Quarkonium isolation

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Quarkonia as Tools 2024
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AdT Comunidad de Madrid
IGFAE Instituto Galego de Física de Altas Enerxías
USC Universidade de Santiago de Compostela
XUNTA DE GALICIA
CENTROS CiGUS
Cofinanciado pola Unión Europea
Fondos Europeos

Contents

1 - Introduction
Why (I am interested in) quarkonium isolation?

- A part of my analysis consists of defining an isolation criterium for J/ψ and applying it to get a measurement of <u>isolated</u> $J/\psi + \gamma$ in pp collisions at 13 TeV at LHCb

- Why isolated J/ψ?

  - Access Transverse Momentum Dependent distributions (TMDs)
    won't cover the interest of this in today's talk

  - **Provide additional information on the production mechanism**

- What is covered by this talk:

  ☑ Isolation criteria designed for photons
  ☑ Quarkonium fragmentation functions
  ☑ Modelization of quarkonia production
  ☑ Measurements of J/ψ *in jets*

1 - Introduction
Isolation criteria

Review by Marius Höfer

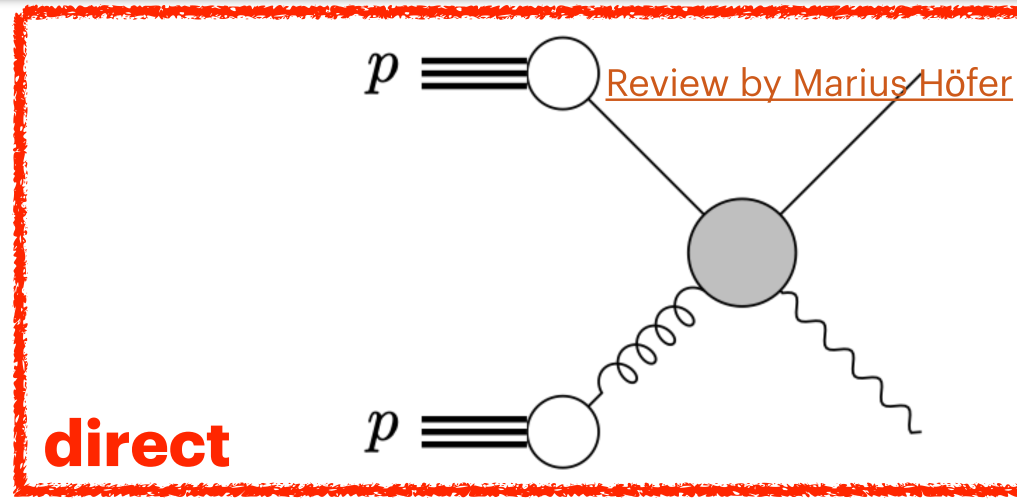
- Lots of work has been done on ***photon isolation***
  - Necessary in hadron collider experiments to distinguish photons produced in hard scattering processes from others

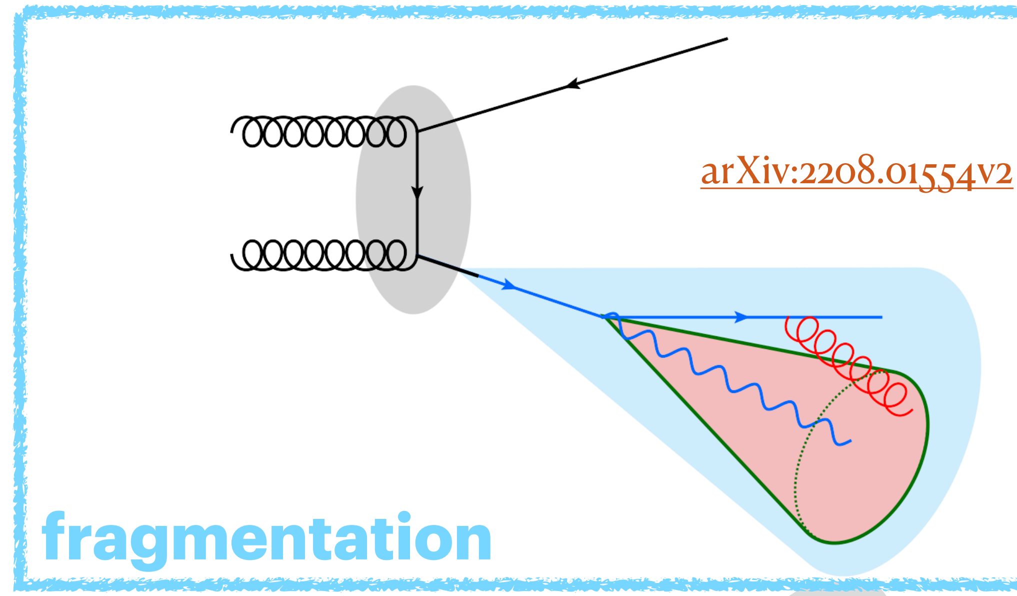
- Philosophy: a photon is isolated if most of the transverse energy around the photon is carried by the photon itself

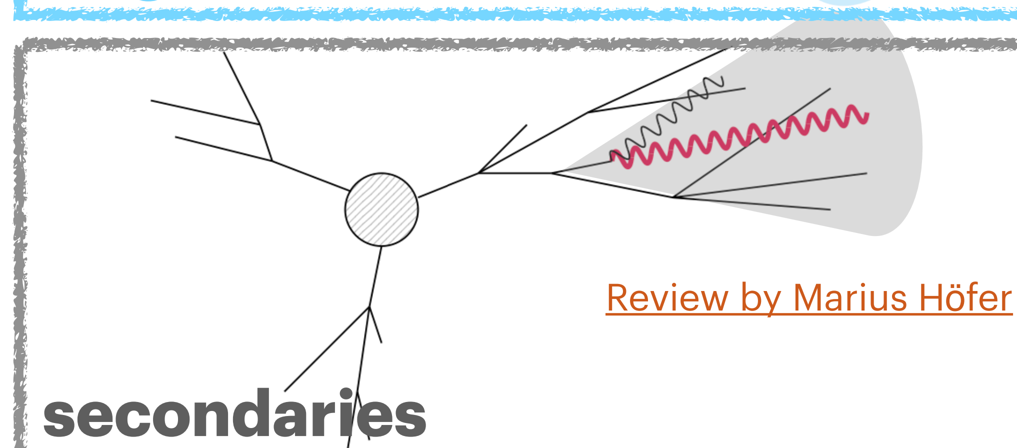
- **Types of isolation criteria**

  (a) Cone-based isolation
    i) Hard cone
    ii) Smooth cone
    iii) Modified versions (backup)

  (b) Clustering-based isolation
    i) Democratic isolation
    ii) Softdrop isolation







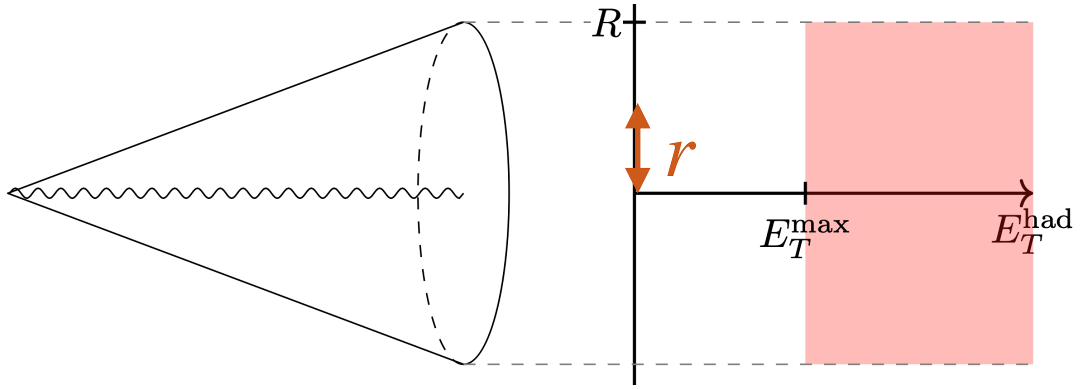
Review by Marius Höfer

▸ **Cone-based isolation**

i) Hard cone

$$\sum E_T^{had} \leq E_T^{max}$$

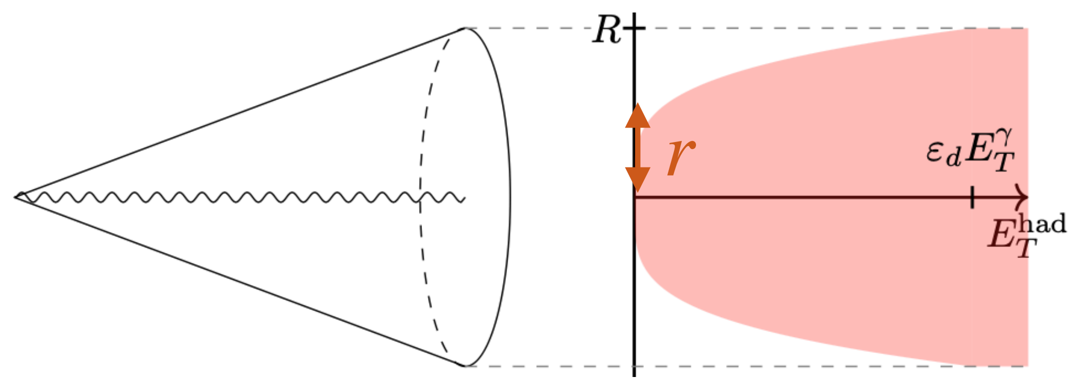
no dependence on how the energy is distributed with r



ii) Smooth cone

$$\sum E_T^{had} \leq f(r \leq R)$$

allowed energy around the photon decreases with r



$$f(r \leq R) = \frac{1 - cos(r)}{1 - cosR}$$

1 - Introduction
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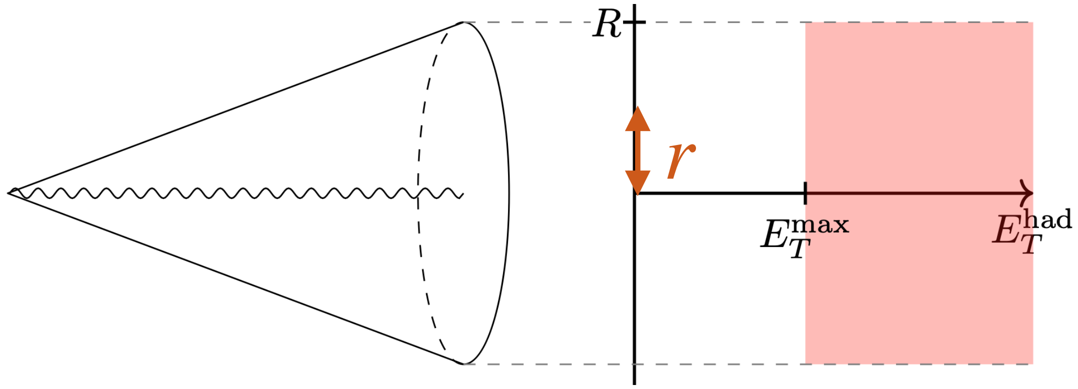

can be implemented experimentally

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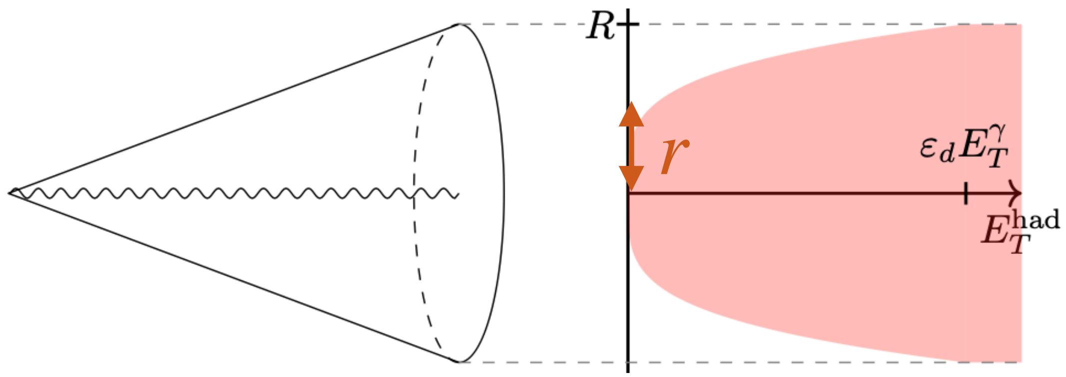

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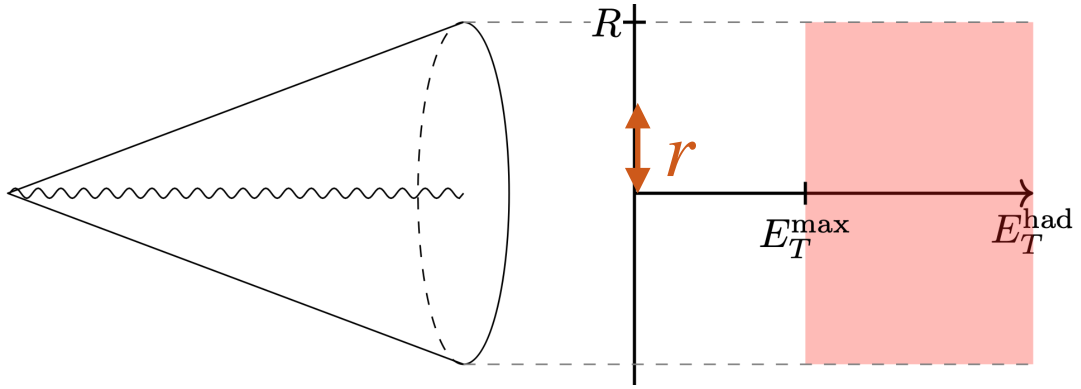

includes fragmentation

can be implemented experimentally

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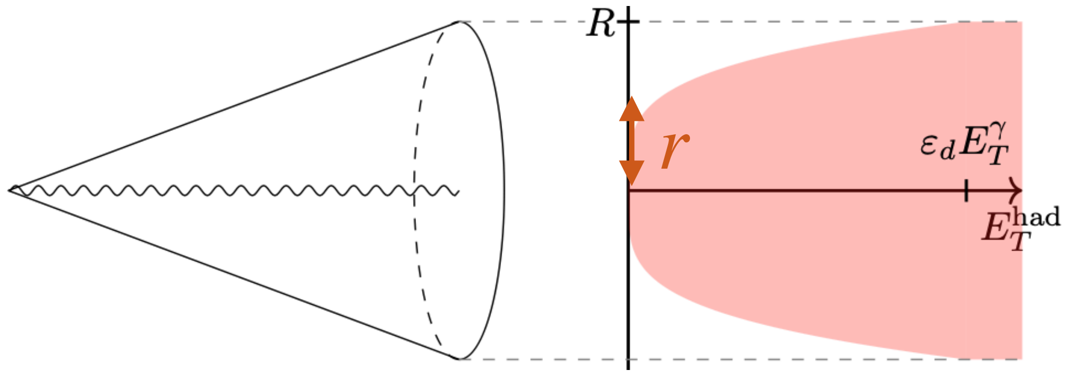


removes fragmentation

can't be implemented experimentally

$$f(r \leq R) = \frac{1 - cos(r)}{1 - cosR}$$

1 - Introduction
Isolation criteria

Review by Marius Höfer

▸ Clustering-based isolation

i) Democratic isolation *(hard-like)*

1) Cluster hadrons + photons democratically into a jet
2) Evaluate the z of jets
3) If one of them fulfils $z > z_{min} \Longrightarrow$ isolated 'photon'

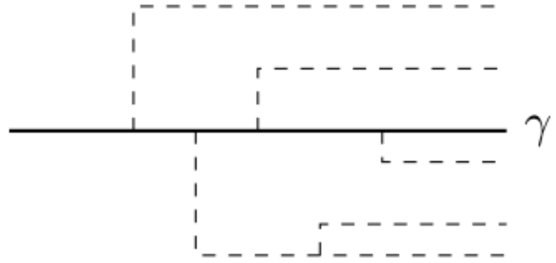
$$z = \frac{z_{EM}}{z_{EM} + z_{HAD}} > z_{min}$$

ii) Soft-drop isolation *(smooth-like)*

1) Cluster hadrons + photons democratically into a parent jet
2) De-cluster into two subjets (with C/A algorithm)
3) Evaluate the soft-drop condition
   a) Passed $\Longrightarrow$ keep parent jet
   b) Failed $\Longrightarrow$ keep softer subjet and repeat 1)
4) If soft-drop condition failed at all steps and remaining constituent is a photon $\Longrightarrow$ isolated photon

Soft-drop condition

$$\frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \geq z_{cut} \left(\frac{R_{12}}{R_0} \right)^{\beta}$$



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removes fragmentation

1 - Introduction
Non-Relativistic QCD (NRQCD)

- The physics of quarkonia involves several energy scales:

$$(m_Q v^2)^2 \quad \ll \quad (m_Q v)^2 \quad \ll \quad m_Q^2$$

kinetic energy	**momentum**	**mass**
interaction time	(spatial size)$^{-1}$	distance range for $Q\overline{Q}$ creation

- NRQCD keeps track of this scale hierarchy:

$$d\sigma(pp \to \mathcal{Q} + X) = \sum_{s,L,J} \langle \mathcal{O}^{\mathcal{Q}}[^{2S+1}L_J] \rangle \cdot d\hat{\sigma}(pp \to Q\overline{Q}[^{2S+1}L_J] + X)$$

long distance effects

short distance effects

Need to be extracted from fits to data

Process independent

Encoded in Long Distance Matrix Elements (LDMEs)

Calculated using perturvative QCD

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$$d\sigma(pp \to \mathcal{Q} + X) = \sum_{s,L,J} \underbrace{\langle \mathcal{O}^{\mathcal{Q}}[^{2S+1}L_J] \rangle}_{\text{long distance effects}} \cdot \underbrace{d\hat{\sigma}(pp \to Q\overline{Q}[^{2S+1}L_J] + X)}_{\text{short distance effects}}$$

- The sum in $d\sigma(pp \to \mathcal{Q} + X)$ for a given physical quarkonium state is over the expansion of its Fock states:

$$|\,\mathcal{Q}[^{2S+1}L_J]\rangle = \mathcal{O}(1)\,|\,Q\overline{Q}[^{2S+1}L_J^{(1)}]\rangle + \mathcal{O}(v)\,|\,Q\overline{Q}[^{2S+1}(L \pm 1)_{J'}^{(8)}]g\rangle$$
$$+\mathcal{O}(v^2)\,|\,Q\overline{Q}[^{2S+1}(L \pm 1)_{J'}^{(8)}]gg\rangle + \ldots$$

1- Introduction
Fragmentation Functions (FFs)

- Collins and Soper (1981): $d\sigma[H+X] = \sum_i d\hat{\sigma}[parton+X] \otimes D_{i\to H}(z)$

$i = parton$

FFs (non-perturbative functions describing the formation of hadrons from partons)

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  FFs (non-perturbative functions describing the formation of hadrons from partons)

- What distinguishes quarkonium FFs is the existence of the subset of scales, which allows (applying NRQCD methodology) to factorise them

$$D_{i\to \mathcal{Q}}(z,\mu) = \sum_n d_{i\to Q\overline{Q}[n]}(z,\mu)\langle \mathcal{O}^{\mathcal{Q}}[n]\rangle$$

short-distance coefficients which describe the production rate of a $Q\overline{Q}$ pair

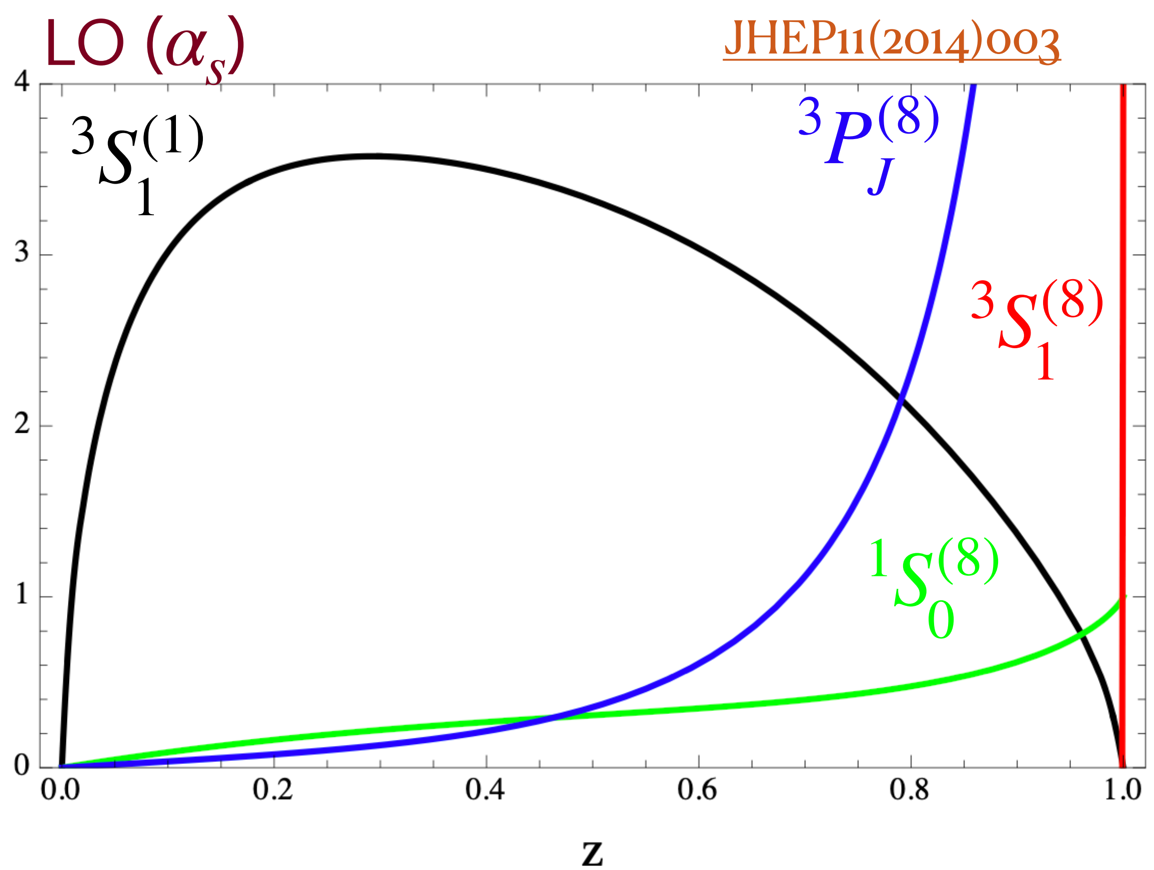
LDMEs from NRQCD

- **Thus, the FFs for quarkonium are *calculable* up to a set of LDMEs**

1 - Introduction
Fragmentation Functions (FFs)

Gluon FFs into various states at $\mu = 2m_c$

z = fraction of the fragmenting gluon's energy carried by the $c\bar{c}$



Potential discrimination power! *

2 - Modelization of quarkonia production

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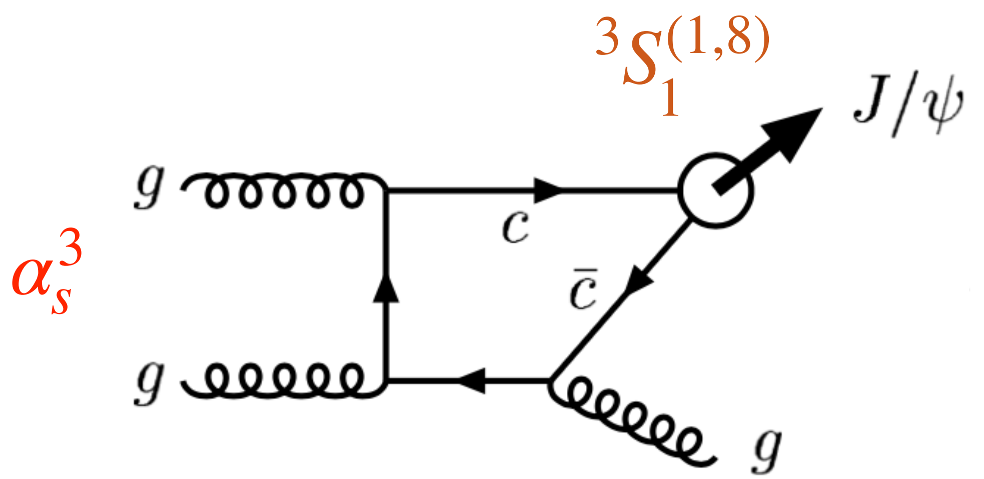
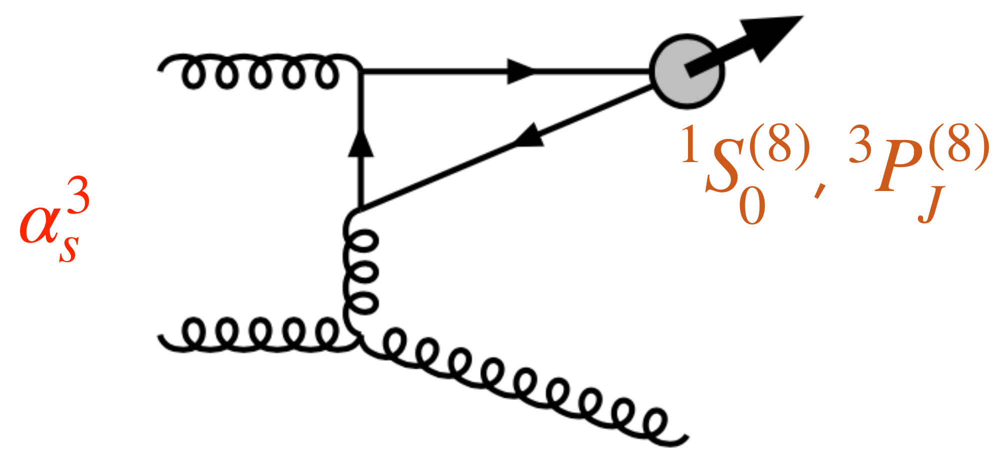
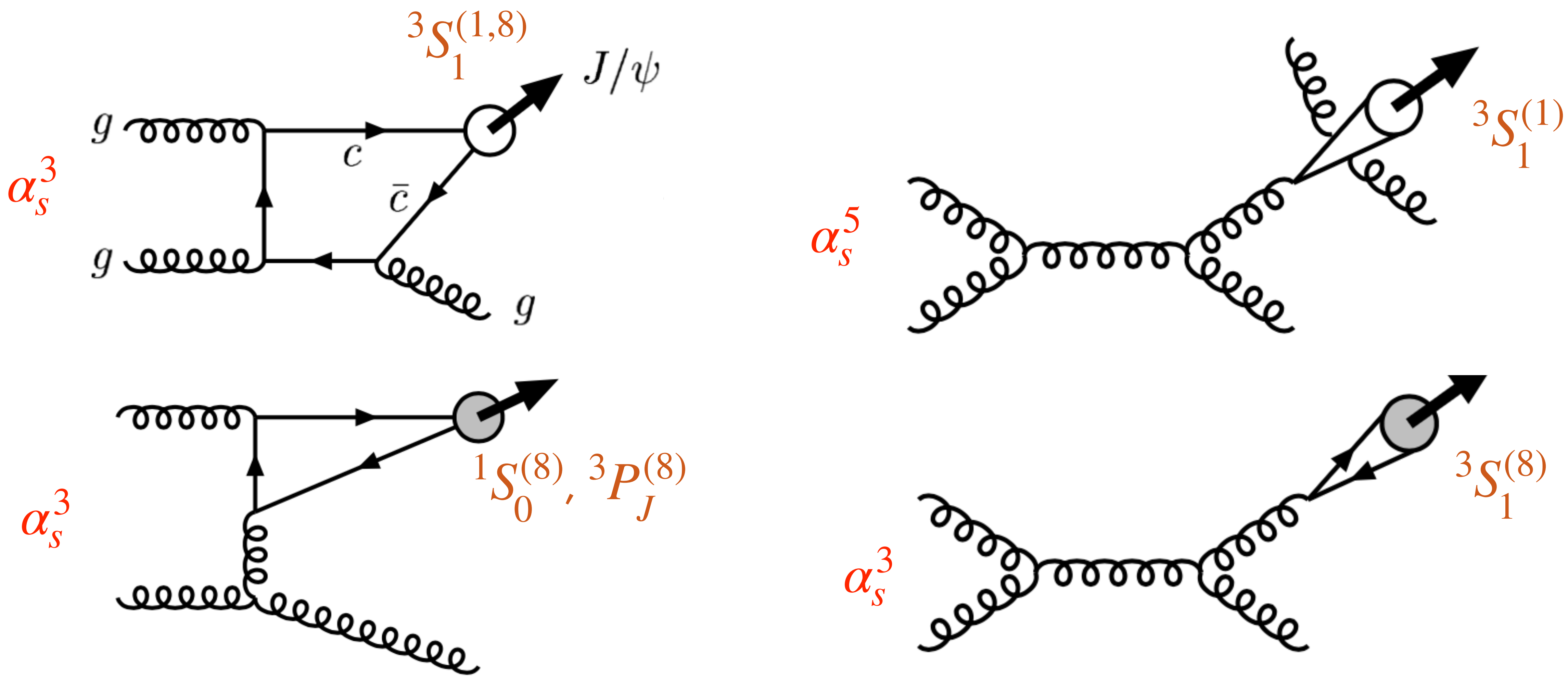
- J/ψ produced...
  - In the hard interaction
    - If in an octet-state, it radiates soft gluons





2 - Modelization of quarkonia production

- J/ψ produced…
  - In the hard interaction
    - If in an octet-state, it radiates soft gluons
  - From the fragmentation of a gluon produced in the hard interaction
    - Dominates at high$-p_T$



2 - Modelization of quarkonia production
PYTHIA8

arXiv:2203.11601

2 - Modelization of quarkonia production PYTHIA8

arXiv:2203.11601

- PYTHIA8 implements a LO NRQCD-based prediction which includes both colour-singlet (cs) and colour-octet (co) mechanisms
  - If the $Q\overline{Q}$ is produced in cs state, it is treated as a cs particle
  - If the $Q\overline{Q}$ is produced in co state, it is treated as a single coloured particle that showers with 2 × splitting function of $q \rightarrow qg$

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- Let's take a closer look into this modelization…
  - Simulation produced with Helac-Onia (hard process) + PYTHIA8 (shower)
  - Hard process: $g + g \to c\bar{c}[^{2S+1}L_J^{(c)}] + g$ in pp collision at $\sqrt{s} = 13$ TeV
  - Particles considered for the activity around the J/ψ: final charged particles with $p > 2$ GeV, $p_T > 200$ MeV
  - More details on the simulation parameters in the backup

2 - Modelization of quarkonia production (Helac-Onia+)PYTHIA8 - our simulation

In an event where the J/ψ was produced *via* singlet, the considered final state charged particles ($p > 2$ GeV, $p_T > 200$ MeV) come from the underlying event

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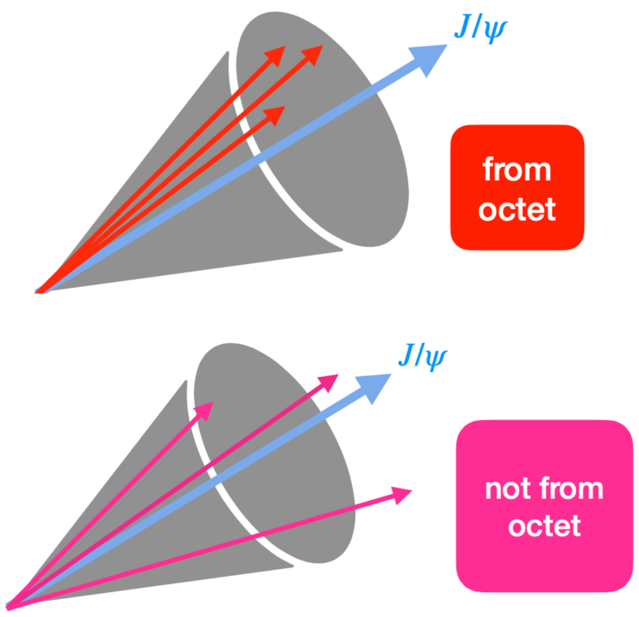

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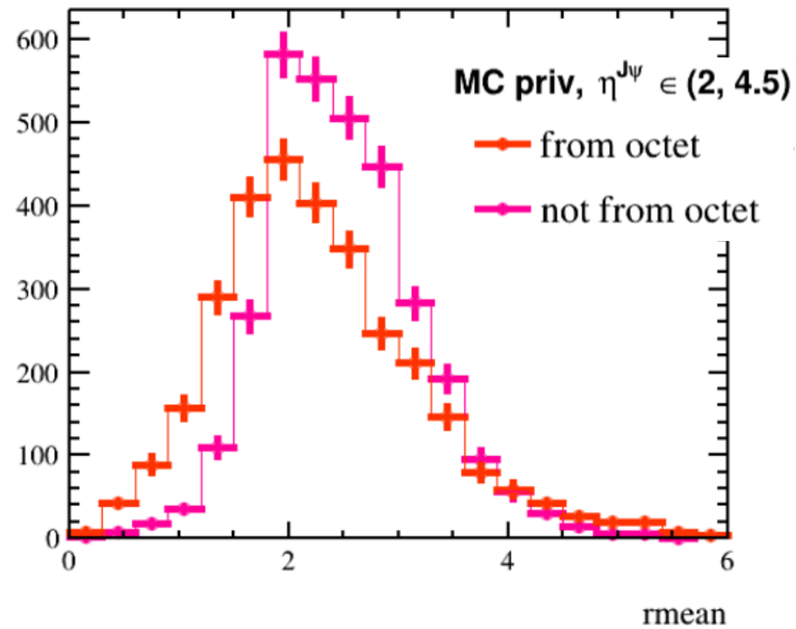
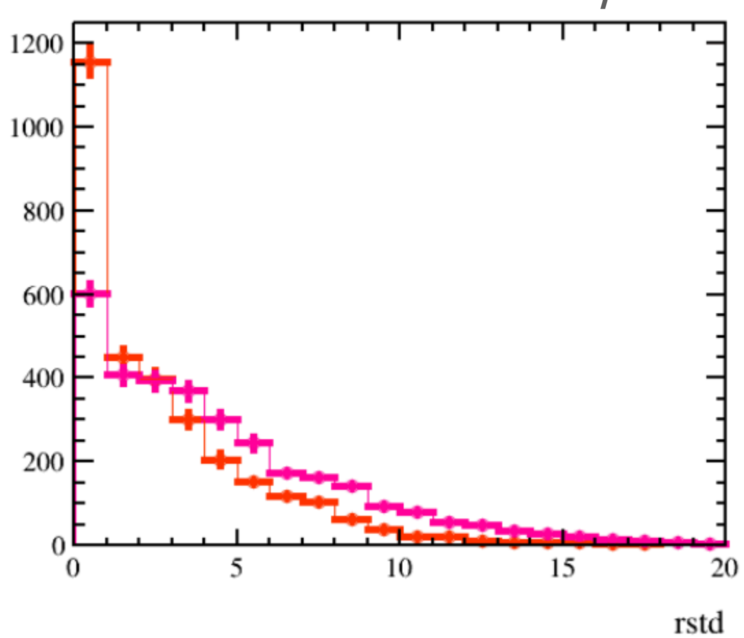
Mean distante to J/ψ



Standard deviation of the mean distante to J/ψ



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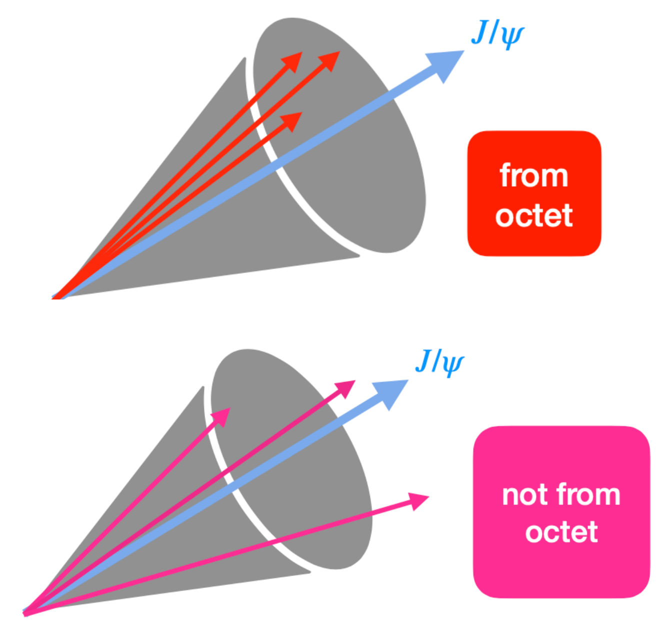
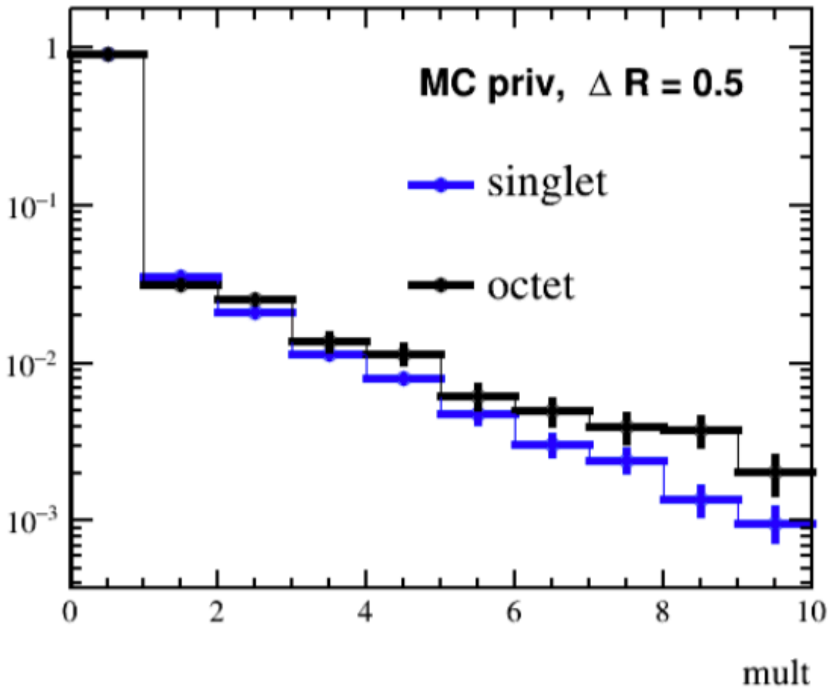


2 - Modelization of quarkonia production (Helac-Onia+)PYTHIA8 - our simulation

Multiplicity inside cone of radius 0.5



This provides already an indication of the limited activity surrounding the J/ψ, as simulated by PYTHIA8

$\Longrightarrow$ In most of the events, the cone is empty

2 - Modelization of quarkonia production (Helac-Onia+)PYTHIA8 - our simulation

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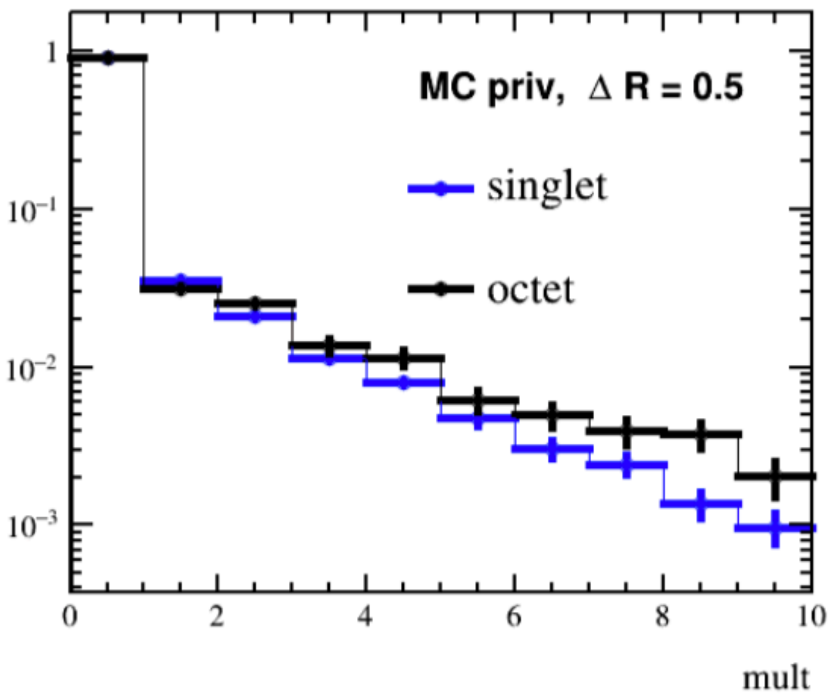

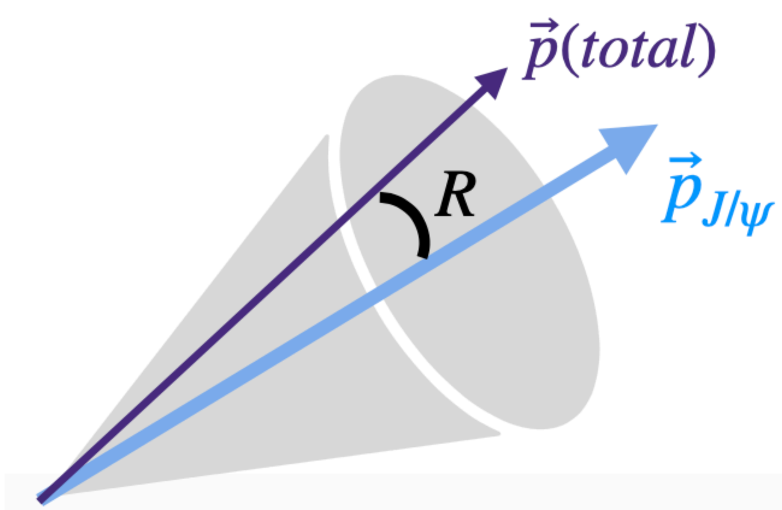

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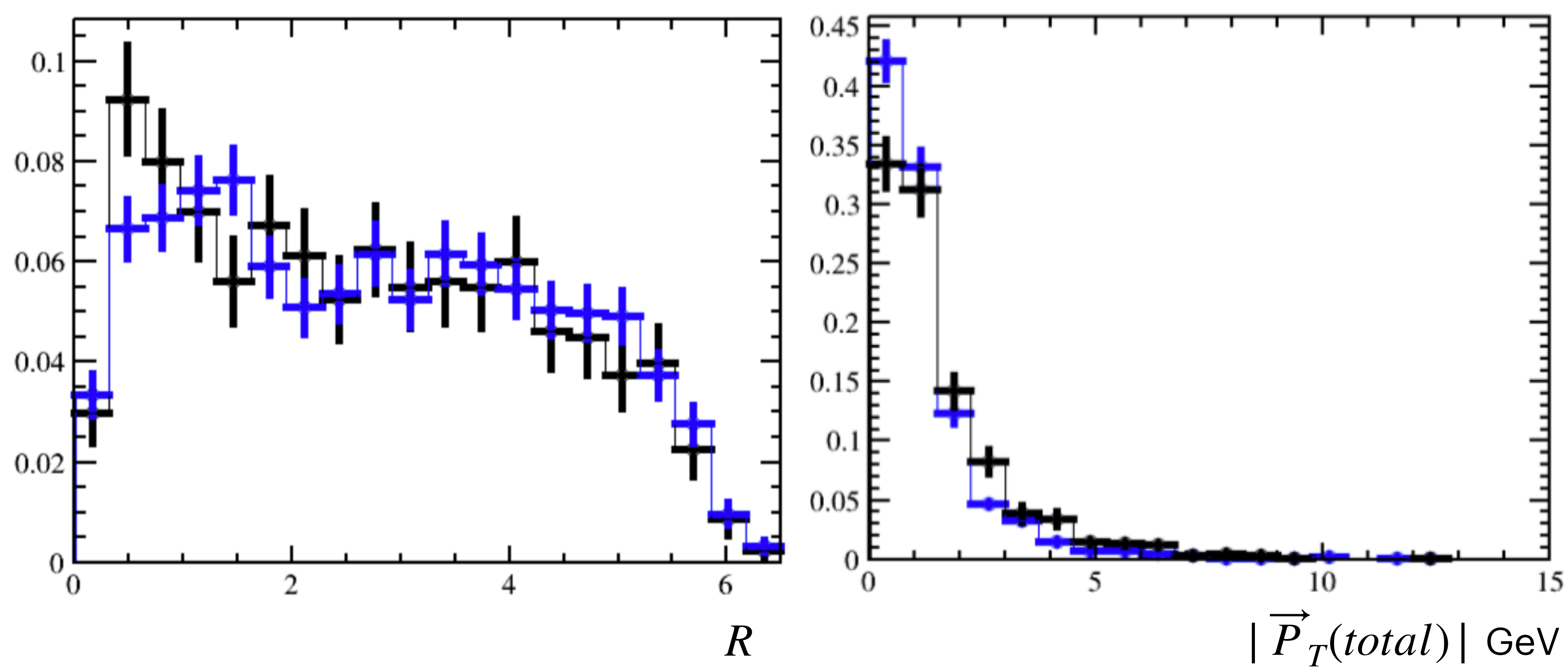
For non-empty cones:



2 - Modelization of quarkonia production

- That was on PYTHIA8's side => J/ψ from hard interaction
- Now, what if the J/ψ comes from $c\bar{c}$ produced within a jet?

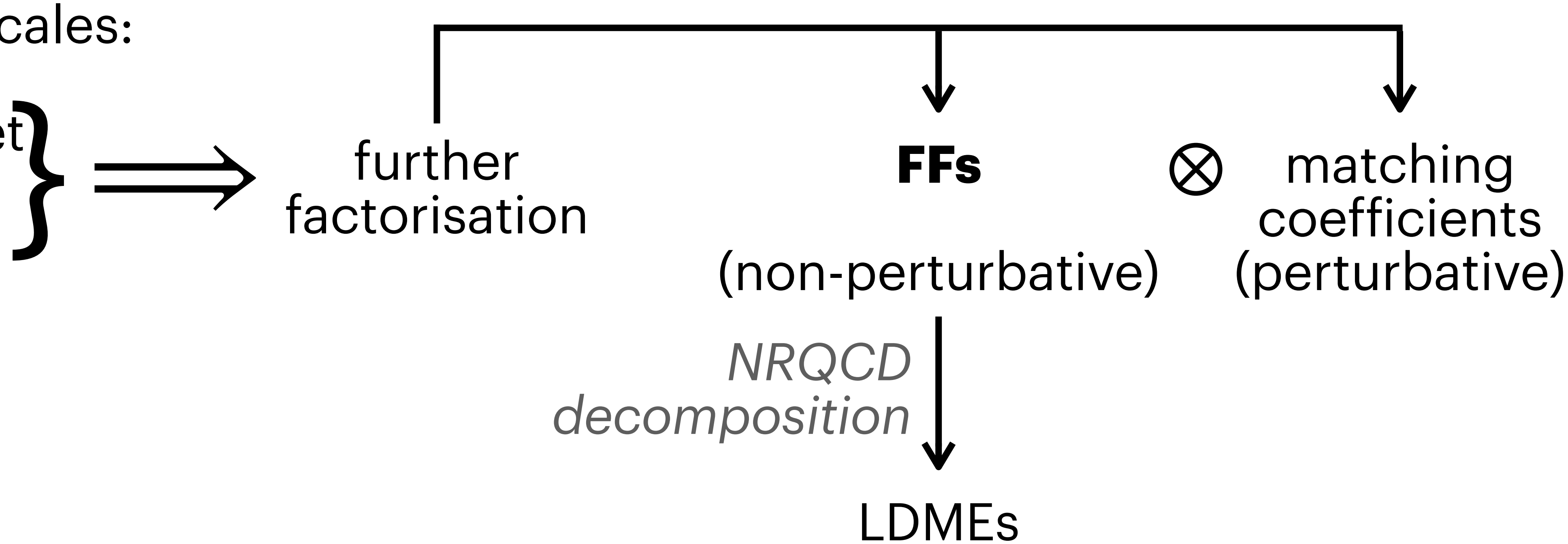
2 - Modelization of quarkonia production
Probing Quarkonium production Mechanisms with jet substructure

JHEP11(2014)003

- Consider that the $Q\overline{Q}$ pair is not produced directly in the hard scattering but is a fragmenting product of a high-p_T jet

- Thus, a generic cross section for producing a J/ψ within a jet (energy E_{jet}, size R) can be factorised into
  - Hard and soft functions describing the production of the $c\overline{c}[n]$ (+ other jets)
  - **Fragmenting Jet Function** (**FJF**) describing the non-perturbative fragmentation of the $c\overline{c}[n]$ into the J/ψ

- **FJF** contains two scales:
  - Energy of the jet
  - Hadron mass



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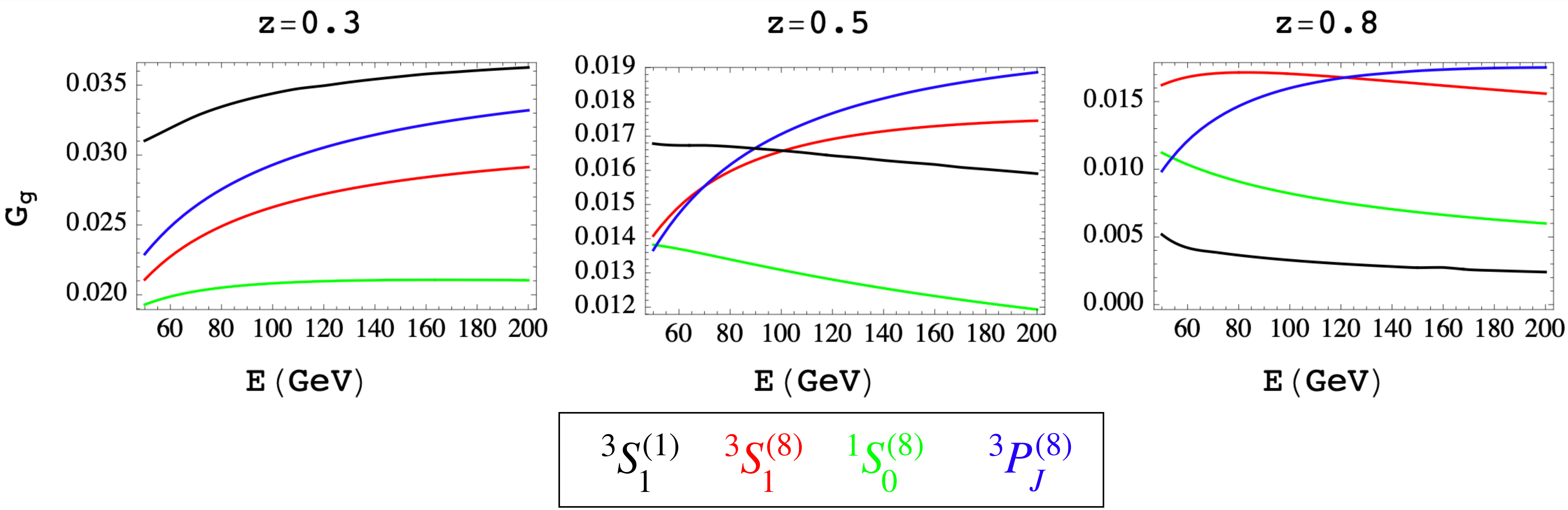


- E_{jet} dependent distributions show a high discriminating power among contributions to quarkonium production

3 - Measurements (of J/ψ in jets)
Summary

Ref.	Collaboration, system, energy	Jet	J/ψ
Phys. Rev. Lett. 118 (2017) 192001	LHCb pp 13 TeV	R = 0.5, anti-kt pt > 20 GeV 2.5 < eta < 4.0	J/ψ : 2.5 < eta < 4.0
Phys. Lett. B 825 (2022) 136842	CMS pp (and PbPb) 5.02 TeV	R = 0.3, anti-kt 20 < pt < 40 GeV |eta| < 2	J/ψ : pt > 6.5 GeV
Phys. Lett. B 804 (2020) 135409	CMS pp 8 TeV	R = 0.5, anti-kt pt > 25 GeV |eta| < 1	J/ψ : E > 15 GeV; |y|<1
D. Bjergaard, PhD thesis, Duke U., 2017. * Unpublished	ATLAS pp 8 TeV	R = 0.4, anti-kt pt > 45 GeV |eta| < 2.5	J/ψ : pt > 45 GeV; |y|<2
PoS (HardProbes2020), vol 387, 072 * Unpublished	STAR pp 500 GeV	R = 0.2 / 0.4 / 0.6, anti-kt pt > 10 GeV |eta| < 1 - R	J/ψ : pt > 5 GeV; |eta| < 1

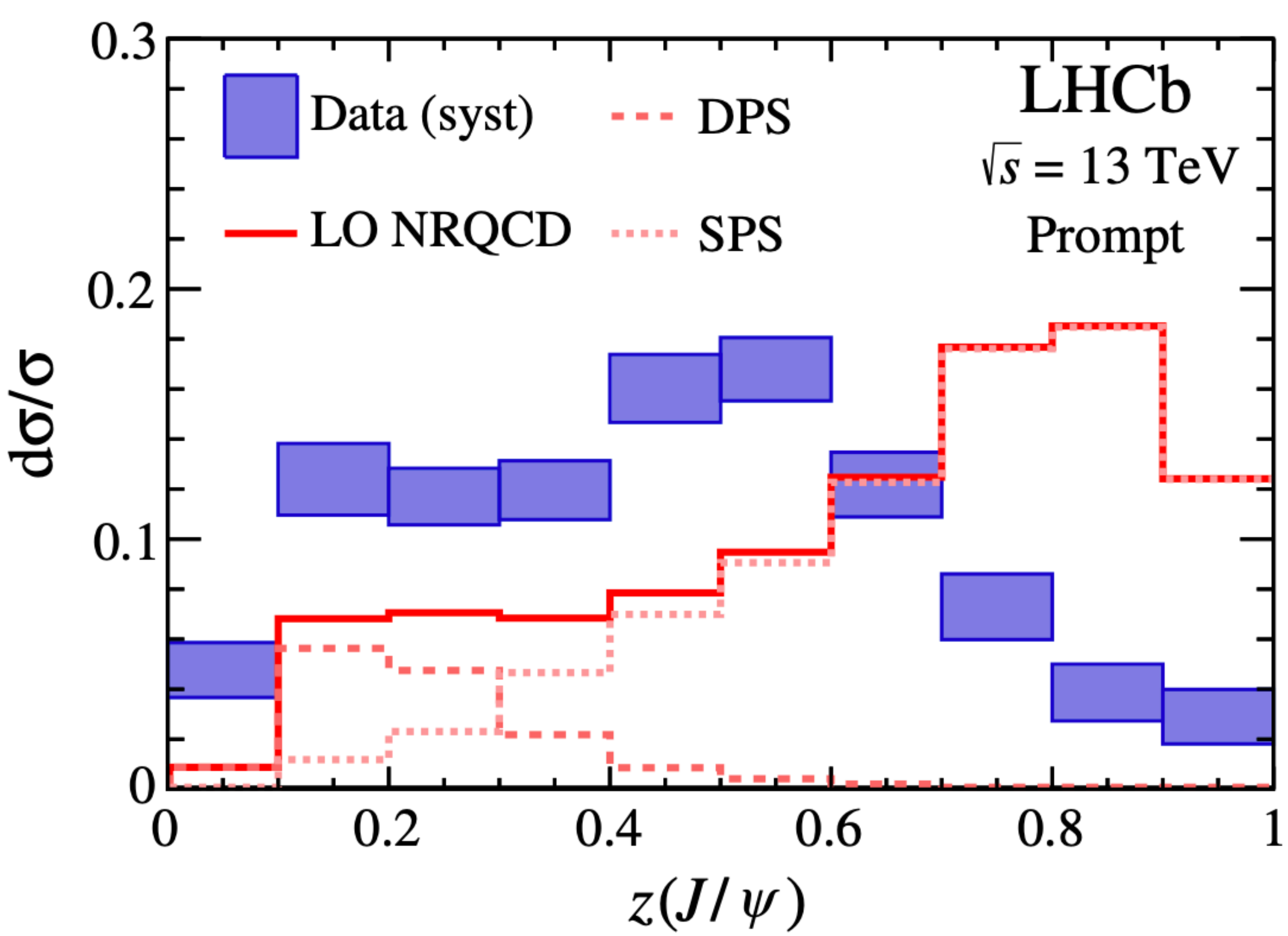
3 - Measurements
Study of J/ψ production in jets

Phys. Rev. Lett. 118 (2017) 192001

- Observable: $z = \frac{p_T(J/\psi)}{p_T(jet)}$ distribution

$z \to 0$ $\qquad$ $z \to 1.0$

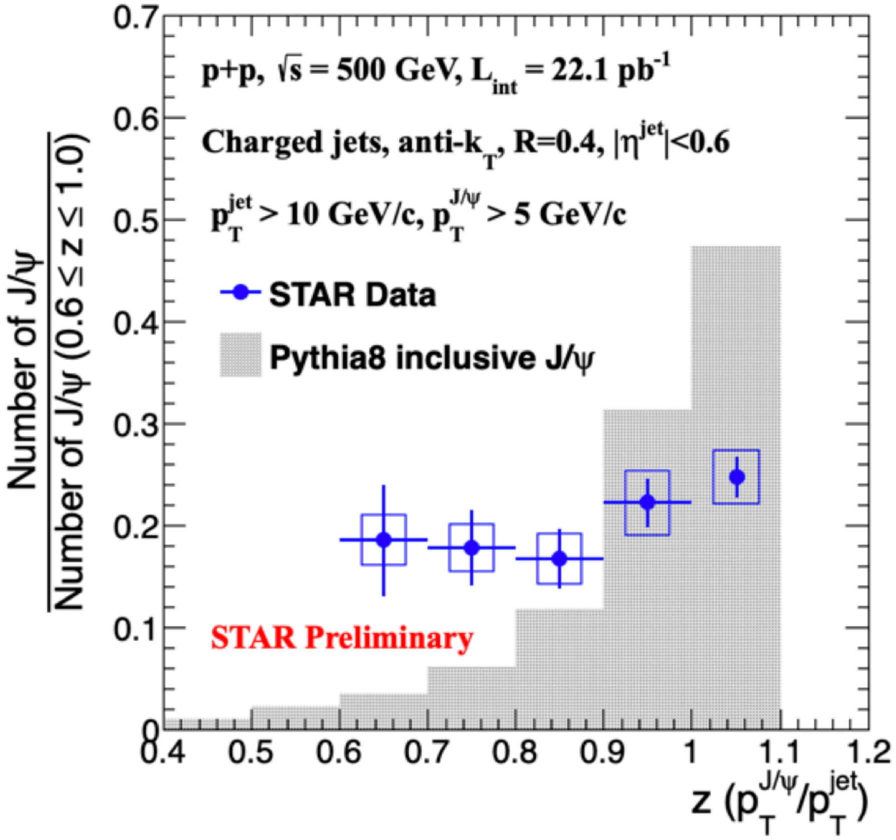
Embedded in high activity $\qquad$ *Isolated*



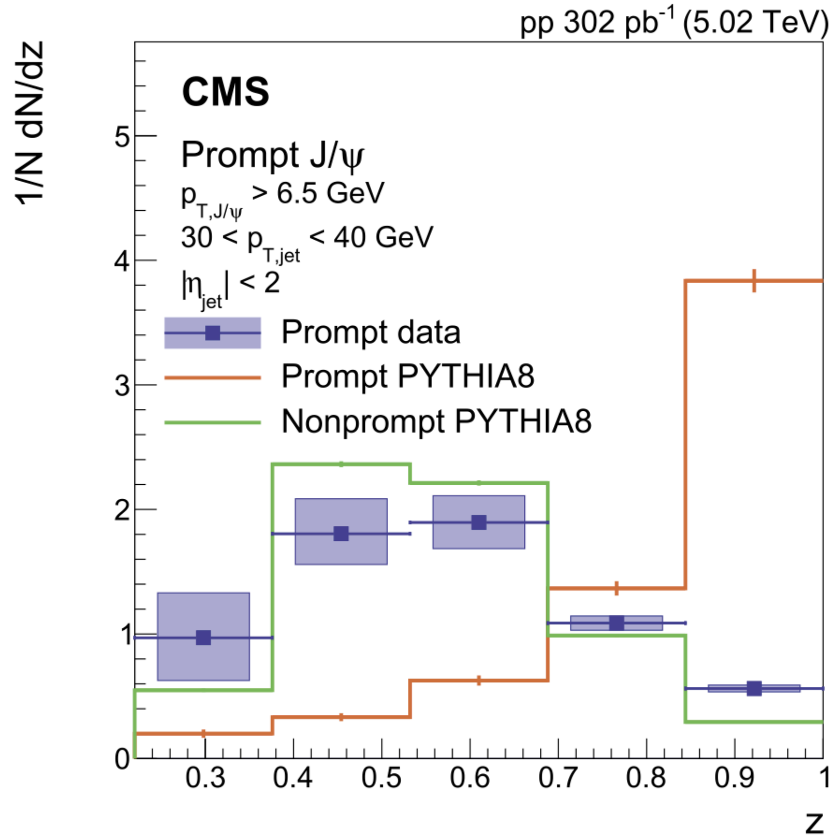
- Jet:
  - Anti$-kt$, $R = 0.5$,
  - $p_T(jet) > 20$ GeV
  - $2.5 < \eta(jet) < 4.0$
  - J/ψ + charged +neutral (`GhostProb<0.1`, $p < 1$ TeV)
- Results:
  - Prompt$-J/\psi$ distributions show a much softer trend than Pythia8 predictions, which underestimate the activity around the J/ψ
- Limitations:
  - Cross-section not provided
  - 'J/ψ *in jet*' notion

3 - Measurements
Other measurements of promt J/ψ in jets

PoS (HardProbes2020), vol 387, 072



Phys. Lett. B 825 (2022) 136842



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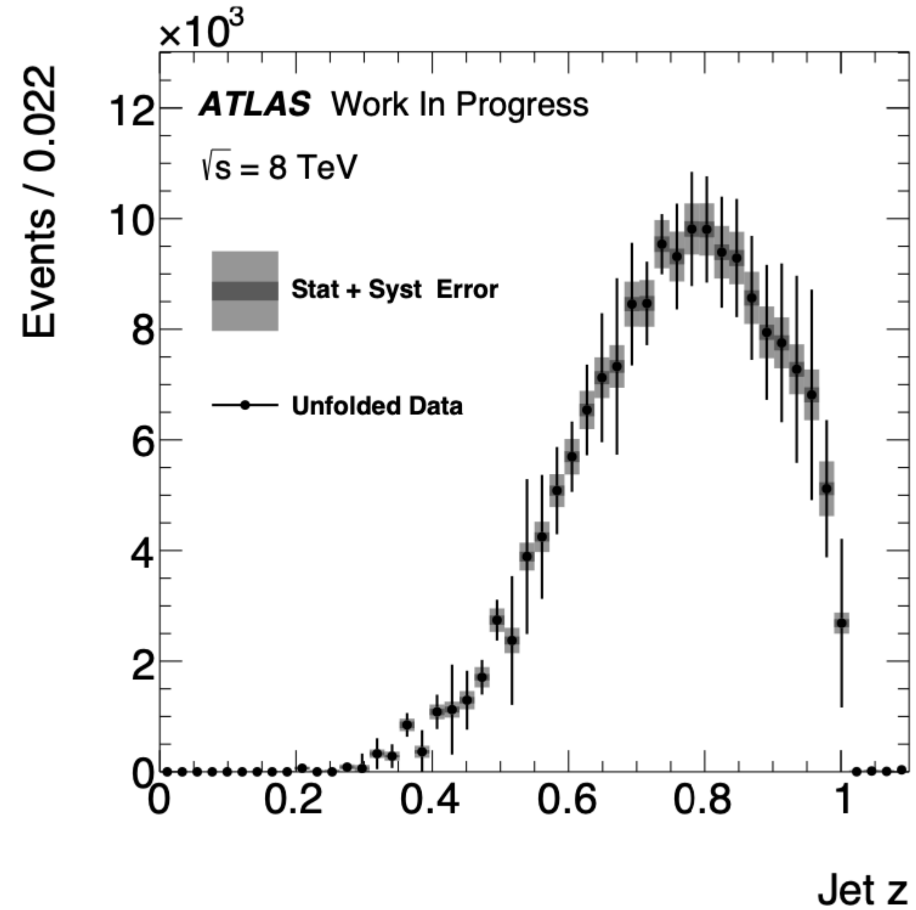


- No significant dependence
  - More statistics
- Less isolated than PYTHIA8 predictions
  - Point at $z = 1$ represent events where $J/\psi = jet$

- Similar to LHCb results
  - Peak at $z \approx 0.5$

- Peak at higher z than LHCb results

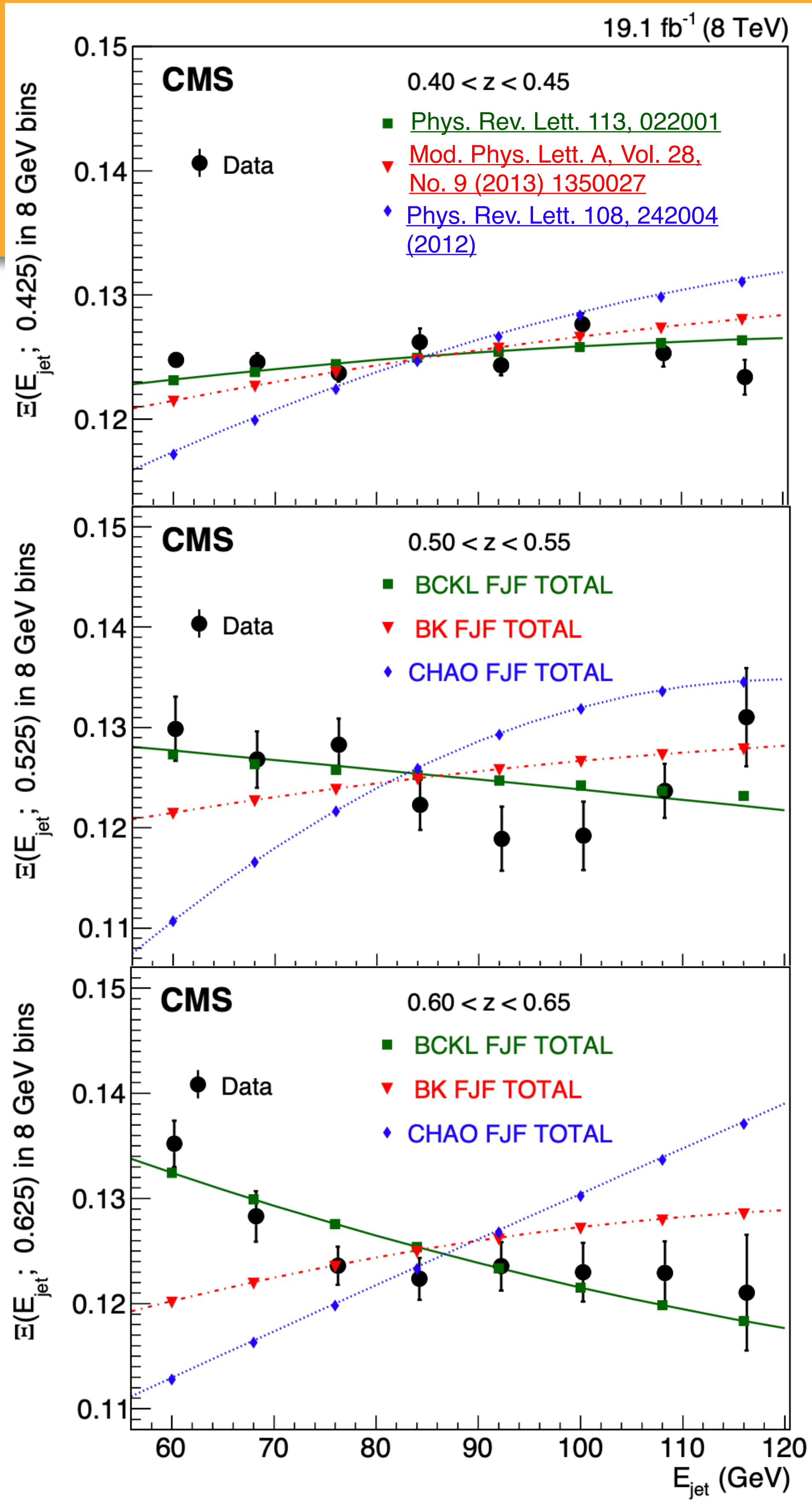
... more in the backup

3 - Measurements

Study of J/ψ meson production inside jets in pp collisions at $\sqrt{s} = 8$ TeV

Phys. Lett. B 804 (2020) 135409

- Comparison of data with FJF predictions
- Observable: self-normalized E_{jet}−dependence in bins of z
- Jet:
  - Anti−kt
  - $R = 0.5$
  - $p_T > 25$ GeV
  - J/ψ *in jet* means that both muons are constituents of the jet
- Results
  - Only FJF predictions using the **BCKL** (Phys. Rev. Lett. 113, 022001) LDME set, based on $p_T(J/\psi) > 10$ GeV data, matches data in all bins
  - In (94.2 ± 0.1) % of events with a jet, the J/ψ is inside the jet



4 - Conclusions and outlook

- The study of the hadronic activity around the J/ψ in our Helac-Onia+PYTHIA8 simulation reveals that the octet-shower is very similar to the underlying event and gives largely isolated J/ψ
- Measurements of J/ψ in jets show that this quarkonium state is largely produced within jets
- Predictions based on quarkonium produced at later stages of the evolution within a jet show good agreement with data

- Outlook
  - Ongoing LHCb analysis for the fragmentation functions of J/ψ, $\psi(2S)$, $\chi_{c1}(3872)$ and the three Υs in pp collisions at $\sqrt{s} = 13$TeV
    Eliane Epple, Naomi Cooke, Philip Ilten, J. Matthew Durham, Cesar da Silva

  - My ongoing analysis…
    … *for which input is welcome!*

Thank you for your attention!

Backup

Isolation criteria

Review by Marius Höfer

▶ **Cone-based isolation**

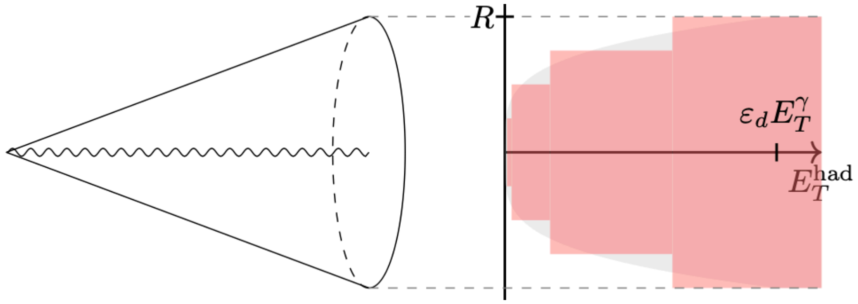
iii) Modified versions

Discretised smooth cone

designed to mimic detector granularity

includes fragmentation

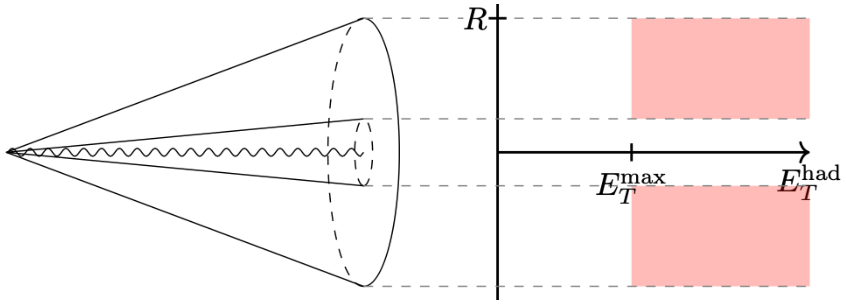
parameter dependence



Hollow cone

designed to mimic detector granularity

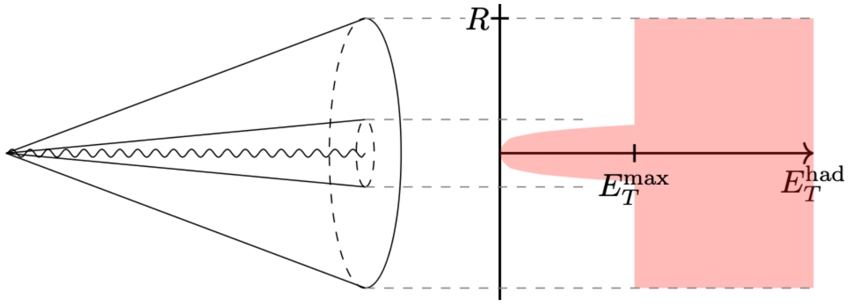
includes fragmentation ?



Hybrid cone

outer cone mimics detector inner soft cone

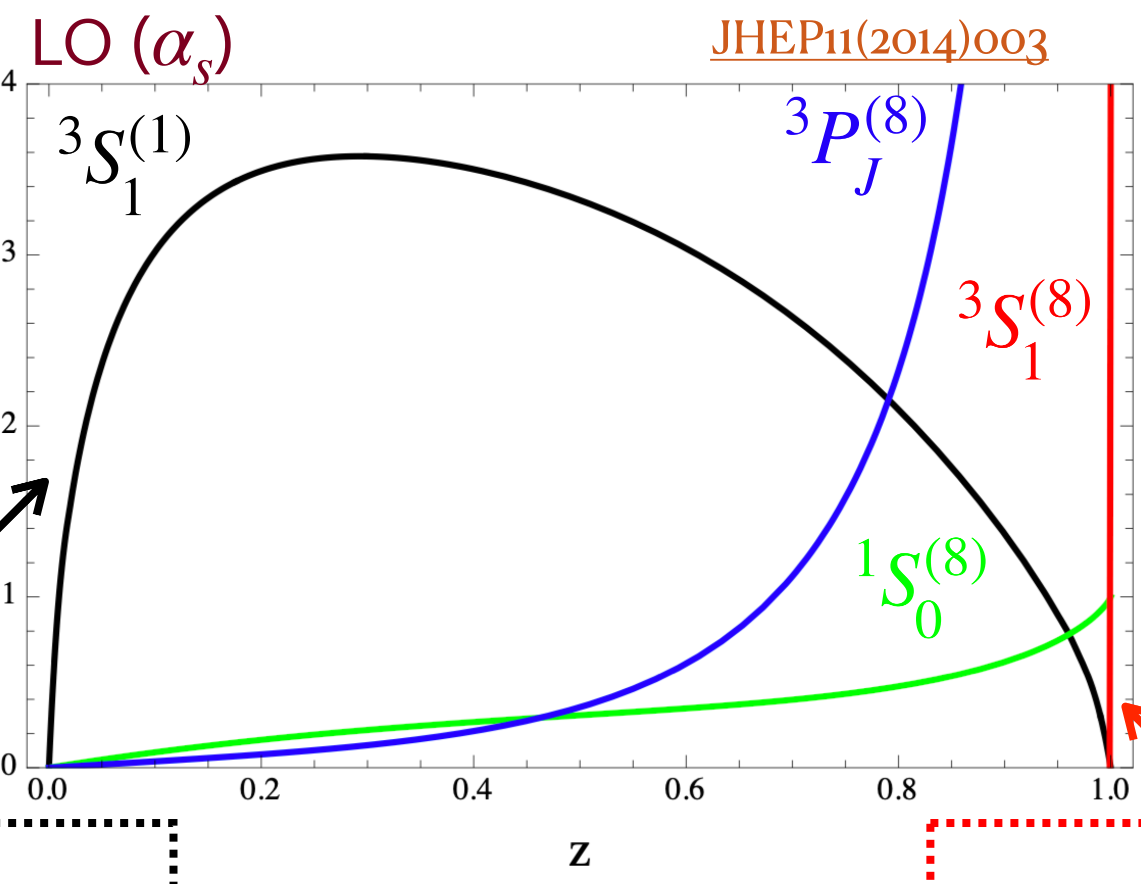
removes fragmentation



1 - Introduction
Fragmentation Functions (FFs)

Gluon FFs into various states at $\mu = 2m_c$

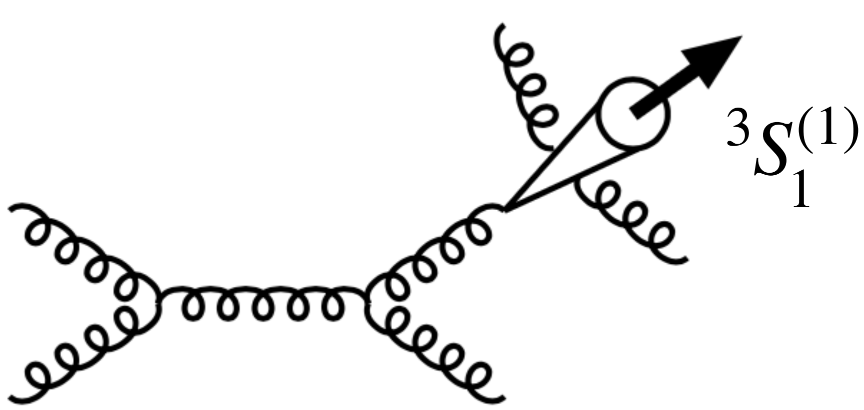
z = fraction of the fragmenting gluon's energy carried by the $c\bar{c}$

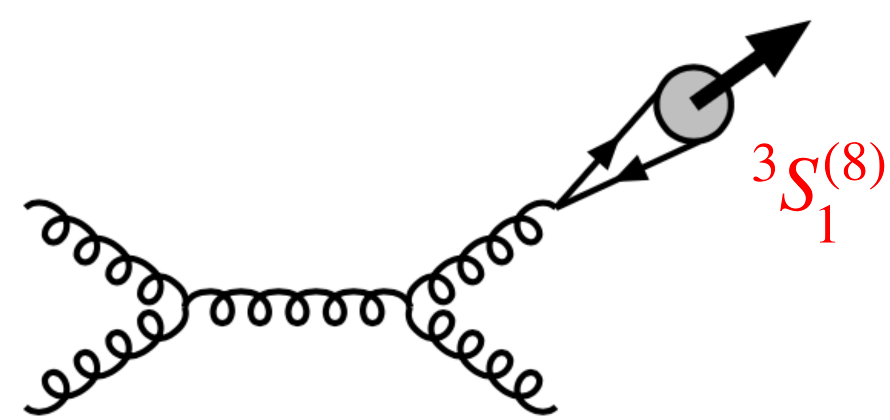


Potential discrimination power! *

softer z

delta at $z = 1$





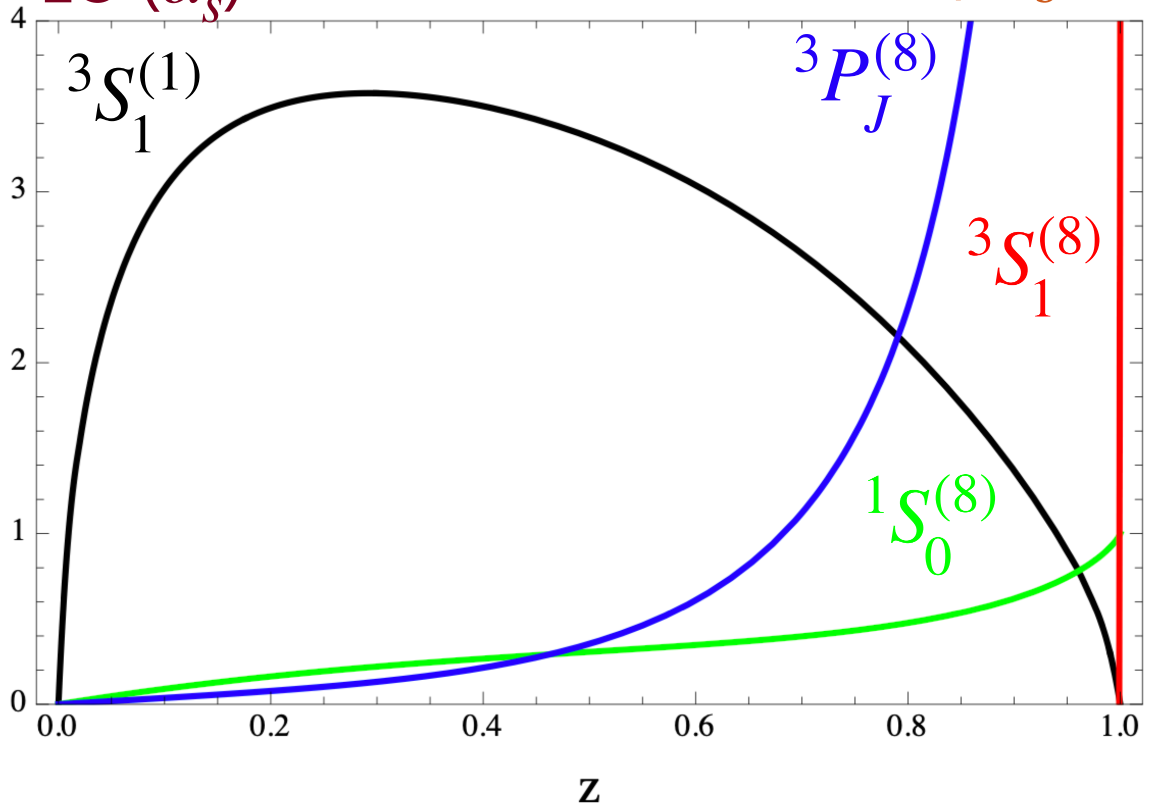
Fragmentation Functions (FFs)

Potential discrimination power! *

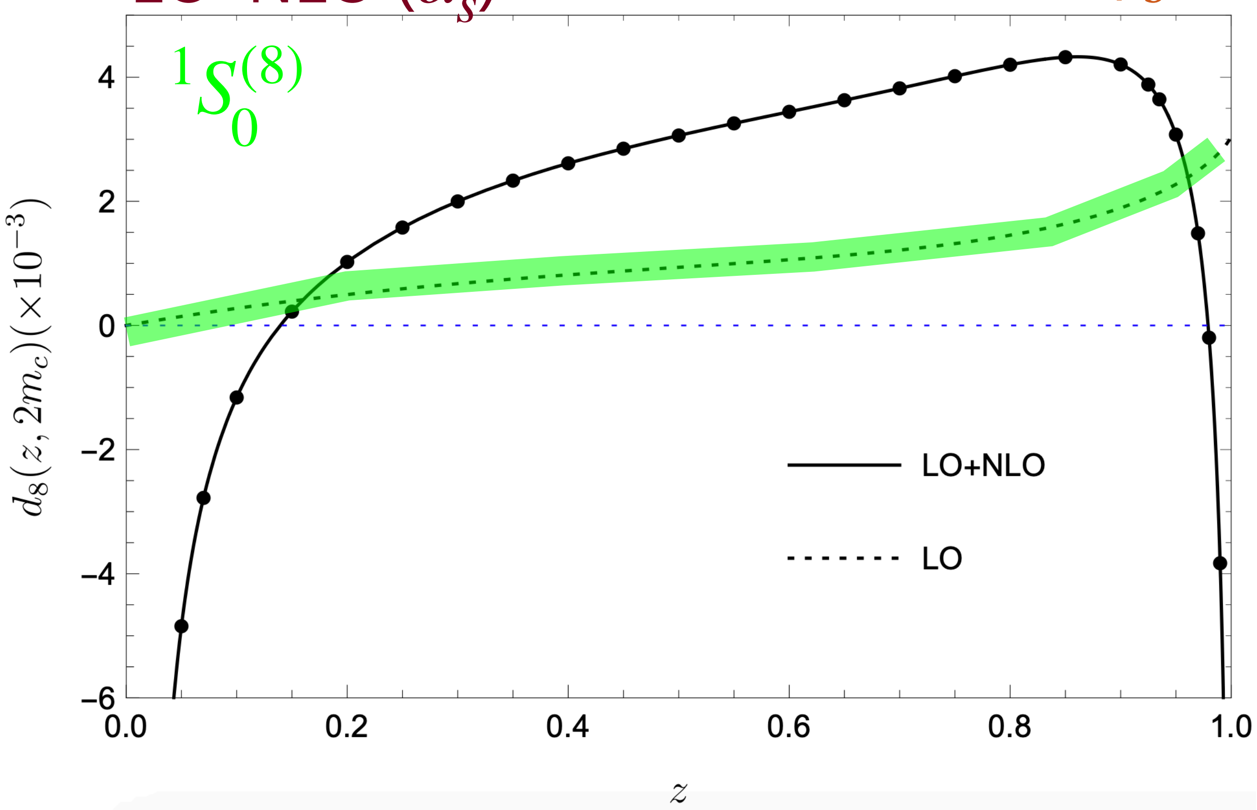
Gluon FFs into various states at $\mu = 2m_c$

* May be washed out with NLO FFs

LO (α_s) JHEP11(2014)003



LO+NLO (α_s) arXiv:1810.04138



Probing Quarkonium production Mechanisms with jet substructure

- Consider that the $Q\overline{Q}$ pair is not produced directly in the hard scattering but is a fragmenting product of a high-p_T jet

- The di-jet cross section for a jet (energy E_{jet}, size R) and a J/ψ with energy fraction z in a pp collision is schematically

$$\frac{d^2\sigma}{dE_{jet}dz} = \sum_{A,B,i,j} f_{A/p} f_{B/p} \cdot d\sigma(c\bar{c}[n]X, J_j^{recoil}) \otimes \mathscr{F}_S \otimes \mathscr{G}_i^{J/\psi}(E_{jet}, z \,|\, R, \mu)$$

Cross section for the production of a $c\bar{c}[n]$ inside a jet + a recoil jet

Fragmenting Jet Function (**FJF**) for the jet containing the J/ψ

- FJF contains two scales:
  - Energy of the jet
  - Hadron mass

Our simulation - main characteristics

Programs

Helac-Onia v2.7.6

Output: LHE file

Pythia v8.3.09

Output: ROOT.TTree

Main characteristics

Automatic calculation of heavy quarkonium amplitudes in NRQCD

- Process ⇨ pp collision at $\sqrt{s} = 13$ TeV
- PDF for the protons ⇨ CT09MCS
- Parton-level process ⇨ $g + g \to c\bar{c}\left[{}^{2S+1}L_J^{(c)}\right] + g$
- Intermediate states ⇨ ${}^3S_1^{(1)}$ and ${}^3S_1^{(8)}$

Masses $[GeV]$	$m_c = 1.5$ $m_b = 4.7$ $m_t = 173$ $m_\tau = 1.777$ $M_Z = 91.188$ $M_W = 80.419$ $M_H = 125$ $m_e = 0.5109989461 \times 10^{-3}$ $m_\mu = 0.1056583745$
Renormalization and factorisation scales $[GeV]$	$\sqrt{m_1^2 + p_{T1}^2}/2$
G_F $[GeV^{-2}]$	1.16639×10^{-5}
$\sin^2\theta_W$	$1 - \left(\frac{M_W}{M_Z}\right)^2$
α_{em}	$\sqrt{2} G_F M_W^2 \frac{\sin^2\theta_W}{\pi}$
α_s	running

In charge of

I. Evolve CO $c\bar{c}$ pairs to physical J/ψ

II. Decay $J/\psi \to \mu^+\mu^-$

III. Showering

NRQCD confronts LHCb Data on Quarkonium production within jets

- **Gluon Fragmentation Improved PYTHIA (*GFIP*)**: *Hard gluons produced in the short distance process with with virtuality of order E_{jet} are allowed to shower until a gluon with virtuality $\sim 2m_c$ hadronizes into the J/ψ*

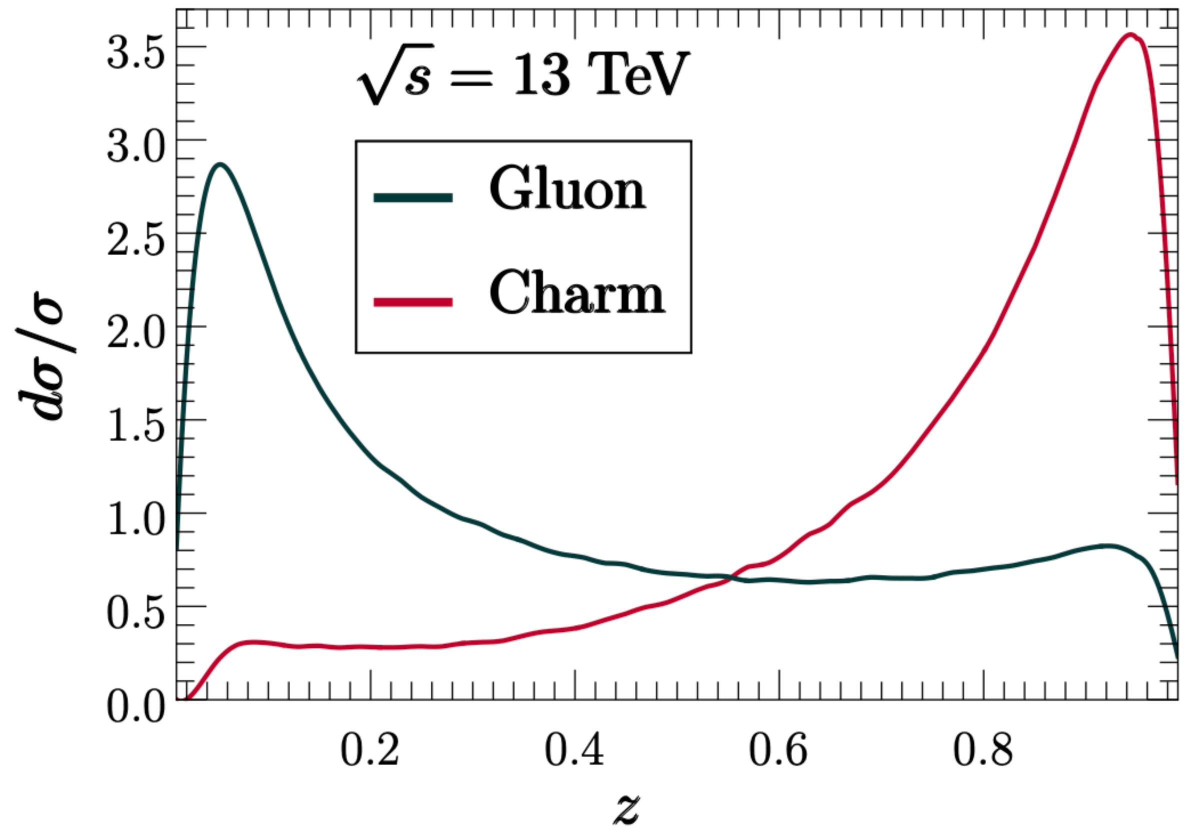
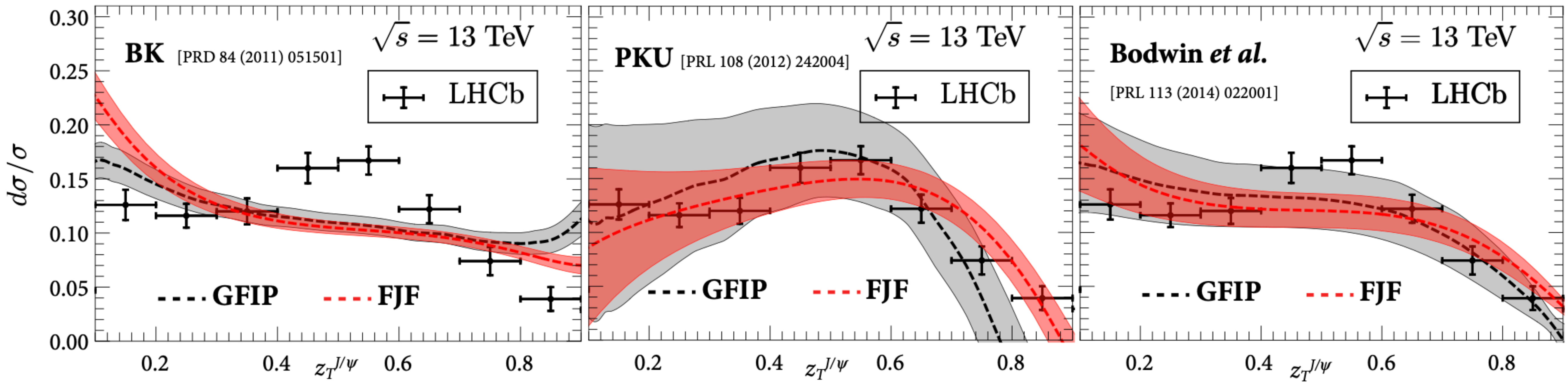


FIG. 1. PYTHIA predictions for c quark and gluon z distributions (where z is the fraction of the energy of the parton initiating the jet) after showering to the scale $2m_c$.

Phys. Rev. Lett. 119, 032002 (2017)

NRQCD confronts LHCb Data on Quarkonium production within jets



Gluon Fragmentation Improved PYTHIA (*GFIP*):
Hard gluons produced in the short distance process with virtuality of order E_{jet} are allowed to shower until a gluon with virtuality $\sim 2m_c$ and convolution with LO-NRQCD FFs to obtain J/ψ distributions

FJF
Combine FJFs with hard events and evolve FFs from $2m_c$ to E_{jet}

Better agreement than default PYTHIA

High$-p_T$ LDME sets better agreement

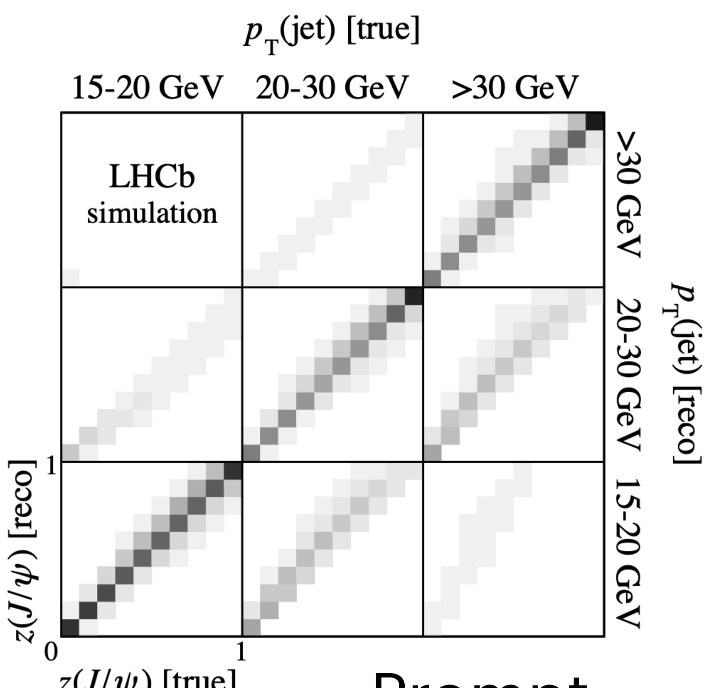
Study of J/ψ production in jets

- Fiducial region

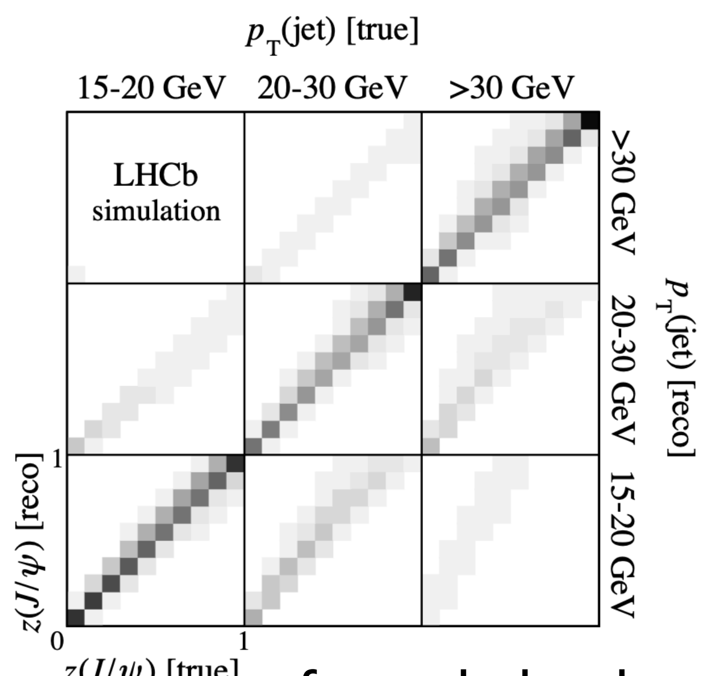
Table 3: Fiducial region employed to measure $p_T(J/\psi)/p_T(j)$.

object	requirement(s)
jets	$p_T(j) > 20\,\text{GeV}, \quad 2.5 < \eta(j) < 4$
J/ψ	$2 < \eta(J/\psi) < 4.5$
muons	$p_T(\mu) > 0.5\,\text{GeV}, \; p(\mu) > 5\,\text{GeV}, \; 2 < \eta(\mu) < 4.5$

- Unfolding matrices

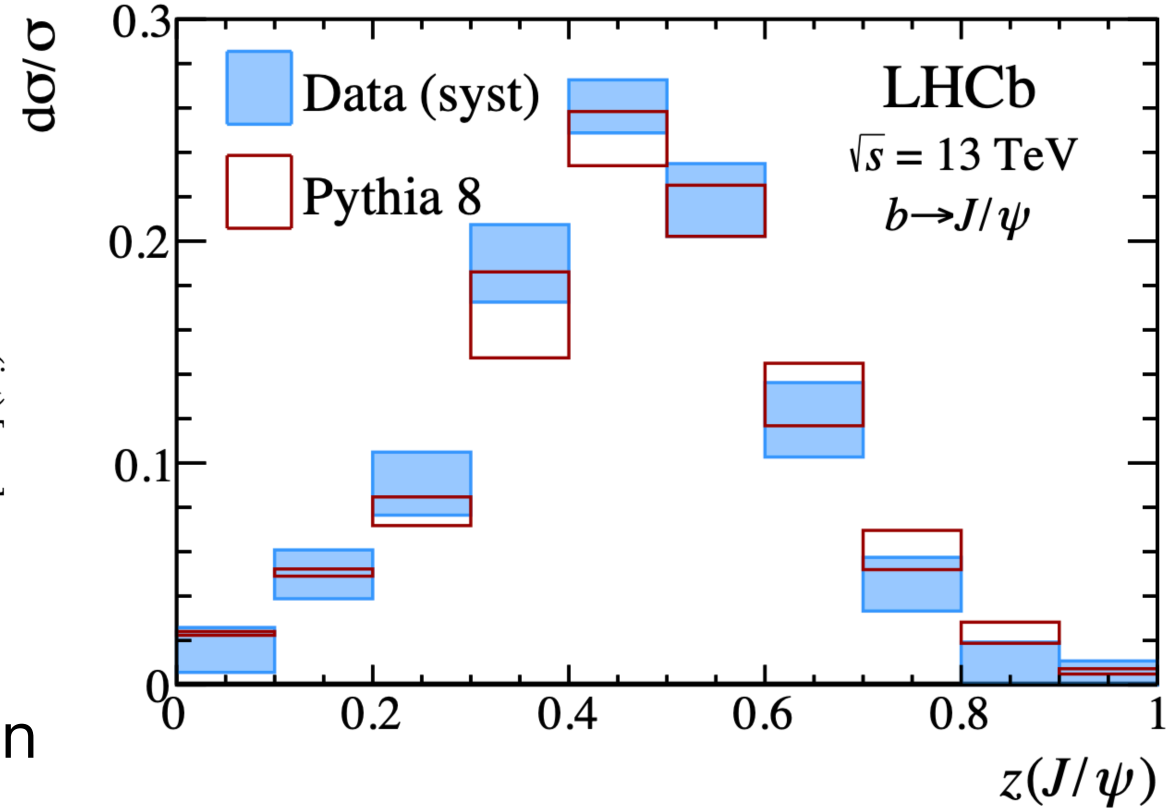


Prompt



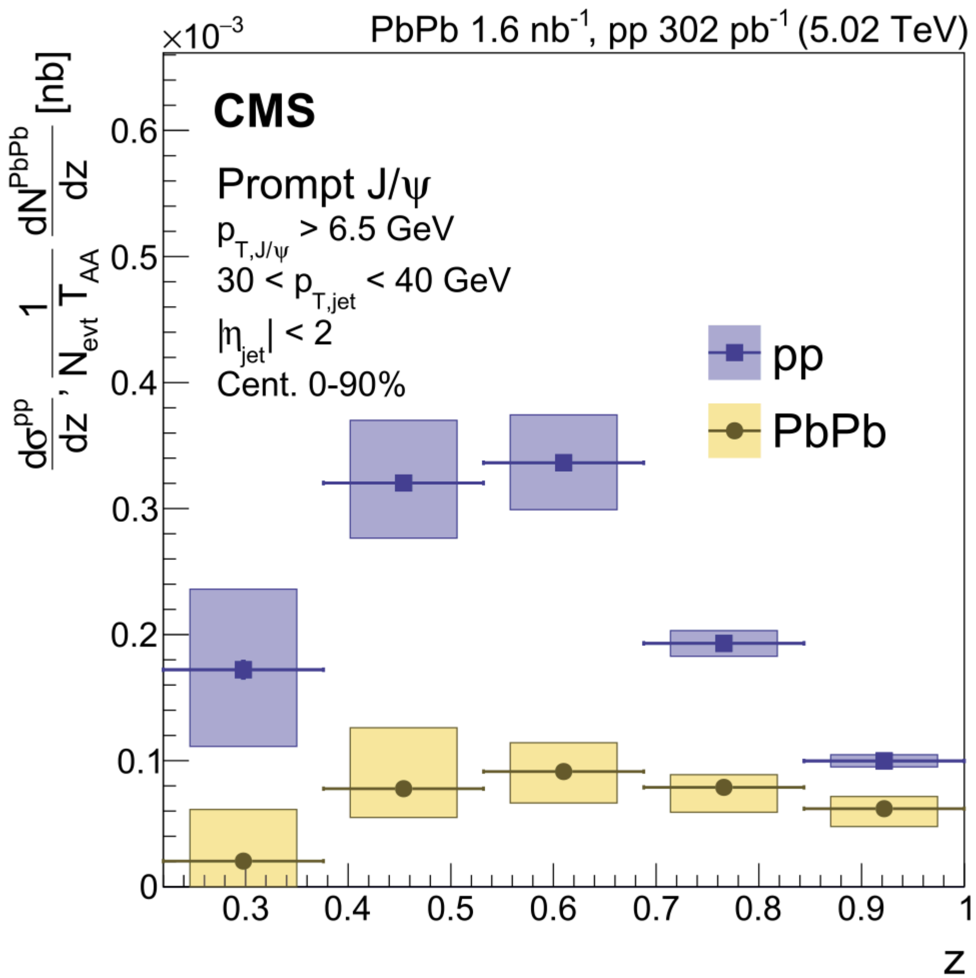
from b-hadron

- Results for J/ψ from b-hadrons



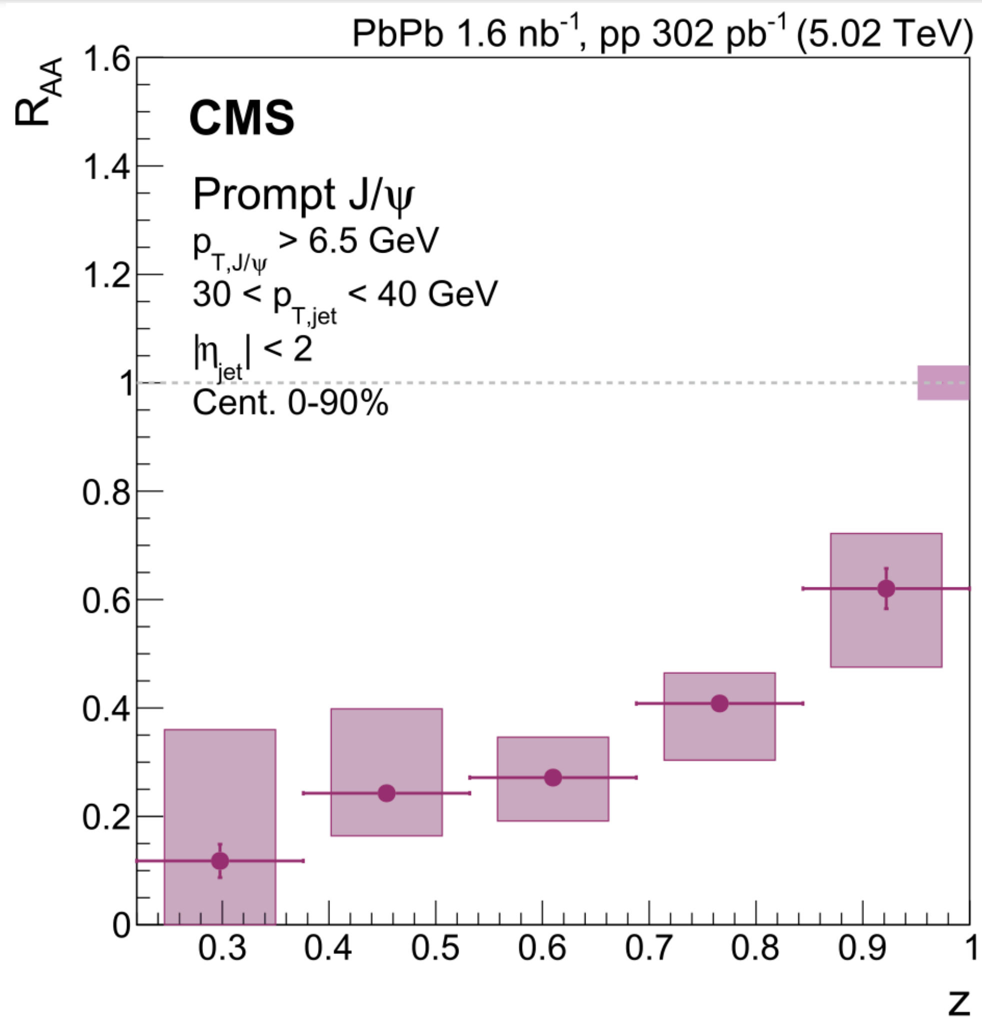
Phys. Lett. B 825 (2022) 136842

Fragmentation of jets containing a prompt J/ψ meson in PbPb and pp collisions at $\sqrt{s} = 5.02$ TeV



J/ψ differential cross section in pp and the T_{AA} scaled yield in PbPb collisions

T_{AA} = average effective nucleon-nucleon luminosity delivered by a single heavy ion collision for a given centrality selection

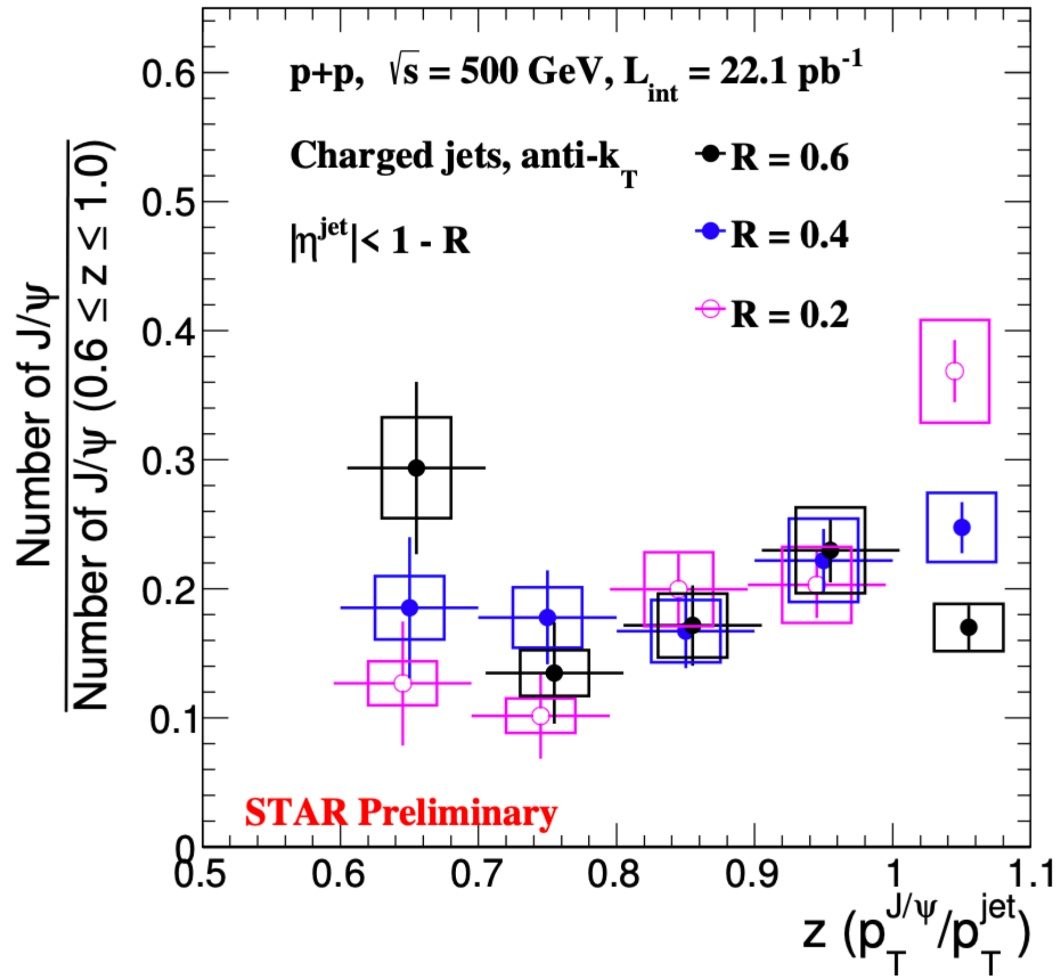


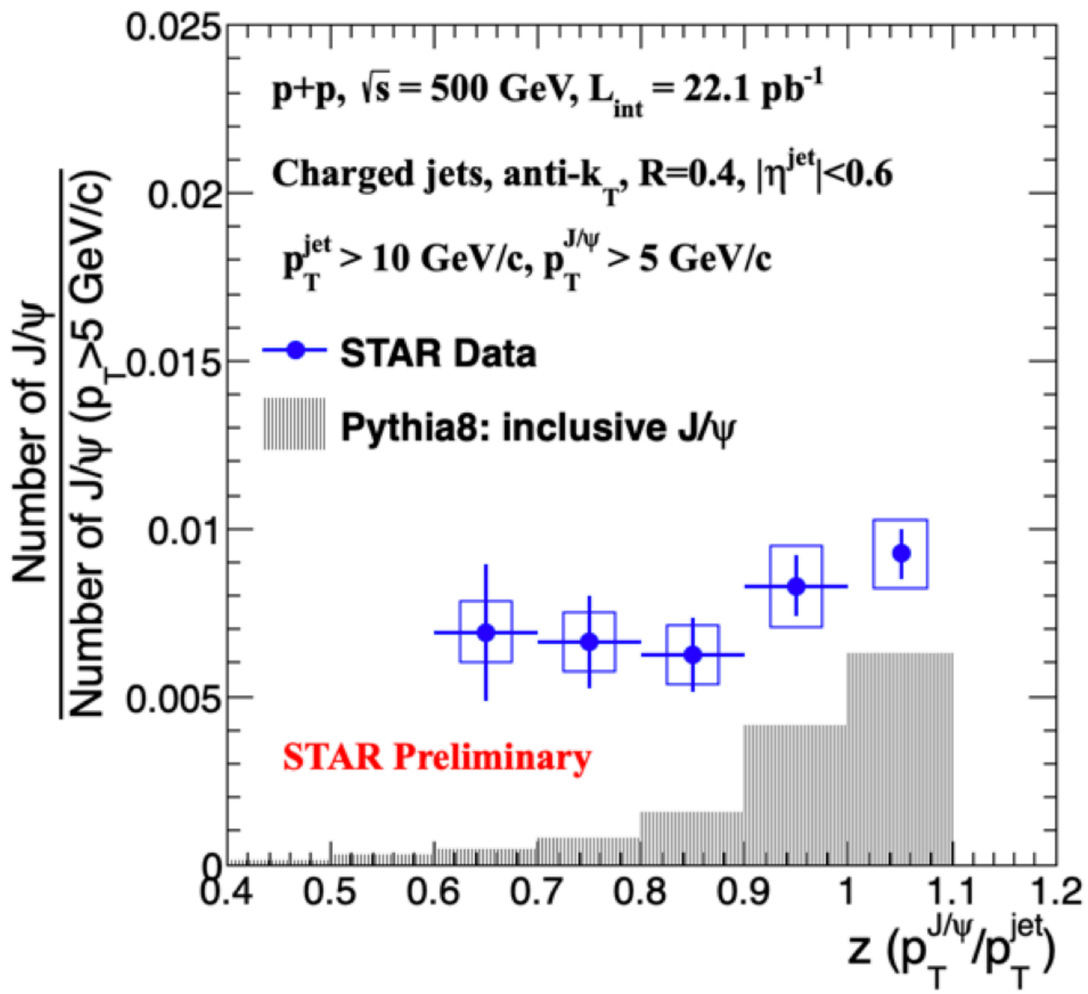
$$R_{AA}(z) = \frac{dN^{AA}/dz}{T_{AA} dN^{pp}/dz}$$

3 - Measurements

J/ψ production in jets in p+p collisions at $\sqrt{s} = 500$ GeV by STAR

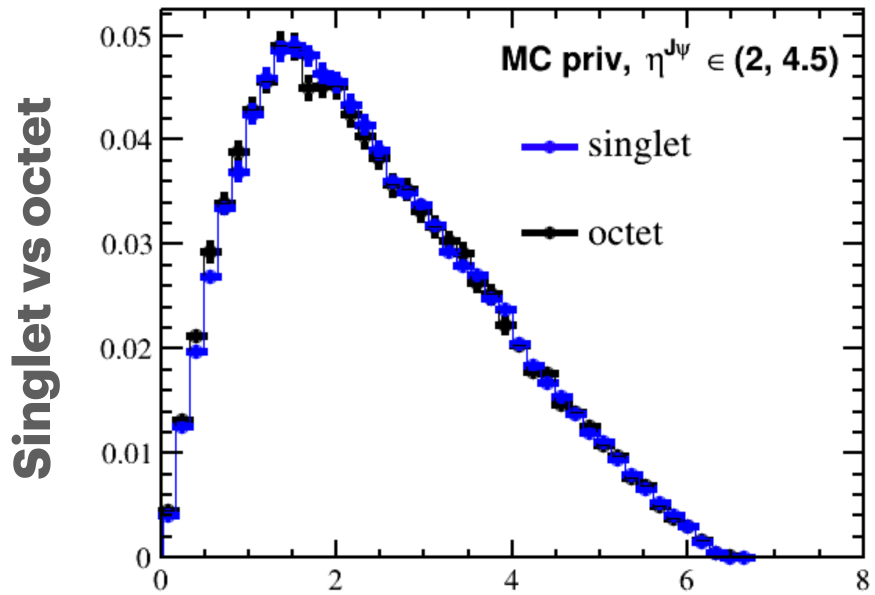
PoS (HardProbes2020), vol 387, 072

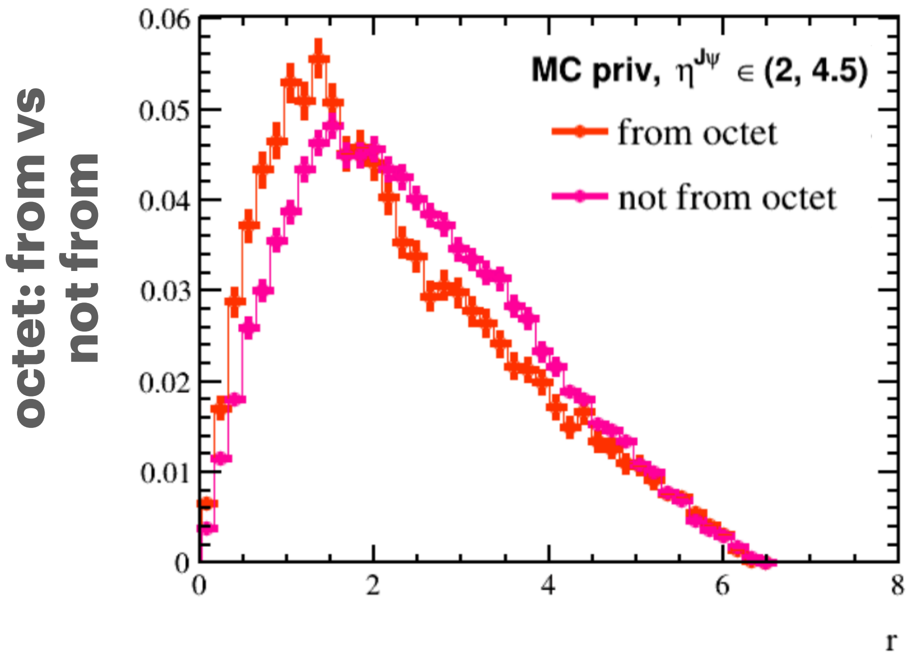


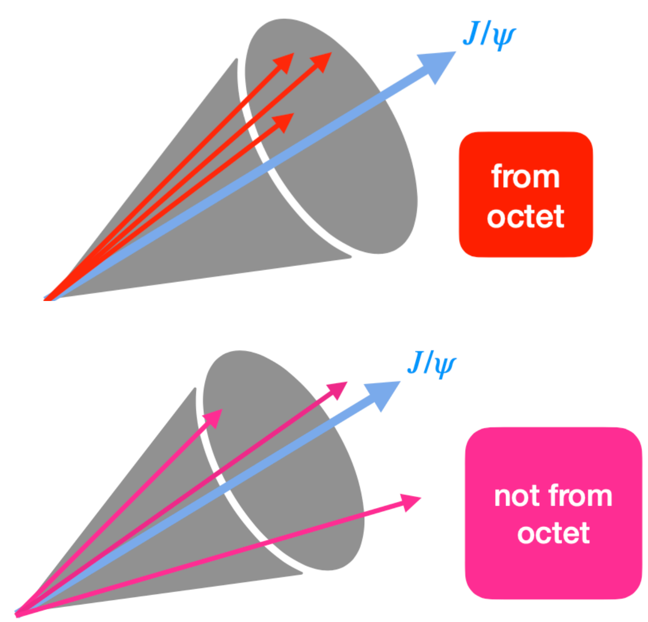


2 - Modelization of quarkonia production PYTHIA8 - our simulation

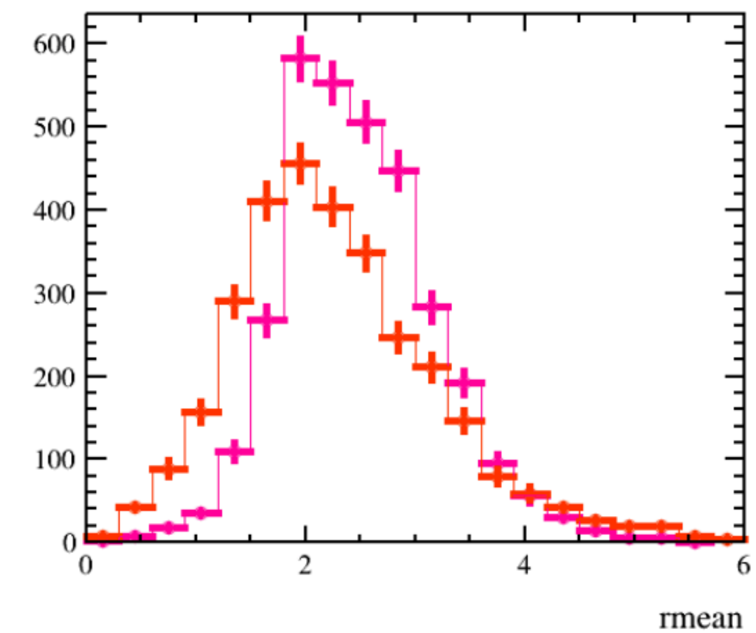
$$r = \sqrt{(\eta_{J/\psi} - \eta_i)^2 + (\phi_{J/\psi} - \phi_i)^2}$$







Mean distante to J/ψ



Standard deviation of the mean distante to J/ψ