Prospects for isolated quarkonium studies

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"Synergies between LHC and EIC for quarkonium physics"
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USC Universidade de Santiago de Compostela
Xunta de Galicia
IGFAE Instituto Galego de Física de Altas Enerxías
25 1999 2024

Motivation
Why isolated quarkonium?

* I will center on J/ψ isolation

- Measurement of isolated J/ψ in proton-proton collisions at $\sqrt{s} = 13$ TeV at LHCb

Why isolated J/ψ?

Motivation
Why isolated quarkonium?

Dominating channel

Motivation
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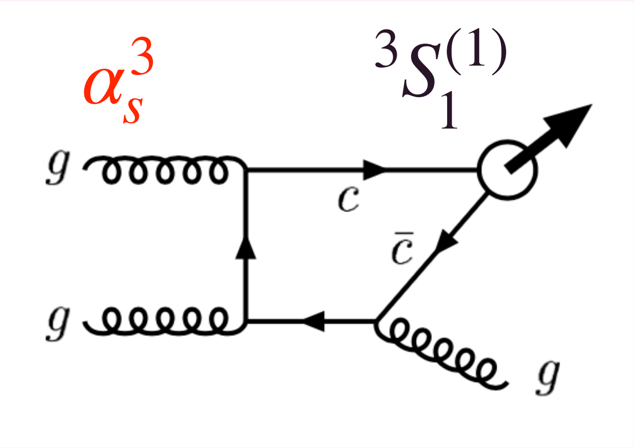
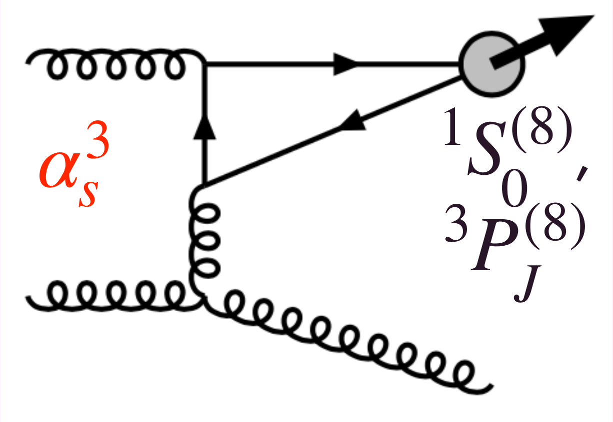
Dominating channel



low $p_T(J/\psi)$ high $p_T(J/\psi)$



○ ≡ no gluon emissions ● ≡ soft gluon emissions

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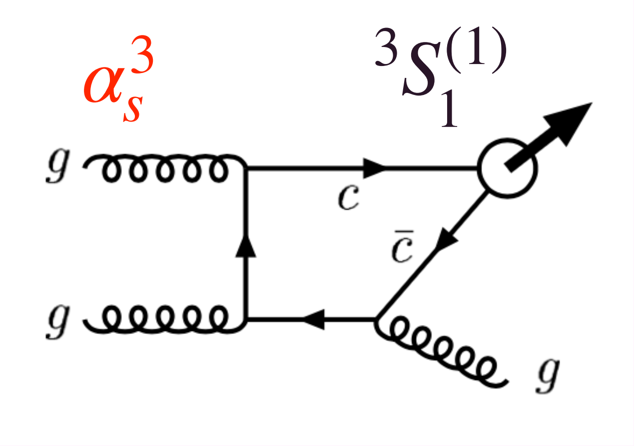
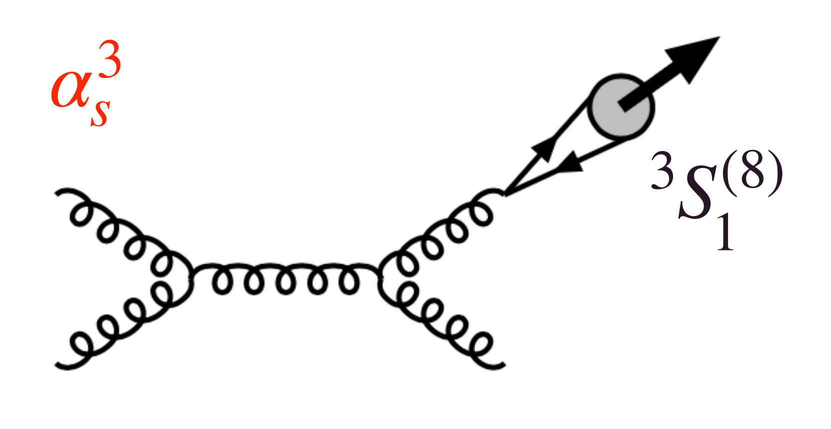
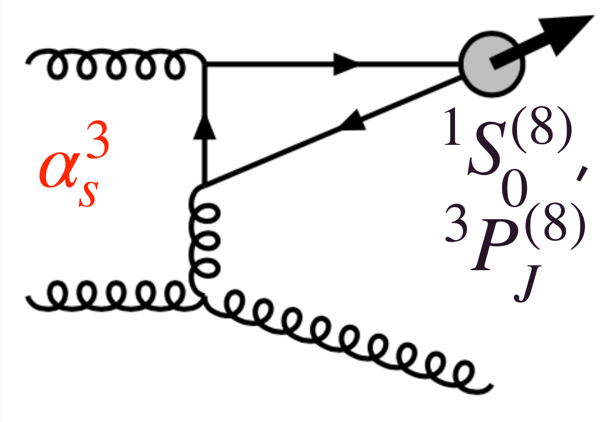
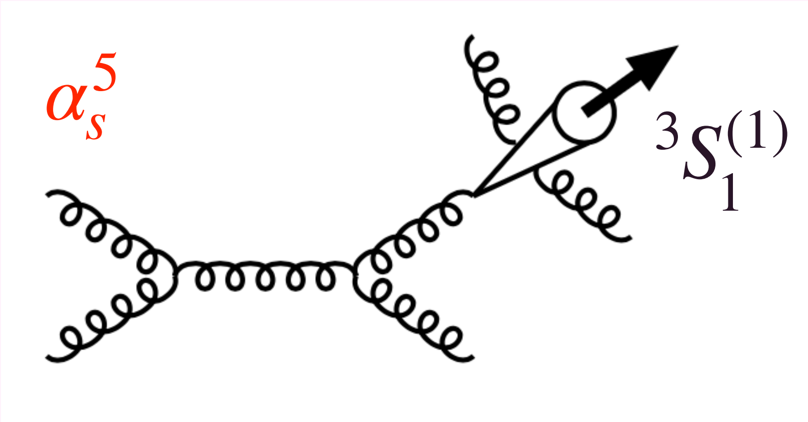




low $p_T(J/\psi)$ → high $p_T(J/\psi)$





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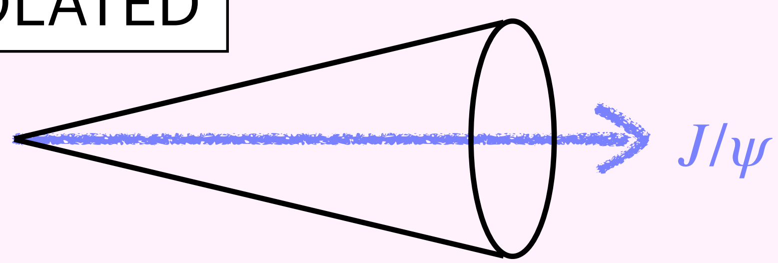

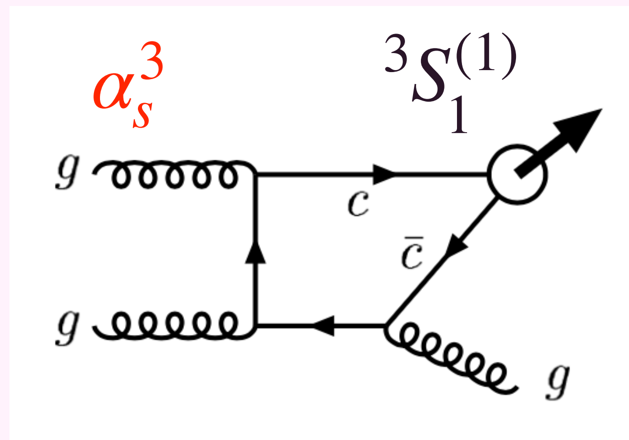

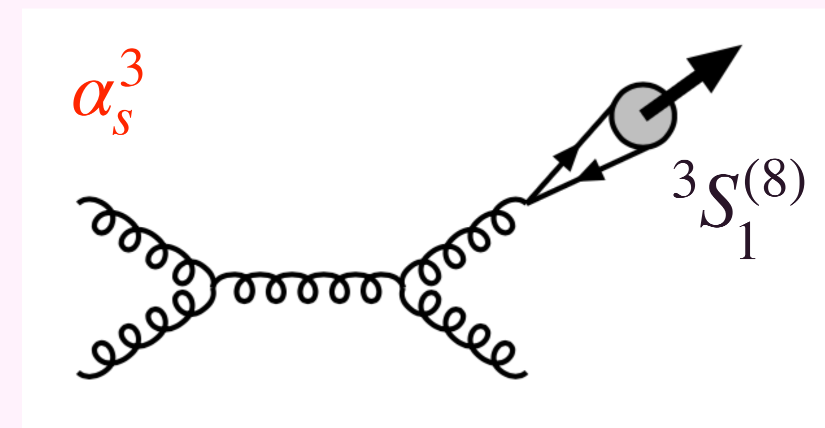

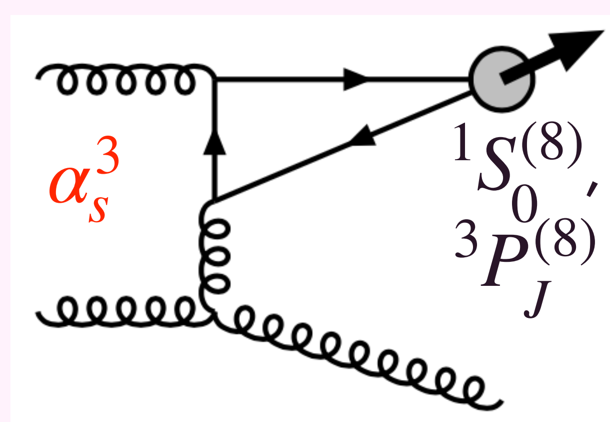

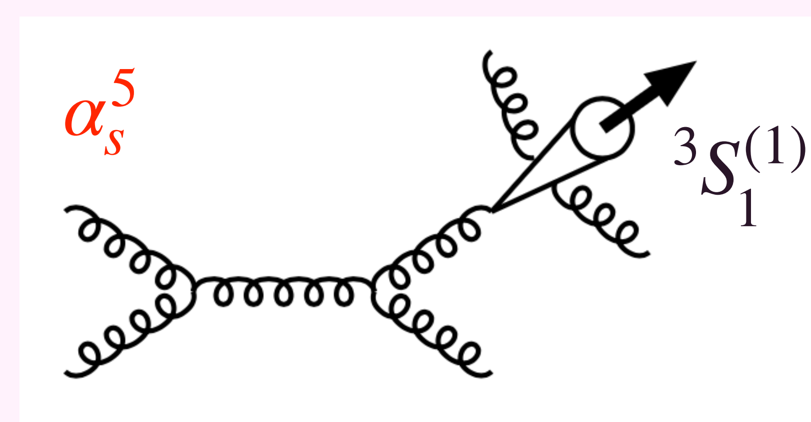

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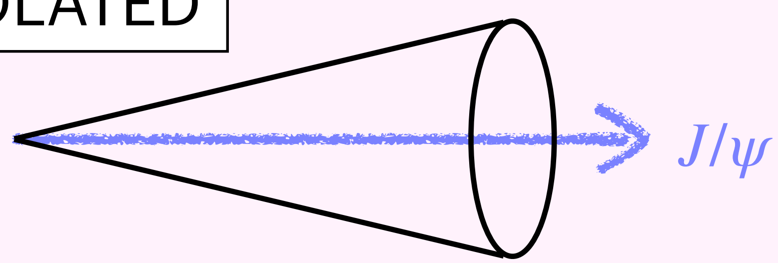

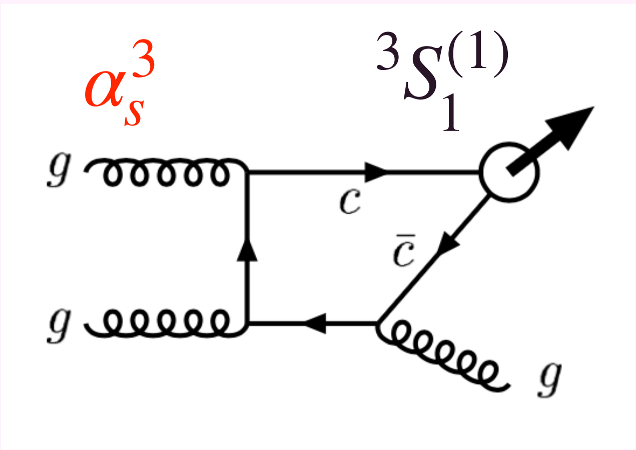

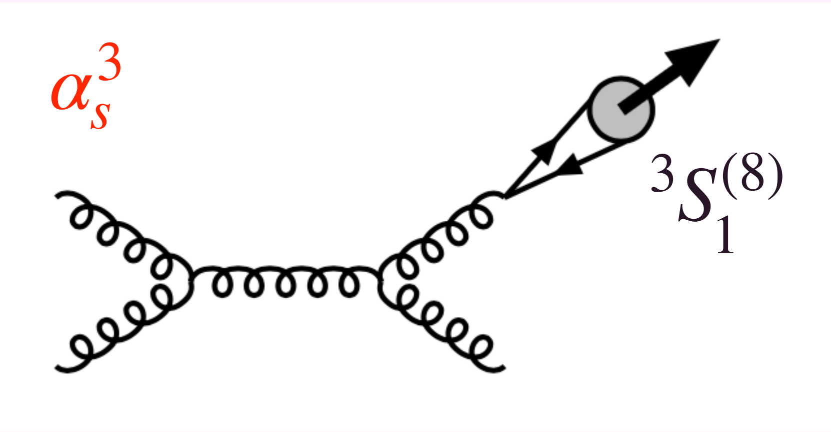

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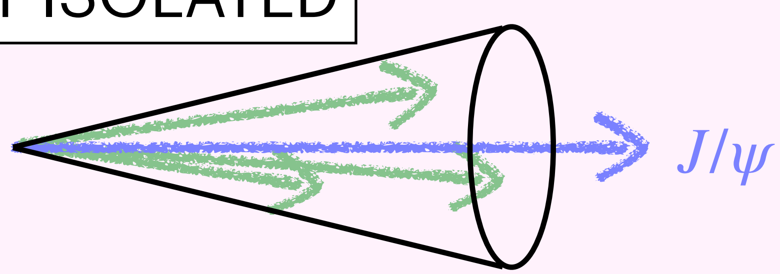

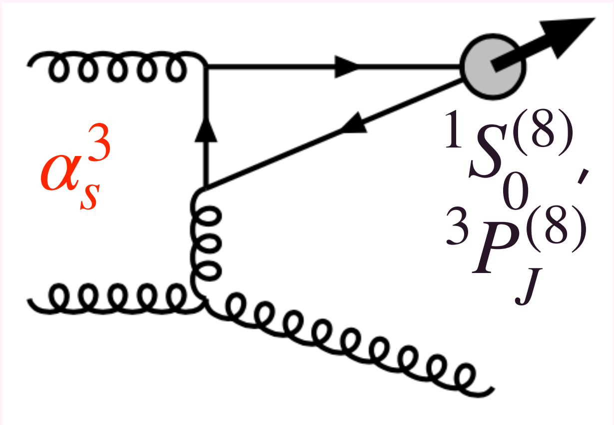

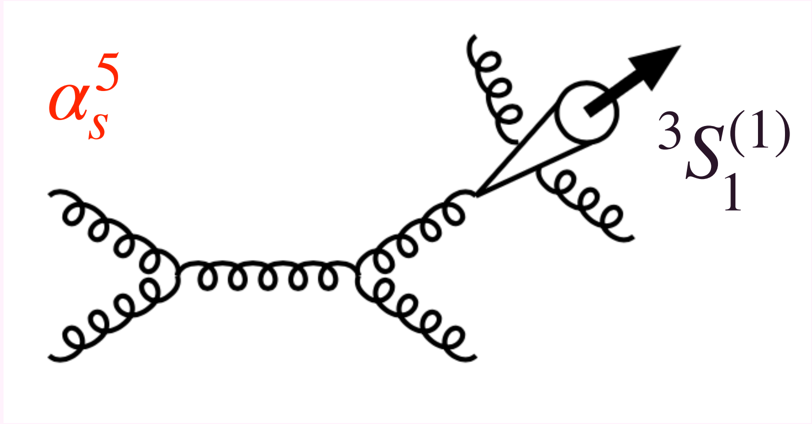

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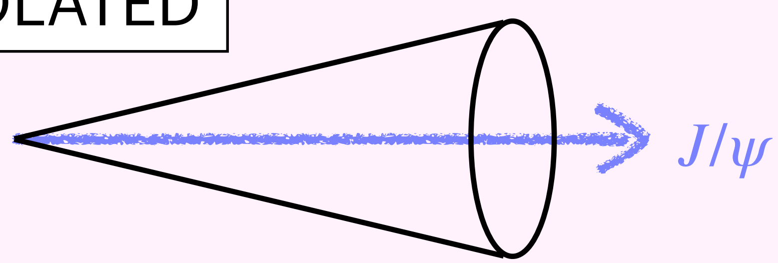

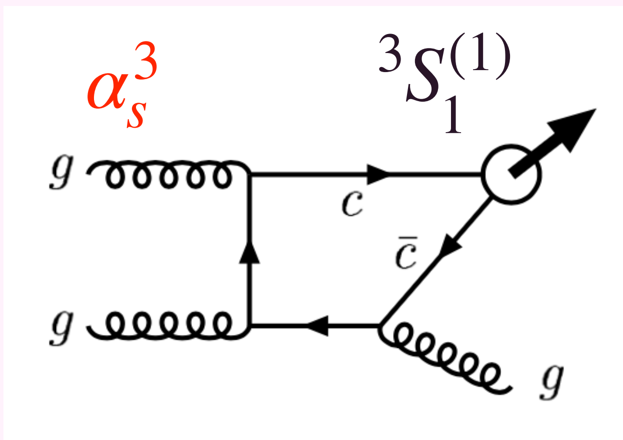

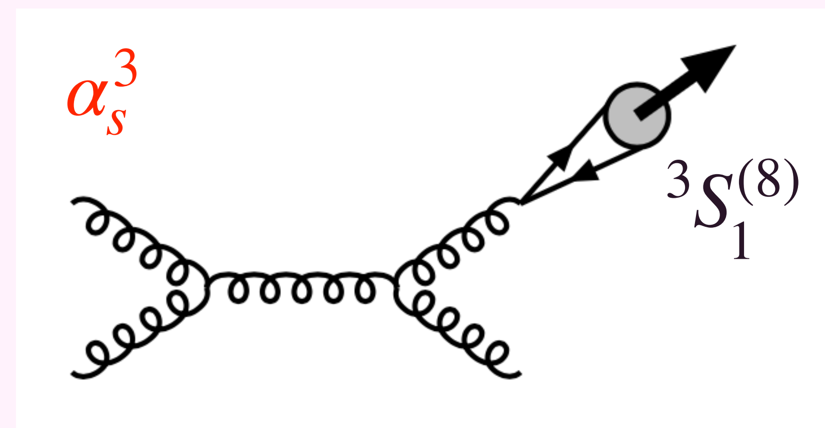

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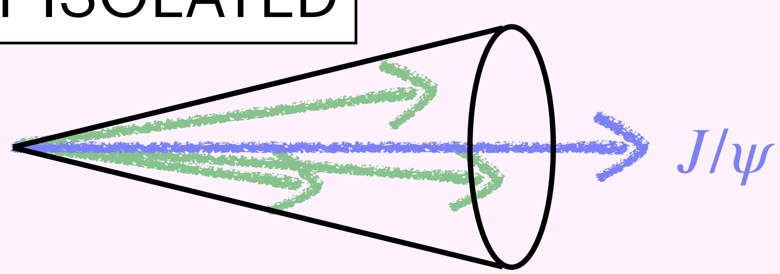

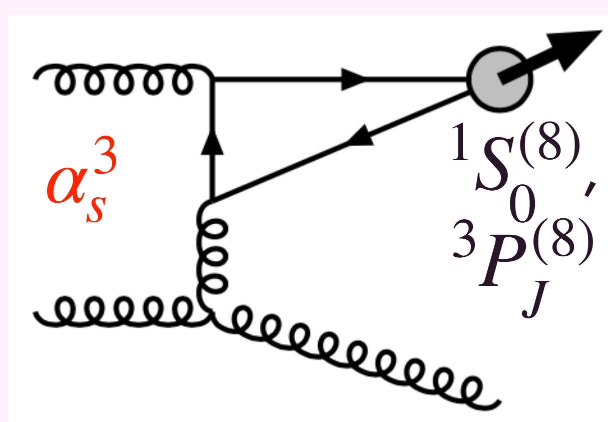

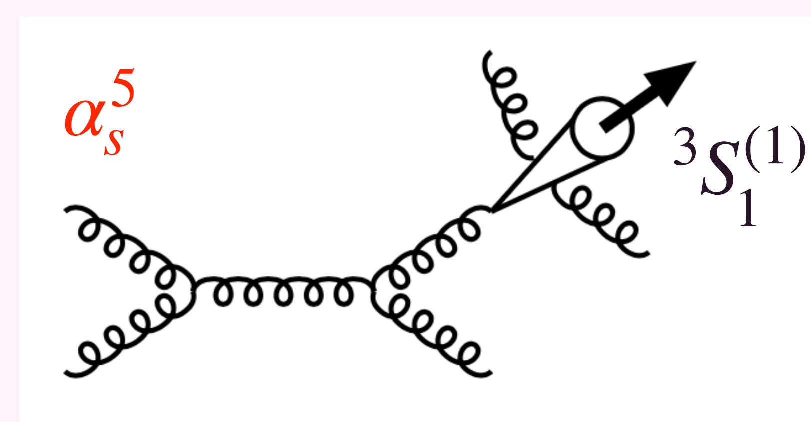

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- **Provide additional information on the production mechanism of quarkonium**

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What information do we already have?

theory & experiment

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What additional information does this measurement provide?

Motivation
Why isolated quarkonium?

- Measurement of **isolated J/ψ** in proton-proton collisions at $\sqrt{s} = 13$ TeV at LHCb

Why isolated J/ψ? → **How do you isolate the J/ψ?**

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

What information do we already have?
theory & experiment

What additional information does this measurement provide?

► Content covered by this talk:

1 - What we know from theory

2 - What we know from experiment

3 - What our measurement provides

4 - Challenges and our strategy

5 - Conclusions

1- What do we know from theory?

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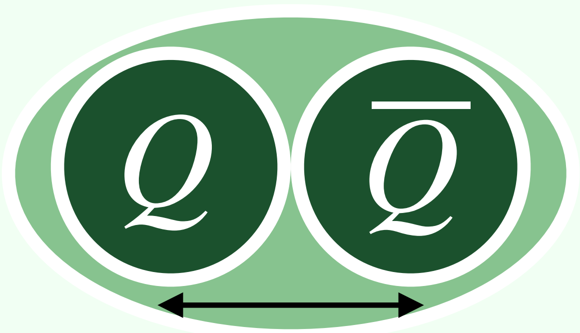
- The physics of quarkonia involves several **energy scales**:

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

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



$v \equiv$ relative velocity

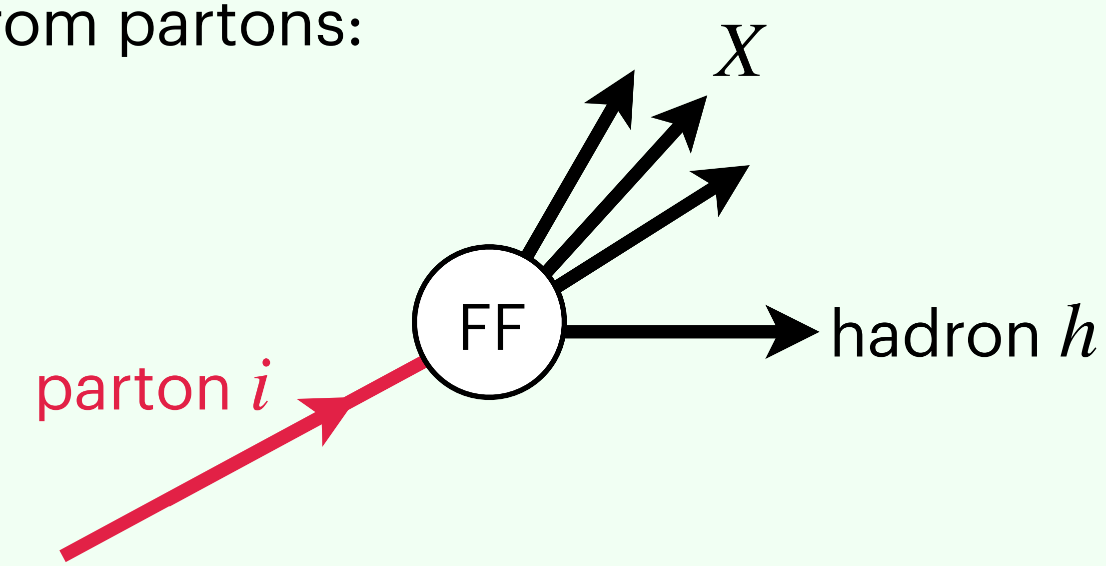
- Nearly all approaches to describe quarkonium production...
  - ✳ Colour Singlet Model (CSM)
  - ✳ Colour Octet Model (COM) within Non-Relativistic QCD (**NRQCD**)
  - ✳ (Improved) Colour Evaporation Model (CEM)

  ... assume a factorisation between the production of the $Q\overline{Q}$ pair and its hadronisation

- However, **none of them is able to describe consistently experimental studies** of transverse momentum spectra and polarisation

1 - What do we know from theory?

- **Fragmentation Functions** (**FFs**) are non-perturbative functions describing the formation of hadrons from partons:



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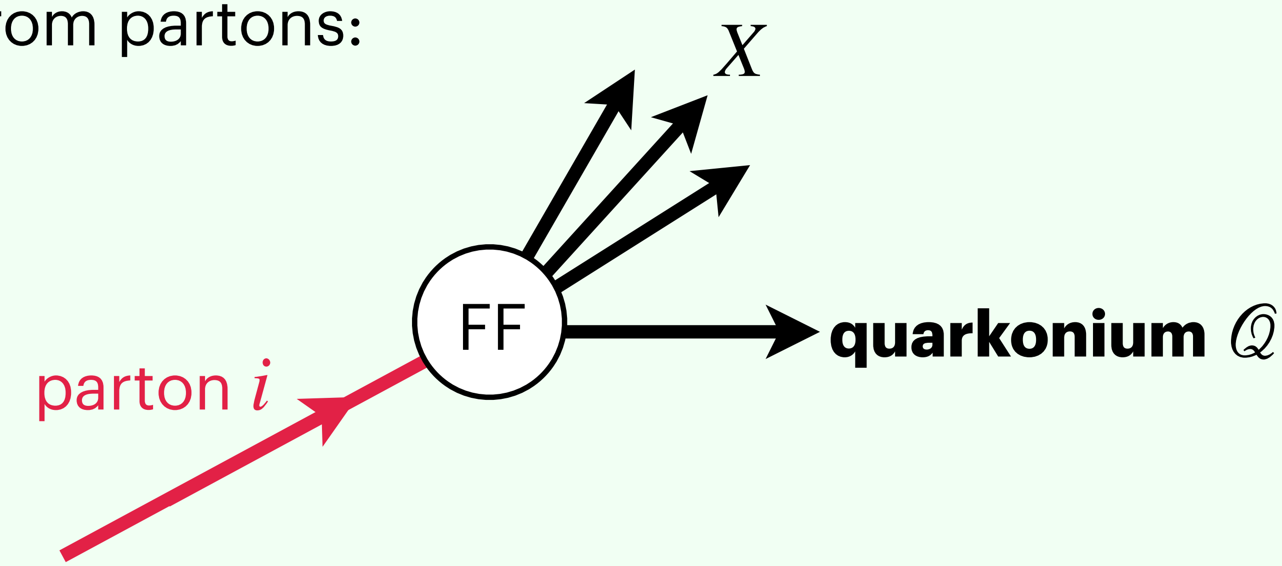


- What distinguishes **quarkonium FFs** is the existence of the subset of scales, which allows (applying NRQCD methodology) to factorise them

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

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

LDMEs from NRQCD

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

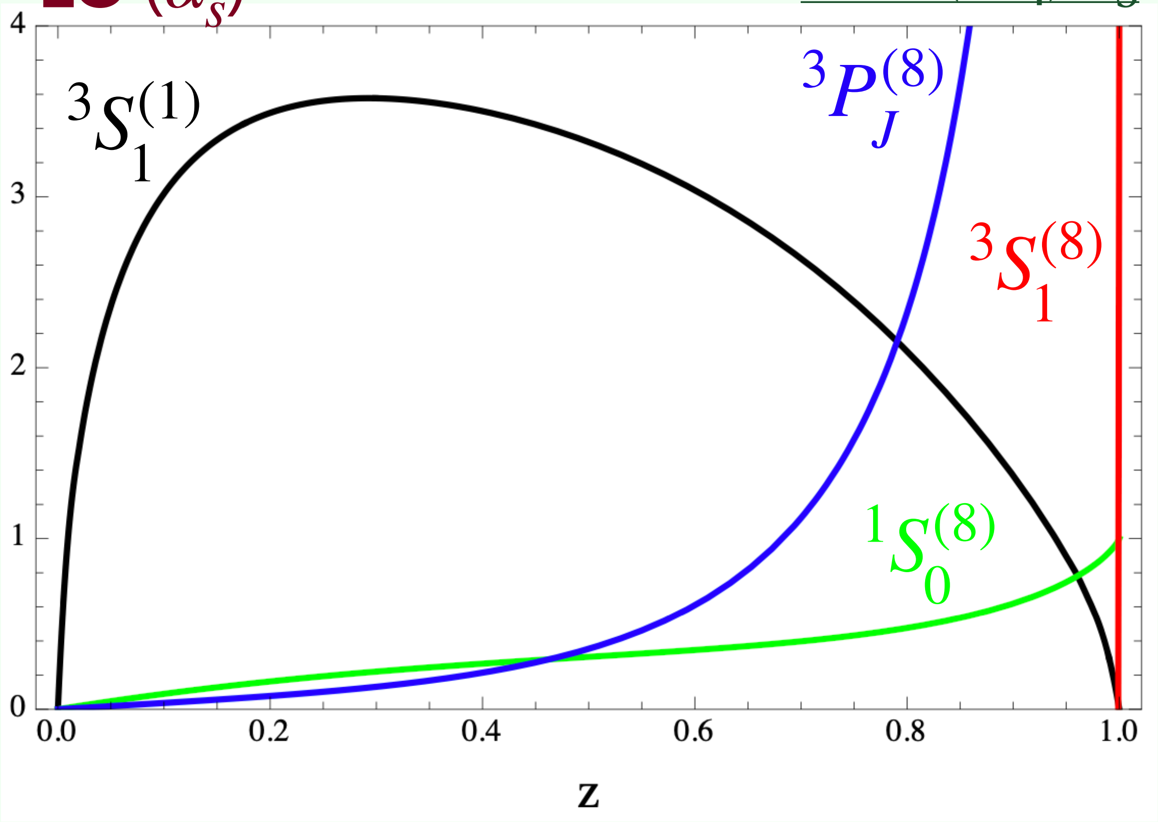
1- What do we know from theory?

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

Gluon FFs into various $c\bar{c}[n]$ states at $\mu = 2m_c$

LO (α_s)

JHEP11(2014)003



- Predictions based on **LO** calculations showed a high discrimination power among the various states

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

1- What do we know from theory?

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

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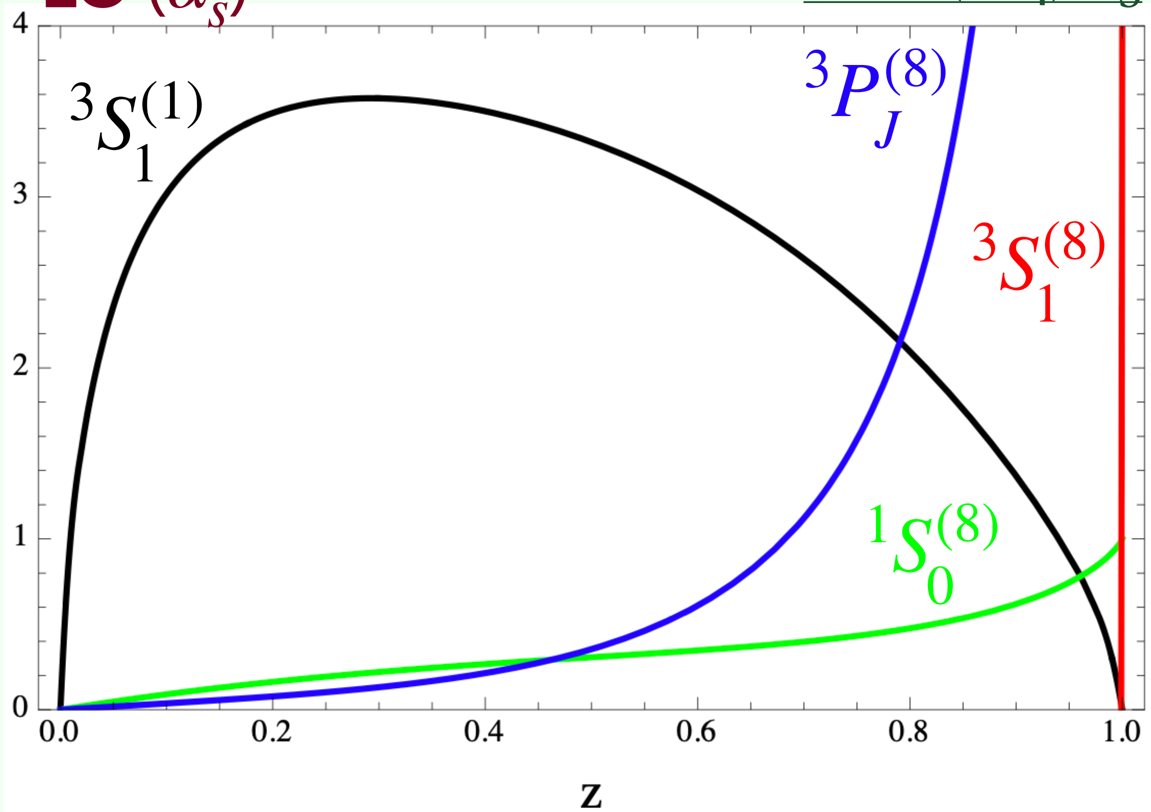
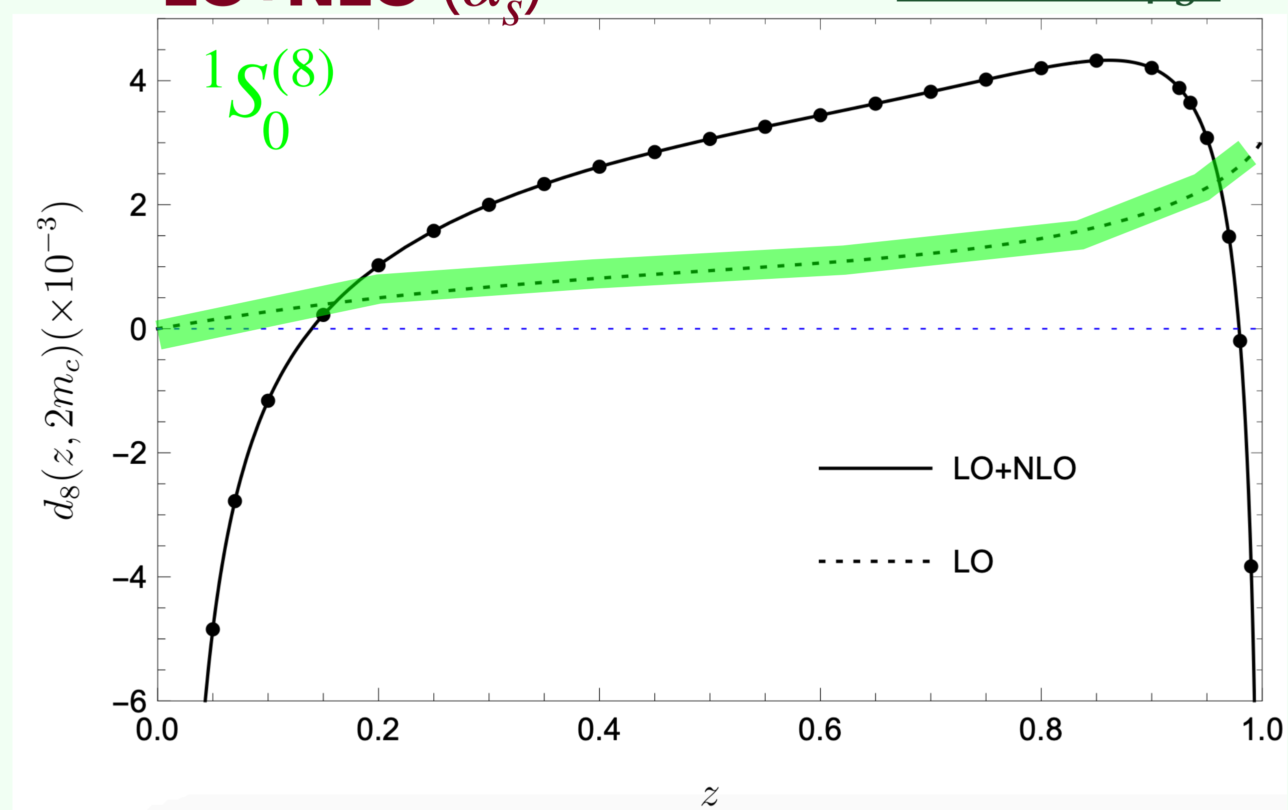


LO+NLO (α_s) arXiv:1810.04138



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

1- What do we know from theory?

- JHEP11(2014)003 proposed an experimentally accesible observable.

- Considering that the $c\bar{c}$ pair is not produced directly in the hard scattering but is produced within high-p_T jet,
  $\Longrightarrow$ the cross section be factorised into:
  a. Hard and soft functions describing the production of the $c\bar{c}[n]$ (+ other jets)
  b. **Fragmenting Jet Function** (**FJF**) describing the non-perturbative fragmentation of the $c\bar{c}[n]$ into the J/ψ

- **FJF** contains two scales:

  ✳ Energy of the jet E_{jet}

  ✳ Hadron mass

  $\Longrightarrow$ further factorisation: **FFs** (non-perturbative) $\otimes$ matching coefficients (perturbative)

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

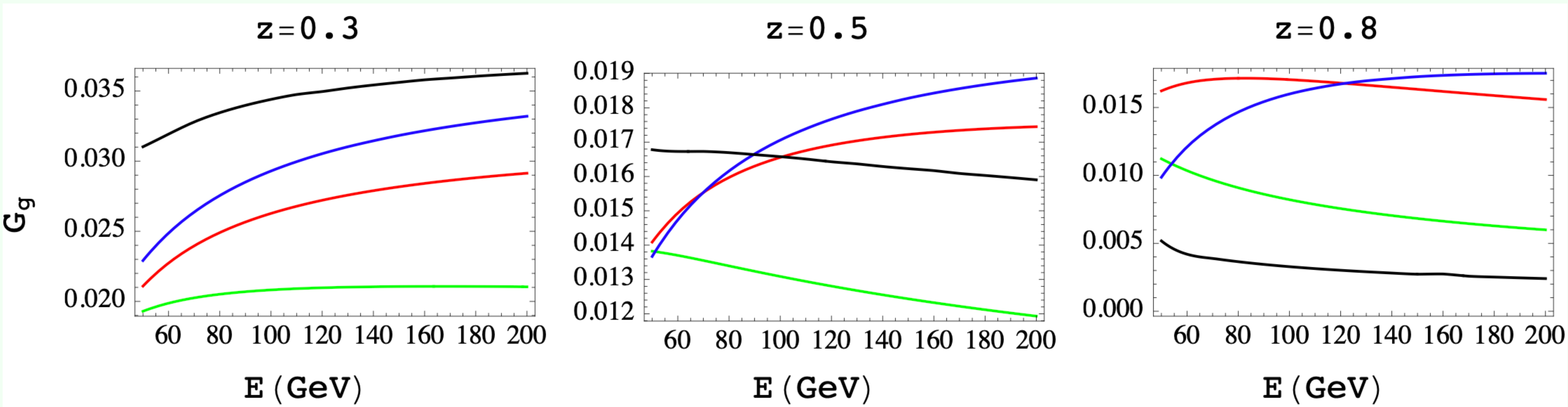
1- What do we know from theory?

- **Energy dependence of gluon FJFs** at three fixed z values

$^3S_1^{(1)}$ $^3S_1^{(8)}$ $^1S_0^{(8)}$ $^3P_J^{(8)}$

$z \equiv$ fraction of the jet's energy carried by the J/ψ

JHEP11(2014)003



- $^3S_1^{(1)}$ and $^1S_0^{(8)}$ decreasing with E_{jet}
- $^3S_1^{(8)}$ and $^3P_J^{(8)}$ increasing with E_{jet}

} $\Longrightarrow$ discrimination power

- Again, these distributions are evaluated from **LO FFs**, so the differences might be washed away with **NLO FFs**

2 - What we know from experiment

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- A wide variety of measurements involving quarkonia exist since these states are powerful tools to:
  - Probe the gluon content of protons and heavy nuclei
  - Study initial stages of ultra-relativistic heavy-ion collisions
  - Investigate multiple-parton interactions (MPIs)

- As in this talk we will discuss J/ψ isolation, we will center only on related experimental measurements, which consist of a set of **measurements of J/ψ in jets**

2 - What we know from experiment

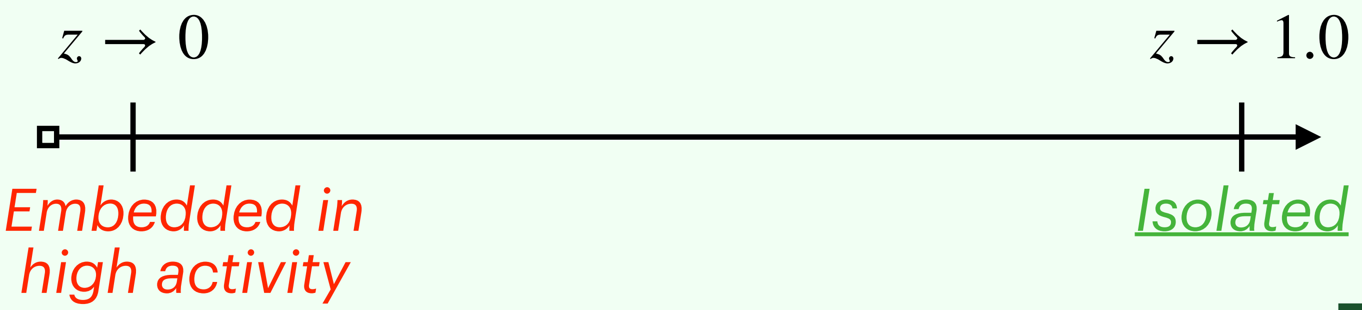
Measurements of J/ψ in jets

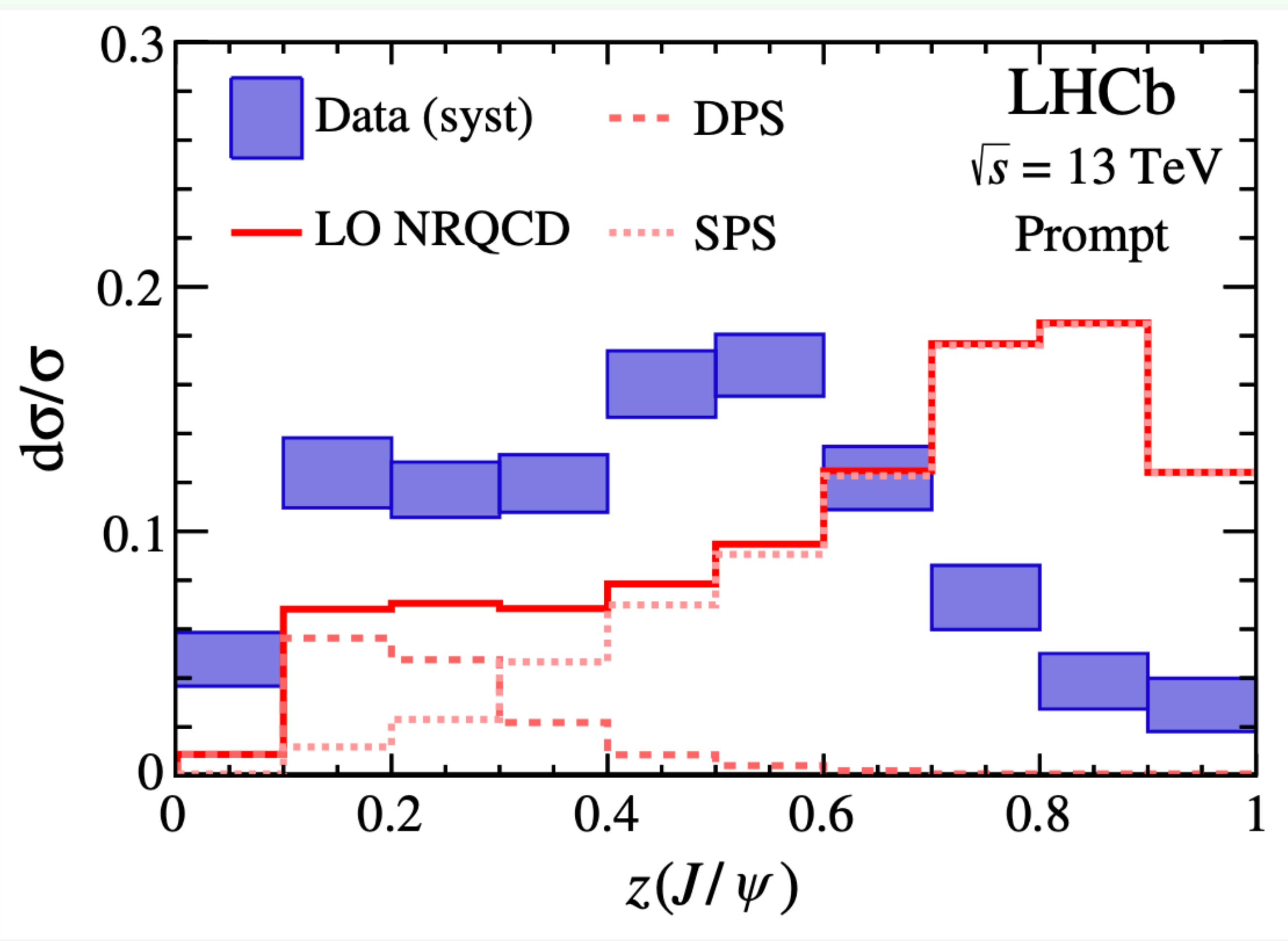
Ref.	Collab, system, energy	Jet	J/ψ
Phys. Rev. Lett. 118 (2017) 192001	LHCb pp 13 TeV	R = 0.5, anti-kt pt > 20 GeV 2.5 < eta < 4.0	J/ψ : 2.5 < eta < 4.0
Phys. Lett. B 825 (2022) 136842	CMS pp (and PbPb) 5.02 TeV	R = 0.3, anti-kt 20 < pt < 40 GeV |eta| < 2	J/ψ : pt > 6.5 GeV
Phys. Lett. B 804 (2020) 135409	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

There are ongoing LHCb and ALICE measurements

2 - What we know from experiment

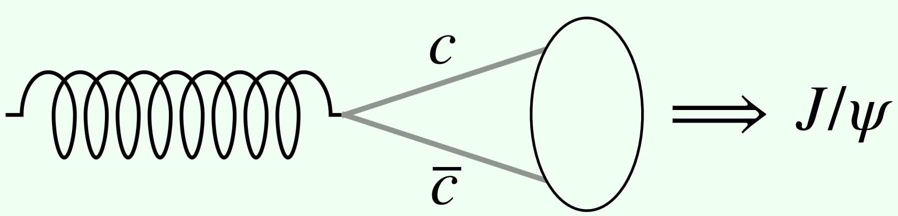
Measurements of J/ψ in jets → **Observable:** $z = \frac{p_T(J/\psi)}{p_T(jet)}$ distribution





Phys. Rev. Lett. 118 (2017) 192001

- System: proton-proton collisions at $\sqrt{s} = 13$ TeV
- Jets with $p_T(jet) > 20$ GeV
- Results for prompt–J/ψ show a softer trend than Pythia8 predictions (LO NRQCD), which underestimate the activity around the J/ψ



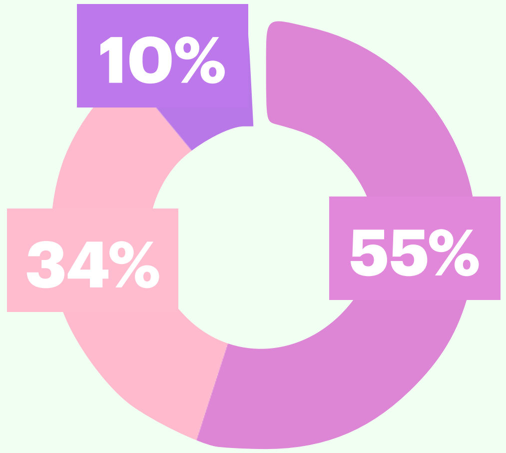
Phys. Rev. Lett. 119, 032002 (2017) [backup]

2 - What we know from experiment

Measurements of J/ψ in jets

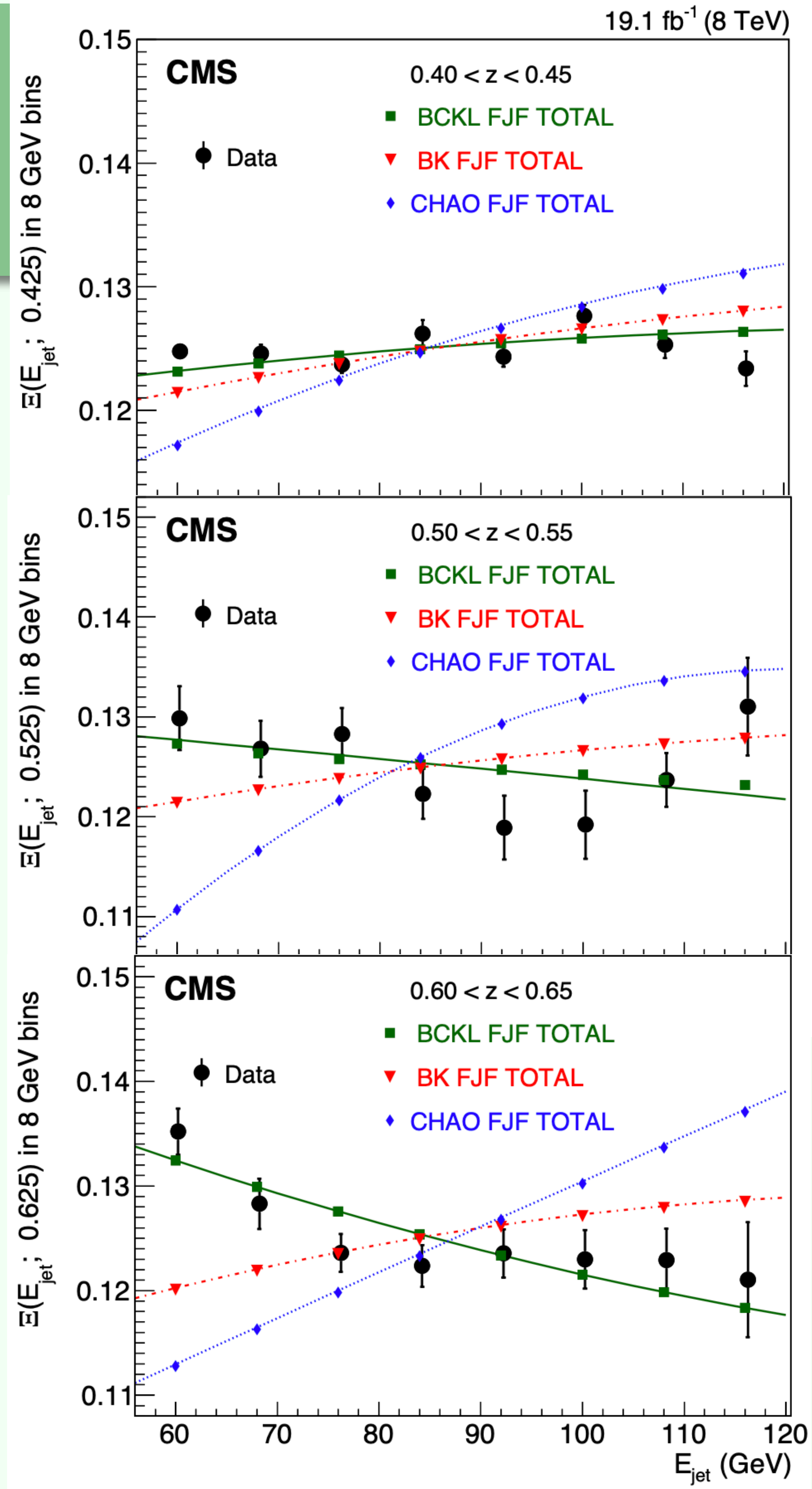
Observable: self-normalized E_{jet}—dependence in three z intervals

- System: proton-proton collisions at $\sqrt{s} = 8$ TeV
- Jets with $p_T(jet) > 25$ GeV
- 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 the three z intervals



Number of *observed* jets in events with prompt J/ψ ($p_T > 10$ GeV, $|\eta| < 2$)

0 1 2



Phys. Lett. B 804 (2020) 135409

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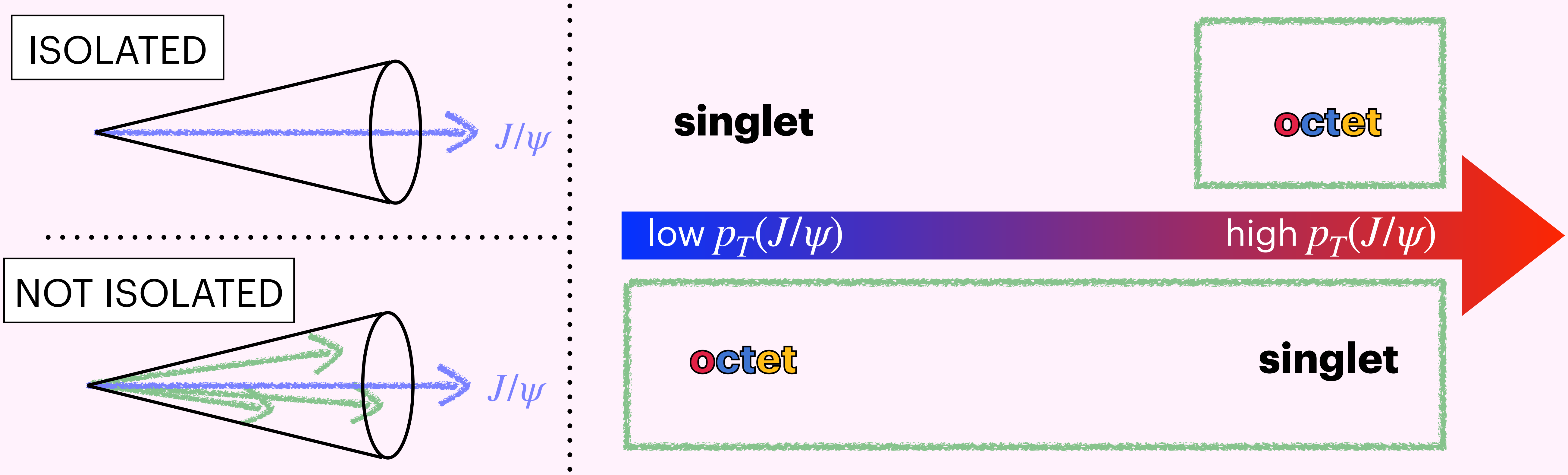
3 - What our measurement provides

- Existing measurements of J/ψ in jets provide information on:
  - Non-isolated J/ψ at low, medium and high $p_T(J/\psi)$
  - Isolated J/ψ $(z = 1)$ at high p_T



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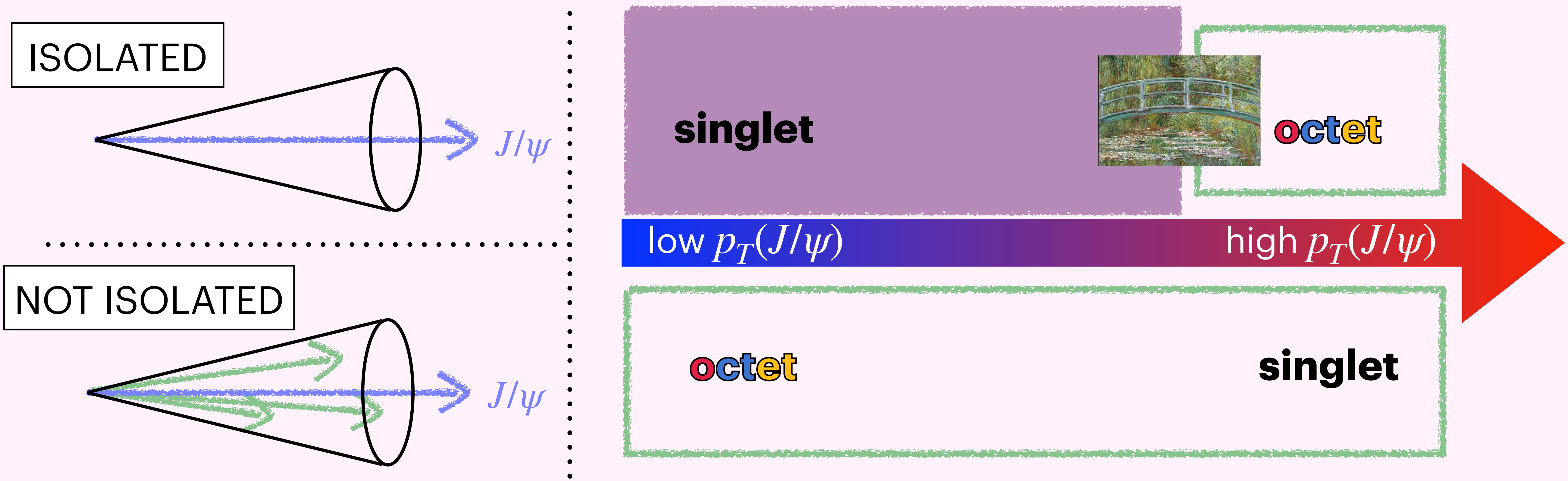

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- Our measurement:
  - Isolated J/ψ at low and medium p_T

    Actual $p_T(J/\psi)$ coverage: $0.3 < p_T(J/\psi) < 20$ [GeV]
- **But that's not all !** We plan to...
  - Provide the cross section for isolated J/ψ in bins of $p_T(J/\psi)$
  - Study how the results differ depending on the size of the considered region around the J/ψ

3 - What our measurement provides

- What **complementary information** could be useful?

  i) Isolation measurements of other quarkonium states

  ii) Isolation measurements in other LHC experiments at higher p_T, where the theoretical interpretation of the results is easier

  iii) Would it be interesting to perform this kind of measurements at EIC?

4 - Challenges and our strategy for J/ψ isolation

4.1 - How to define isolation?

4 - Challenges and our strategy for J/ψ isolation

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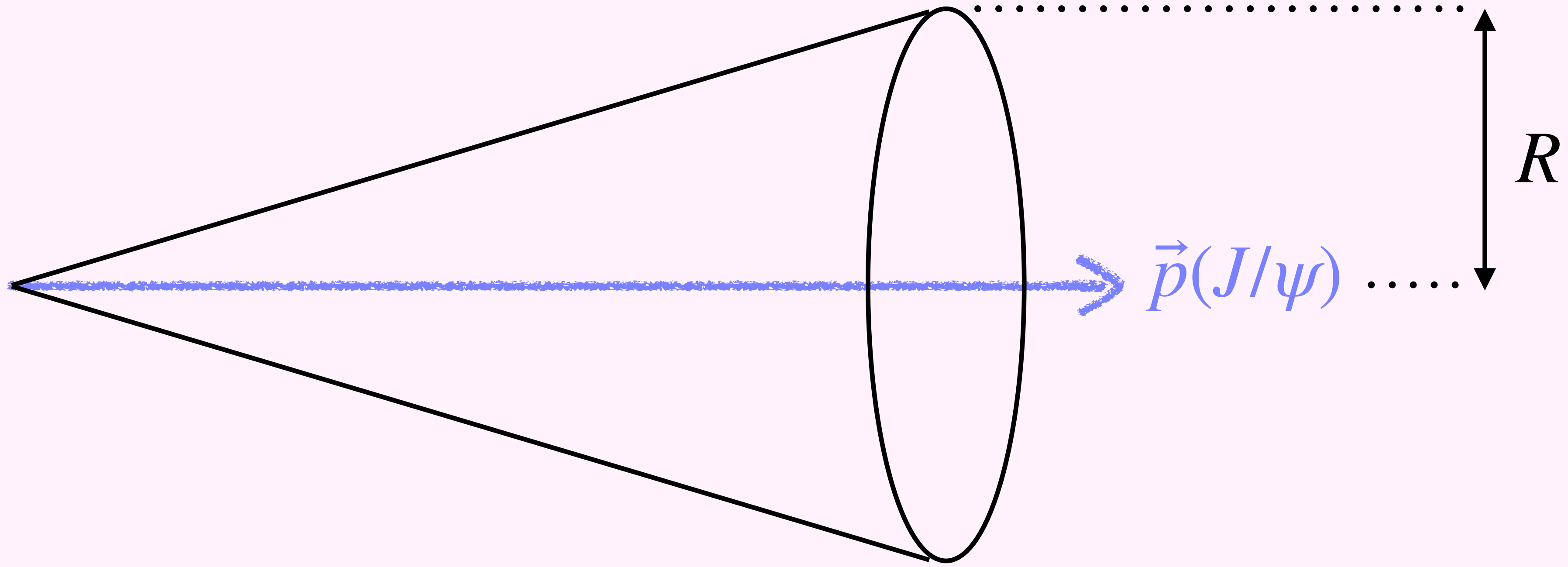

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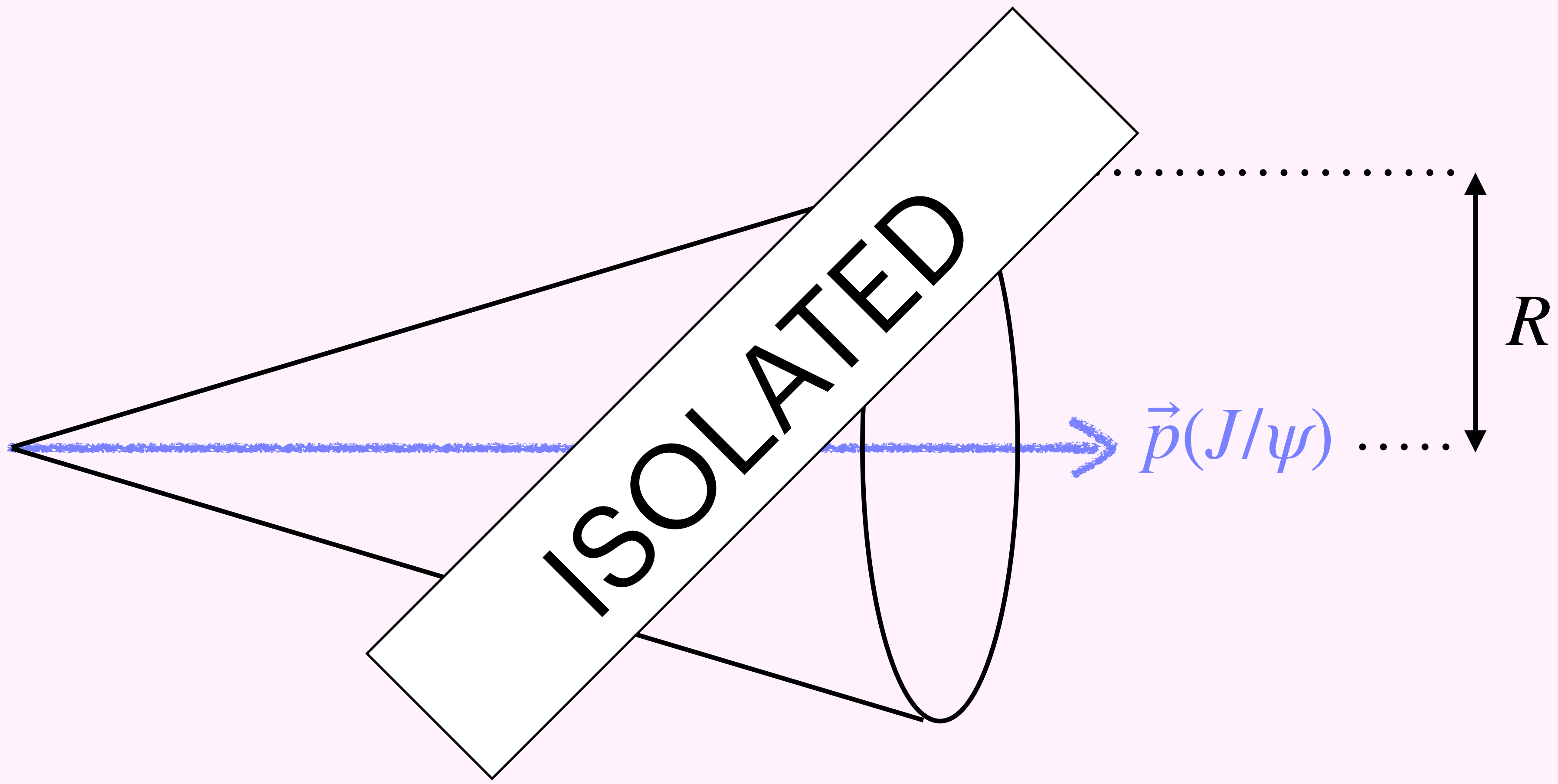

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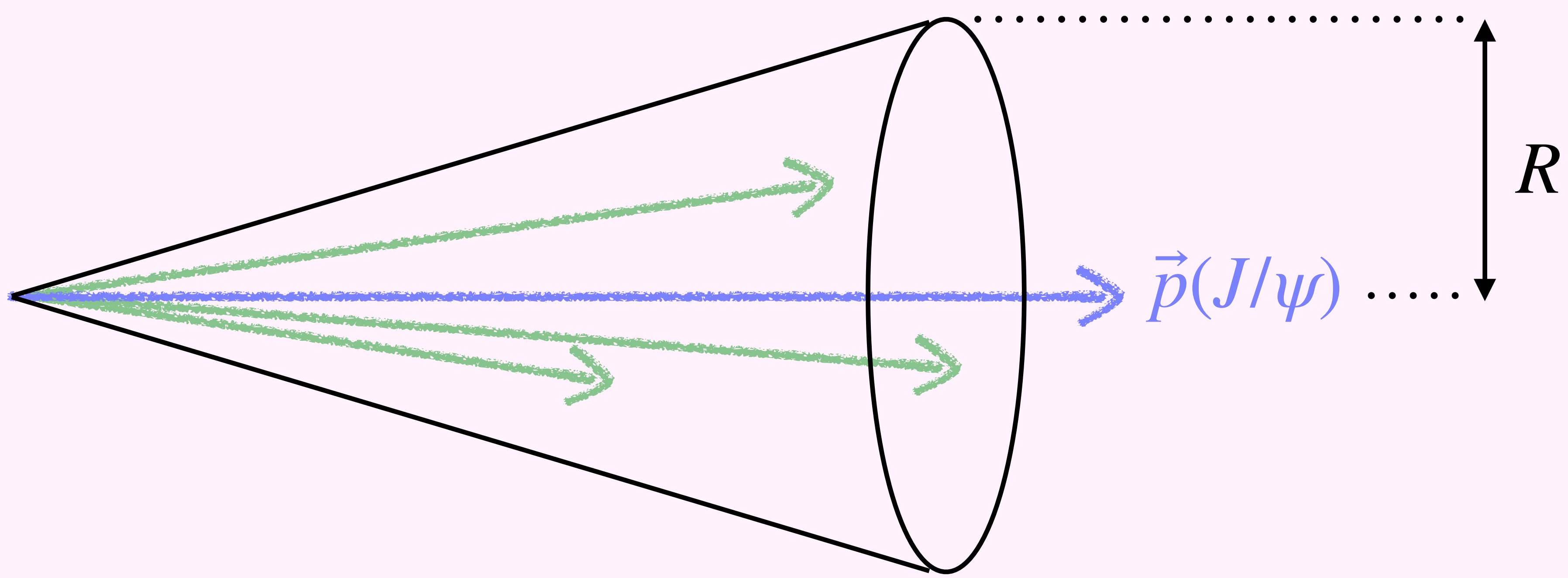

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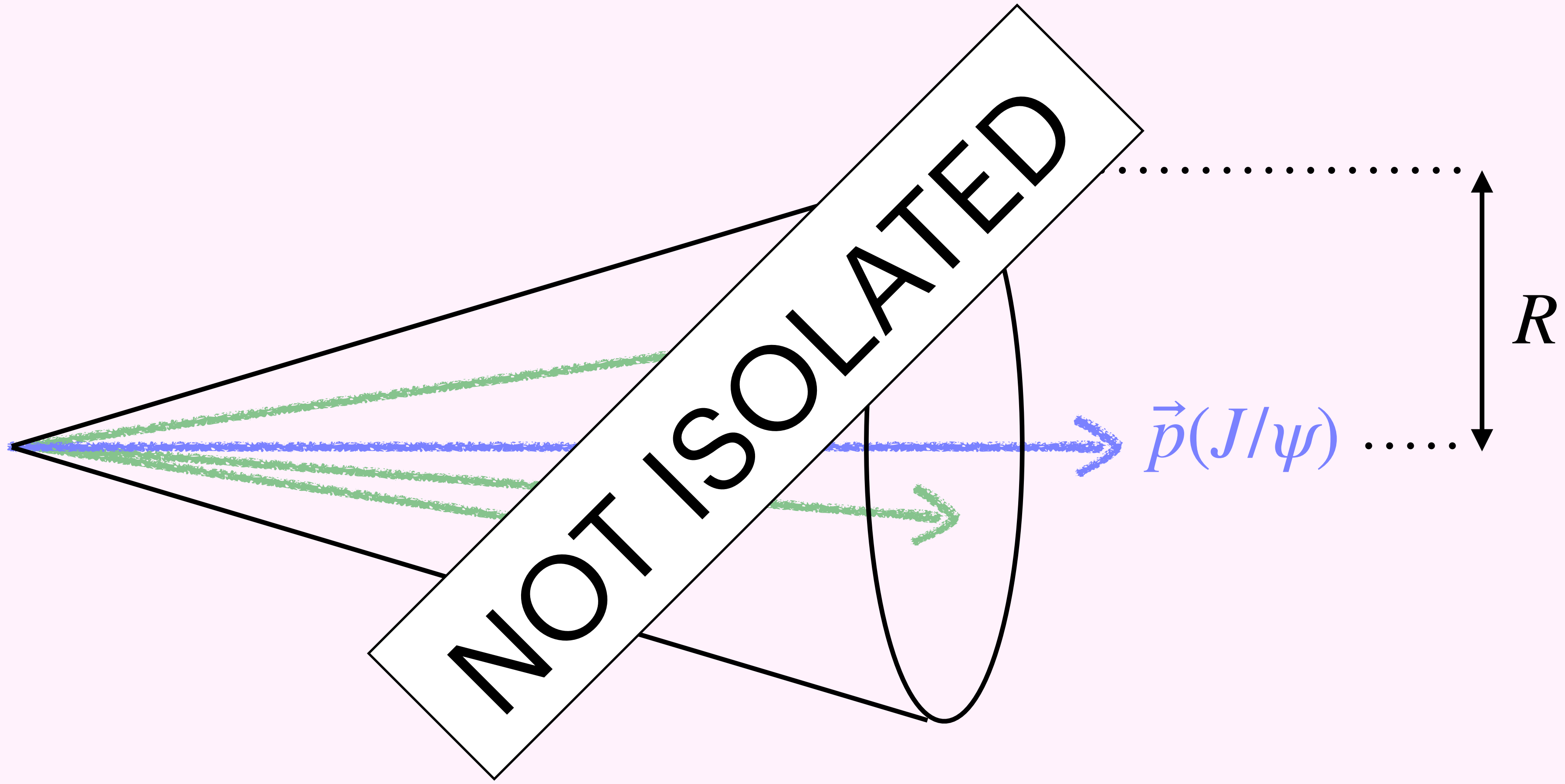
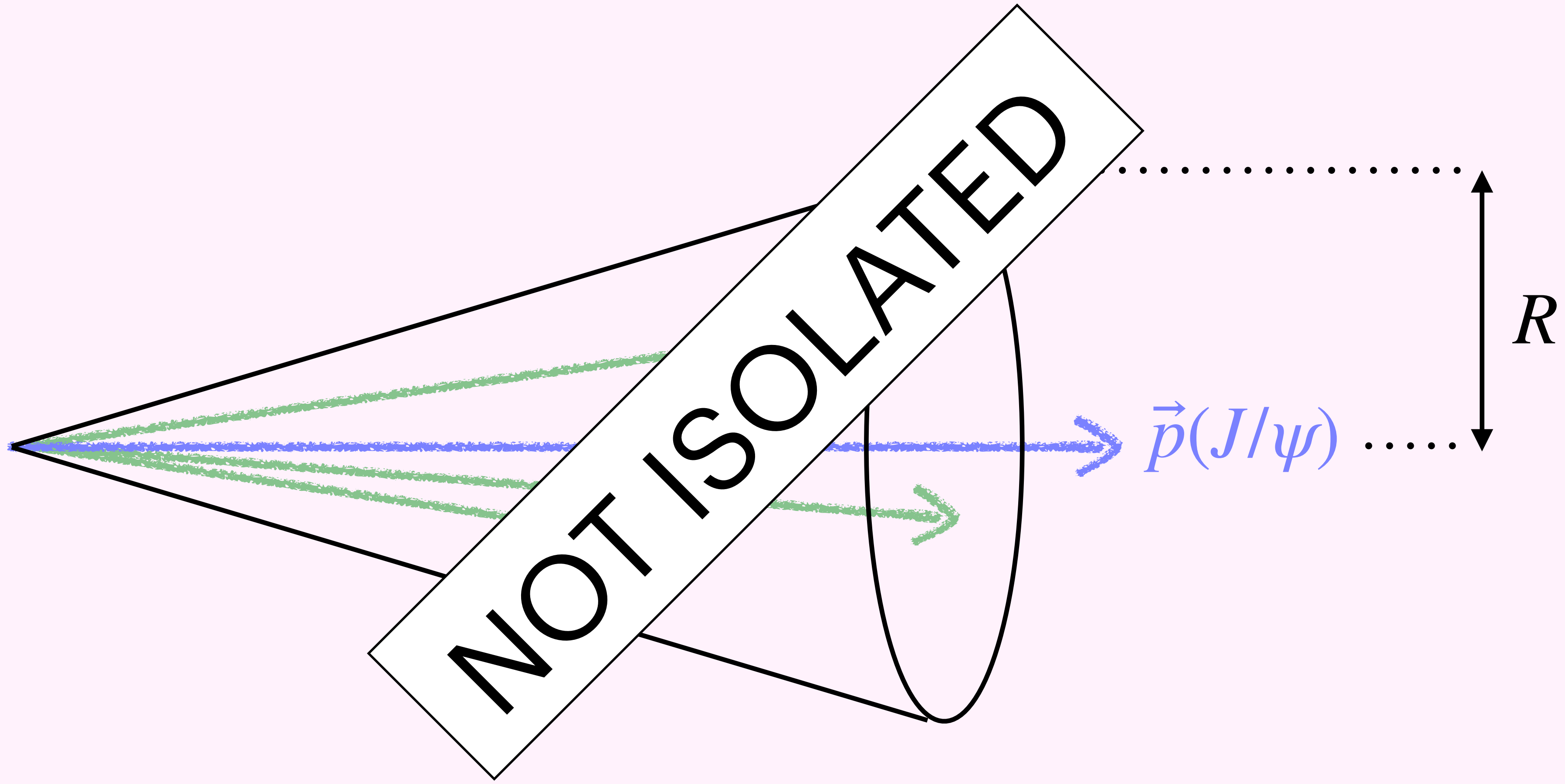


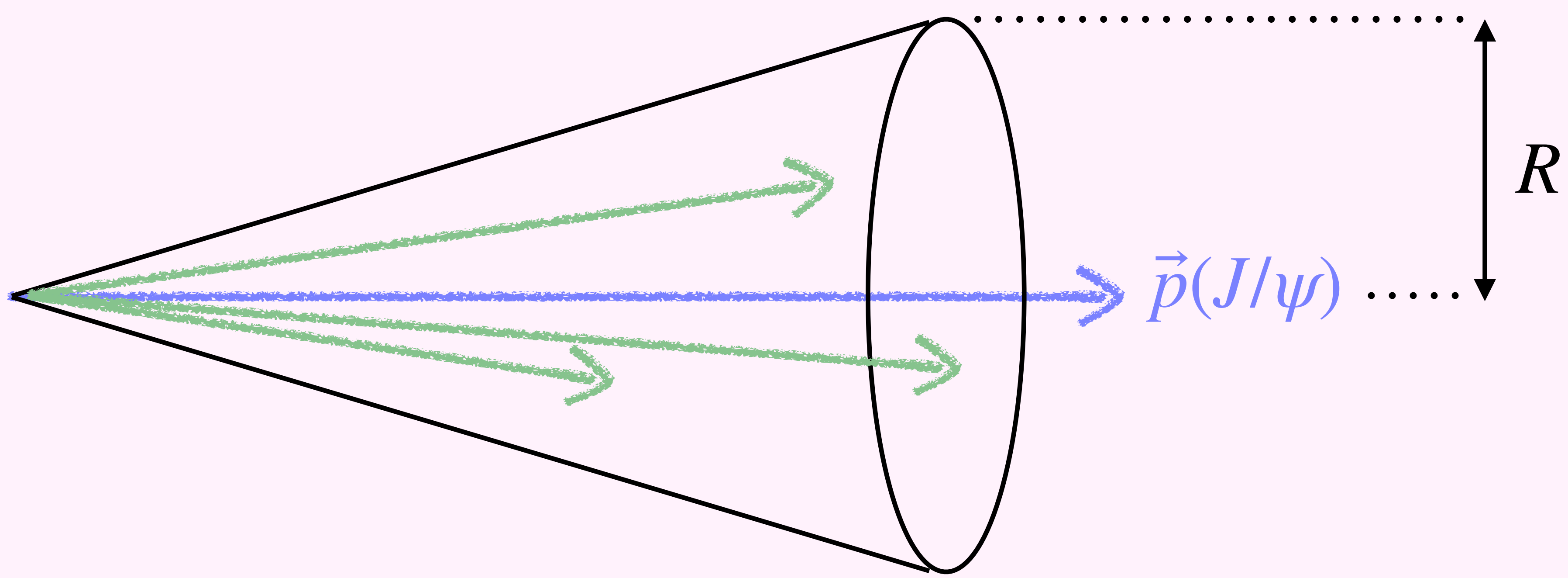
4 - Challenges and our strategy for J/ψ isolation



BUT...

4 - Challenges and our strategy for J/ψ isolation

Challenge: hadronic collisions are busy environments

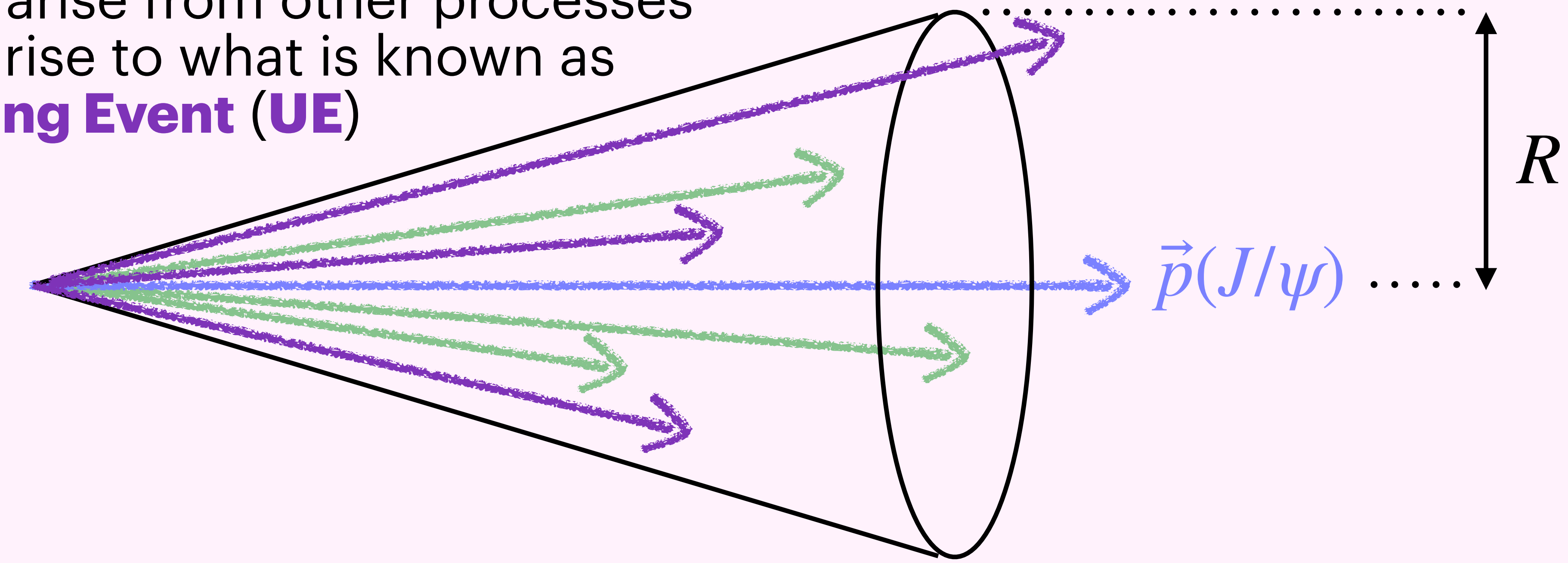


BUT...

4 - Challenges and our strategy for J/ψ isolation

Challenge: hadronic collisions are busy environments

- Apart from the particles produced in the **hard interaction**, additional particles arise from other processes and give rise to what is known as **Underlying Event** (**UE**)



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4 - Challenges and our strategy for J/ψ isolation

Challenge: hadronic collisions are busy environments

- Apart from the particles produced in the **hard interaction**, additional particles arise from other processes and give rise to what is known as **Underlying Event** (**UE**)

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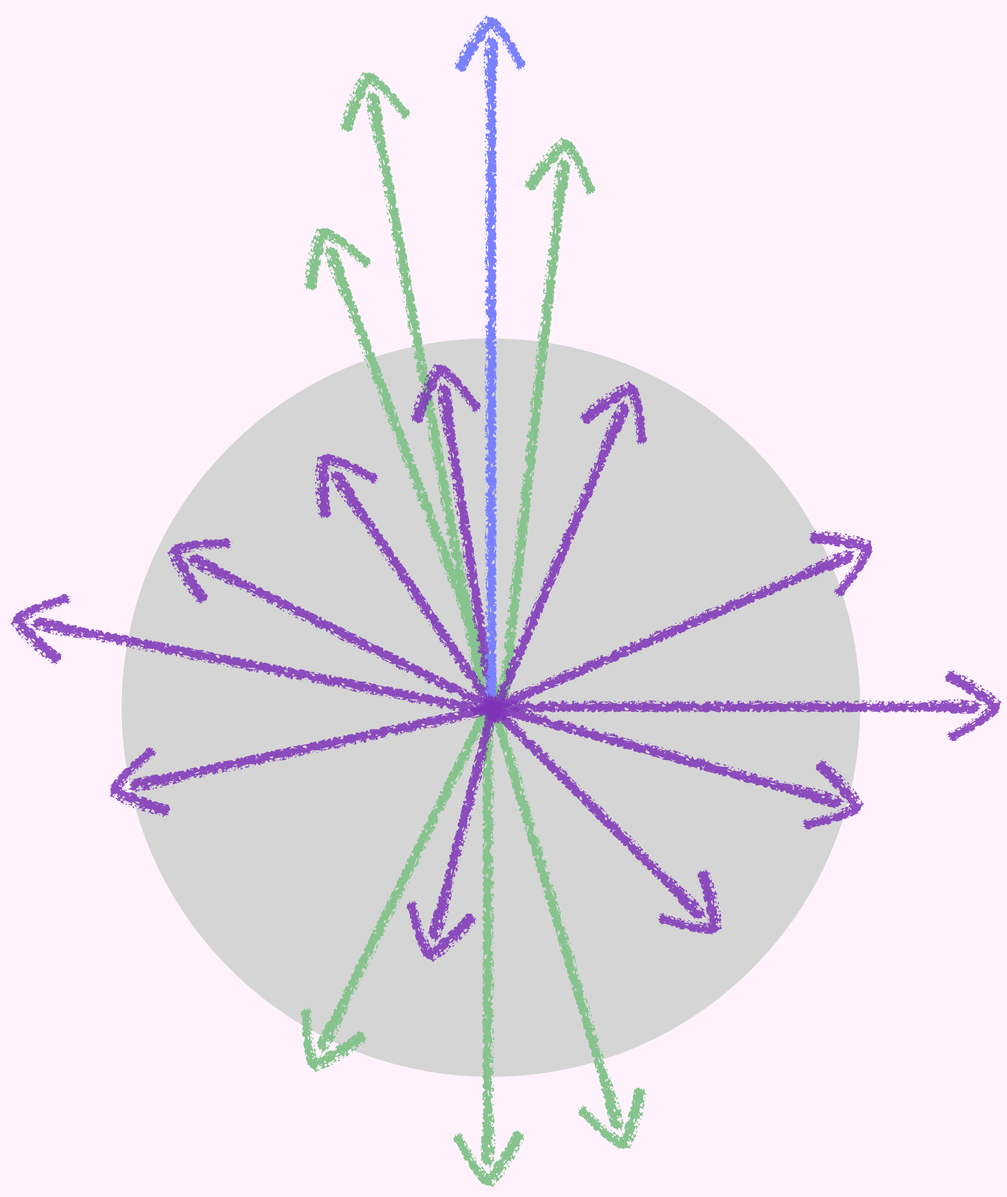
  - Model dependent
  - Not completely well reproduced by any model



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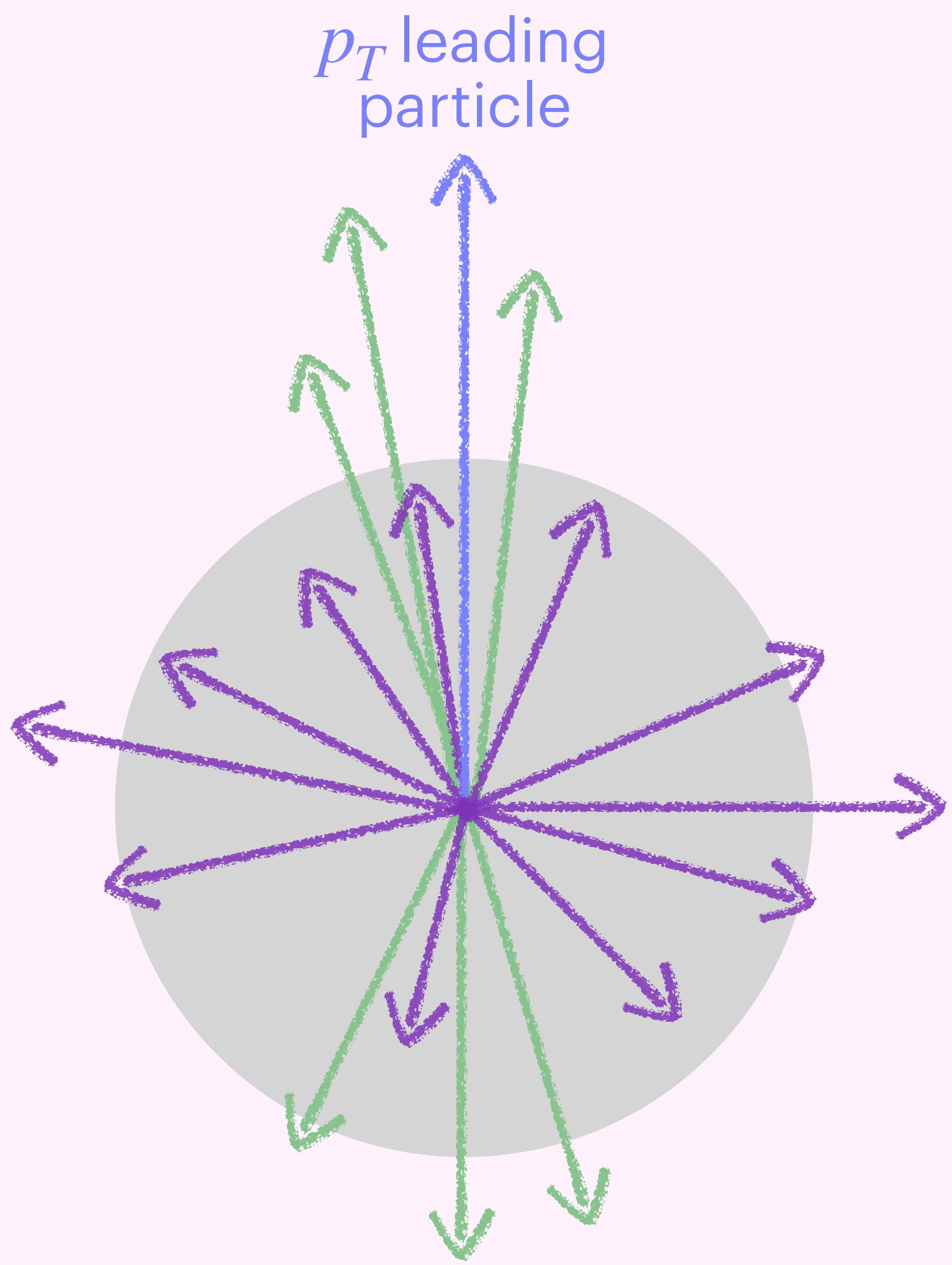

4 - Challenges and our strategy for J/ψ isolation

Challenge: hadronic collisions are busy environments

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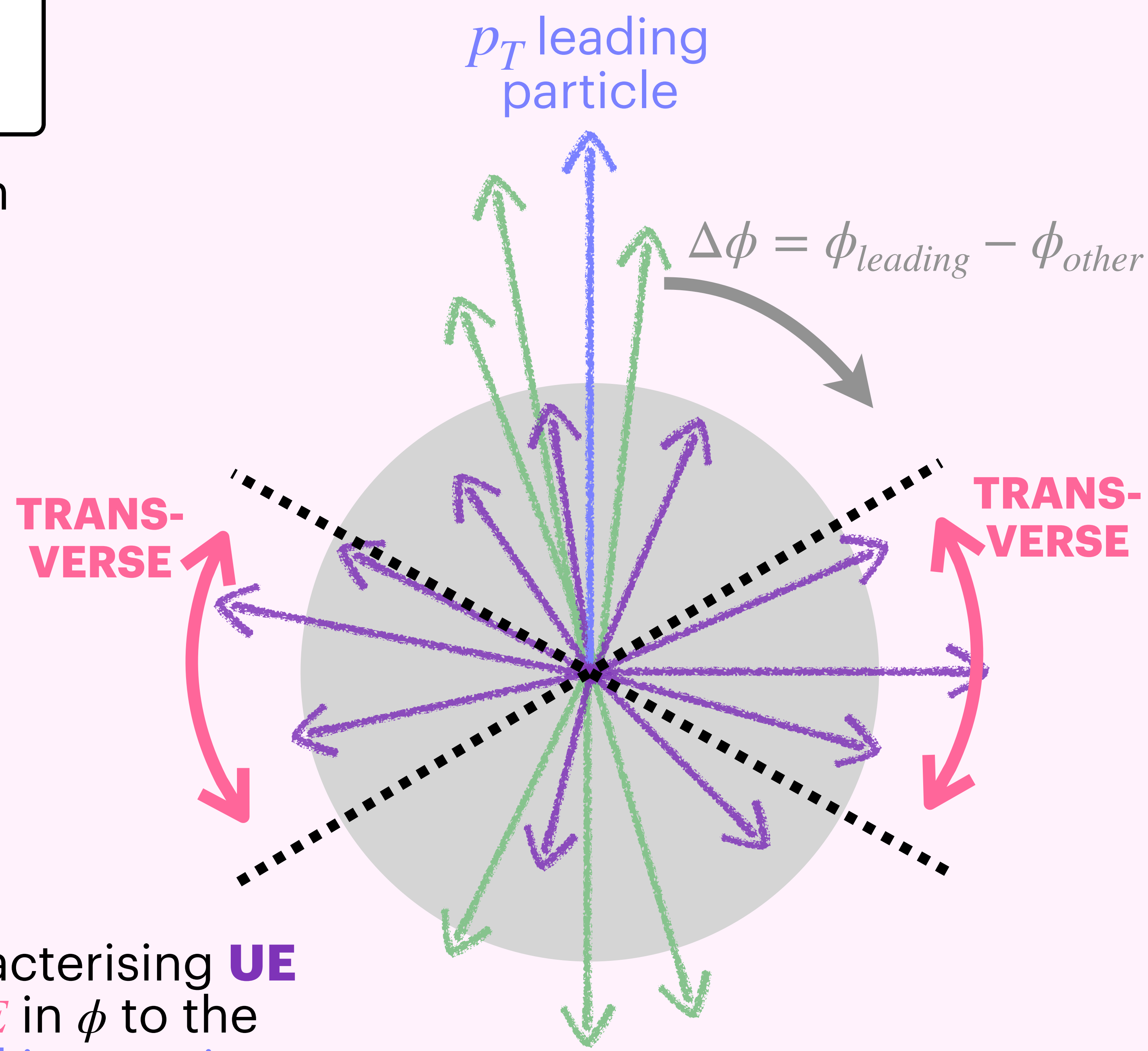
  - Not completely well reproduced by any model

How can we proceed?

- A well stablished procedure of characterising **UE** is by taking the regions *TRANSVERSE* in ϕ to the direction of the products of the hard interaction



JHEP04 (2020) 192 arXiv:1110.5530

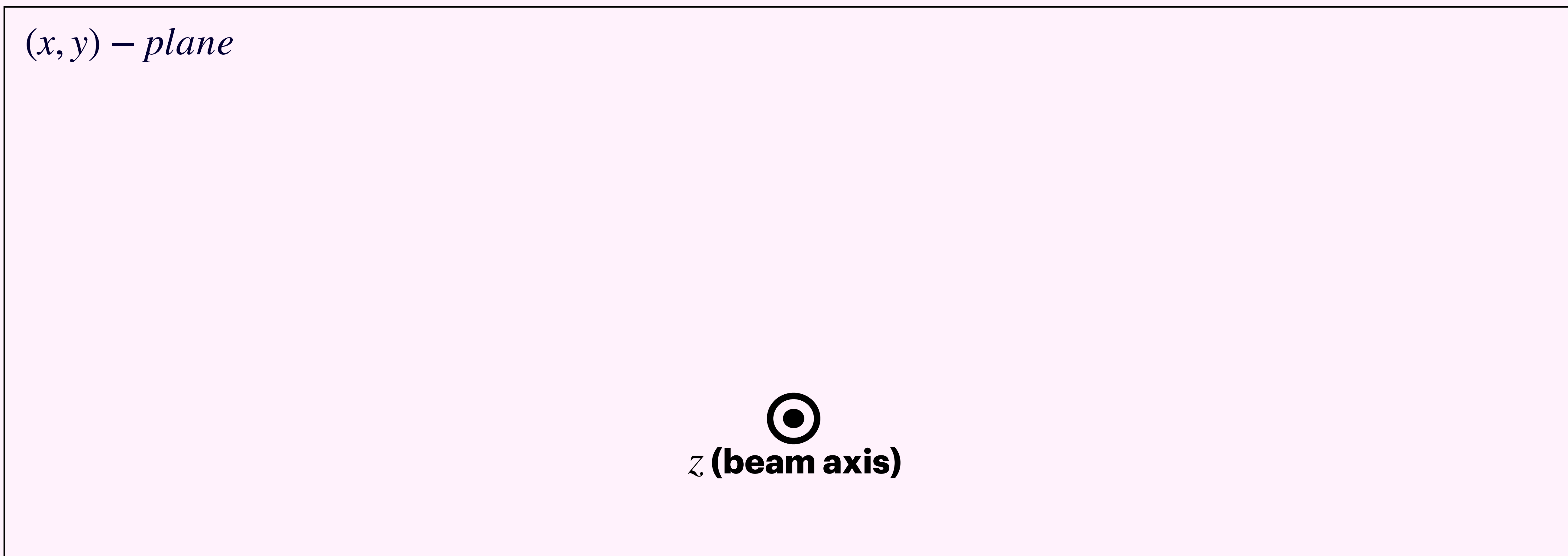
4 - Challenges and our strategy for J/ψ isolation

STEP 1

4 - Challenges and our strategy for J/ψ isolation

STEP 1

- Instead of taking only a cone around the J/ψ, we can construct 3 cones:



4 - Challenges and our strategy for J/ψ isolation

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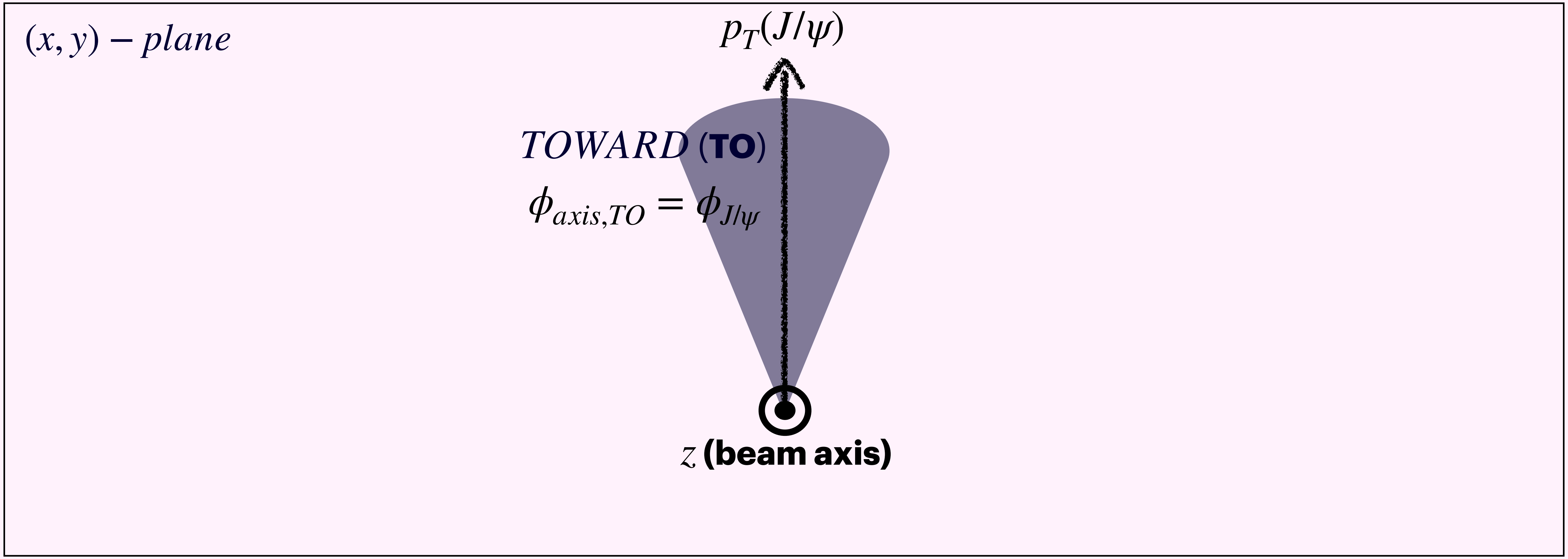

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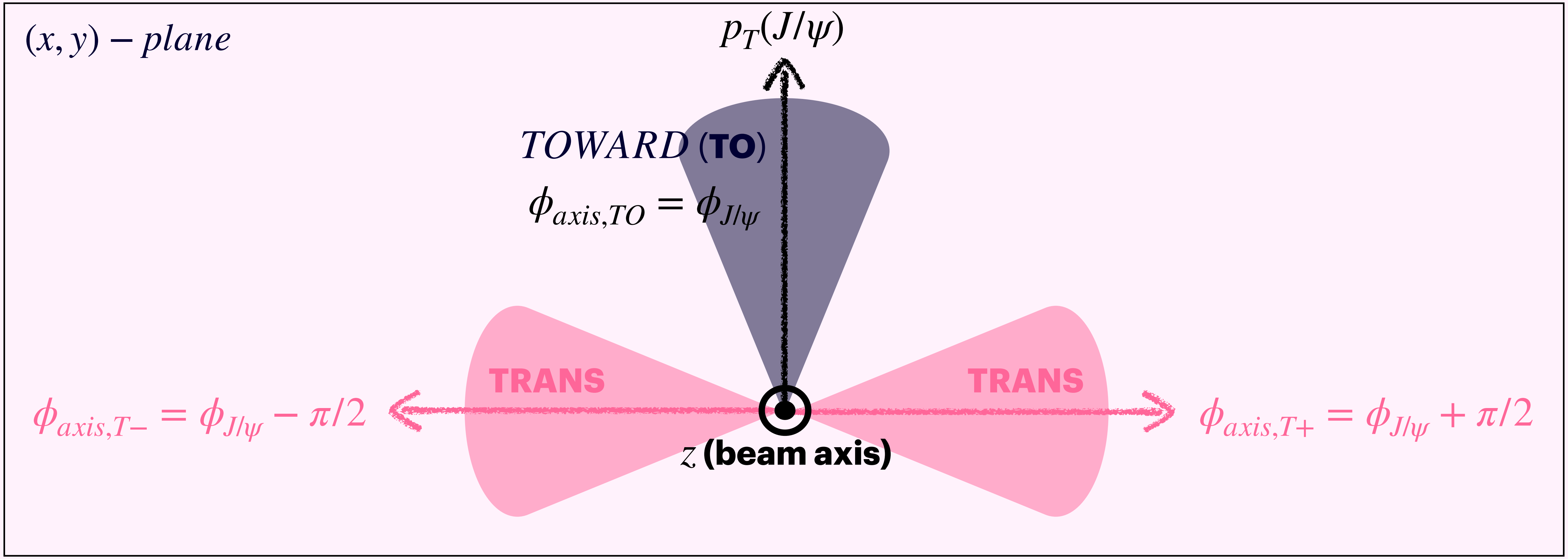

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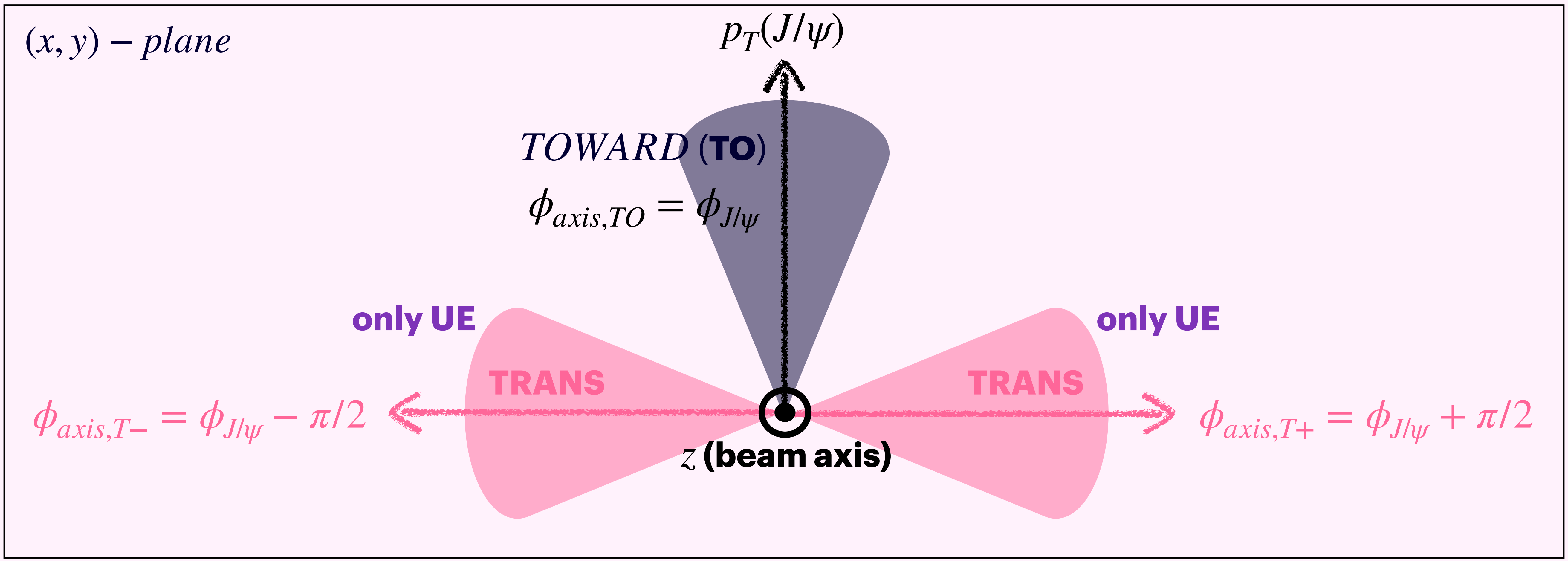

4 - Challenges and our strategy for J/ψ isolation

STEP 1 | STEP 2

4 - Challenges and our strategy for J/ψ isolation

STEP 1 | **STEP 2**

- For each cone:

  i) Take all reconstructed charged particle tracks within a distance

$$r = \sqrt{(\eta_{axis} - \eta_{track})^2 + (\phi_{axis} - \phi_{track})^2} < R = 0.5$$

  ii) Compute the sum of their transverse momenta

$$\textbf{sPT}(\text{cone}) = \sum |\vec{p}_T| (i^{th}\ track)$$

4 - Challenges and our strategy for J/ψ isolation

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* **The J/ψ is not included in the TO cone, it's just the axis**

4 - Challenges and our strategy for J/ψ isolation

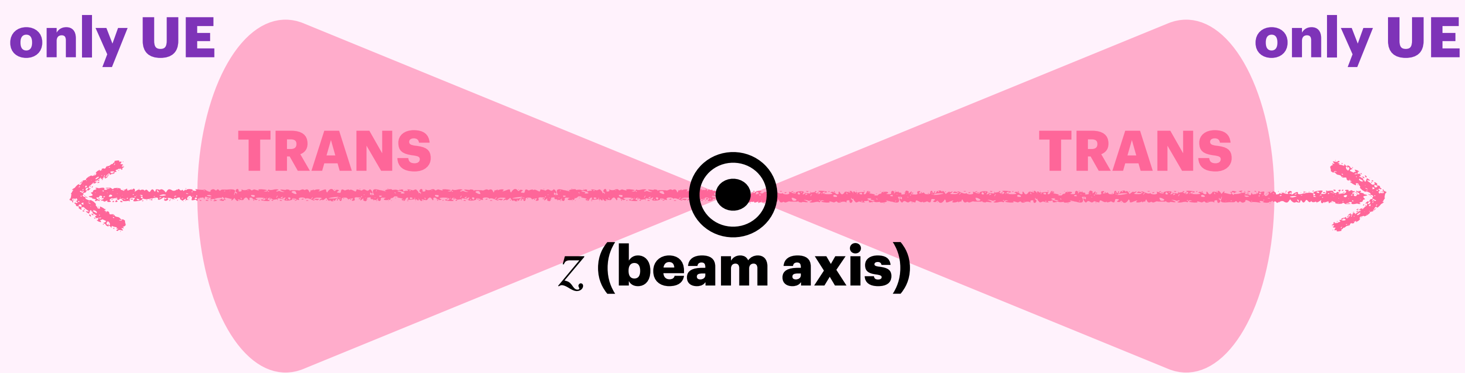
STEP 1	STEP 2	STEP 3

4 - Challenges and our strategy for J/ψ isolation

STEP 1 | STEP 2 | **STEP 3**

- Estimate the **UE** contribution to **sPT**(**TO**) as

<**sPT**(**TRANS**)> = average of **sPT** over the two **TRANS** cones, determined individually for every event



4 - Challenges and our strategy for J/ψ isolation

STEP 1	STEP 2	STEP 3	STEP 4

4 - Challenges and our strategy for J/ψ isolation

STEP 1 | **STEP 2** | **STEP 3** | **STEP 4**

- Define isolated J/ψ as those which fulfil

$$\textbf{sPT(TO)} \leq \langle \textbf{sPT(TRANS)} \rangle$$

Our estimator for **UE** contribution to the **TO** cone

4 - Challenges and our strategy for J/ψ isolation

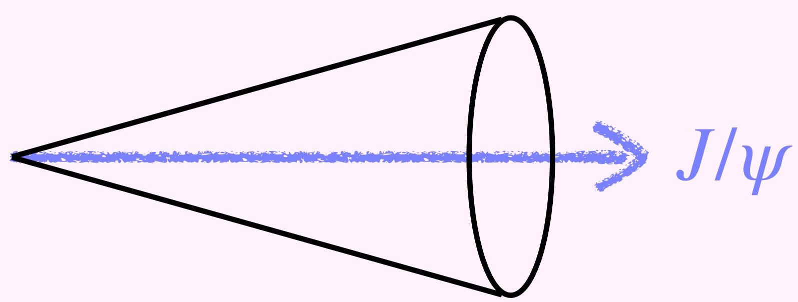
4.2 - Studies made on MC

4 - Challenges and our strategy for J/ψ isolation

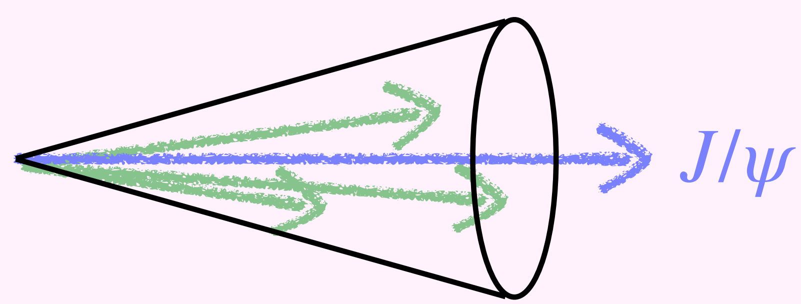
- Even though Monte Carlo (MC) models for **UE** don't completely reproduce data, we can use MC to test the proposed strategy

- Also, for our study case, having a MC sample where we can distinguish if the J/ψ was produced by the hadronisation of a **singlet** or **octet** state is very interesting:

  a) Produced via **singlet** $\Longrightarrow$ $c\bar{c}$ doesn't radiate $\Longrightarrow$ J/ψ is produced in isolation

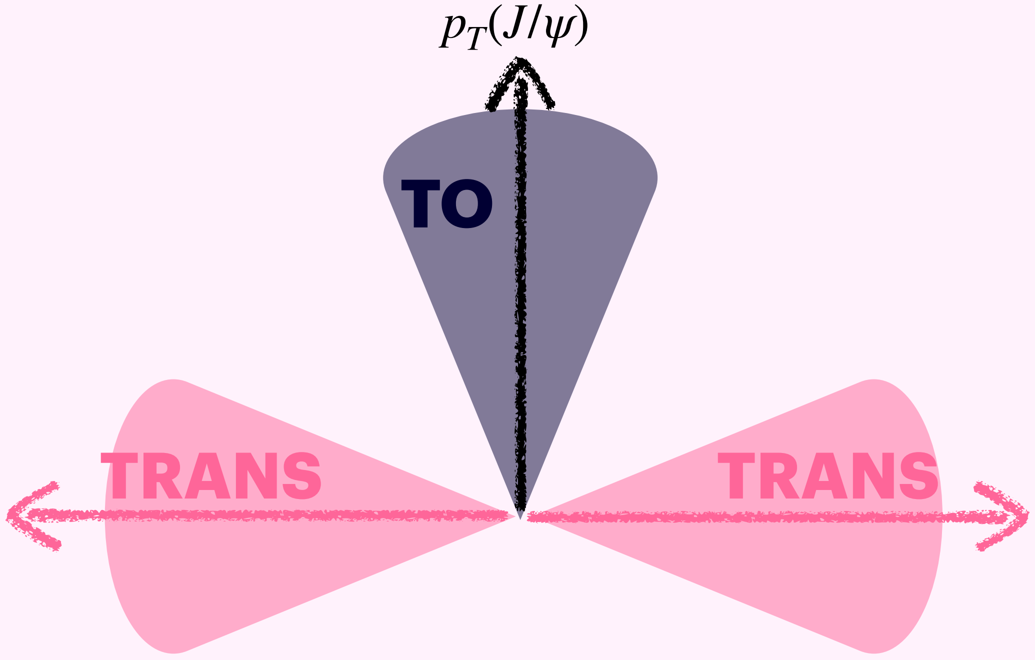


  b) Produced via **octet** $\Longrightarrow$ $c\bar{c}$ needs to radiate a number of soft gluons to neutralise its color $\Longrightarrow$ a shower can evolve $\Longrightarrow$ J/ψ embedded in hadronic activity



4 - Challenges and our strategy for J/ψ isolation

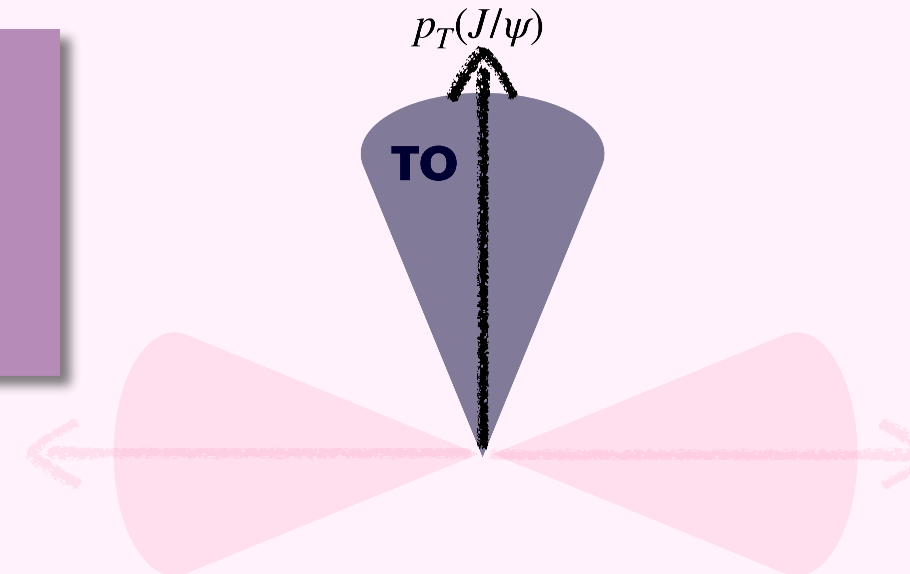
- We have produced MC samples using HELAC-Onia + Pythia8 with the J/ψ being produced via **singlet** and **octet**
- And we have constructed the 3 cones presented in the strategy
- Particles considered inside the cones
  - Charged final-state particles
  - $p_T > 200$ MeV
  - $p > 2$ GeV
  - $2 < \eta < 5$



- **We will be showing plots at generator-level (no detector or reconstruction effects)**

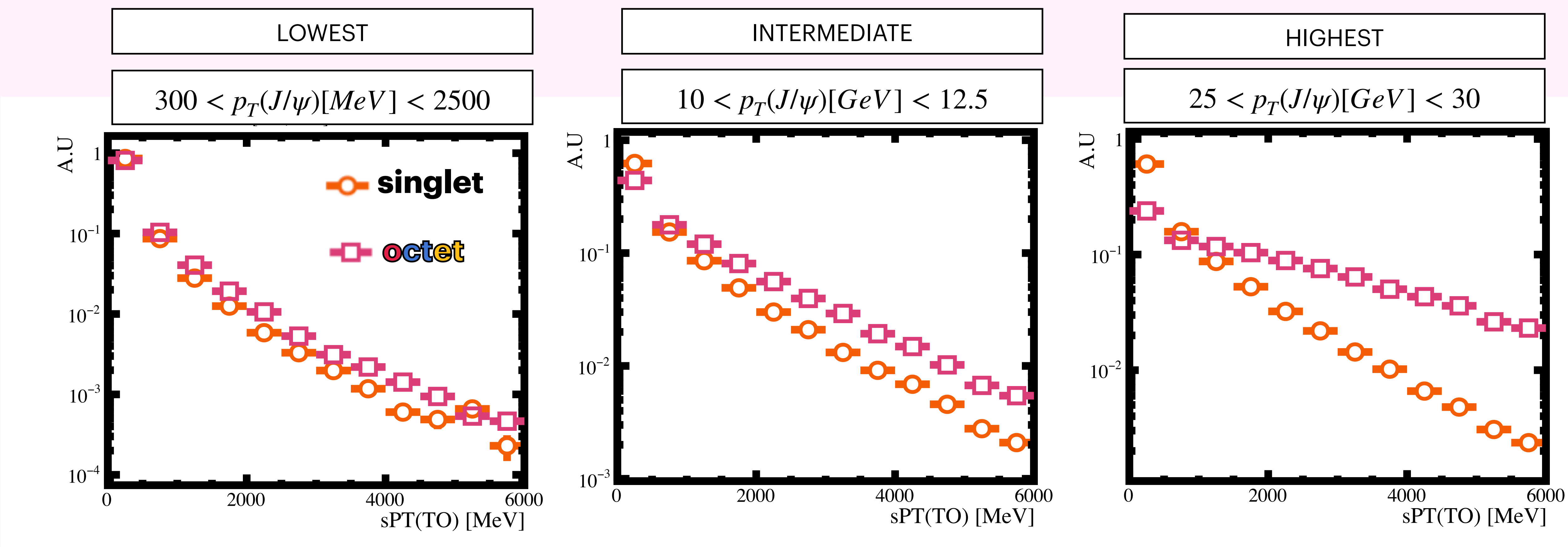
- More details on how the simulation was produced in the backup and here

4 - Challenges and our strategy for J/ψ isolation



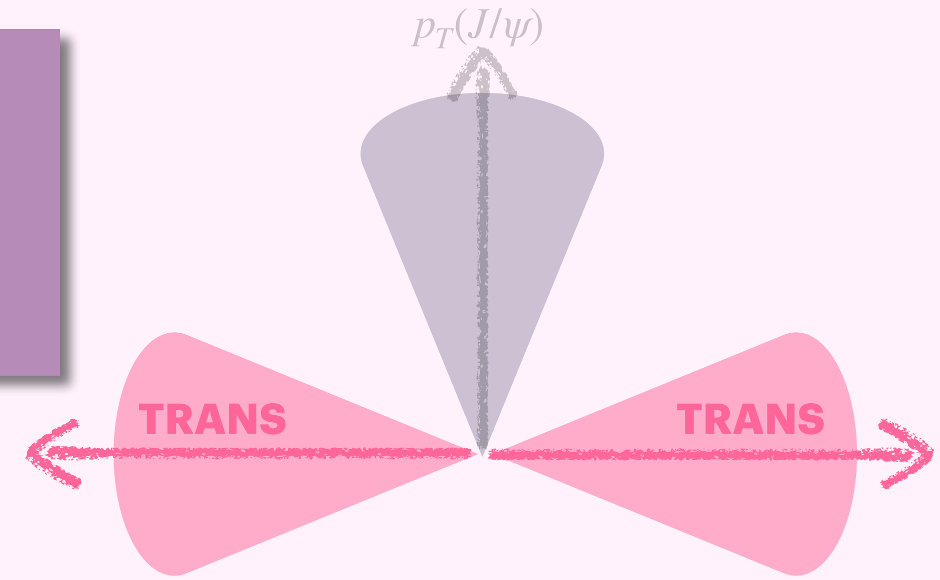
- **sPT**(**TO**) in three $p_T(J/\psi)$ bins

$$\text{sPT} = \sum |\vec{p}_T|$$



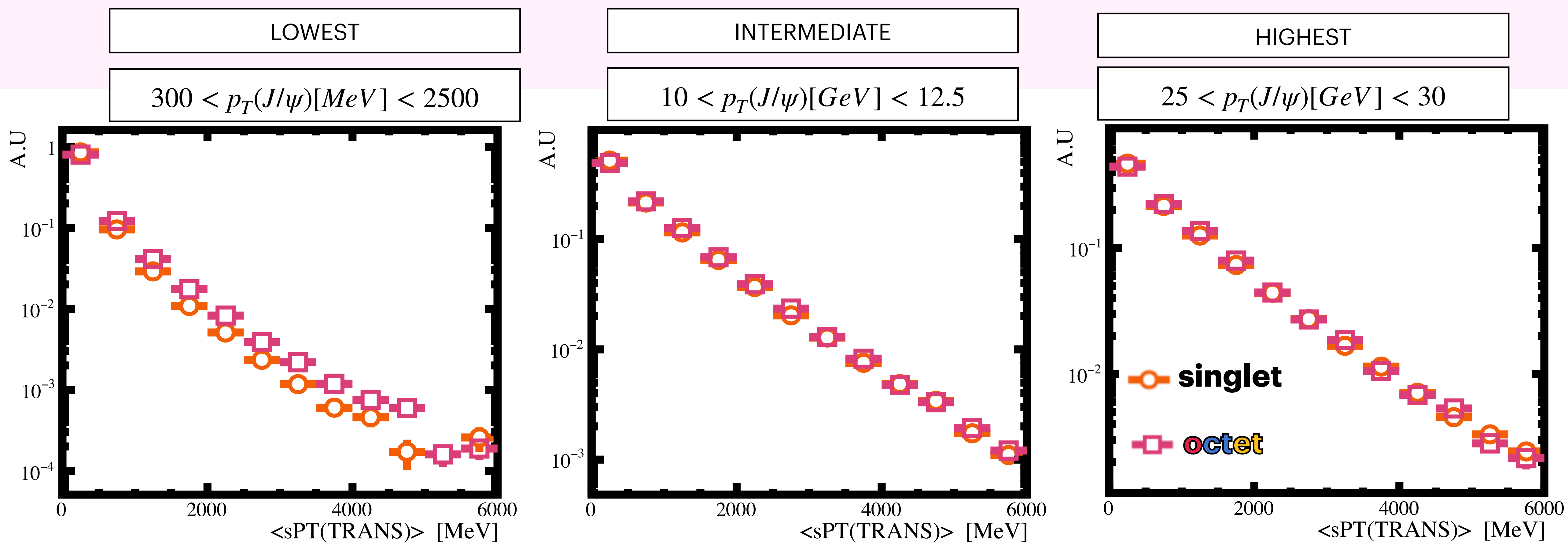
- At high $p_T(J/\psi)$ we observe **sPT**(**TO**,**singlet**) < **sPT**(**TO**,**octet**)
- At low $p_T(J/\psi)$ differences are not so clear

4 - Challenges and our strategy for J/ψ isolation



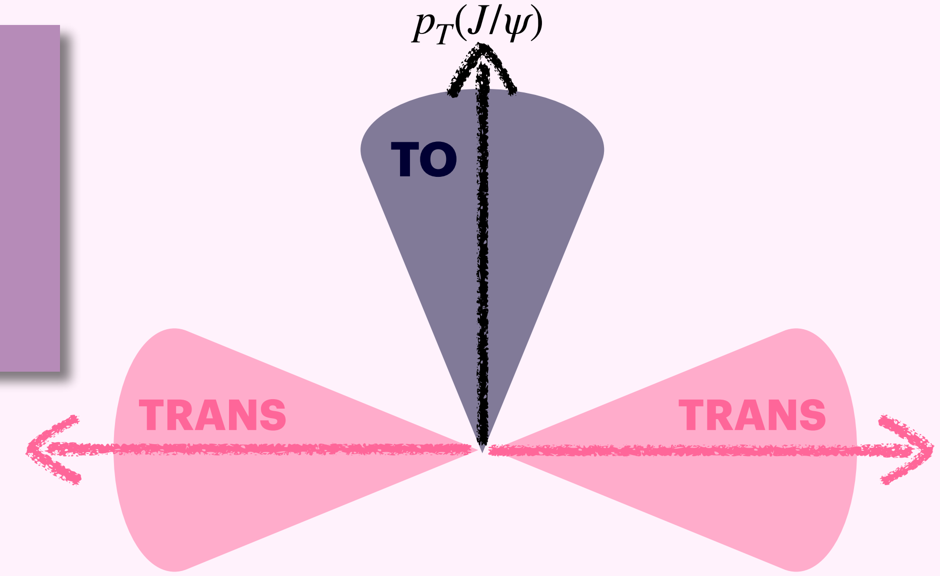
- <**sPT**(**TRANS**)> in three $p_T(J/\psi)$ bins

$$\textbf{sPT} = \sum |\vec{p}_T|$$

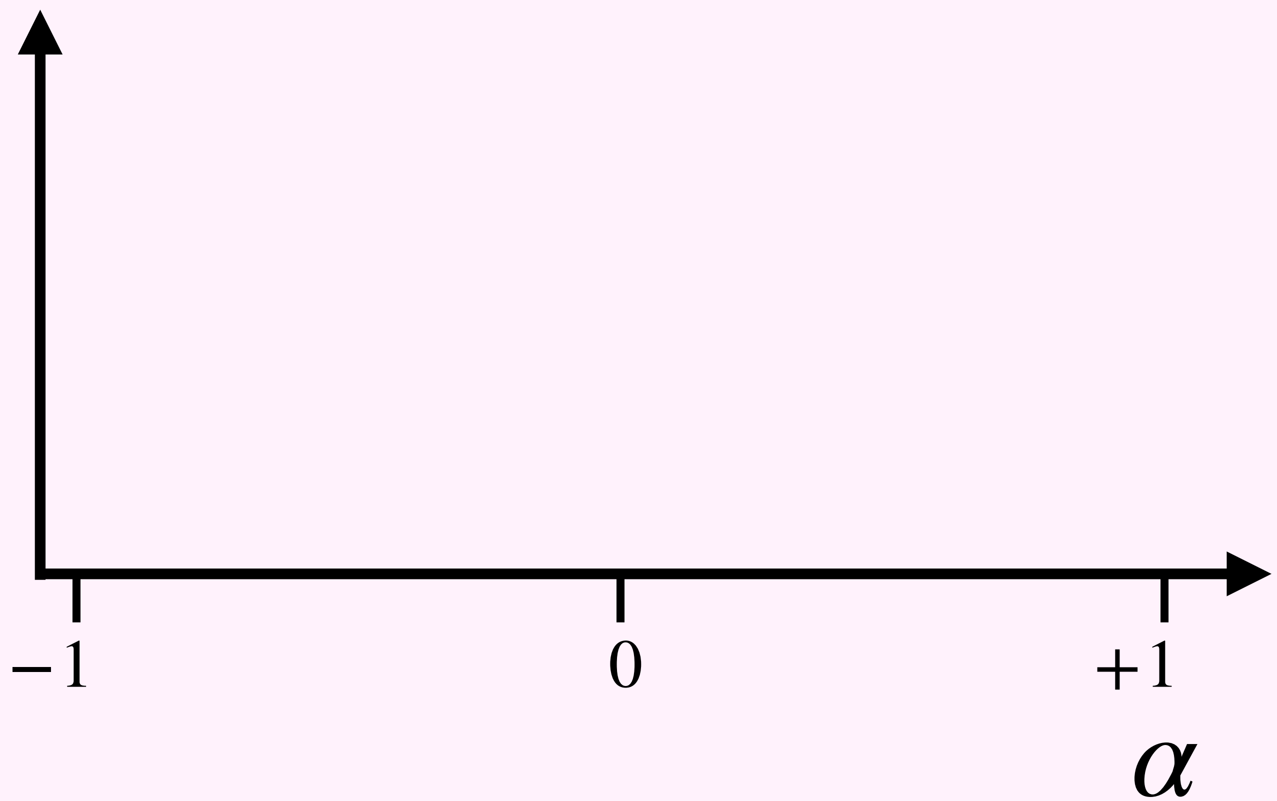


👍 Small differences, which is what we expected if the **octet** radiation doesn't contaminate the **TRANS** cones

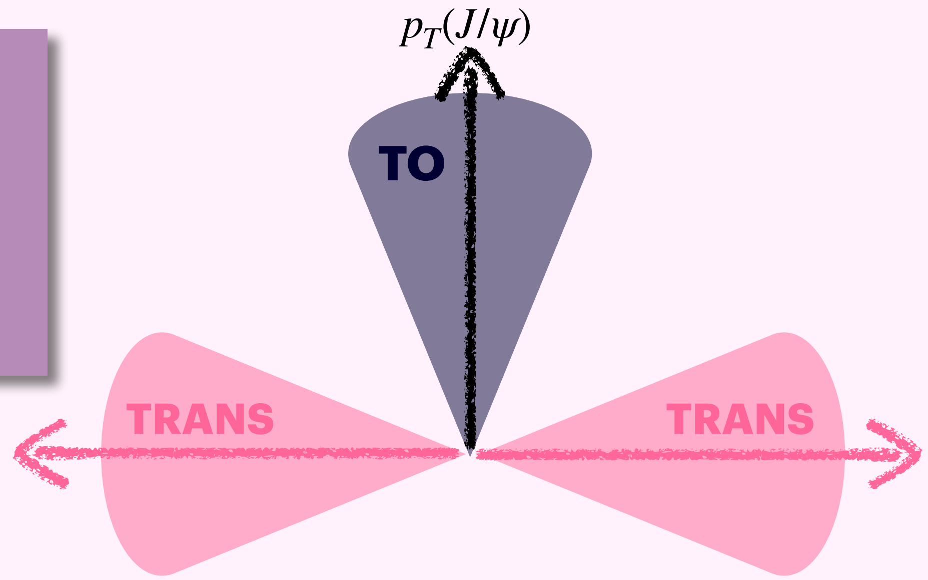
4 - Challenges and our strategy for J/ψ isolation



- $$\alpha = \frac{\text{sPT(TO)} - \langle\text{sPT(TRANS)}\rangle}{\text{sPT(TO)} + \langle\text{sPT(TRANS)}\rangle}$$

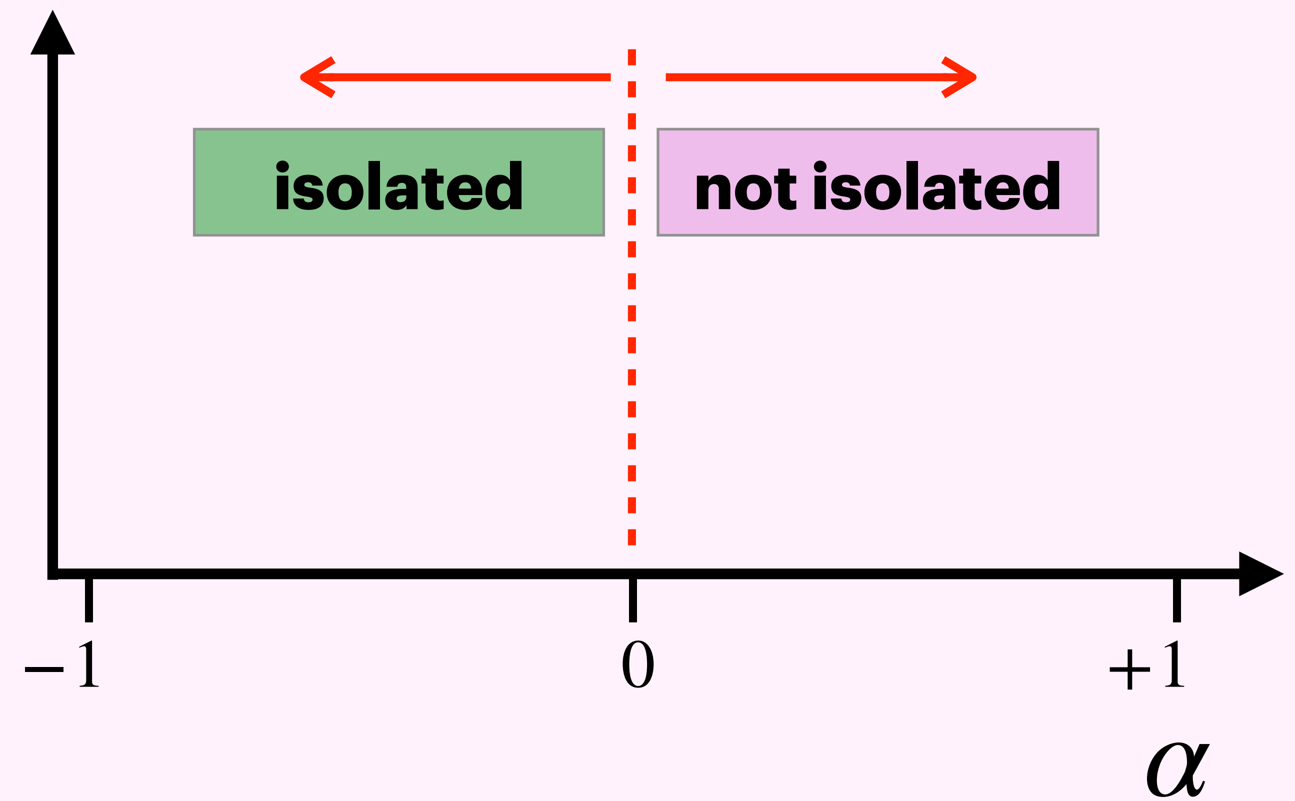


4 - Challenges and our strategy for J/ψ isolation



- $\alpha = \dfrac{\text{sPT(TO)} - \langle\text{sPT(TRANS)}\rangle}{\text{sPT(TO)} + \langle\text{sPT(TRANS)}\rangle}$

Our isolation criterion: sPT(TO) $\leq$ <sPT(TRANS)>



5 - Conclusions

- **Why isolated quarkonium?**
  - Provide additional information to help disentangle the importance of CS and CO contributions
  - *Extend the use of quarkonia to TMDs in hadroproduction**
- **What do we know from theory?**
  - A full calculation of NLO FFs is needed to *clarify* if the proposed observables are useful to disentangle the production mechanism
- **What do we know from experiment?**
  - Measurements of J/ψ in **jets** with $z = p_T(J/\psi)/p_T(jet)$ provide, at $z = 1$, information on isolated J/ψ at high $p_T(J/\psi)$
- **What our measurement provides?**
  - Extend our knowledge to lower $p_T(J/\psi)$
  - Establish a possible procedure to future quarkonium isolation measurements

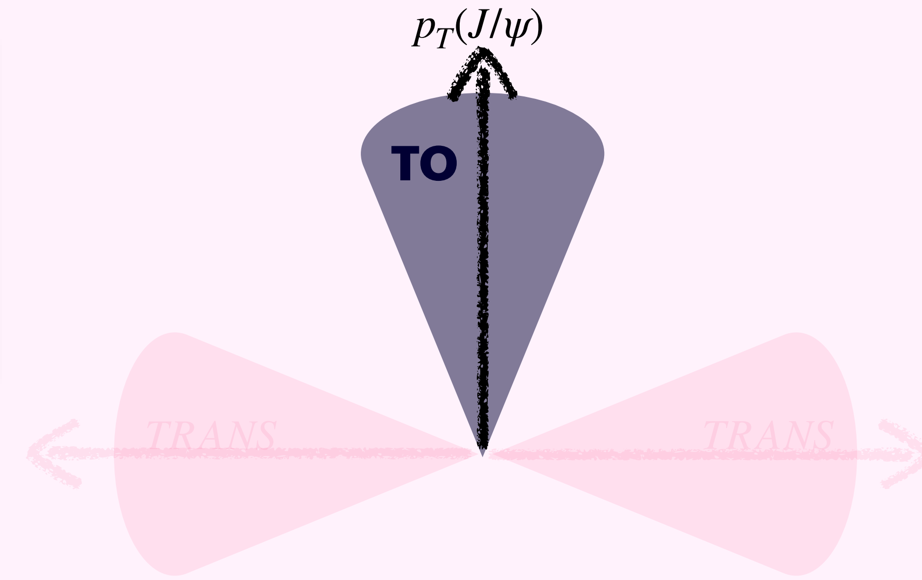
Thank you for your attention! ☻

Backup

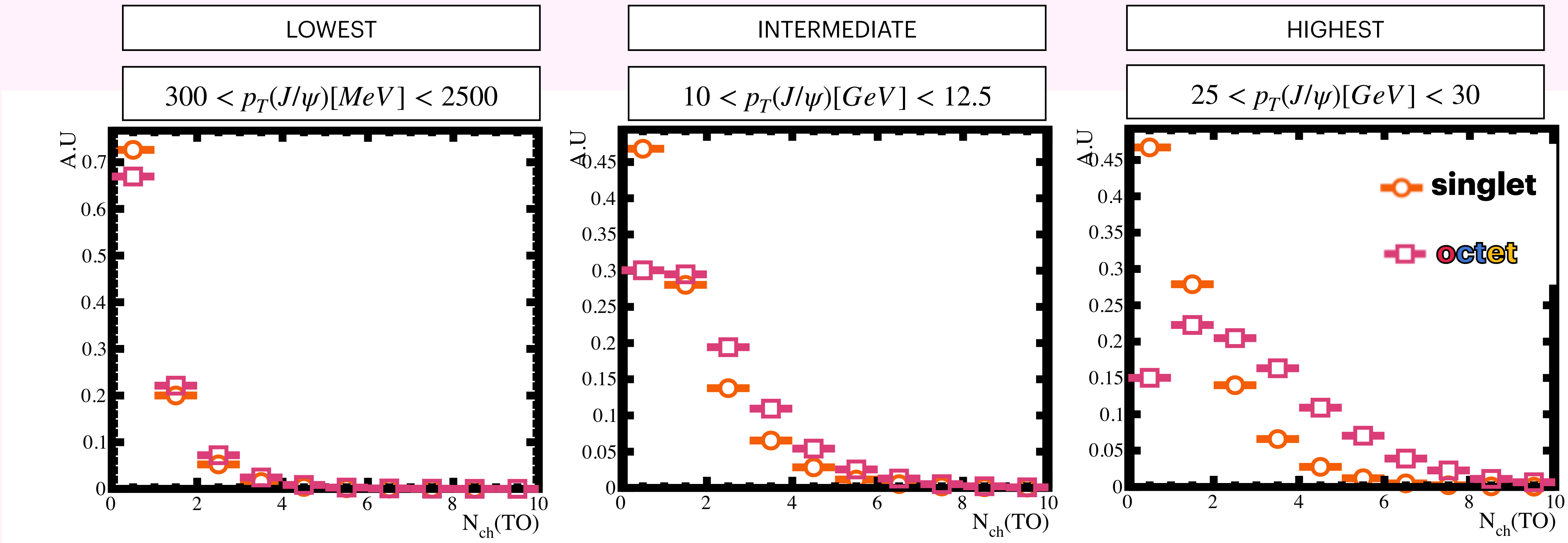
Simulation further information

- The simulation was produced with:
  - Helac-Onia v2.7.6
    - Compute kinematics of $g + g \rightarrow c\bar{c}[^{2S+1}L_J^{(c)}] + g$
  - Pythia v8309 (with LHCb settings)
    - Evolve $c\bar{c}[^{2S+1}L_J^{(c)}]$ to the physical J/ψ
    - Decay $J/\psi \rightarrow \mu^+\mu^-$
    - Include all the processes giving rise to **UE**
    - Hadronisation
- **This is a generator-level MC** (doesn't include reconstruction effects)
- More details on how the simulation was produced here

3 - Studies made on MC



- Multiplicity of the **TO** cone in three $p_T(J/\psi)$ bins
  - Charged final-state particles with $p_T > 200$ MeV, $p > 2$ GeV and $2 < \eta < 5$



- At high $p_T(J/\psi)$ we observe N_{ch}(**singlet**) $< N_{ch}$(**octet**)
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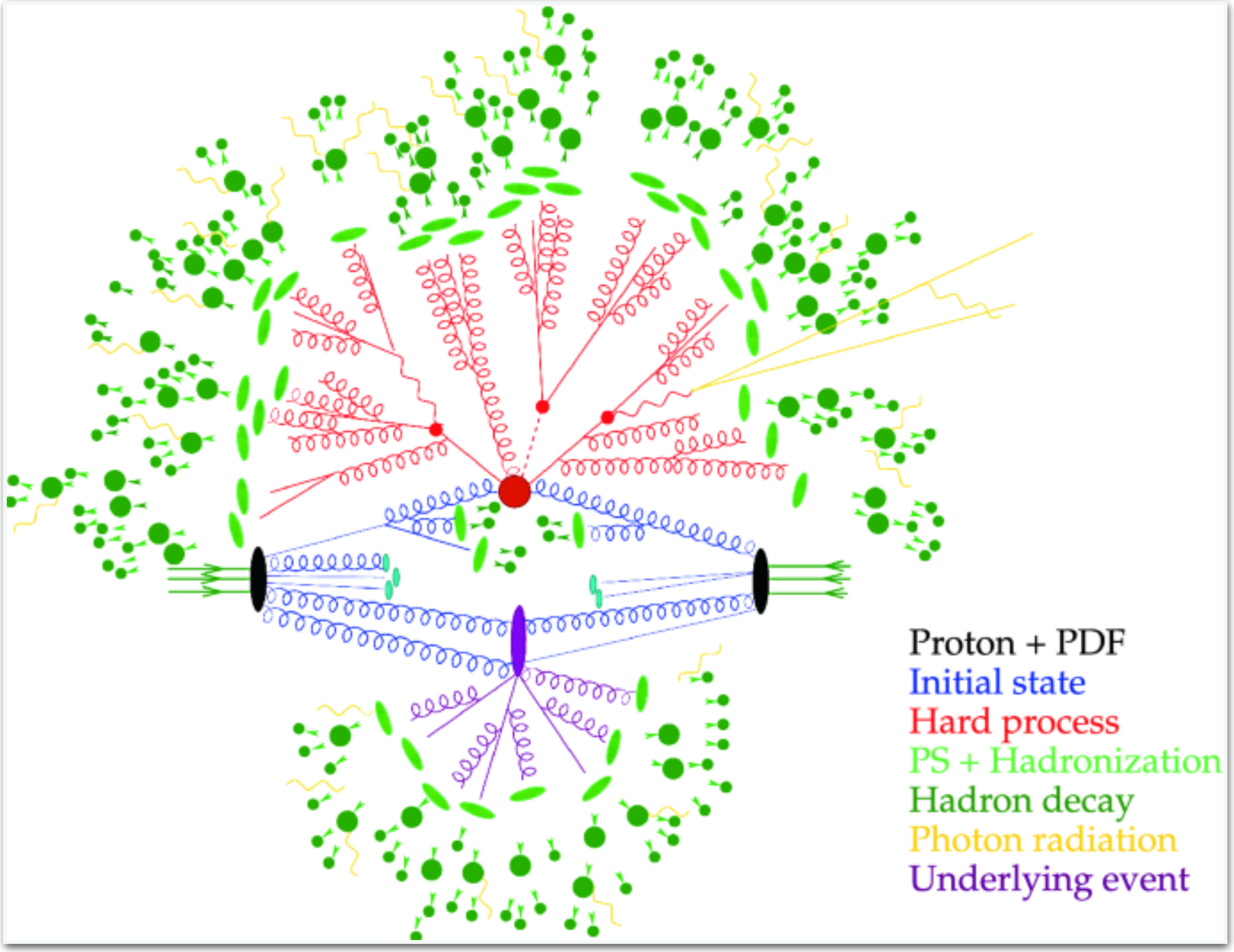
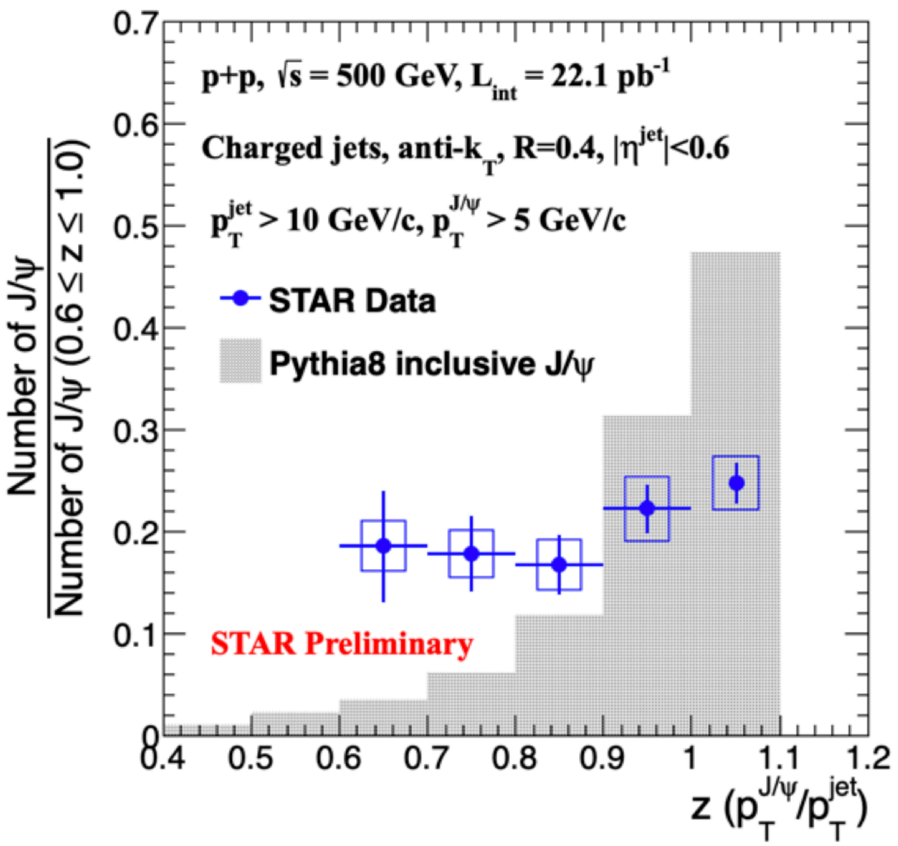
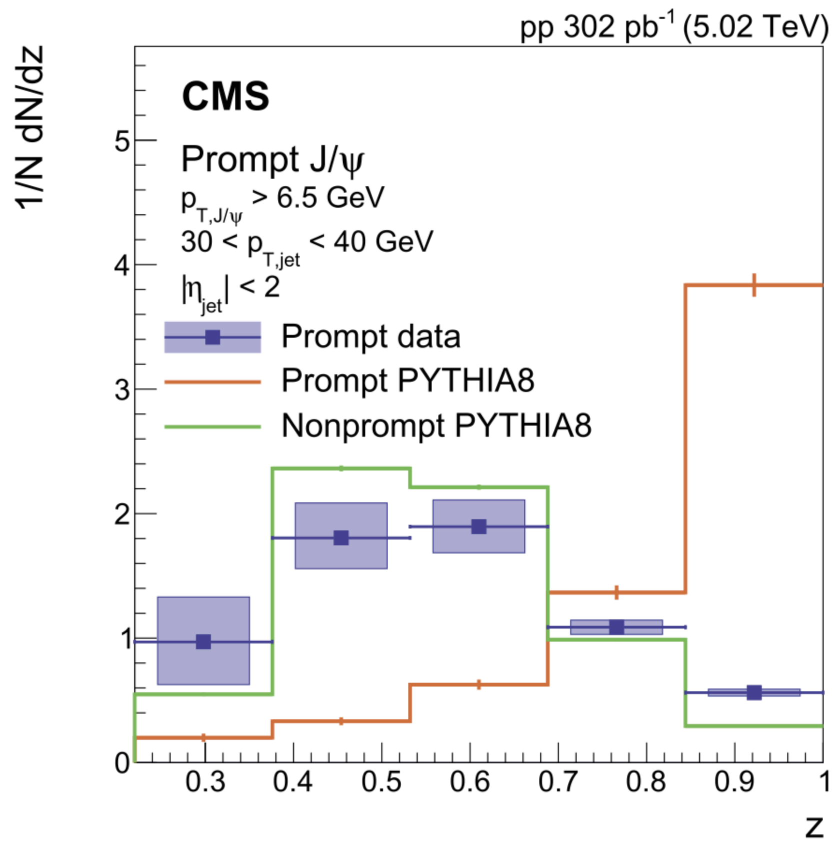
Underlying Event

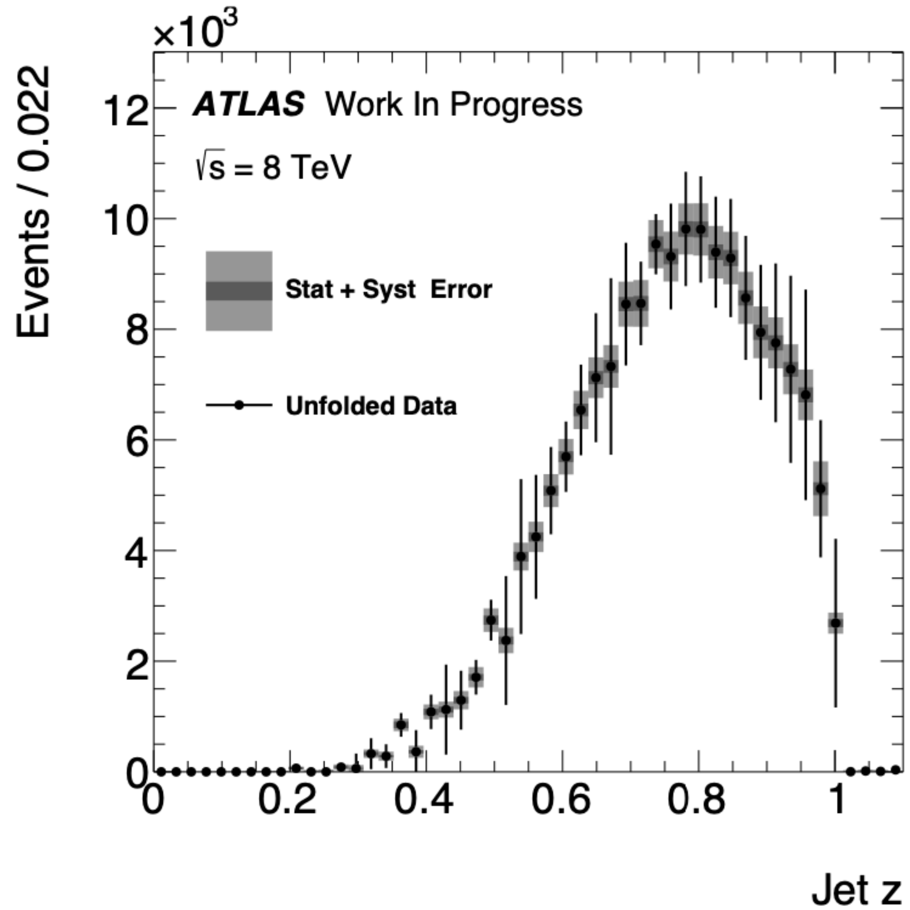


Measurements
More for prompt J/ψ in jets

[PoS (HardProbes2020), vol 387, 072](#) [Phys. Lett. B 825 (2022) 136842](#) [D. Bjergaard, PhD thesis, Duke U., 2017.](#)





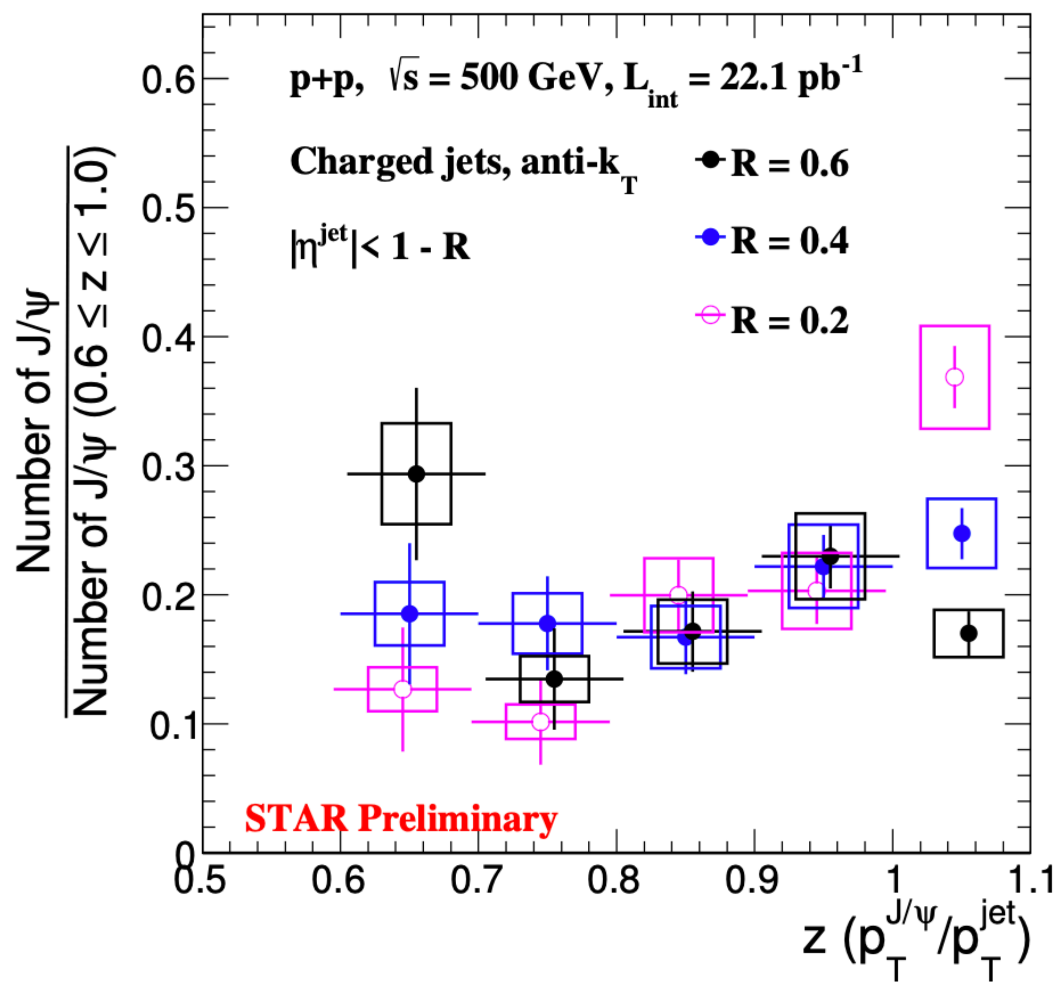


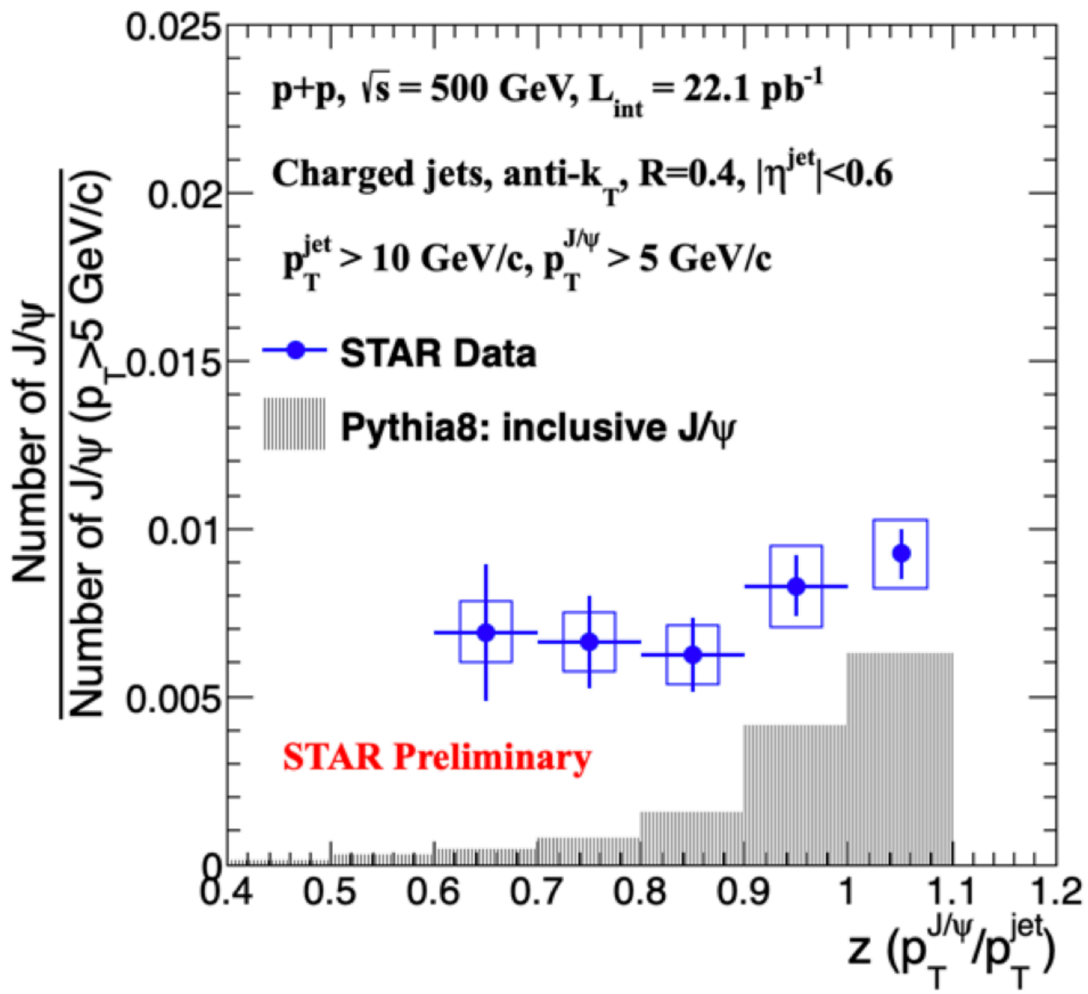
- No significant dependence
  - More statistics
- Less isolated than PYTHIA8 predictions
  - Point at $z = 1$ represent events where $J/\psi = jet$
- Similar to LHCb results
  - Peak at $z \approx 0.5$
- Peak at higher z than LHCb results

Measurements

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

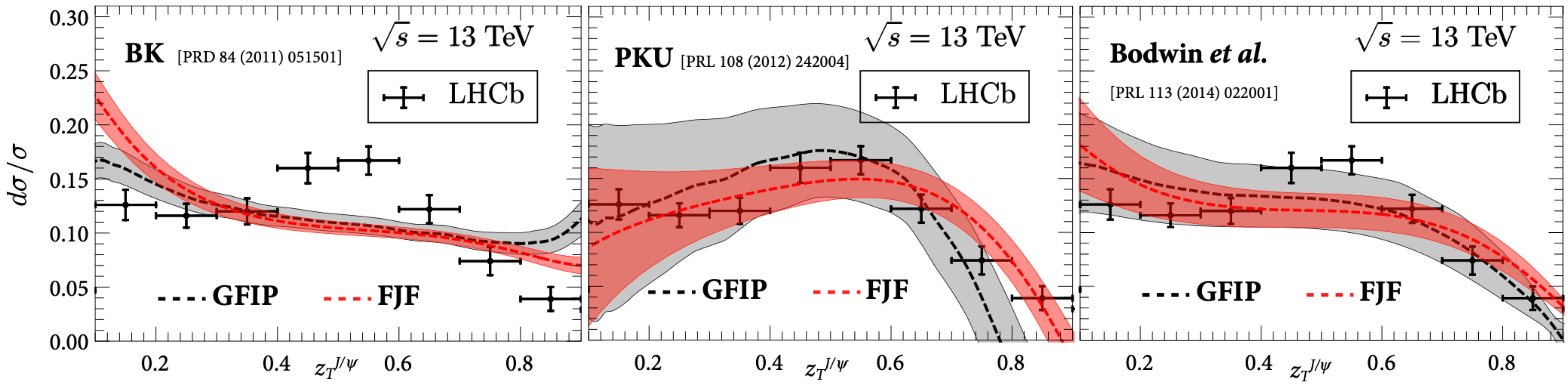
PoS (HardProbes2020), vol 387, 072





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