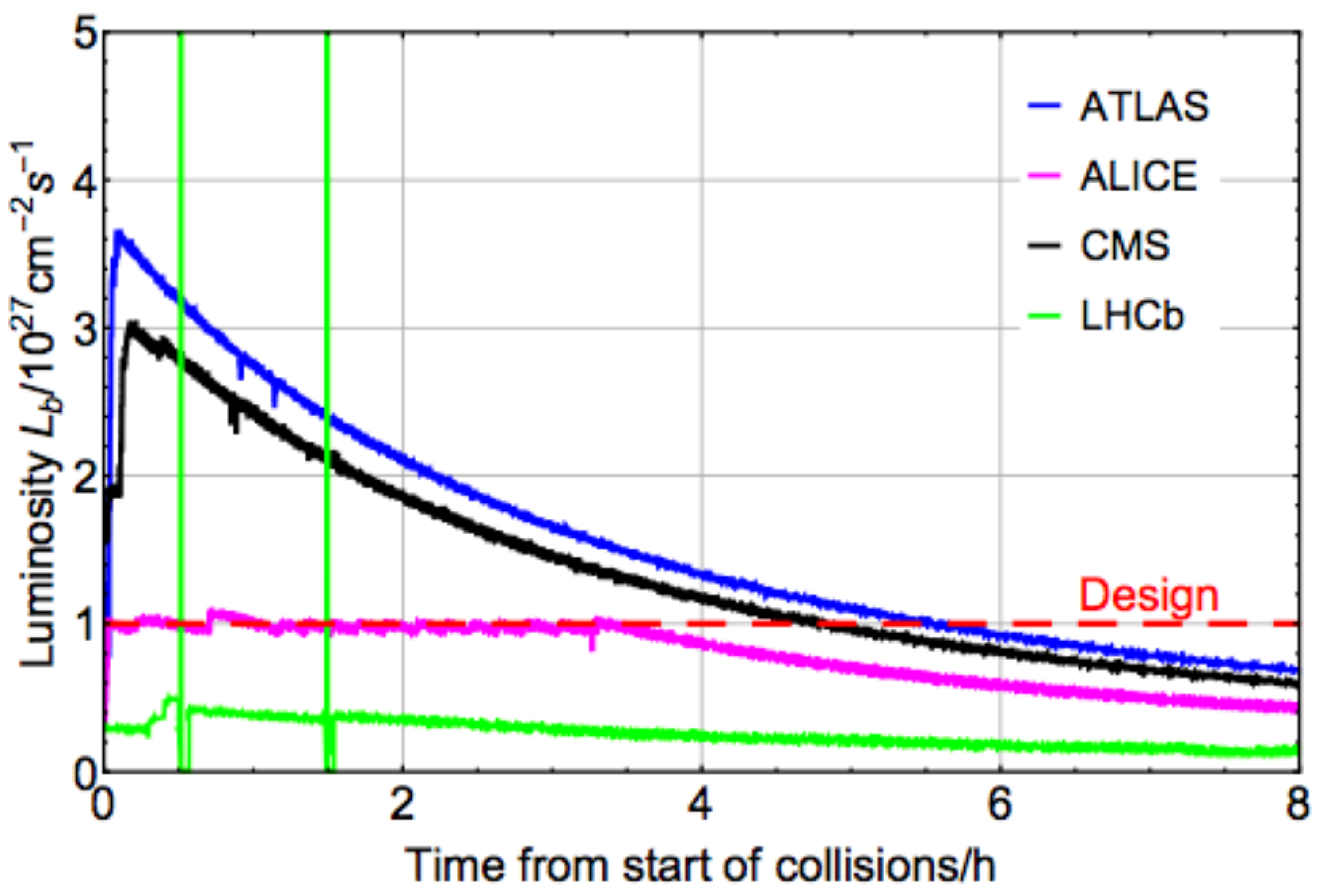
- **Photons are quasi-real, have ~no transverse momentum and can initiate γA or $\gamma\gamma$ collisions at high $\sqrt{s}$**

A pernicious example: bound-free pair production

- $\gamma\gamma \rightarrow e^+e^-$ where electron captured by nuclear Coulomb field
  - $\sigma^{BFPP} \sim Z_1^2\, Z_2^2\, |\psi_2(0)|^2 \sim Z_1^2\, Z_2^2\, (Z_2^{3/2})^2 \sim Z^7 \sim$ 250b @LHC
- In ion colliders results in: $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^+$
- Well-collimated secondary beam (~ 10's of Watts!) can cause magnet quenches, requires orbit bumps
- Huge beam losses results luminosity burn off, short half-life (3 hrs vs 12 hrs for *pp*)

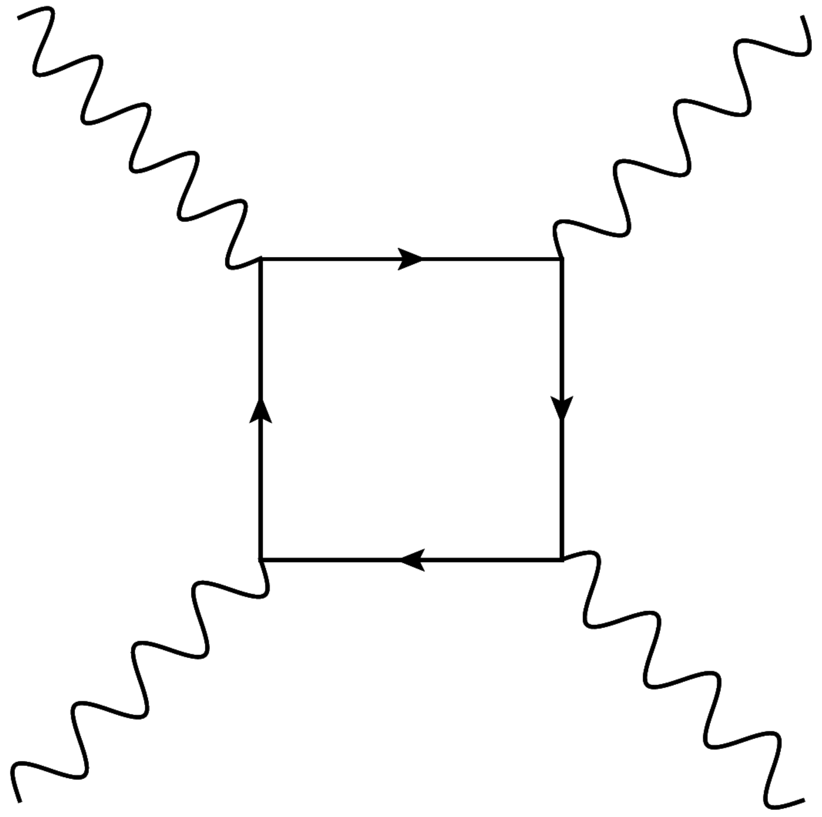


J. Jowett, this conference



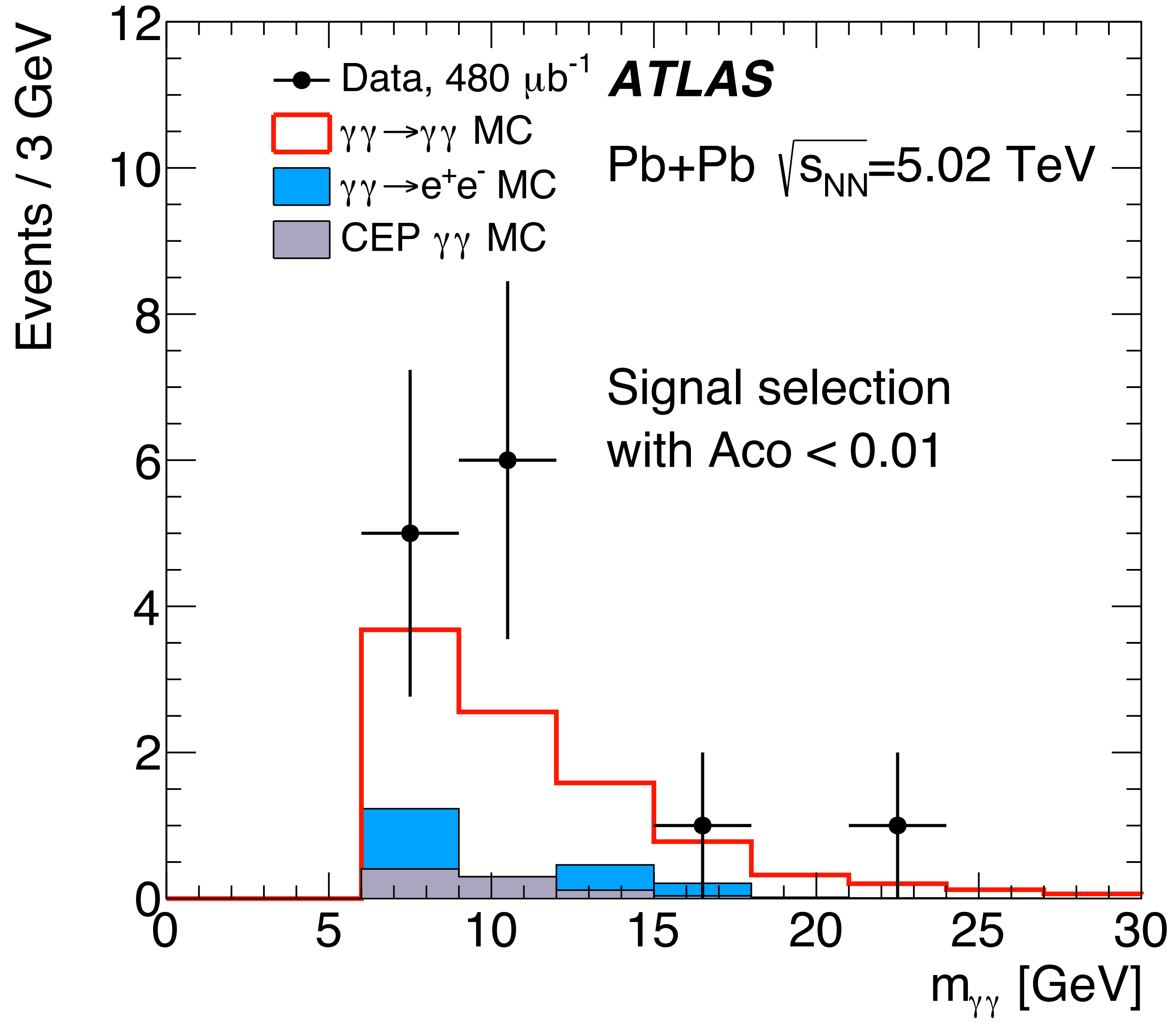
J. Jowett, Proceedings of IPAC2016

An exotic example: light-by-light scattering

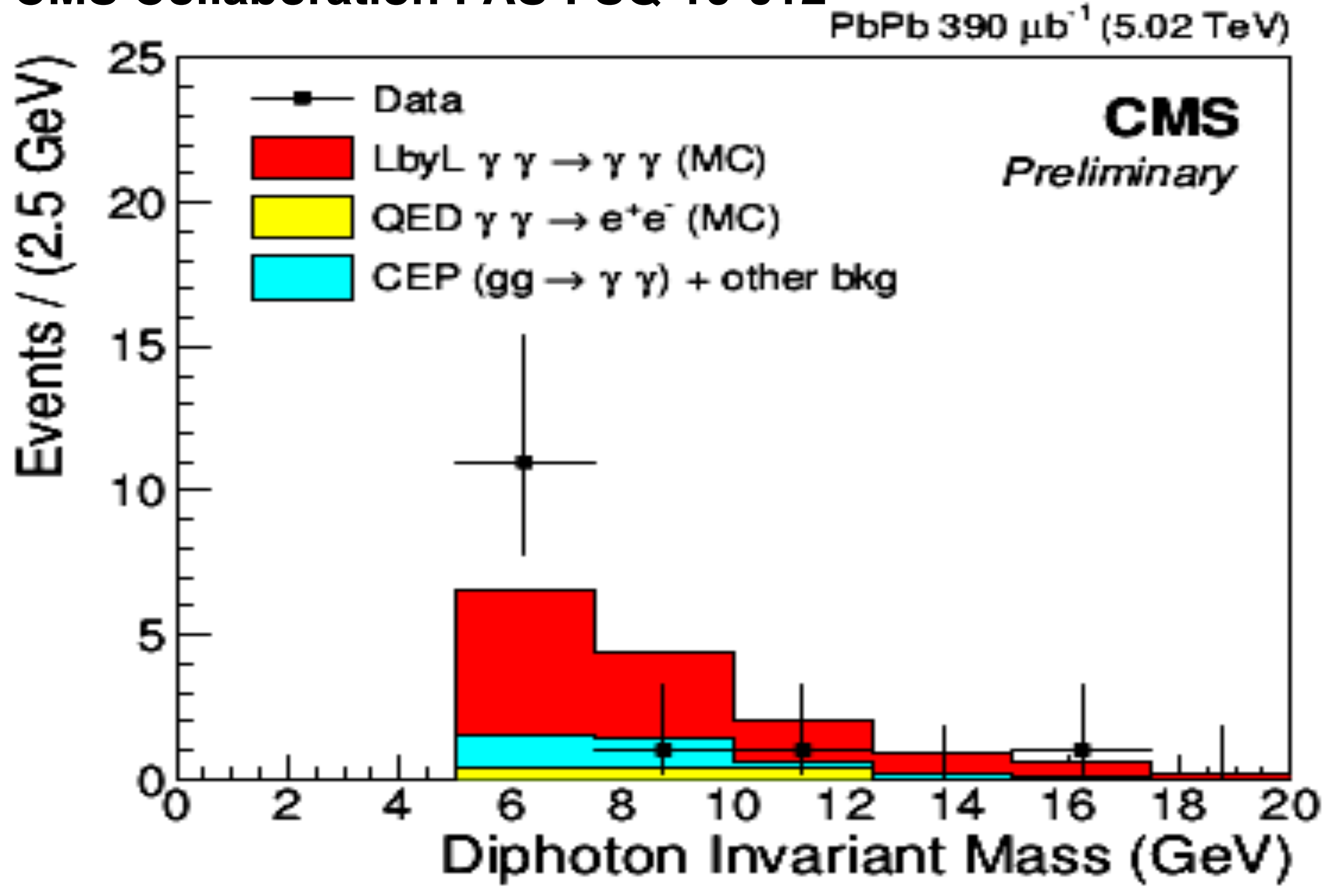


- Forbidden by *classical* EM but elementary consequence of *quantum* electrodynamics
  - Had not been ***directly*** observed previously
- ATLAS and new CMS preliminary results show
  - $> 4\sigma$ significance for signal
  - Fiducial cross sections consistent with SM

ATLAS Collaboration
Nature Phys. 13 (2017) no.9, 852-858



CMS Collaboration PAS-FSQ-16-012



See talk by D. d'Enterria, Wed. 18 May.

Photo-production: a reminder

- Similar to DIS except photon is quasi-real ($Q^2 = 0$)
  - In *nuclear case*, photons also have small transverse momentum ($p_T \lesssim 15$ MeV)
  - To apply pQCD something else must provide hard scale
- Just like in DIS, photon serves as "well-calibrated" probe to study structure of nucleon/ nuclear target
  - Measurements have straightforward interpretation and provide direct access nuclear parton densities
- Contrast with hadronic collisions: *pp*, *p*A & AA
  - Forced to simultaneously understand dynamics of "target" and "probe"

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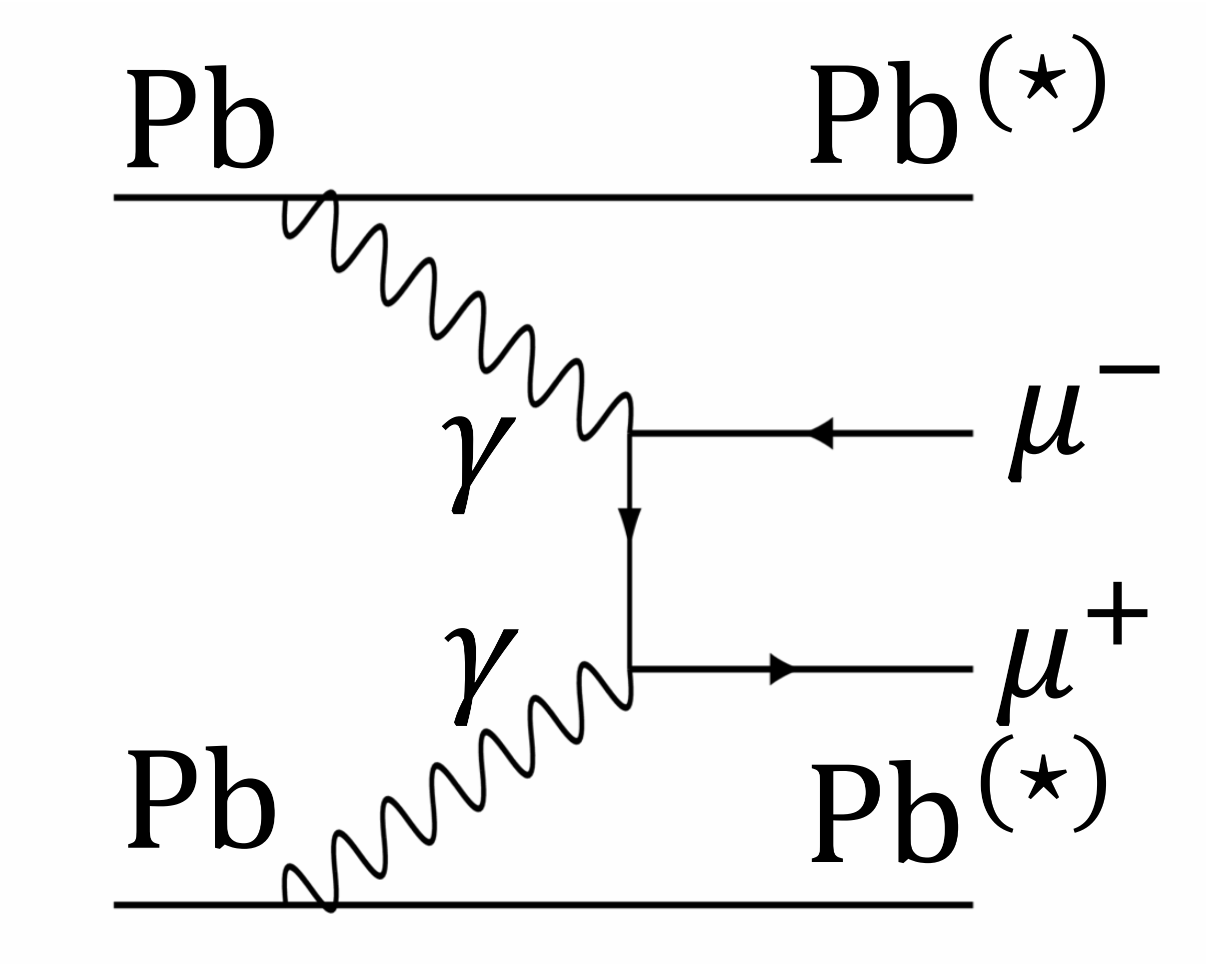
➡ Studies of photo-production using UPCs provide an immediate opportunity to study questions addressed by future EIC program
  - Quantifying and hopefully describing nPDF modifications
  - Prevalence of saturated matter at small *x* with universal features

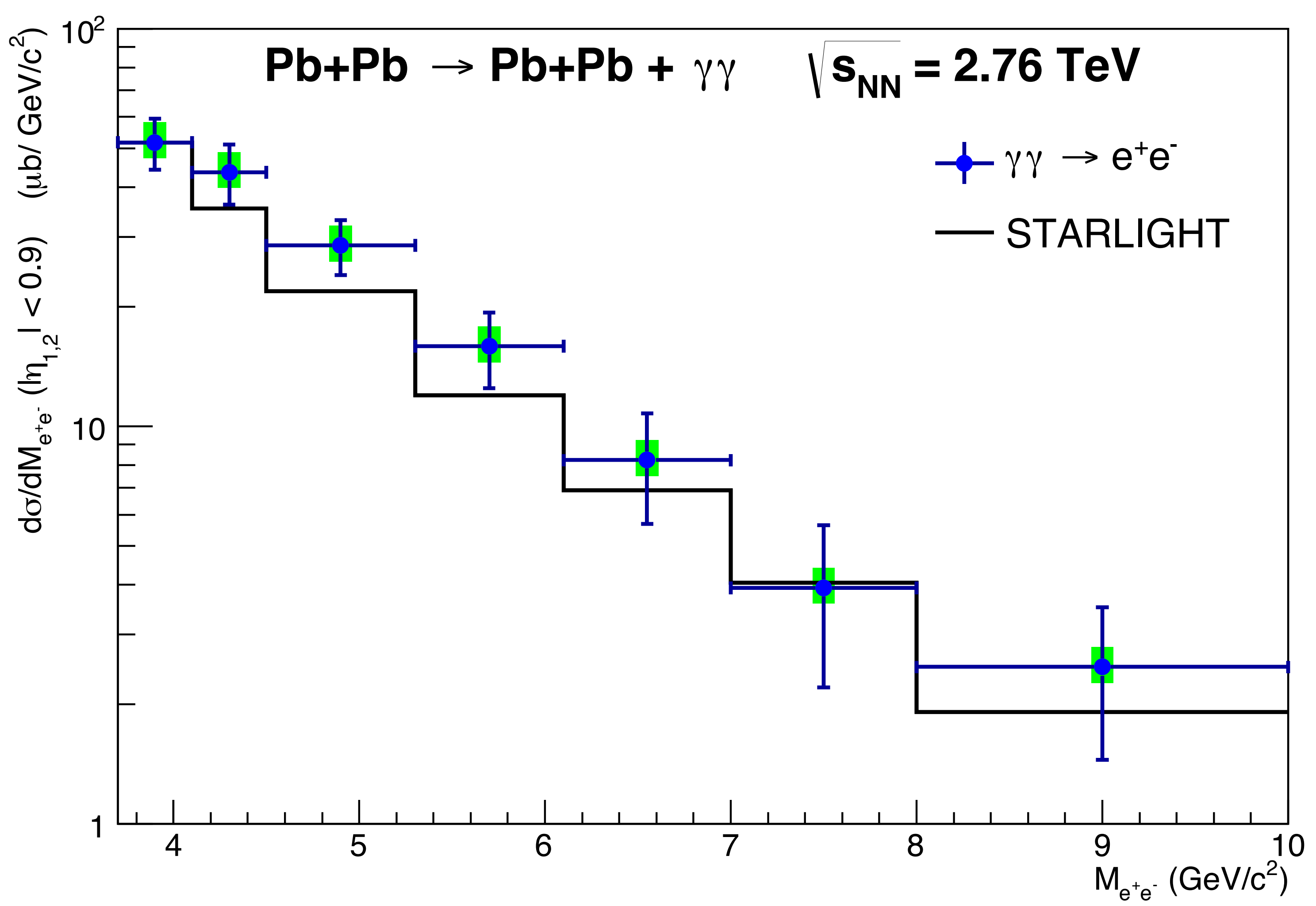
Calibrating the “probe”: exclusive dilepton production



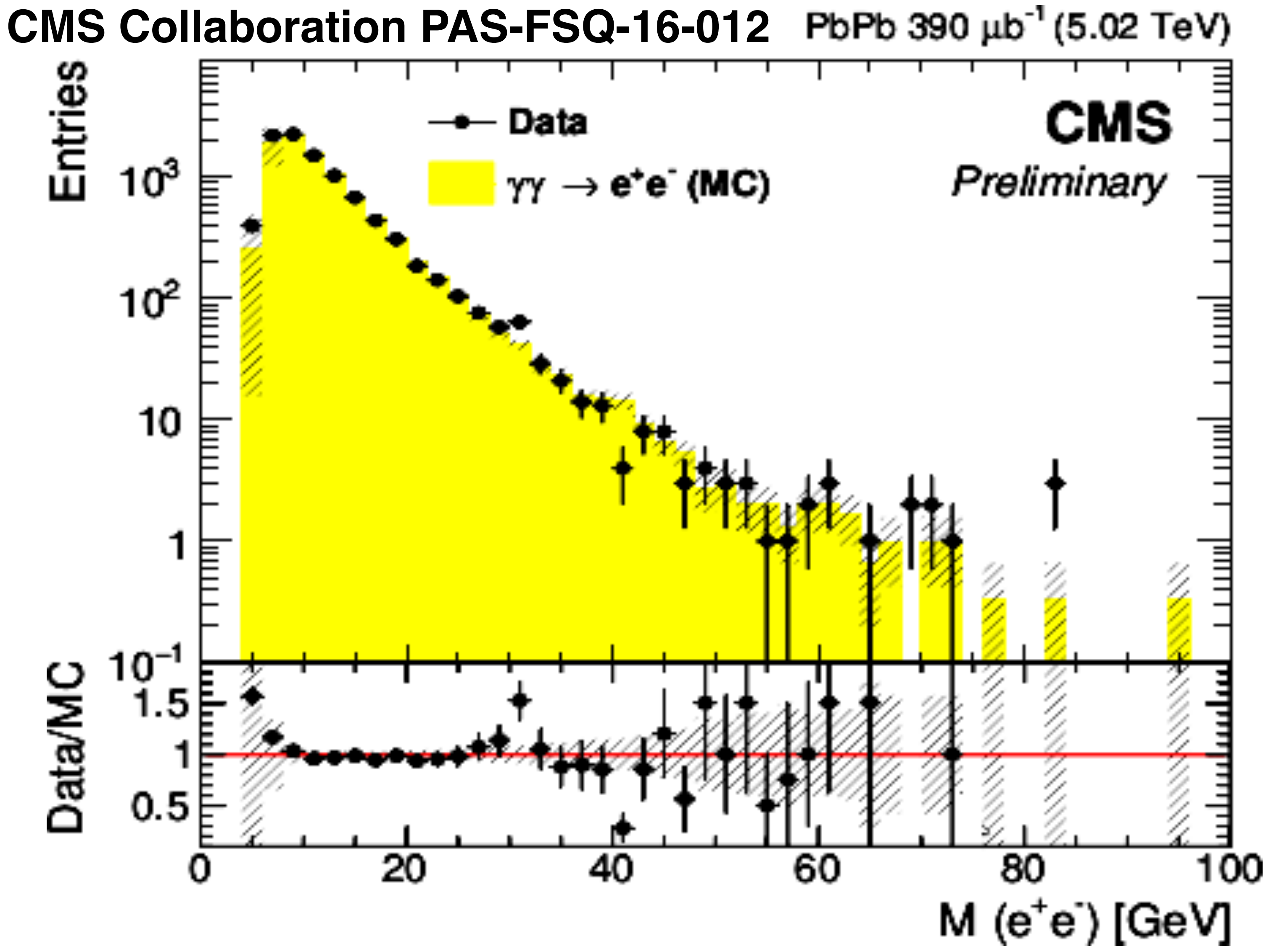
- Another basic QED process
- Cross section measurement can validate EPA approach and evaluation of nuclear photon fluxes
- Exclusive process, clean final state

Calibrating the “probe”: exclusive dilepton production

ALICE Collaboration, Eur. Phys. J. C 73 (2013) 2617



CMS Collaboration PAS-FSQ-16-012



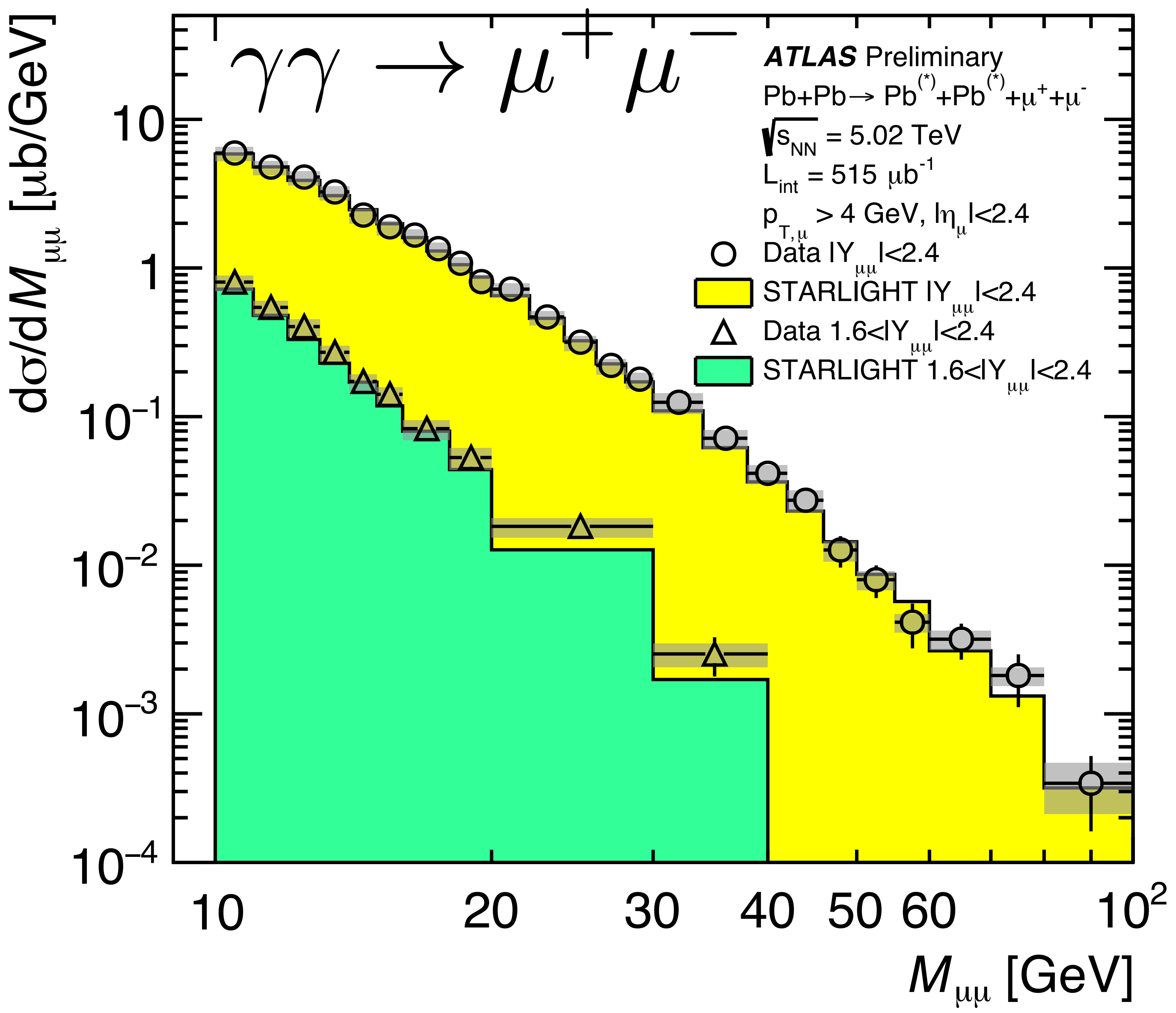
$\gamma\gamma \to e^+e^-$

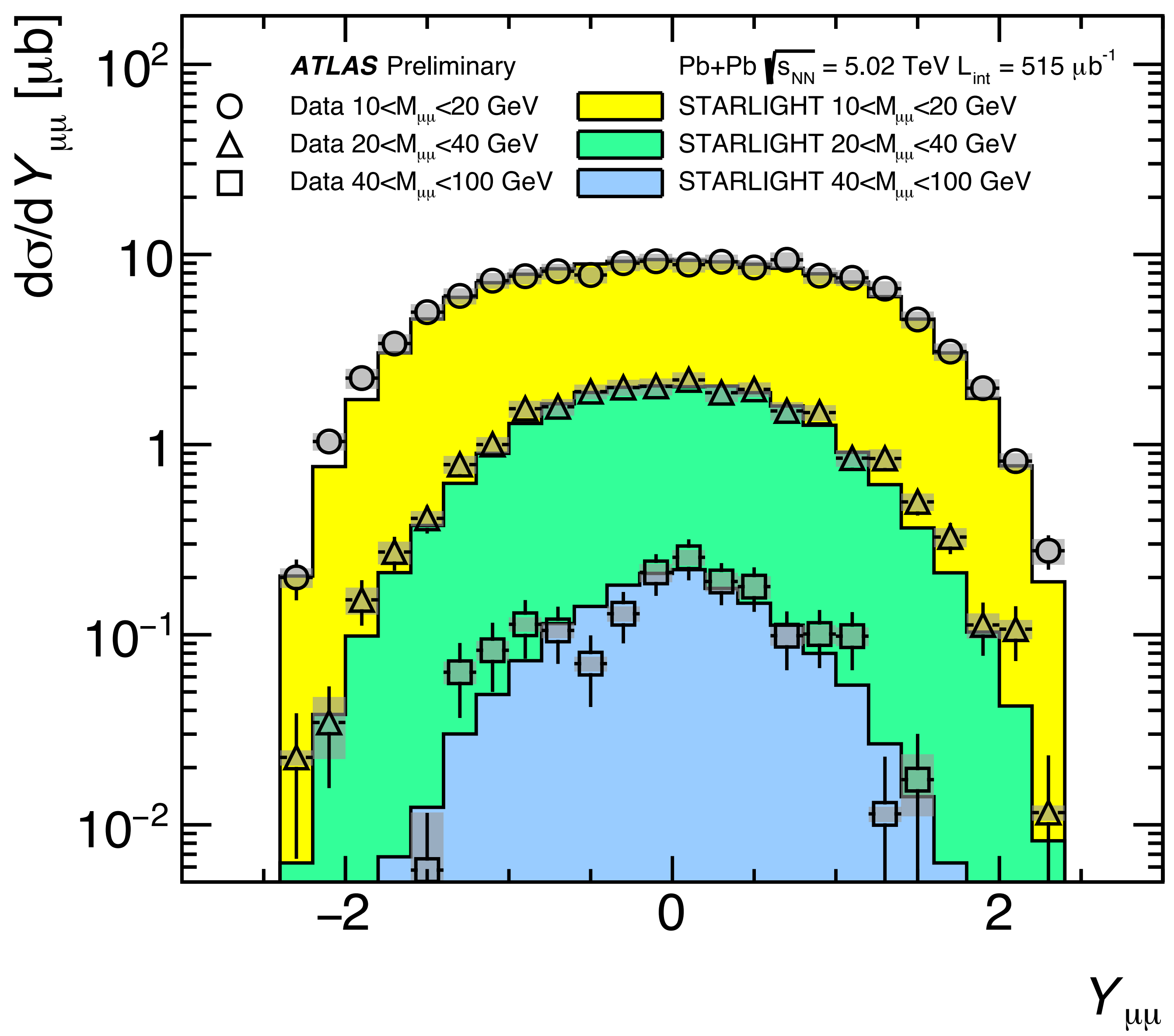
- Backgrounds to other measurements (quarkonia, light-by-light)

- Kinematic distributions and overall rates well described by STARlight generator

S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comp. Phys. Comm. 212 (2017) 258.

ATLAS-CONF-2016-025



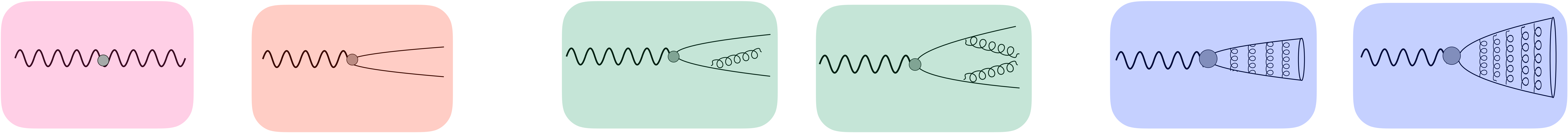


Calibrating the “probe”: critical details

- Photon has significant hadronic component
- **Need to understand hadronic/partonic structure of photon or we are stuck in same situation as in hadronic collisions**

  - **Partonic structure influences interpretation of hard processes**
  - **Soft structure leads to nucleon shadowing**

$$|\gamma\rangle \equiv \sqrt{Z}\,|\gamma\rangle_{\mathrm{direct}} + \sum_{\ell=e,\,\mu,\,\tau} \frac{e}{f_{\ell\ell}}\,|\ell^+\ell^-\rangle + \sum_q \frac{e}{f_{q\bar{q}}}\,|q\bar{q}\rangle + \cdots + \sum_V \frac{e}{f_V}\,|V\rangle$$



Point-like photon

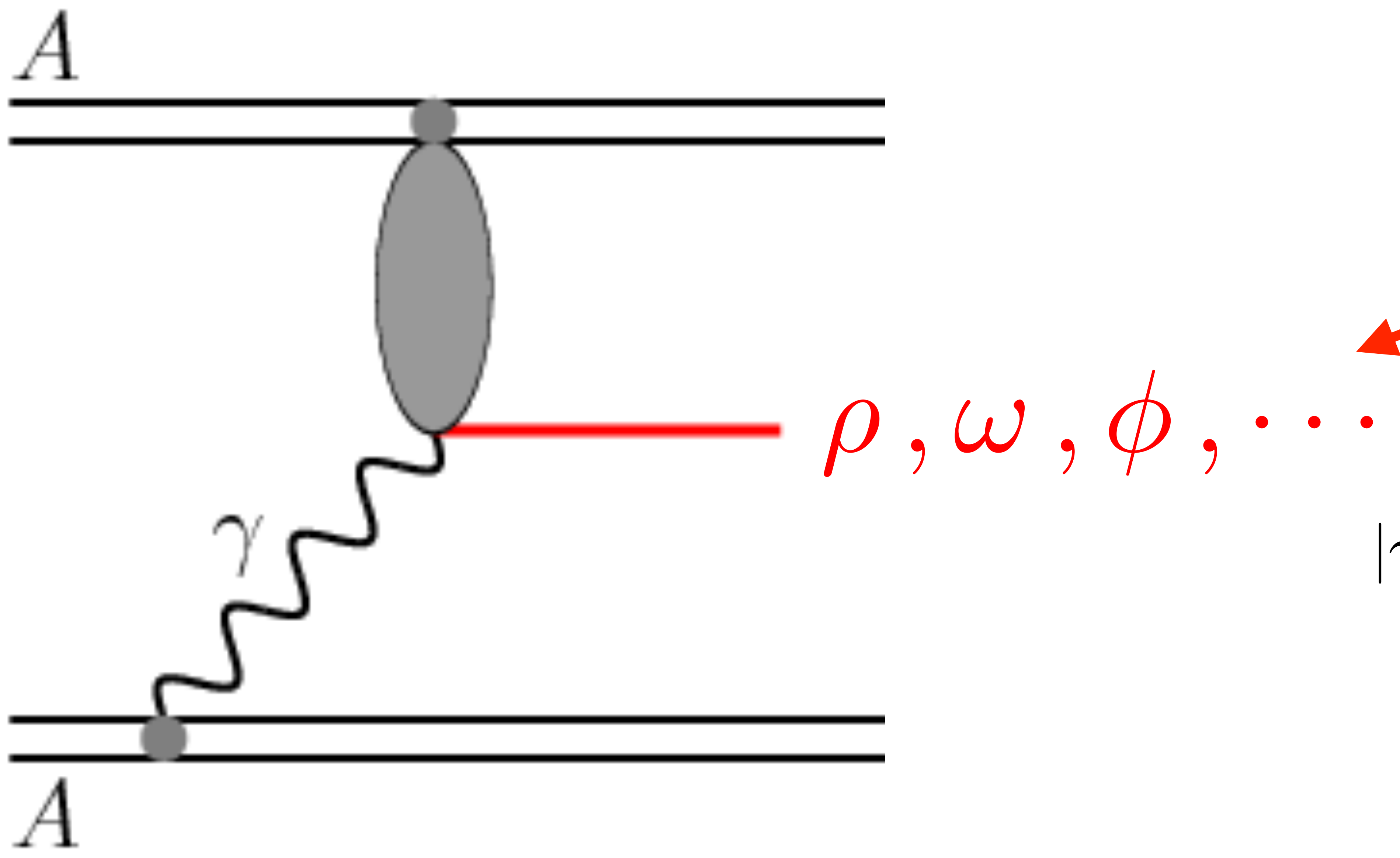
Dipole

Multi-parton configurations

Vector mesons

Increasing size/interaction strength →

Photo-production: exclusive vector mesons



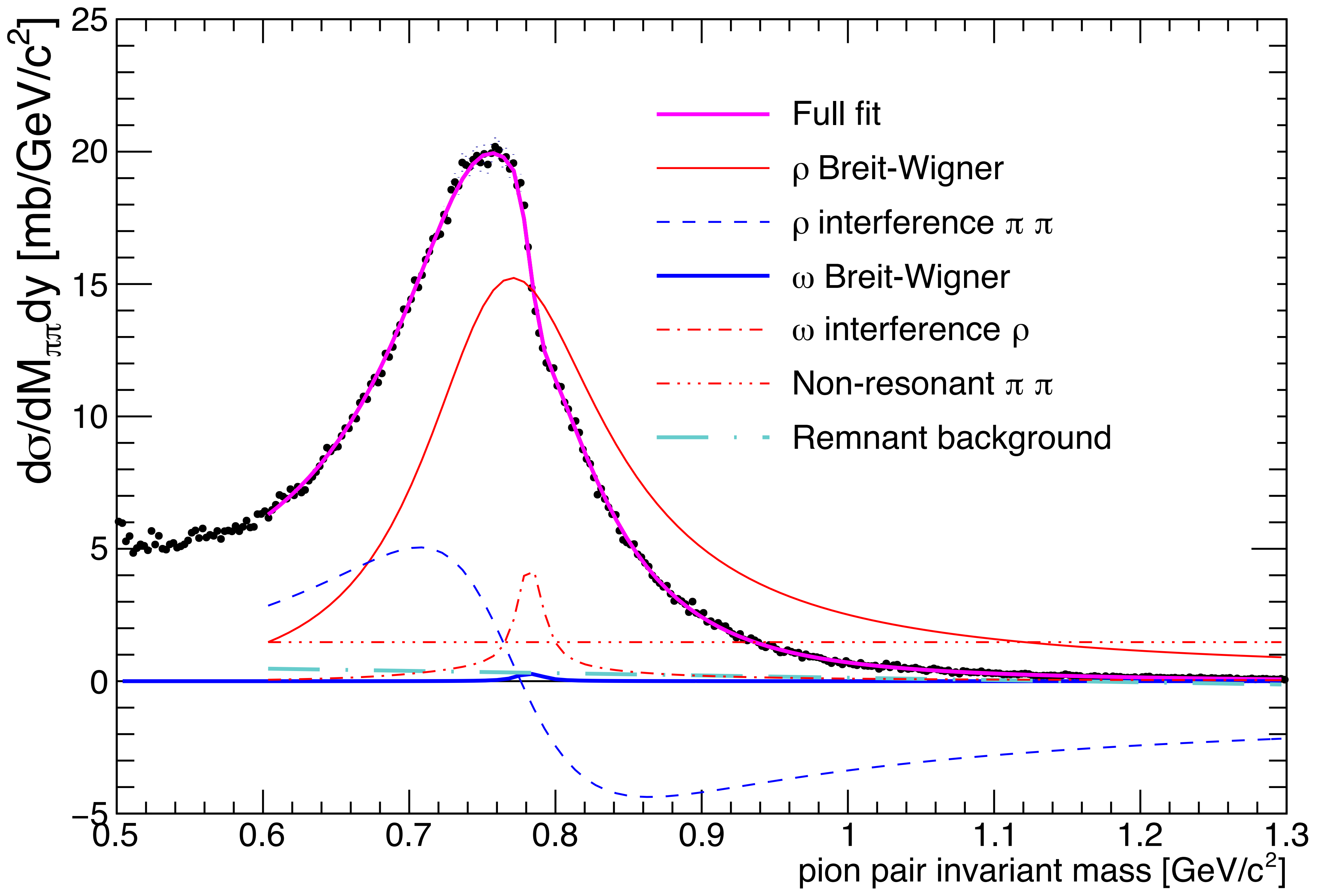
VMs picked out by colorless scattering with target, produced diffractively

$$|\gamma\rangle = \sqrt{Z}\,|\gamma\rangle_{\text{bare}} + \sum_{\ell} \frac{e}{f_{\ell\ell}}\,|\ell^+\ell^-\rangle + \sum_{V} \frac{e}{f_V}\,|V\rangle + \sum_{q} \frac{e}{f_{q\bar{q}}}\,|q\bar{q}\rangle + \cdots$$

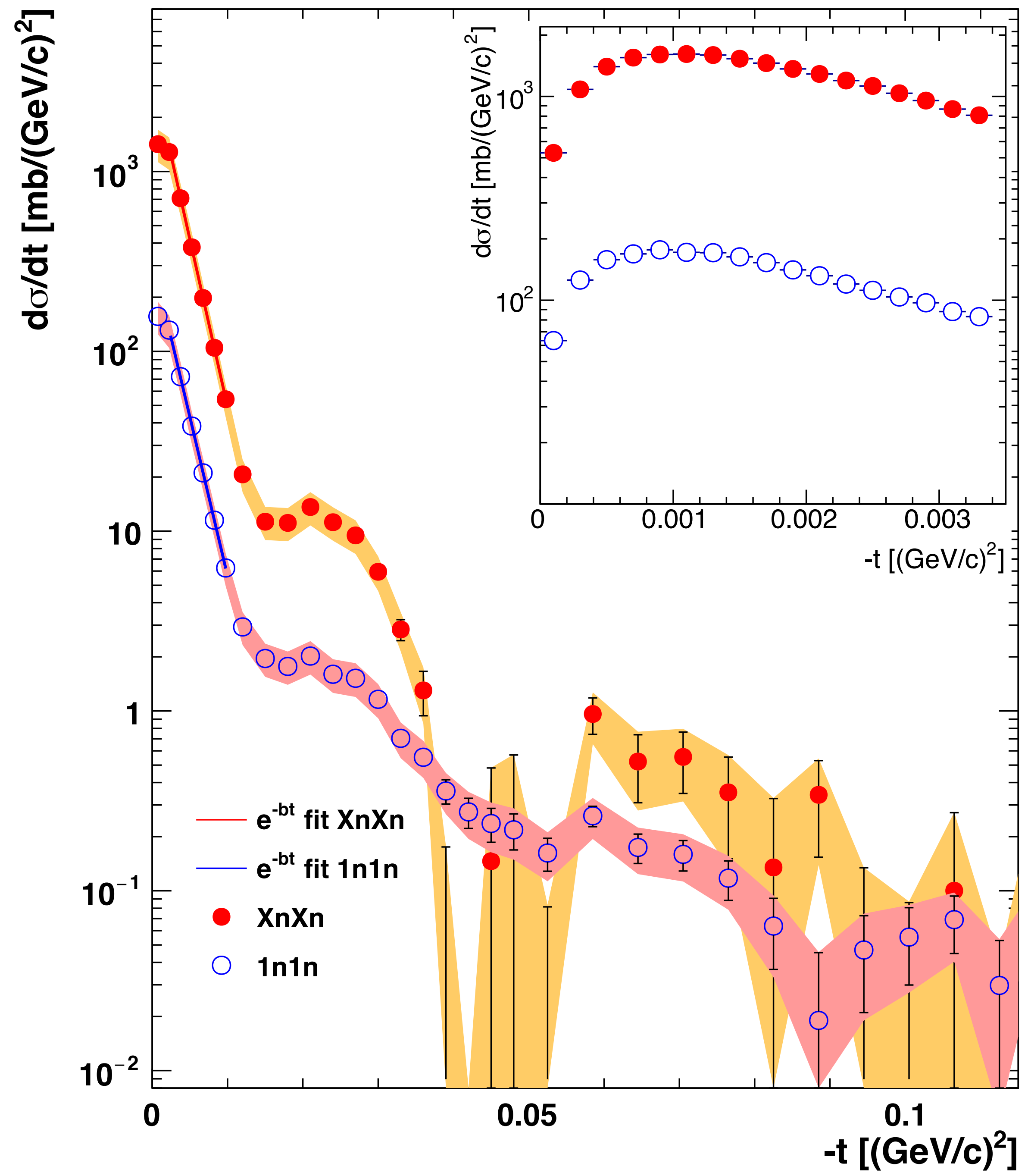
- Coherent production: Target remains intact
  - No forward neutrons
  - Colorless exchange couples to entire nucleus
    - Restricted to small momentum transfers
    - Diffraction pattern determined by nuclear size
- Incoherent production: Target breaks up
  - Colorless exchange can couple to single nucleons
    - Diffraction pattern determined by nucleon size

Note here "coherent" refers to the target, you can still have photons emitted incoherently by the projectile interact coherently with the target

Exclusive ρ production



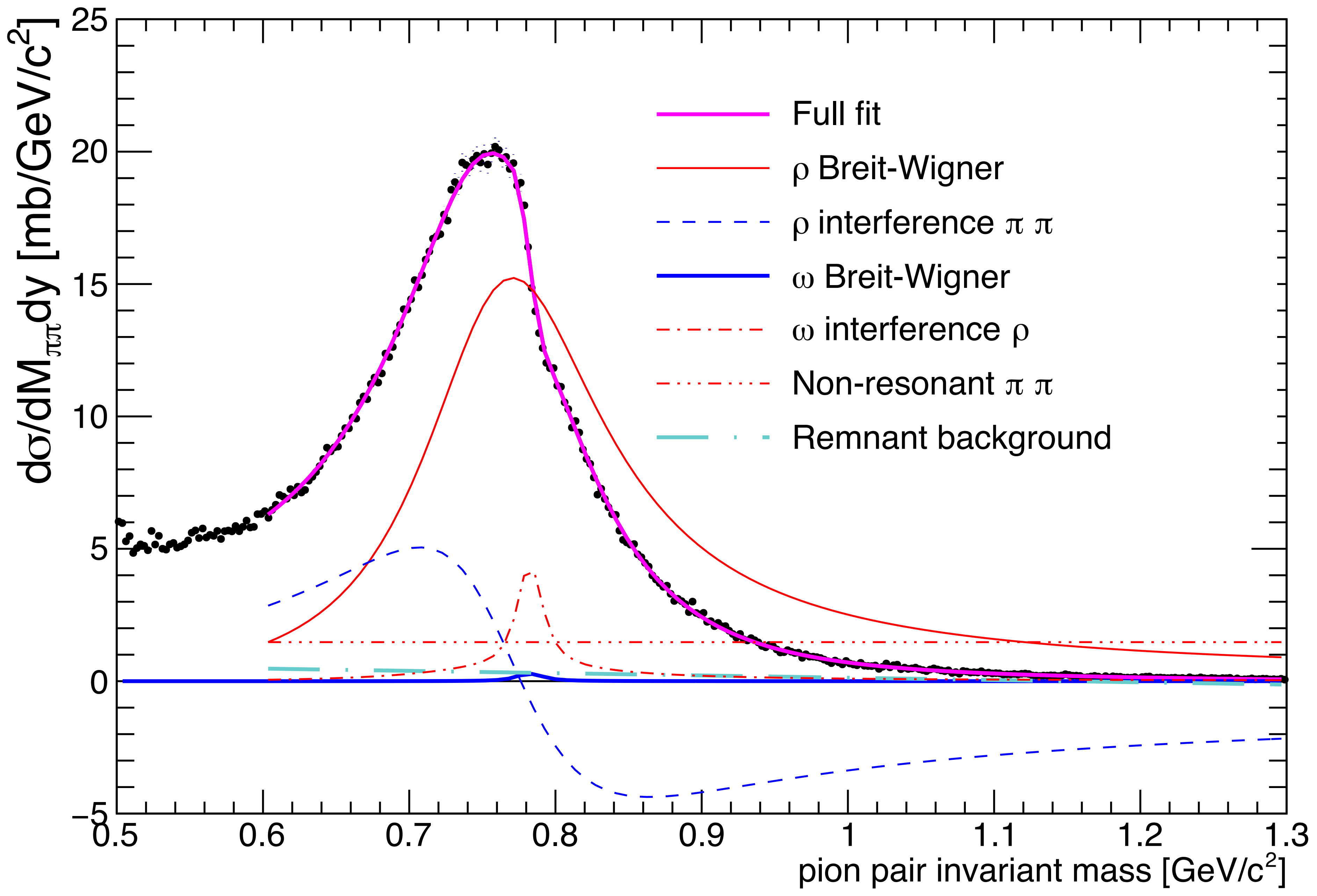
<u>STAR</u>: Careful fitting of ρ mass peak including nominal ρ, ω, non-resonant $\pi^+\pi^-$ and their interferences (dashed)



Diffraction pattern is determined by nuclear size

<u>STAR Collaboration Phys.Rev. C96 (2017) no.5, 054904</u>

Exclusive ρ production



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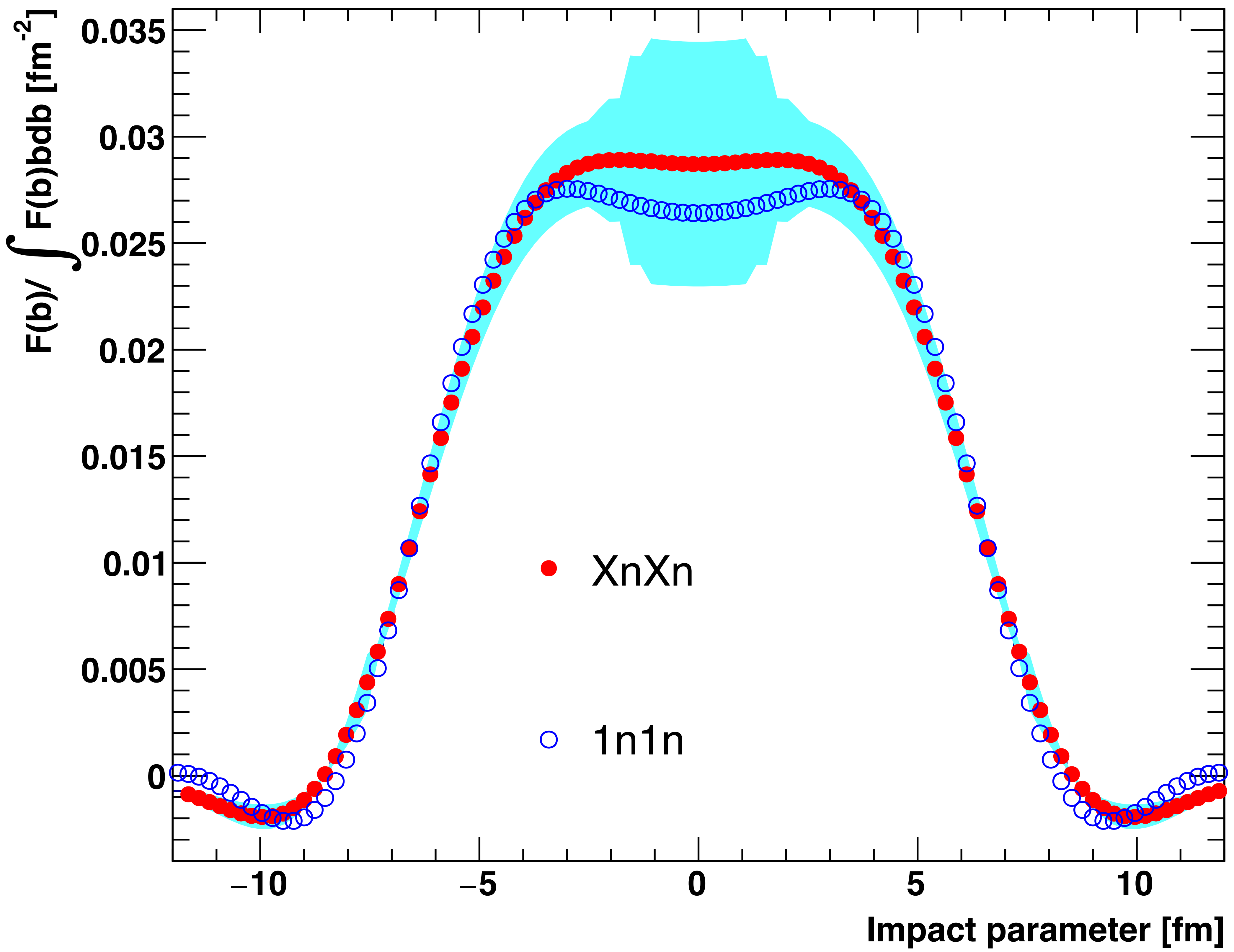
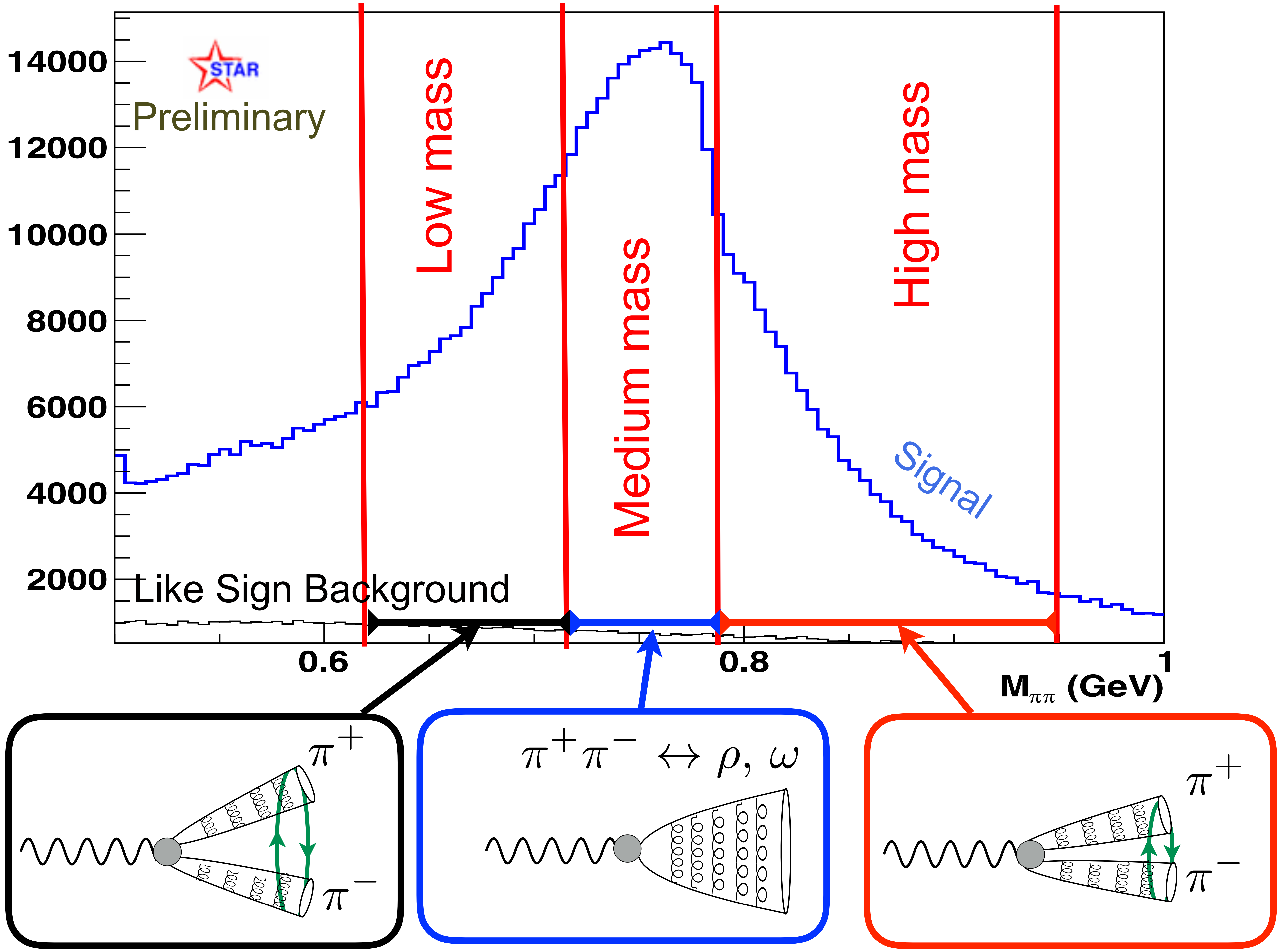


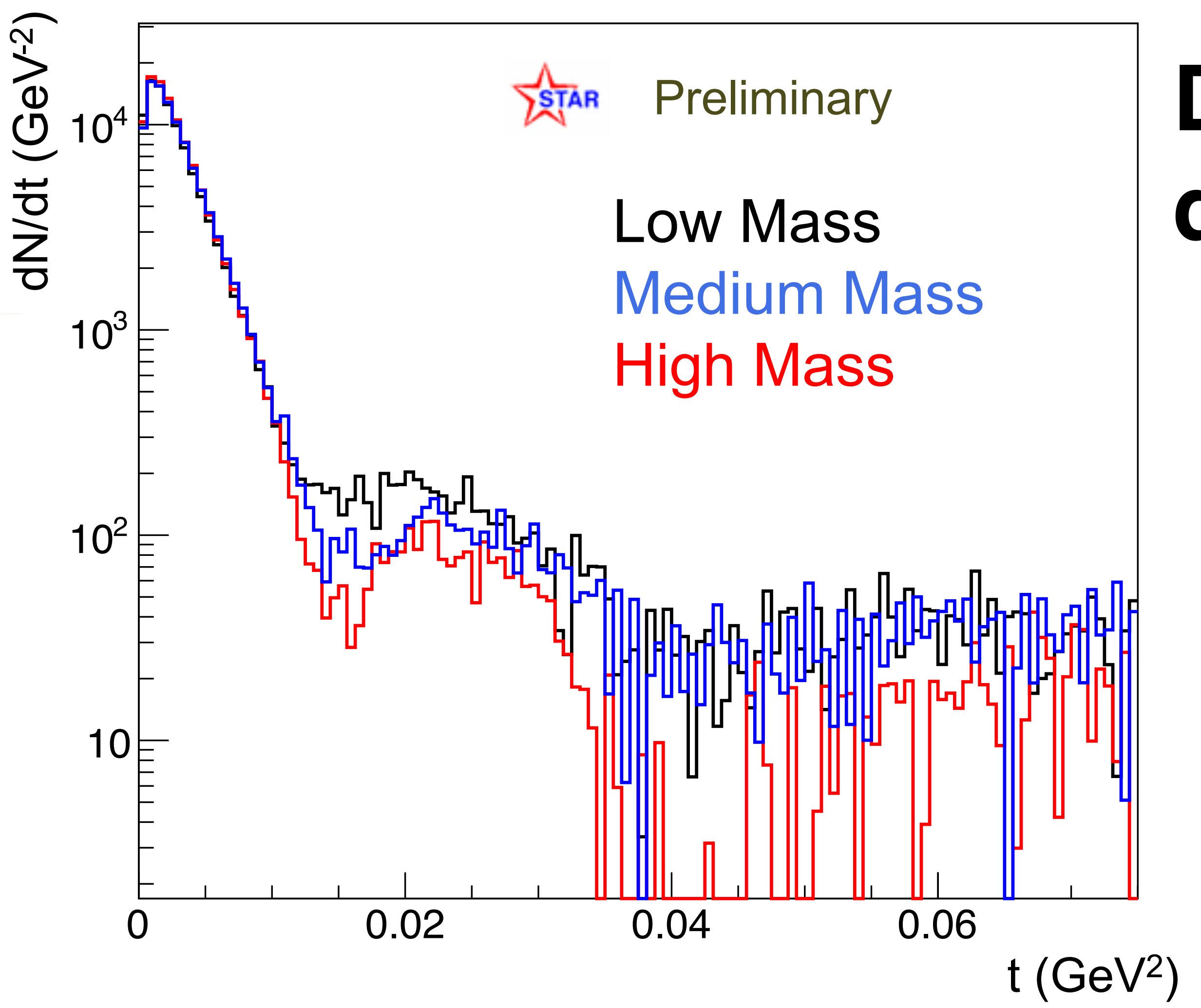
$$F(b) \propto \frac{1}{2\pi} \int_0^\infty \mathrm{d}p_T \, p_T J_0(bp_T) \sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

STAR Collaboration Phys.Rev. C96 (2017) no.5, 054904

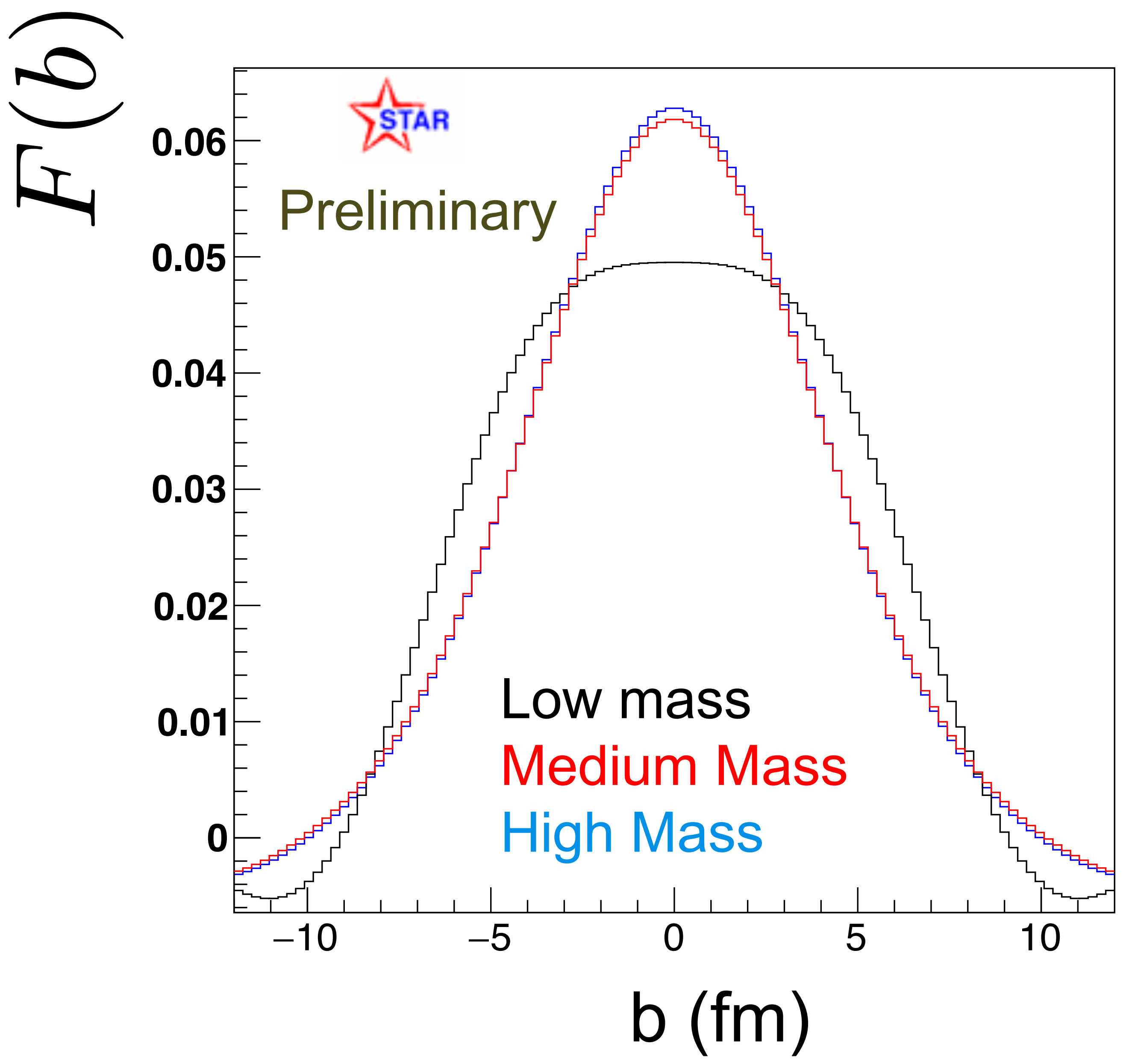
Exclusive di-pion production



S. Klein talk at DIS 2018



Diffraction pattern depends on di-pion mass



Smaller mass di-pion has "larger" size

More likely to be absorbed by target

Less likely to "see" center of nucleus

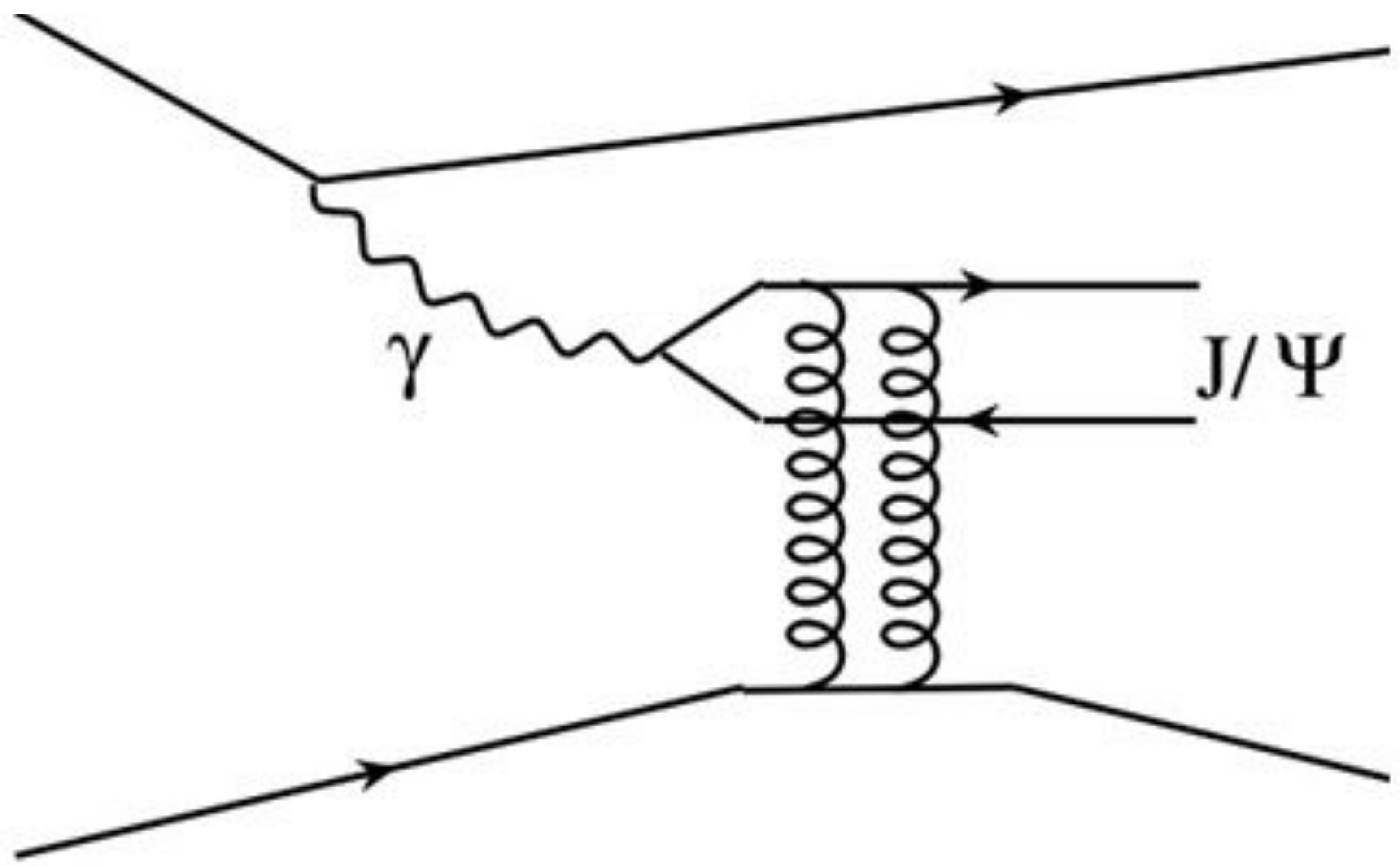
Nucleon shadowing!

What about quarkonia?

- J/ψ mass provides hard scale, apply pQCD to problem.
  - Leading contribution requires two gluon exchange
  - Sensitive to target gluon distribution ***squared***

$$\frac{\mathrm{d}\sigma^{\gamma^{\star}\mathrm{A}\rightarrow J/\psi\,\mathrm{A}}}{\mathrm{d}t} \propto \left(xG_{\mathrm{A}}(x,Q^2)\right)^2$$

- Multiple (related) theoretical approaches
  - pQCD w/ 2 gluon exchange + LT shadowing corrections
  - Dipole amplitude from saturation picture
  - Light-front holography
- How under control are either of these theoretically?
  - NLO corrections, skewness, VM wavefunction
- Open question of if/how this should be used in global NPDF fits



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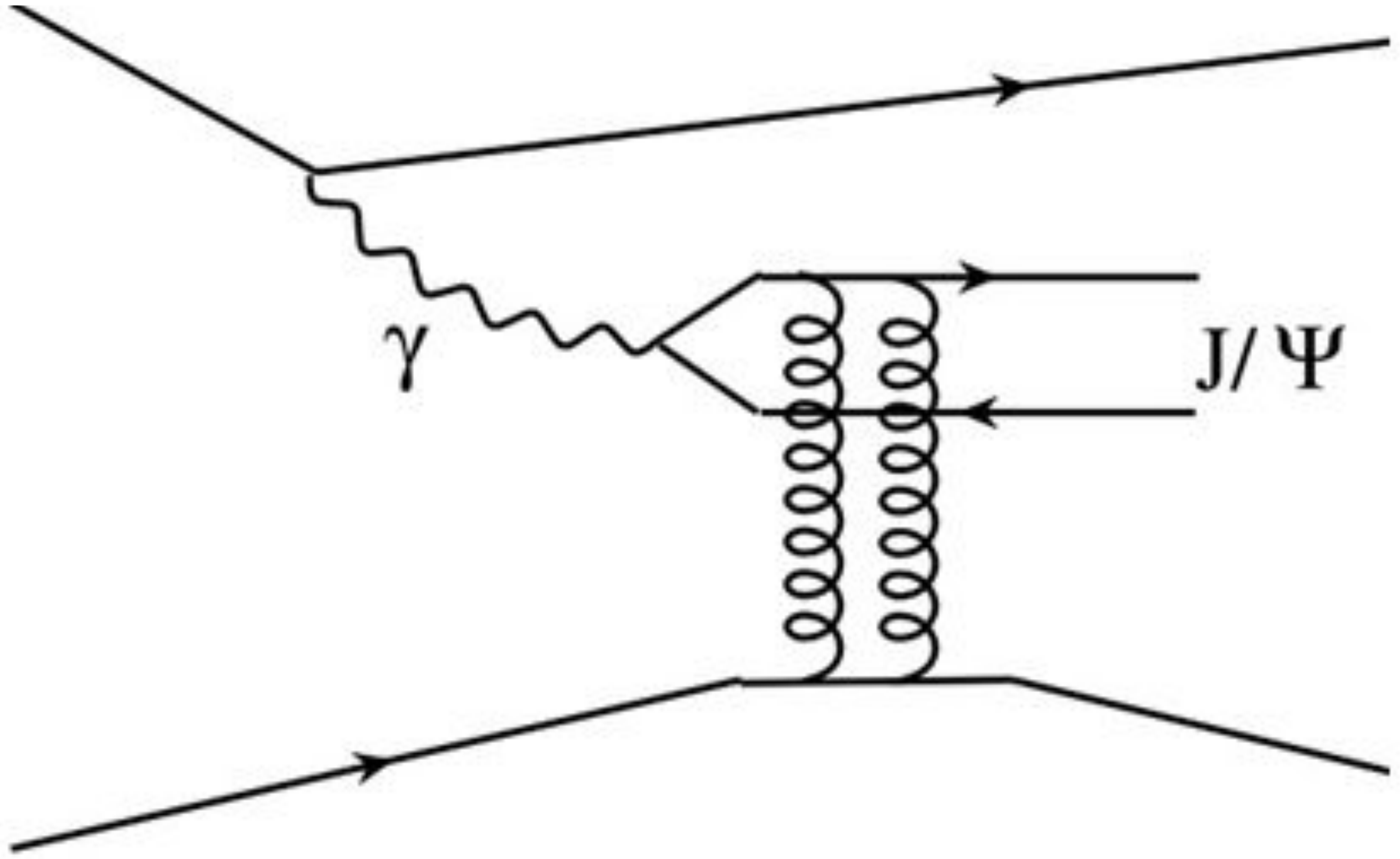
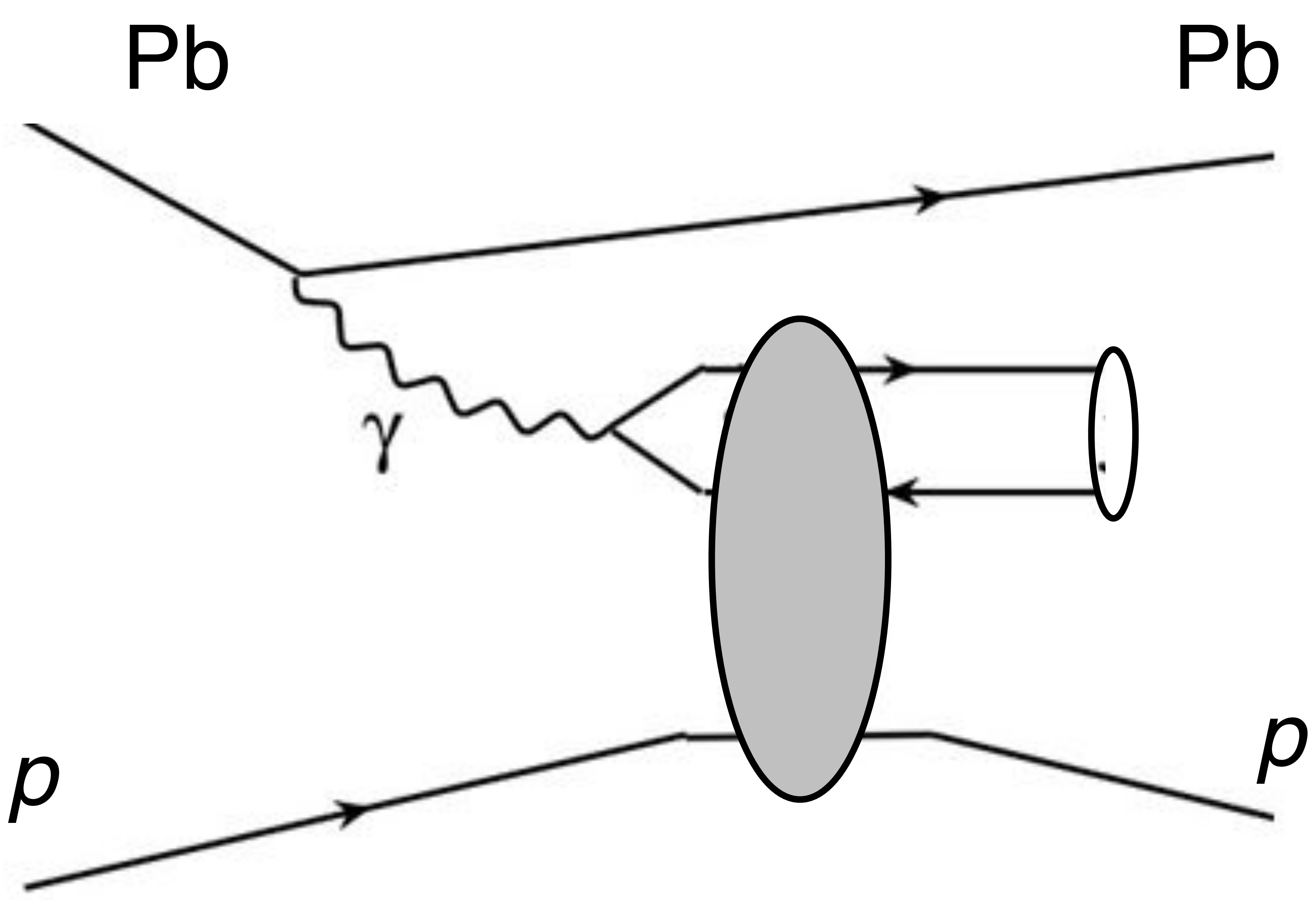


- How under control are either of these theoretically?
  - NLO corrections, skewness, VM wavefunction
- Open question of if/how this should be used in global NPDF fits
- Both photo- and electro-production of *J/ψ* are potentially powerful tools that can be used at the EIC. What can we learn from current data to improve their future utility?

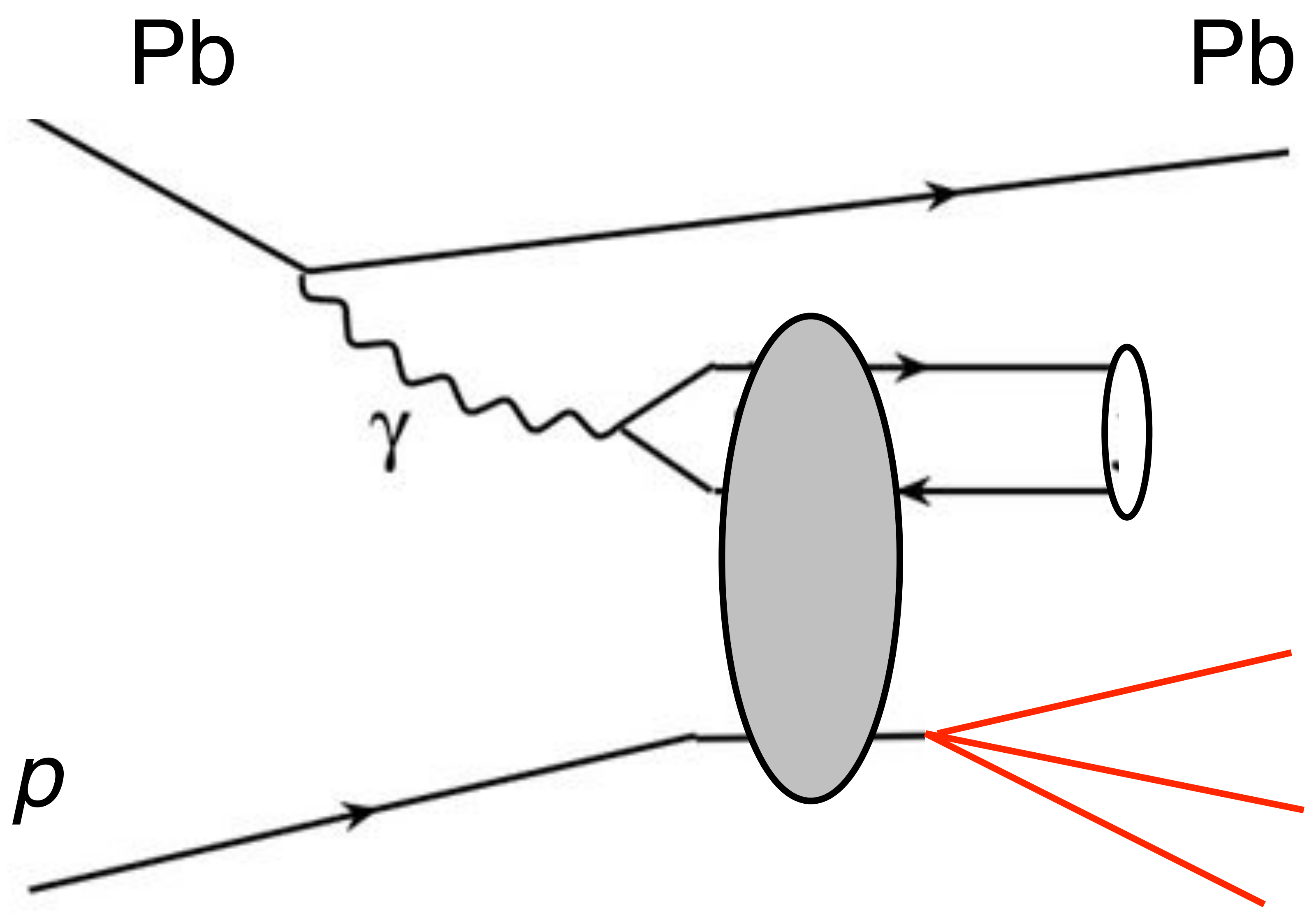
Quarkonia: baseline from *p*+Pb

- In *p*+Pb collisions nucleus is usually photon emitter and the proton is the "target"
  - Photo-production in *p*+Pb ⇔ γp collisions

"elastic": proton remains intact



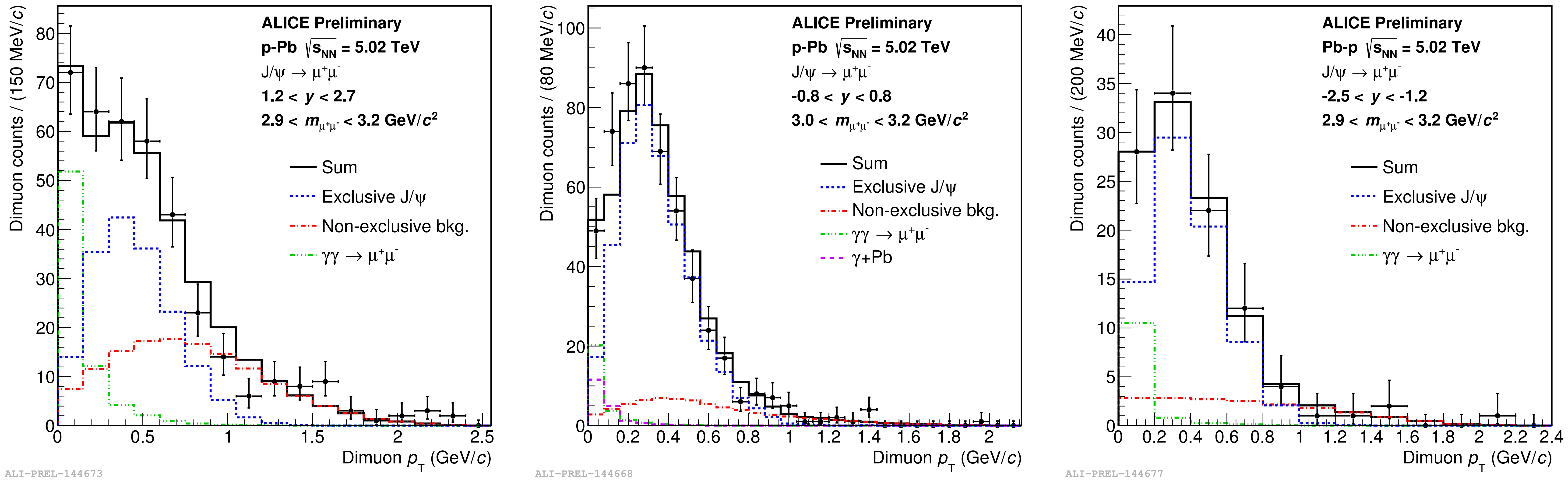
"dissociative": proton destroyed

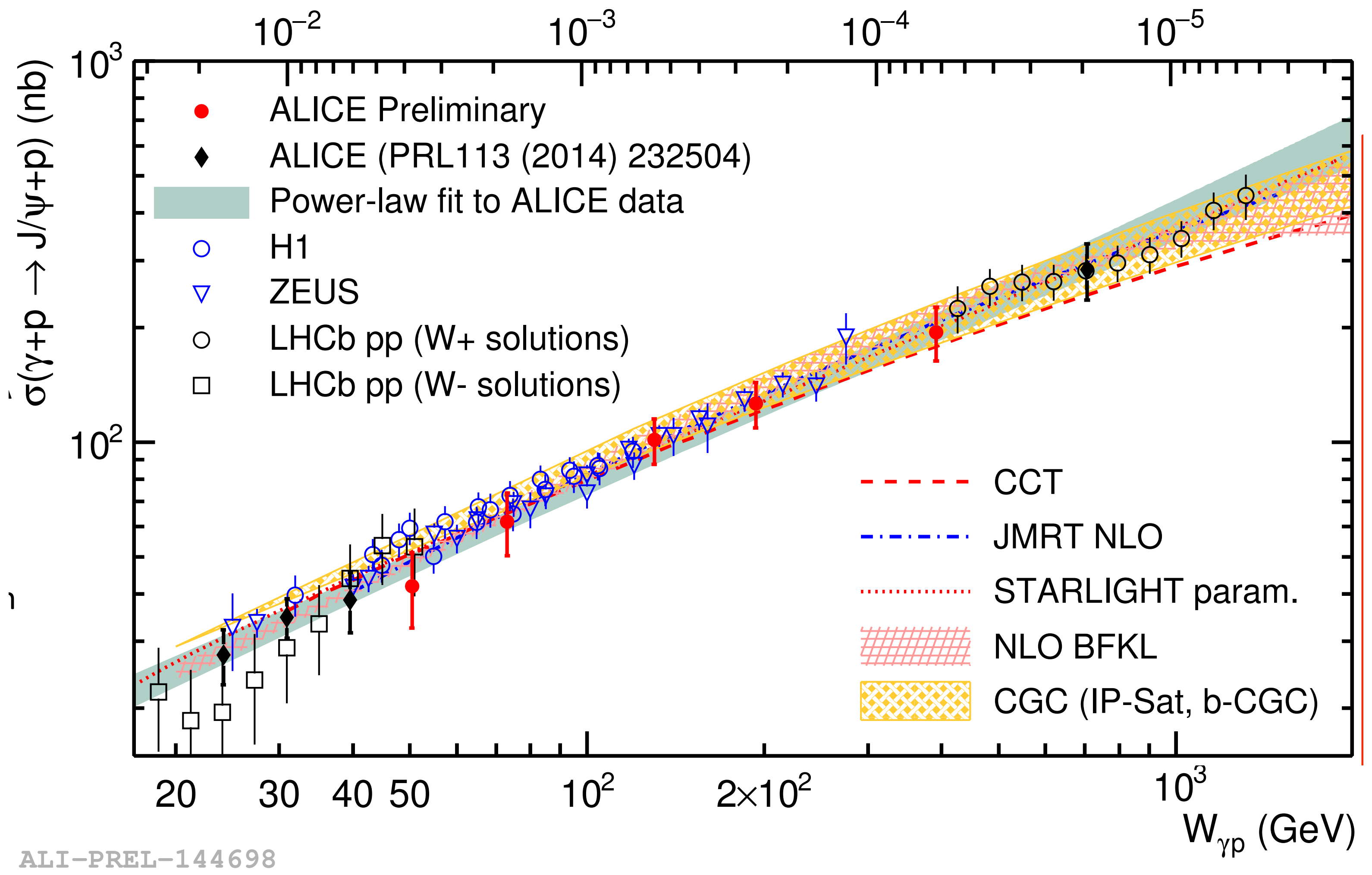


ALICE results on *J/ψ* photo-production in *p*+Pb

Increasing *Wγp* →

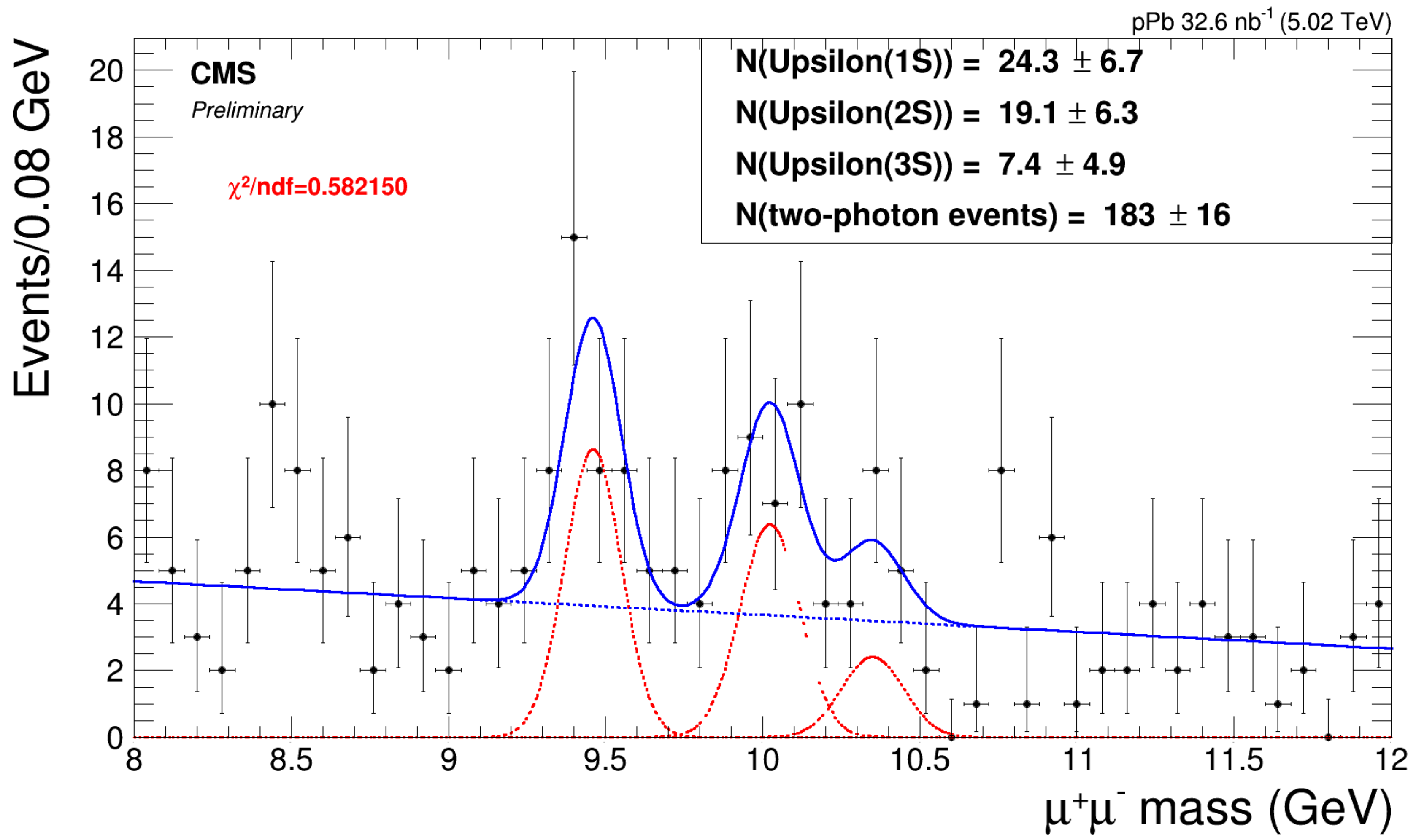
See talk by C. Mayer Mon. 14 May





Dissociative increasing more slowly than elastic, consistent with HERA

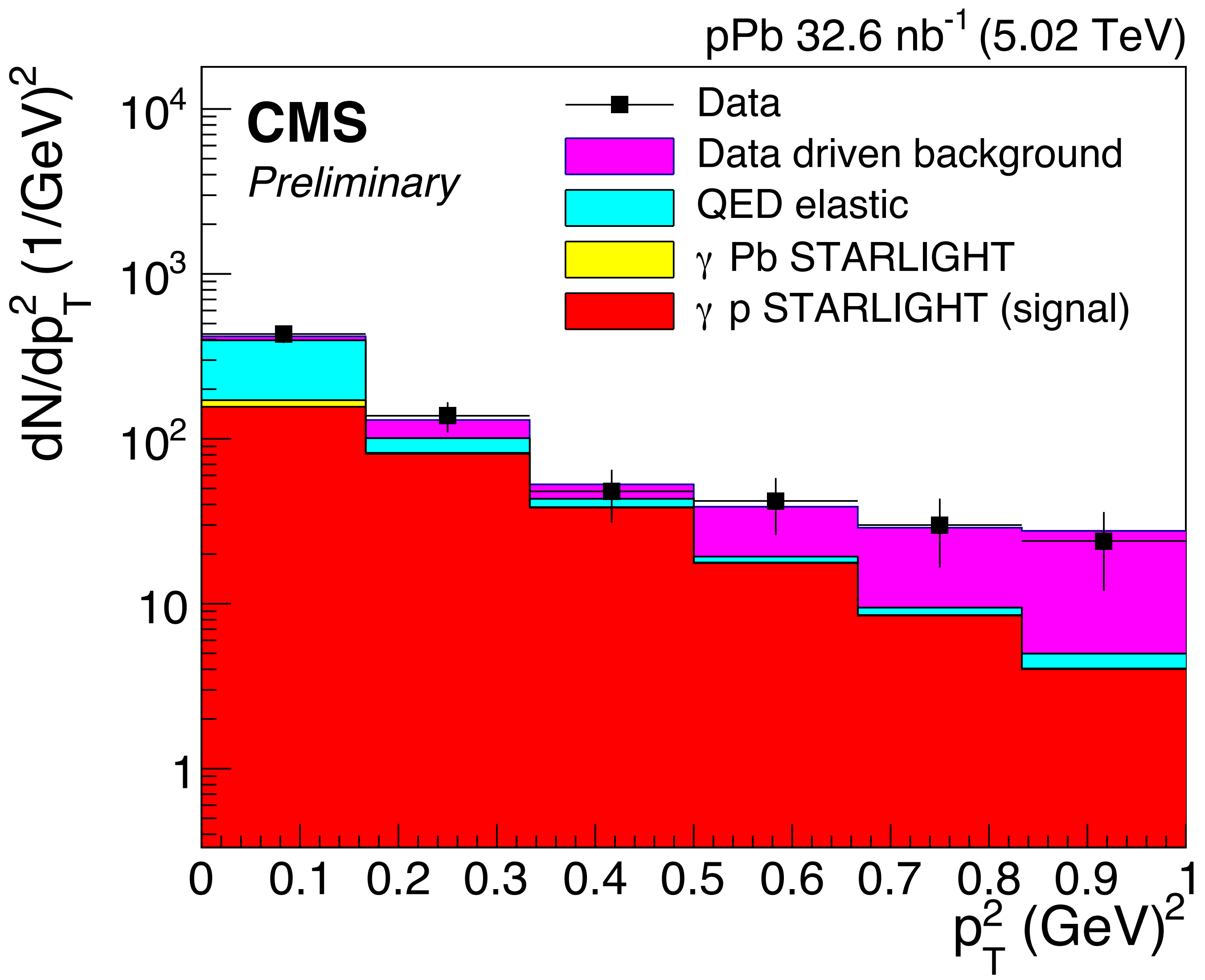
CMS results on Υ photo-production in p+Pb

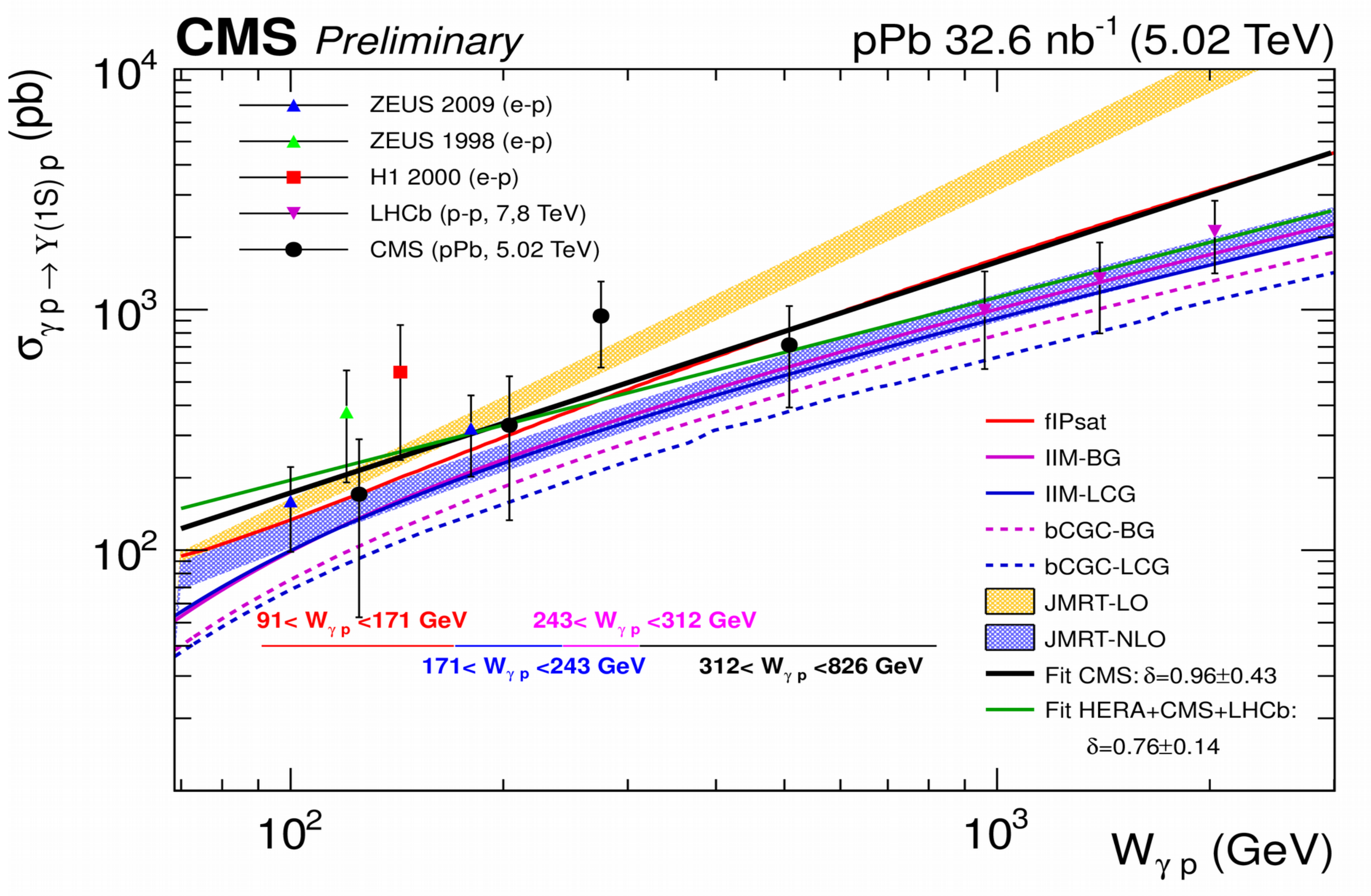


CMS-FSQ-13-009

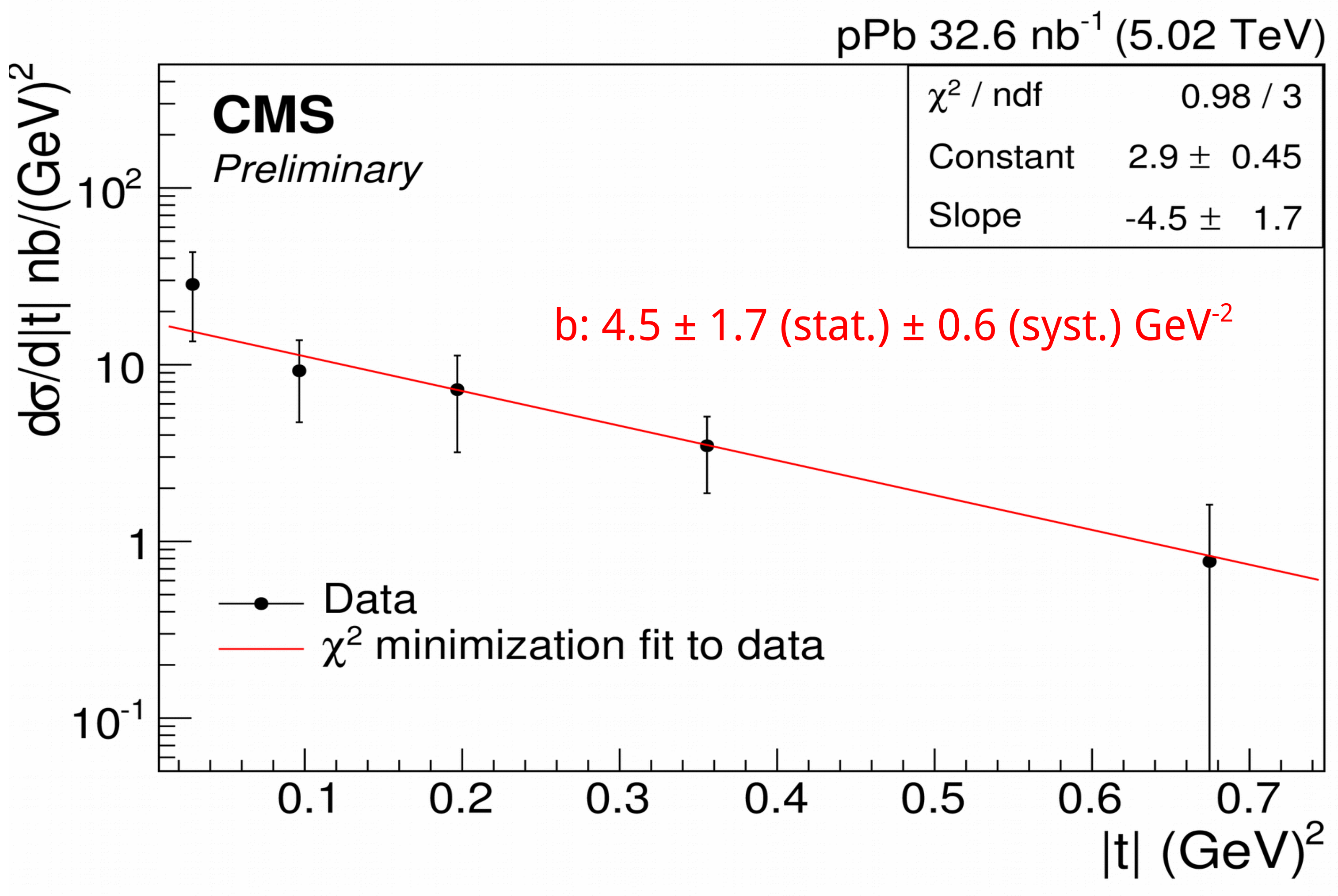
See talk by R. Chudasama Mon 14 May

Challenging as $\gamma\gamma \rightarrow \mu\mu$ background is large, can't be removed with max p_T cut

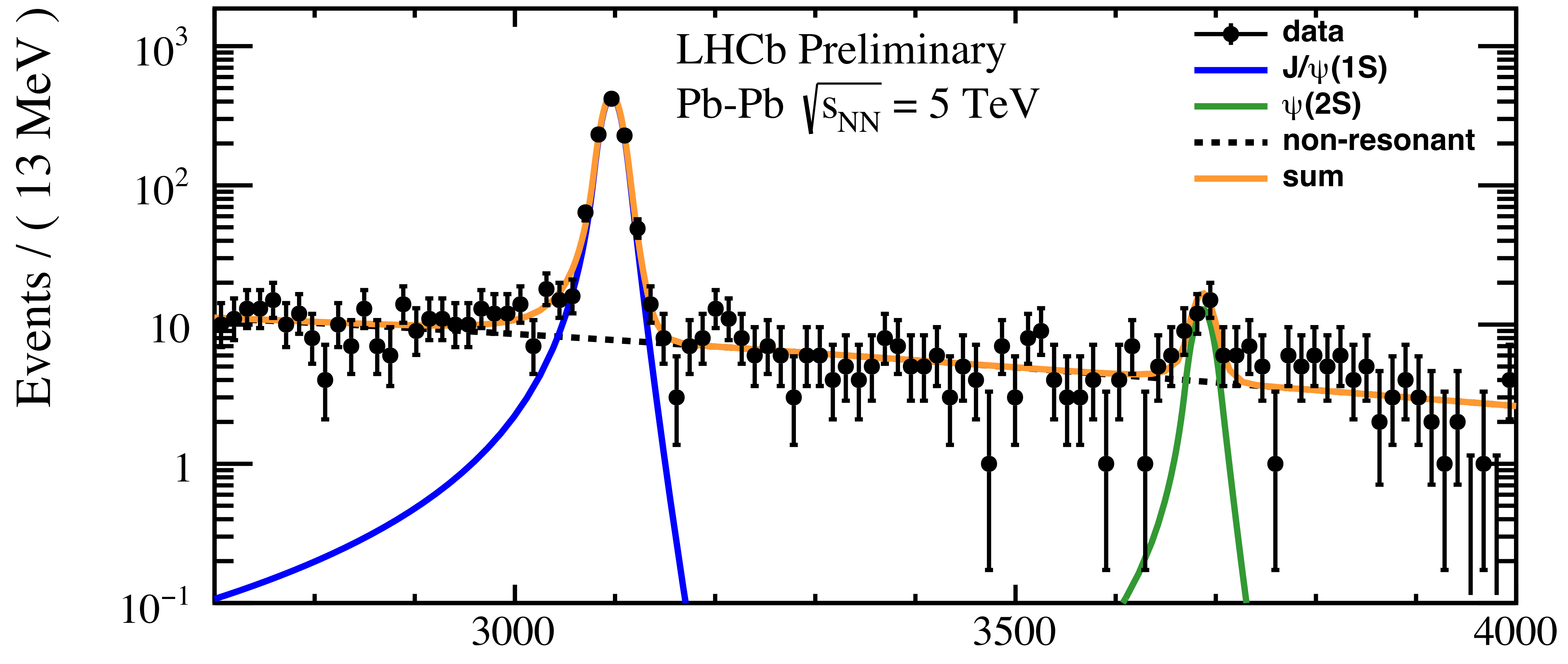


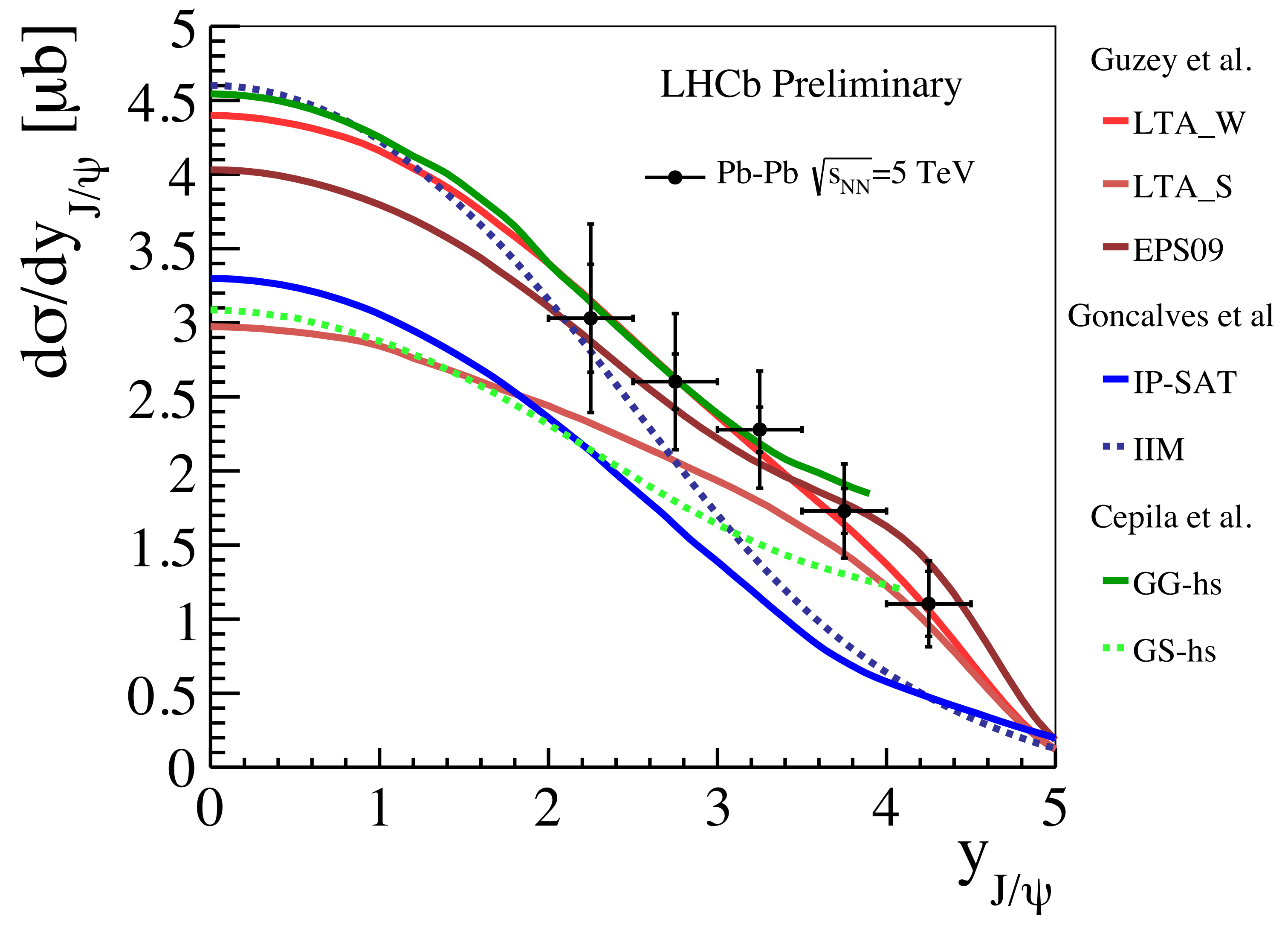


Slope of t distribution (4.5 GeV^{-2}) consistent with HERA

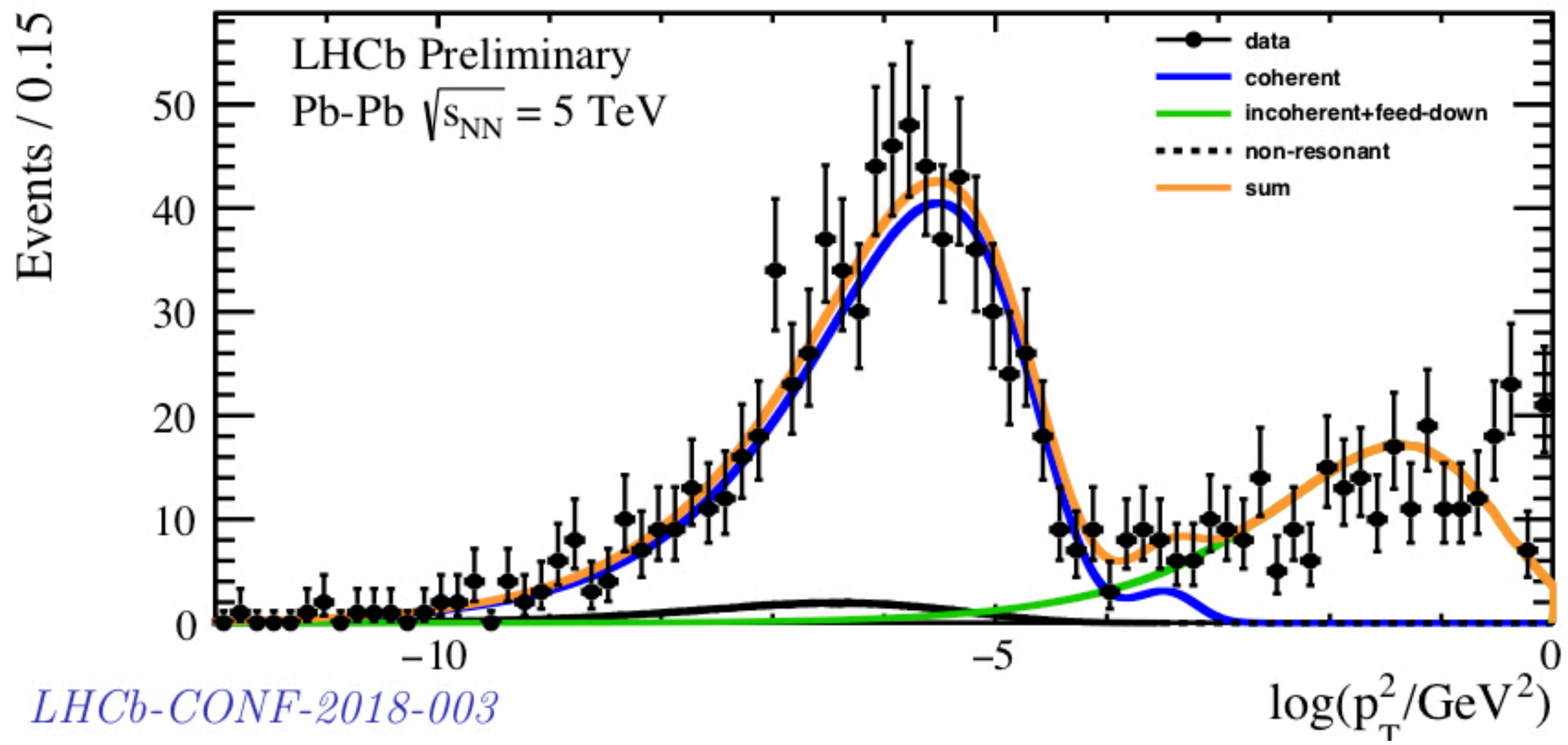


New LHCb results on charmonium in UPC





See talk by A. Bursche Mon. 14 May

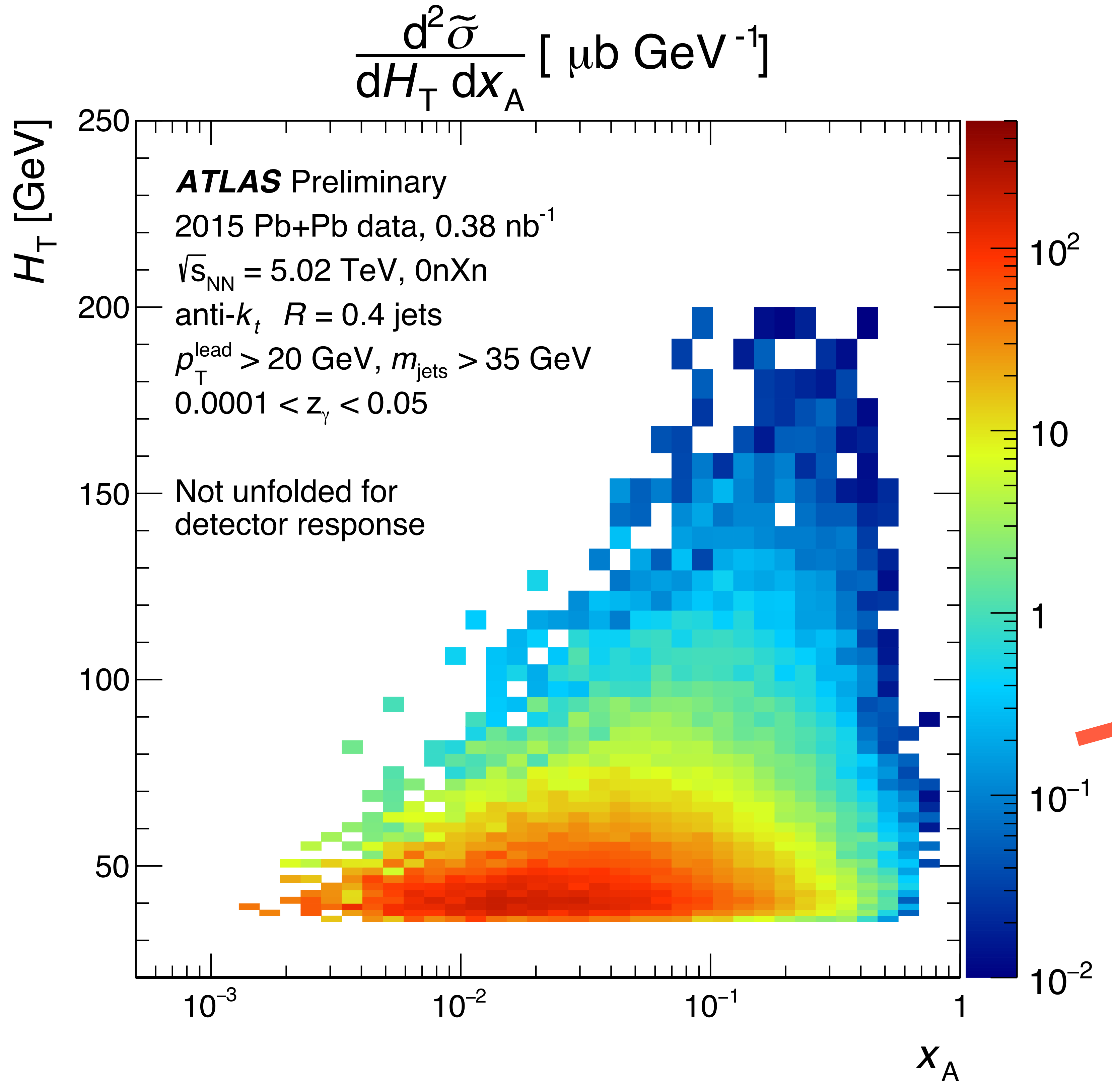


Excellent momentum resolution, can see detailed structure of *t* distribution

Cross sections consistent with ALICE where they overlap in rapidity.

Photo-nuclear jet production

- Use $\gamma A \rightarrow$ jets + X to study parton distribution in nucleus potentially at small x
  - Strikman, Vogt and White Phys.Rev.Lett. 96 (2006) 082001



ATLAS-CONF-2017-011

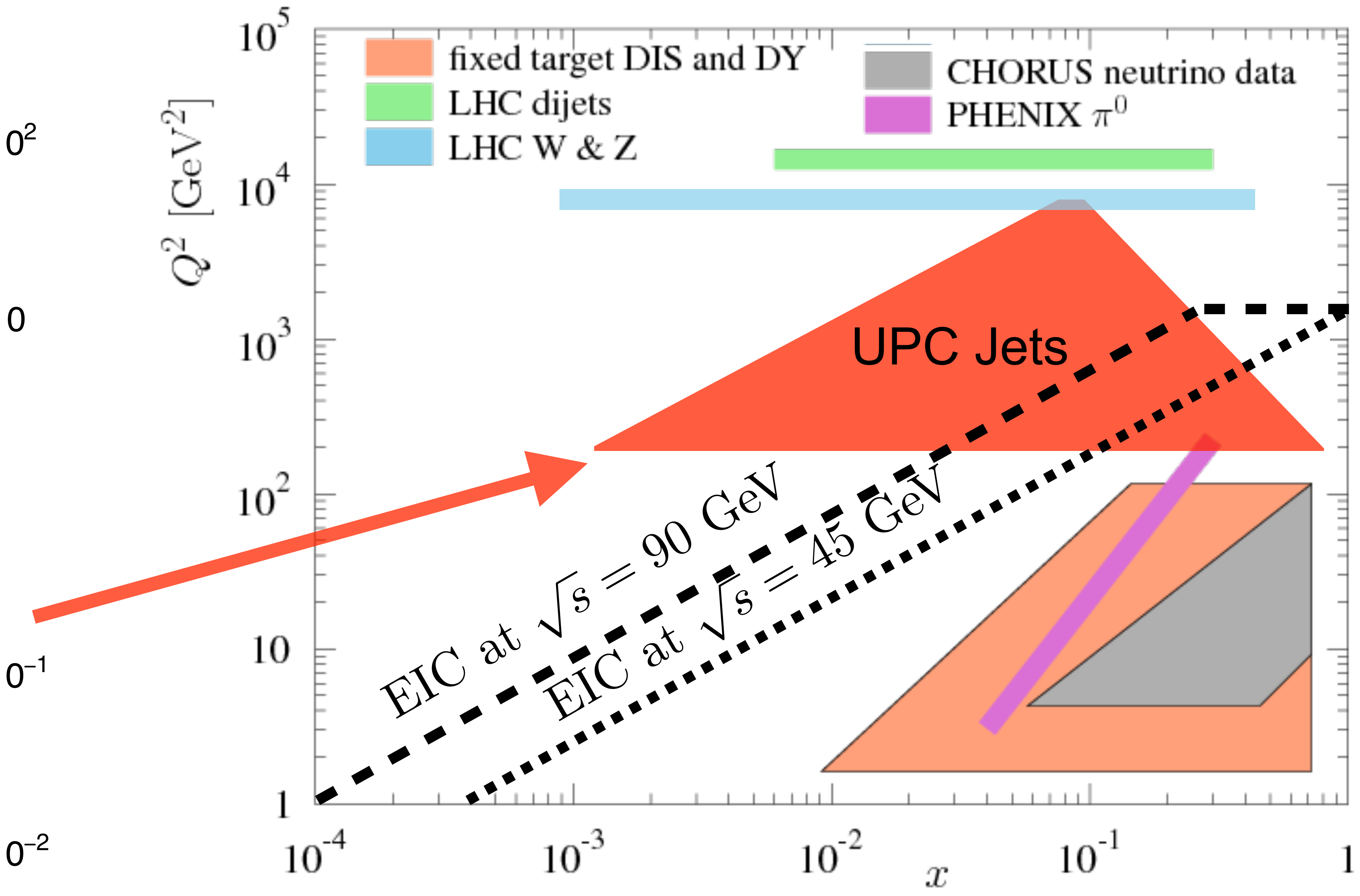
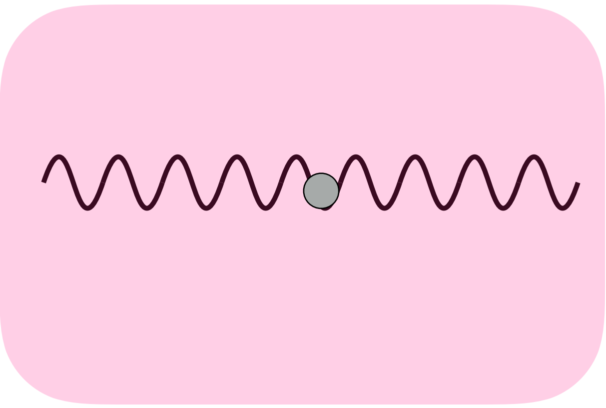


Figure adapted from EPPS16 1612.05741 [hep-ph]

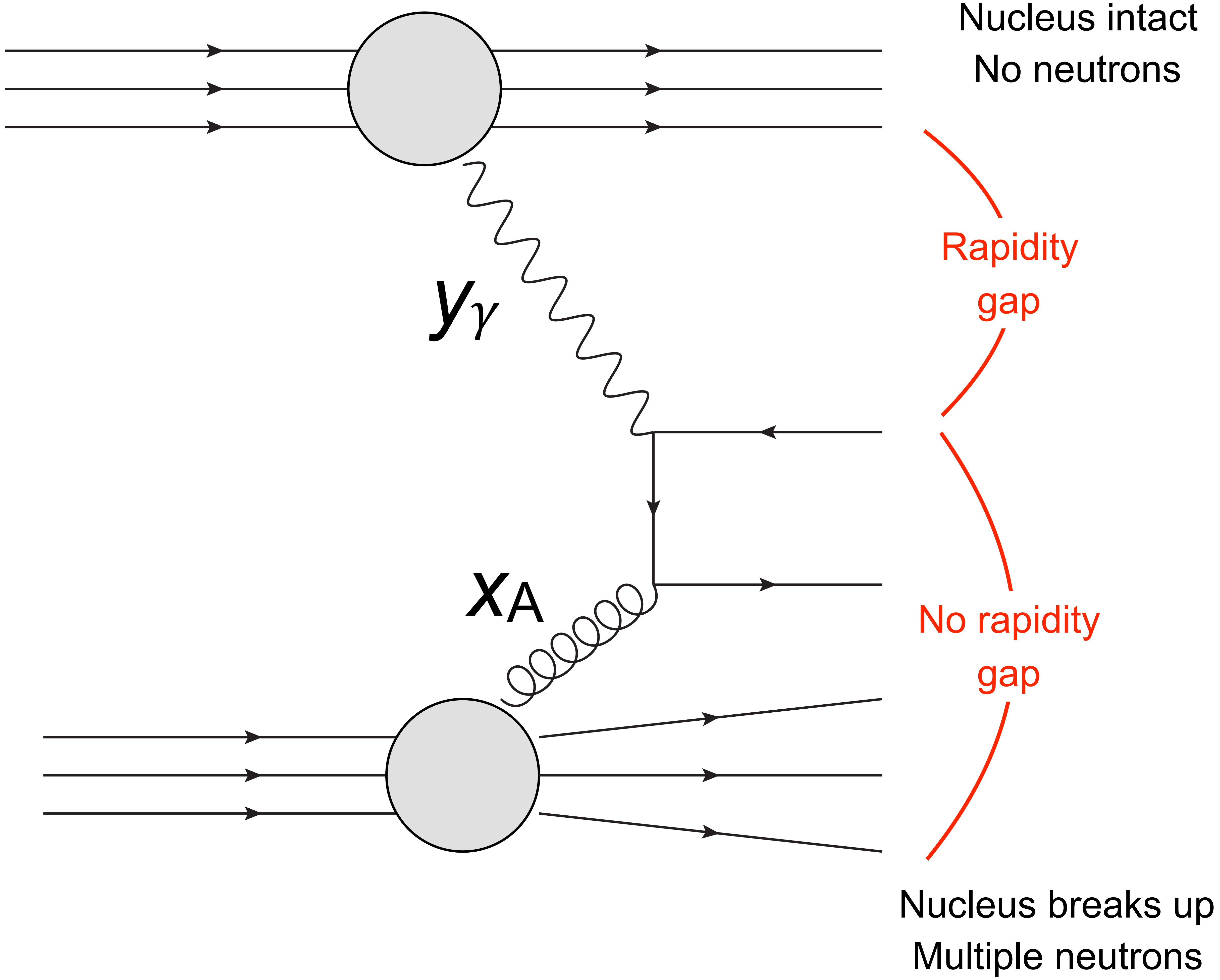
Domain accessible by UPC is

- Spans region where nPDFs go from significant to small
- Has considerable overlap with EIC

Photo-production of jets: direct

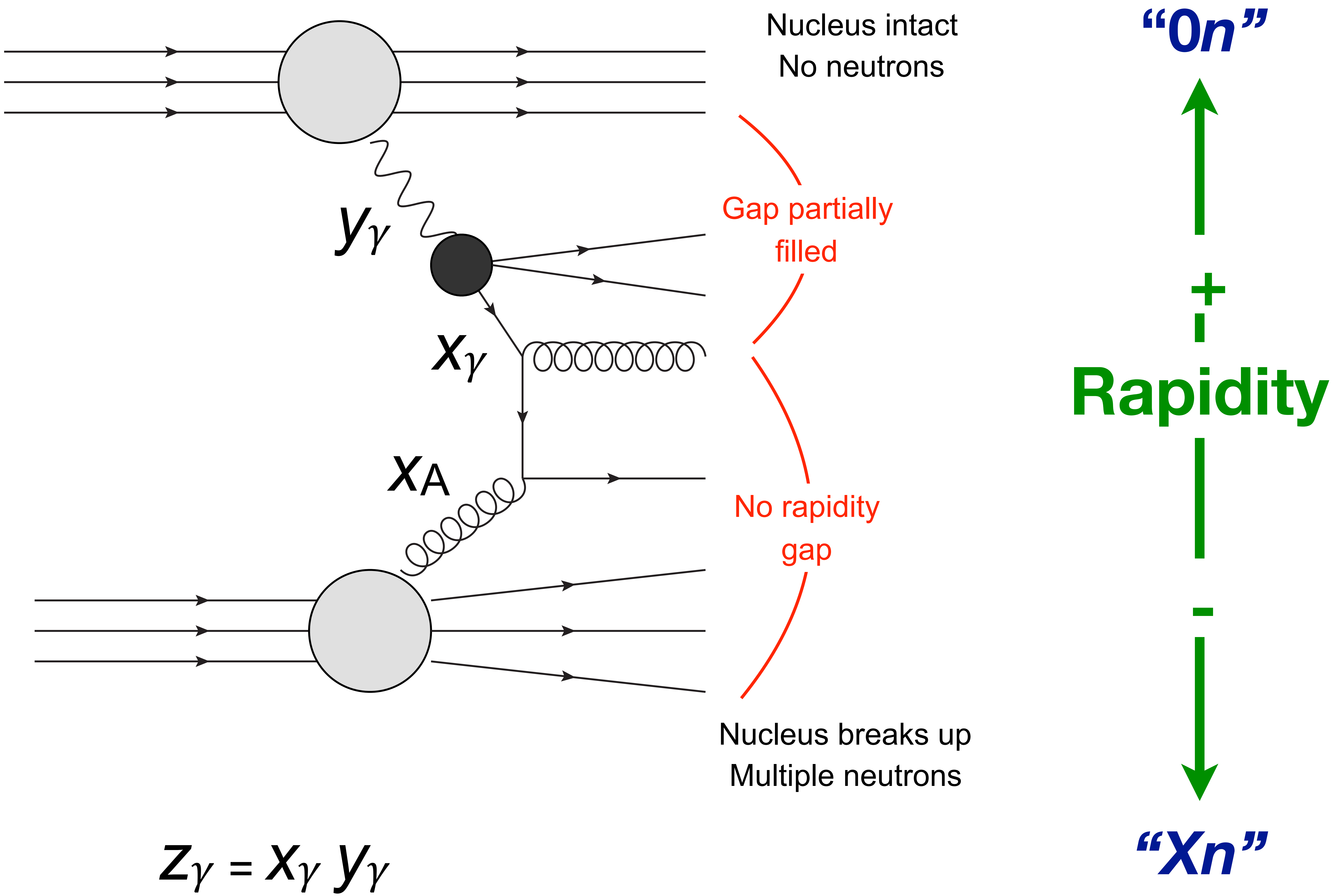


Point-like photon



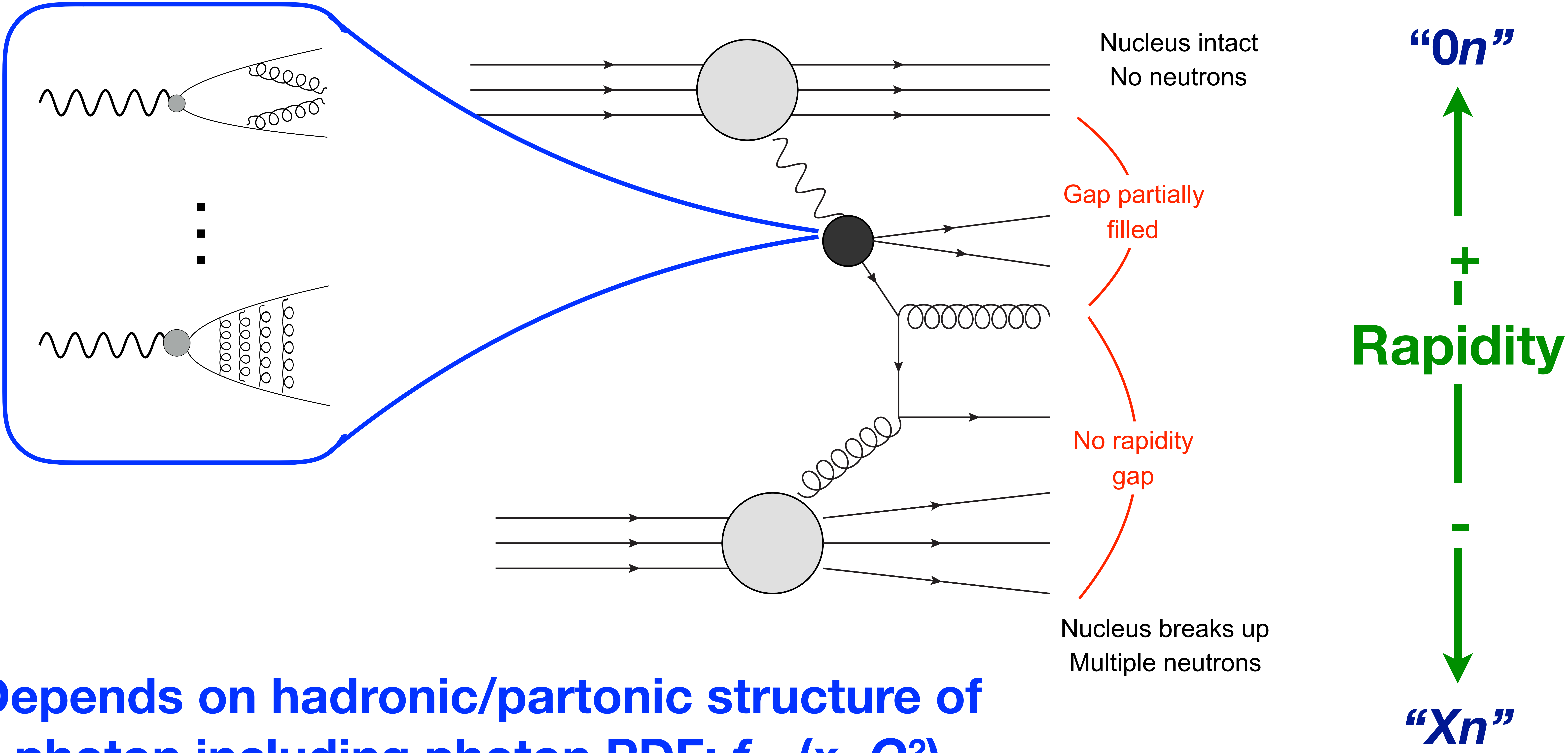
Photon participates directly in hard scattering

Photo-production of jets: resolved



$$z_\gamma = x_\gamma \, y_\gamma$$

Photo-production of jets: resolved



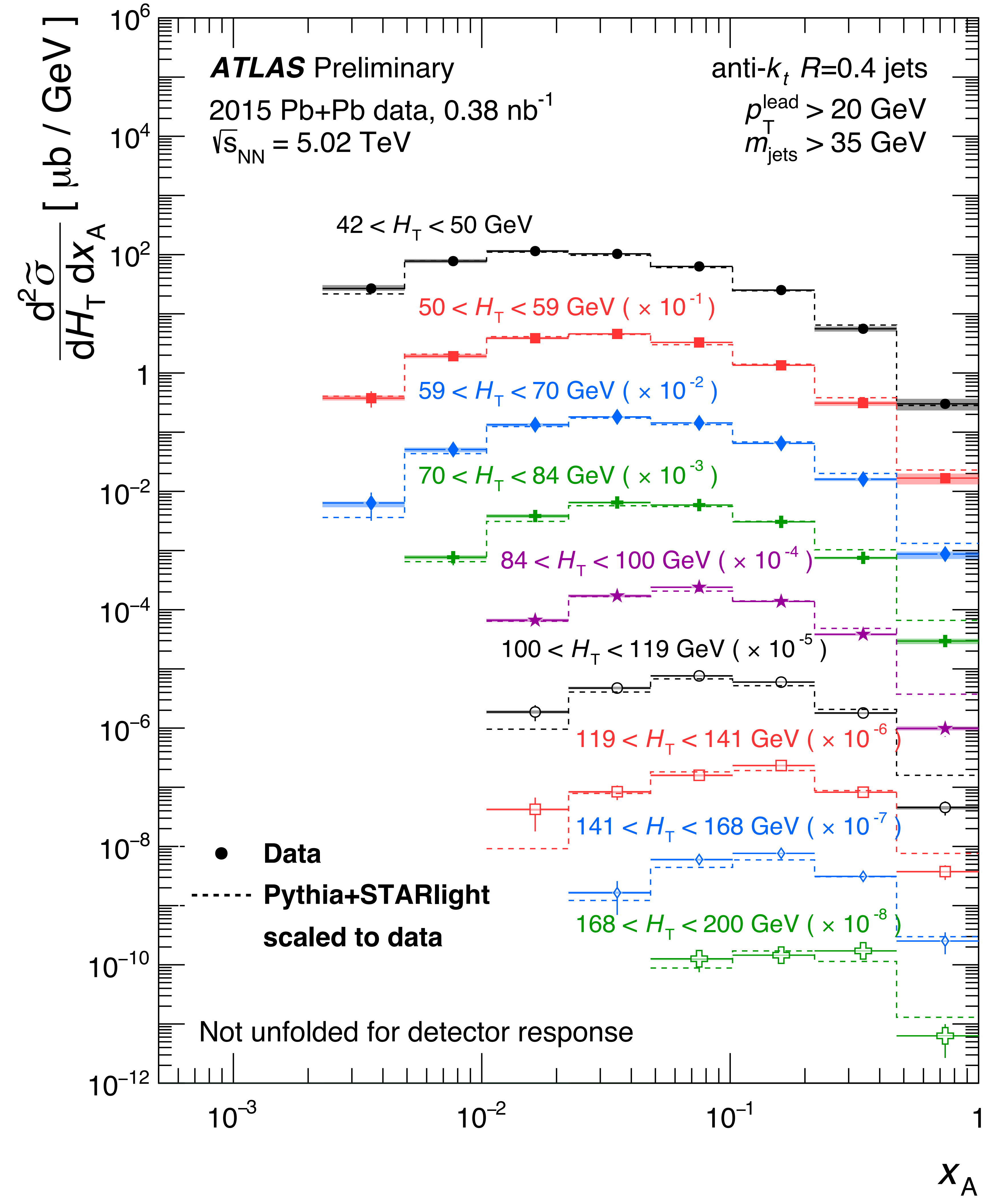
Depends on hadronic/partonic structure of photon including photon PDF: $f_{a/\gamma}(x_\gamma,Q^2)$

Photo-nuclear jet production

[ATLAS-CONF-2017-011]

- Result shows photo-nuclear jet production is experimentally-realizable tool to measure nPDFs

- **Will be important to use additional information to separate direct and resolved contributions**
  - Relationship between jet and gap positions
  - Resolved contribution involves photon PDFs



Applications to the QGP: small systems

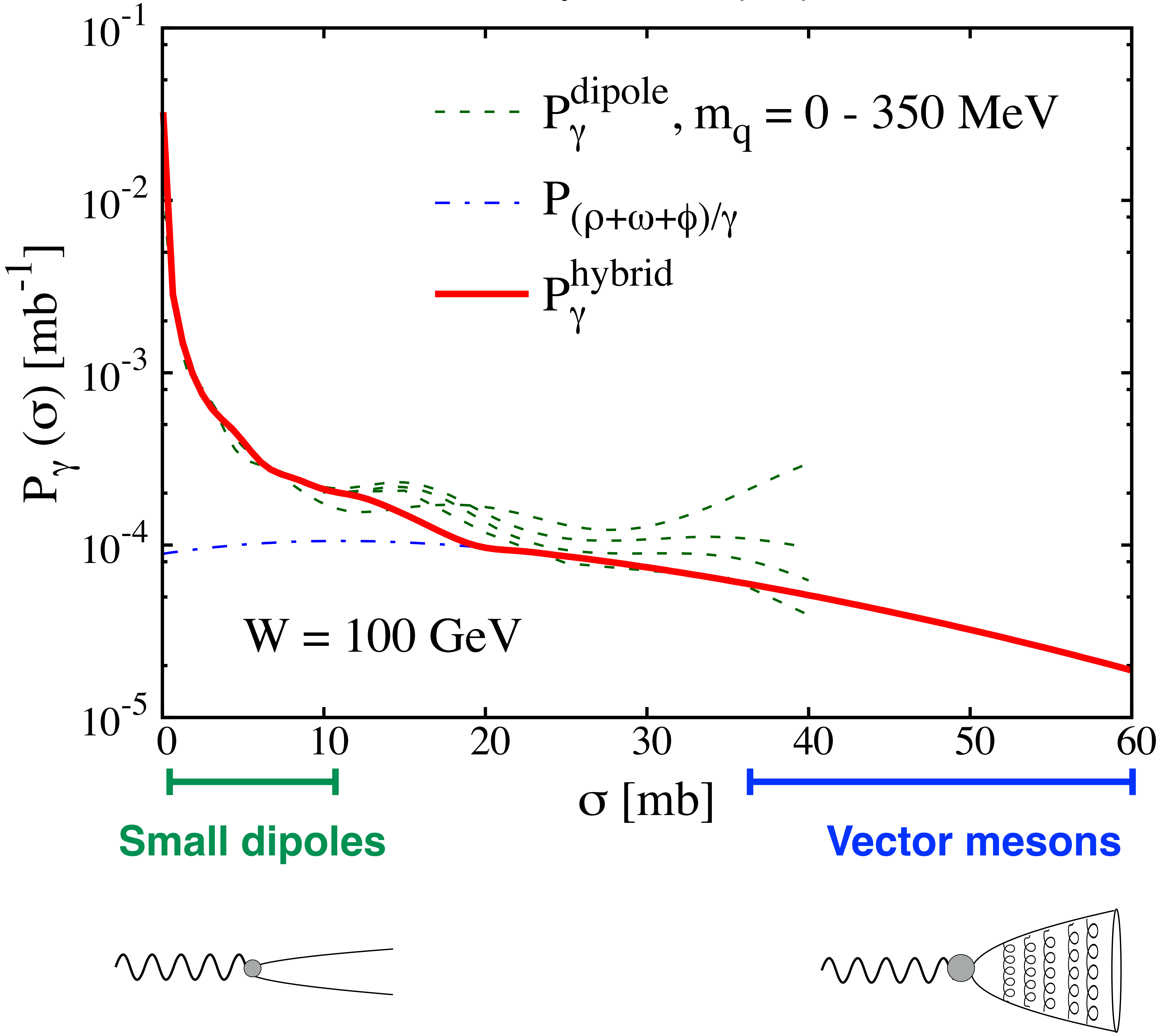
- Much discussion at this conference about signatures associated with collectivity in small systems
  - Diffractive processes can be used to furnish models of initial conditions in these systems

$$\left.\frac{d\sigma^{\rm inel}_{\rm diff}}{dt}\right|_{t=0} \propto \langle A^2\rangle - \langle A\rangle^2$$

⇨ fluctuating "geometry"

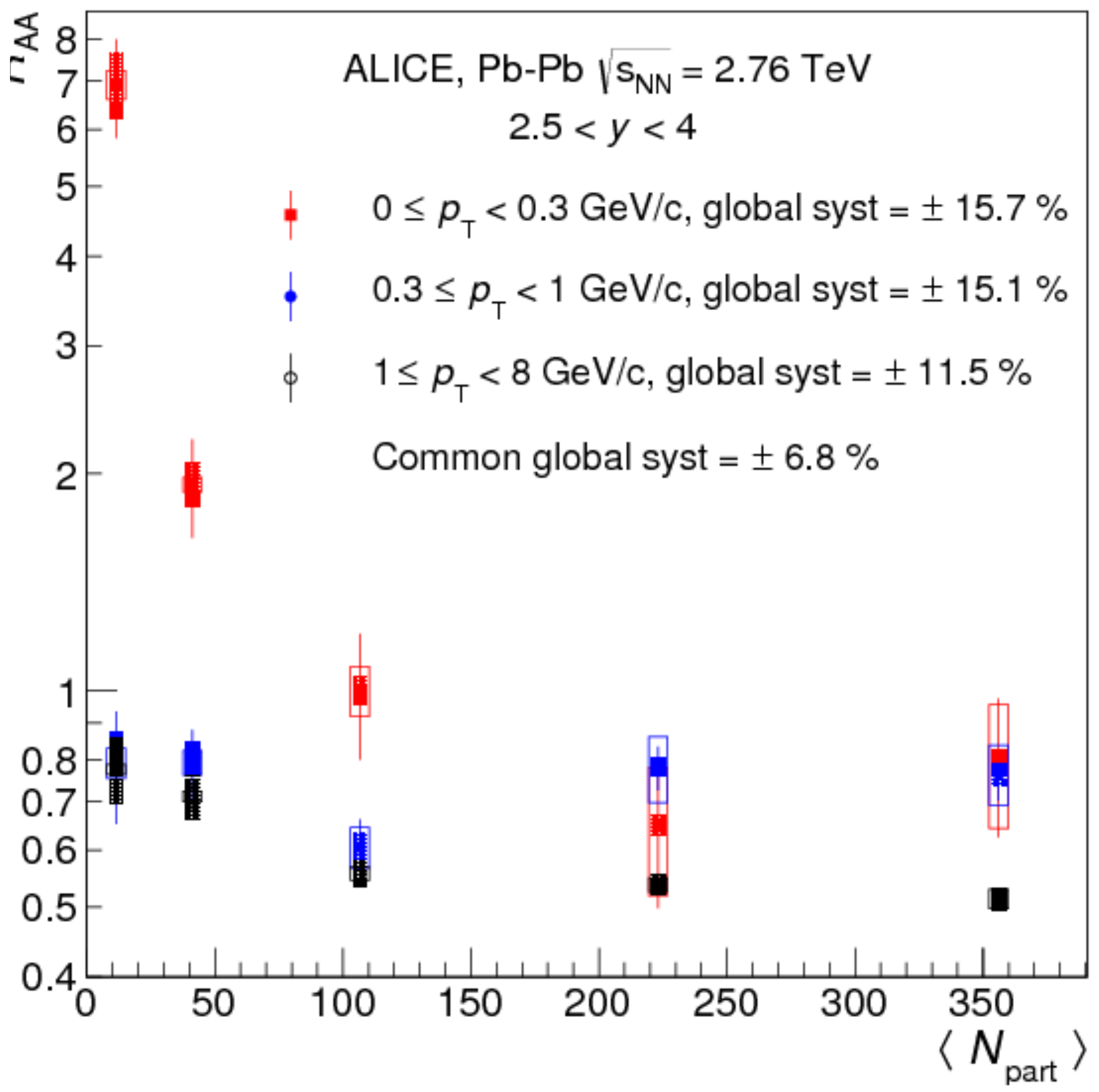
- Photons allow for creation of QCD systems of multiple sizes
  - Potentially much smaller than in *pp* collisions
  - Especially in "resolved" $\gamma\gamma$ collisions

Alvioli et. al. Phys. Lett. B767 (2017) 450-457

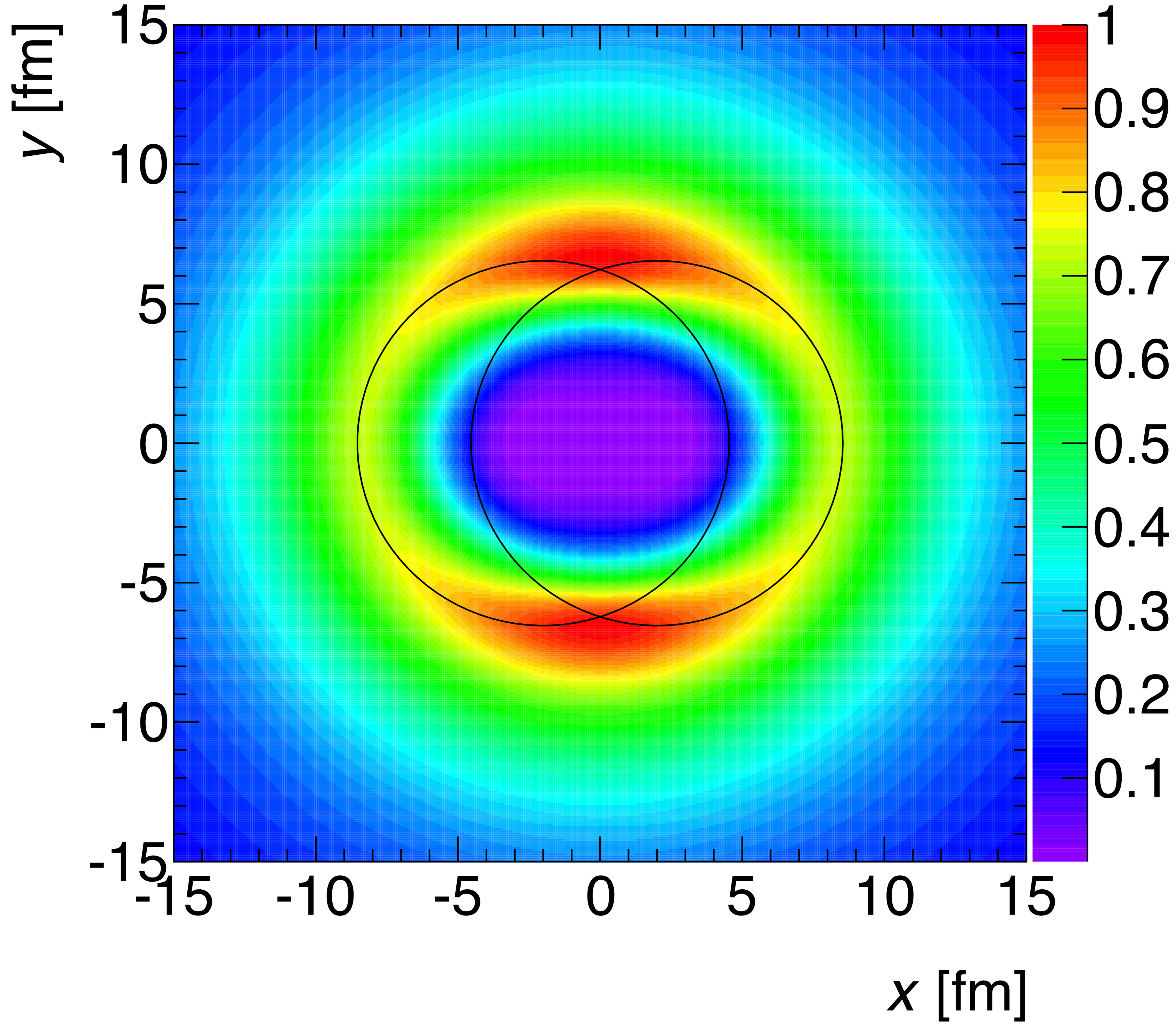


Applications to the QGP: hard probes

- UPC-like processes have been observed in peripheral AA collisions
  - ALICE: excess of low p_T J/ψ
  - STAR: persistence of p_T dielectron pairs



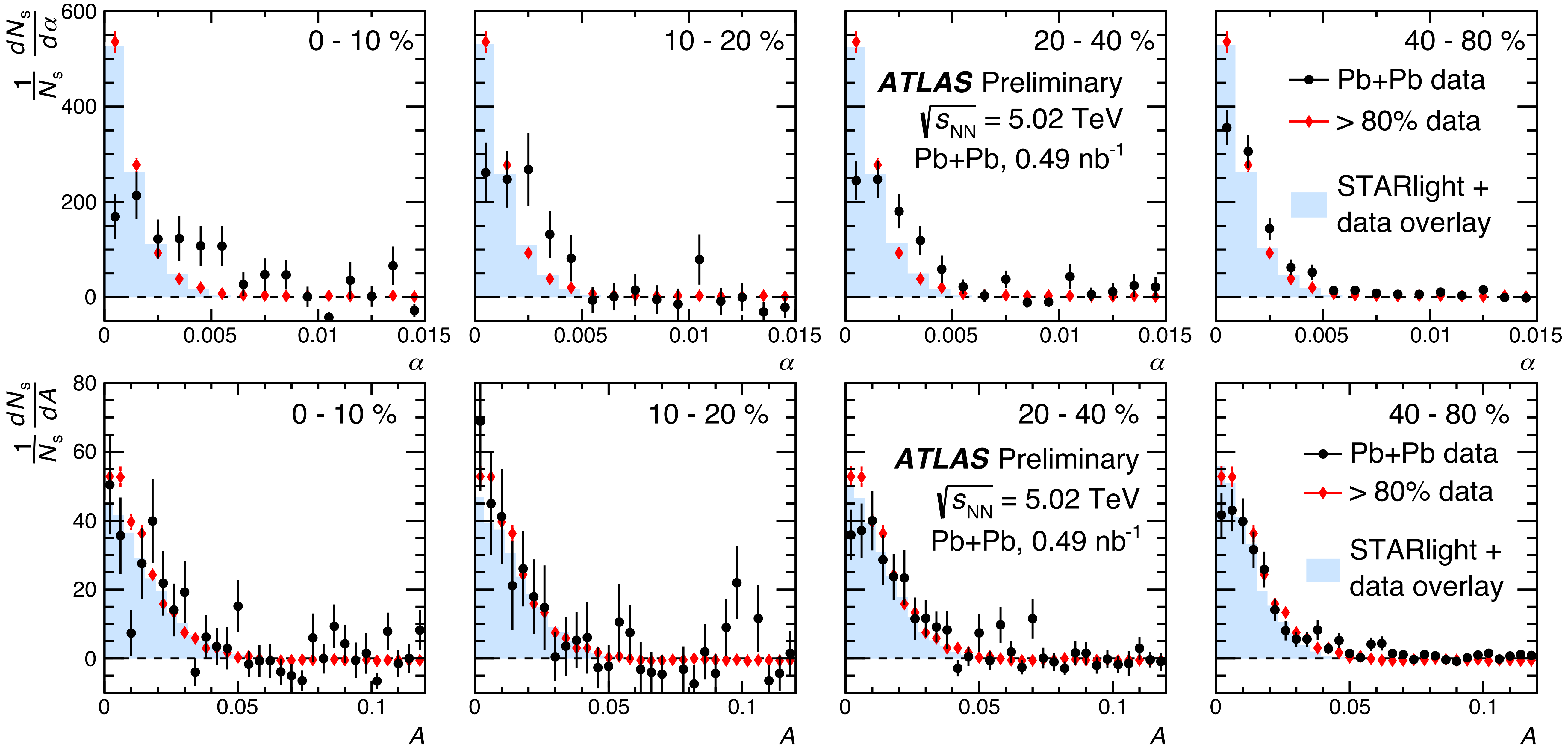
ALICE Collaboration Phys. Rev. Lett. 116



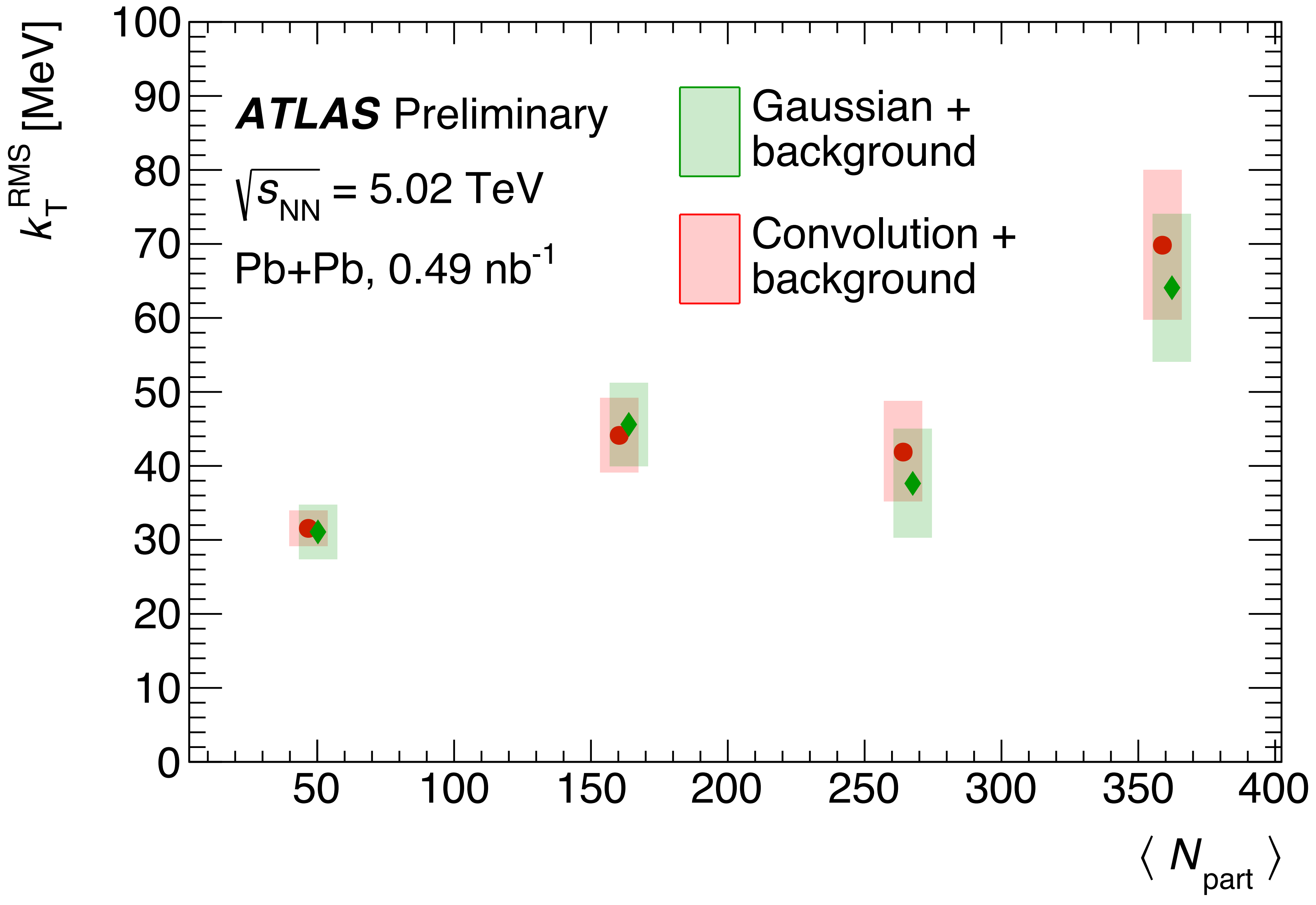
- Question: can $\gamma\gamma$ in non-UPC collisions processes provide us with probes of the QGP?
  - Important feature: coherent $\gamma\gamma$ systems have very small initial momentum $p_T^{\gamma\gamma} \ll \Lambda_{QCD}$
  - Expectation of much better momentum balance than for QCD processes

Product of two photon fluxes in transverse plane for b=4 fm using Woods-Saxon charge distribution, $W_{\gamma\gamma}$ =10 GeV, Y=0
Normalized by maximum

Applications to the QGP: hard probes



- ▸ Acoplanarity of $\mu\mu$ (p_T > 4 GeV) observed to gradually broaden in central collisions
- ▸ Not accompanied by broadening of asymmetry distribution that would indicate significant dissociative / incoherent contribution



- ▸ Extract transverse momentum scale from Gaussian fits
  - 0—10% : 70 ±10 MeV
  - Consistent with order of magnitude estimates from kinetic theory for multiple scattering off electric charges in thermal plasma

$$\langle k_T^2 \rangle \propto \alpha_{EM}^2 T^3 L \ln(p_T/\alpha_{EM} T)$$

- ▸ **What can this tell us about the nature of these scattering centers in the medium?**

Summary and outlook

- Photons as a tool to probe structure of nuclear matter
  - Partonic: nPDF measurements
  - “Geometric”: diffractive processes
- Processes studied in UPC environment may have applications to the QGP
  - Photons as QCD systems with multiple “sizes”
    - ➡ Potentially much smaller than in pp
  - Possible new hard probes
- Compliment similar measurements at future EIC
  - EIC program will benefit from experience currently being developed studying UPC phenomena

EXTRAS

Inelastic diffraction and "geometry"

- Cross section for *inelastic diffraction* proportional to *fluctuations in interaction strength*
- Magnitude and *nature* of fluctuations influences shape of t distribution
  - not just spacial size, also number, rapidities, etc.

$$\left.\frac{d\sigma_{\text{diff}}^{\text{inel}}}{dt}\right|_{t=0} \propto \langle A^2 \rangle - \langle A \rangle^2$$

- CGC-based approach applied to J/ψ
  - Spacial fluctuations important for describing elastic and inelastic t distributions at HERA (Mäntysaari & Schenke Phys.Rev.Lett. 117, 052301)
  - Applied to UPCs (Phys. Lett. B 772 (2017) 832-838)

- Key component of Glauber-Gribov Color Fluctuations model (GGCF)
  - Account for off-shell propagation of projectile by allowing for intermediate states with different interaction strengths $\Longrightarrow$ cross section fluctuations

Exclusive di-leptons: next steps

- Push to %-level accuracy
- Correlate with neutron activity
  - Contribution at higher $M_{\mu\mu}$ comes from smaller impact parameters, potentially sensitive to details of nuclear charge distribution and incoherent contribution

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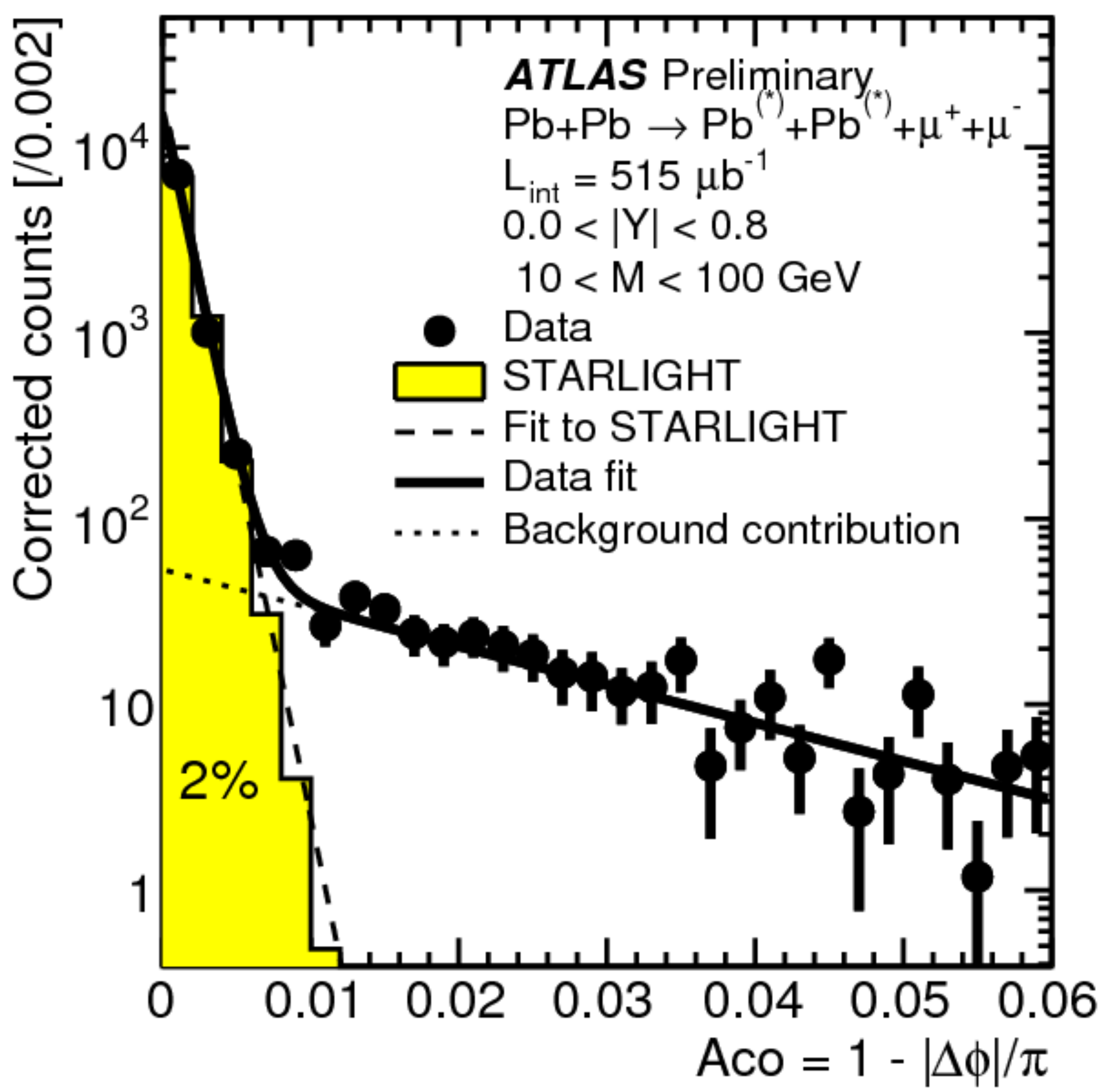
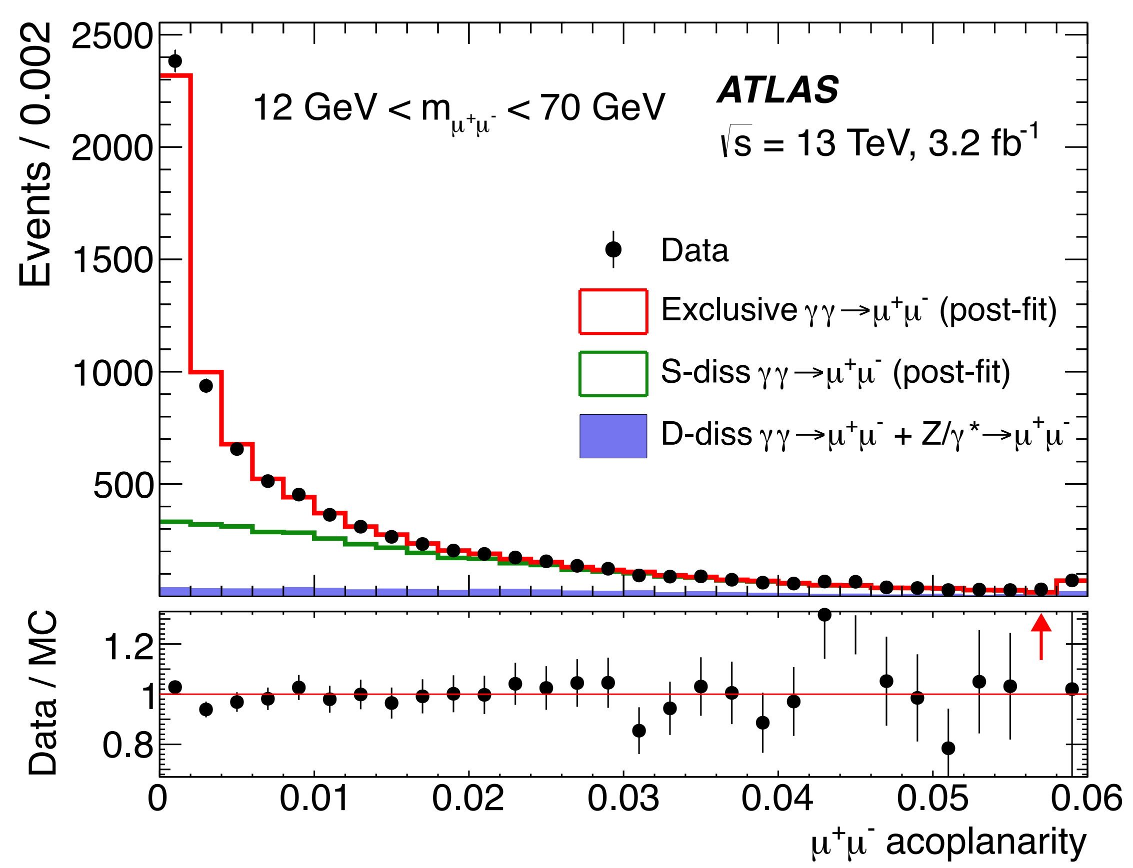


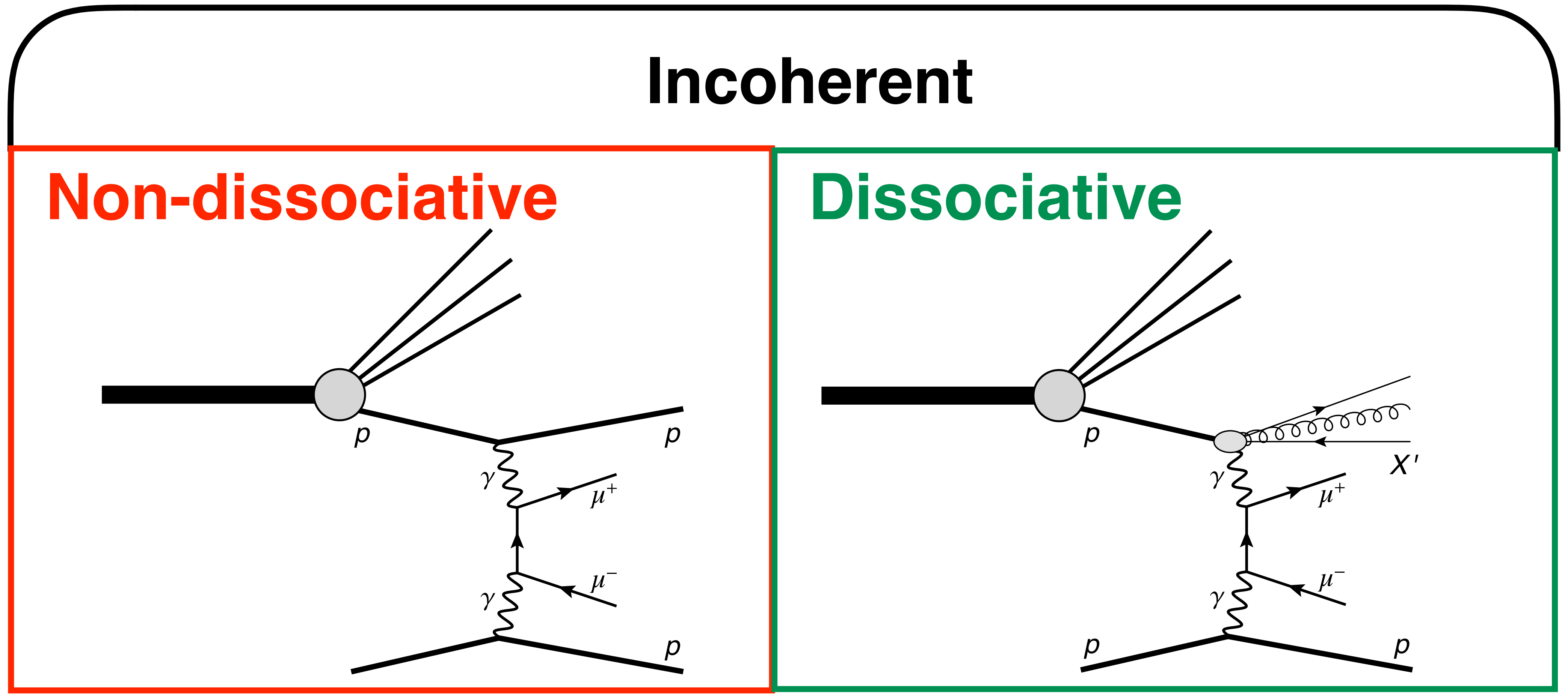
Are tails QED radiation? Parton-shower like or real NLO?

Contribution from proton dissociation, subset of incoherent in which projectile proton breaks up while emitting photon

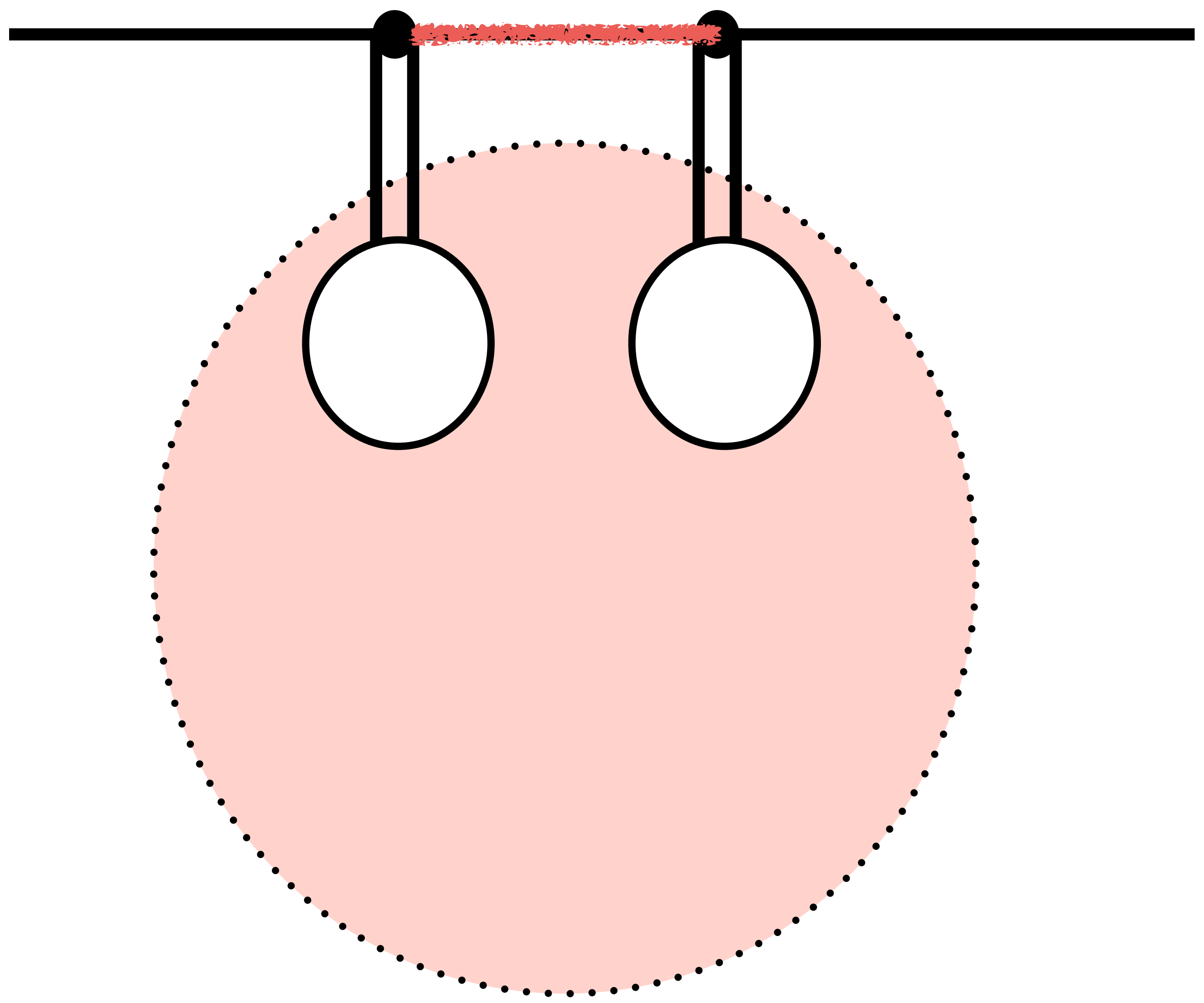
***pp:* incoherent only**

ATLAS Collaboration Phys. Lett. B 777 (2018) 303





Color fluctuations



In multiple scattering at high energies, need to consider **off-shell propagation of projectile** between scatterings in target

This is not included in standard Glauber picture

Glauber-Gribov Color Fluctuation model:
Include these effects by allowing for intermediate states interact with different strengths ⟹ "cross section fluctuations"

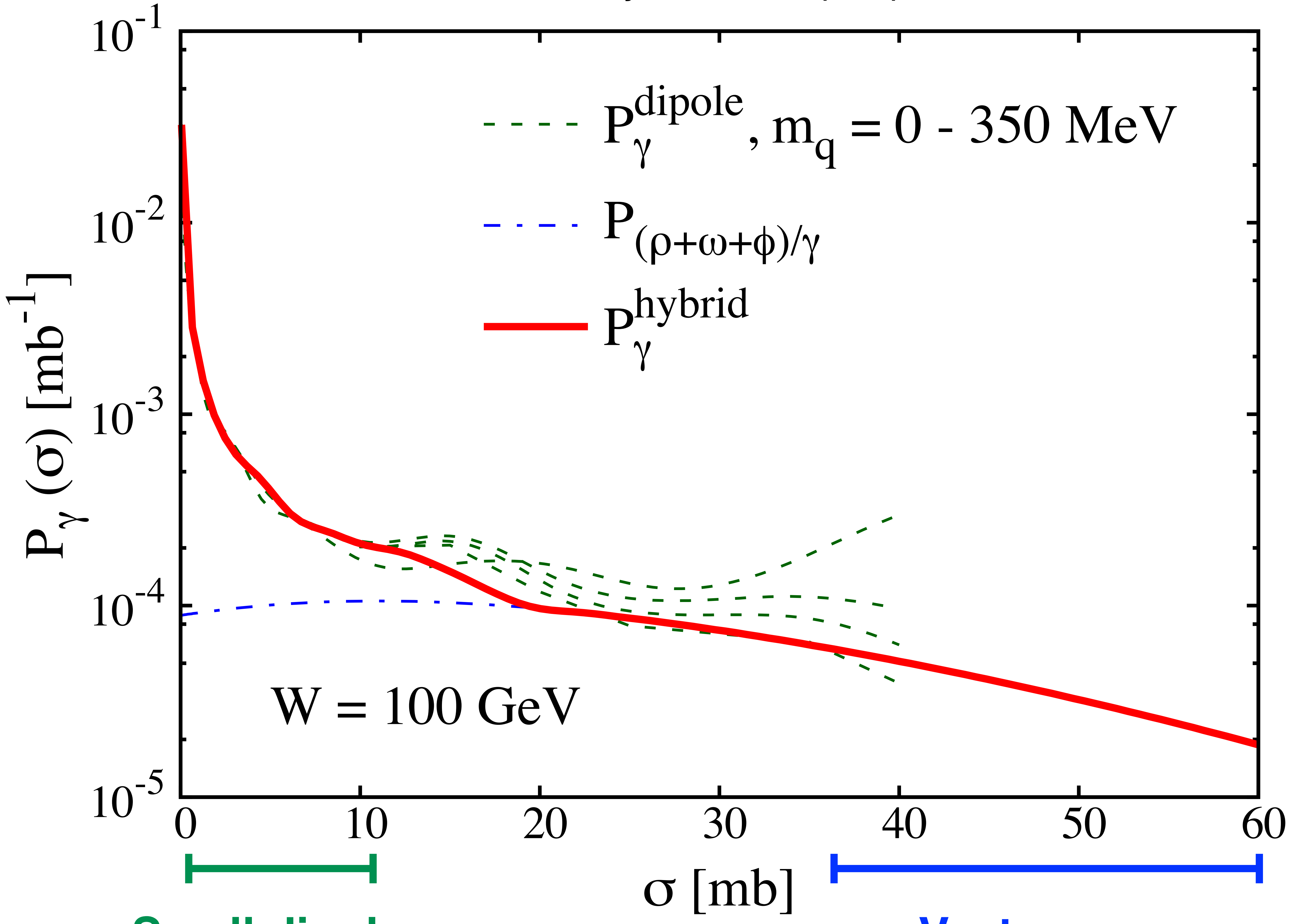
$\boldsymbol{P(\sigma)}$

$$\langle P(\sigma)\rangle = \sigma^{\mathrm{inel}} \qquad \mathrm{Var}[P(\sigma)] = \left.\frac{\mathrm{d}\sigma^{\mathrm{inel}}_{\mathrm{diff}}}{\mathrm{d}t}\right|_{t=0}$$

Color fluctuations of nucleon has been successful in describing centrality dependence of observables in *pA*

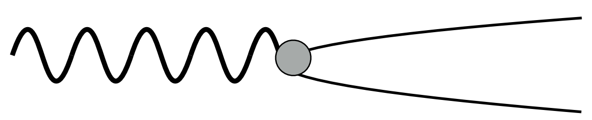
Color fluctuations of the photon

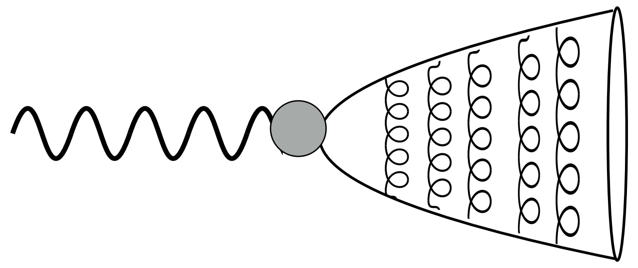
Alvioli et. al. Phys. Lett. B767 (2017) 450-457

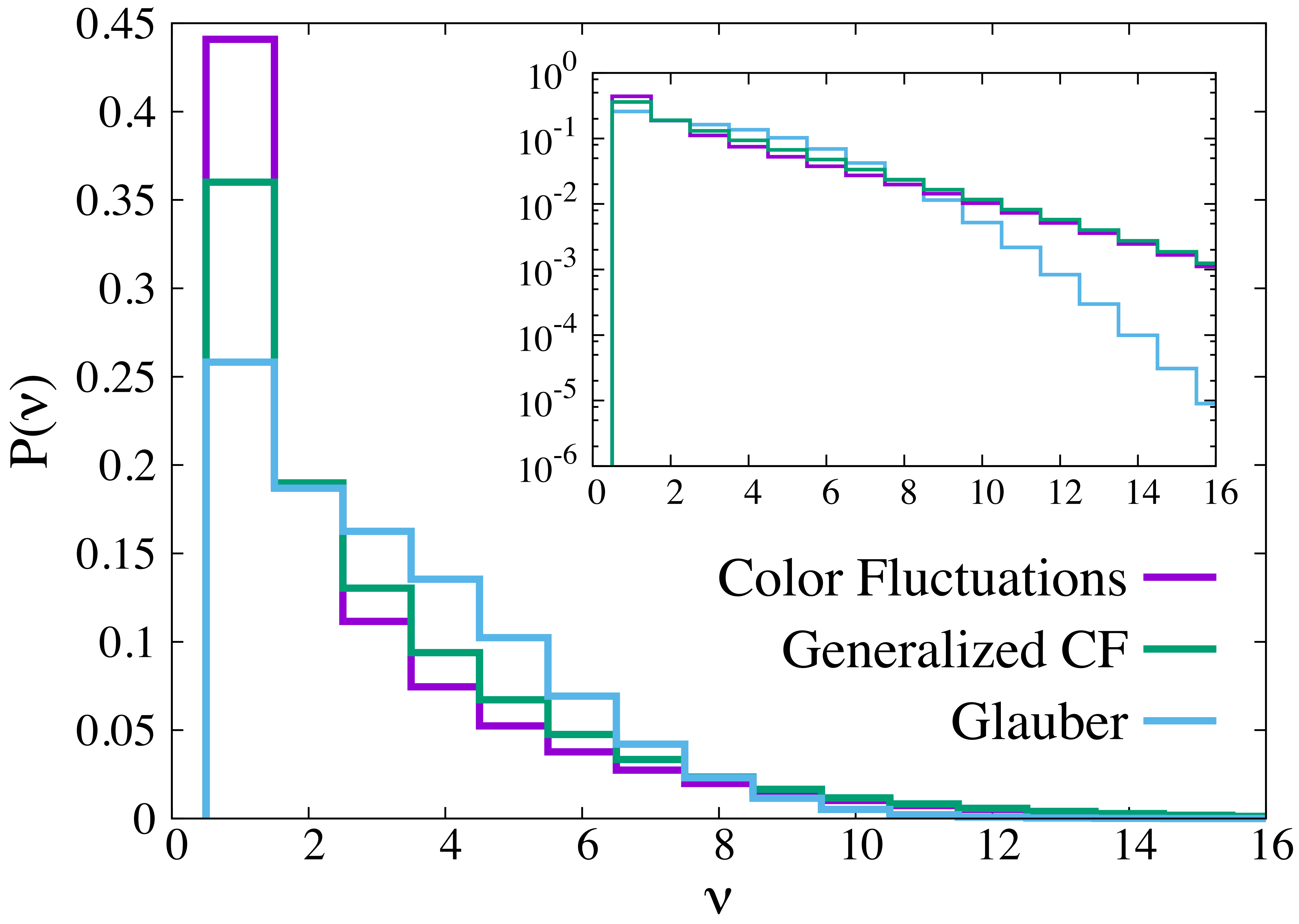


Small dipoles

Vector mesons



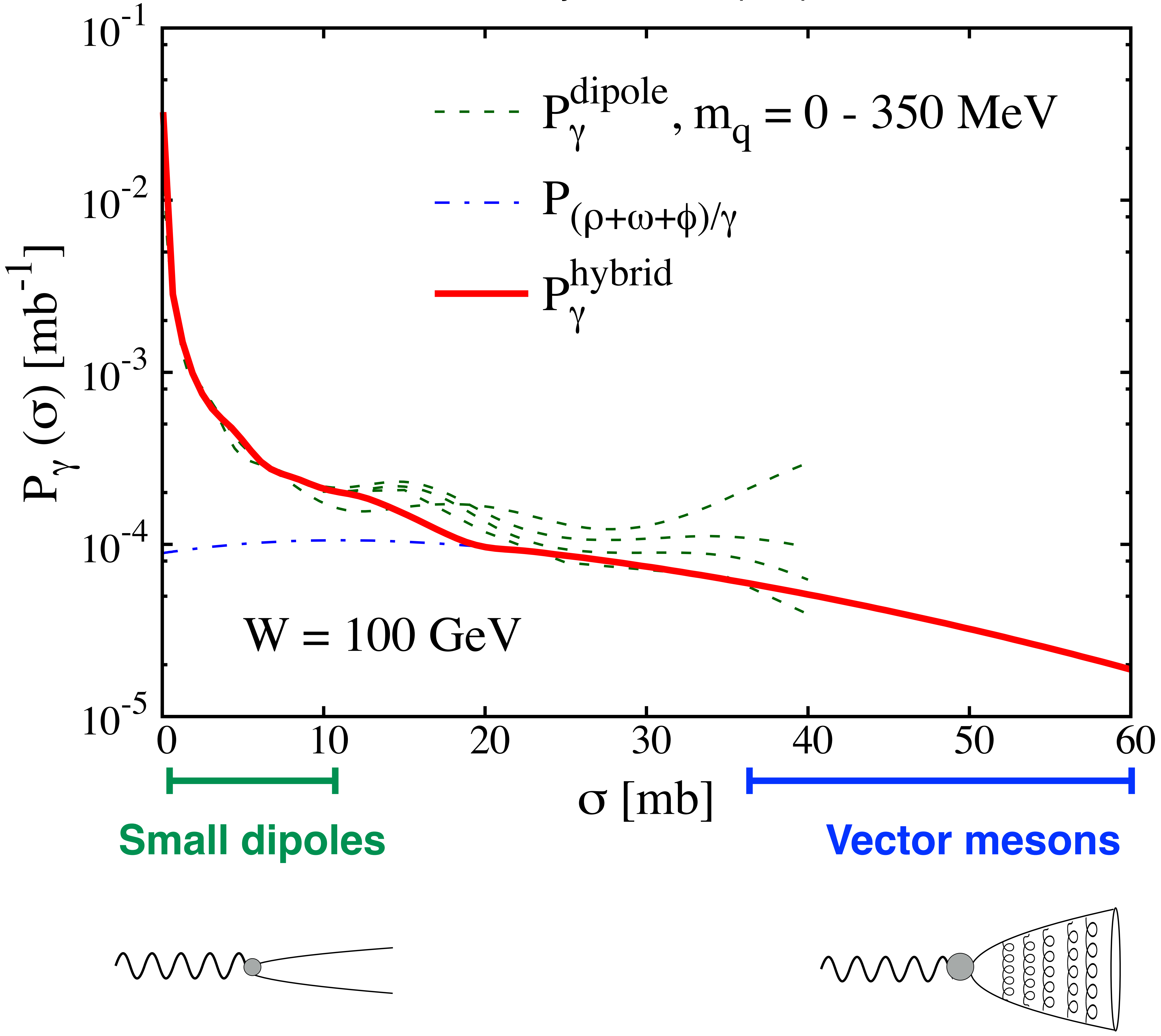


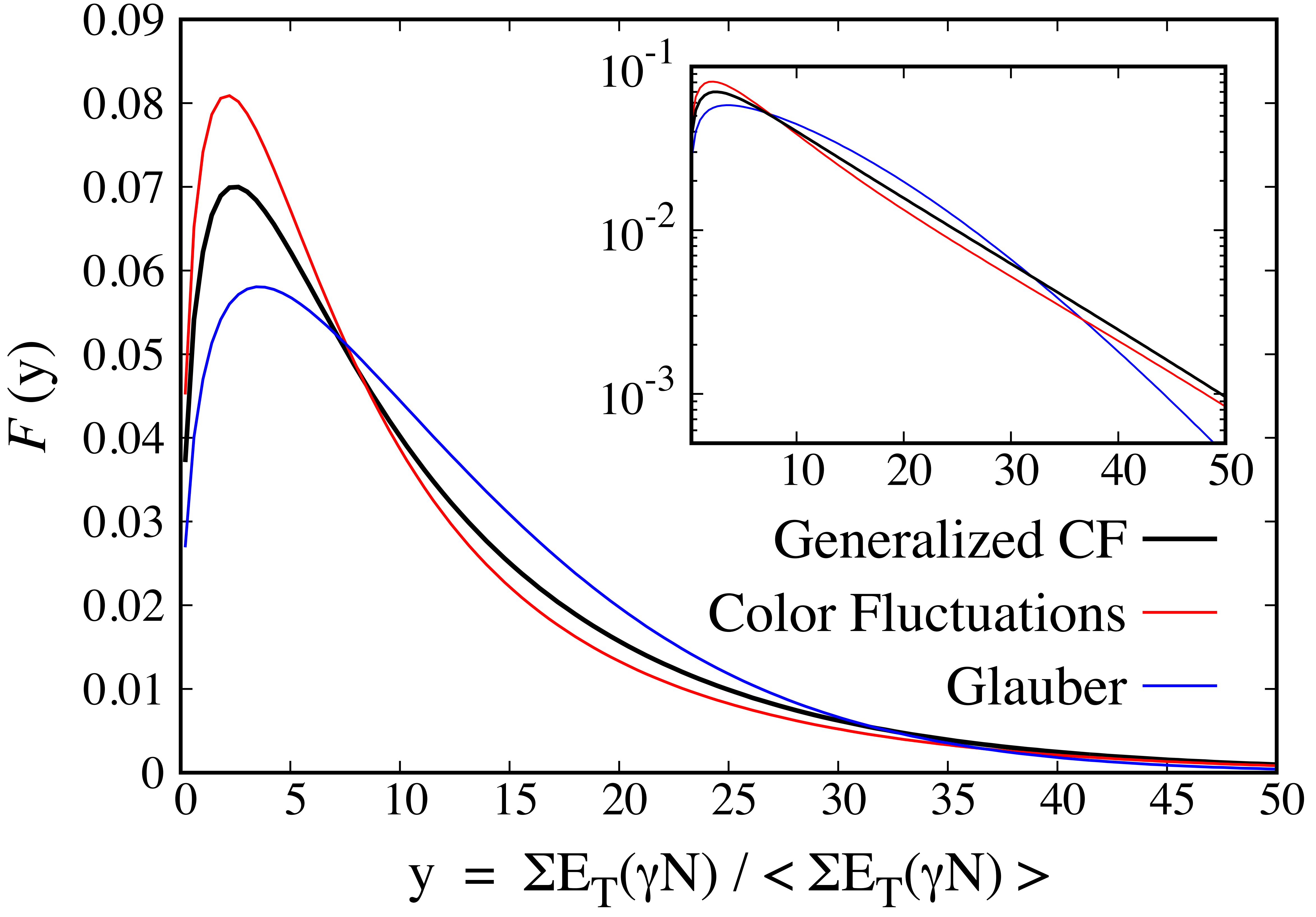


CFs dramatically increases 1 wounded nucleon contribution

Color fluctuations of the photon

Alvioli et. al. Phys. Lett. B767 (2017) 450-457

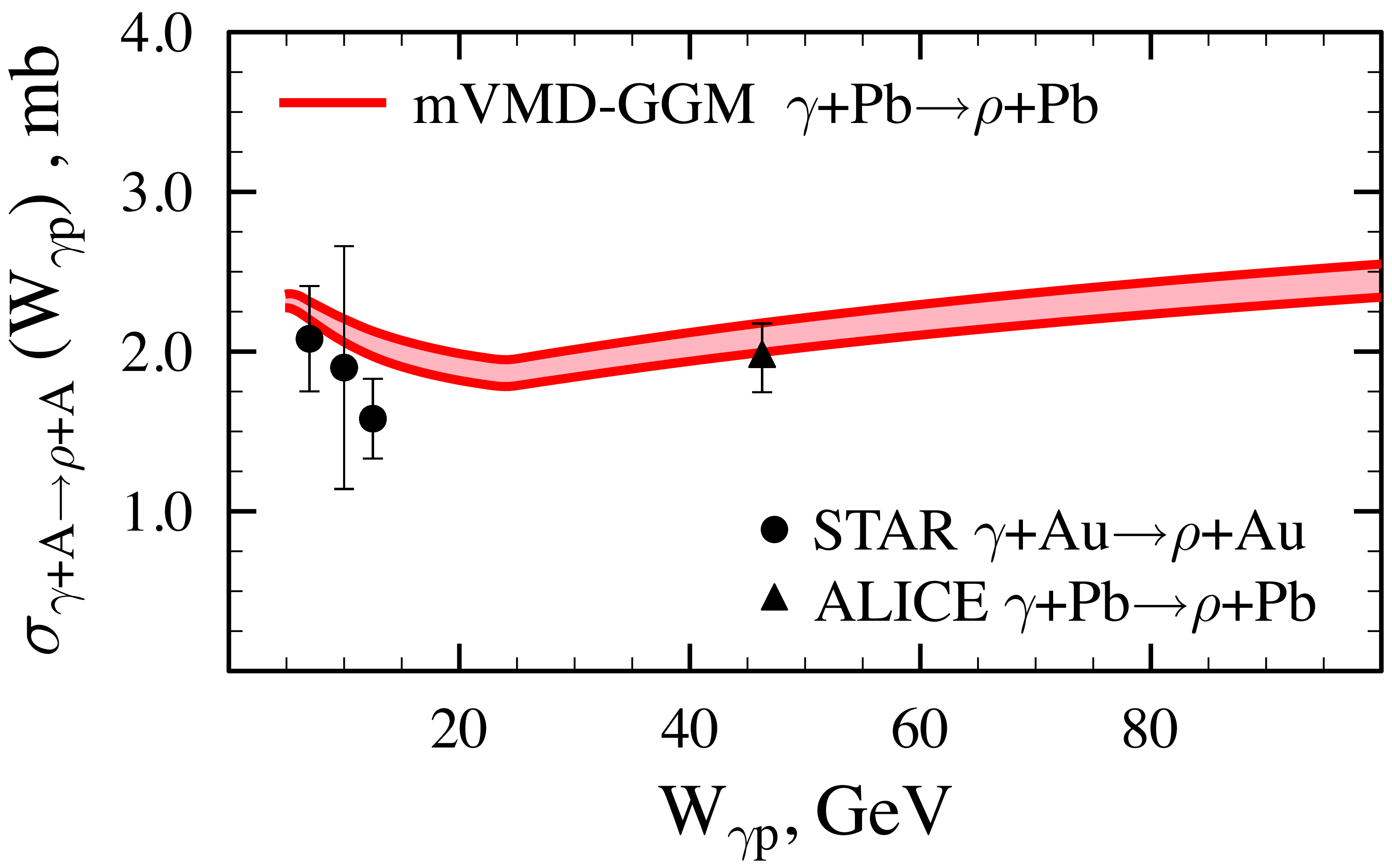


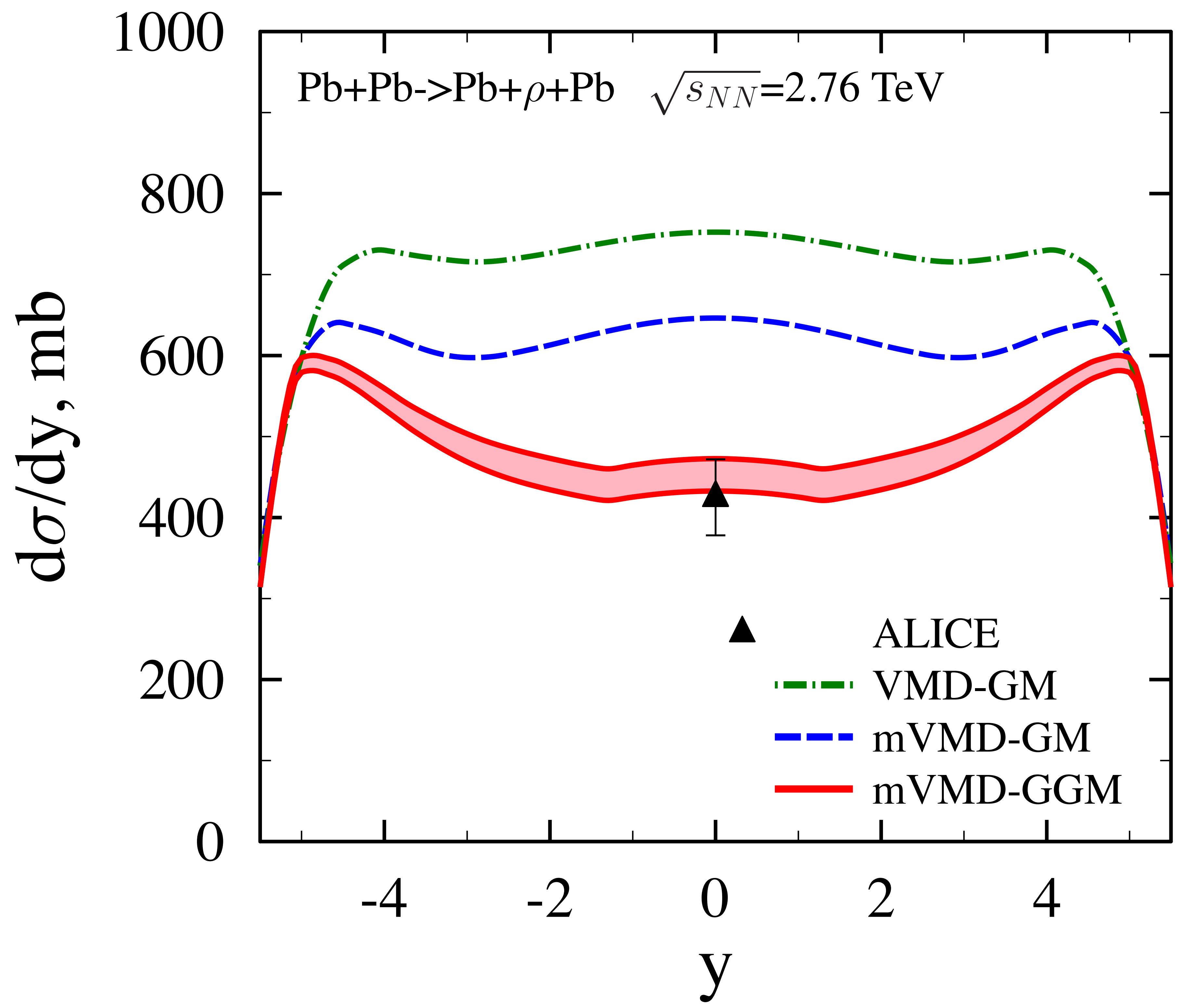


Significant impact on total particle production

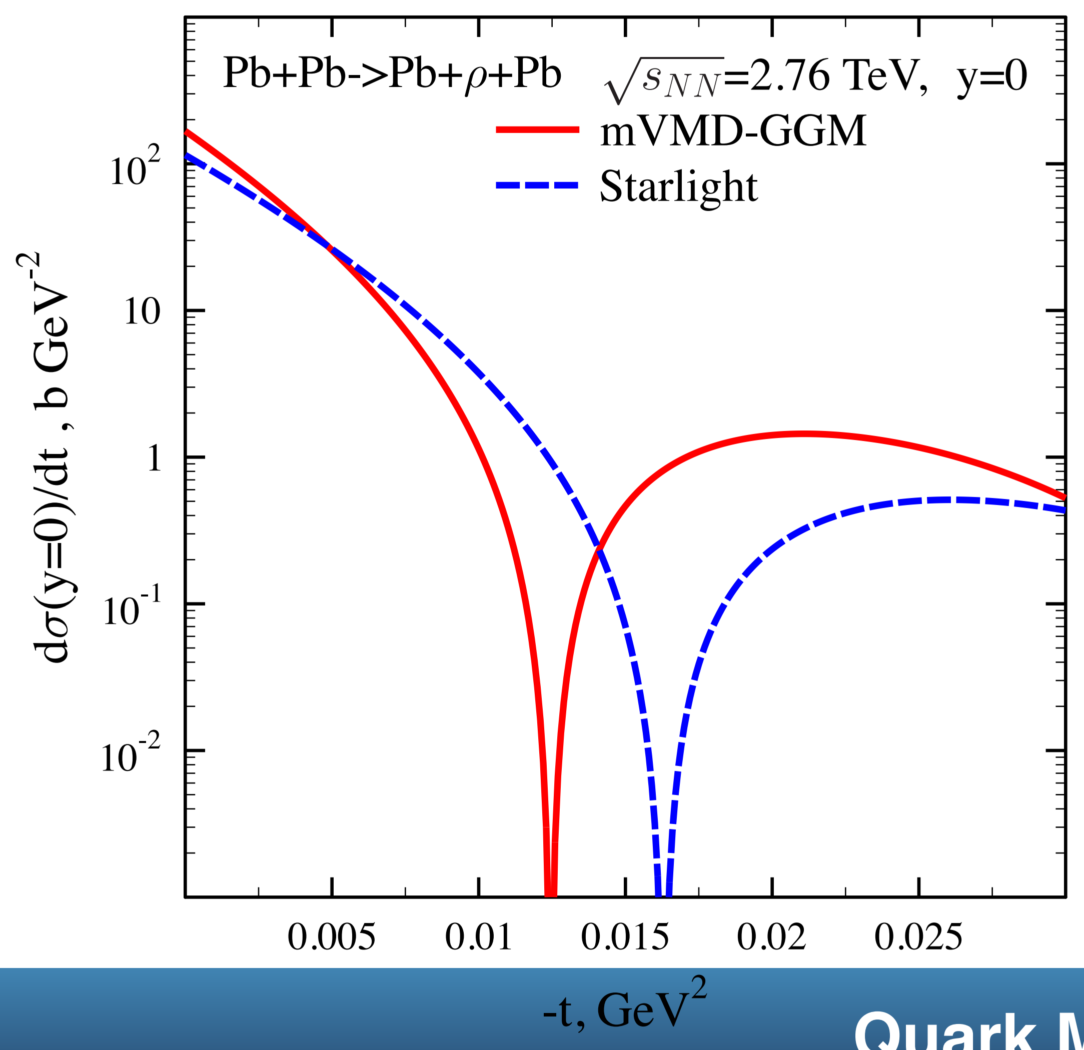
Mechanisms for constraining *P*(σ) with data

Exclusive ρ production: theoretical description





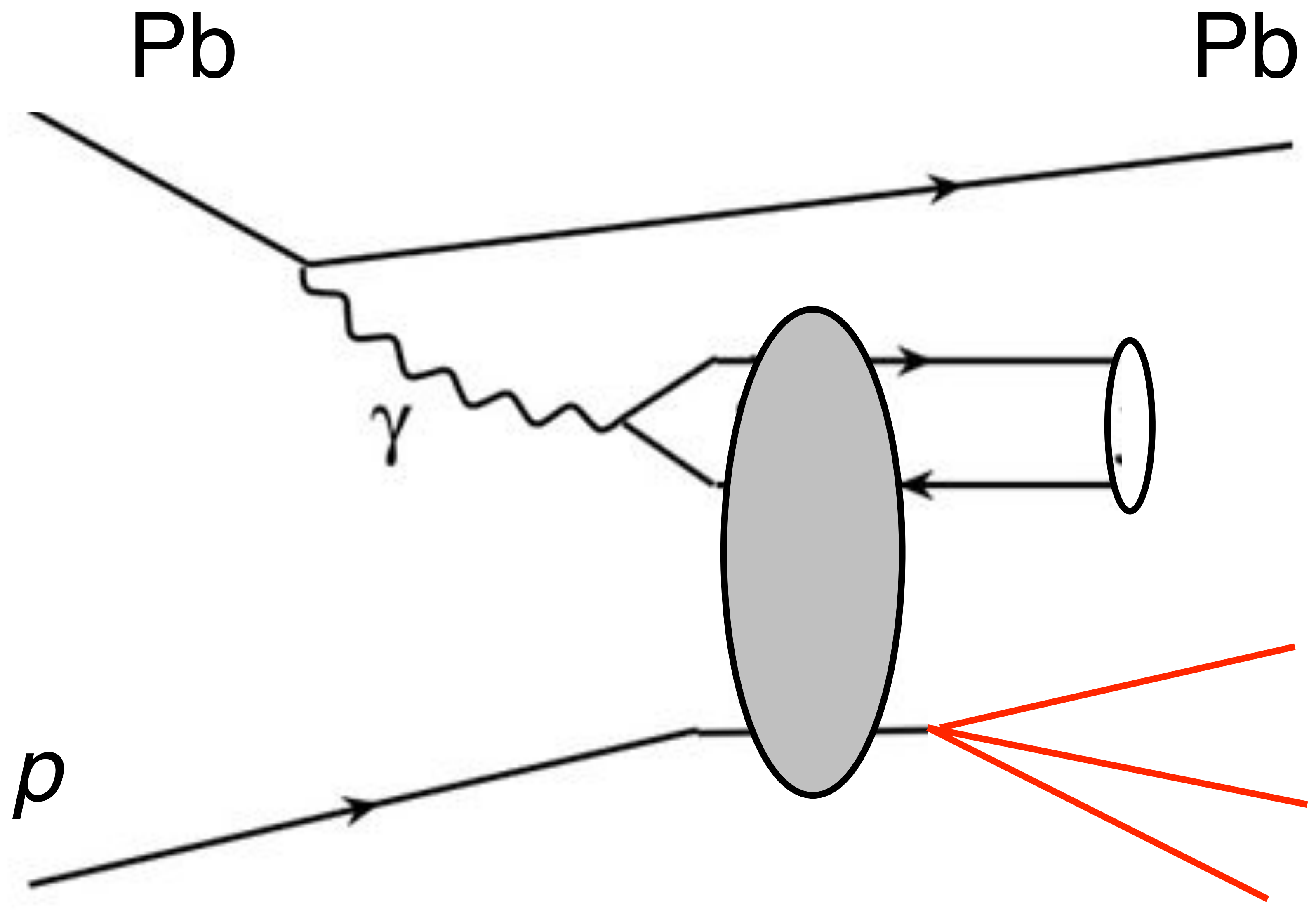
ρ has large size/interaction strength
Large shadowing correction from GGCF needed



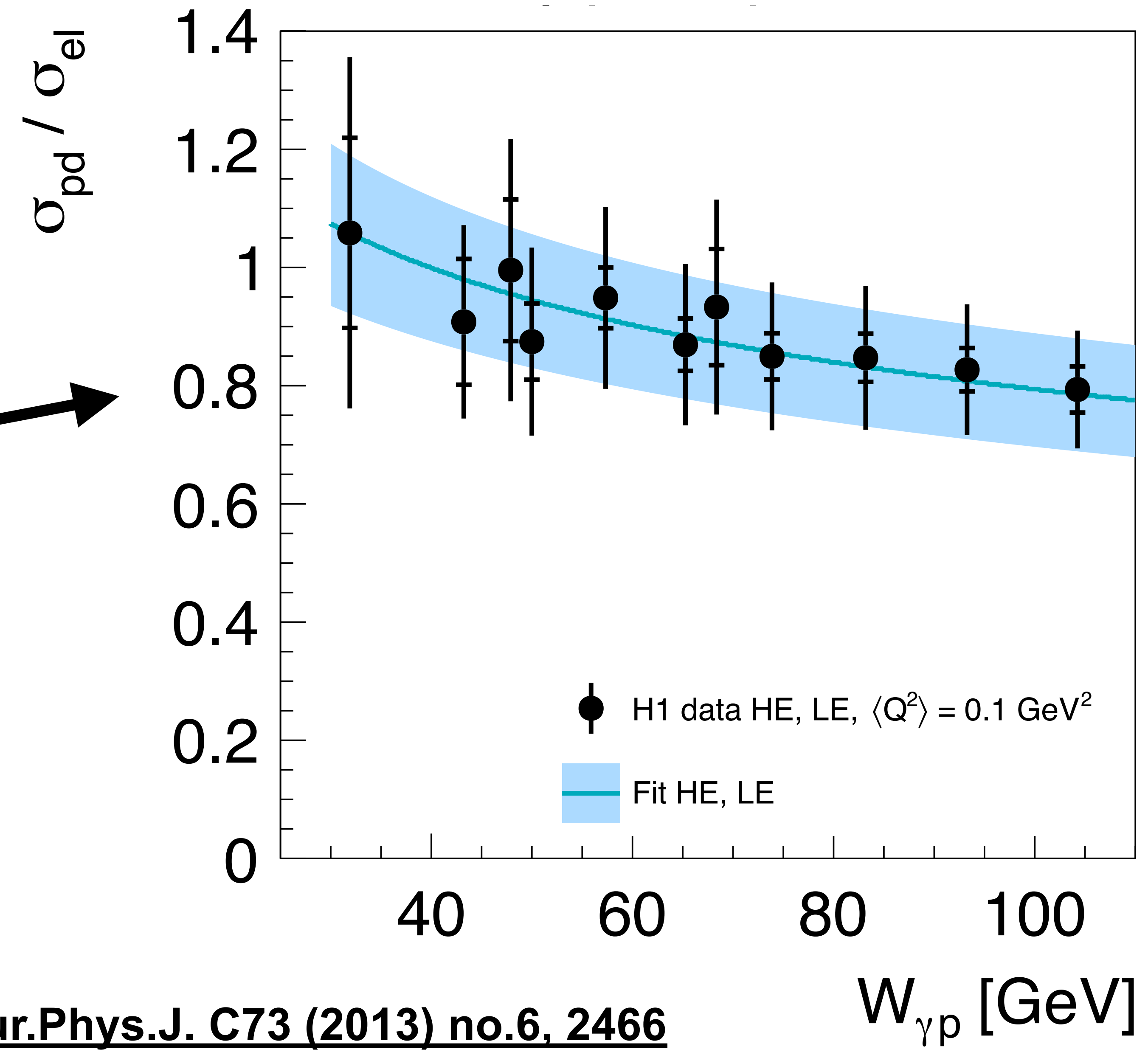
Causes shift in diffraction pattern

Frankfurt, Guzey, Strikman & Zhalov
Phys.Lett. B752 (2016) 51-58

Quarkonia: baseline from *p*+Pb



- **In p+Pb collisions nucleus is usually photon emitter and the proton is the "target"**
  - **Photo-production in *p*+Pb ⇔ γp collisions**
- **Two cases:**
  - **(quasi-) "elastic": proton target remains intact**
  - **"dissociative": proton breaks apart**
- **Expectation is that dissociative contribution grows more slowly with energy than elastic, e.g. slope determined by "universal" pomeron**
- **Feature present in HERA data**



H1 Collaboration Eur.Phys.J. C73 (2013) no.6, 2466