FNSPE CTU in Prague

Charmonium photoproduction at the LHC

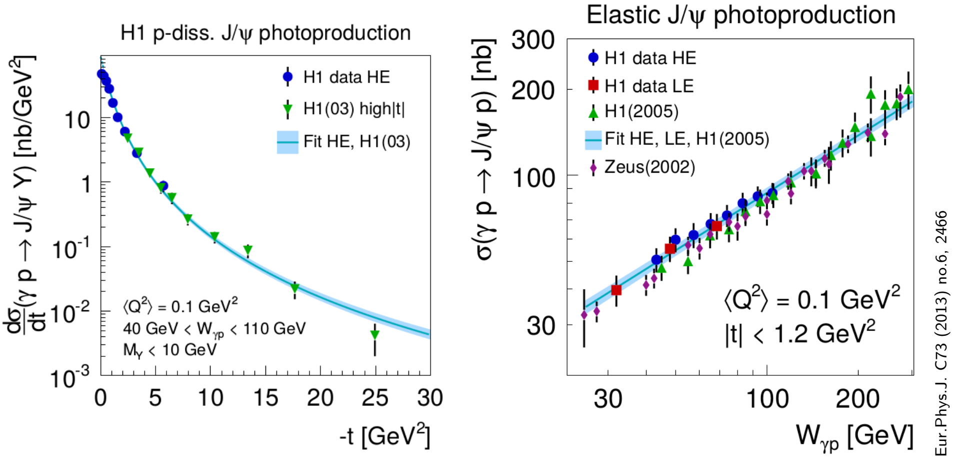
WEJCF 2020

Roman Lavička

Jan 16, 2020, Bily Potok

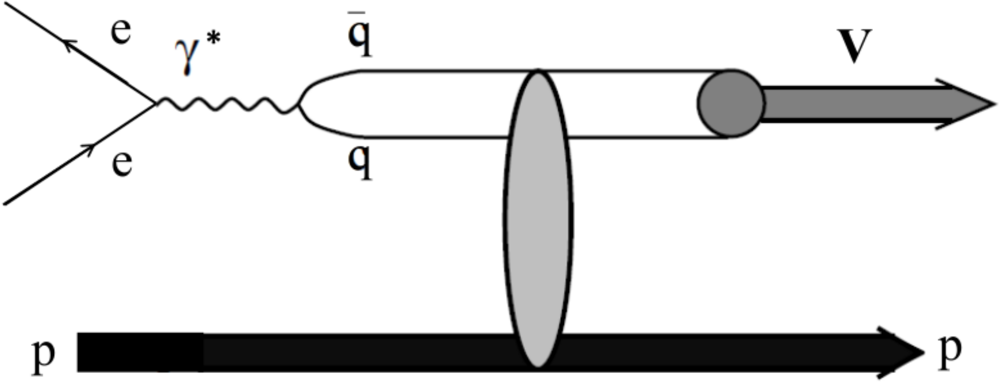
Supervisor: Guillermo Contreras

Published results - ep collisions at HERA



- High precision data covering a large part of the phase space is available from HERA.

Process used at HERA - exclusive electro-production



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

- Electron emits virtual photon which fluctuates into quark-antiquark.
- Quark-antiquark pair interacts with proton and creates vector meson.

Content

1 Description

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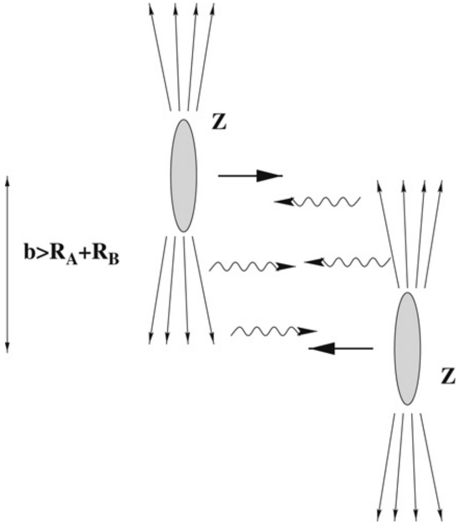
Description

How we differ to HERA conditions...

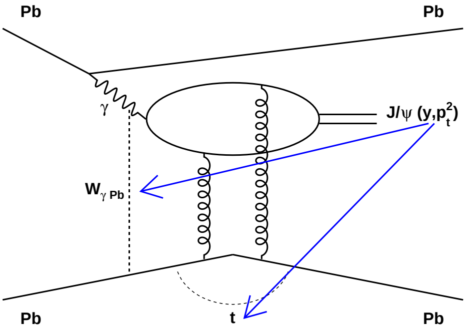
Available tools now - Ultra-peripheral collisions

- Collisions with impact parameter $b > R_A + R_B$.
  - Strong interaction suppressed.
  - EM interaction remains.
- EM field of ultra-relativistic electrically charged particle $\sim$ flux of photons.
  - Interaction intensity increasing with Z^2.



Phys.Rept. 458 (2008) 1-171

Process used at LHC - coherent photo-production



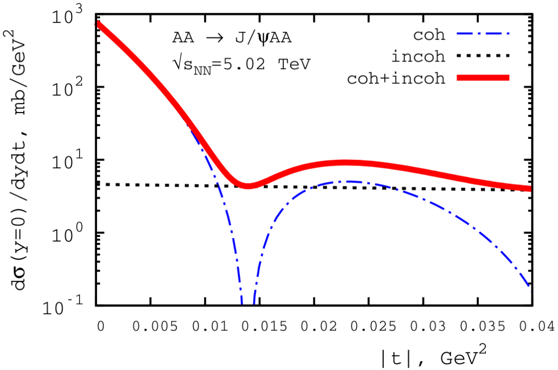
- Coherent J/ψ photoproduction.
  - Hard scale (pQCD valid).
  - Large cross section.
  - Clean experimental signal.

- Provides information on gluon saturation in the proton and shadowing in nuclei at low-x.

$$\left.\frac{\mathrm{d}\sigma_{\gamma A\to J/\psi A}}{\mathrm{d}t}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

Ryskin: Z. Phys. C 57, 89 (1993)

Extensions - $|t|$-dependence



Phys. Rev. C 95, 025204 (2017)

- Nuclear shadowing effects, gluon saturation, distribution functions...
- Cross section t-dependence.

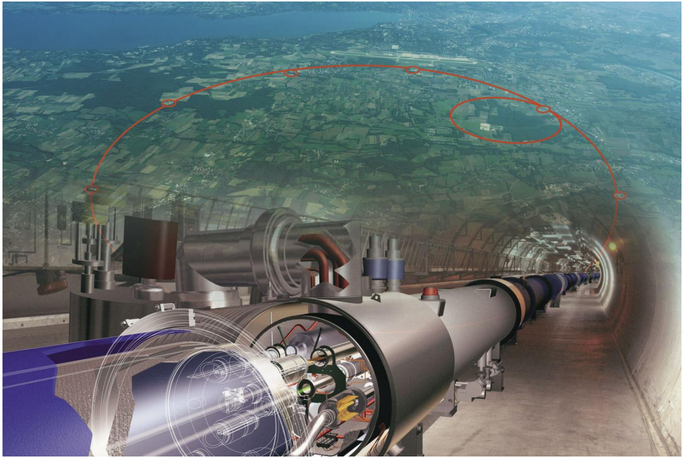
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{\mathrm{d}\sigma}{\mathrm{d}t}\bigg|_{t=0} |F(t)|^2$$

Equipment

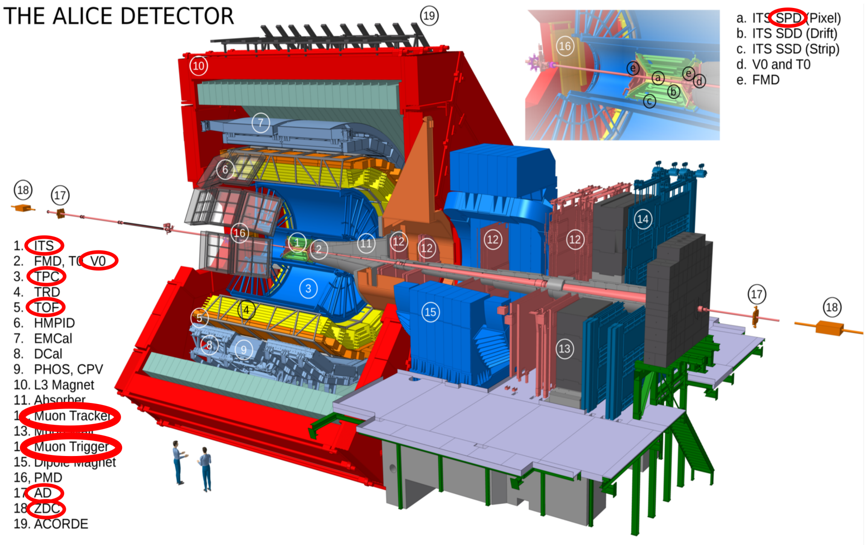
Paper, pencil and...

LHC beams

- Very cool accelerator!
- Much energy!
- So many heavy ions!
- Such people!

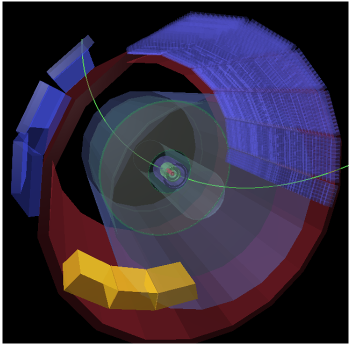


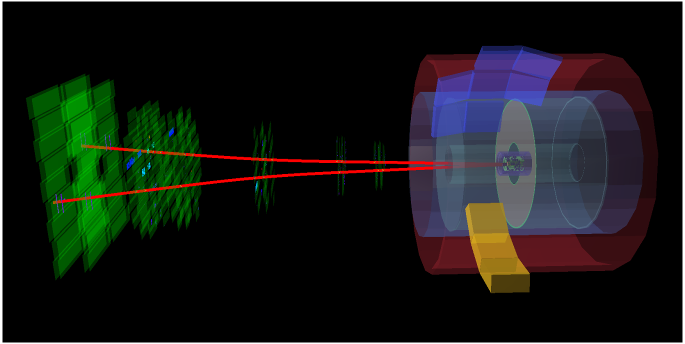
ALICE detector systems



Event displays - what we look for in a collision

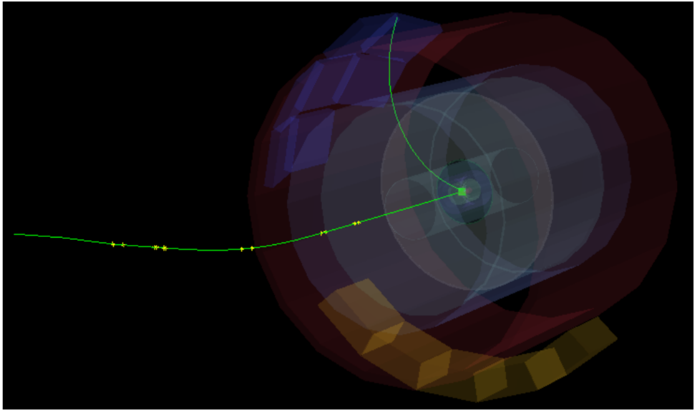
- Central rapidity events:
  - VETOs in forward detectors,
  - 2 back-to-back leptons (ITS/TPC/TOF).
- Forward rapidity events:
  - VETOs in forward/central detectors,
  - 2 muons (Muon chambers).





Event displays - semi-forward rapidity

- Semi-forward rapidity events:
  - ALICE apparatus has no detectors here.
  - Exactly one track in forward detectors and one track in central barrel detectors.



Prepare for the measurement

It is not about just to press a button...

Trigger system - definition

- You cannot record every event because time between two possible collisions < time needed to read out event.
- Triggers quickly choose to read out only events with possible interesting physics.
- Example of UPC trigger:
- CCUP8 = !0VBA & !0VBC & !0UBA & !0UBC & 0STP & 0OMU
  - !0VBX - veto on V0 detector (A or C side)
  - !0UBX - veto on AD detector (A or C side)
  - 0STP - back-to-back event according to SPD topology
  - 0OMU - back-to-back event according to TOF topology
- Basically, you trigger on 2 back-to-back tracks in otherwise empty detector.

Trigger system - simulation definition

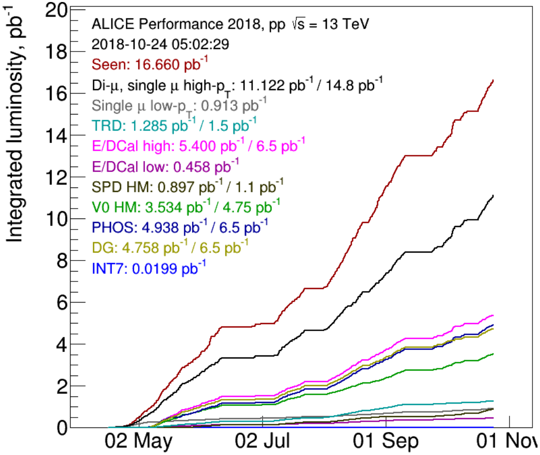
- When a trigger decides to record the collision, ALICE needs some time to read out the event $\rightarrow$ it takes more time than collision rate $\rightarrow$ ALICE is blind to several upcoming events.
- Different triggers set to different physics $\rightarrow$ when recording one trigger, you are loosing some other interesting physics.
- Important task: Set up sensitivity of each trigger to ensure enough data for each segment of physics.
- You simulate rates, when your triggers are fired/read out (due to detector is busy) and compare.
- At the end, you find the best sensitivity (some triggers off even when detector is not busy) to give a chance to more rare triggers.

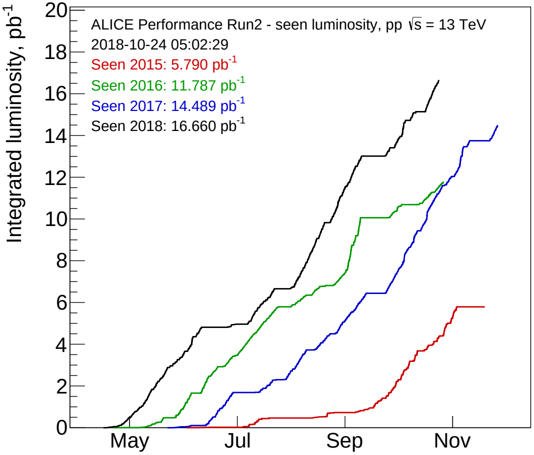
Trigger system - simulation and reality

Trigger	Decision [Hz]	Simulated read out [Hz]	Real read out [Hz]
Min. Bias	7997	226	214
Central	798	167	170
Semi-central	1596	126	129
UPC central barrel	130	36	31
EMCal high	43	12	15
EMCal low peripheral	44	13	7
PHOS semi-peripheral	12	3	4
Lifetime:		0.271	

	Min. Bias [%]	Semi-central [%]	Central [%]
Simulated ds:	10.5	29.5	78
Real ds:	7.5	20	55

Online luminosity trending plots



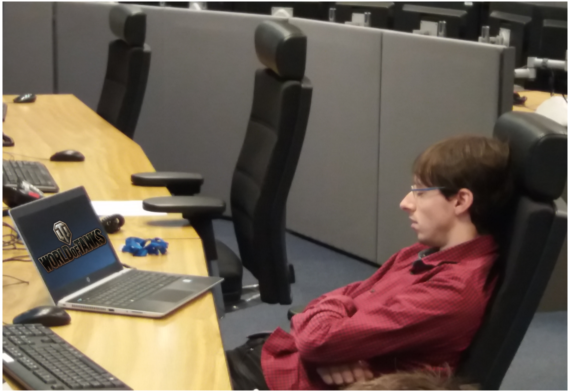


ALICE control room - first beams

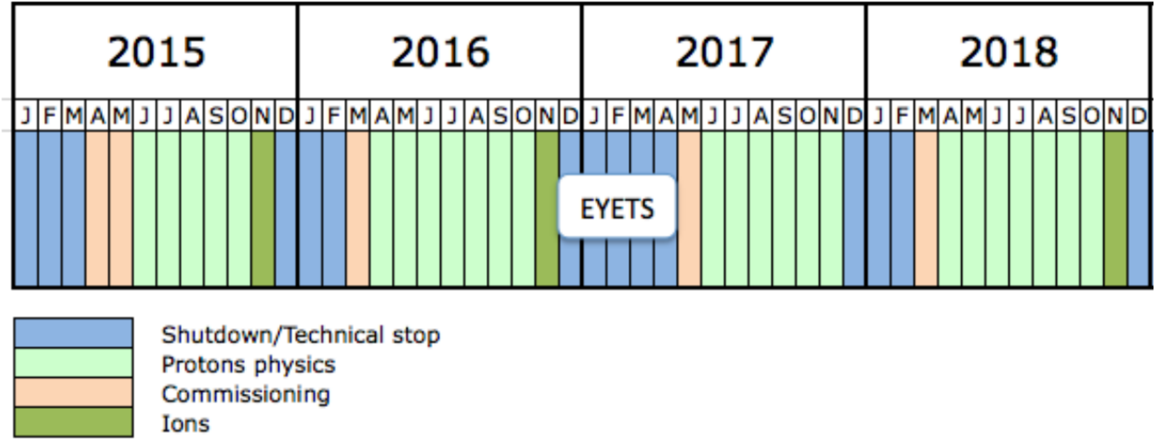
- A lot of computers to control the experiment.
- DAQ, DCS, ECS and shift leader + run coordination.

ALICE control room - reality

- Usually only few people and not much to do...

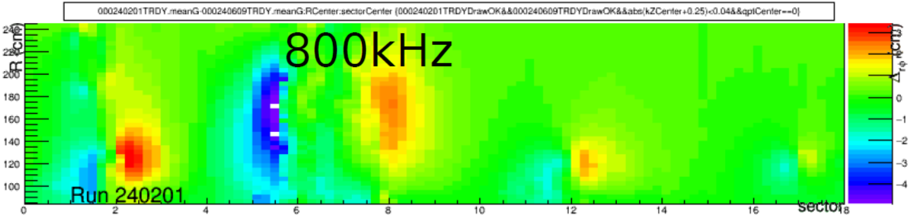


Available data



2015 data tragedy

- New gas filling of TPC - polluted $\rightarrow$ caused distortion (found after data taking).
- Fixing this took $\sim$ 1 year.



- Next, bad understanding of our trigger:
  - First, wrong detector maps for SPD trigger - fixing this took another year.
  - Then, TOF trigger efficiency mismatch with simulations.
  - Was not fixed before new data in 2018 $\rightarrow$ 2015 dataset abandoned.

Analysis

It has several parts...

Cross section measurement

$$\frac{\mathrm{d}^2\sigma^{\mathrm{coh}}_{\mathrm{J}/\psi}}{\mathrm{d}y\mathrm{d}p_t^2} = \frac{N^{\mathrm{coh}}_{\mathrm{J}/\psi}}{(\mathrm{Acc}\times\epsilon)^{\mathrm{coh}}_{\mathrm{J}/\psi}\cdot\epsilon^{\mathrm{VETO}}\cdot\mathrm{BR}(\mathrm{J}/\psi\to\mu^+\mu^-)\cdot\mathscr{L}_{int}\cdot\Delta p_t^2\cdot\Delta y}.$$

- $N^{\mathrm{coh}}_{J/\psi}$ - number of coherently produced J/ψ
- $(\mathrm{Acc}\times\epsilon)^{\mathrm{coh}}_{J/\psi}$ - correction on acceptance and detector efficiencies
- ϵ^{VETO} - correction on inefficiency of VETO detectors
- $\mathrm{BR}(J/\psi\to l^+l^-)$ - branching ratio
- $\mathscr{L}_{int}$ - integrated luminosity of UPC triggers
- Δy - rapidity region
- Δp_t^2 - transversal momentum region

Analysis steps and formulas

$$N^{\text{coh}}_{\text{J}/\psi} = \frac{N^{\text{measured}}}{1 + f_I + f_D^{\text{neutrals}} + f_D^{\text{charged}}},$$

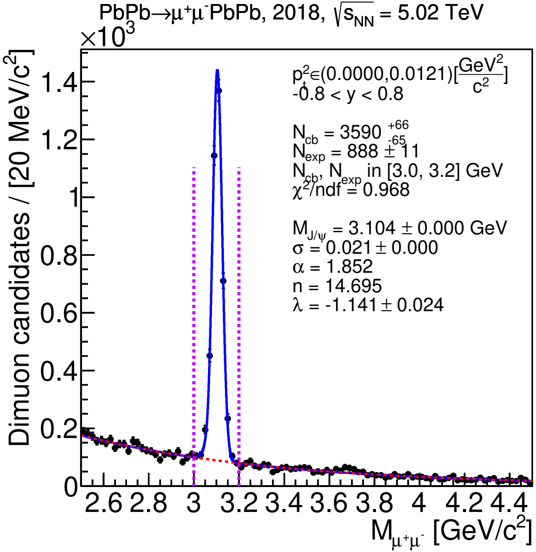
$\rightarrow$ **UNFOLDING** $\rightarrow$

$$\frac{\mathrm{d}^2\sigma^{\text{coh}}_{\text{J}/\psi}}{\mathrm{d}y\mathrm{d}p_t^2} = \frac{N^{\text{coh}}_{\text{J}/\psi}}{(\text{Acc} \times \epsilon)^{\text{coh}}_{\text{J}/\psi} \cdot \epsilon^{\text{VETO}} \cdot \mathrm{BR}(\text{J}/\psi \rightarrow \mu^+\mu^-) \cdot \mathscr{L}_{int} \cdot \Delta p_t^2 \cdot \Delta y}.$$

Application of selection criteria: $J/\psi \rightarrow \mu\mu$

Selection	Data LHC18qr No. events
Total no. of events	2755740
DPG official run list	2682043
CUP31 trigger	2430827
No ITS standalone track	1941414
Tracks are muons	1557878
Muon PID$_{TPC}(\sigma^2_{\text{trk1}} + \sigma^2_{\text{trk2}}) < 9$	1360029
Mass $\in$ (2.5,4.5) [GeV/c^2]	21251
ADA offline veto	21181
ADC offline veto	21135
V0A offline veto	18533
V0C offline veto	16998
Rapidity $\in$ (-0.8,0.8)	16807
Tracks have opposite charge	15317
max(p_T^{trk1},p_T^{trk2})$>$ 1 [GeV/c]	15288
$p_T^{\text{dimuon}} < 0.11$ [GeV/c]	10505
Mass $\in$ (3.0,3.2) [GeV/c^2]	4496
No. of selected events for invariant mass fit	10505

Invariant mass fit - full p_T range



- α and n fixed with MC.
- Good fit.
- Done also for each p_T bin.

Feed down coherent Ψ(2S) contributions (there are two)

- $\psi(2S) \rightarrow J/\psi + \pi^+\pi^-$:

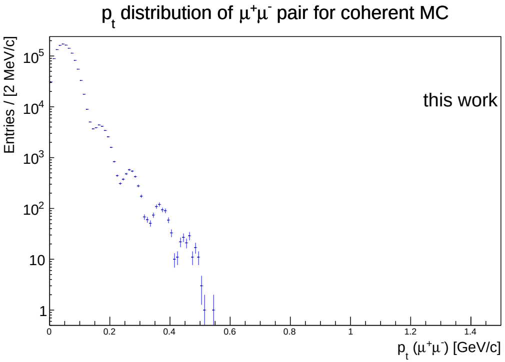
$$ {}^{\text{ibin}}f_D^{\text{charged}} = \frac{{}^{\text{nocut}}\sigma^{\text{coh}}_{\psi(2S)} \cdot {}^{\text{nocut}}_{\text{gen}}N^{\text{coh}}_{J/\psi}}{{}^{\text{nocut}}\sigma^{\text{coh}}_{J/\psi} \cdot {}^{\text{nocut}}_{\text{gen}}N^{\text{coh}}_{\psi(2S)}} \cdot \frac{{}^{\text{ibin}}_{\text{rec}}N^{\text{coh}}_{\psi(2S)}}{{}^{\text{ibin}}_{\text{rec}}N^{\text{coh}}_{J/\psi}} \cdot \mathrm{BR}(\psi(2S) \rightarrow J/\psi + \pi^+\pi^-). \tag{1} $$

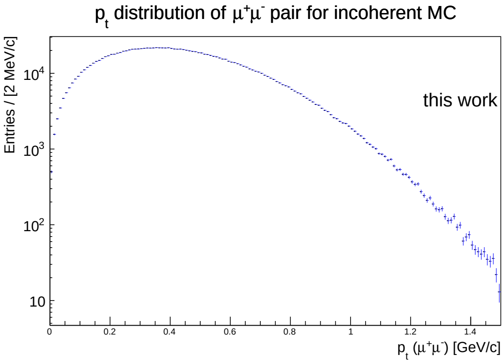
- $\psi(2S) \rightarrow J/\psi + \textit{neutrals}$:

$$ {}^{\text{ibin}}f_D^{\text{neutral}} = \frac{{}^{\text{nocut}}f_D^{\text{neutral}}}{{}^{\text{nocut}}f_D^{\text{charged}}} \cdot {}^{\text{ibin}}f_D^{\text{charged}}. \tag{2} $$

- Assuming p_t-dependence is the same for neutrals and charged.
- Using MC data and cross sections defined in STARlight.
- Cross sections ratio compared with measured result.

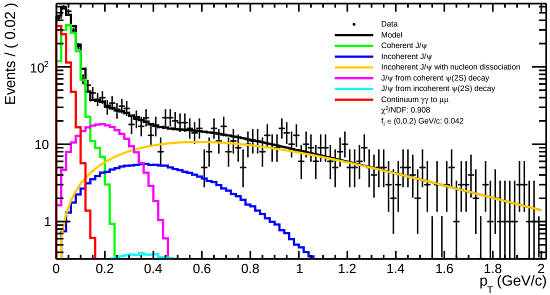
Coherent vs. Incoherent

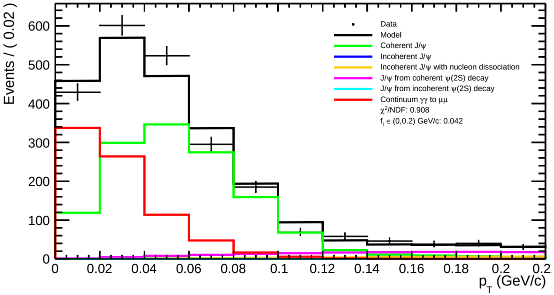




- Coherent:
  - interaction with a whole nucleus,
  - diffractive pattern,
  - low transversal momentum.
- Incoherent:
  - interaction with a part of a nucleus,
  - no diffractive pattern,
  - high transversal momentum.

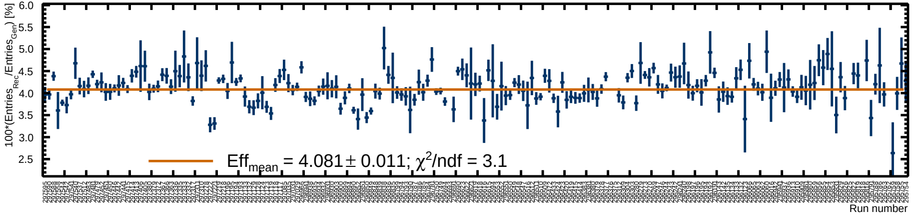
Incoherent J/ψ contributions - p_T fit from MC templates

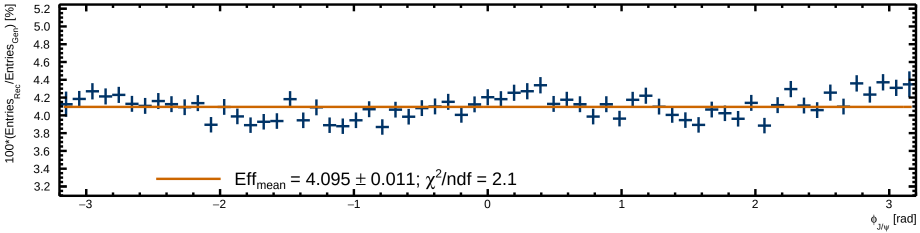




- Feed down fixed (see previous slide). Incoherent $\Psi(2S) \sim 6.9\%$ of coherent $\Psi(2S)$.
- Continuum from invariant mass fit. Nucleon dissociation from H1 paramaetrization.

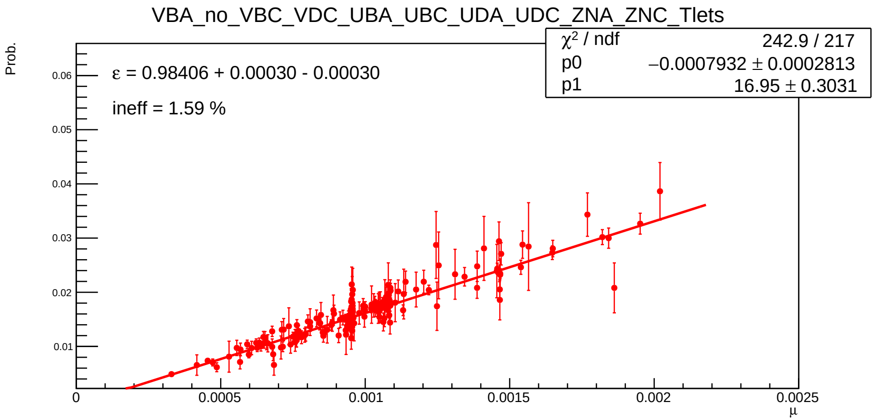
Acceptance X efficiency





- Reconstructed particles after cuts to generated particles after y/p_T cut for each run.
- Modulation in azimuthal angle.

VETO inefficiencies



- Events, when your veto detector was fired in otherwise empty detector, to cases with empty detector with no requirement on the veto detector.

Luminosity

- In theory.

$$\mathscr{L}_{int} = \frac{R}{\sigma}$$

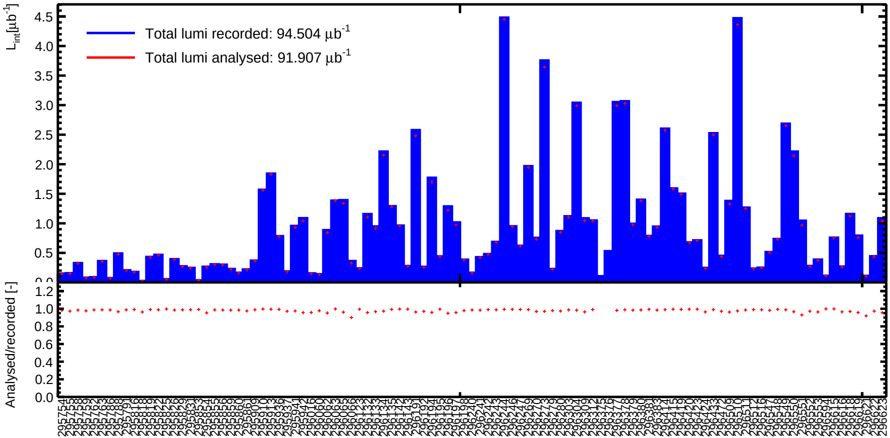
- In ALICE (real) world.

$$\mathscr{L}_{UPC} = \frac{R^{B}_{REF}}{\sigma_{REF}} F(\mu_{REF}) \frac{R^{A}_{UPC}}{R^{B}_{UPC}}$$

$\mathscr{L}_{int}$ - integrated luminosity of UPC triggers
σ_{REF} - corresponding reference cross section
R - number of reference and UPC triggers (A)fter/(B)efore CTP veto.

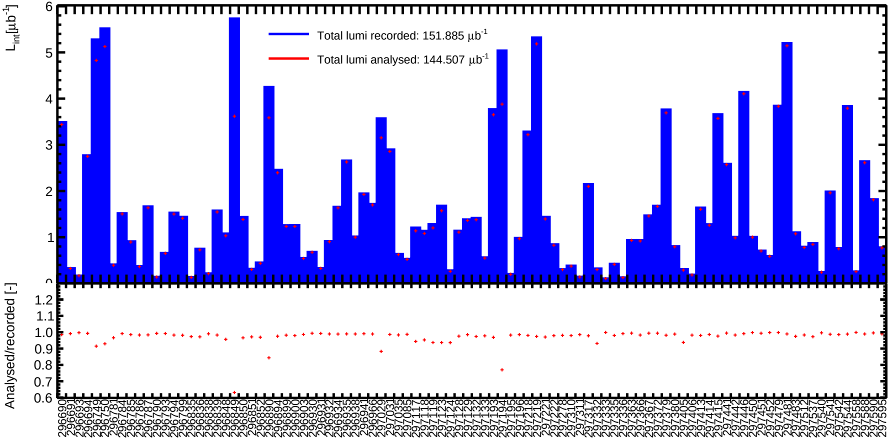
- σ_{REF} taken from Van der Meer scan.
- This gives total recorded luminosity.
- Needs to be corrected for the size of analysed sample.

Luminosity Analysed/Recorded LHC18q



Very well pre-selected data sample.

Luminosity Analysed/Recorded LHC18r



Only few runs not fully analysed → minor effect on statistics.

Unfolding - theory

$$f_{meas}(y) = \int R(x, y) f_{true}(x) dx,$$

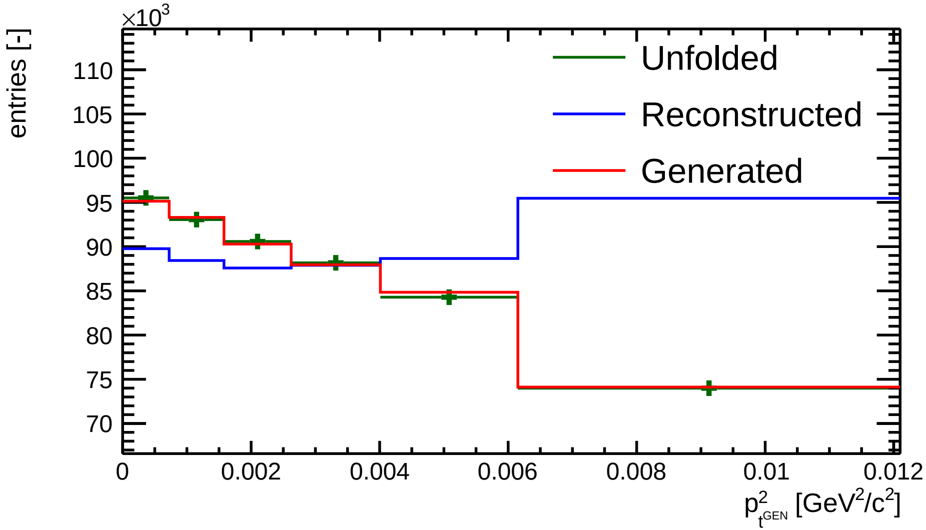
$f_{meas}(y)$ - measured distribution
$f_{true}(x)$ - true distribution
$R(x, y)$ - response function

- Response function contains:
  - detector acceptance,
  - efficiencies,
  - bin migrations.
- Unfolding = inversion of response matrix and its application on measured distribution (in discrete notation).

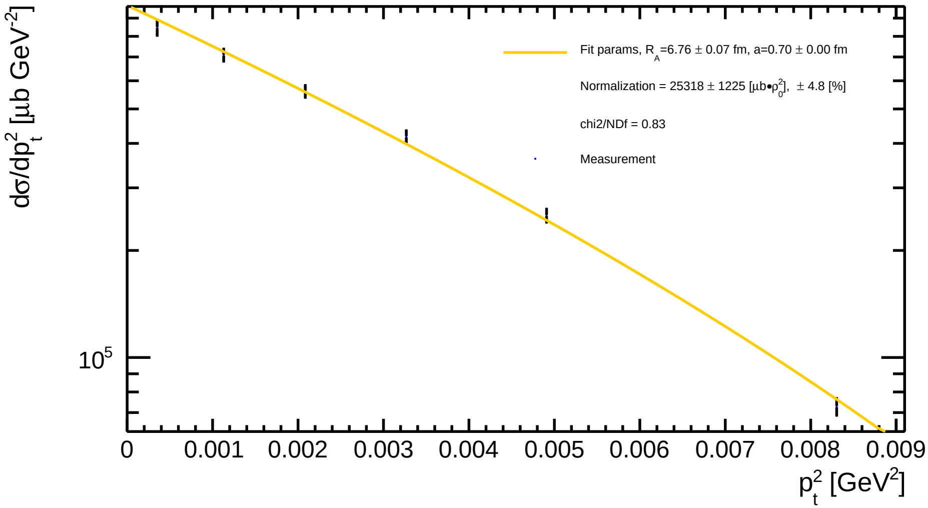
Unfolding methods

- You need to somehow modify the response function (matrix).
- In general, you add bias and smaller variance.
- Theoretical prediction in form of Monte Carlo.
- Without regularisation:
  - Response matrix inversion. (large variance)
  - Method of correction factors. (large bias)
- With regularisation:
  - TUnfold (likelihood or χ^2 test).
  - Singular Value Decomposition (SVD)
- Iterative:
  - Bayes by D'Agostiny (iteration).

Full MC proof it is working



Putting all these ingredients together - release coming in 2020!



Summary

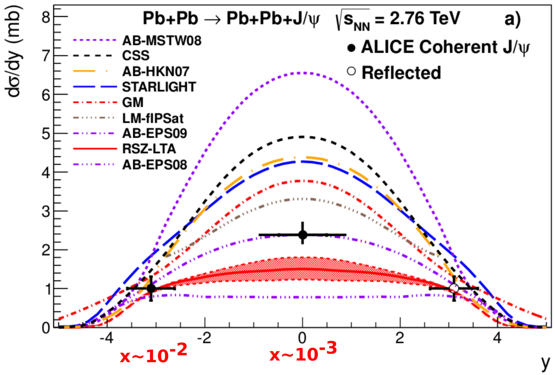
- We have tools to follow up research at H1 experiment.
- We learnt the preparations and data taking flow.
- We learnt the analysis flow.
- We learnt that more is coming!!!

BACK UP

Published results

It has several parts...

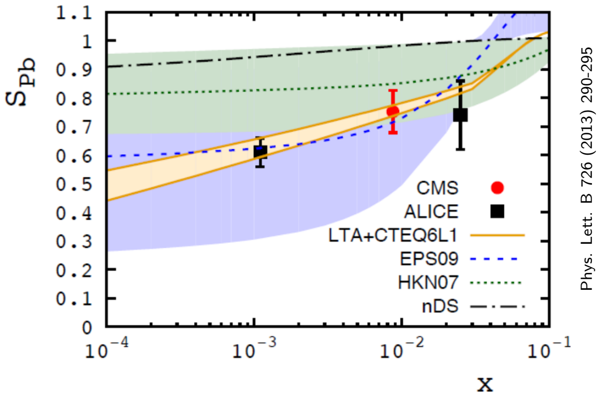
Previously presented results - Pb-Pb collisions at ALICE of Run 1



Eur.Phys.J. C73 (2013) no.11, 2617
Phys.Lett. B718 (2013) 1273

- Coherent J/ψ cross sections were measured in the forward and the central rapidity region.
- Large spread of predictions before the measurement.
- Disfavour no and strong nuclear shadowing models in central rapidity.

Previously presented results - What we have learnt

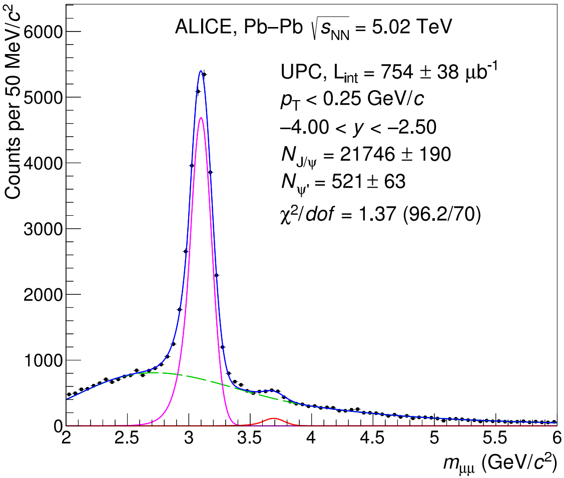


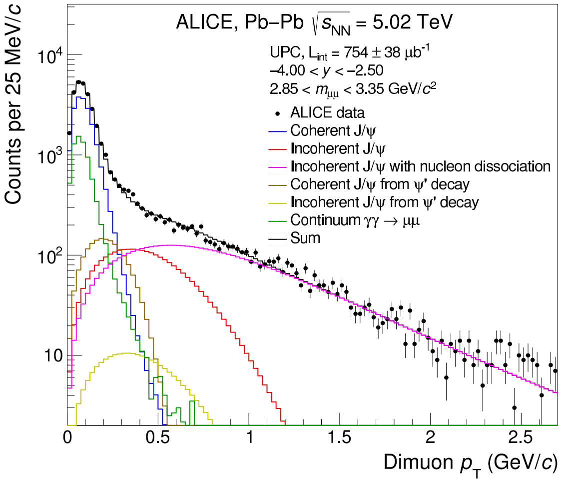
$$S_{Pb}(W_{\gamma p}) = \left[\frac{\sigma^{exp}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}{\sigma^{IA}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}\right]^{1/2}$$

$$x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}}$$

- Based on experimental inputs.
- Pb-Pb UPC experimental cross section.
- Impulse approximation (γ-p data).
- Good agreement with EPS09 and LTA.

Recent results - Pb-Pb collisions at ALICE of Run 2

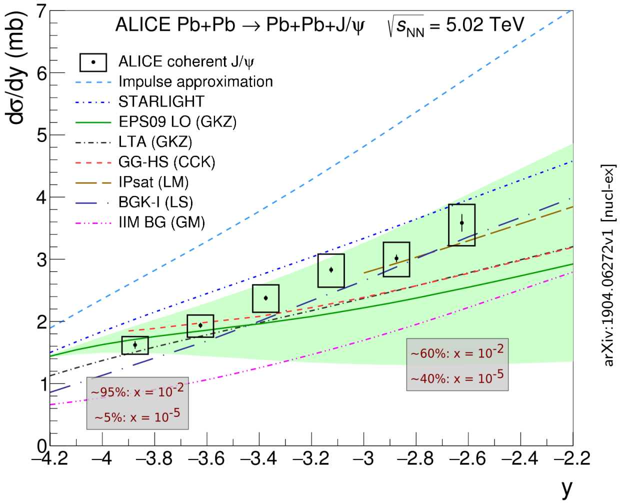




arXiv:1904.06272v1 [nucl-ex]

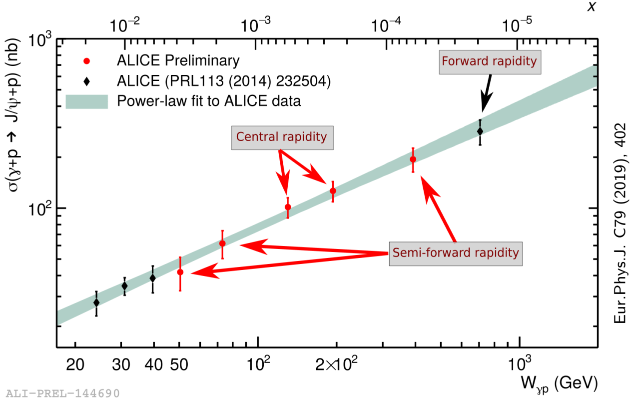
- Clear J/ψ signal, p_T spectrum is well understood, 200x larger lumi wrt. Run 1.

Recent results - Pb-Pb collisions at ALICE of Run 2



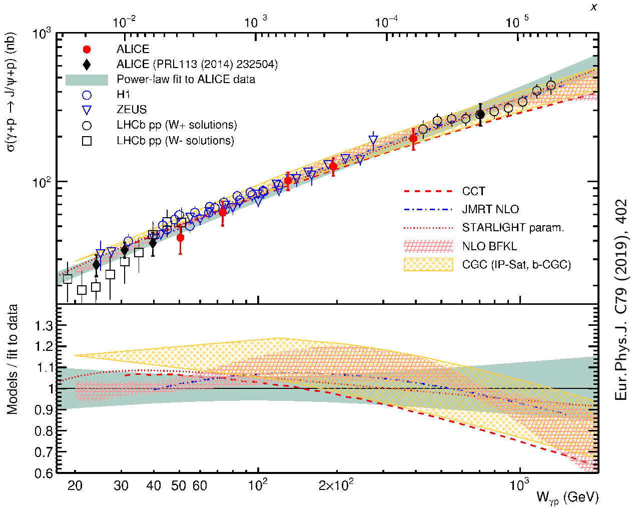
- Large statistics allowed to split in 6 rapidity intervals.
- Examined Bjorken x depends on which nucleus emitted a probing photon.
- Comparison of data to the impulse approximation implies moderate shadowing.
- The best description of data is by LM and LS models, which are based on saturation ideas.

Looking inside proton - p-Pb collisions at ALICE of Run 1



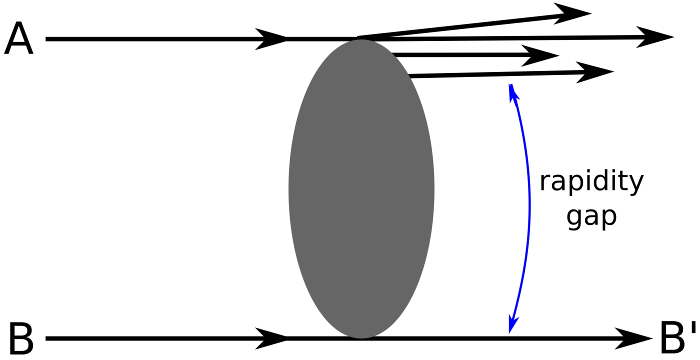
- Measurement from 20 GeV to 700 GeV.
- Exponent value compatible with previous ALICE data.
- Exponent value compatible with HERA measurements as well.

Looking inside proton - p-Pb collisions at ALICE of Run 1



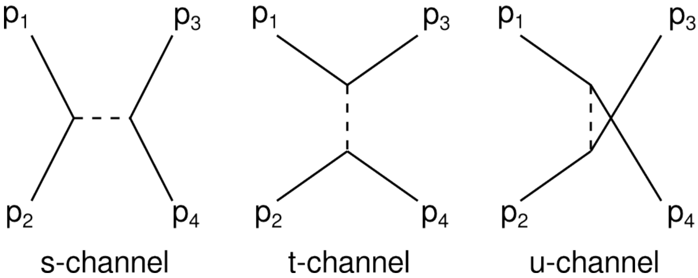
- Agreement with HERA data..
- Agreement with various models and LHCb measurements.
- Measurement of Run 2 data in forward region allows us to reach $W_{\gamma p} > 1$ TeV!

Diffractive physics - definition



- No quantum number exchange.
- High energy.
- Rapidity gap.

Diffractive physics - kinematics



- t - transferred momentum (Mandentelstam variable).

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

- y - rapidity.

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

Bayes method (1/2)

x_i - true event with momentum in bin i
y_j - measured event with momentum in bin j
P(x_i) - probability of x_i
P(y_j,x_i) - probability of measurement of event y_j caused by event x_i

- From Bayes theorem:

$$P(x_i \mid y_j) = \frac{P(y_i \mid x_j)P(x_j)}{\sum_l^{nbins} P(y_i \mid x_l)P(x_l)}, \tag{3}$$

Bayes method (2/2)

x_i - true event with momentum in bin i

y_j - measured event with momentum in bin j

P(x_i) - probability of x_i

P(y_j,x_i) - probability of measurement of event y_j caused by event x_i

- Procedure:
  1. Choose first P(x_j) from MC,
  2. Do the Bayes estimation and get no. of true events,

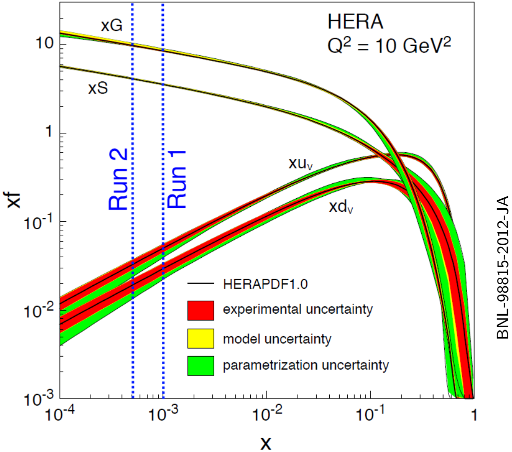
$$n(x_j) = \sum_{l}^{nbins} n(y_l) P(x_j \mid y_l),$$

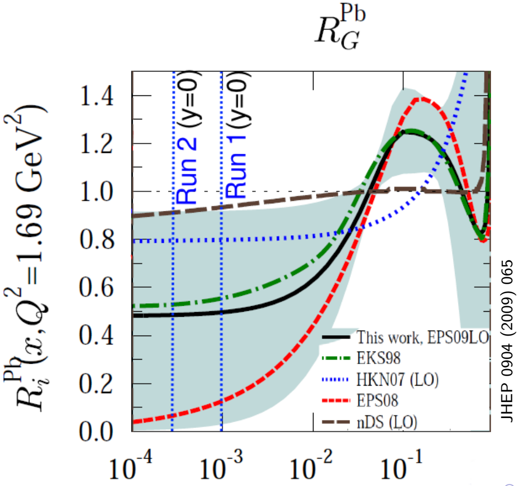
  3. Do χ^2 test,
  4. If condition not fulfilled, repeat with

$$P(x_j) = \frac{n(x_j)}{\sum_l^{nbins} n(y_l)}.$$

Where is QCD now

- Proton is mainly gluons at Bjorken $x \sim 10^{-3}$ (HERA).
- LHC provides possibility to study lead nuclei at small Bjorken x.





What we are going to study

- Coherent production of J/ψ in Pb-Pb UPC at mid rapidity at ALICE.
  - Run 1: $x \sim 10^{-3}$; Run 2: $x \sim 0.5 \cdot 10^{-3}$.
- t-Dependence of the cross section.
- Sensitive to the gluon distribution of the target in the impact parameter plane.