Double-parton scattering (and more) in heavy-ion collisions

Cynthia Hadjidakis
IPN Orsay

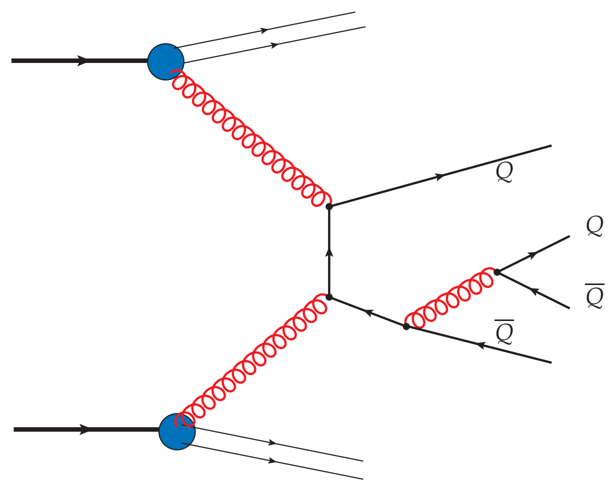
GDR-QCD, Orsay, September 30th 2016

- Multi-parton interaction in p-p collisions: single-parton scattering (SPS) vs double-parton scattering (DPS)
- Multi-parton interaction and more in heavy-ion collisions: SPS, DPS and double-nucleon scattering (DNS)
- LHC expected yields in Run2 for pair production of hard probes in p-Pb and Pb-Pb collisions

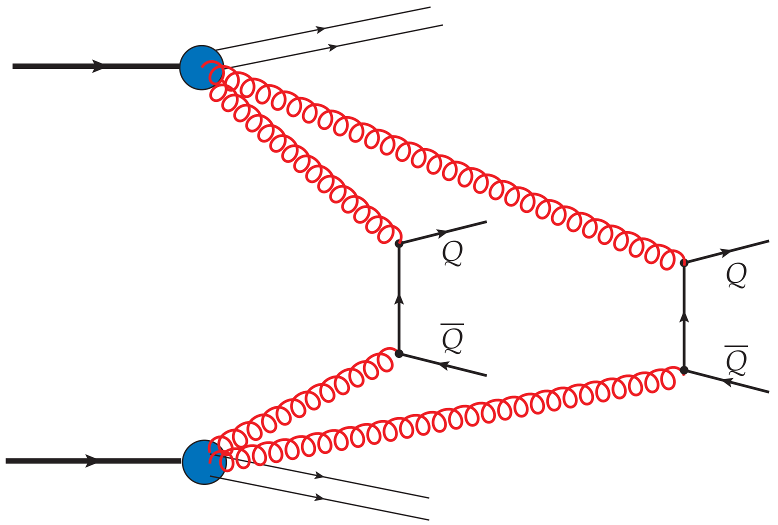
Multi-parton scattering in p-p collisions

At high energy in p-p collisions: probability of multiple-parton scattering is expected to increase, particularly in the case of double hard production:

Single-Parton Scattering (SPS)



Double-Parton Scattering (DPS)



SPS:

- single-parton scattering from a single hadron-hadron collision

DPS:

- double-parton scattering from a single hadron-hadron collision
- provide inputs on correlation between pairs of partons in the proton
- hand-pocket formula considering the two parton interactions are independent

$$\sigma^{P_1+P_2} = \frac{m}{2\sigma_{\text{eff}}}\sigma^{P_1}\sigma^{P_2}$$

with m = 1/2, 1, 2 symmetry factor depending on the process

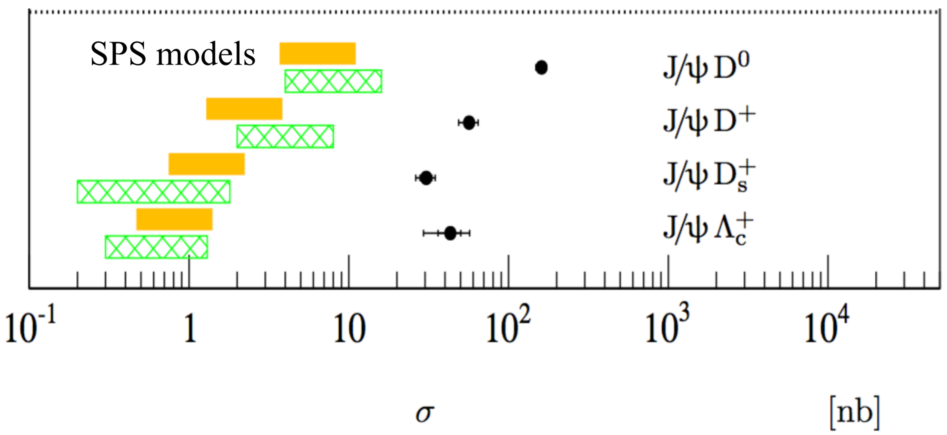
σ_{eff} :

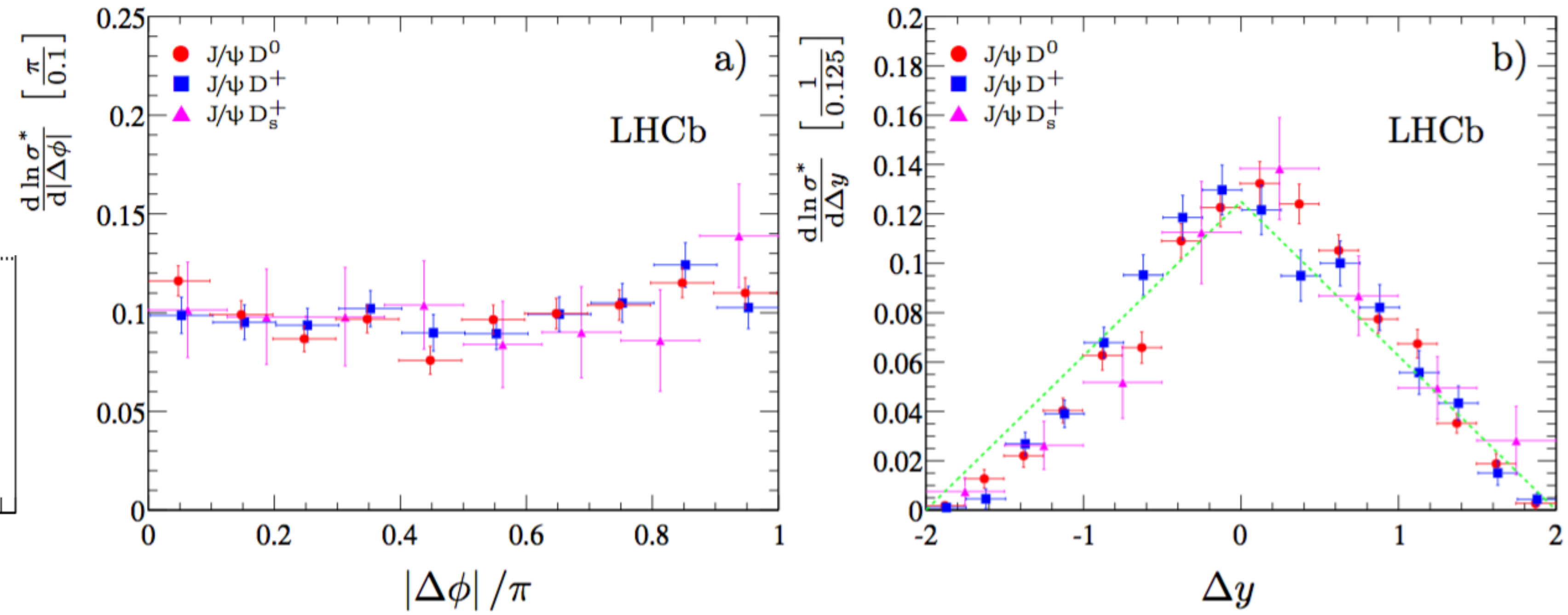
- parametrizes the effective spatial area of the parton-parton interactions
- universal (process and energy-independent)

Multi-parton scattering in p-p collisions

Disentangling SPS vs DPS via rapidity and angular dependence

J/ψ + open charm in LHCb at 7 TeV ***JHEP06 (2012) 141***



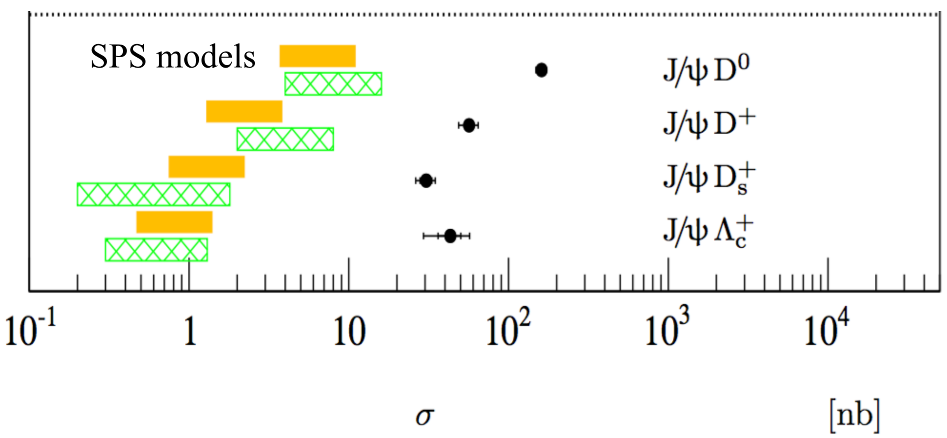


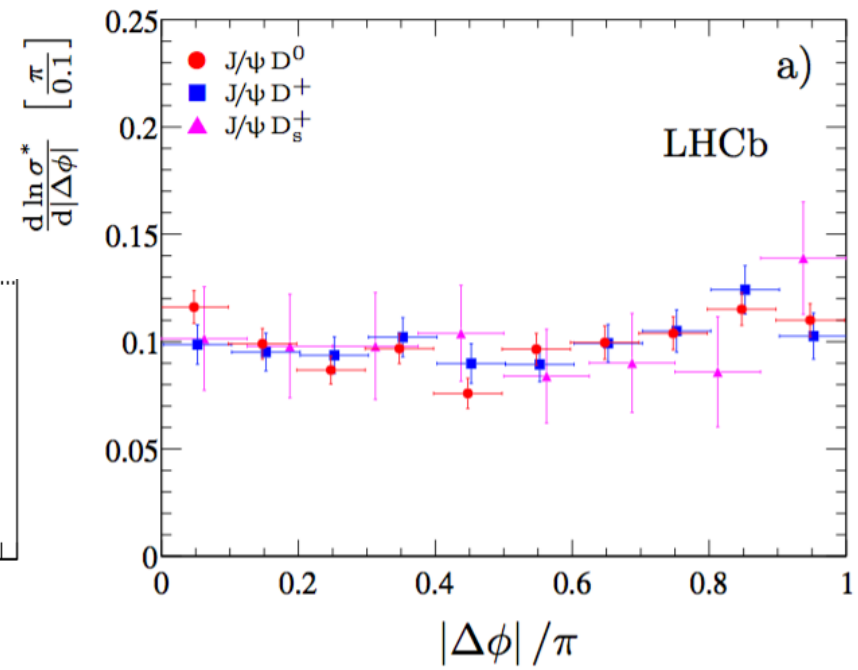
→ cross-sections 10 times larger than SPS models and DPS supported by rapidity and angular dependence

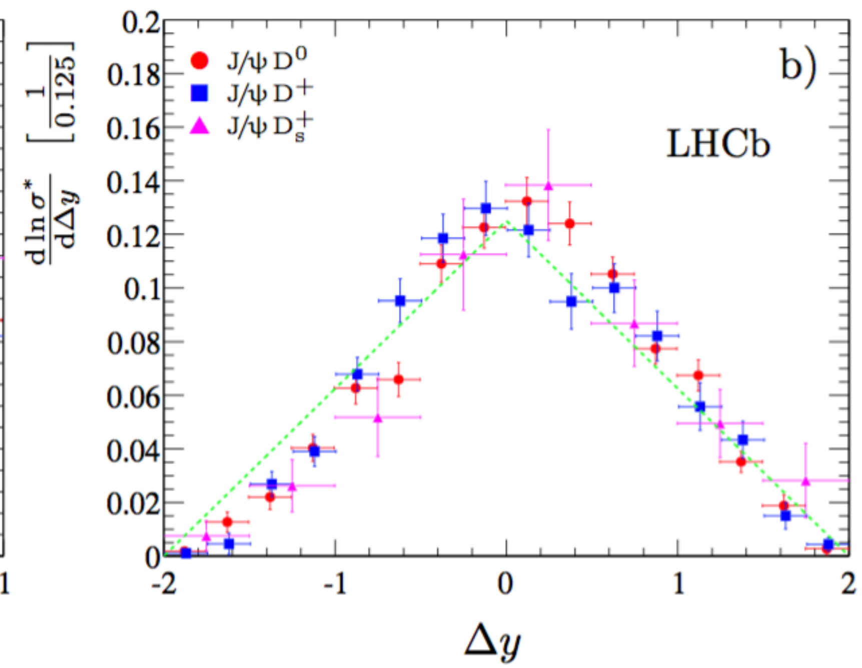
Multi-parton scattering in p-p collisions

Disentangling SPS vs DPS via rapidity and angular dependence

J/ψ + open charm in LHCb at 7 TeV ***JHEP06 (2012) 141***

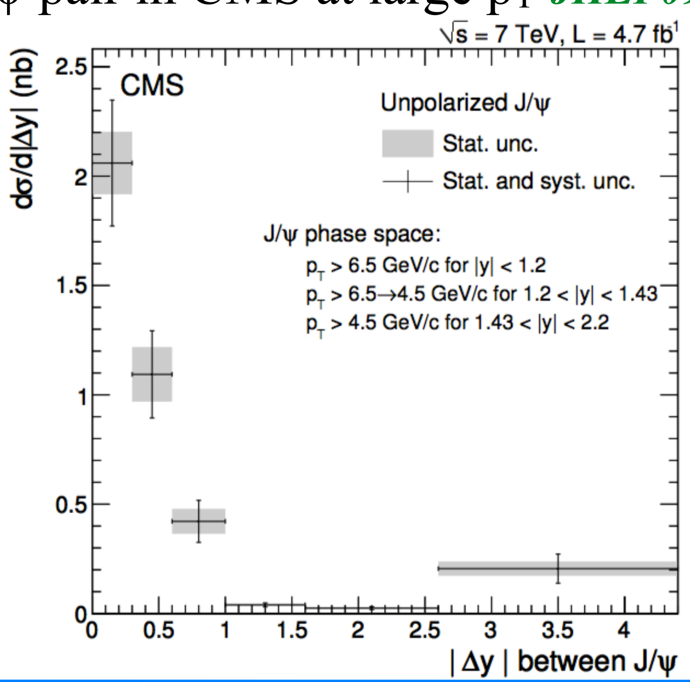






→ cross-sections 10 times larger than SPS models and DPS supported by rapidity and angular dependence

J/ψ pair in CMS at large p$_T$ ***JHEP09 (2014) 094***

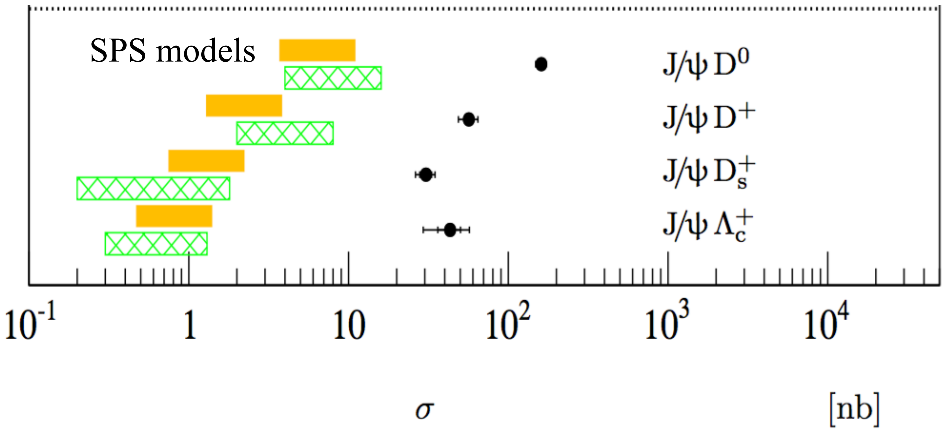


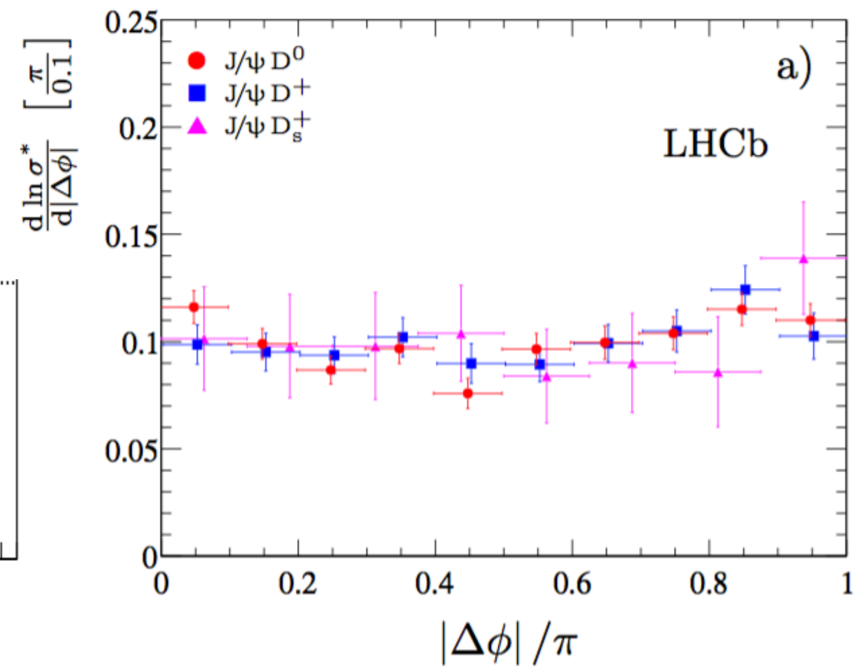
→ contribution at large Δy expected from DPS only

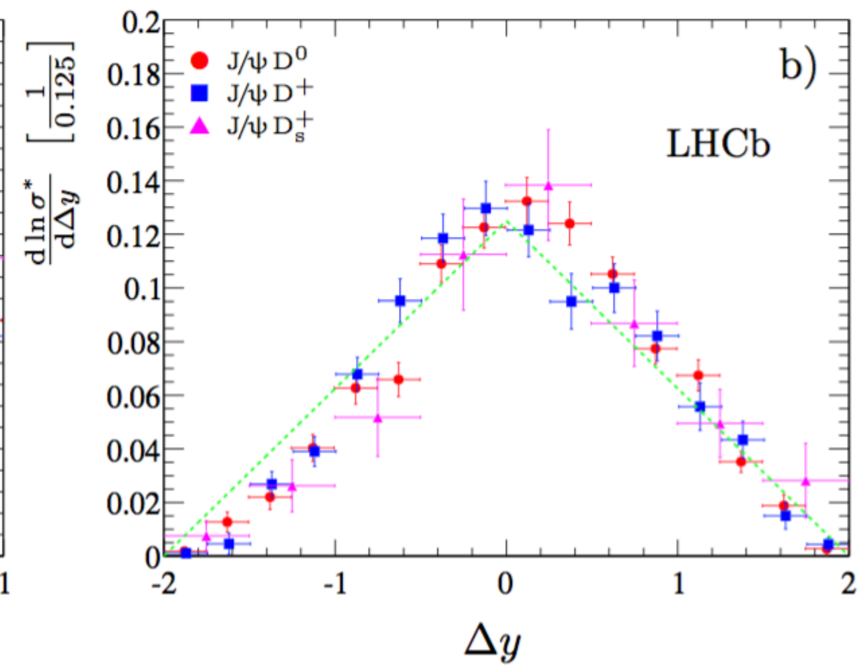
Multi-parton scattering in p-p collisions

Disentangling SPS vs DPS via rapidity and angular dependence

J/ψ + open charm in LHCb at 7 TeV ***JHEP06 (2012) 141***

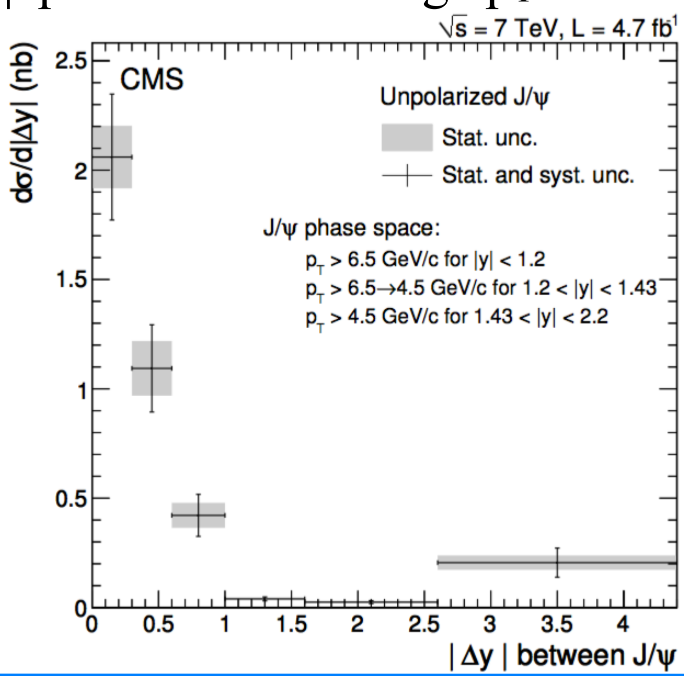






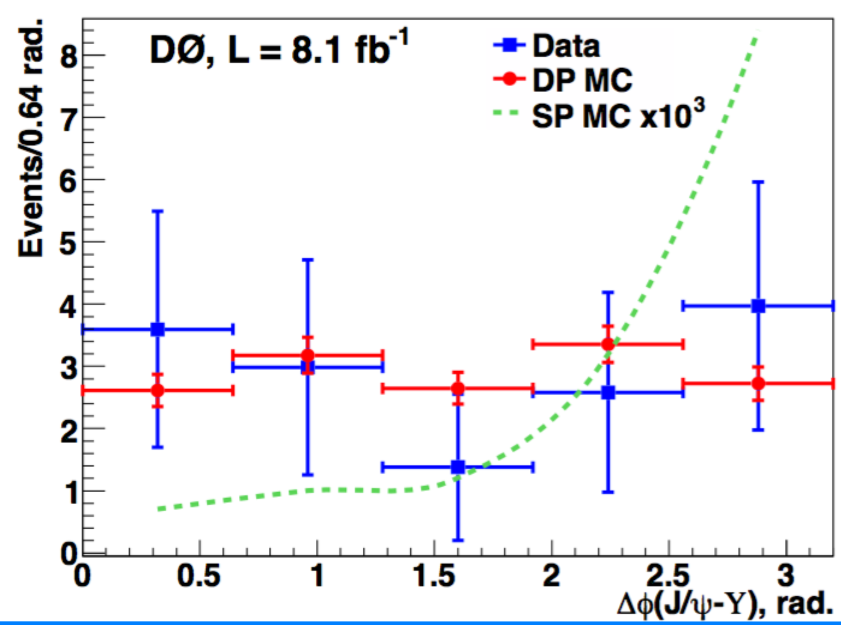
→ cross-sections 10 times larger than SPS models and DPS supported by rapidity and angular dependence

J/ψ pair in CMS at large p_T ***JHEP09 (2014) 094***



→ contribution at large Δy expected from DPS only

J/ψ + ϒ with D0 ***PRL 116, 082002 (2016)***

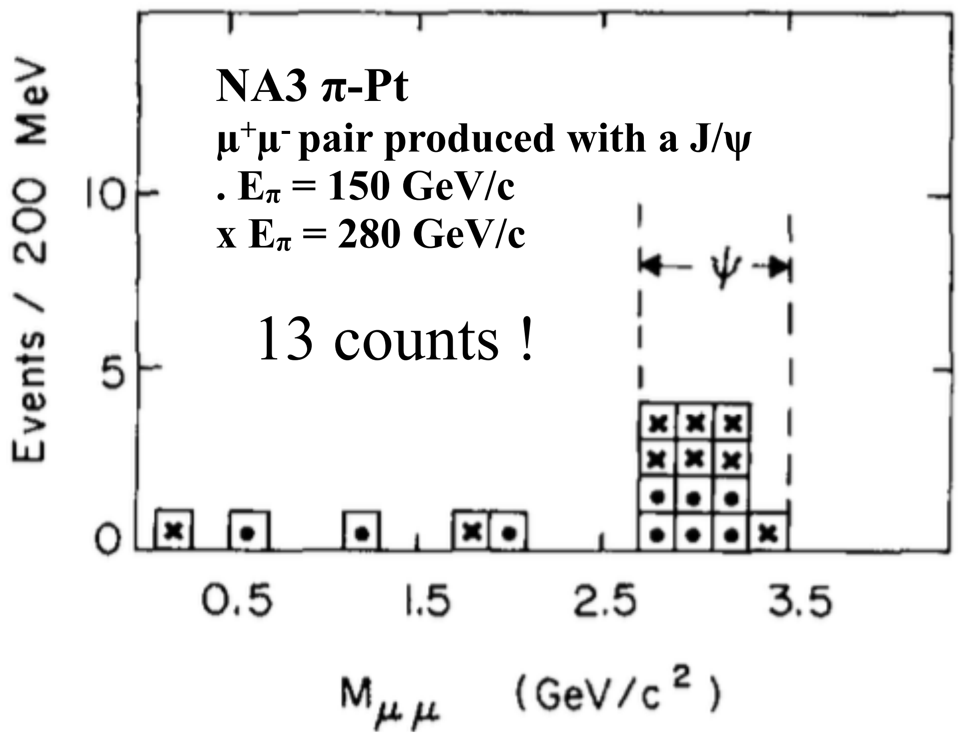


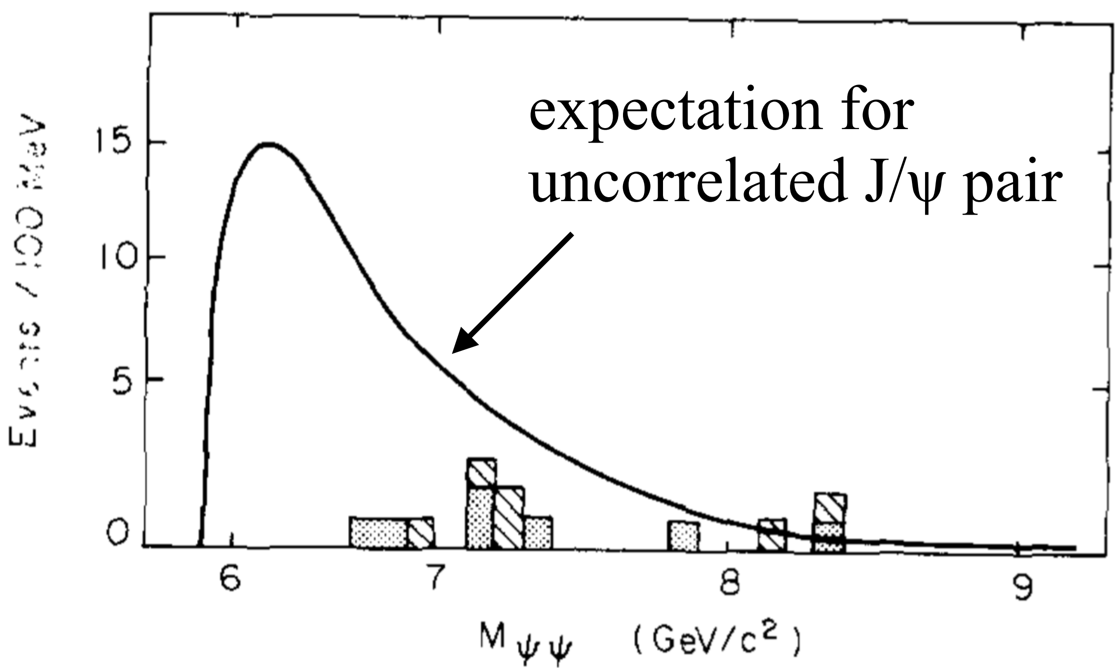
→ DPS contribution supported by angular dependence

Double hard production in heavy-ion collisions

Experimental results so far:

Double J/ψ production observed first at CERN/SPS by NA3 collaboration in π-Pt and p-Pt ***PLB 114 (1982) 457, PLB 158 (1985) 85***





In p-A collisions, double hard production are expected to be enhanced by nuclear scaling

Strikman and Treleani PRL88(2002)031801
d'Enterria and Snigirev, PLB 718 (2013) 1395

Nuclear scaling in heavy-ion collisions

Hard probes

- Hard scattering in pp collisions described by pQCD calculations using universal non-perturbative functions such as (n)PDF and Fragmentation Function
- Produced in the initial hard partonic collisions in the early stage of the collisions ($\tau \simeq 1/m$)
- In p-A and A-A, production of hard probes can be modified by initial (shadowing, gluon saturation, multiple interaction with the initial state, …) or final-state effects (energy loss, multiple scattering with the formed medium, …)

Nuclear modification factor

- In A-A (p-A), without interaction with the partonic/hadronic matter and initial state effects, hard processes are expected to be a superposition of independent nucleon-nucleon collisions and the cross section in A-A (p-A) scales with A^2 (A)

$$R_{AB} = \frac{1}{A\,B} \frac{d\sigma^{AB}/dp_T dy}{d\sigma^{pp}/dp_T dy}$$

- $R_{AB} = 1$: no modification
- $R_{AB} > 1$: enhancement
- $R_{AB} < 1$: suppression

References

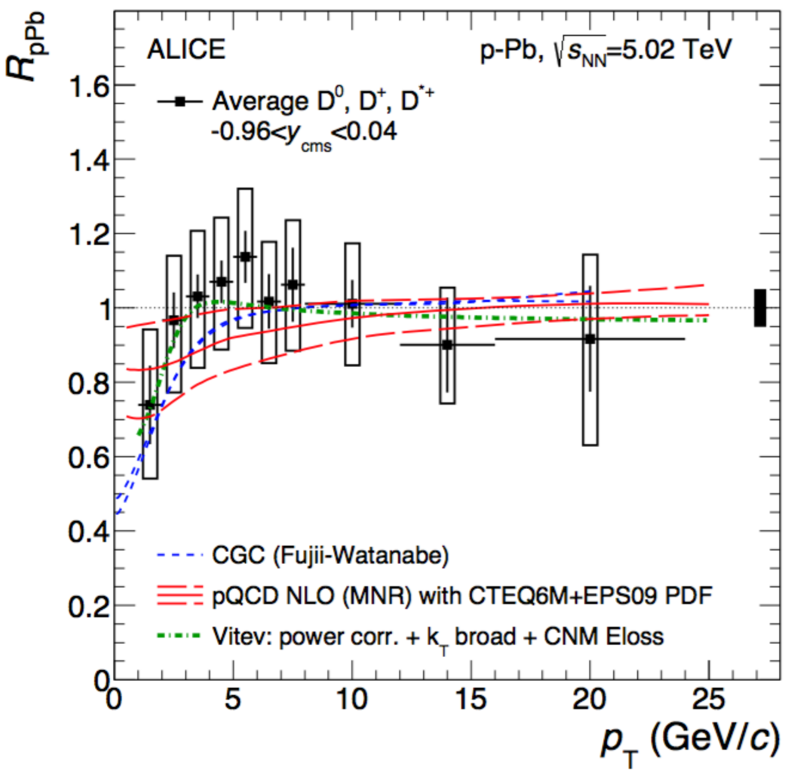
- pp collisions: test of production models and reference for A-A and p-A collisions

Selected R_{AB} measurements for single production

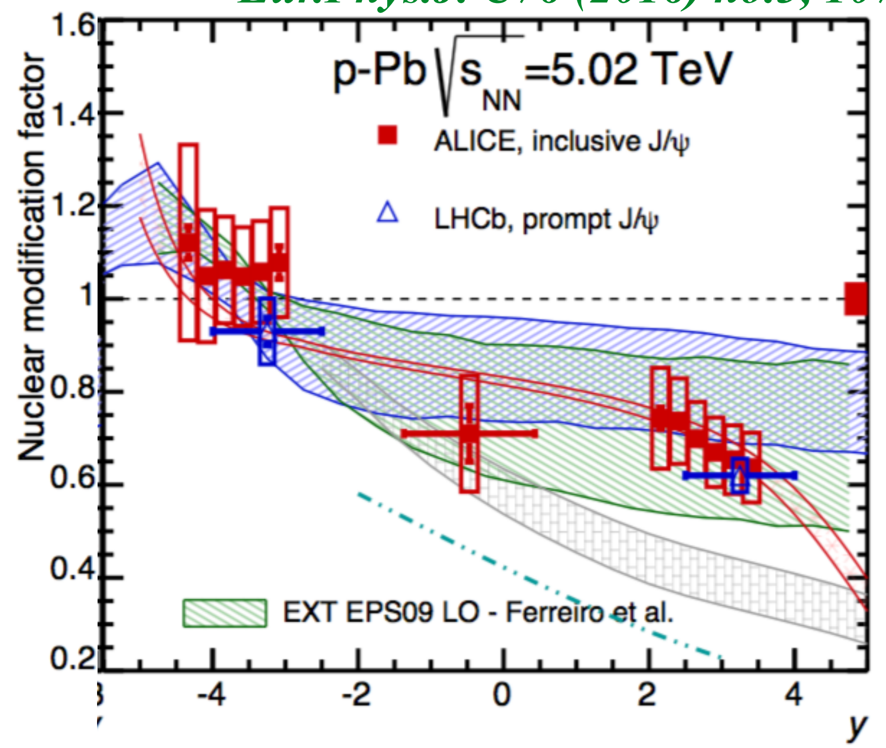
$$R_{pA} = \frac{1}{A}\frac{d\sigma^{pA}/dp_T dy}{d\sigma^{pp}/dp_T dy}$$

$$R_{AA} = \frac{1}{A^2}\frac{d\sigma^{AA}/dp_T dy}{d\sigma^{pp}/dp_T dy}$$

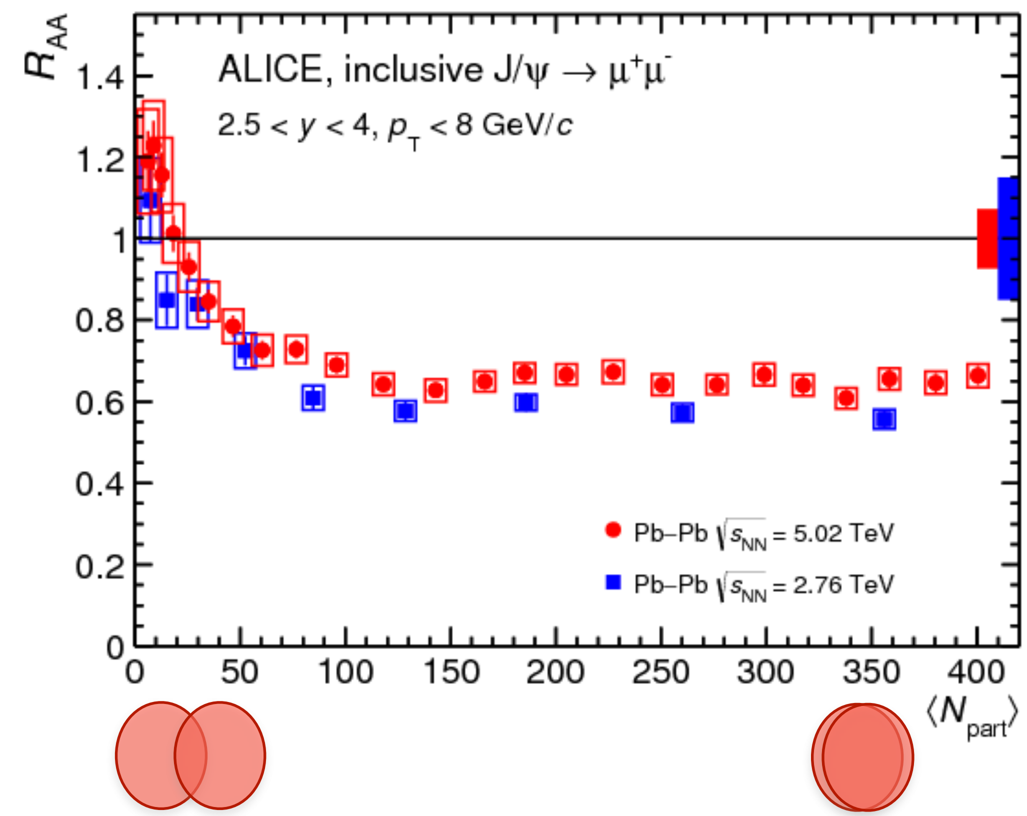
PRL113 (2014) 23, 232301



Sapore Gravis Review
Eur.Phys.J. C76 (2016) no.3, 107



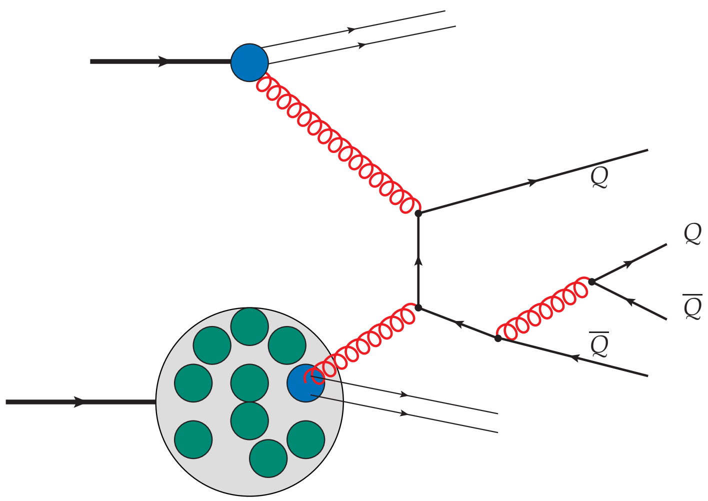
arXiv:1606.08197



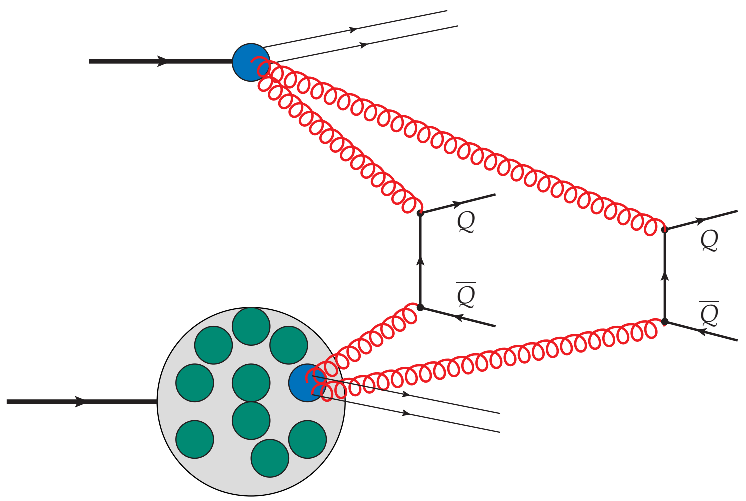
– A-scaling is observed for D meson production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV at mid-rapidity and p_T > 2 GeV/c
– Inclusive J/ψ production in p-Pb and Pb-Pb collisions: nuclear effects in p-Pb at $\sqrt{s_{NN}}$ = 5 TeV and Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 and 5 TeV
– What about nuclear scaling for DPS in p-A and A-A collisions?

Multi-parton scattering in p-A collisions

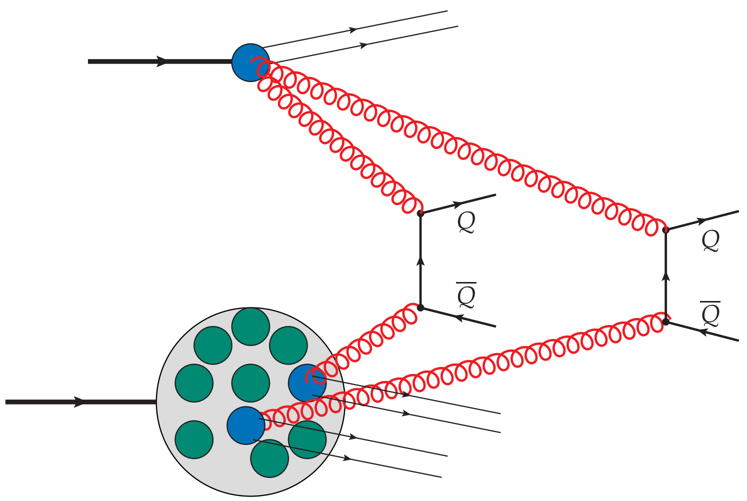
Scalings of double hard cross-section in p-A wrt p-p collisions depends on the production mechanism:



(a) SPS (as in p-p)



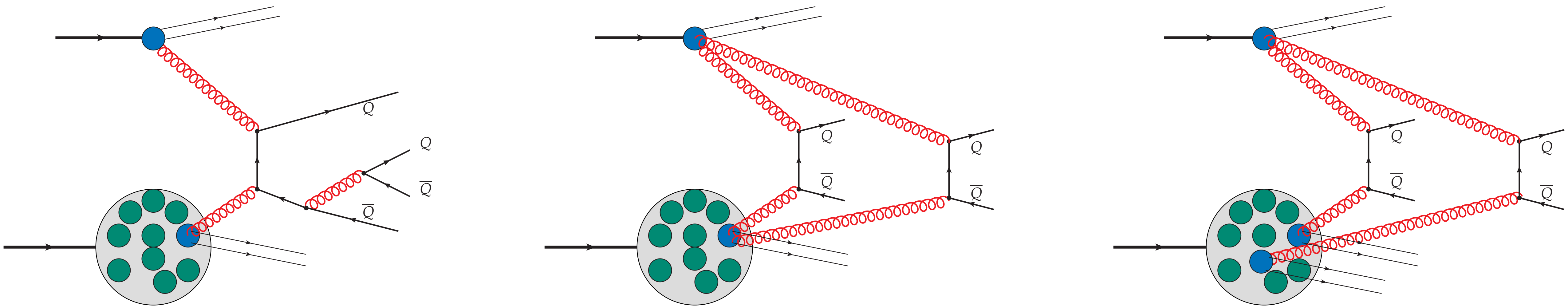
(b) DPS: colliding partons belong to the same pair of nucleons (as in p-p)



(c) DPS: two partons of one nucleon collide with two partons from different nucleons: unique to pA

Multi-parton scattering in p-A collisions

Scalings of double hard cross-section in p-A wrt p-p collisions depends on the production mechanism:



(a) SPS (as in p-p)

(b) DPS: colliding partons belong to the same pair of nucleons (as in p-p)

(c) DPS: two partons of one nucleon collide with two partons from different nucleons: unique to pA

- SPS: nuclear scaling = A (if no nuclear effect, as for single hard production)
- DPS: nuclear scaling in p-A collisions higher than A

- For Pb nucleus, enhancement of double hard production from DPS by ~600 in ***d'Enterria and Snigirev, PLB 718 (2013) 1395*** : relative contribution of (b) and (c) from Glauber nuclear thickness function
- Enhancement of DPS in p-A wrt p-p by $A^{1.5}/\sqrt{10}$ in ***Strikman and Treleani PRL88(2002)031801*** (~950 for Pb nucleus)
- DPS is enhanced wrt to SPS in p-A collisions thanks to (c)!

Nuclear modification factor for hard pair production in p-A collisions

One defines the relative DPS contributions in p-p collisions:

$$\mathcal{F} = \frac{\mathrm{DPS}}{\mathrm{DPS} + \mathrm{SPS}}$$

$\mathcal{F} = 0$ → only SPS

$\mathcal{F} = 1$ → only DPS

Nuclear modification factor for hard pair production in p-A collisions

One defines the relative DPS contributions in p-p collisions:

$$\mathcal{F} = \frac{\mathrm{DPS}}{\mathrm{DPS} + \mathrm{SPS}}$$

$\mathcal{F} = 0$ → only SPS

$\mathcal{F} = 1$ → only DPS

Nuclear modification factor in proton-nucleus assuming:

– factorization of nuclear effects

– scaling of SPS and DPS according to ***Strikman and Treleani PRL88(2002)031801***

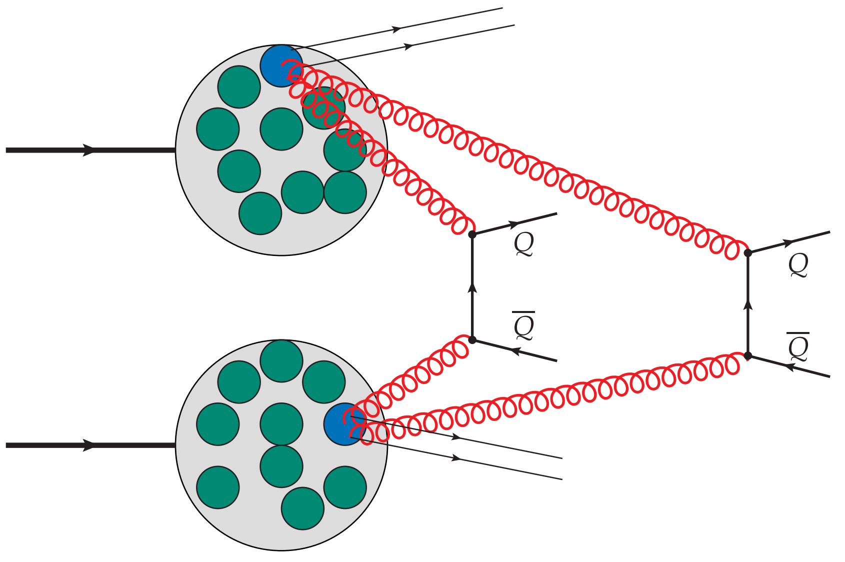
$$\mathrm{R}_{\mathrm{pA}}^{P_1+P_2} = \frac{\sigma_{pA}^{P_1+P_2}}{A\sigma_{pp}^{P_1+P_2}} \longrightarrow \mathrm{R}_{\mathrm{pA}}^{P_1+P_2} = \mathrm{R}_{\mathrm{pA}}^{P_1} \times \mathrm{R}_{\mathrm{pA}}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

– Measurements of R_{pA} of double hard processes give hints on the DPS relative contributions in p-p collisions

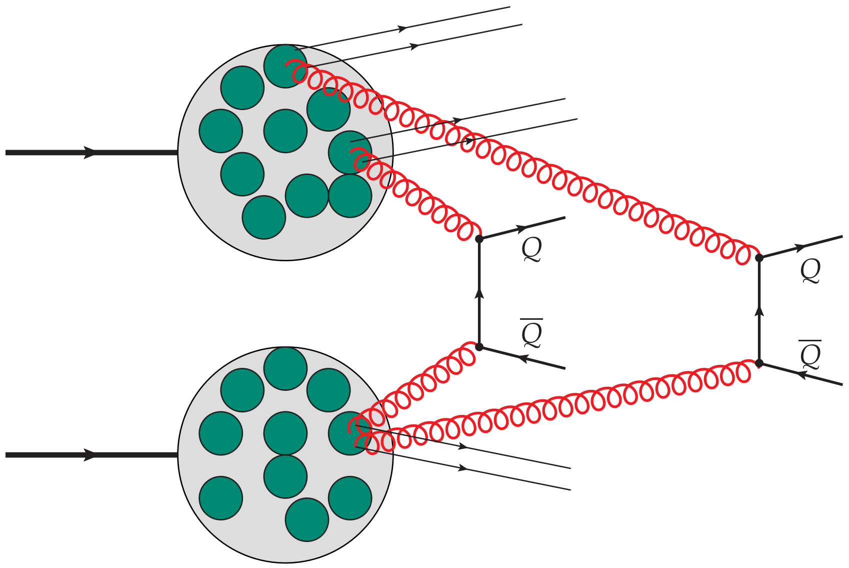
– If $\mathcal{F} = 1$ and hard probe production is not affected by nuclear effects, hard pair R_{pA} can be as high as ~ 4

Multi-parton and nucleon scattering in A-A

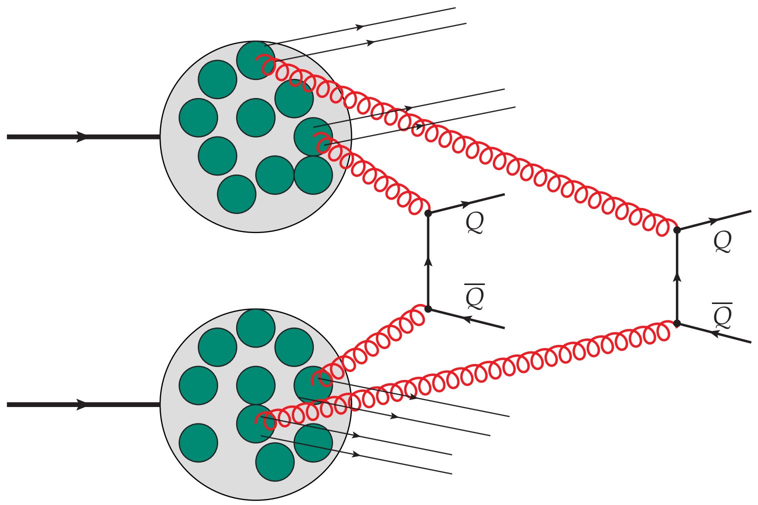
In A-A collisions, nuclear scalings depend also on the production mechanism. On top of SPS and DPS, there are also double nucleon scatterings (DNS)
– SPS: nuclear scaling = A^2 (if no nuclear effect, as for single hard cross-section)
– DPS and DNS (unique to A-A) nuclear scaling higher than A^2



(a) DPS: colliding partons belong to the same pair of nucleons (as in p-p)



(b) DPS: two partons of one nucleon collide with two partons from different nucleons (as in p-A)



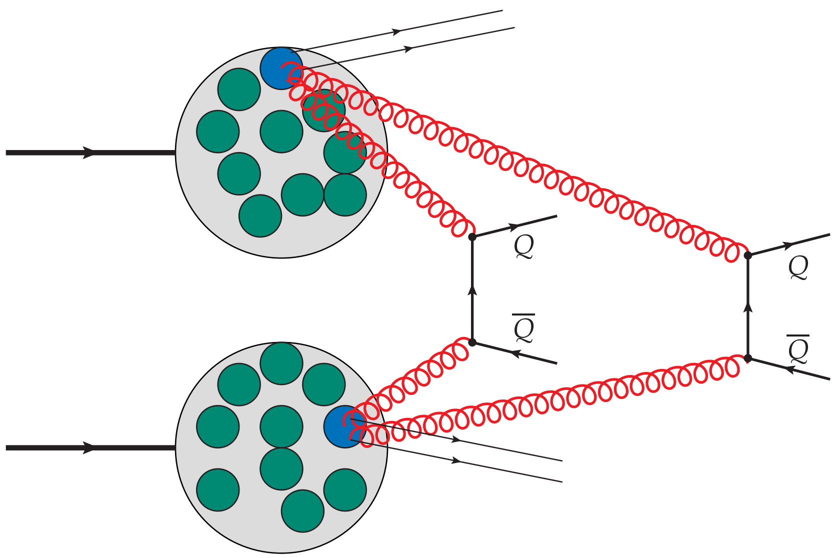
(c) DNS: colliding partons belong to different nucleons

Multi-parton and nucleon scattering in A-A

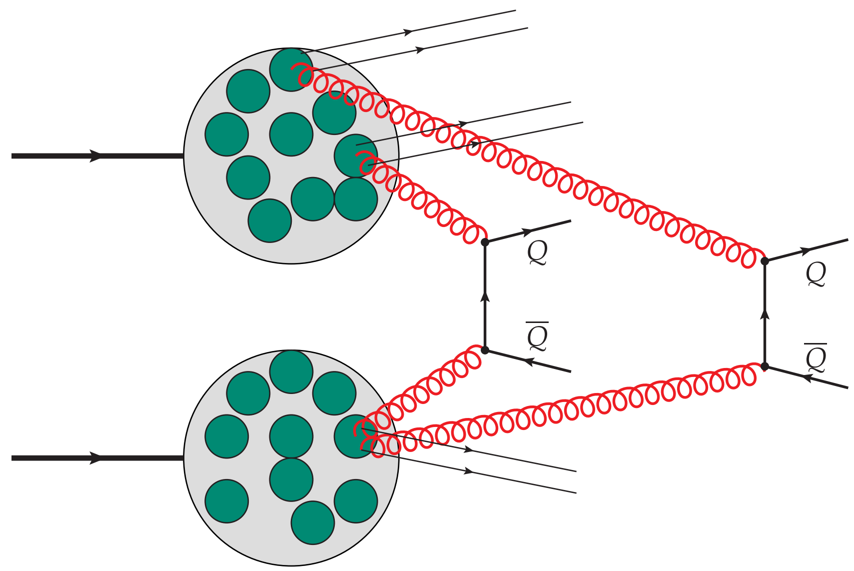
In A-A collisions, nuclear scalings depend also on the production mechanism. On top of SPS and DPS, there are also double nucleon scatterings (DNS)

– SPS: nuclear scaling = A^2 (if no nuclear effect, as for single hard cross-section)

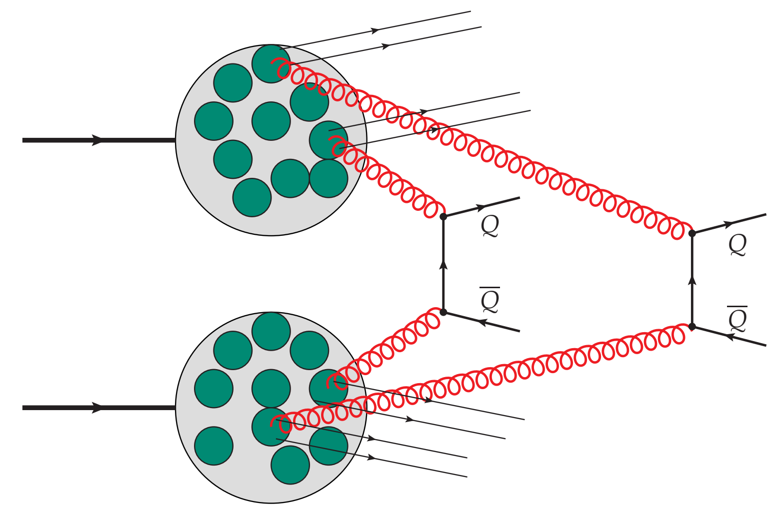
– DPS and DNS (unique to A-A) nuclear scaling higher than A^2



(a) DPS: colliding partons belong to the same pair of nucleons (as in p-p)



(b) DPS: two partons of one nucleon collide with two partons from different nucleons (as in p-A)



(c) DNS: colliding partons belong to different nucleons

Relative DPS+DNS contributions are (a)1:(b)4:(c)200 in Pb-Pb ***d'Enterria and Snigirev, PLB 727 (2013) 157***

– Geometric factor in heavy-ion collisions: enhancement of double-hard production in A-A wrt p-p by $A^{3.3}/5$. For Pb nuclei, enhancement by 9e6.

– DNS clearly dominates the yield in A-A collisions!

– Nuclear modification factor for hard pair production: $\mathrm{R}_{\mathrm{AA}}^{P_1+P_2} = \mathrm{R}_{\mathrm{AA}}^{P_1} \times \mathrm{R}_{\mathrm{AA}}^{P_2} \times \left[\frac{A^{1.3}}{5}\right]$

– If hard probe production is not affected by nuclear effects, hard pairs R_{AA} can be as high as ~200

Expected rates of double hard production at the LHC

Focus on forward rapidities (ALICE and LHCb) at the LHC on:

- J/ψ pair production
- $J/\psi+\mu$ ($p_{T,\mu} > 4$ GeV/c) as a probe of J/ψ + open heavy flavour in ALICE
- J/ψ+D in LHCb

See also ***d'Enterria and Snigirev, PLB 718 (2013) 1395*** for $J/\psi(Y)+J/\psi$, $J/\psi(Y)+Y$, $J/\psi(Y)+W$, $J/\psi(Y)+Z$ in ALICE, ATLAS and CMS

Expected delivered luminosity in Run 2:

- p-p collisions at $\sqrt{s} = 13$ TeV with $\mathscr{L}_{ALICE} = 40$/pb and $\mathscr{L}_{LHCb} = 10$/fb
- p-Pb (Pb-p) collisions at $\sqrt{s_{NN}} = 8$ TeV with $\mathscr{L}_{ALICE} = \mathscr{L}_{LHCb} = 10$/nb
- Pb-Pb collisions at $\sqrt{s_{NN}} = 5$ TeV with $\mathscr{L}_{ALICE} = 1$/nb

J/ψ pair production: nuclear modification factor

p-Pb collisions

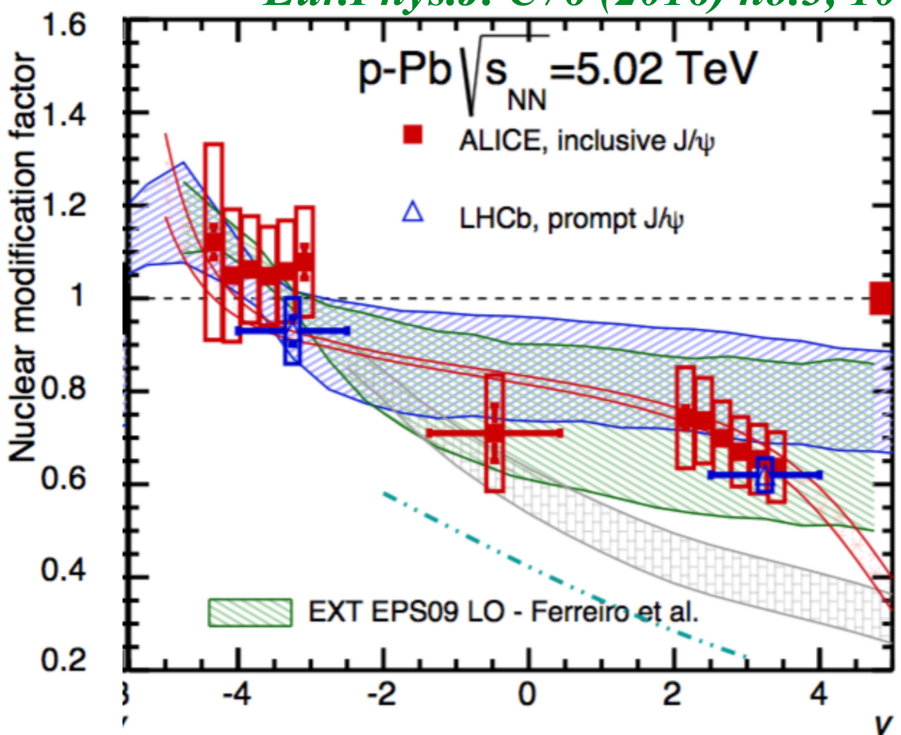
$R_{pPb}(J/\psi) \sim 0.7$ at $y_{cms} > 0$

$$R_{pA}^{P_1+P_2} = R_{pA}^{P_1} \times R_{pA}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1$ $\quad \rightarrow R_{pPb}(J/\psi+J/\psi) \sim 0.5, 1, 2$

→ nuclear modification factor increases with the DPS relative contribution in p-p collisions

Sapore Gravis Review
Eur.Phys.J. C76 (2016) no.3, 107



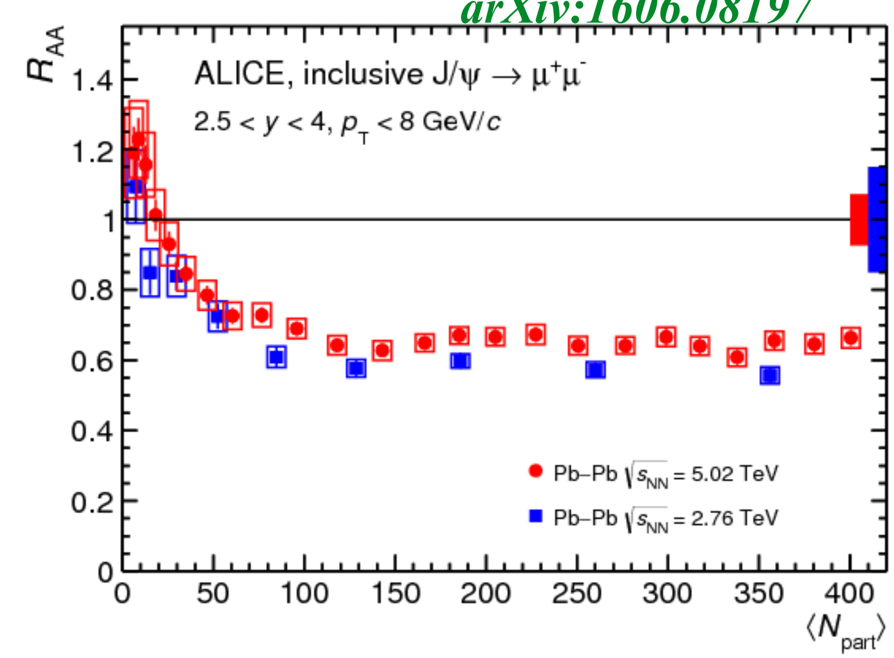
Pb-Pb collisions

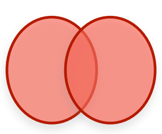
$R_{PbPb}(J/\psi) \sim 0.6$

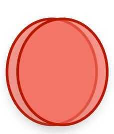
$$R_{AA}^{P_1+P_2} = R_{AA}^{P_1} \times R_{AA}^{P_2} \times \left[\frac{A^{1.3}}{5}\right] \quad \rightarrow R_{PbPb}(J/\psi+J/\psi) \sim 75$$

→ very large R_{AA} : DNS only in AA (not p-p…)

arXiv:1606.08197







J/ψ pair production rates

J/ψ pair production at 7 TeV in LHCb for $2 < y < 4.5$: $\sigma = 5.1 \pm 0.1 \pm 0.1$ nb ***PLB 707 (2012) 52***

Simple assumptions based on DPS hand-pocket formula are used to estimate the cross-section in different rapidity and energy domains in p-p, as well as previous R_{pA}/R_{AA} for cross-sections in pA/AA

$$N_{J/\psi J/\psi} = (BR_{J/\psi\to\mu\mu})^2\, \sigma_{J/\psi J/\psi}\, L_{int}\, A\, \epsilon$$

ALICE ($2.5 < y < 4$): $A\,\varepsilon \sim 0.05$ ***arXiv:1506.08804***

LHCb ($2 < y < 4.5$): $A\,\varepsilon \sim 0.23$ ***PLB 707 (2012) 52***

J/ψ pair yield in Run 2	p-p@13 TeV	p-Pb@8 TeV	Pb-Pb@5 TeV
ALICE (2.5<y<4)	50 ($\mathscr{L}$= 40/pb)	<10 ($\mathscr{L}$= 10/nb)	500 ($\mathscr{L}$= 1/nb)
LHCb (2<y<4.5)	107k ($\mathscr{L}$= 10/fb)	<10,20,30 ($\mathscr{L}$= 10/nb)	

– p-p: high statistical sample in LHCb, statistically limited in ALICE
– p-Pb: possibility to sum-up p-Pb and Pb-p to search for signals
– Pb-Pb: seems feasible depending on uncorrelated background

J/ψ+μ production

Since luminosities are limited in p(Pb)-Pb in Run2, try out J/ψ+μ as a probe of J/ψ+open heavy flavour in ALICE

Only high-p_T μ ($p_{T,\mu}$ > 4 GeV/c) are considered (large hadronic background at lower $p_{T,\mu}$)

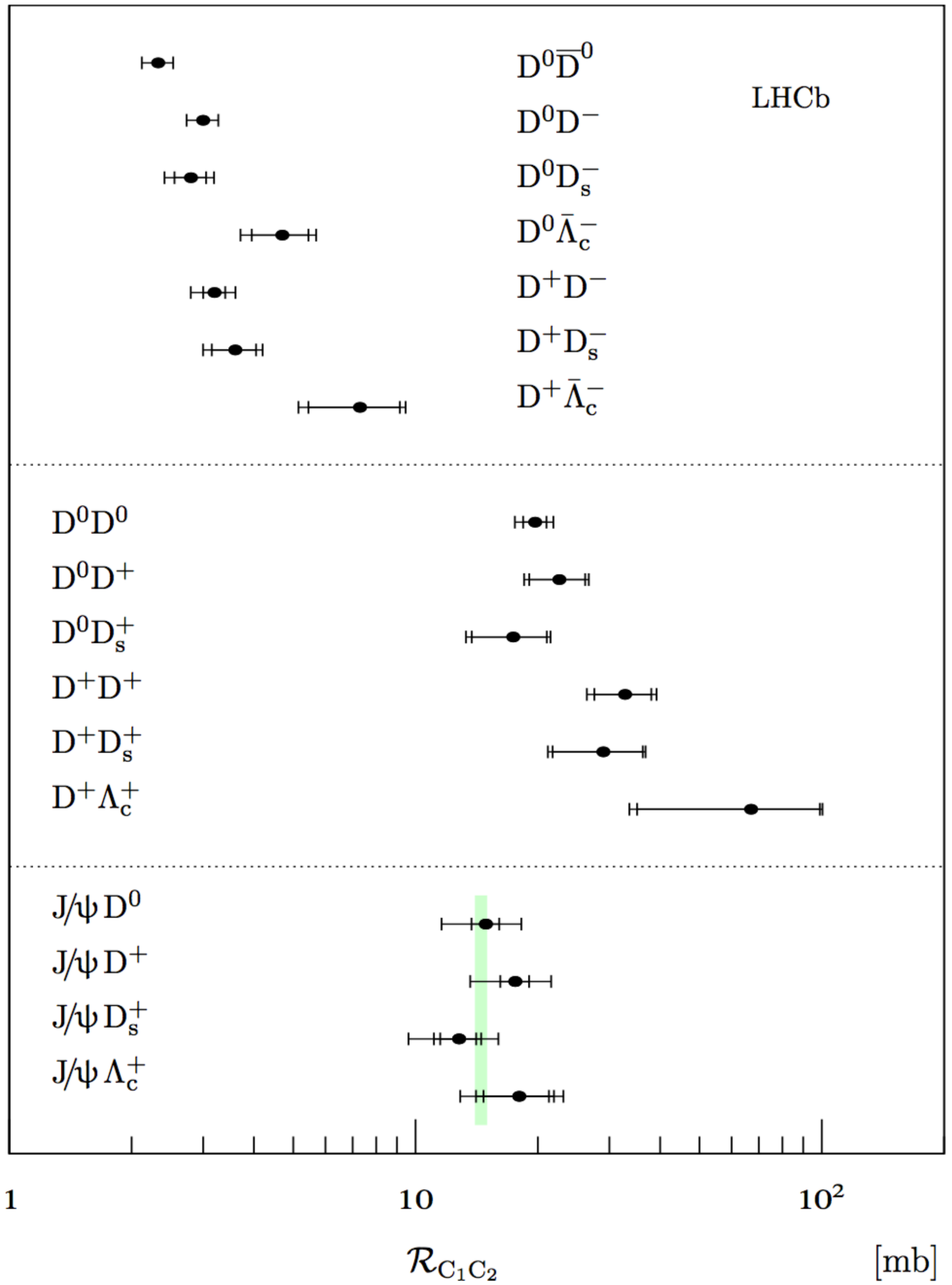
LHCb results on J/ψ+open charm support DPS contribution with σ_{eff} ~ 14 mb

Yields calculated using DPS formula and linear dependence on √s for single muon production:

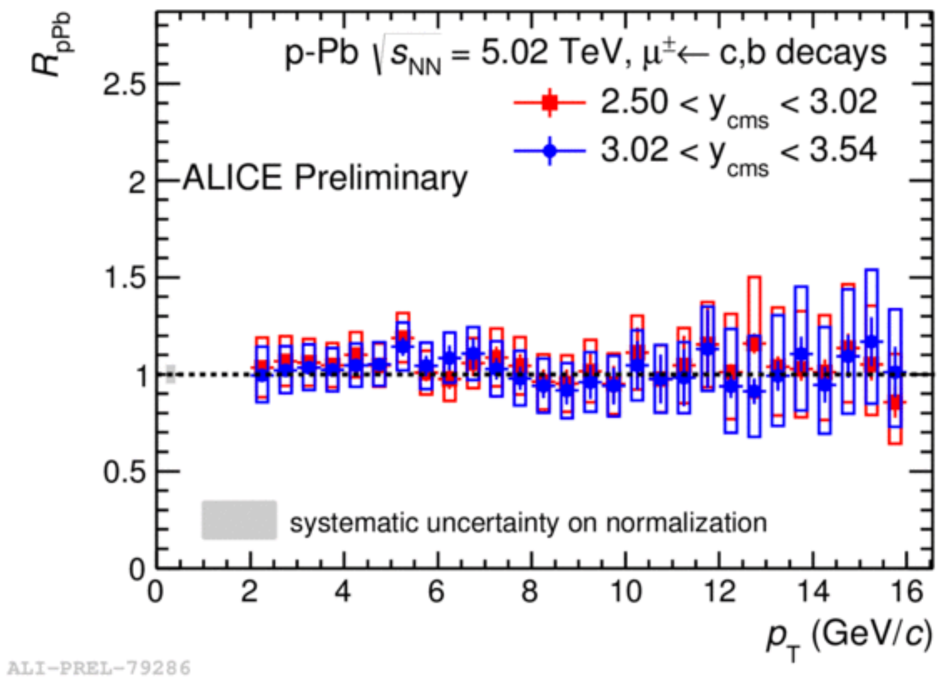
$$\left.\frac{d\sigma^{J/\psi+\mu}}{dp_T}\right|_{p_T^\mu=4\ \mathrm{GeV}/c} = \frac{1}{\sigma_{\mathrm{eff}}} \times \sigma^{J/\psi} \times \left.\frac{d\sigma^\mu}{dp_T}\right|_{p_T^\mu=4\ \mathrm{GeV}/c}$$

with σ_{eff} = 14 mb

JHEP06 (2012) 141 Addendum



J/ψ+μ production: nuclear modification factor



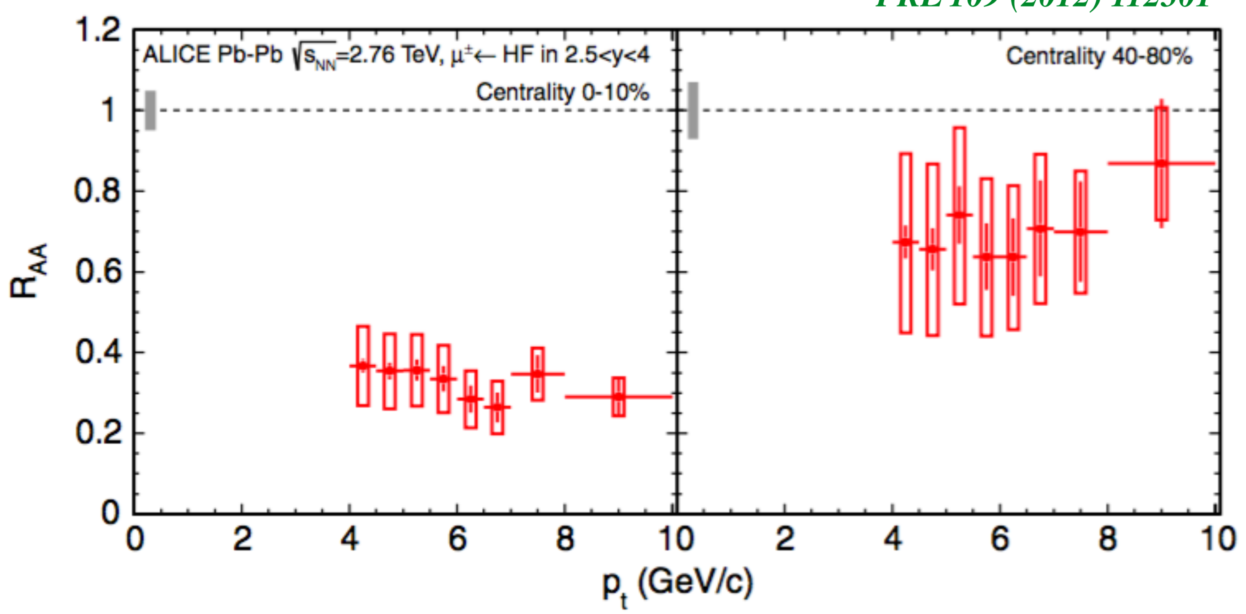
p-Pb collisions

$\mathrm{R_{pPb}}\,(\mu) = 1$

$$\mathrm{R}_{\mathrm{pA}}^{P_1+P_2} = \mathrm{R}_{\mathrm{pA}}^{P_1} \times \mathrm{R}_{\mathrm{pA}}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1 \quad \rightarrow \mathrm{R_{pPb}}\,(\mathrm{J}/\psi+\mu) = 0.7,\ 1.9,\ 3.2$

PRL 109 (2012) 112301



Pb-Pb collisions

$\mathrm{R_{PbPb}}\,(\mu) \sim 0.35$

$$\mathrm{R}_{\mathrm{AA}}^{P_1+P_2} = \mathrm{R}_{\mathrm{AA}}^{P_1} \times \mathrm{R}_{\mathrm{AA}}^{P_2} \times \left[\frac{A^{1.3}}{5}\right]$$

$\rightarrow \mathrm{R_{PbPb}}\,(\mathrm{J}/\psi+\mu) = 45$

J/ψ+μ production rates

$$N_{J/\psi\mu} = BR_{J/\psi\to\mu\mu}\,\sigma_{J/\psi\mu}\,L_{int}\,A\,\epsilon$$

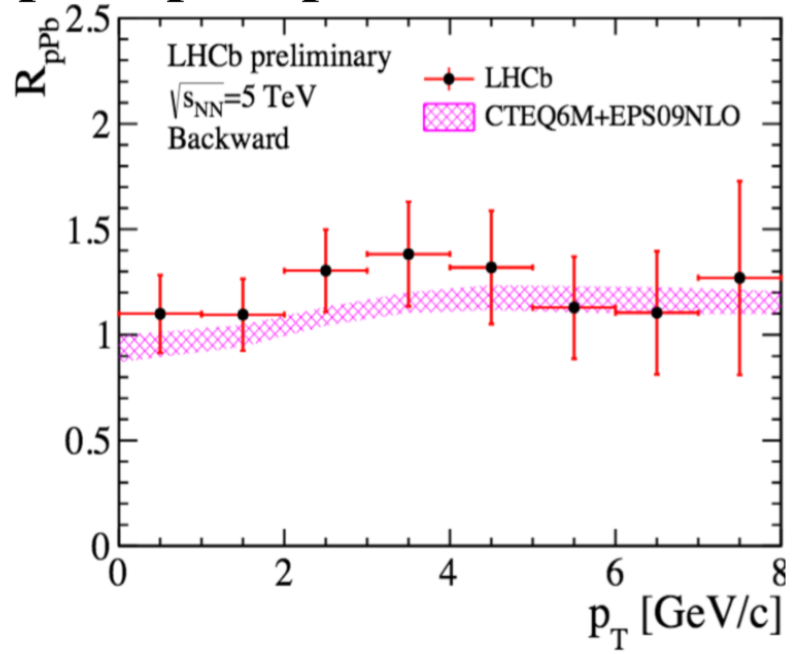
ALICE: $A\,\varepsilon \sim 0.15 \times 0.9 = 0.13$

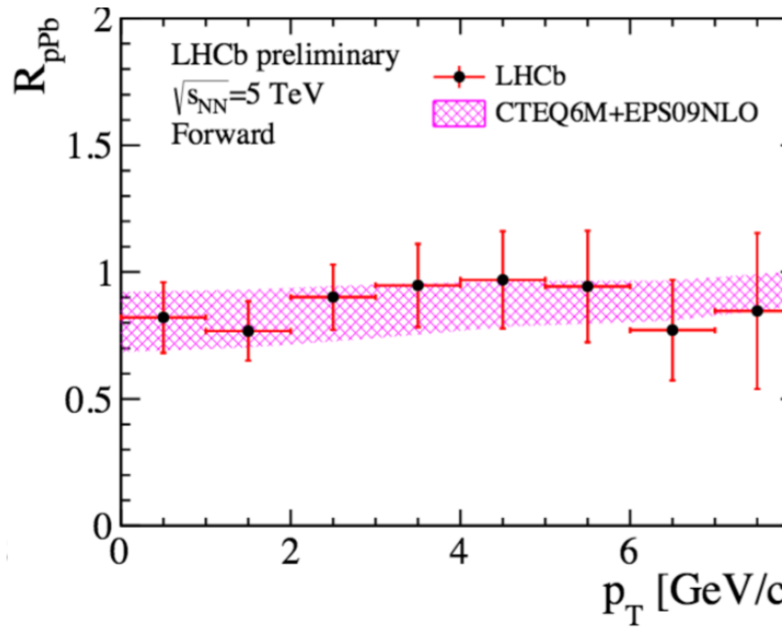
$dN_{J/\psi+\mu}/dp_T$ ($p_{T,\mu}$ = 4GeV/c)	p-p@13 TeV	p-Pb@8 TeV	Pb-Pb@5 TeV
ALICE (2.5 < y < 4)	270 ($\mathscr{L}$= 40/pb)	<10,15,20 ($\mathscr{L}$= 10/nb)	2700 ($\mathscr{L}$= 1/nb)

- p-p and p-Pb studies statistically limited in ALICE: decreasing the p_T muon threshold (4→2 GeV/c) leads to an increase of cross-section by a factor 10, resulting however to a larger background contribution
- Pb-Pb: feasible

J/ψ+D production rates

prompt D p-Pb collisions





J/ψ+D
LHCb results @7TeV *JHEP06 (2012) 141*
$2 < y_{J/\psi,D} < 4$ and $p_{T,D} > 3$ GeV/c
L_{int} = 355/pb and N (J/ψ+D) ~ 5k
σ (J/ψ+D) = 161±3.7±12.2 nb

R_{pPb} (D) ~ 1

$$R_{pA}^{P_1+P_2} = R_{pA}^{P_1} \times R_{pA}^{P_2} \times \left[(1-\mathcal{F}) + \sqrt{\frac{A}{10}}\mathcal{F}\right]$$

$\mathcal{F} = 0, 1/2, 1 \rightarrow R_{pPb}$ (J/ψ+D) = 0.7, 1.9, 3.2

$N_{J/\psi+D}$ ($p_{T,D} > 3$ GeV/c)	p-Pb@8 TeV
LHCb (2 < y < 4)	20,54,90 ($\mathscr{L}$= 10/nb)

→ Same luminosity expected in Pb-p
→ Statistically limited for J/ψ + D but feasible

Conclusion

- Production of pairs of hard probes is enhanced by nuclear scaling in heavy-ion collisions.

- In p-A collisions, nuclear scaling is different from the one in single-hard production and depends on the relative contribution of single and double-parton scattering in p-p collisions. Nuclear modification factor of double-hard process can be as large as ~4.

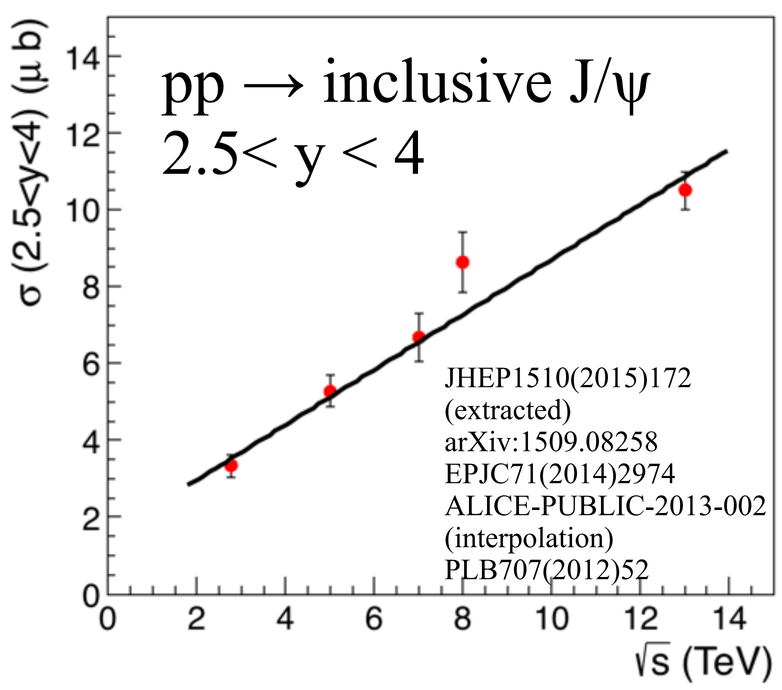
- In A-A collisions, double-nucleon scattering dominates the yield and nuclear modification factor of double-hard process can be as large as ~200.

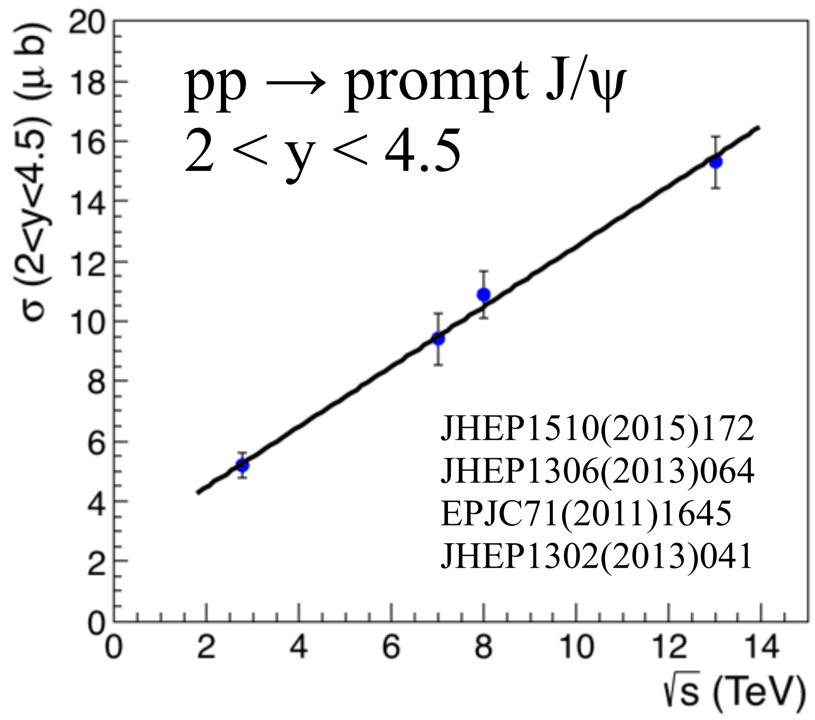
- Simple assumptions allow one to calculate the expected yields at forward rapidity for J/ψ pair, J/ψ+μ (p_T>4 GeV/c) and J/ψ+D production at LHC in Run 2:
  - J/ψ pair production can be nicely studied in p-p@13TeV with LHCb and with limited statistics in Pb-Pb@5TeV with ALICE in Run 2
  - J/ψ+μ (p_T>4 GeV/c) production can be used as a probe of J/ψ+open heavy flavour with reasonable statistics in p-p@13TeV and Pb-Pb@5TeV with ALICE
  - J/ψ+D is a promising probe in p-Pb@8TeV with LHCb

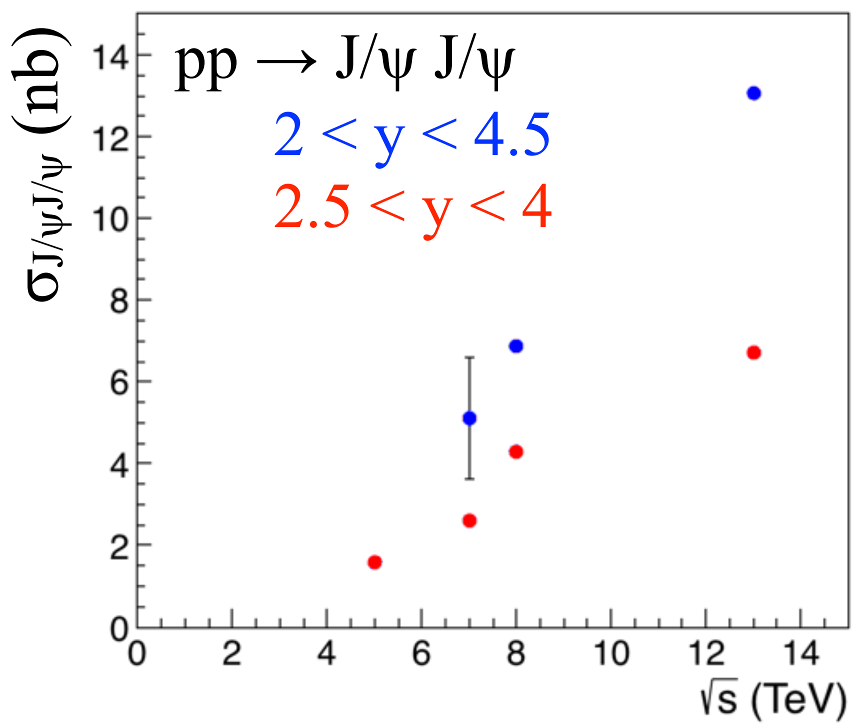
J/ψ pair production at forward-y vs √s

Inputs:

- J/ψ pair production at 7 TeV in LHCb for $2 < y < 4.5$: $\sigma = 5.1 \pm 0.1 \pm 0.1$ nb PLB707(2012)52
- Assumptions based on the DPS hand-pocket formula:
  1. energy dependence $\propto [\sigma_{J/\psi}(s)]^2$
  2. rapidity dependence $\propto [\sigma_{J/\psi}(y)]^2$
- inclusive J/ψ for $2.5 < y < 4$ (from ALICE+LHCb data)
- prompt J/ψ for $2 < y < 4.5$ (from LHCb data and $\sqrt{s}$ = 5 TeV obtained from a linear fit of existing data)







Inclusive J/ψ pair: beauty contribution

In Run 2 in ALICE/forward-y: no forward tracker before the absorber to select/remove non-prompt J/ψ (planned for Run 3)

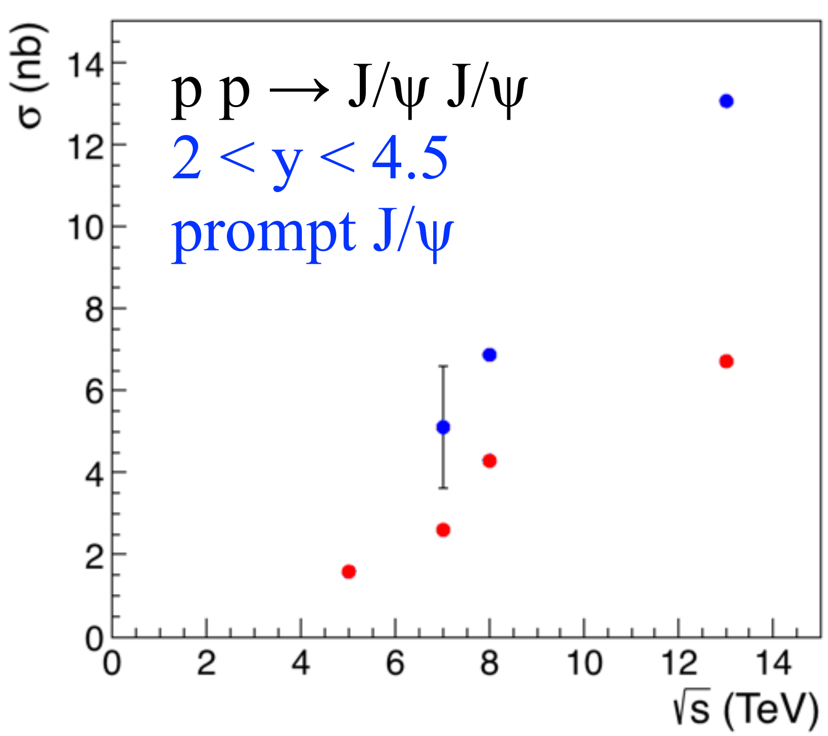
Simple estimation of beauty contribution @13 TeV in LHCb, JHEP1510(2015)172

$\sigma_{4\pi}(pp \rightarrow bb) = 515 \pm 2 \pm 53$ μb

BR $(b \rightarrow J/\psi) = (1.16 \pm 0.10)\%$

$\sigma_{4\pi}(pp \rightarrow bb \rightarrow J/\psi\ J/\psi) = (BR_{b \rightarrow J/\psi})^2 \times \sigma_{4\pi}(pp \rightarrow bb) = 70$ nb

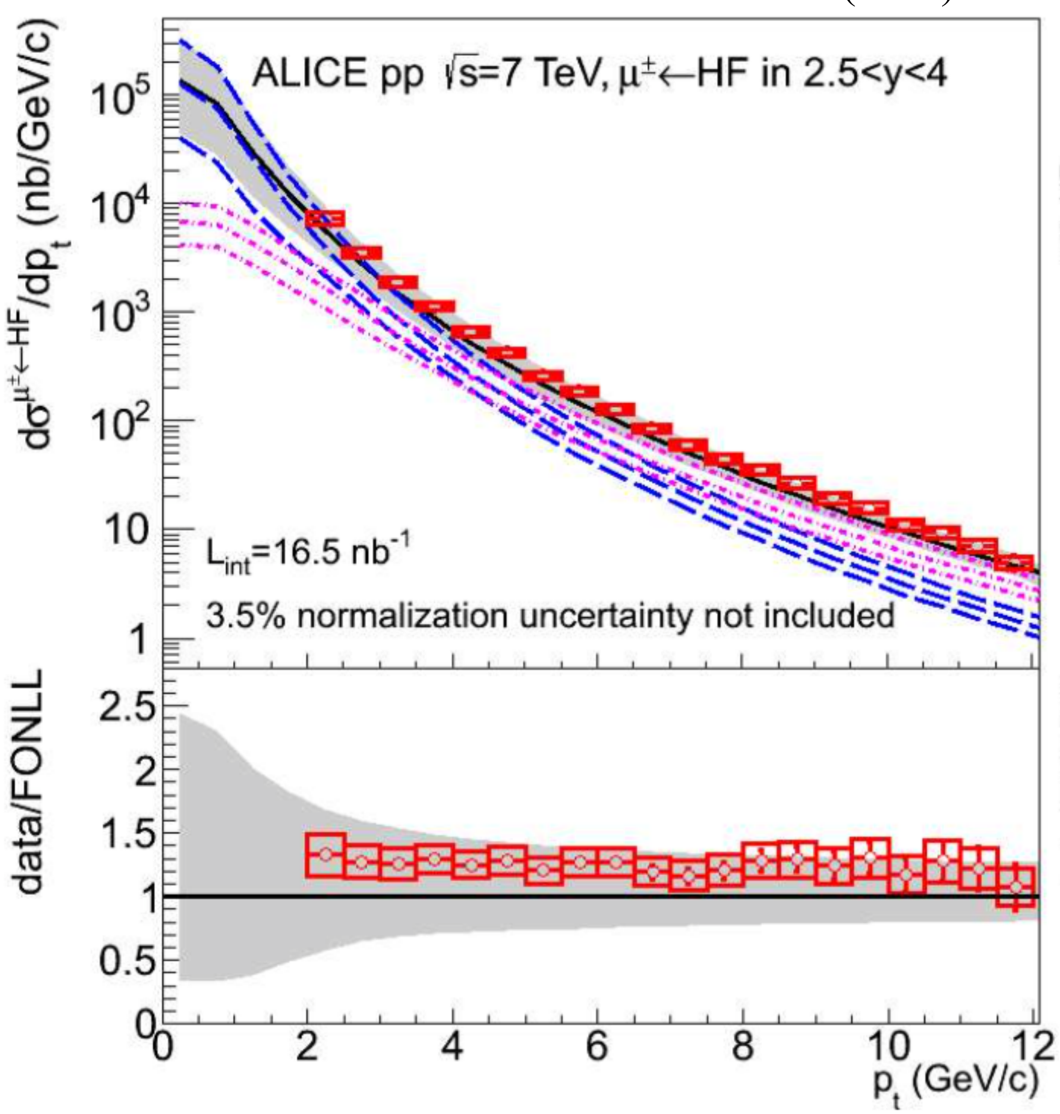
bb from 4π to $2 < y < 4.5$ => 30%: $\sigma\,(pp \rightarrow bb \rightarrow J/\psi\ J/\psi,\ 2 < y_{bb} < 4.5) \sim 14$ nb



(bb → J/ψ J/ψ) same order of magnitude than (prompt J/ψ J/ψ) → it will dilute R_{AA} (J/ψ+J/ψ)

J/ψ+μ production at forward-y vs √s

JHEP06 (2012) 141



Assumption for √s-dependence: single muon production increases linearly with √s