Incoherent photoproduction of J/ψ with ALICE

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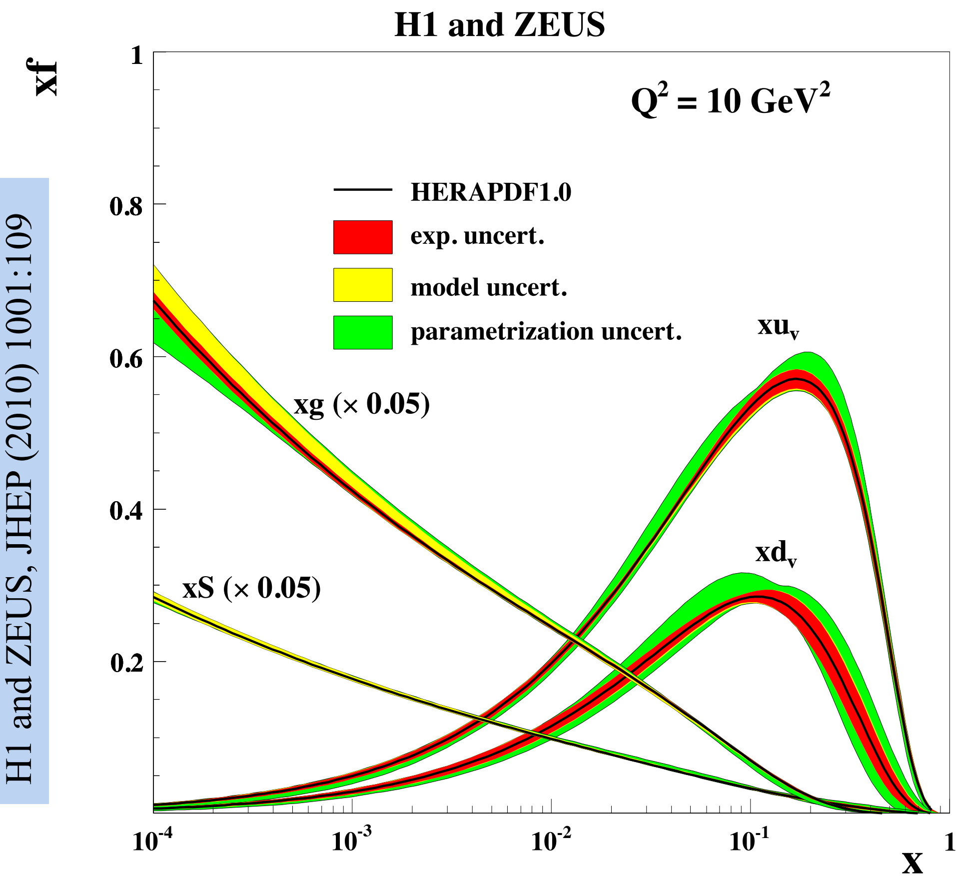
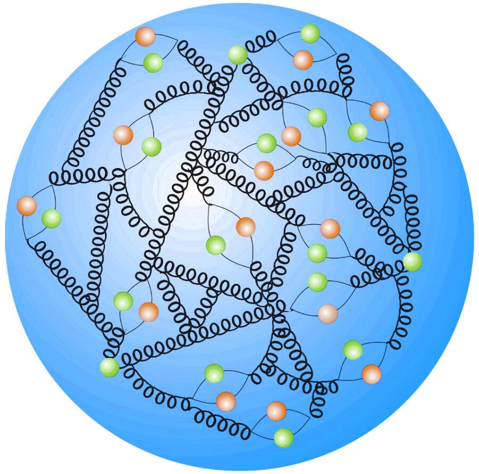
Motivation

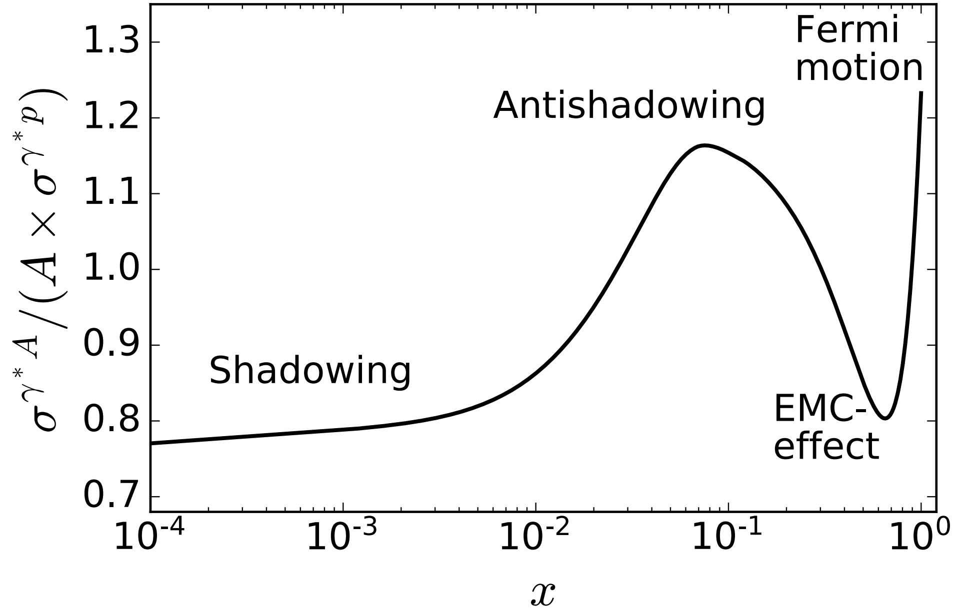


H1 and ZEUS, JHEP (2010) 1001:109



Low-x phenomena:

- p → Pb: nuclear shadowing
- Gluon saturation?



Nature Rev.Phys. 1 (2019) 11, 662-674

- We use the LHC as a “photon collider”
- We look inside lead nuclei at large energies = low Bjorken-x!

Outline

- Ultra-peripheral collisions: why do we need them?
- Photoproduction of vector mesons
- ALICE as a tool to measure UPCs
- Details about the ongoing analysis

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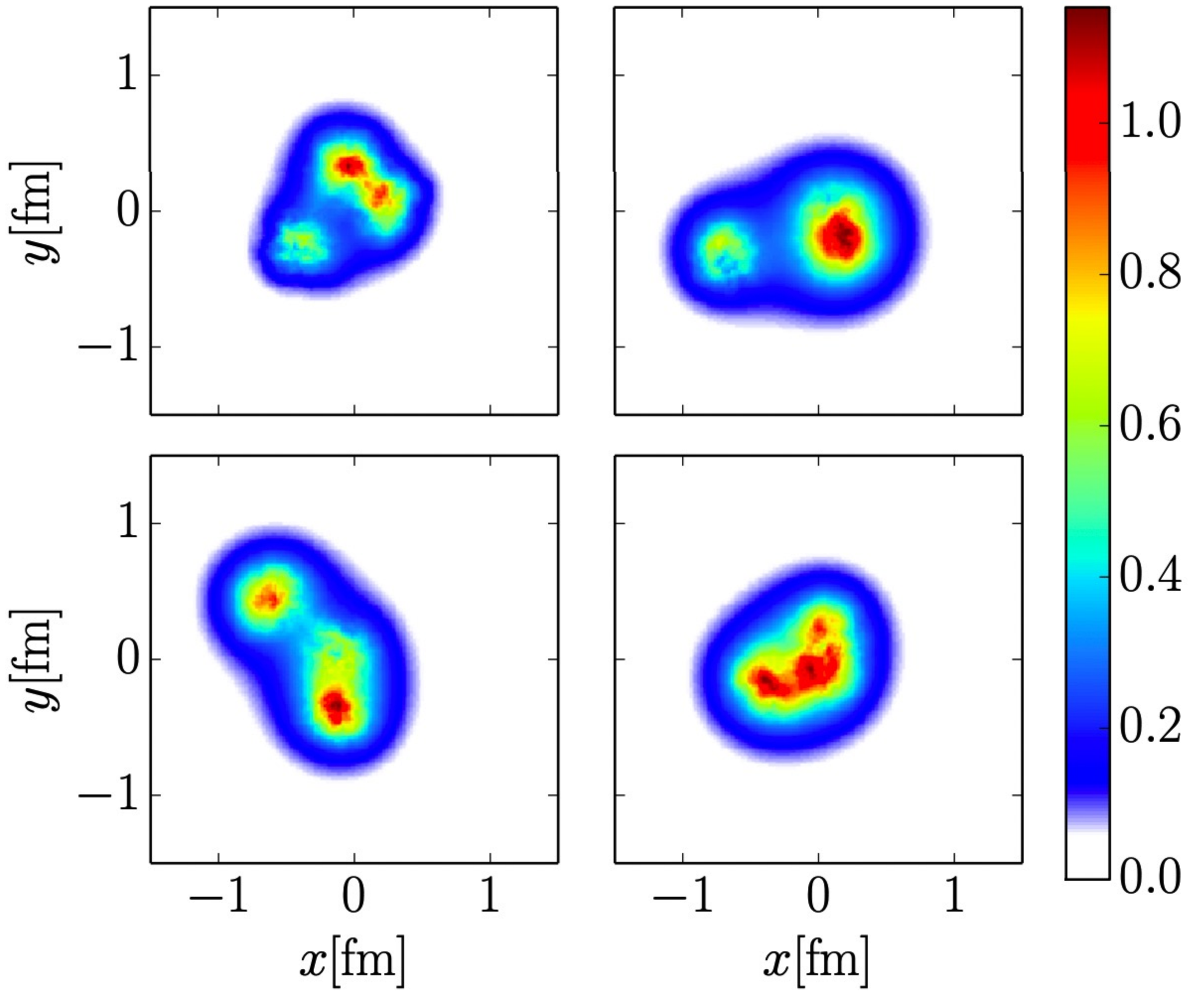
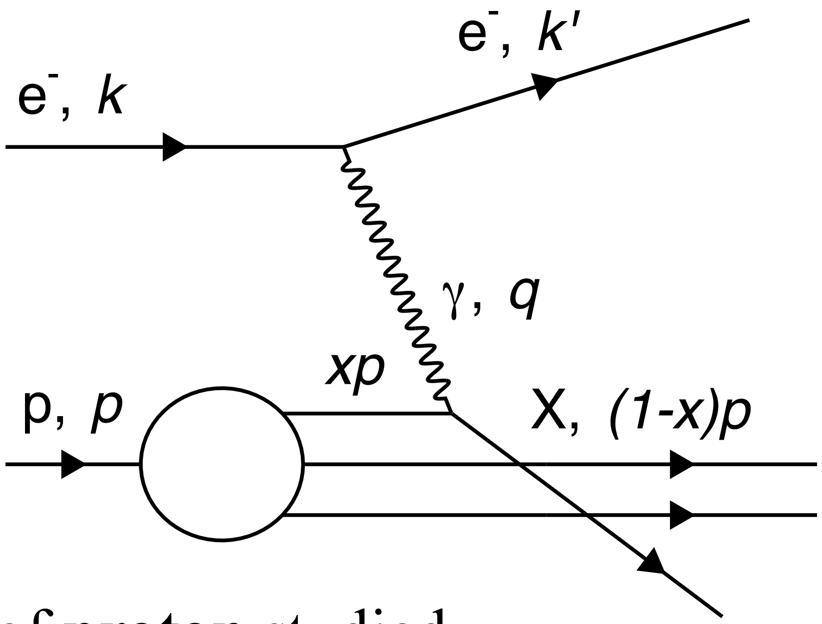
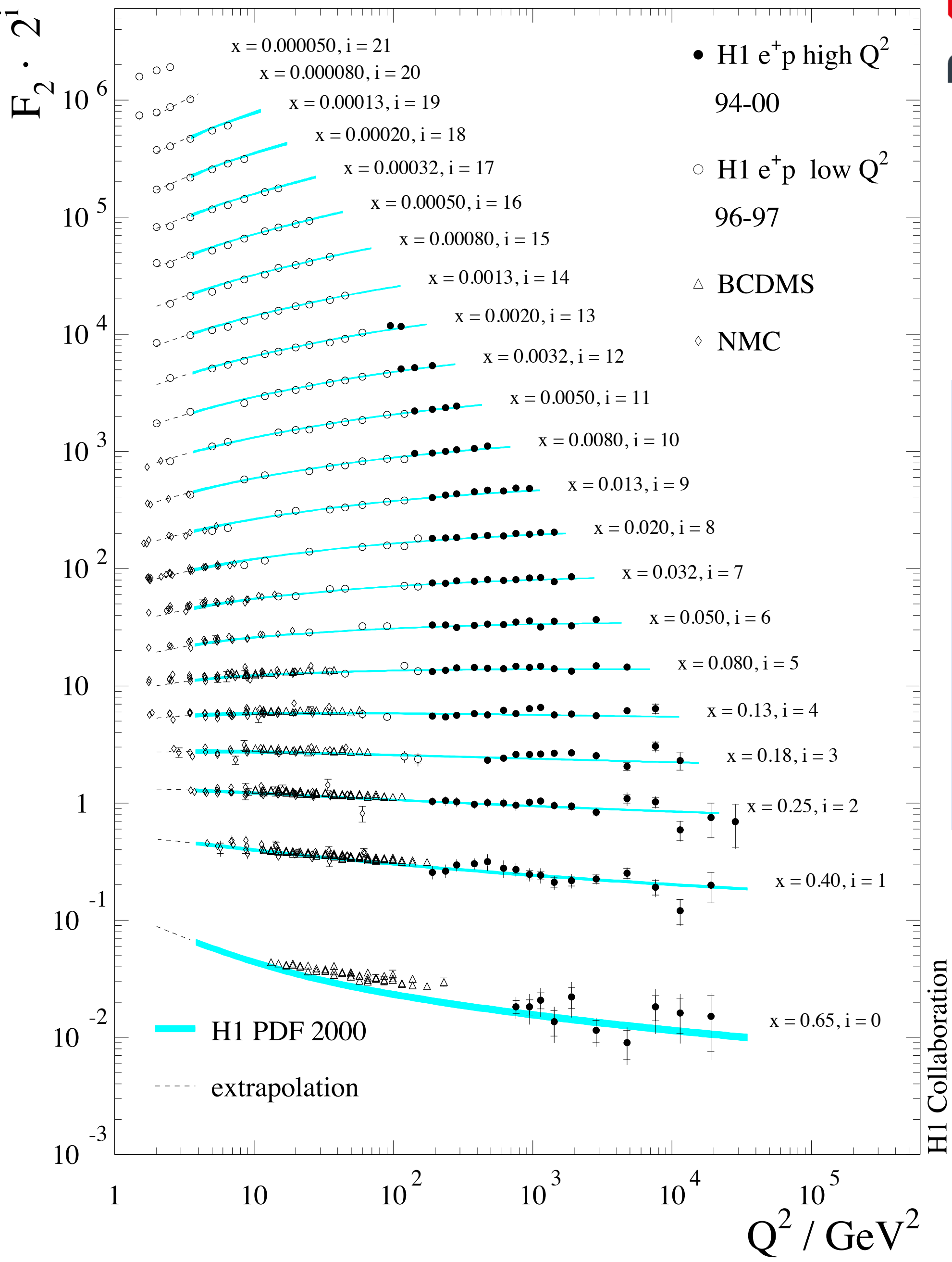


HERA: deep inelastic scattering

- Electron-proton collider in DESY (1992-2007)



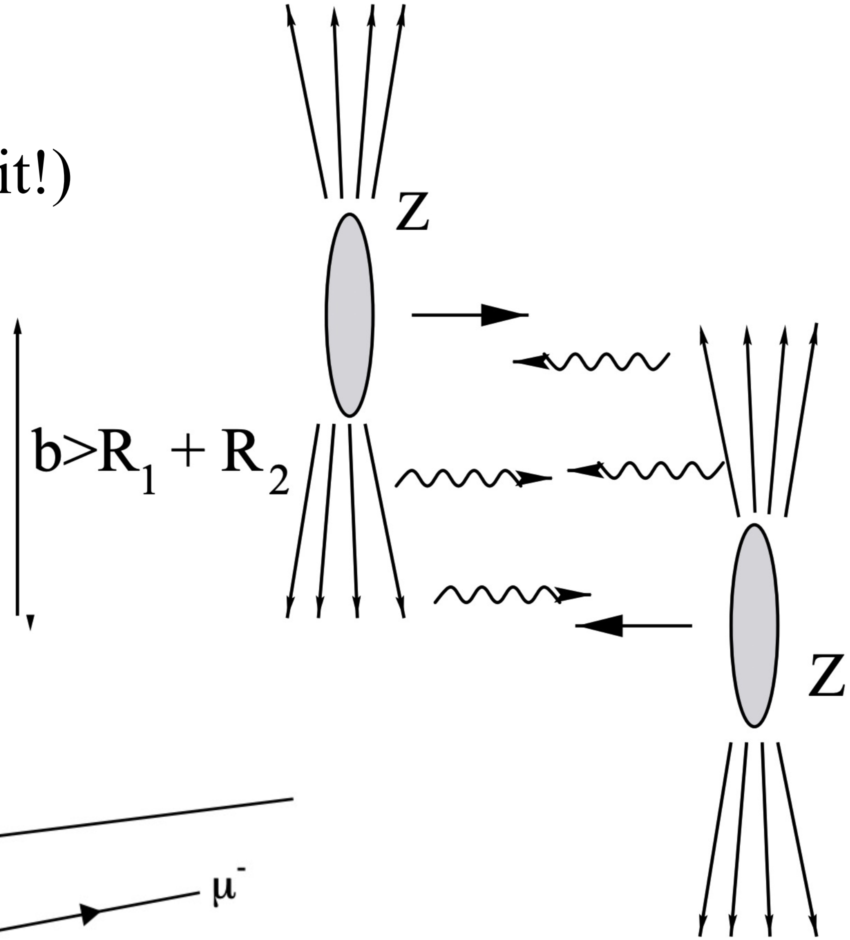
- Structure of **proton** studied
- Measurements of structure functions ($F_2(x, Q^2)$) and PDFs of quarks and gluons
- Region of $10^{-4} < x < 0.02$ covered



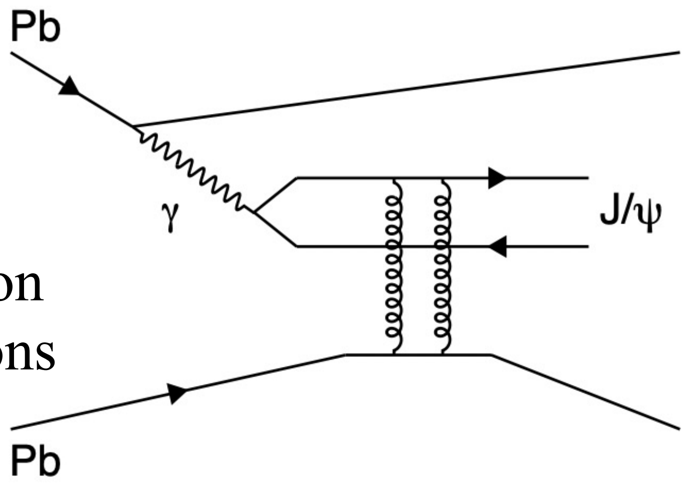
Eur.Phys.J.C 30 (2003) 1-32

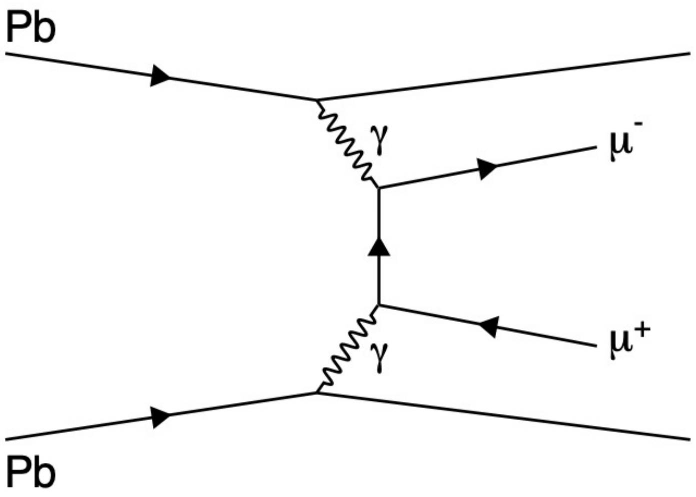
Ultra-peripheral collisions – why?

- Because we currently have no EIC ☹ (only plans for it!)
- Either p-A or A-A (at the LHC: Pb, at RHIC: Au)
- The impact parameter $b > 2R$
  - Hadronic interactions suppressed
  - Processes induced by **quasi-real photons** (EM fields of ultra-relativistic ions)
    - Photon flux $\propto Z^2$



Left: Diffractive photoproduction of vector mesons



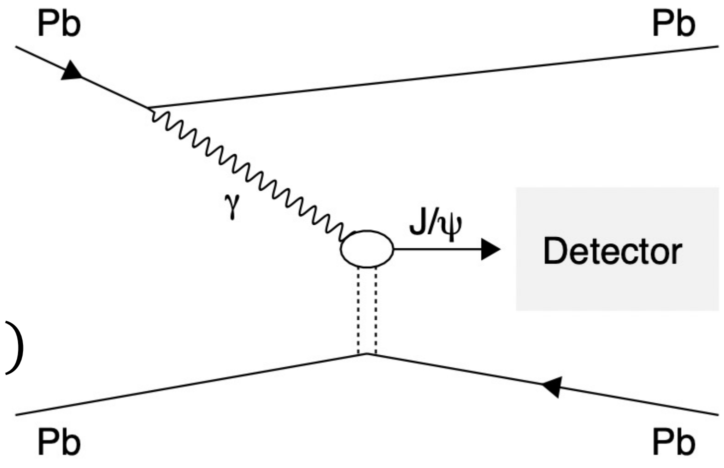


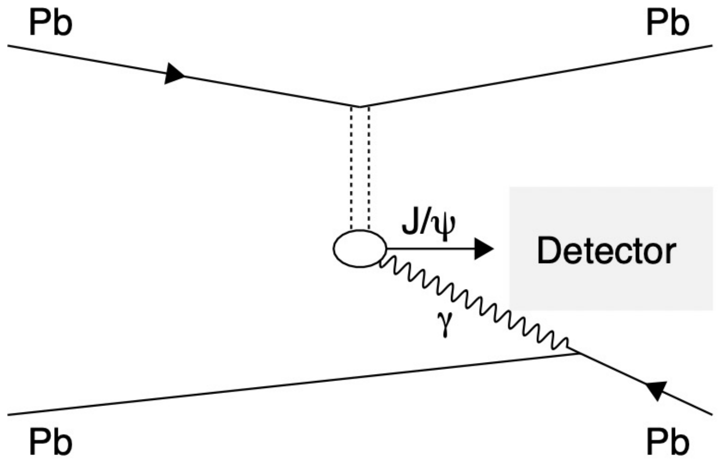
Right: Two-photon processes: background

Photoproduction of vector mesons

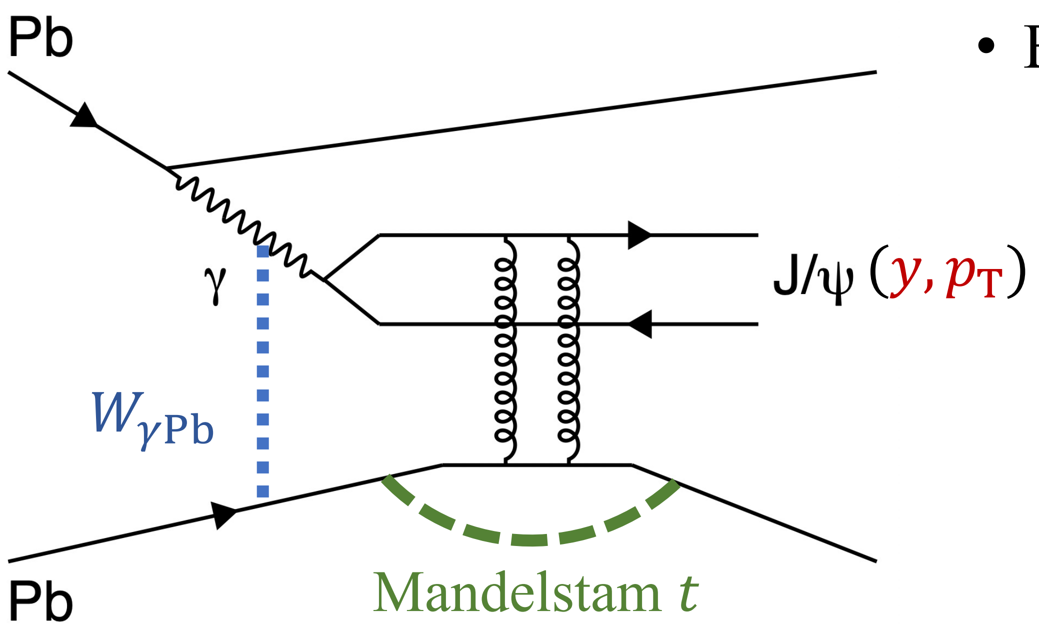
- Provides more detailed pictures than inclusive DIS:
  - Distribution of partons in the transverse plane
  - Event-by-event fluctuations of the transverse structure
- **Colour dipole approach**: γ fluctuates into a $q\bar{q}$ pair
  - Pomeron exchange, at the lowest order: 2 gluons, $\sigma \sim g^2(x, Q^2)$
  - Vector meson ($J^P = 1^-$) is created
- Cross section: a product of the photon flux (QED) and the photonuclear cross section (QCD enters here):

$$\frac{d\sigma_{PbPb}(y)}{dy} = N_{\gamma Pb}(y,\{\boldsymbol{b}\})\sigma_{\gamma Pb}(y) + N_{\gamma Pb}(-y,\{\boldsymbol{b}\})\sigma_{\gamma Pb}(-y)$$





Photoproduction kinematics



- Hard scale (pQCD applicable): $Q^2 \sim M_V^2/4$
- Experimental signatures:
  - Rapidity of the VM $\leftrightarrow x$:

$$x_{\pm} = \frac{M_V}{\sqrt{s_{\mathrm{NN}}}} e^{\pm y}$$

    - "J/ψ scattering angle traces the energy evolution"
    - At the LHC: $10^{-5} \lesssim x \lesssim 10^{-2}$
  - Transverse momentum of the VM $\leftrightarrow t$:

$$|t| \approx -p_{\mathrm{T}}^2$$

  - Why only an approximate relation?

$$\vec{p}_{\mathrm{T,J/}\psi} = \vec{p}_{\mathrm{T},\gamma} + \vec{p}_{\mathrm{T,pom}}$$

Coherent vs. incoherent photoproduction

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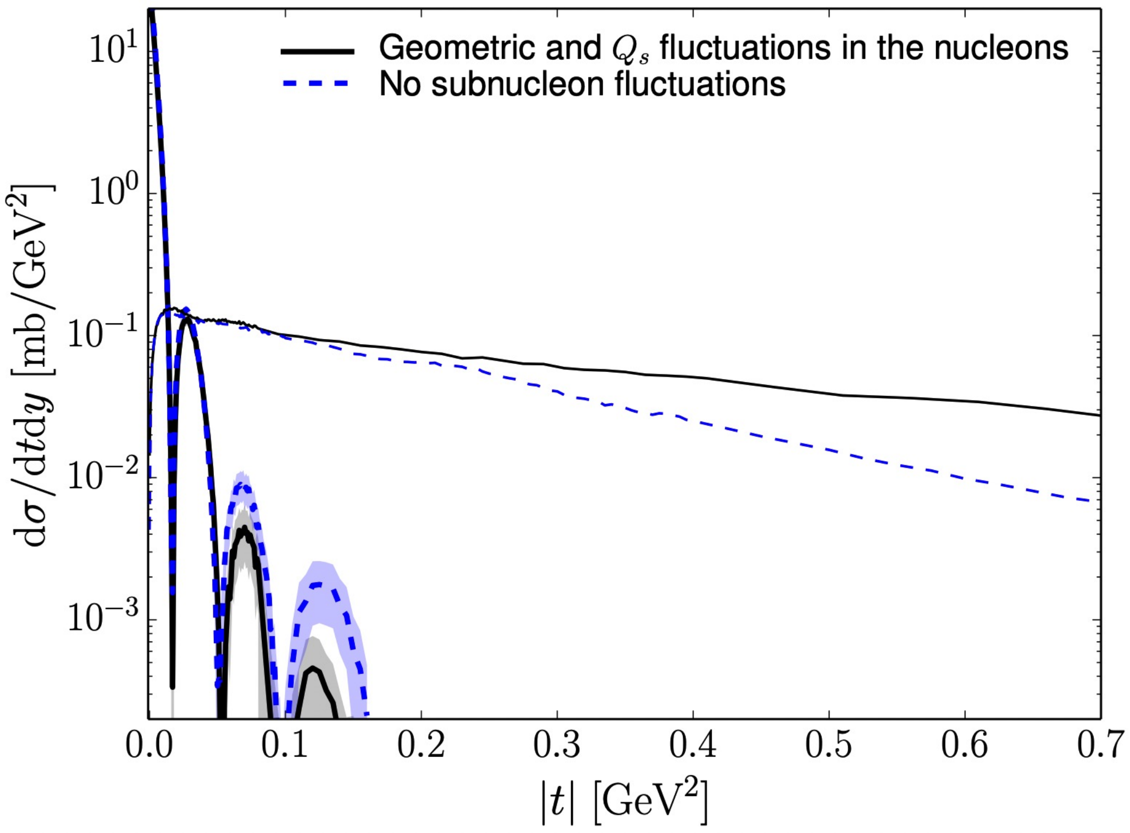
Type of a process	γ interacts with	$\sigma_{\gamma \mathrm{Pb}}$ sensitive to (Good-Walker)
Coherent	The whole nucleus	The **average** target configuration
Incoherent	A single nucleon	The **variance** over target configurations



- Nucleus > nucleon
  $\Longrightarrow$ p_T of coherent J/ψ > p_T of incoherent J/ψ

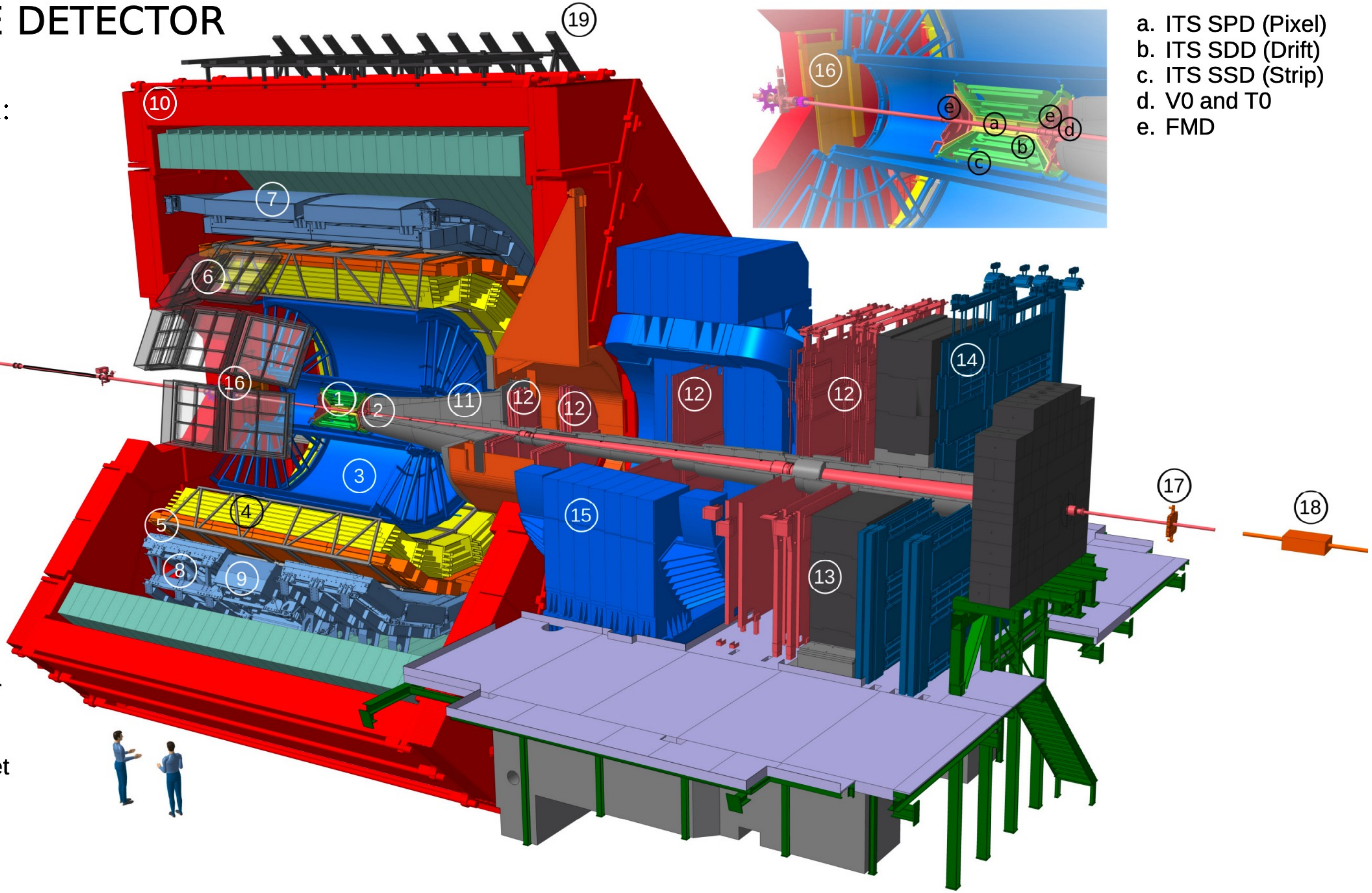
  $\langle p_T \rangle \sim 60$ MeV $\langle p_T \rangle \sim 500$ MeV

- **Nuclear breakup** very likely in the inc. case (but can also happen in coh.)
- The target nucleon in the inc. process can **dissociate** $\Longrightarrow$ even larger p_T

Our tool: ALICE at Point 2

THE ALICE DETECTOR

Central barrel:
$|\eta| < 0.9$



1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

A. Tauro: ALICE Schematics (2017)

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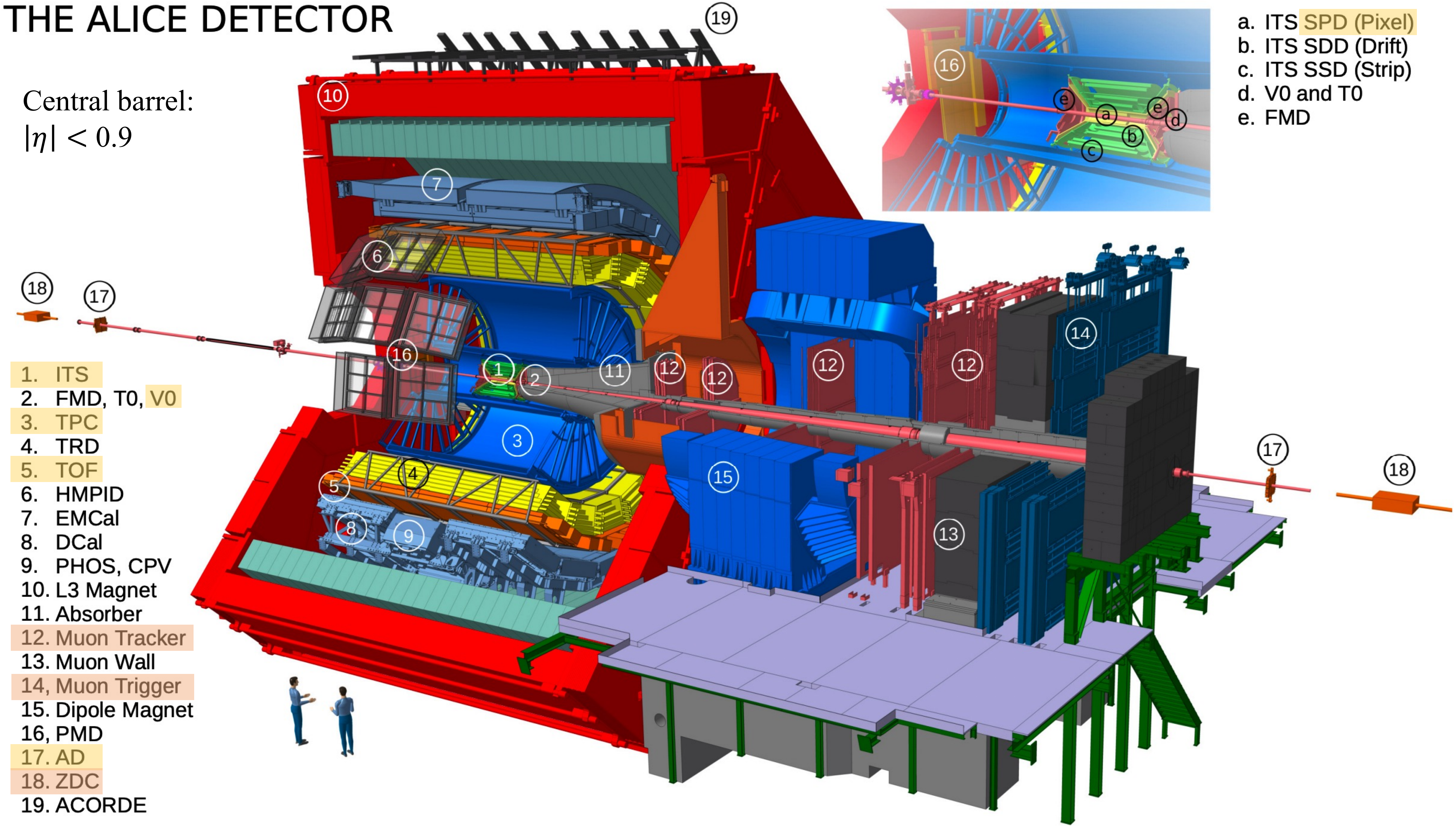

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
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ALICE

A. Tauro: ALICE Schematics (2017)

What we want to measure with ALICE?

- The $|t|$-dependence of the photonuclear cross section of incoherent J/ψ production
  - At the energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - At midrapidity, $|y| < 0.8$
  - In dimuon decay channel, J/ψ → $\mu\mu$

$$\left.\frac{\mathrm{d}^2\sigma^{\mathrm{inc}}_{\mathrm{J}/\psi}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2}\right|_{y=0} = 2n_{\gamma\mathrm{Pb}}(y=0)\frac{\mathrm{d}\sigma_{\gamma\mathrm{Pb}}}{\mathrm{d}|t|}$$

What we **measure**: double-differential UPC cross section

What we **calculate**: midrapidity photon flux

What we **want**: photonuclear cross section

$$\frac{\mathrm{d}^2\sigma^{\mathrm{inc}}_{\mathrm{J}/\psi}}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2} = \frac{N^{\mathrm{inc}}_{\mathrm{J}/\psi}}{(\mathrm{Acc}\times\varepsilon)_{\mathrm{J}/\psi}\cdot\mathrm{BR}(\mathrm{J}/\psi\to\mu^+\mu^-)\cdot\mathcal{L}\cdot\Delta y\cdot\Delta p_{\mathrm{T}}^2}$$

$N^{\mathrm{inc}}_{\mathrm{J}/\psi}$ → Number of incoherent J/ψ events

$(\mathrm{Acc}\times\varepsilon)_{\mathrm{J}/\psi}$ → Acceptance and efficiency of signal reconstruction

$\mathcal{L}$ → Integrated luminosity of the data sample

How we measure it?

- Data from Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV (LHC18q, LHC18r) + anchored MC simulations with STARlight (LHC20g1)
- We cannot measure $N^{\mathrm{inc}}_{\mathrm{J}/\psi}$ directly…
- Instead, we measure yields from the fits of invariant mass distributions:

$$N_{\mathrm{yield}} = N^{\mathrm{inc}}_{\mathrm{J}/\psi} + N^{\mathrm{coh}}_{\mathrm{J}/\psi} + N^{\mathrm{FD}} = N^{\mathrm{inc}}_{\mathrm{J}/\psi} + f_C \cdot N^{\mathrm{inc}}_{\mathrm{J}/\psi} + f_D \cdot N^{\mathrm{inc}}_{\mathrm{J}/\psi} = N^{\mathrm{inc}}_{\mathrm{J}/\psi}(1 + f_C + f_D)$$

- Then we get: $N^{\mathrm{inc}}_{\mathrm{J}/\psi} = \dfrac{N_{\mathrm{yield}}}{1 + f_C + f_D}$

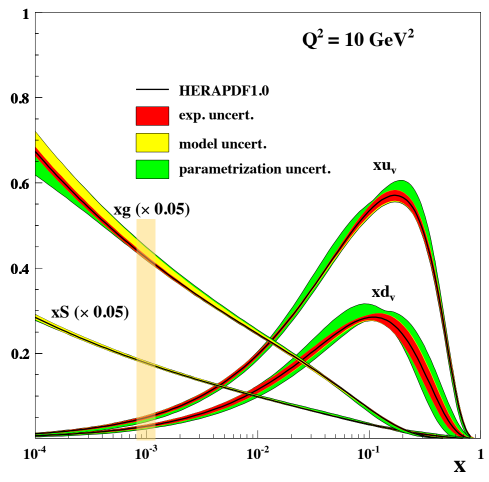
- **Coherent contamination**
- **Feed-down contamination**: reactions $\psi(2S) \rightarrow$ J/ψ + X (undetected)
  - X is most likely a pair of charged ($\pi^+\pi^-$) or neutral ($\pi^0\pi^0$) pions
  - $\psi(2S)$ can be coherent or incoherent: $f_D = f_D^{\mathrm{coh}} + f_D^{\mathrm{inc}}$

Selection of events

2 good SPD && 2 good TPC tracks

No.	Selection	Remaining events
S1	Two good central tracks	3,206,564
S2	Central UPC CCUP31 trigger	2,175,623
S3	Primary vertex: # of contributors	2,168,339
S4	Primary vertex: z distance	2,163,340
S5	Run number from the DPG run lists	2,155,837
S6	AD offline veto	2,125,258
S7	V0 offline veto	1,424,147
S8	SPD clusters match FOhits	615,894
S9	Muon pairs only	540,240
S10	The dilepton rapidity $\|y\| < 0.8$	529,748
S11	The pseudorapidity of both tracks $\|\eta\| < 0.8$	437,569
S12	Opposite charges	356,366
S13	The dimuon inv. mass $2.2 < m_{\mu\mu} < 4.5$ GeV/c^2	16,744
S14	The dimuon transverse momentum $0.2 < p_T < 1.0$ GeV/c	3,722
-	The dimuon inv. mass $3.0 < m_{\mu\mu} < 3.2$ GeV/c^2	734

$x \in (0.3, 1.4) \times 10^{-3}$



At lower p_T dominated by coherent events…

At larger p_T by background

These events contain:

- Signal
- Background
- Coherent and FD contamination

Central trigger: what events do we seek?

- We aim to leptonic decays of J/ψ: two back-to-back electron/muon central tracks with the invariant mass around $m_{ll} \approx 3.097\ \text{GeV}/c^2$

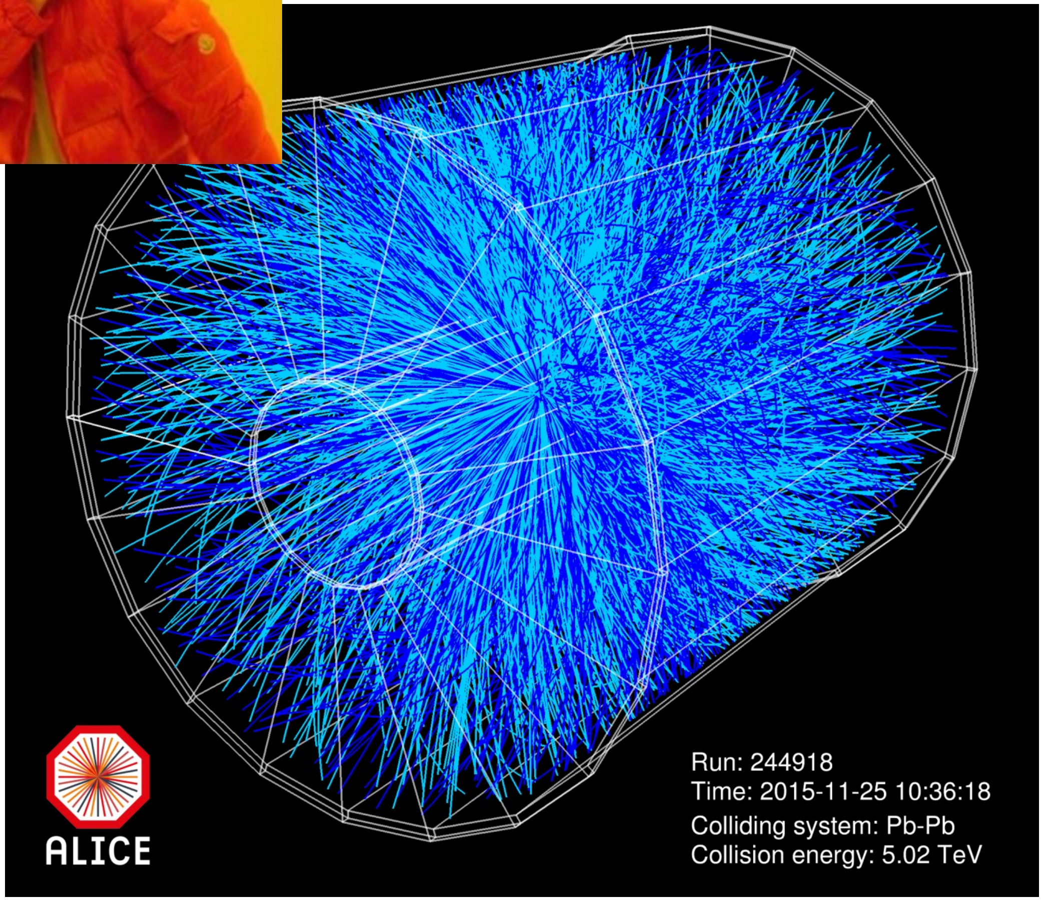
CCUP31 = !0VBA !0VBC !0UBA !0UBC 0STG 0OMU

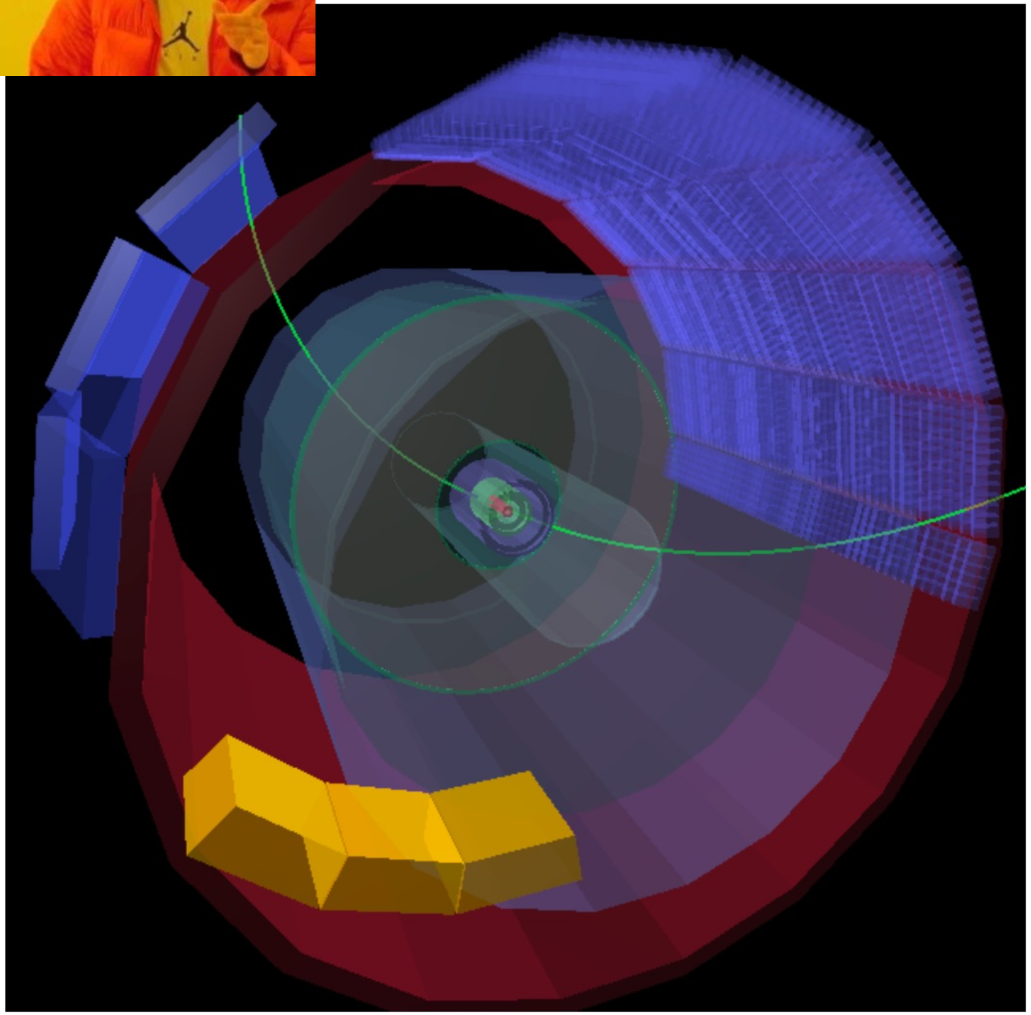
- Online vetoes:
  - !0VBA (!0VBC): no signal in V0A (V0C) during the B-B time window
  - !0UBA (!0UBC): no signal in ADA (ADC) during the B-B time window

Rejecting events with potential hadronic contamination

- Topological triggers: events with back-to-back tracks
  - 0STG: SPD
  - 0OMU: TOF

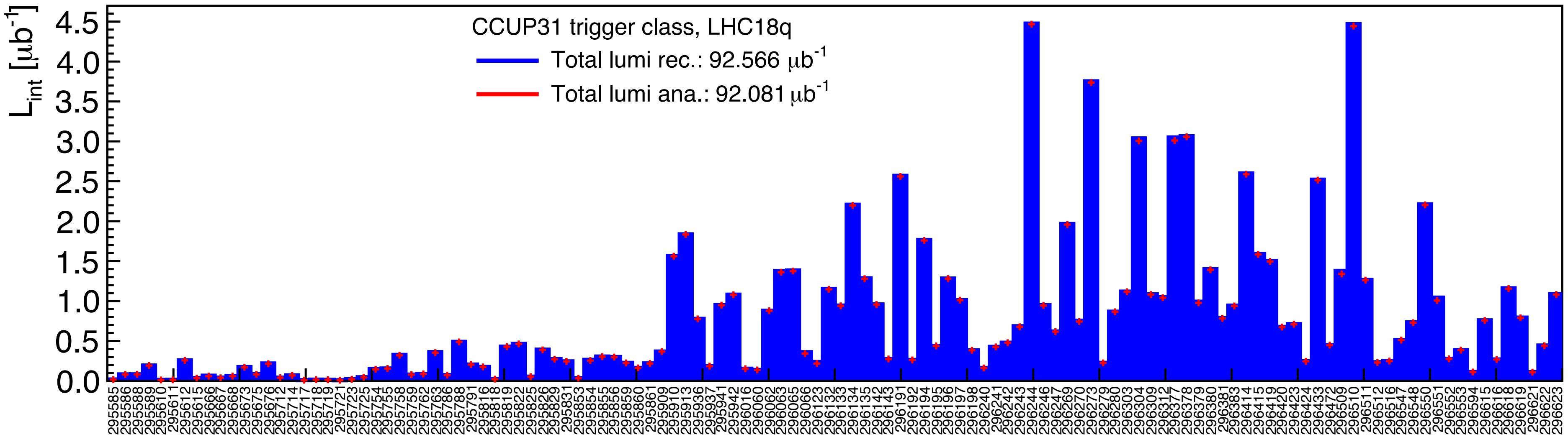
- Otherwise, we want an empty detector ⇒ very clean events!

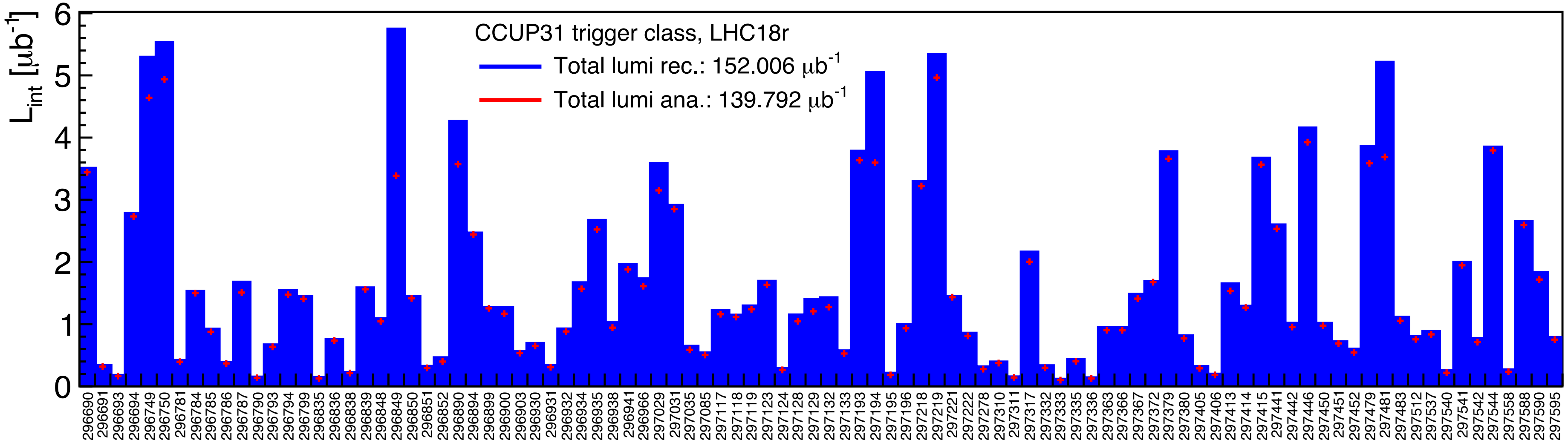

ALICE
Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV



Integrated luminosity of the data sample

- Recorded lumi: reference trigger (V0, ZDC) + VdM scan
- Analyzed lumi: scaled by $N_{\text{ana}}/N_{\text{rec}}$
- Total: $\mathcal{L} = 231.9\ \mu\text{b}^{-1}$

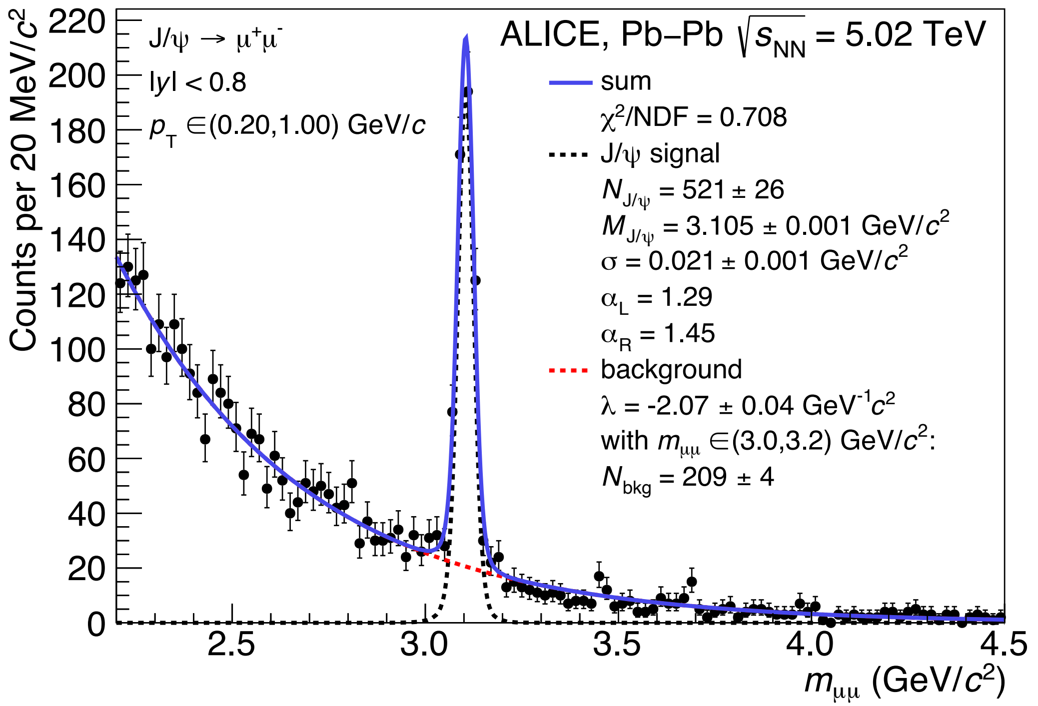


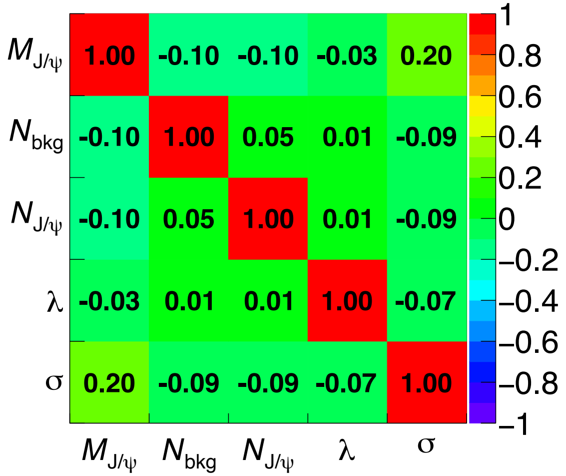


Choice of binning in p_T (and $|t|$)

- Out of ≈ 730 events with $0.2 < p_T < 1.0$ GeV/c:
  - 520 J/ψ candidates (Double-sided CB function)
  - 210 background events (exponential)
- Tail parameters fixed to the values from fits to MC
- Five bins in p_T created so that the yield of J/ψ is uniformly distributed

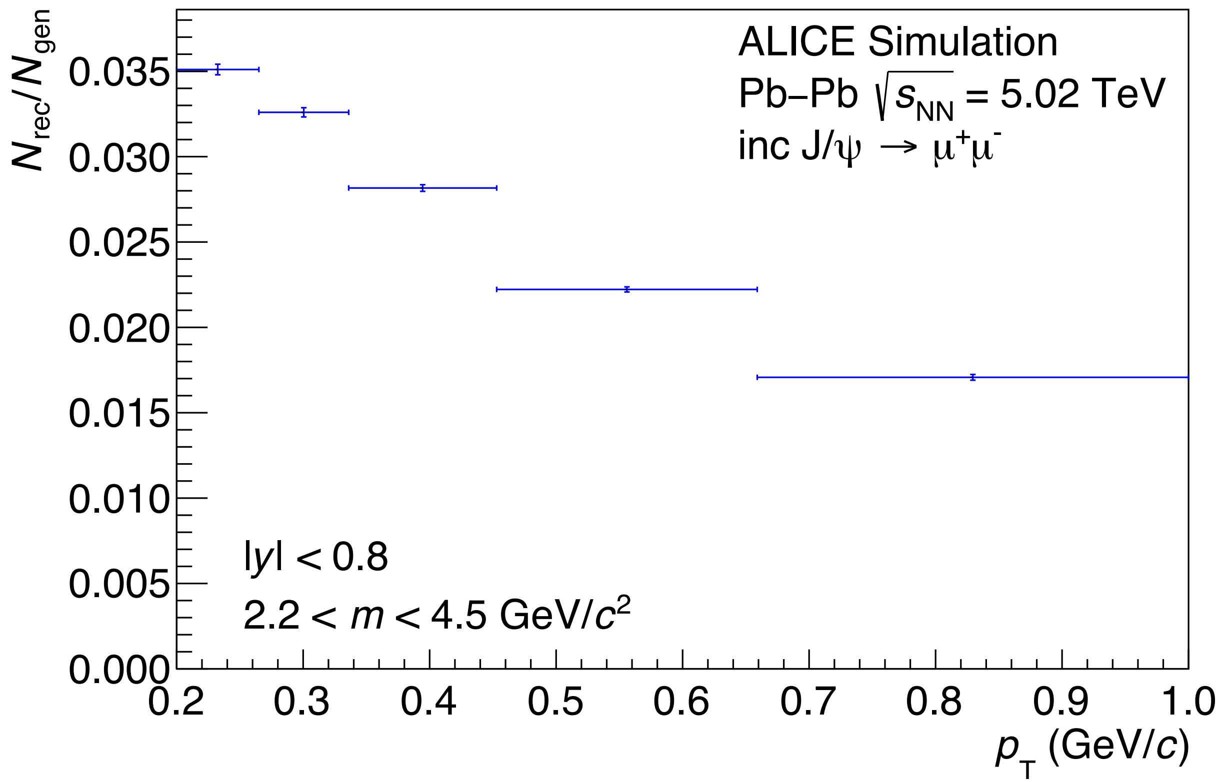
Bin	Boundaries in p_T (GeV/c)	Boundaries in p_T^2 (GeV^2/c^2)	N_{yield}
1	(0.200, 0.265)	(0.040, 0.070)	106 ± 11
2	(0.265, 0.336)	(0.070, 0.112)	106 ± 11
3	(0.336, 0.453)	(0.112, 0.205)	104 ± 12
4	(0.453, 0.659)	(0.205, 0.434)	104 ± 12
5	(0.659, 1.000)	(0.434, 1.000)	102 ± 12

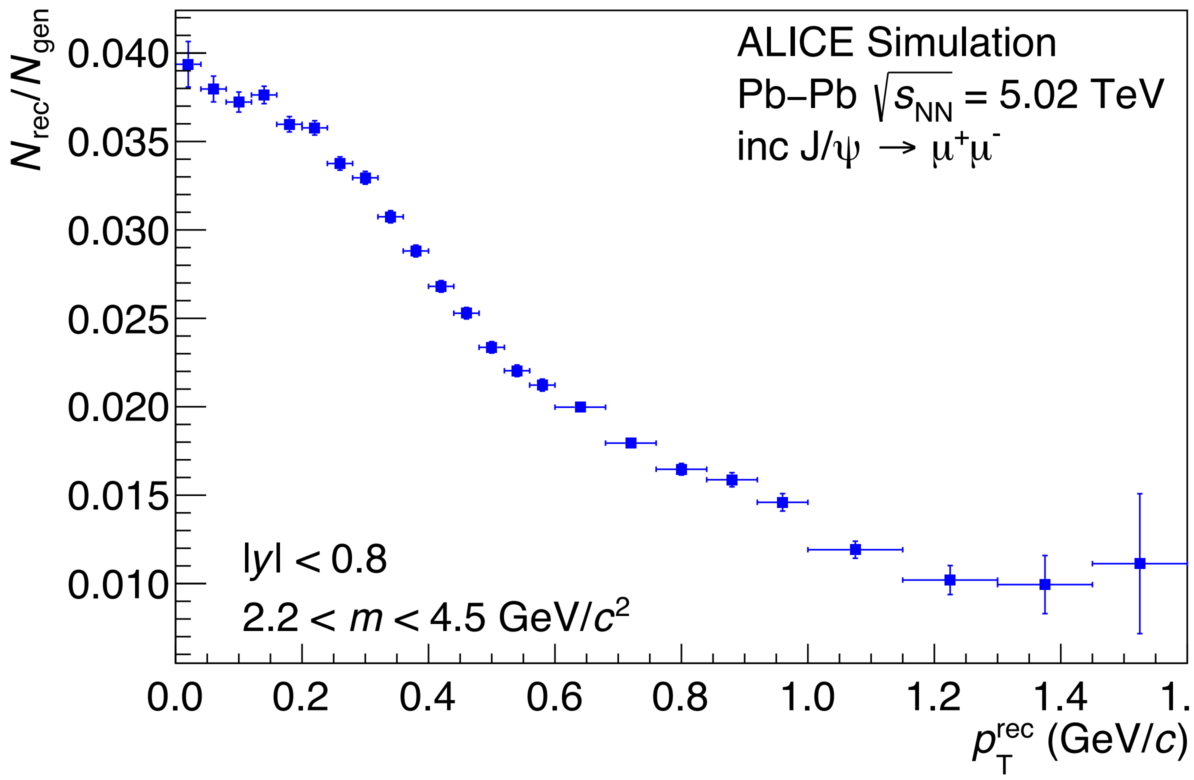




Acceptance and efficiency of the signal reconstruction

- The total value: $(\mathrm{Acc} \times \varepsilon) = (\mathrm{Acc} \times \varepsilon)_{\mathrm{MC}} \times \varepsilon_{\mathrm{pile-up}} \times \varepsilon_{\mathrm{EMD}}$
- MC part: drop at large p_{T} expected
  - At $p_{\mathrm{T}} \approx 0$: muon tracks are back-to-back in azimuth, curvature of tracks not significant
  - At larger p_{T}: the opening angle decreases





Pile-up and EMD corrections

- **Pile-up**:
  - Photoproduction can be accompanied by an independent hadronic or EM interaction in the same bunch crossing that can leave a signal in AD/V0
  - Results from the previous ALICE paper [1] cannot be applied (correction is p_{T}-dependent)
  - *Work in progress*

- **Electromagnetic dissociation (EMD)**:
  - After photoproduction takes place, the nucleus can be left in an excited state and later dissociate which might result in a signal left in AD/V0
  - Results from [1]: $\varepsilon_{\mathrm{EMD}} = (92.0 \pm 1.8)\%$

Fit of the transverse momentum distribution

- Data with $p_T < 2$ GeV/c fitted with 5 templates:
    - coh J/ψ
    - inc J/ψ
    - coh feed-down
    - inc feed-down
    - inc J/ψ with nucleon dissociation

Created from MC data samples (STARlight) [coh J/ψ, inc J/ψ, coh feed-down, inc feed-down]

H1 parametrization [2]: [inc J/ψ with nucleon dissociation]

$$b_{\mathrm{pd}} = 1.79\ (\mathrm{GeV}/c)^{-2},\ n_{\mathrm{pd}} = 3.58$$

$$\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}} \sim p_{\mathrm{T}} \left(1 + \frac{b_{\mathrm{pd}}}{n_{\mathrm{pd}}} p_{\mathrm{T}}^2\right)^{-n_{\mathrm{pd}}}$$

- Background subtracted via invariant mass fits in p_T bins ⇒ no background template needed
- Free parameters: N_{coh}, N_{inc}, N_{diss}
- Coherent and FD contamination:

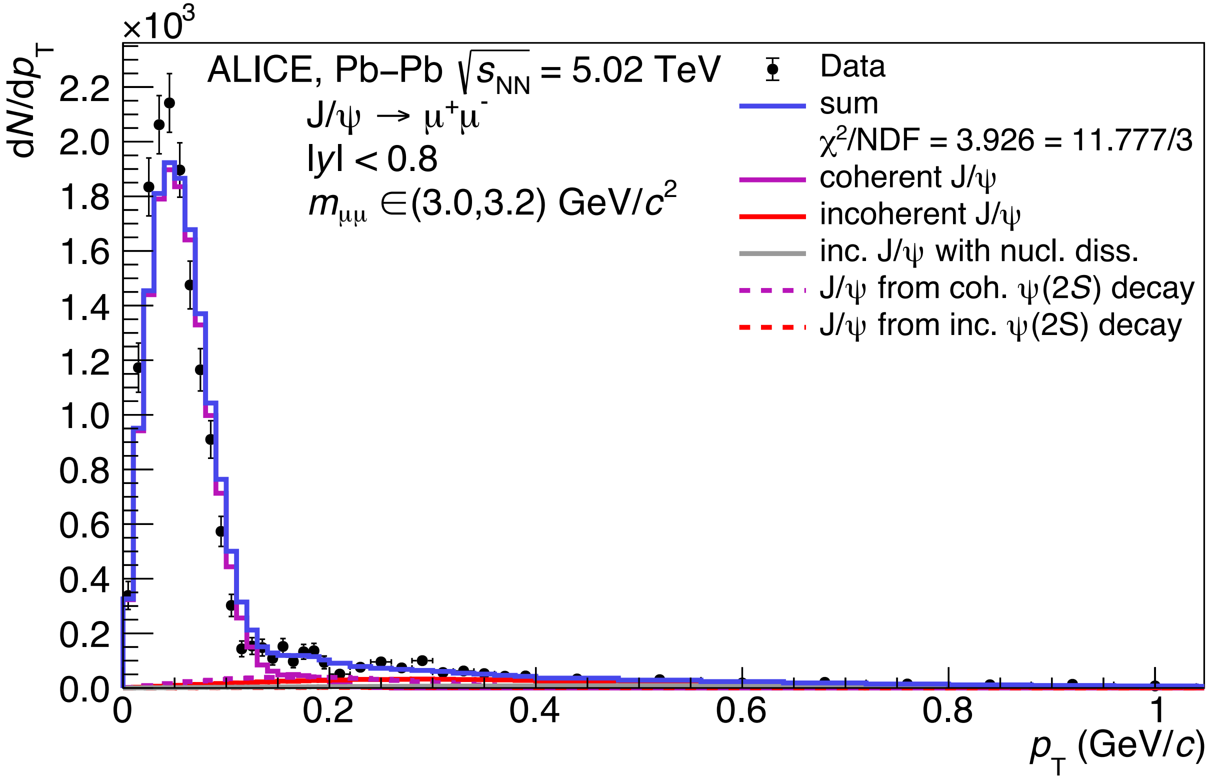
$$f_C = \frac{N_{\mathrm{coh}}^{\mathrm{bin}}}{N_{\mathrm{inc}}^{\mathrm{bin}} + N_{\mathrm{diss}}^{\mathrm{bin}}}$$

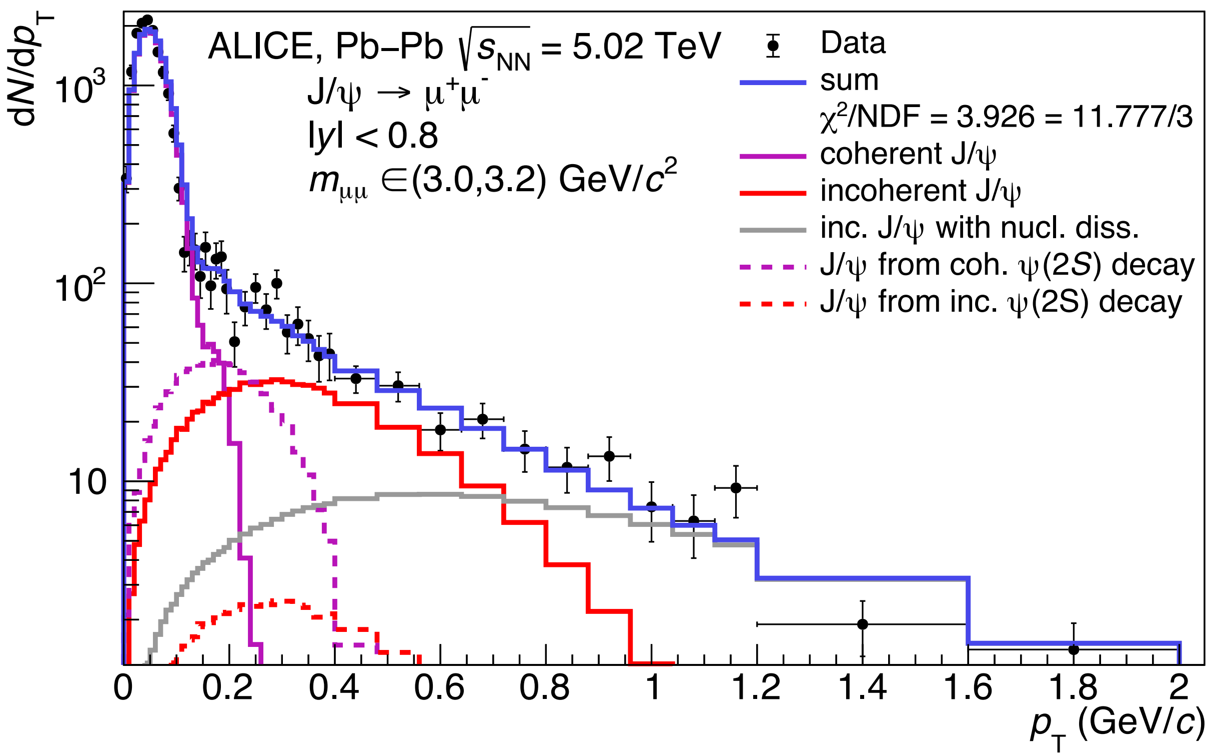
$$f_D^{\mathrm{coh}} = \frac{N_{\mathrm{FD,coh}}^{\mathrm{bin}}}{N_{\mathrm{inc}}^{\mathrm{bin}} + N_{\mathrm{diss}}^{\mathrm{bin}}}$$

$$f_D^{\mathrm{inc}} = \frac{N_{\mathrm{FD,inc}}^{\mathrm{bin}}}{N_{\mathrm{inc}}^{\mathrm{bin}} + N_{\mathrm{diss}}^{\mathrm{bin}}}$$

Fit using original MC data samples

- Data and the model not compatible around the "coherent peak"
  - Manifested by rather large value of χ^2/NDF





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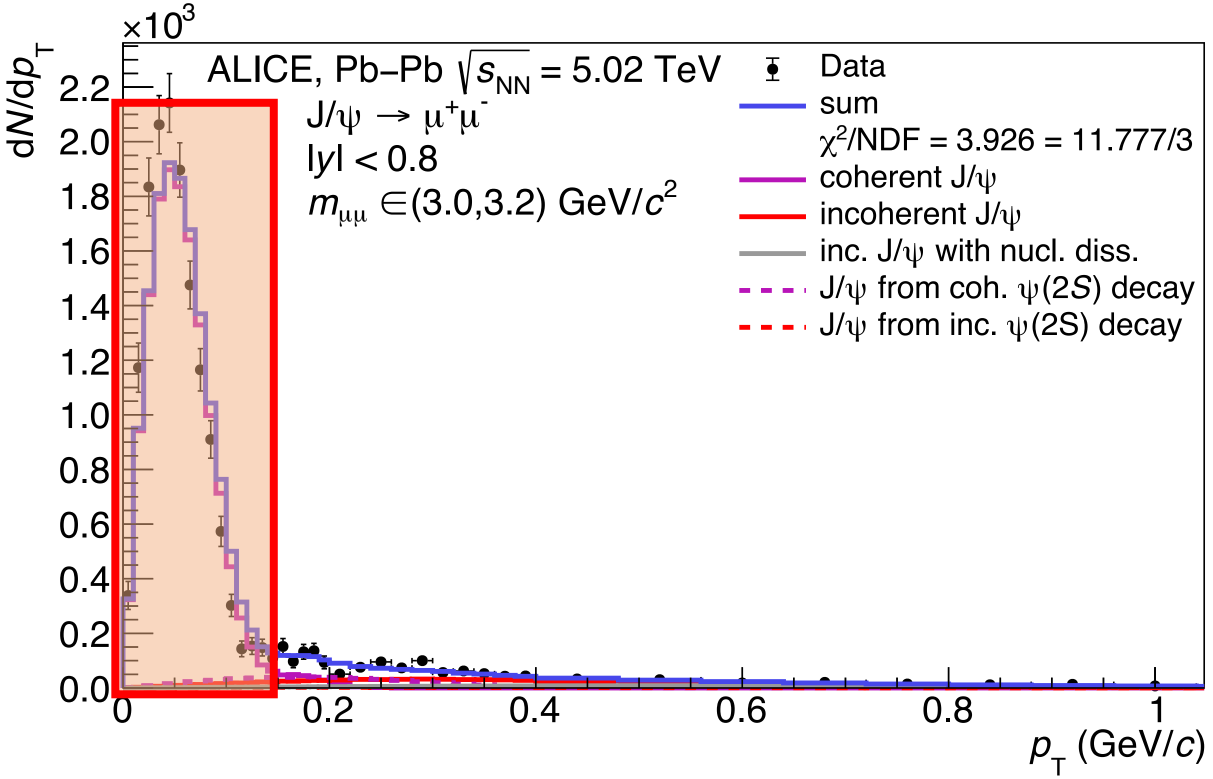
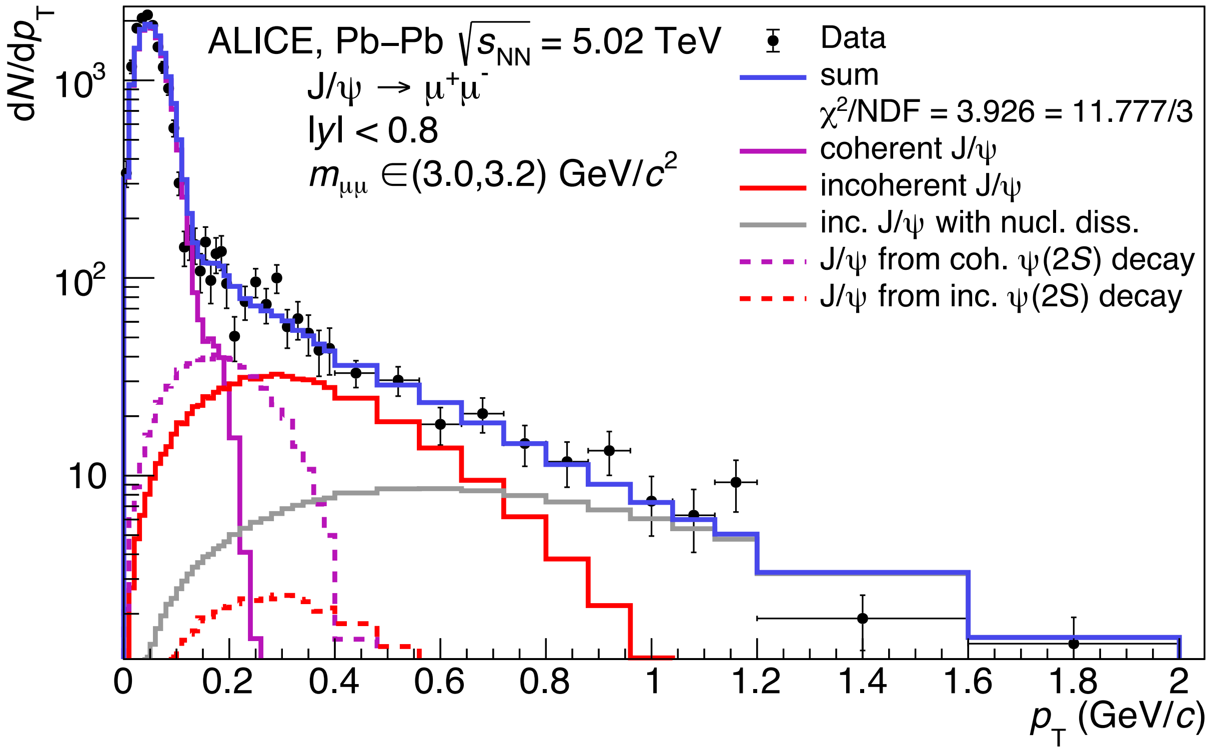
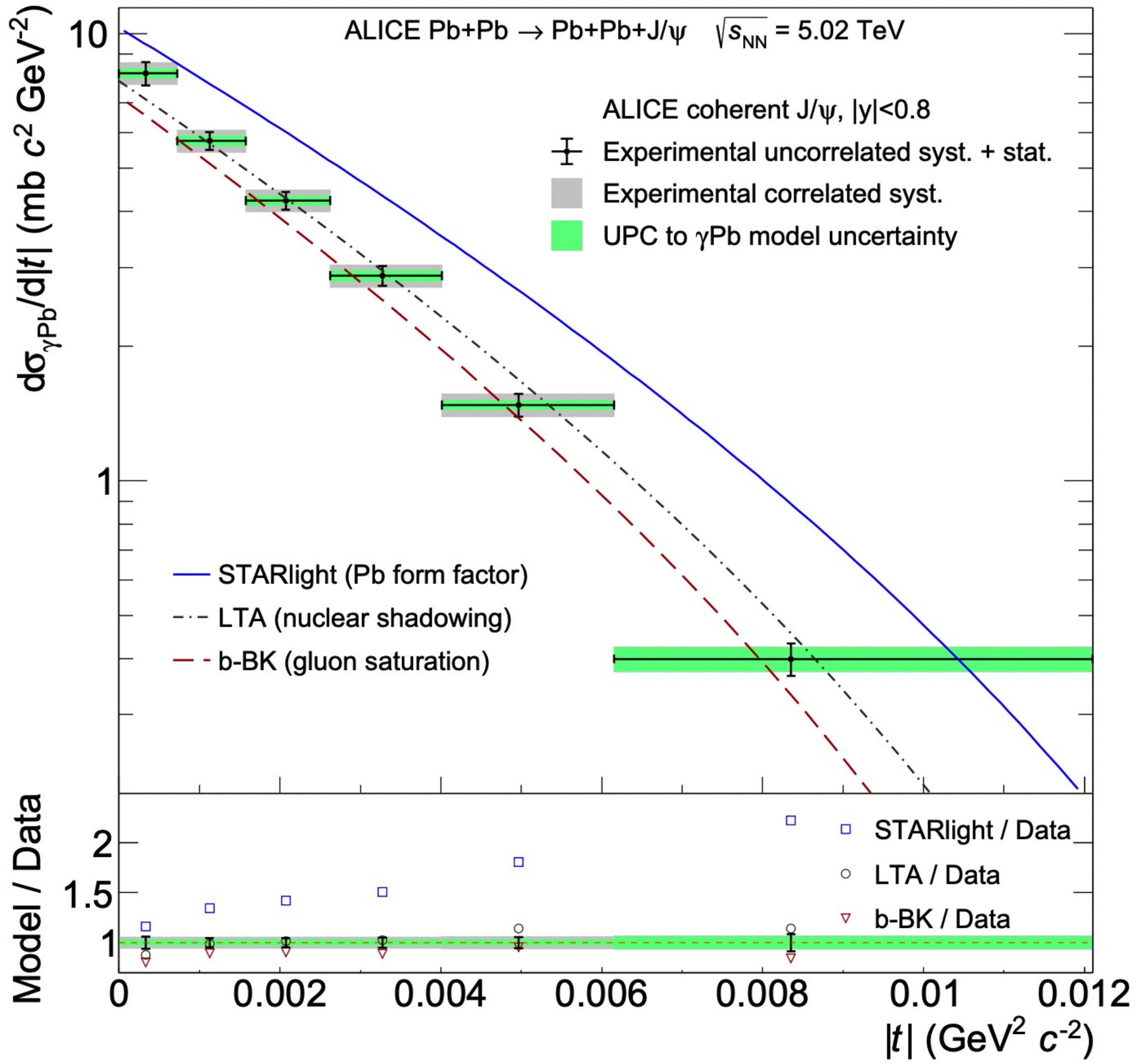




Coherent peak in data shifted to lower p_T than STARlight predicts…

What did we learn from the ALICE results on $|t|$-dependence of coherent photoproduction [1]?



- STARlight doesn't reproduce the data!
- Within SL:

$$\sigma(\gamma\ \mathrm{Pb} \rightarrow \mathrm{VM\ Pb}) = \left.\frac{\mathrm{d}\sigma(\gamma\ \mathrm{Pb} \rightarrow \mathrm{VM\ Pb})}{\mathrm{d}t}\right|_{t=0} |F(t)|^2$$

where the nuclear form factor

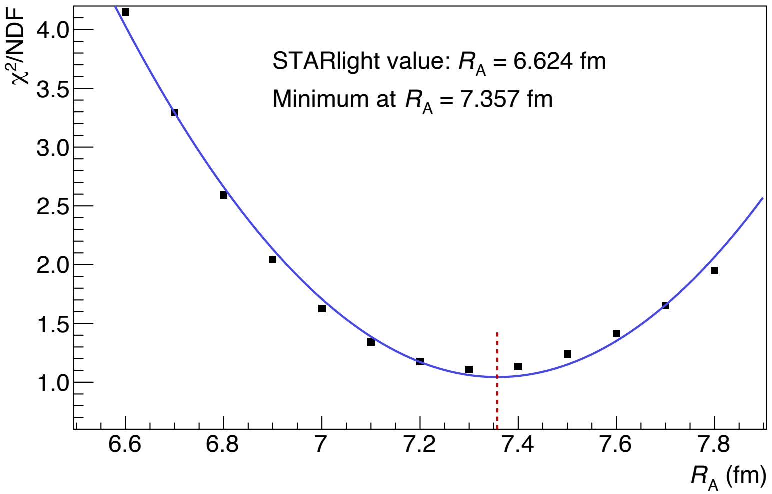
$$F(q=\sqrt{|t|}) = \frac{4\pi\rho_0}{Aq^3}\frac{\sin(qR_A) - qR_A\cos(qR_A)}{1+a^2q^2}$$

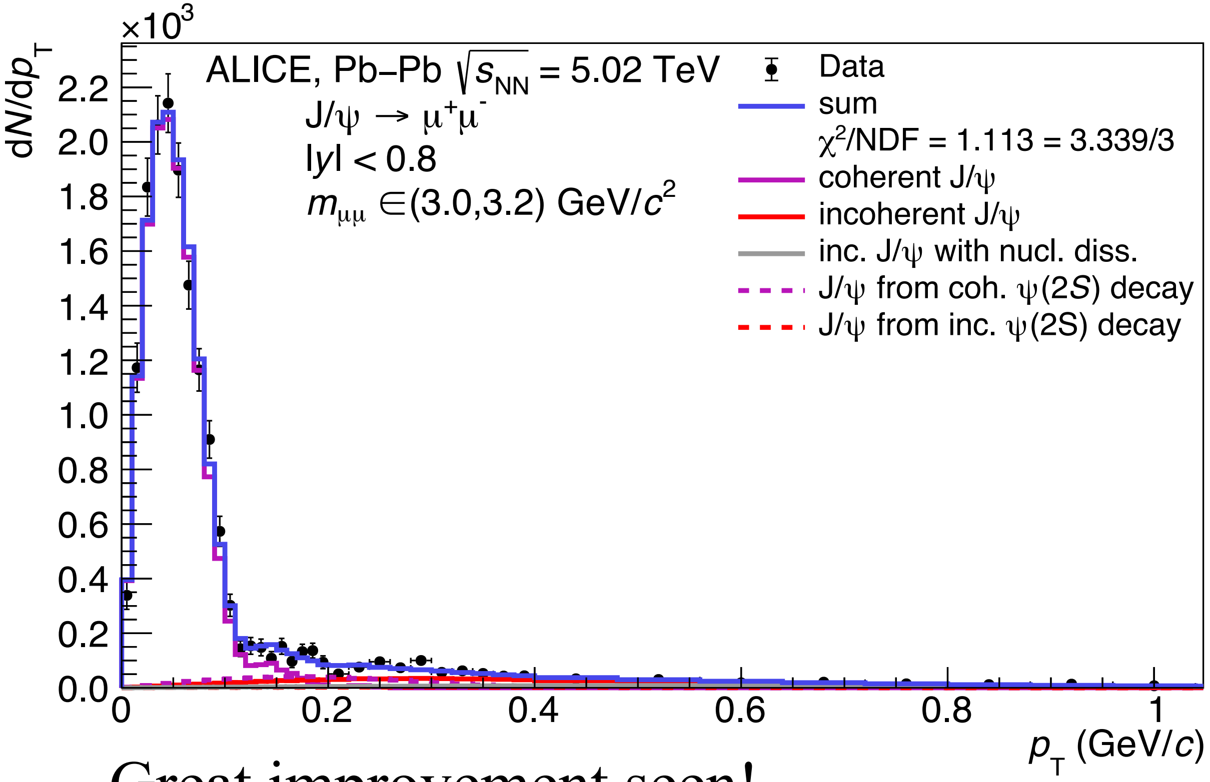
A = nuclear mass number
a = range of Yukawa potential
R_A = nuclear radius (default value for Pb: **6.624 fm**)

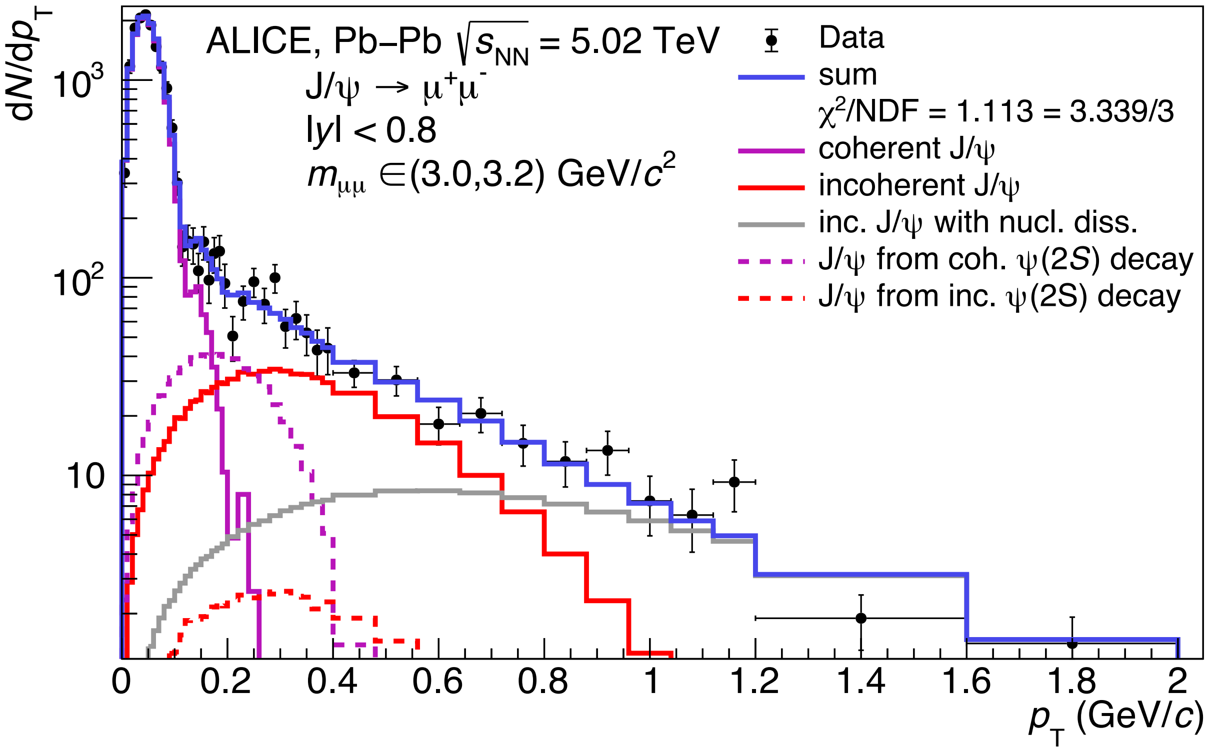
- Measurements can be reproduced if the value of R_A is increased…

Fits using the optimal value of $R_A = 7.35$ fm

- Values of $R_A \in (6.6,7.8)$ fm tried out, we searched for a minimum in χ^2/NDF
- p_T shapes of reconstructed MC events reweighted



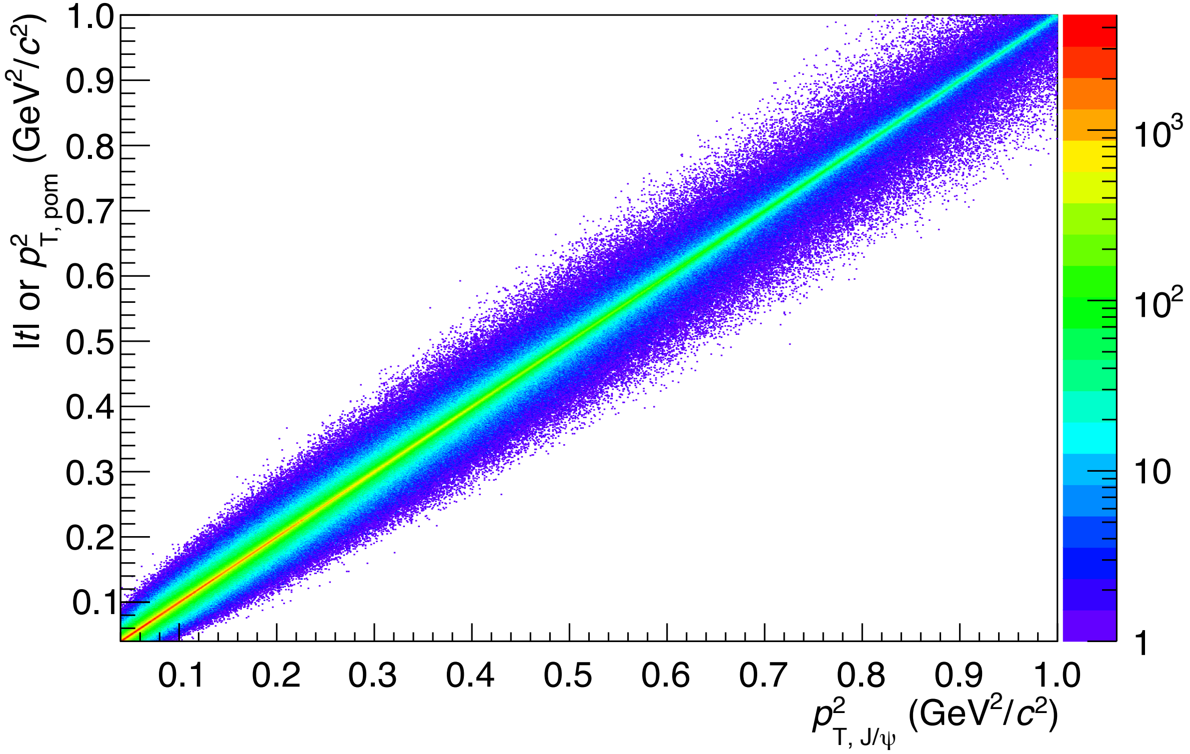


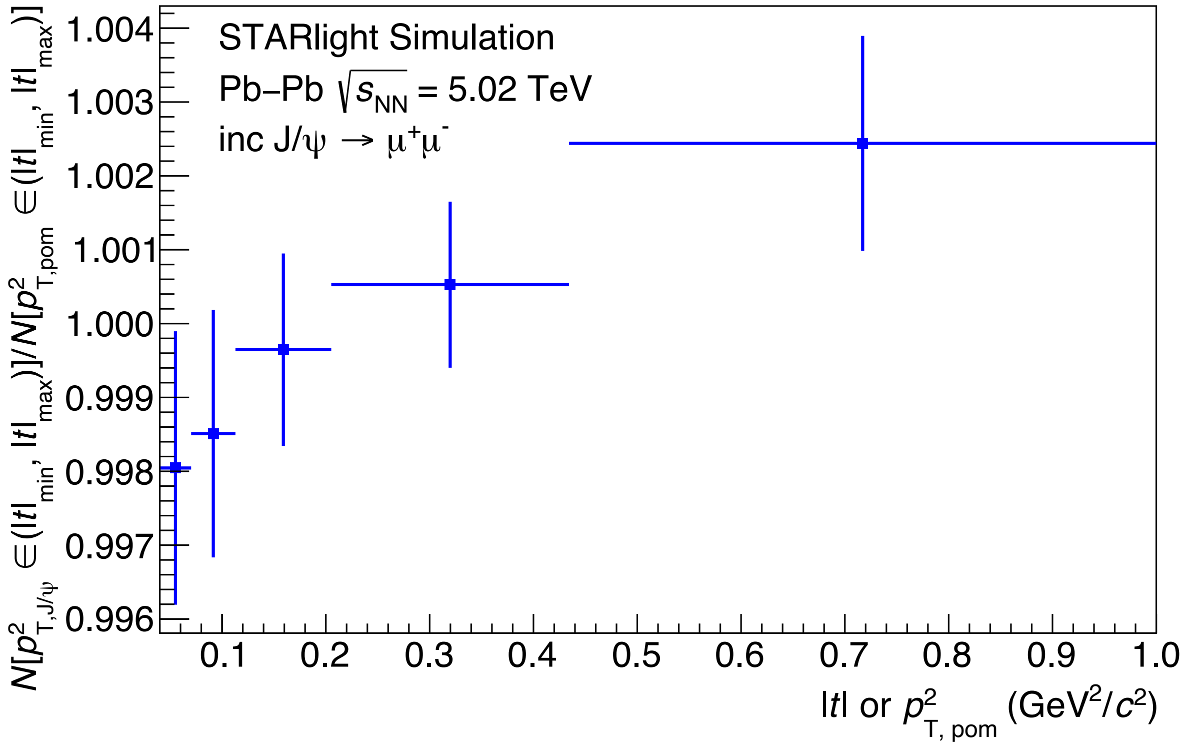


Great improvement seen!

Transition from p_{T}^2 to $|t|$

- STARlight predicts:





No additional correction related to this is needed…

Systematic uncertainties

Source	Uncertainty (4 bins) [%]	Uncertainty (5 bins) [%]
Signal extraction	$(1.0, 2.2)$	$(1.1, 2.1)$
f_C	$(0.0, 0.4)$	$(0.0, 0.5)$
f_D	$(0.4, 3.7)$	$(0.3, 3.8)$
Integrated luminosity	2.7	
EM dissociation	2.0	
ITS-TPC tracking	2.8	
SPD and TOF trigger efficiency	1.3	
Branching ratio	0.6	
Value of the photon flux at $y = 0$	2.0	
The conversion $p_{\mathrm{T}}^2 \to \lvert t\rvert$	negligible	

Tables of results

ALICE

$\mathcal{L}$ [μb^{-1}]	Δy [-]	BR($J/\psi \to \mu\mu$) [%]	$\varepsilon_{\text{veto}}$ [%]	ε_{EMD} [%]	$n_{\gamma\text{Pb}}(y=0)$
232 ± 6	1.6	5.961 ± 0.033 [3]	94.0 ± 2.8 [1] (!)	92.0 ± 1.8 [1]	84.9 ± 1.7 [1]

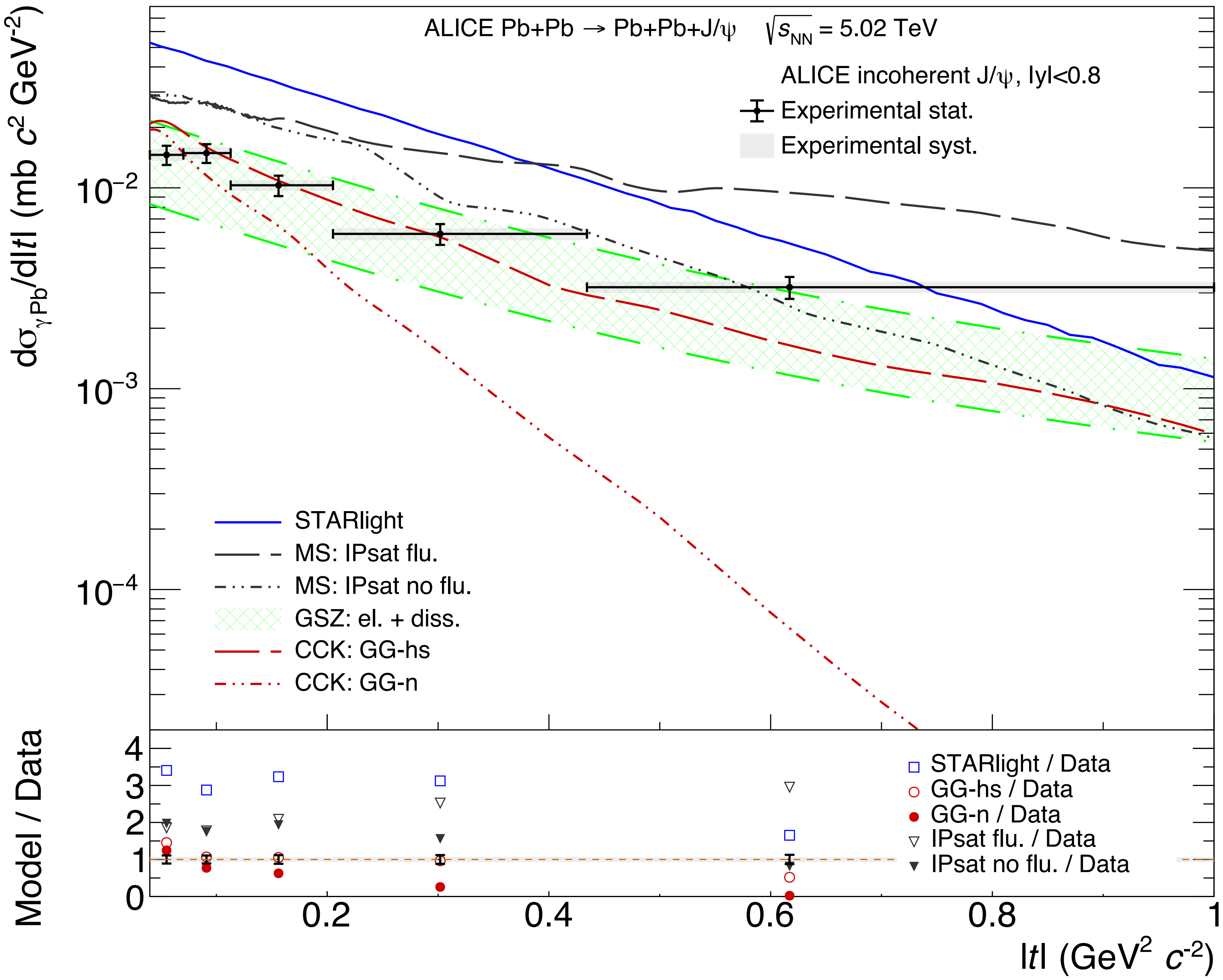
p_{T}^2 interval [GeV$^2/c^2$]	Δp_{T}^2 [GeV$^2/c^2$]	N_{yield}	(Acc $\times\ \varepsilon$)$_{\text{MC}}$ [%]	f_D [%]	f_C [%]	$\frac{d^2\sigma^{\text{inc}}_{J/\psi}}{dy dp_{\text{T}}^2}$ [mb c^2/GeV^2]
(0.040, 0.070)	0.0302	106 ± 11	3.51 ± 0.03	98.5 ± 7.8	12.6 ± 1.1	2.48 ± 0.26(stat.) ± 0.17(syst.)
(0.070, 0.113)	0.0427	106 ± 11	3.26 ± 0.03	58.1 ± 4.4	0.102 ± 0.008	2.53 ± 0.27(stat.) ± 0.16(syst.)
(0.113, 0.205)	0.0923	104 ± 12	2.82 ± 0.02	19.4 ± 1.3	0	1.75 ± 0.20(stat.) ± 0.10(syst.)
(0.205, 0.434)	0.2291	104 ± 12	2.22 ± 0.01	5.8 ± 0.6	0	1.01 ± 0.12(stat.) ± 0.06(syst.)
(0.434, 1.000)	0.5657	102 ± 12	1.71 ± 0.02	2.8 ± 0.3	0	0.54 ± 0.06(stat.) ± 0.03(syst.)

Interval [GeV$^2/c^2$]	$\langle\lvert t\rvert\rangle$ [GeV^2]	$\frac{d\sigma_{\gamma\text{Pb}}}{d\lvert t\rvert}$ [μb/GeV^2]
(0.040, 0.070)	0.055	14.6 ± 1.6(stat.) ± 1.0(syst.)
(0.070, 0.113)	0.091	14.9 ± 1.6(stat.) ± 1.0(syst.)
(0.113, 0.205)	0.156	10.3 ± 1.2(stat.) ± 0.6(syst.)
(0.205, 0.434)	0.302	5.9 ± 0.7(stat.) ± 0.4(syst.)
(0.434, 1.000)	0.617	3.2 ± 0.4(stat.) ± 0.2(syst.)

$|t|$-dependence of the cross section

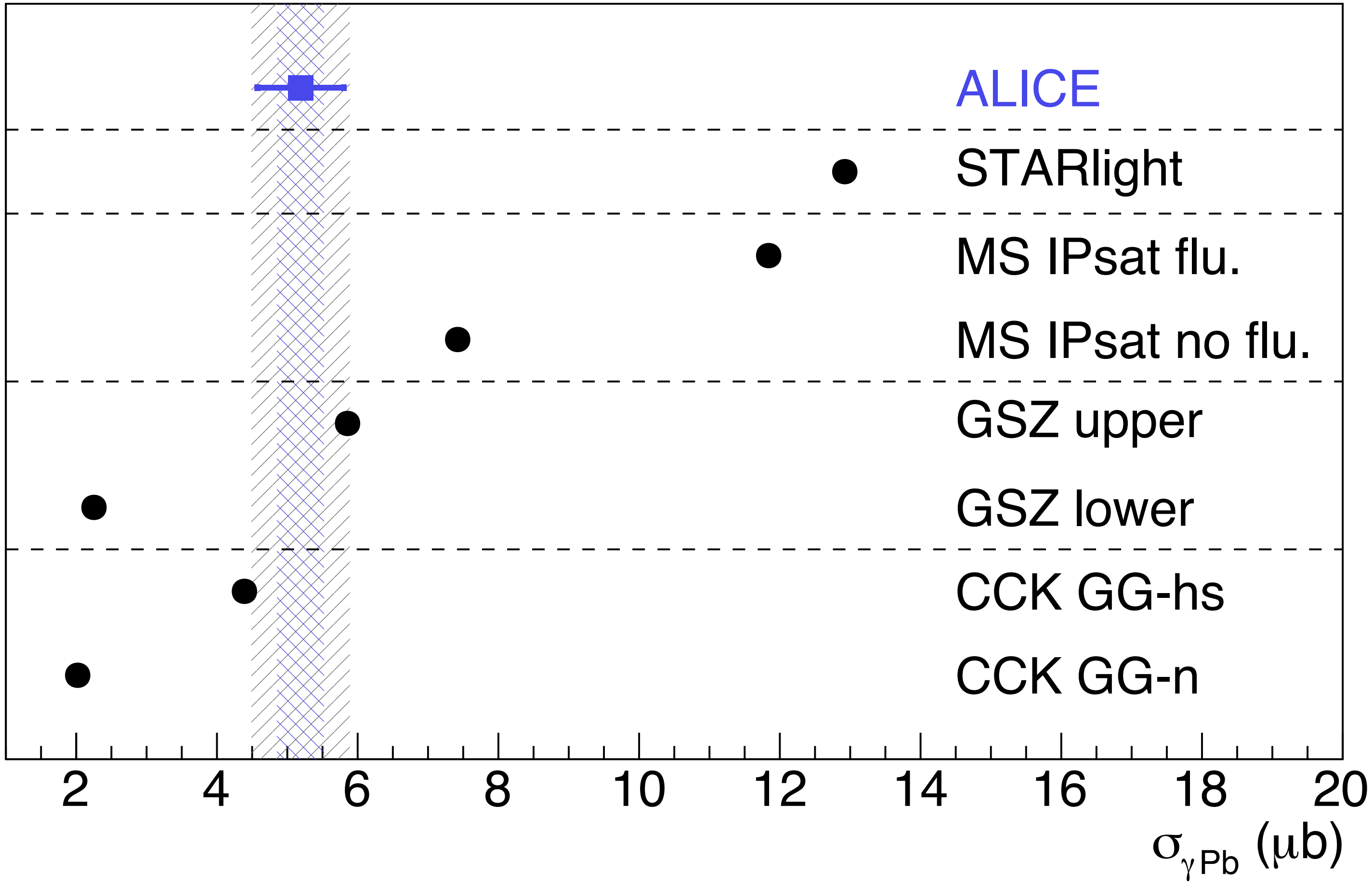
- STARlight [4]
- Mäntysaari et al. (MS) [5]
- Guzey et al. (GSZ) [6]
- Čepila et al. (CCK) [7]: energy-dependent hot-spot model

- Scenarios with/without subnucleonic degrees of freedom distinguished



Total (integrated) photonuclear cross section

$$\sigma_{\gamma\mathrm{Pb}} = (5.19 \pm 0.61(\mathrm{stat.}) \pm 0.33(\mathrm{syst.}))\ \mathrm{mb}$$



Gray shaded area = statistical uncr.
Blue shaded area = systematic uncr.
Blue horizontal bar = combined in quadrature

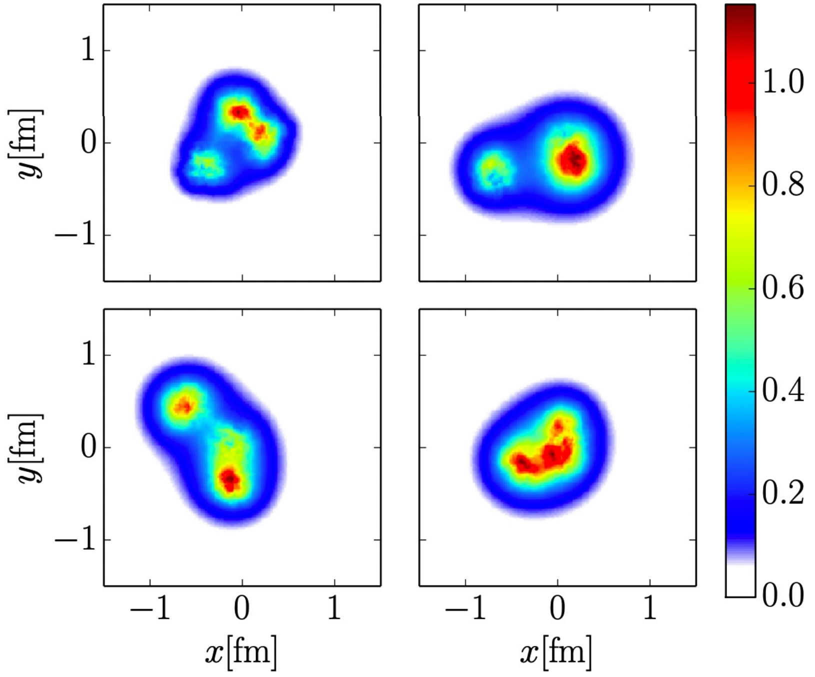
What is there that needs to be finished?

- Analysis Review Committee (ARC) formed, we now go through the process of answering all their questions ☺

- Efficiency of the pile-up veto needs to be calculated
  - Very limited amount of data available for the study
  - Should be finished soon

Summary

- Photoproduction of VMs in UPCs is an excellent tool to look inside hadrons and investigate their structure
- We measure the $|t|$-dependence of the cross section of incoherent J/ψ photoproduction
  - Can tell us more about **fluctuations inside nucleons**
- Statistical uncertainty is dominant ($\approx$ 11%, systematic $\approx$ 5-7%)
- Looks like the slope we measured favors the scenario where fluctuations are present!



Nature Rev.Phys. 1 (2019) 11, 662-674

References

[1] ALICE Collaboration: "First measurement of the $|t|$-dependence of coherent J/ψ photonuclear production" (2021). arxiv.org/abs/2101.04623

[2] C. Alexa et al.: "Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA" (2013). arxiv.org/abs/1304.5162

[3] P. A. Zyla et al.: "Review of Particle Physics" (2020). doi.org/10.1093/ptep/ptaa104

[4] S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comp. Phys. Comm. 212 (2017) 258. starlight.hepforge.org

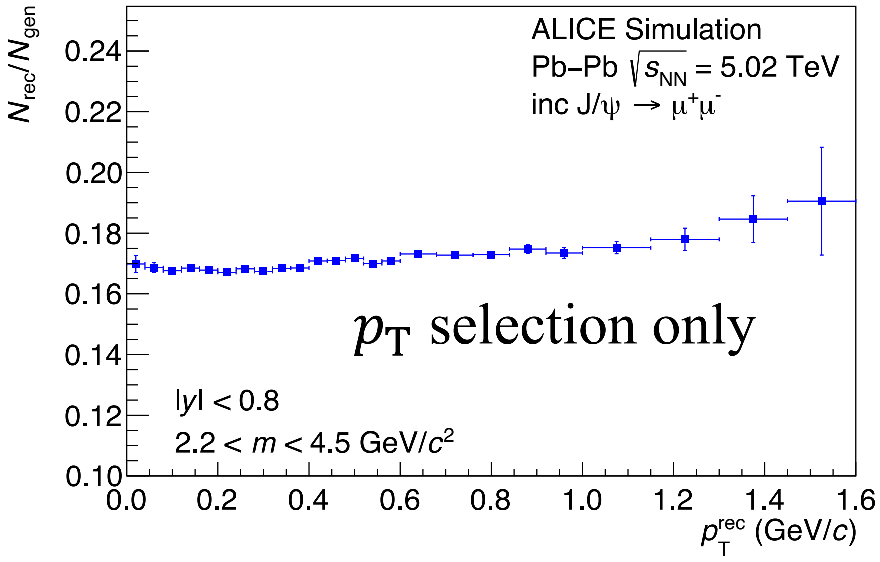
[5] H. Mäntysaari and B. Schenke: Probing subnucleon scale fluctuations in ultraperipheral heavy ion collisions (2017). inspirehep.net/literature/1519841

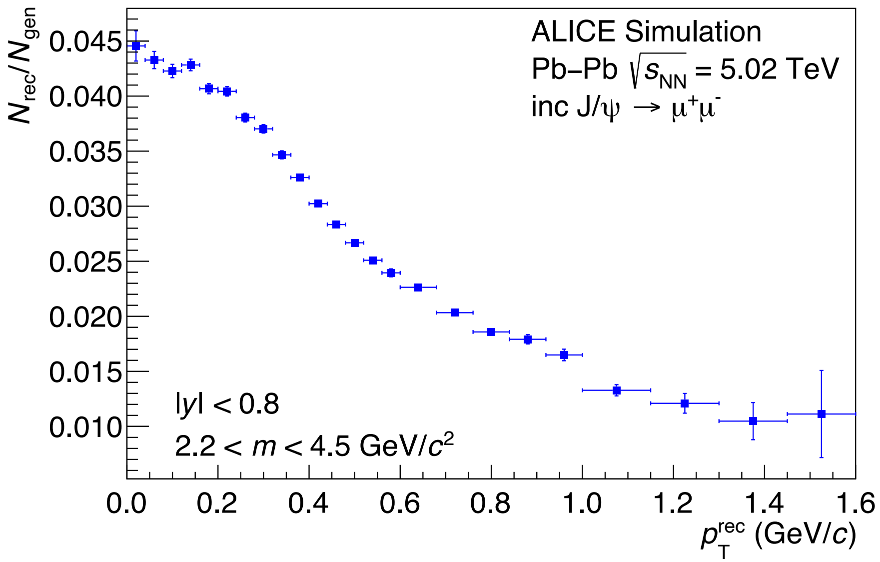
[6] V. Guzey, M. Strikman and M. Zhalov: Nucleon dissociation and incoherent J/ψ photoproduction on nuclei in ion ultraperipheral collisions at the Large Hadron Collider (2019). iinspirehep.net/literature/1684846

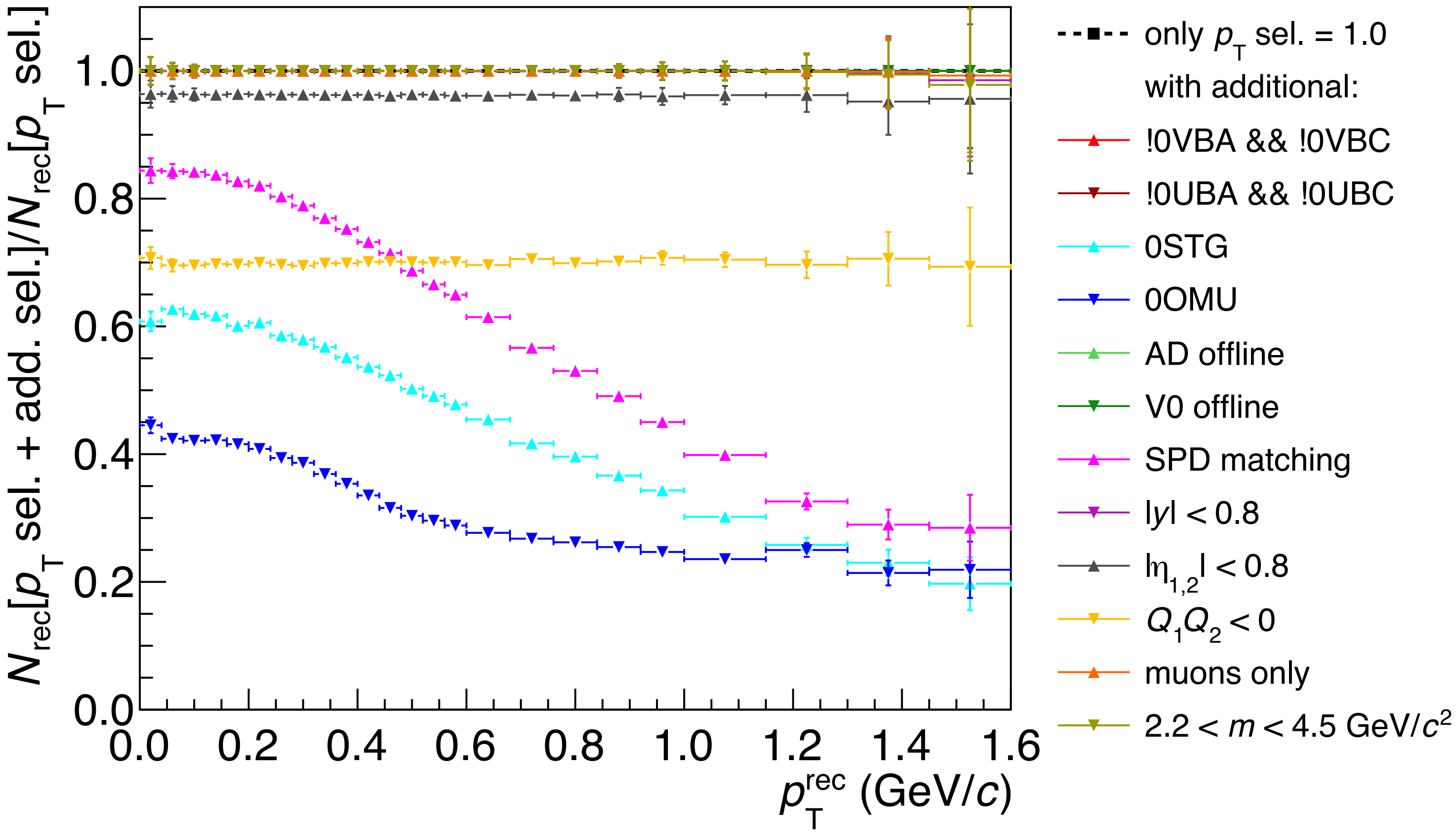
[7] J. Cepila, J. G. Contreras and M. Krelina: Coherent and incoherent J/ψ photonuclear production in an energy-dependent hot-spot model (2018). inspirehep.net/literature/1634637

Backup slides

Source of the spotted p_T dependence of $(\mathrm{Acc} \times \varepsilon)_{\mathrm{MC}}$







0OMU, 0STG and SPD matching only

Migration of events across bins