Report from the Theory Working Group

Alessandro Bacchetta, Wim Cosyn, Felix Ringer, ***Anna Staśto***

Who are we ?

Theory Working Group

We solicit overarching questions/topics from the EIC community for discussions involving both **theorists** and **experimentalists**.

Please submit questions for the EIC User Group's Theoretical Physics Working Group using **google form** from the **wiki page**

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https://wiki.bnl.gov/eicug/index.php/Theory

Any input is welcome, thank you for your help!

Activities: topics and speakers

Radiative corrections

Barbara Badełek

Jianwei Qiu

Polarized Bethe-Heitler

Andrei Afanasev

Beyond single photon approximation (lessons from low/intermediate energies)

Jose Manuel Udias

Diffractive minima

Heikki Mantysaari

Peter Steinberg

Good-Walker picture

Bjoern Schenke

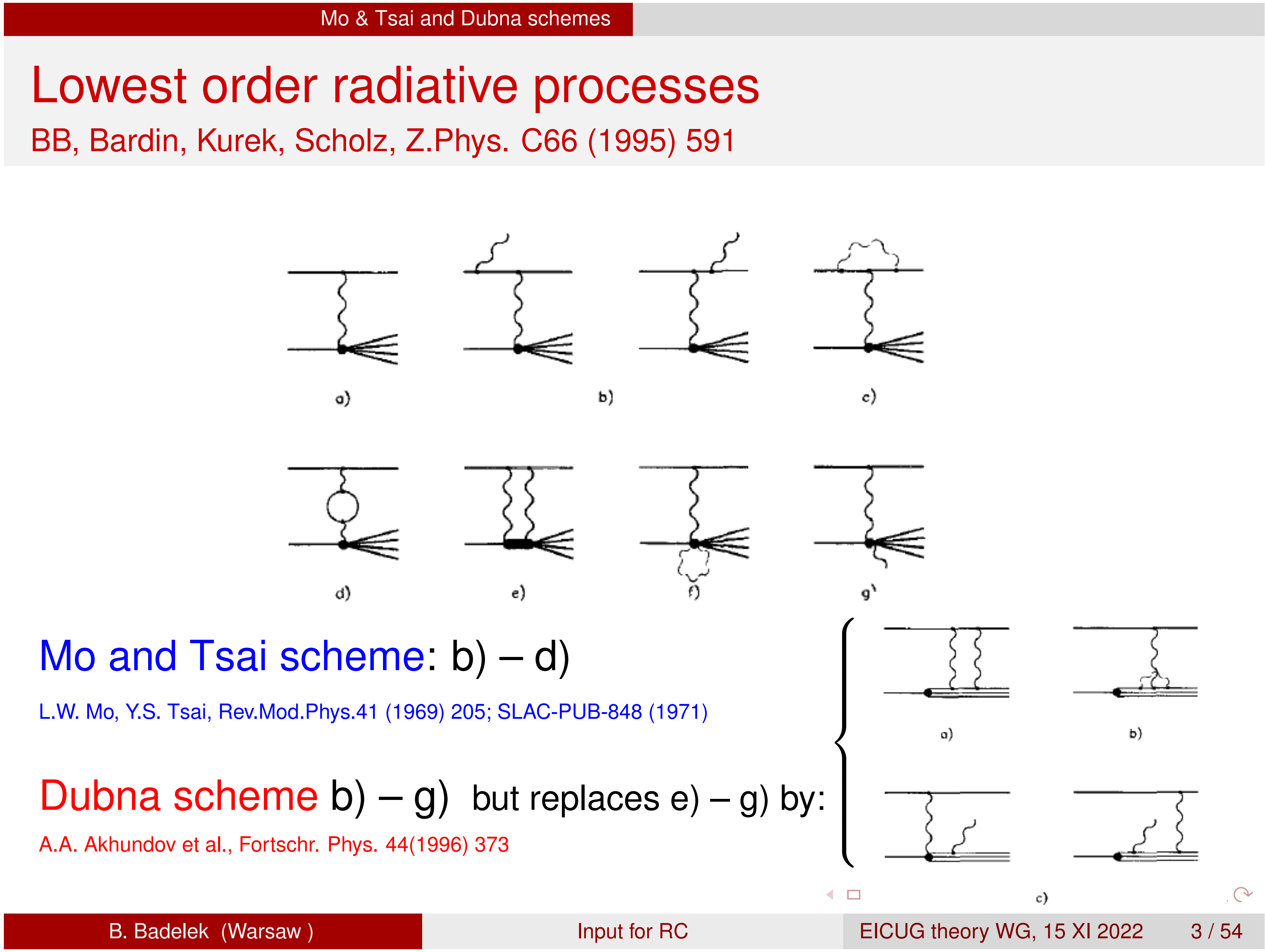
Spencer Klein

Diffraction and light nuclei

Matteo Rinaldi

Radiative corrections

Barbara Badełek



Mo & Tsai and Dubna schemes

Lowest order radiative processes

BB, Bardin, Kurek, Scholz, Z.Phys. C66 (1995) 591

Mo and Tsai scheme: b) – d)

L.W. Mo, Y.S. Tsai, Rev.Mod.Phys.41 (1969) 205; SLAC-PUB-848 (1971)

Dubna scheme b) – g) but replaces e) – g) by:

A.A. Akhundov et al., Fortschr. Phys. 44(1996) 373

B. Badelek (Warsaw) Input for RC EICUG theory WG, 15 XI 2022 3 / 54

Radiative corrections

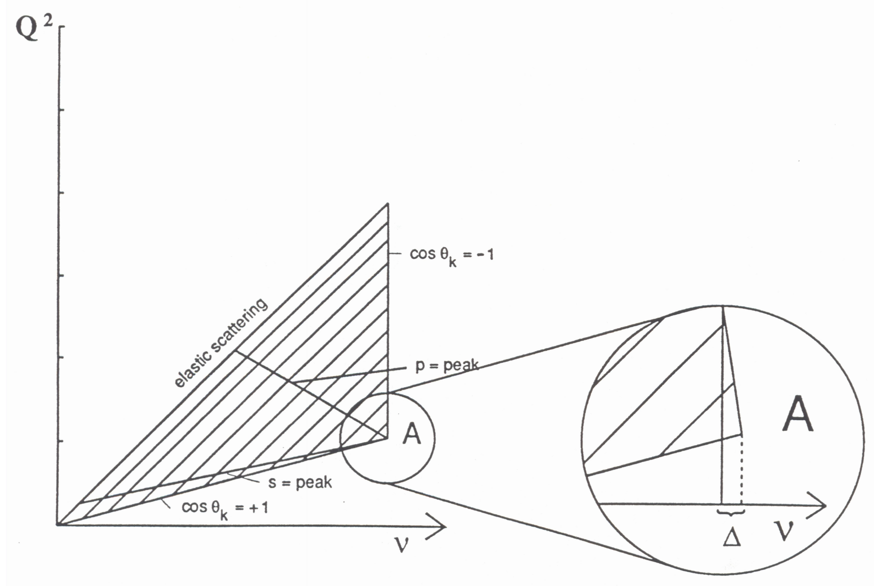
Barbara Badełek

- At (unpolarised) DIS: $\frac{\mathrm{d}^2\sigma_{meas}}{\mathrm{d}Q^2\mathrm{d}x} = f\left[F_{el}(Q^2), F_{qel}(Q^2), F_L(x,Q^2), F_2(x,Q^2)\right]$

  Here:

  $F_{el}(Q^2)$ – target elastic form factor
  $F_{qel}(Q^2)$ – target quasi-elastic form factor
  $F_L(x,Q^2), F_2(x,Q^2)$ – DIS structure functions
  must be known for $x_{meas} < x < 1, \quad 0 < Q^2 < Q^2_{max}$
- In case of polarised DIS, also $g_1(x,Q^2), g_2(x,Q^2)$ must be included in the x-section $\mathrm{d}^2\sigma_{meas}/(\mathrm{d}Q^2\mathrm{d}x)$
- TERAD provides only inclusive radiative corrections (cross sections
- Measurements are corrected event-by-event by a radcorr factor $\eta(x,Q^2) = \sigma 1\gamma/\sigma_{meas}$
- Different input functions were collected for p, d and nuclear targets
- Attention! Elastic radiative tail which fakes inelastic one!
- TERAD used in NMC, SMC, COMPASS;

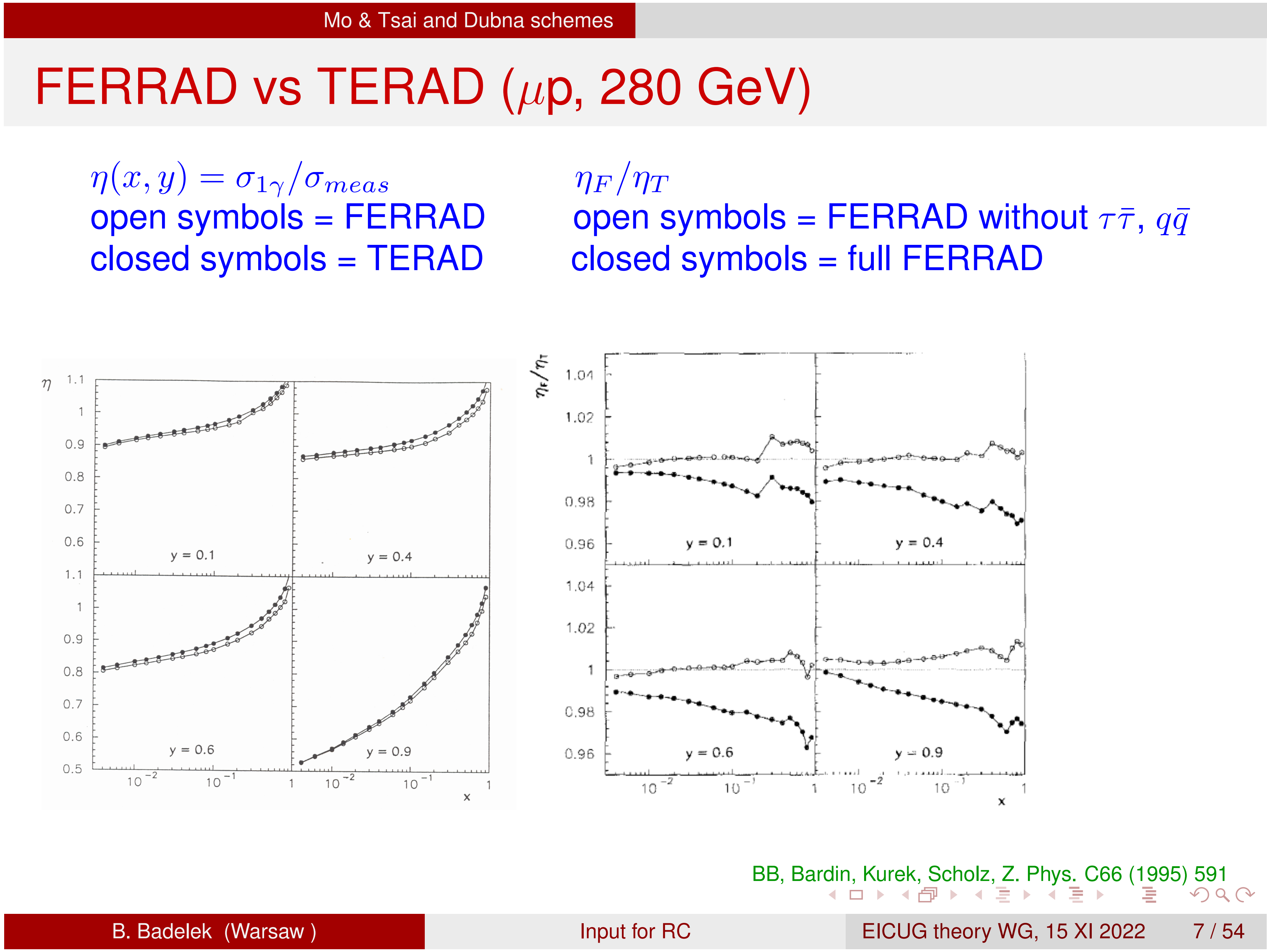
  exact calculations $\Longrightarrow$ tables $\Longrightarrow$ 2-D interpolation



Even if we measure at DIS, information on F_L, F_2 (or R, F_2) needed down to Q^2 =0!

Radiative corrections : consistency between schemes

Barbara Badełek



Mo & Tsai and Dubna schemes

FERRAD vs TERAD (μp, 280 GeV)

$\eta(x, y) = \sigma_{1\gamma}/\sigma_{meas}$
open symbols = FERRAD
closed symbols = TERAD

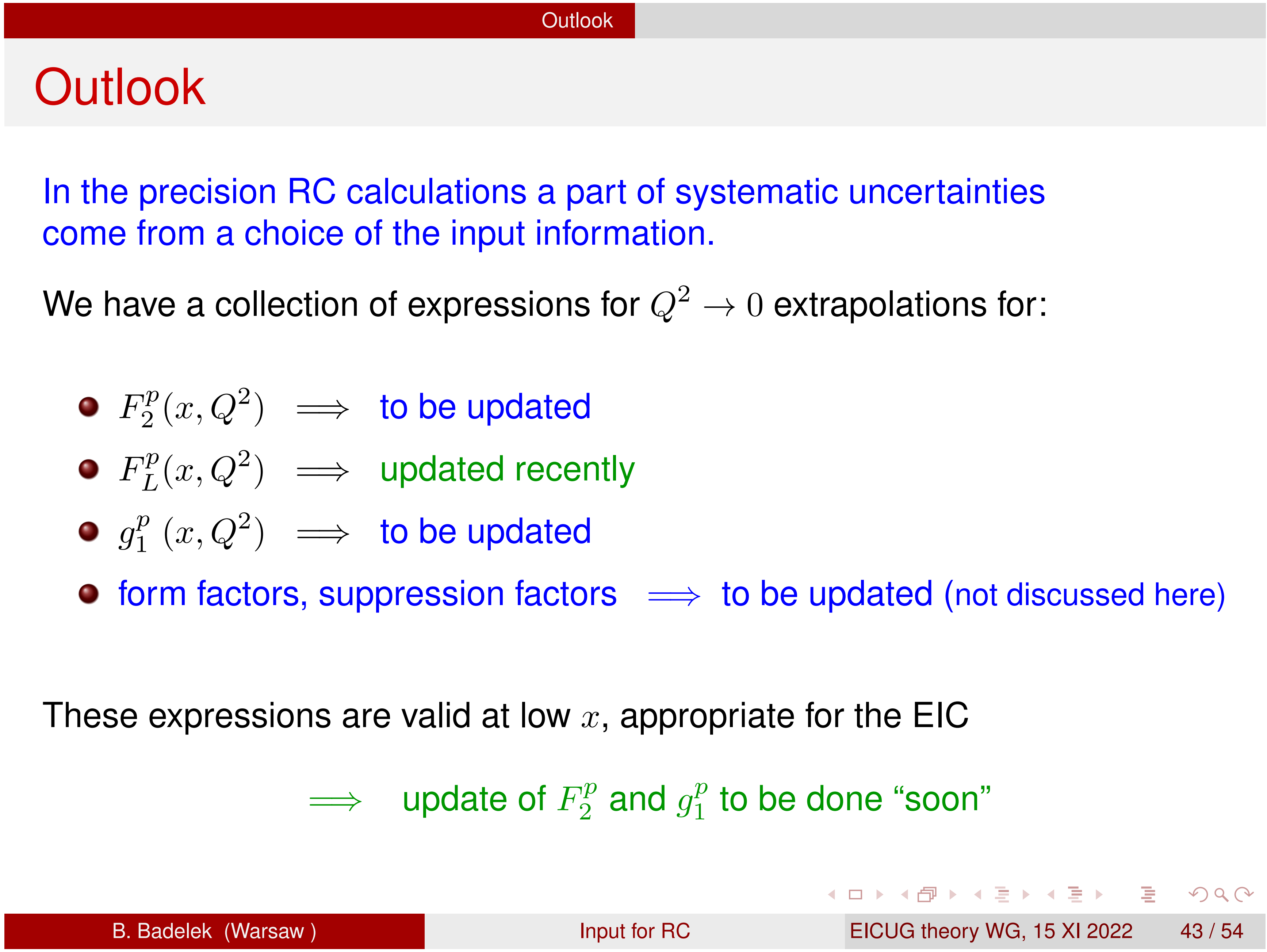
η_F/η_T
open symbols = FERRAD without $\tau\bar{\tau}$, $q\bar{q}$
closed symbols = full FERRAD

BB, Bardin, Kurek, Scholz, Z. Phys. C66 (1995) 591

B. Badelek (Warsaw) Input for RC EICUG theory WG, 15 XI 2022 7 / 54

Outlook for the EIC: updates for the low Q^2 needed

Barbara Badełek



Outlook

Outlook

In the precision RC calculations a part of systematic uncertainties come from a choice of the input information.

We have a collection of expressions for $Q^2 \rightarrow 0$ extrapolations for:

- $F_2^p(x, Q^2) \quad \Longrightarrow$ to be updated
- $F_L^p(x, Q^2) \quad \Longrightarrow$ updated recently
- $g_1^p\ (x, Q^2) \quad \Longrightarrow$ to be updated
- form factors, suppression factors $\Longrightarrow$ to be updated (not discussed here)

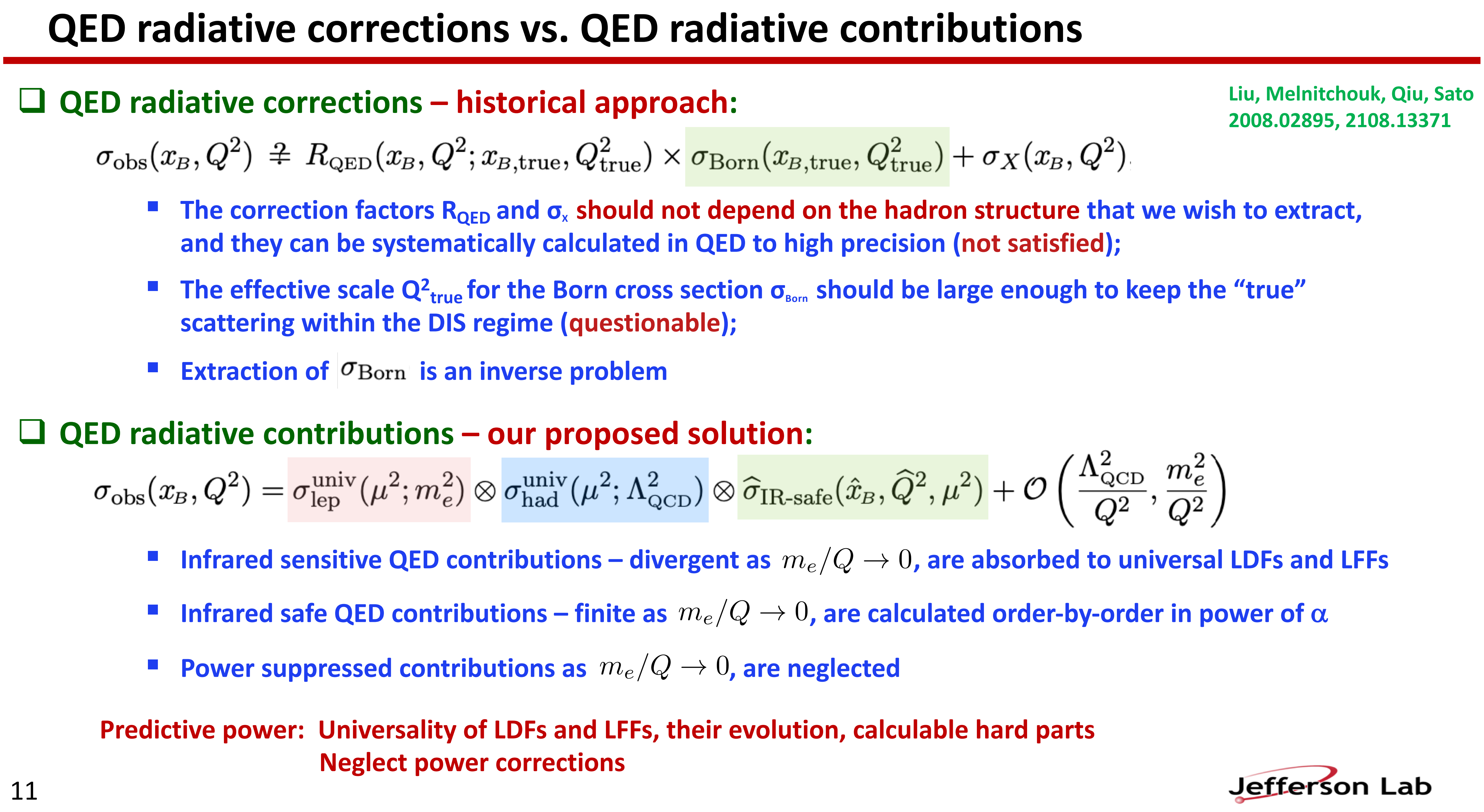
These expressions are valid at low x, appropriate for the EIC

$\Longrightarrow$ update of F_2^p and g_1^p to be done “soon”

B. Badelek (Warsaw) | Input for RC | EICUG theory WG, 15 XI 2022 | 43 / 54

Radiative corrections

Jianwei Qiu



QED radiative corrections vs. QED radiative contributions

Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371

☐ **QED radiative corrections – historical approach:**

$$\sigma_{\rm obs}(x_B, Q^2) \overset{?}{=} R_{\rm QED}(x_B, Q^2; x_{B,\rm true}, Q^2_{\rm true}) \times \sigma_{\rm Born}(x_{B,\rm true}, Q^2_{\rm true}) + \sigma_X(x_B, Q^2)$$

- The correction factors $R_{\rm QED}$ and σ_x should not depend on the hadron structure that we wish to extract, and they can be systematically calculated in QED to high precision (not satisfied);
- The effective scale $Q^2_{\rm true}$ for the Born cross section $\sigma_{\rm Born}$ should be large enough to keep the "true" scattering within the DIS regime (questionable);
- Extraction of $\sigma_{\rm Born}$ is an inverse problem

☐ **QED radiative contributions – our proposed solution:**

$$\sigma_{\rm obs}(x_B, Q^2) = \sigma^{\rm univ}_{\rm lep}(\mu^2; m_e^2) \otimes \sigma^{\rm univ}_{\rm had}(\mu^2; \Lambda^2_{\rm QCD}) \otimes \widehat{\sigma}_{\text{IR-safe}}(\hat{x}_B, \widehat{Q}^2, \mu^2) + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{Q^2}, \frac{m_e^2}{Q^2}\right)$$

- Infrared sensitive QED contributions – divergent as $m_e/Q \to 0$, are absorbed to universal LDFs and LFFs
- Infrared safe QED contributions – finite as $m_e/Q \to 0$, are calculated order-by-order in power of α
- Power suppressed contributions as $m_e/Q \to 0$, are neglected

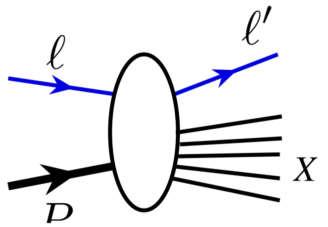
Predictive power: Universality of LDFs and LFFs, their evolution, calculable hard parts
Neglect power corrections

Radiative corrections: QED/QCD factorization

Jianwei Qiu

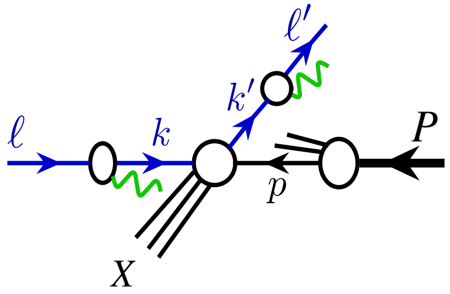
Inclusive lepton-hadron deep inelastic scattering (DIS)

❑ **Inclusive production of single high p_T lepton in lepton-hadron collision:**



$$e(\ell,\lambda_\ell) + N(P,S) \to e(\ell') + X$$

$$d\sigma_{\ell(\lambda_\ell)P(S)\to\ell' X} = \frac{1}{2s}\left|M_{\ell(\lambda_\ell)P(S)\to\ell' X}\right|^2 d\text{PS}$$



$$E'\frac{d\sigma_{\ell P\to\ell' X}}{d^3\ell'} \approx \frac{1}{2s}\sum_{ija}\int_{\zeta_{\min}}^{1}\frac{d\zeta}{\zeta^2}\int_{\xi_{\min}}^{1}\frac{d\xi}{\xi}\,D_{e/j}(\zeta,\mu^2)\,f_{i/e}(\xi,\mu^2)$$

$$\times\int_{x_{\min}}^{1}\frac{dx}{x}\,f_{a/N}(x,\mu^2)\,\widehat{H}_{ia\to jX}(\xi\ell, xP, \ell/\zeta,\mu^2) + \cdots$$

Collinear QED & QCD factorization

Lepton distribution functions (LDFs): $f_{i/e}(\xi,\mu^2)$

Lepton fragmentation functions (LFFs): $D_{e/j}(\zeta,\mu^2)$ $\quad i.j = e,\gamma,\bar{e},\ldots,q,g,\ldots$

Parton distribution functions (PDFs): $f_{a/N}(x,\mu^2)$ $\quad a = q,g,\bar{q},e,\gamma,\bar{e},\ldots$

Short-distance hard coefficients: $\widehat{H}_{ia\to jX}(\xi\ell, xP,\ell/\zeta,\mu^2)$

$$\approx \widehat{H}^{(m,n)}_{ia\to jX}(\xi\ell, xP,\ell/\zeta,\mu^2) \approx \mathcal{O}(\alpha^m\alpha_s^n)$$

Photon is charge neutral
QED factorization works

- **No DIS "Structure Functions"!**

  Concept of one-photon exchange

- **QED & QCD contribution are factorized at the same scale: μ**

  $$(x_B, Q^2) \;\to\; (y, \ell'_T)$$

- **Corrections suppressed by power**

  $$(1/\ell'_T)^\alpha$$

Nayak, Qiu, Sterman, Phys.Rev.D 72 (2005) 114012

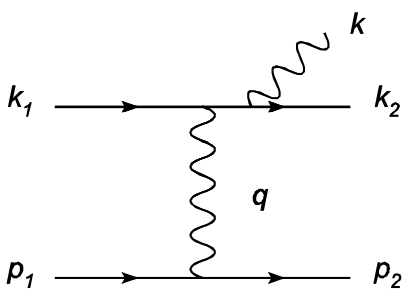
Radiative corrections: QED/QCD factorization

Jianwei Qiu

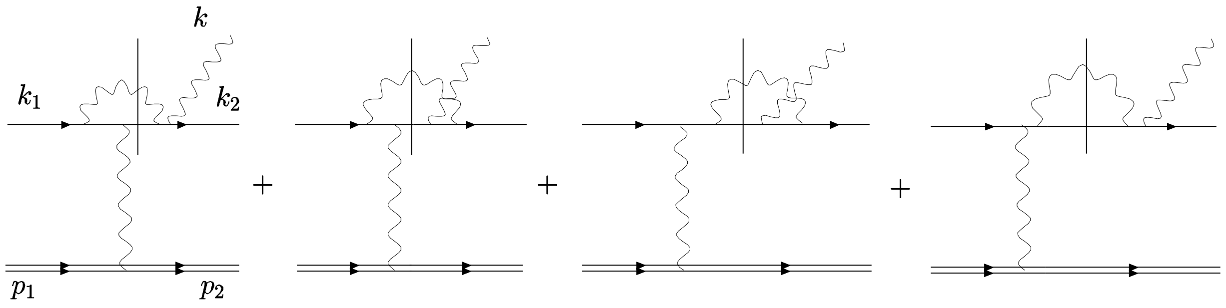
- ❑ **Factorization approach to include both QCD and QED radiative contributions provides a consistent and controllable approximation**
  - ○ **QED radiation is a part of production cross sections, treated in the same way as QCD radiation from quarks and gluons**
  - ○ **No artificial and/or process dependent scale(s) introduced for treating QED radiation, other than the standard factorization scale, universal lepton distribution and fragmentation functions**
  - ○ **All perturbatively calculable hard parts are IR safe for both QCD and QED**
  - ○ **All lepton mass or resolution sensitivity are included into "Universal" lepton distribution and fragmentation functions (or jet functions)**

Radiative corrections to Bethe-Heitler process and DVCS

Andrei Afanasev

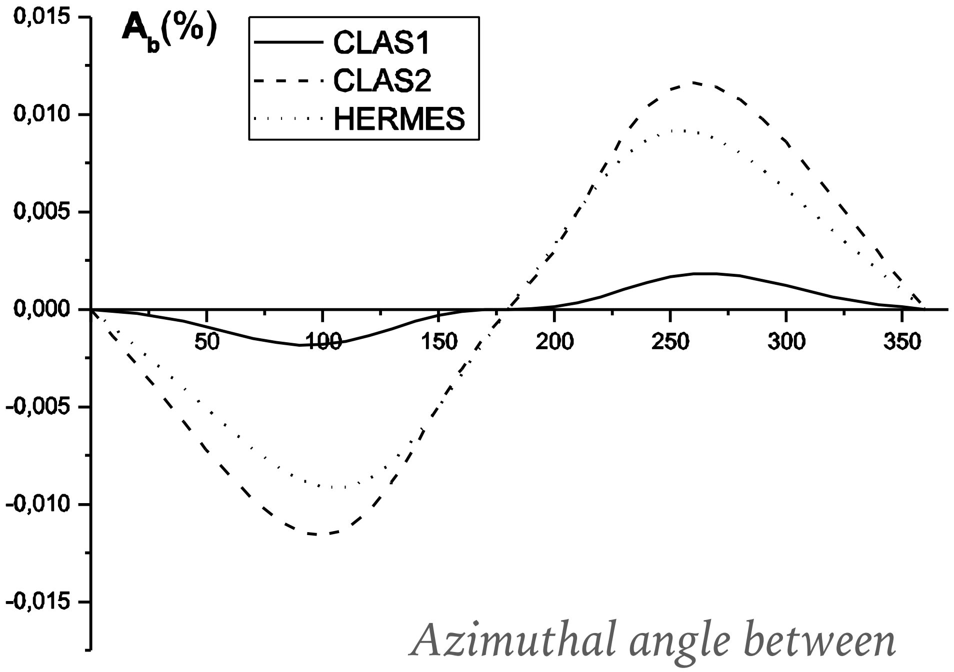


Tree-level real amplitude



QED loop diagrams

Numerical results



Azimuthal angle between $(\mathbf{q}_1, \mathbf{k}_1)$ *and* $(\mathbf{q}_1, \mathbf{p}_1)$ *planes*

Asymmetry less than 0.015%

Radiative corrections to DVCS : interference with BH

Andrei Afanasev

RC to Polarized DVCS

- Akushevich, Illyichev PRD **98**, 013005 (2018) : brem corrections to DVCS cross section and asymmetry, (leading-log approx, both e and p detected)

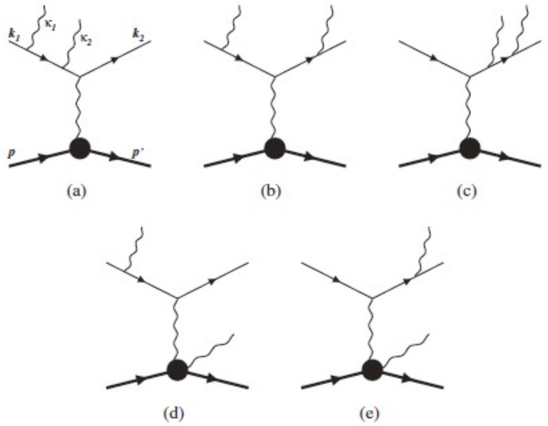


FIG. 2. Feynman graphs with two real photons in the final state: both photons produced by leptons (a), (b), and (c) and by leptons and hadrons (d) and (e).

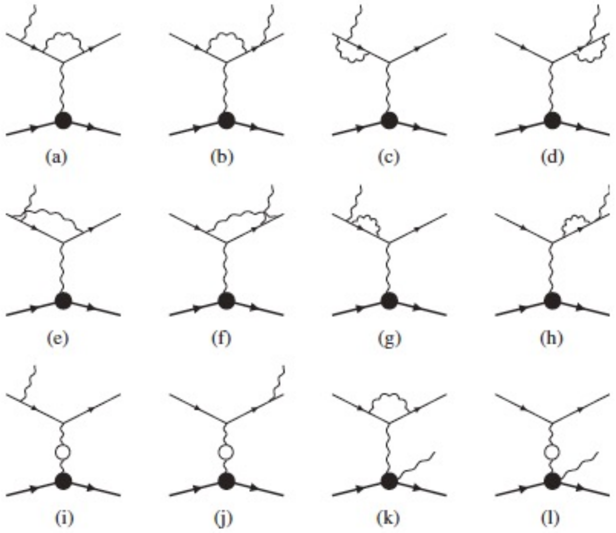


FIG. 4. The one-loop Feynman graphs for the BH (a-h) and DVCS (k) amplitudes containing the infrared divergence and the graphs for the vacuum polarization (i), (j), and (l).

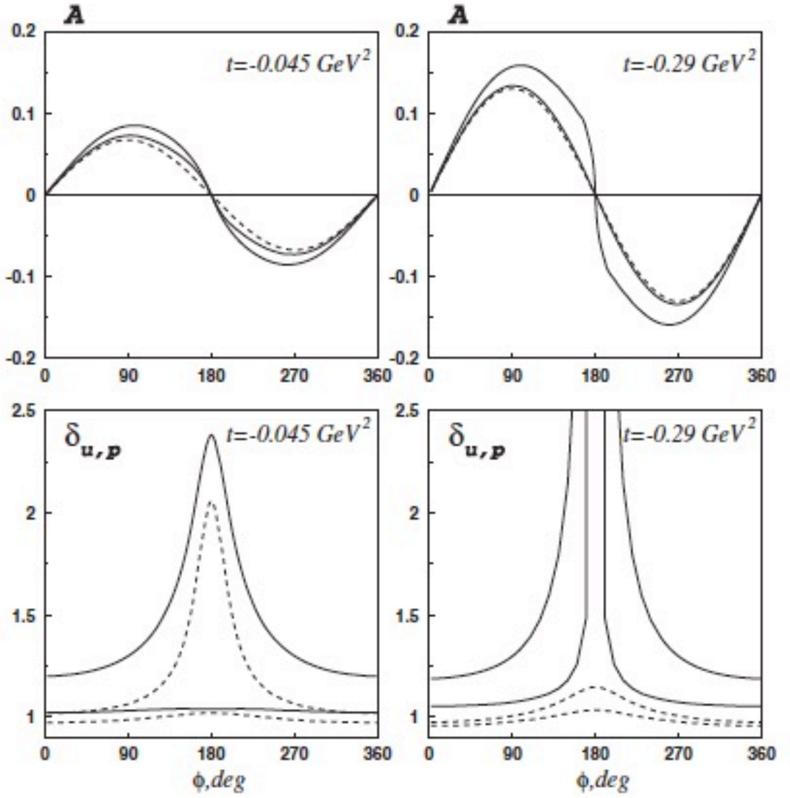
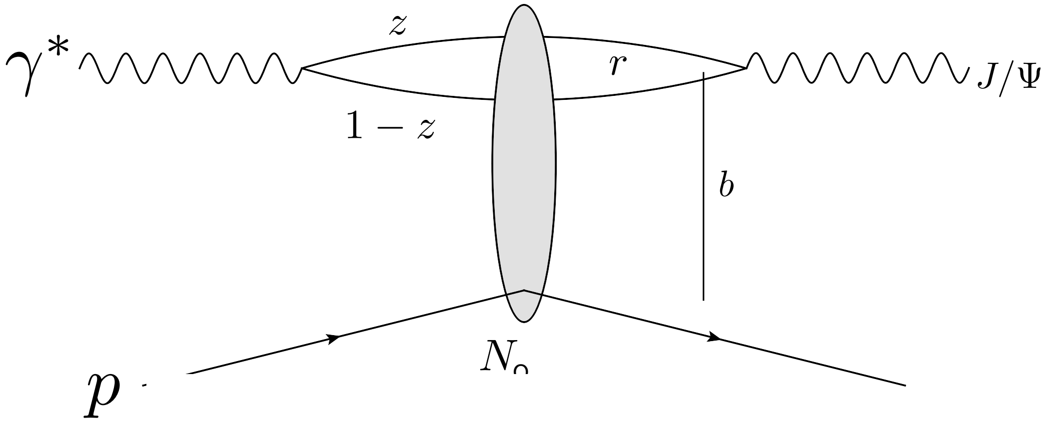


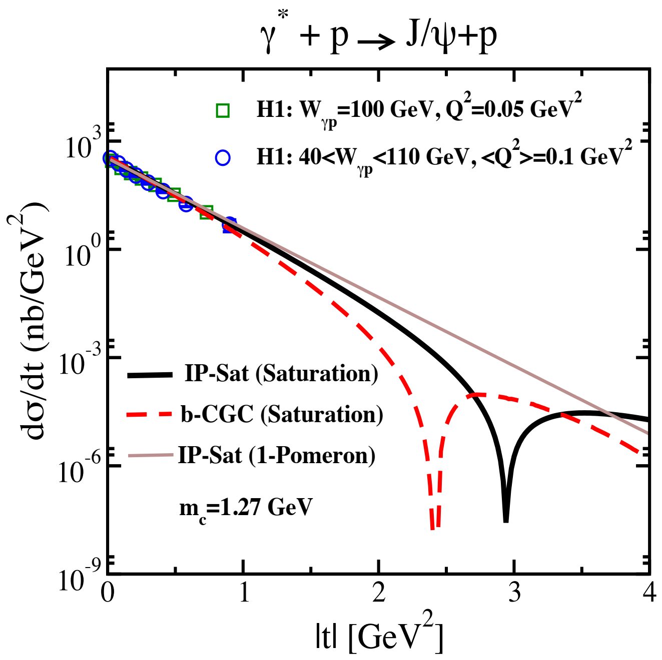
FIG. 5. The ϕ-dependence of the asymmetry (upper) and RC factors (lower plots). The dashed curve at the upper plots gives the $\sigma_{1\gamma}$ and the solid curve shows the observed cross sections with $V^2_{\rm cut} = 0.3$ GeV^2 (the curve closer to dashed curve) and without cuts. Dashed and solid curves at the bottom plots show $\delta_{u,p}$ with and without the cut, respectively. The curves with higher values corresponds to δ_p, i.e., $\delta_p > \delta_u$. Kinematical variables used for this example were $x = 0.1$, $Q^2 = 2$ GeV^2, and $E_{\rm beam} = 11$ GeV.

$$A = A_{1\gamma}\frac{\delta_p}{\delta_u}$$

Diffraction : exclusive VM and dips

Heikki Mantysaari





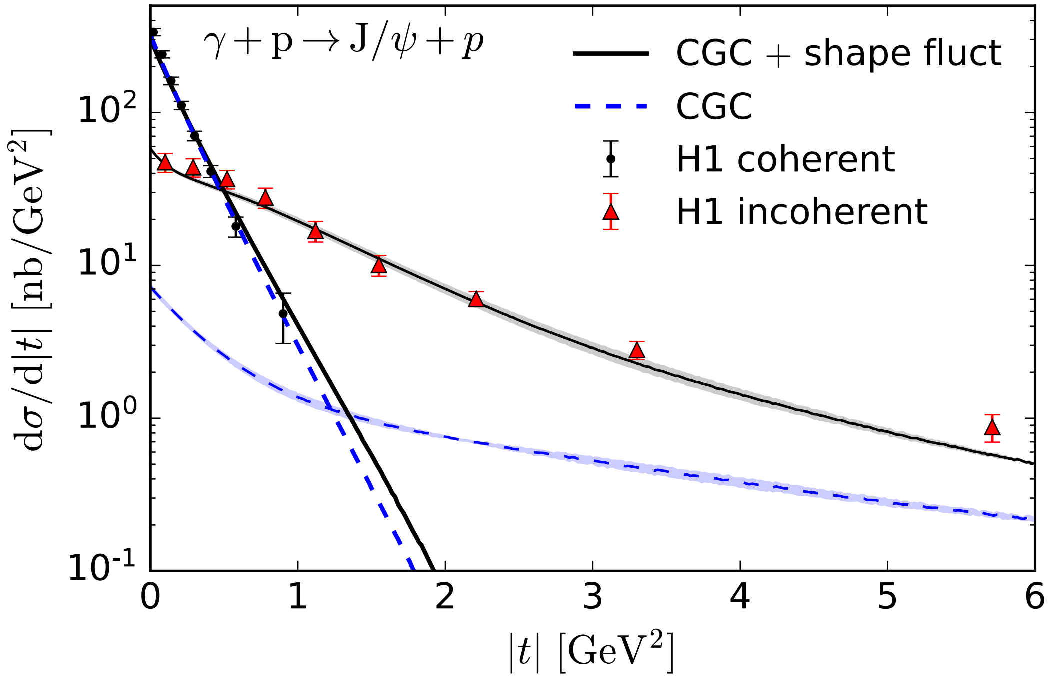
Armesto, Rezaeian, 1402.4831

Whether there are diffractive dips depends on

- Actual density profile
- Non-linear dynamics

Diffractive processes

- Exclusive process:
  $\mathcal{A} \sim \int \mathrm{d}^2\mathbf{b} e^{-i\mathbf{b}\cdot\Delta}\Psi^* \otimes \Psi_V \otimes N$

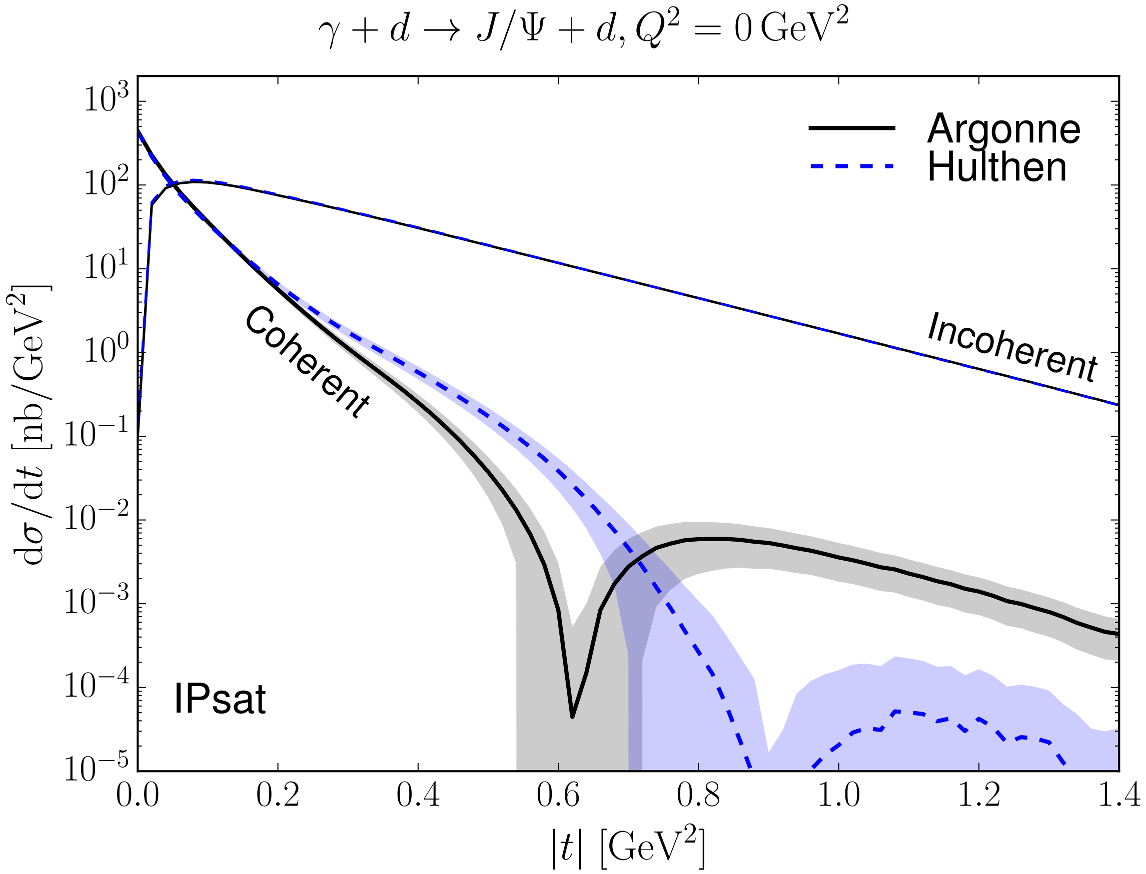


- Observing dips requires one to suppress incoherent background by 2 . . . 3 orders of magnitude
- Even if can't see the dips, pushing coherent spectra measurements towards high $|t|$ important: probe potential deviations from the Gaussian profile

Diffraction : exclusive VM on deuteron

Heikki Mantysaari

Predictions for the EIC: deuteron wave function



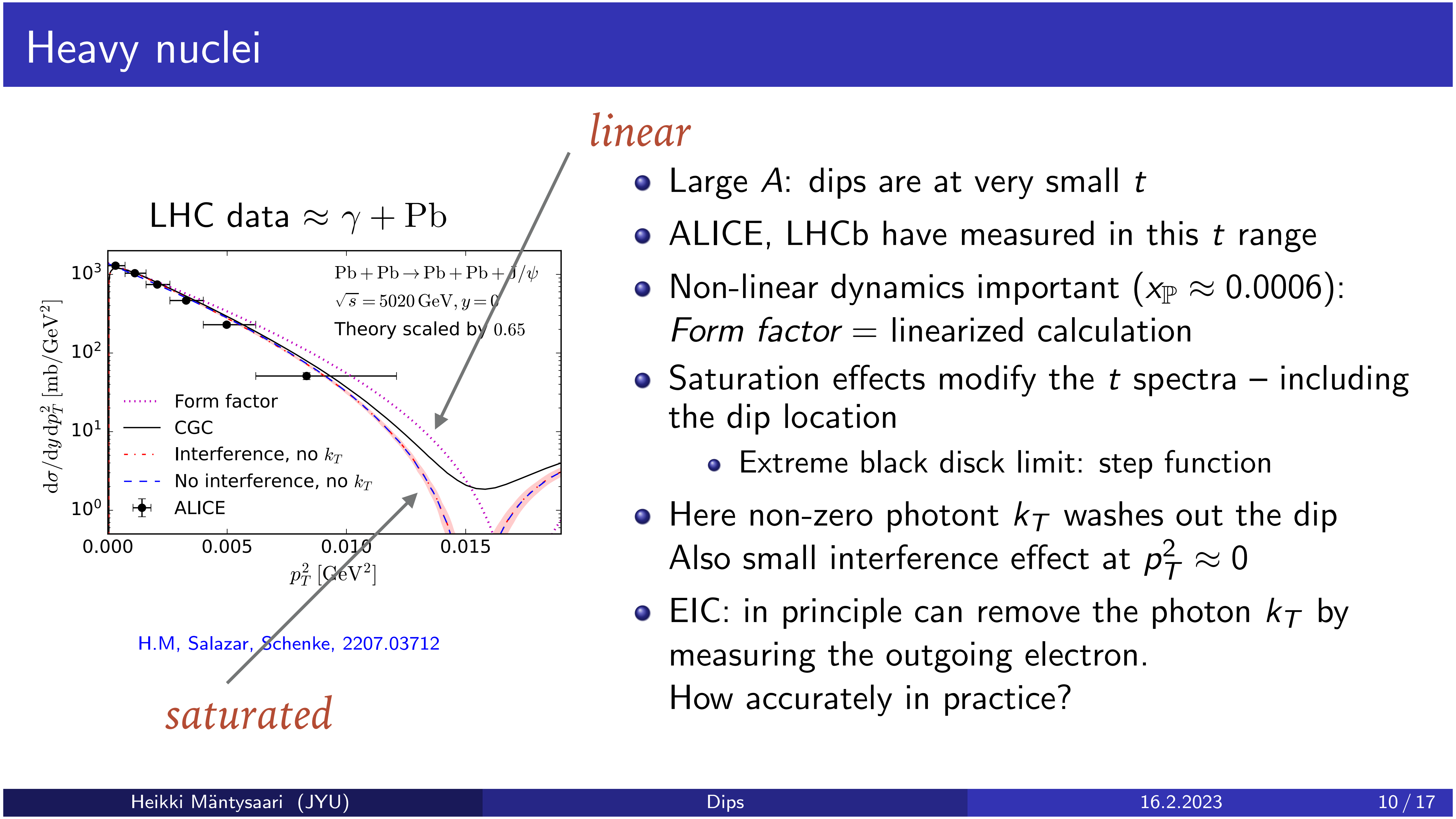
H.M, Schenke, 1910.03297

Hulthen vs Argonnev18 wave functions:

- Coherent spectra at $|t| \gtrsim 0.3\mathrm{GeV}^{-2}$ sensitive to short range correlations in WF
- Difference similar also after the JIMWLK evolution, but dips $\to$ smaller $|t|$
- Note: same RMS sizes, dip position differs due to different shapes
- Tiny effect on the incoherent cross section
- Observing the dip would require a huge reduction of the incoherent background

Diffraction in UPCs

Heikki Mantysaari



Heavy nuclei

LHC data $\approx \gamma + \mathrm{Pb}$

H.M, Salazar, Schenke, 2207.03712

linear

saturated

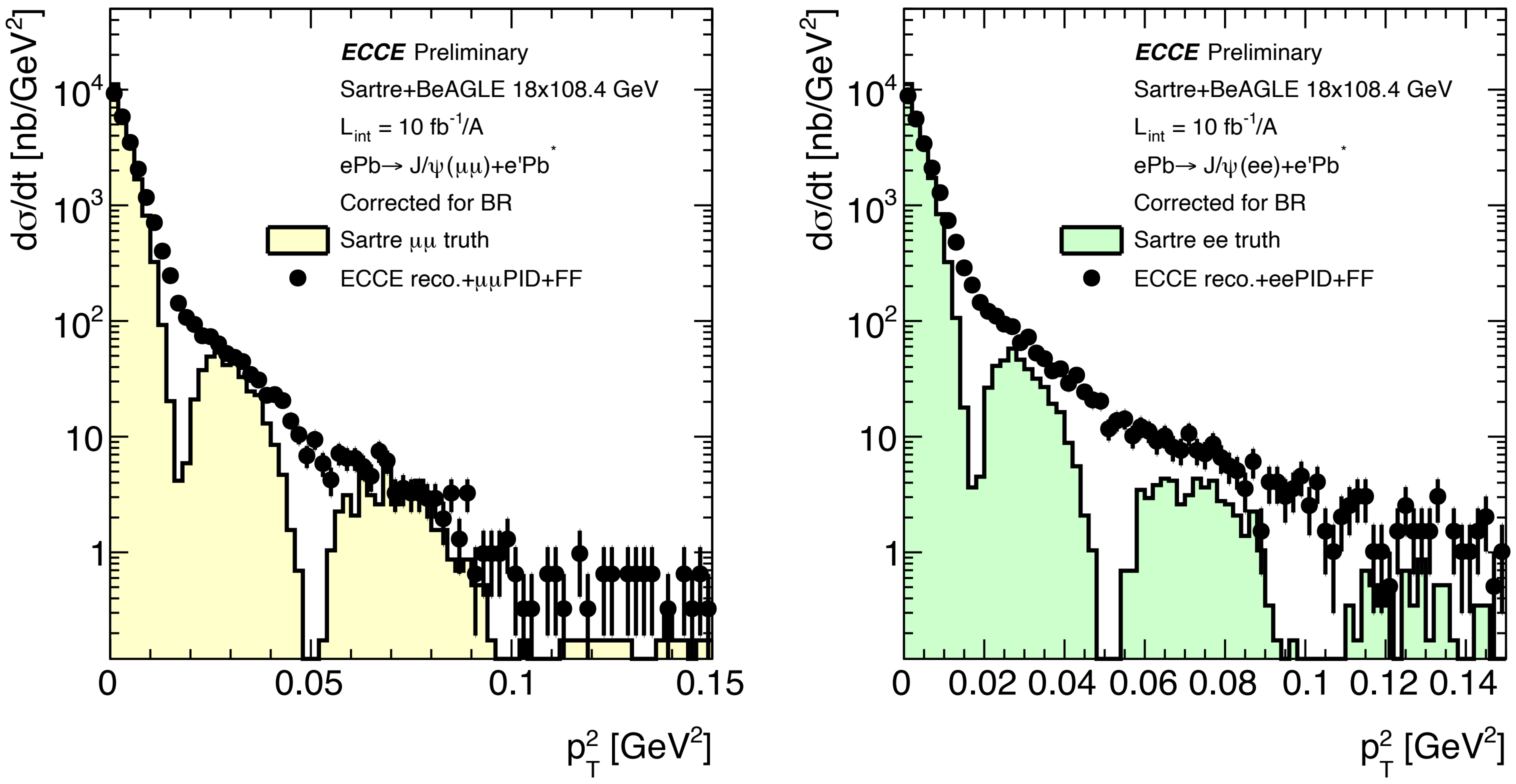
- Large A: dips are at very small t
- ALICE, LHCb have measured in this t range
- Non-linear dynamics important ($x_{\mathbb{P}} \approx 0.0006$):
  Form factor = linearized calculation
- Saturation effects modify the t spectra – including the dip location
  - Extreme black disck limit: step function
- Here non-zero photont k_T washes out the dip
  Also small interference effect at $p_T^2 \approx 0$
- EIC: in principle can remove the photon k_T by measuring the outgoing electron.
  How accurately in practice?

Heikki Mäntysaari (JYU) Dips 16.2.2023 10 / 17

Diffractive dips : experimental considerations

Peter Steinberg

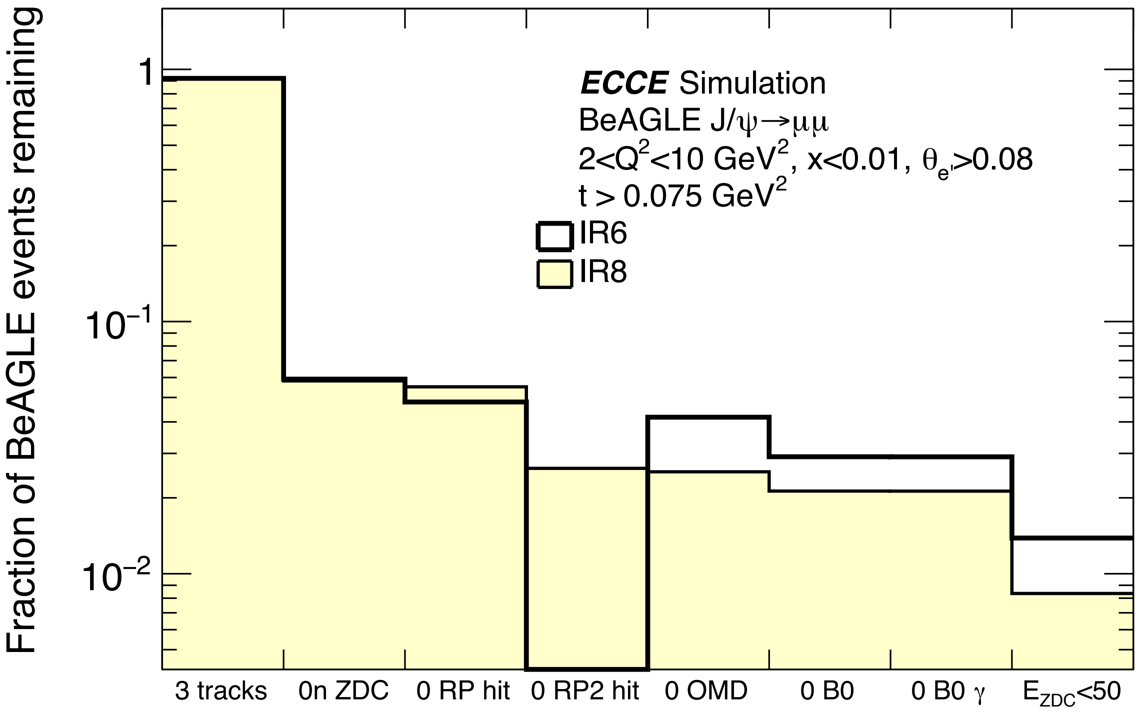
Coherent-only cross section



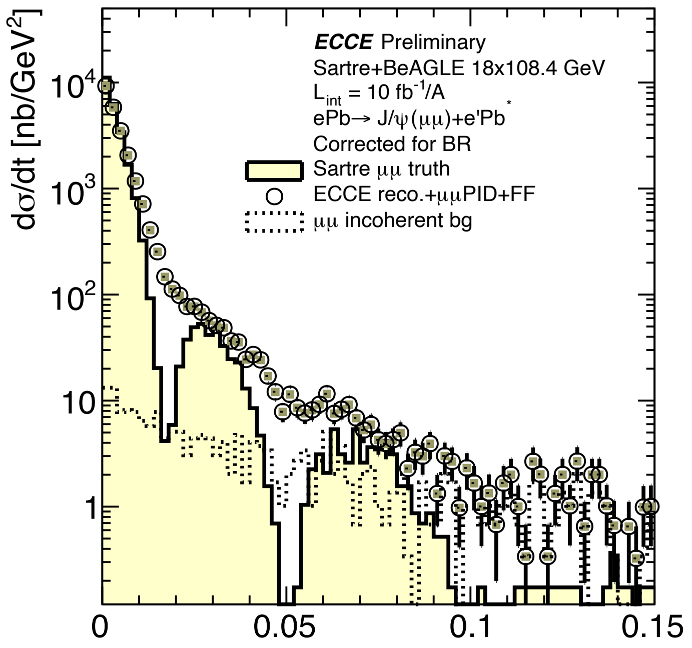
- Again, p_T^2 is used as proxy for *t*
- Correction is just simple integral of reconstructed counts over truth
- Efficiency vs Q^2 is mostly constant but composed of many parts: e' efficiency (track & cluster), charged decay products, PID cuts, kinematic constraints, etc.
- Aggregate efficiency is 40% for ee, 60% for μμ. Expect 15% systematics or better, as many efficiencies should be measurable in data using tag & probe technique
- Tracking resolution sufficient for observation of "kinks" in the μμ channel - weaker for ee

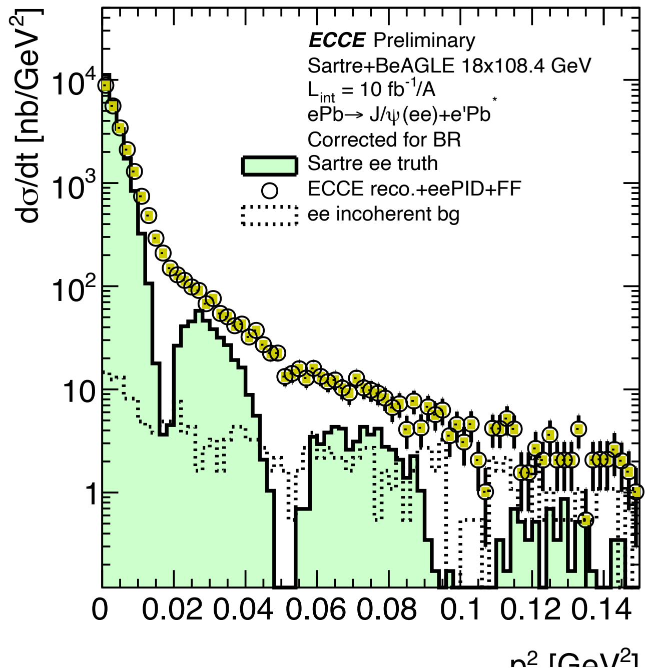
Incoherent background

Peter Steinberg



Simple representation of removing events with successive cuts on the ECCE forward detectors, at moderate $t > 0.075$ GeV^2

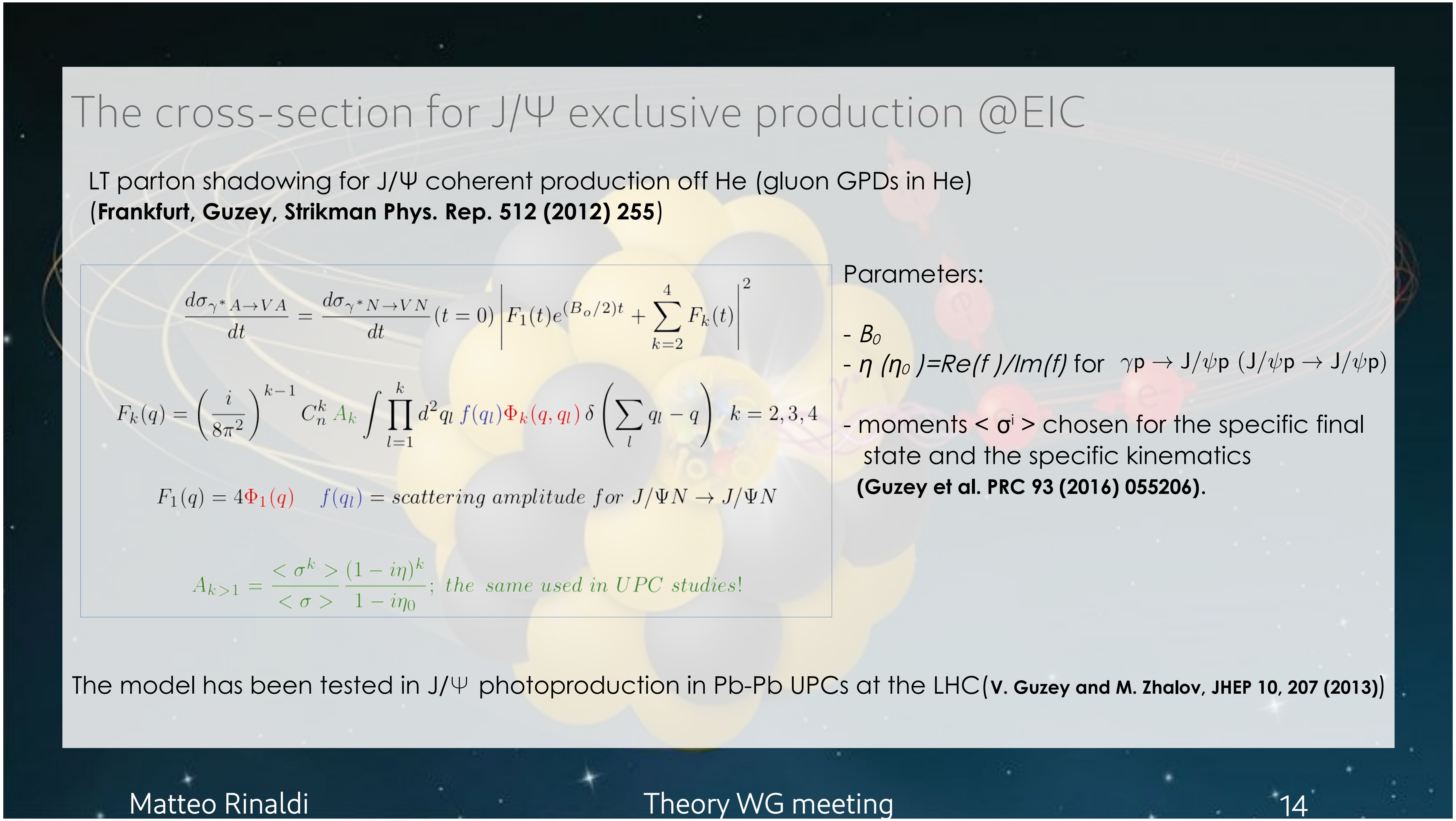




- **Total J/ψ yield compared to signal (filled) and incoherent (dashed histogram)**
  - Expect improvements with further optimization of detector design (e.g. B0 EMCal) and analysis methodology
- **Backgrounds modest up to second diffractive peak**
  - Cut more effective at larger t, but signal distribution drops rapidly

Coherent VM production on light nuclei

Matteo Rinaldi



The cross-section for J/Ψ exclusive production @EIC

LT parton shadowing for J/Ψ coherent production off He (gluon GPDs in He)
(**Frankfurt, Guzey, Strikman Phys. Rep. 512 (2012) 255**)

$$\frac{d\sigma_{\gamma^* A \to VA}}{dt} = \frac{d\sigma_{\gamma^* N \to VN}}{dt}(t=0)\left| F_1(t) e^{(B_o/2)t} + \sum_{k=2}^{4} F_k(t) \right|^2$$

$$F_k(q) = \left(\frac{i}{8\pi^2}\right)^{k-1} C_n^k\, A_k \int \prod_{l=1}^{k} d^2 q_l\, f(q_l) \Phi_k(q, q_l)\, \delta\left(\sum_l q_l - q\right) \quad k = 2,3,4$$

$$F_1(q) = 4\Phi_1(q) \qquad f(q_l) = scattering\ amplitude\ for\ J/\Psi N \to J/\Psi N$$

$$A_{k>1} = \frac{<\sigma^k>}{<\sigma>} \frac{(1-i\eta)^k}{1-i\eta_0};\ the\ \ same\ used\ in\ UPC\ studies!$$

Parameters:

- B_0
- η (η_0)=Re(f)/Im(f) for γp → J/ψp (J/ψp → J/ψp)

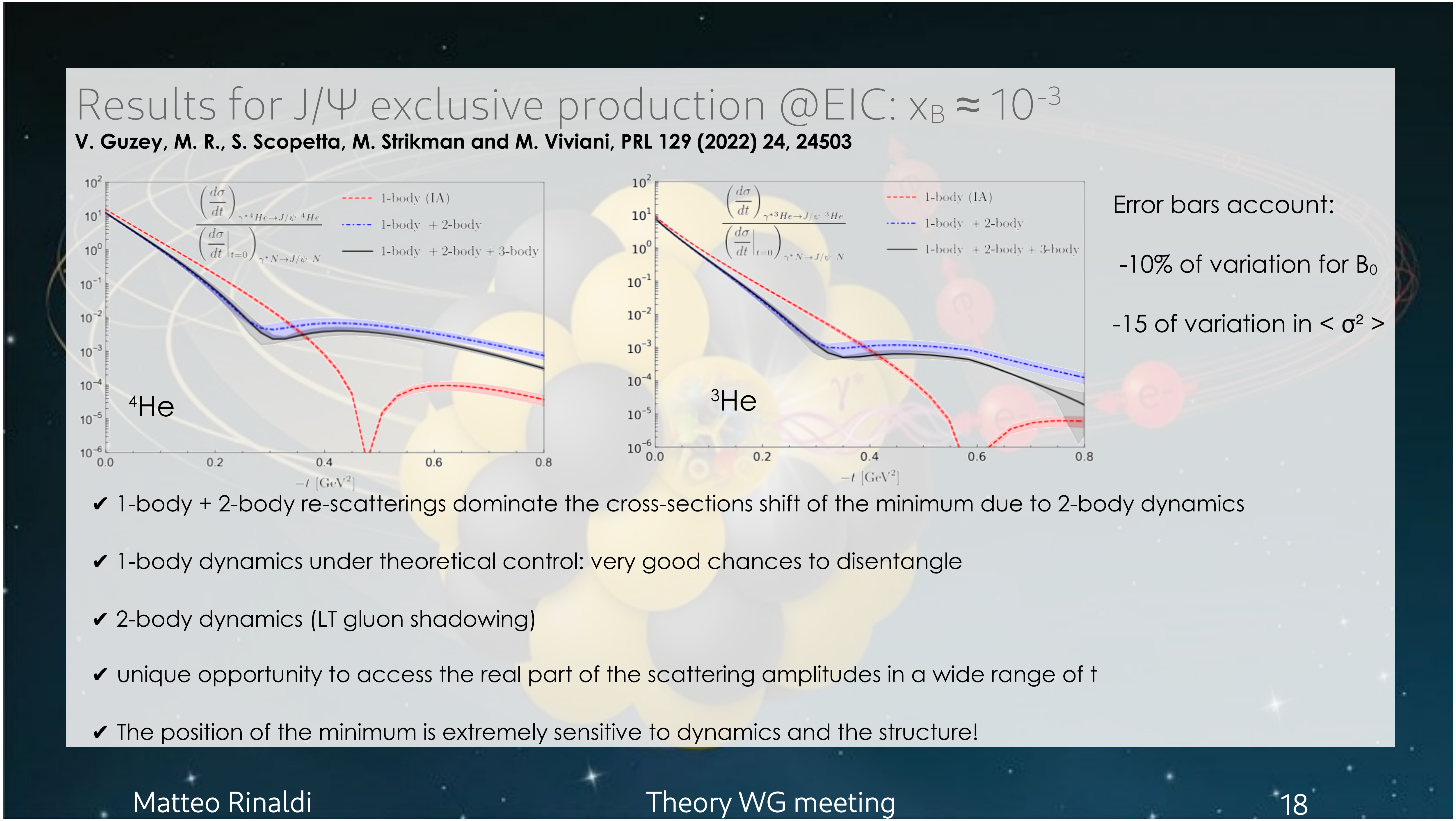
- moments < σ^i > chosen for the specific final state and the specific kinematics
(Guzey et al. PRC 93 (2016) 055206).

The model has been tested in J/Ψ photoproduction in Pb-Pb UPCs at the LHC(**V. Guzey and M. Zhalov, JHEP 10, 207 (2013)**)

Matteo Rinaldi Theory WG meeting 14

Coherent VM production on light nuclei

Matteo Rinaldi



Results for J/Ψ exclusive production @EIC: $x_B \approx 10^{-3}$

V. Guzey, M. R., S. Scopetta, M. Strikman and M. Viviani, PRL 129 (2022) 24, 24503

Error bars account:

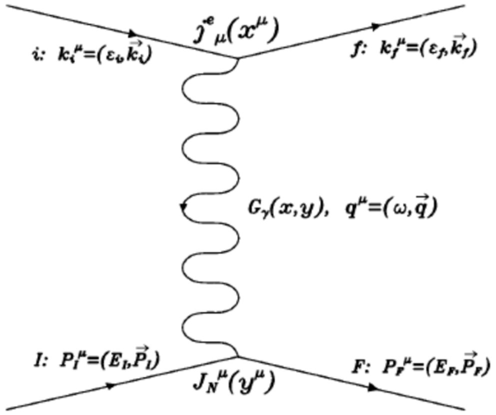
-10% of variation for B_0

-15 of variation in $< \sigma^2 >$

- ✔ 1-body + 2-body re-scatterings dominate the cross-sections shift of the minimum due to 2-body dynamics
- ✔ 1-body dynamics under theoretical control: very good chances to disentangle
- ✔ 2-body dynamics (LT gluon shadowing)
- ✔ unique opportunity to access the real part of the scattering amplitudes in a wide range of t
- ✔ The position of the minimum is extremely sensitive to dynamics and the structure!

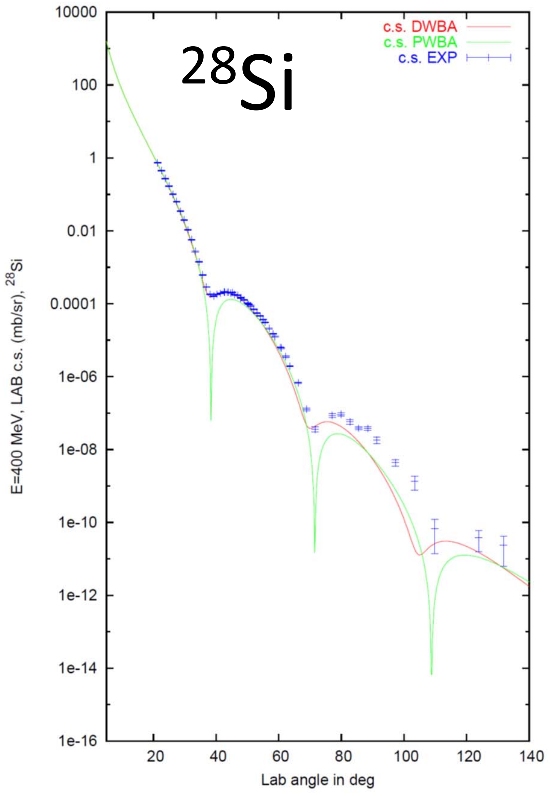
Elastic scattering off nuclei: beyond single photon approximation

Jose Manuel Udias



$$\frac{d\sigma}{d\Omega} = \sigma_{\mathrm{M}}\left|F_p(q)\right|^2$$

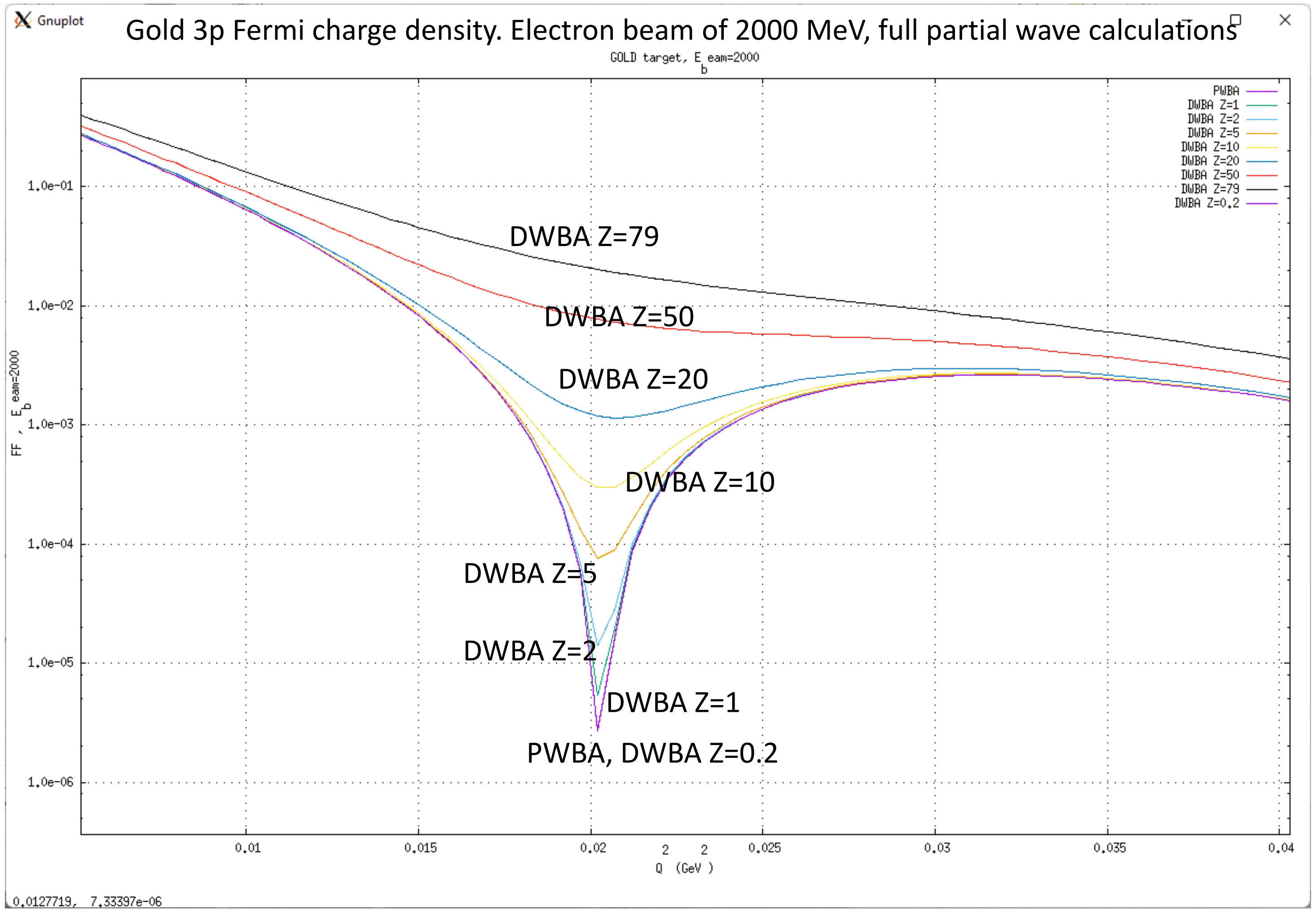
$$\sigma_{\mathrm{M}}(\theta) = \left(\frac{Ze^2}{2E}\right)^2 \frac{\cos^2(\theta/2)}{\sin^4(\theta/2)} \qquad F_p(q) = \int d^3r\, j_0(qr)\rho_{ch}(r)$$



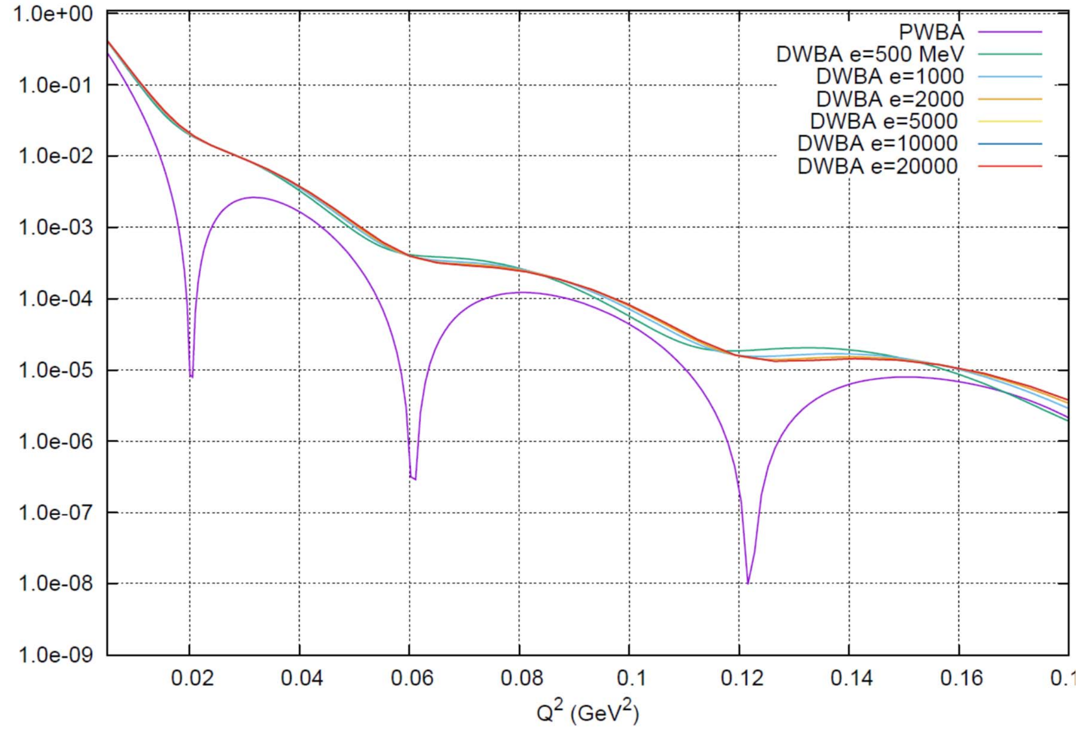
However, to compare with data the PWBA results are not good enough. The data show minima filled in and the maxima semared. The cross-section is shifted with regards to the data

Distorted wave Born approximation

Jose Manuel Udias



Gold 3p Fermi charge density. Electron beam of 2000 MeV, full partial wave calculations



Relevant for low and intermediate energies

Is there an effect at EIC and diffraction ?

Good–Walker picture for diffraction

Bjoern Schenke

Target: Average optical potential

Beam particle: $|B\rangle = \sum_k C_k |\psi_k\rangle$ (linear combination of the eigenstates of diffraction $|\psi_k\rangle$)

With $\mathrm{Im}T = 1 - \mathrm{Re}S$ the imaginary part of the scattering amplitude operator, we have

$\mathrm{Im}T|\psi_k\rangle = t_k|\psi_k\rangle$

with t_k the probability for eigenstate $|\psi_k\rangle$ to interact with the target (absorption coefficients)

Total cross section:

$$d\sigma_{\mathrm{tot}}/d^2\vec{b} = 2\langle t\rangle$$

$$\langle B|\mathrm{Im}T|B\rangle = \sum_k |C_k|^2 t_k = \langle t\rangle$$

Elastic cross section:

$$d\sigma_{\mathrm{el}}/d^2\vec{b} = \langle t\rangle^2$$

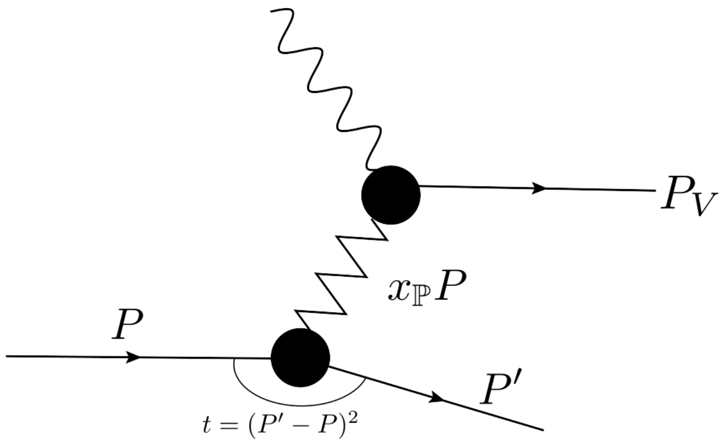
Incoherent diffractive cross section:

$$d\sigma_{\mathrm{diff}}/d^2\vec{b} = \langle t^2\rangle - \langle t\rangle^2$$

Diffractive VM cross section in the dipole picture

Bjoern Schenke

Diffractive vector meson production

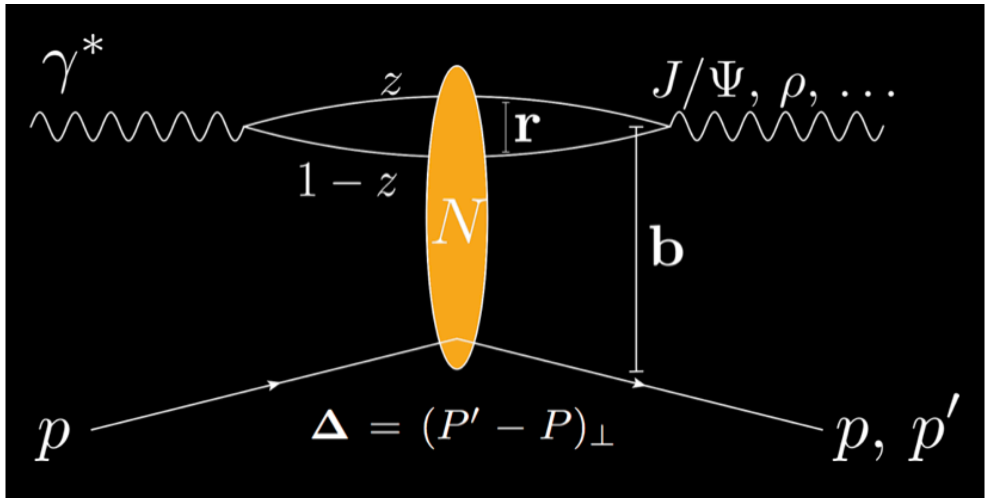


- Coherent diffraction: $$\frac{d\sigma^{\gamma^* p\to Vp}}{dt} = \frac{1}{16\pi}\left|\left\langle A^{\gamma^* p\to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right\rangle\right|^2$$

sensitive to the average size of the target

- Incoherent diffraction: $$\frac{d\sigma^{\gamma^* p\to Vp^*}}{dt} = \frac{1}{16\pi}\left(\left\langle\left|A^{\gamma^* p\to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right|^2\right\rangle - \left|\left\langle A^{\gamma^* p\to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right\rangle\right|^2\right)$$

sensitive to fluctuations (including geometric ones)



$$A \sim \int d^2b\, dz\, d^2r\, \psi^*\psi^V(\vec{r}, z, Q^2)\, e^{-i\vec{b}\cdot\vec{\Delta}}\, N(\vec{r}, x, \vec{b})$$

- Impact parameter ***b*** is the Fourier conjugate of transverse momentum transfer ***Δ*** → Access to spatial structure ($t = -\Delta^2$)

Diffractive VM cross section: incoherent

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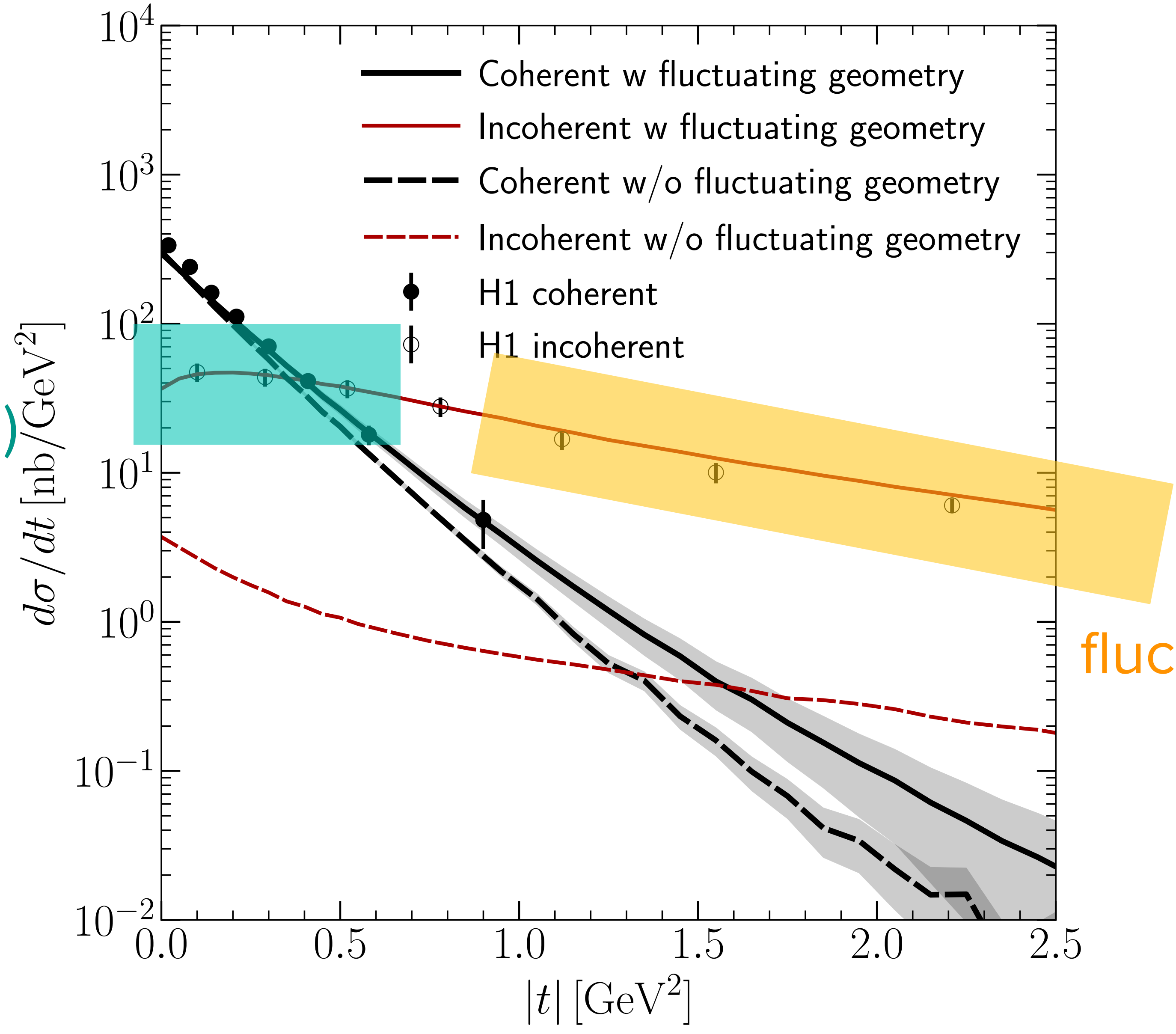
Information in the diffractive cross sections



larger scale fluctuations (>0.2 fm)

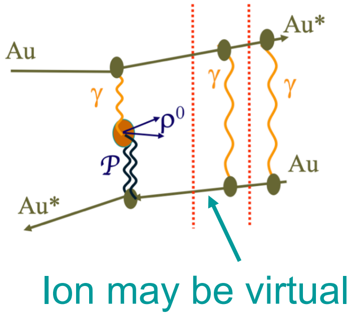
short scale fluctuations (<0.2 fm)

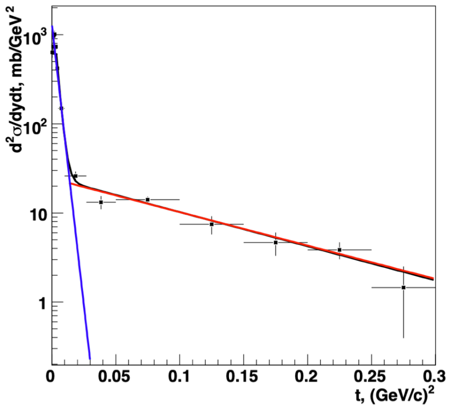
Limitations of Good – Walker

Spencer Klein

Examples of coherent photoproduction where Good-Walker predicts it should not occur

- Coherent peak with $p_T \sim$ hbar/R_A
- AA -> A*A* V
  - Coherent photoproduction with nuclear excitation
- All published STAR UPC analyses REQUIRE mutual Coulomb excitation in trigger
- ALICE also sees coherent photoproduction in events containing neutrons
- Can be explained by diagram with independent photon emission
  - Also possible with single photons, especially at larger p_T
- Good-Walker does not have an exception for mostly separable reactions





STAR, Phys. Rev C77, 034910 (2008)

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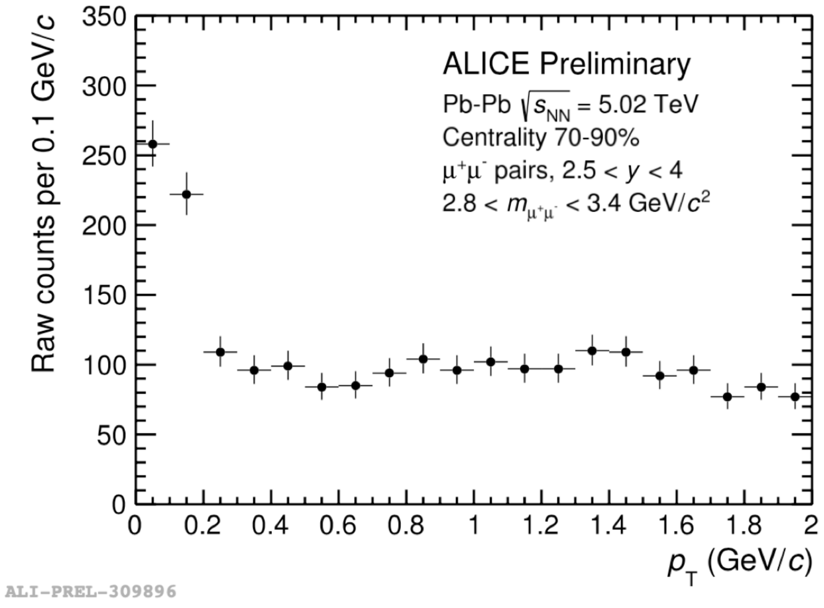
Coherent photoproduction in peripheral collisions

- Coherent J/ψ photoproduction in peripheral hadronic collisions
  - Peak at $p_T <\sim$ hbar/R_A
- Seen by ALICE and STAR



Undetected particles

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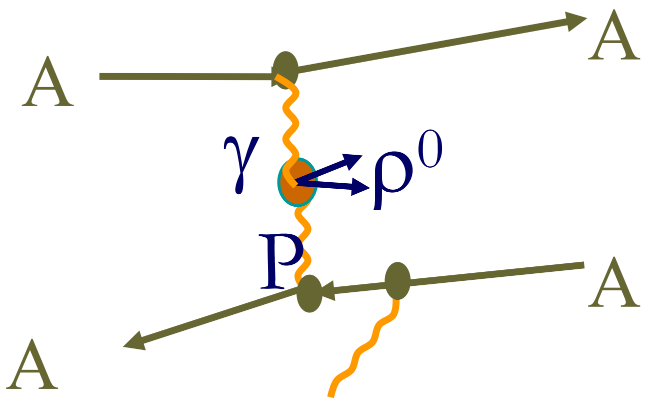
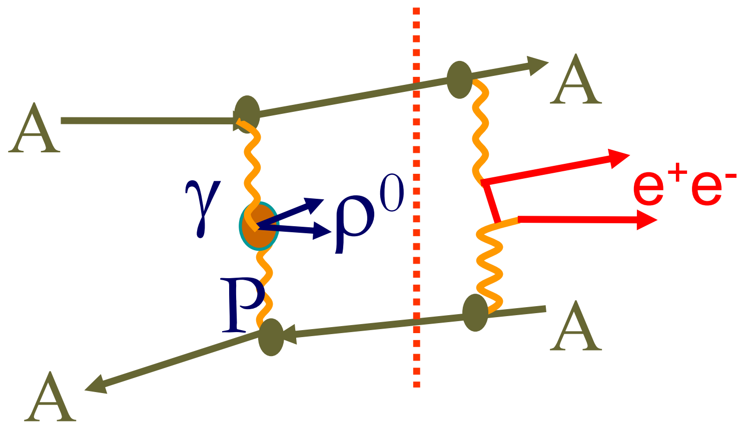
Other possible sub-reactions

- Bremsstrahlung from the ion
  - 1/k photon energy spectrum
    - Logarithmically divergent
- Pair production
  - Electron mass keeps cross-section finite, but large
    - 200,000 barns for Pb-Pb at the LHC
    - P(pair) ~ >1 for b>= 2 R_A
    - Lepton p_T peaked at ~ few m_e
    - Leptons are at large rapidity
  - Most of these pairs are invisible
- There are many ways to have additional, unseen particles
- Little change to overall kinematics, but Good-Walker requires exclusive reactions!





Challenges to GW formulation

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Conclusions

- The Good-Walker approach connects coherent photoproduction with the transverse distribution of targets, and incoherent photoproduction with target fluctuations.
- We observe coherent VM photoproduction in two regimes where GW says it should not be present. A semi-classical calculation can explain this data.
- GW expects a single incident photon, whereas UPCs and eA collisions may involve multiple photons.
- There are many ways for VM photoproduction to produce unseen particles, complicating the separation into coherent and incoherent interactions, further confusing the picture.
- The GW formalism should be extended to account for more complicated reactions involving additional particles. Coherent production might gradually disappear in the presence of soft particles, rather than the current abrupt disappearance.

Summary and outlook

Few notes:

- Radiative corrections: input parametrization vs theory modeling. Comparison ?
- Polarization influence on the photon spectrum in Bethe-Heitler: talk by Dhevan Gangadharan on 28.07.
- Reality of dips in diffraction ? More theoretical models needed, smearing of depth dips or position.
- Radiative corrections impact on acceptance of electron in diffraction
- Inclusive diffraction: more theory work needed (generators)
- Validity of Good-Walker picture : coherent peak in reactions where GW does not predict coherent, stable/unstable particles, undetected particles, gradual transition

Please submit suggestions through:

https://wiki.bnl.gov/eicug/index.php/Theory