Rare and novel probes for heavy ion physics at CMS

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For the CMS Collaboration

CERN-LHC Seminar

23 June 2020
Geneva (Switzerland)

Outline

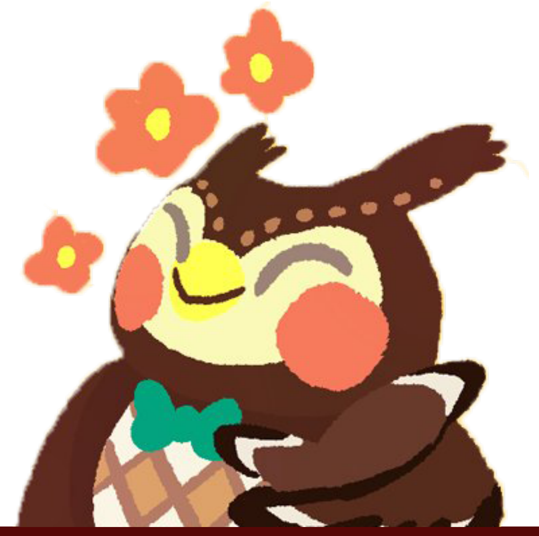
What you expect in this talk

「Rare & Novel Probes」

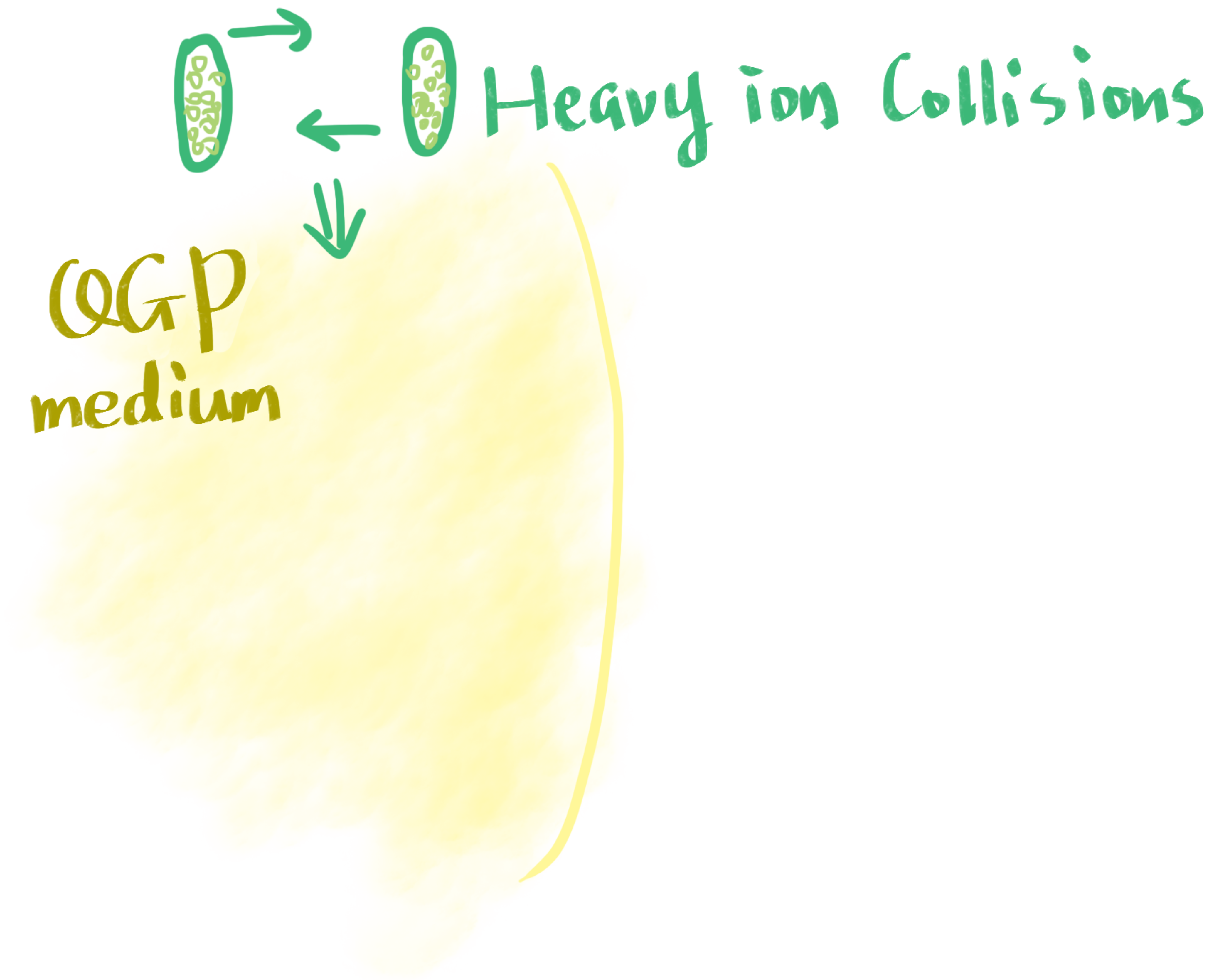
Jet R_{AA} with large radius in PbPb
[CMS-PAS-HIN-18-014] …… S24

$t\bar{t}$ Cross-section in PbPb
[arXiv:2006.11110] …… S39

X(3872) production in PbPb
[CMS-PAS-HIN-19-005] …… S54



Heavy-ion collisions



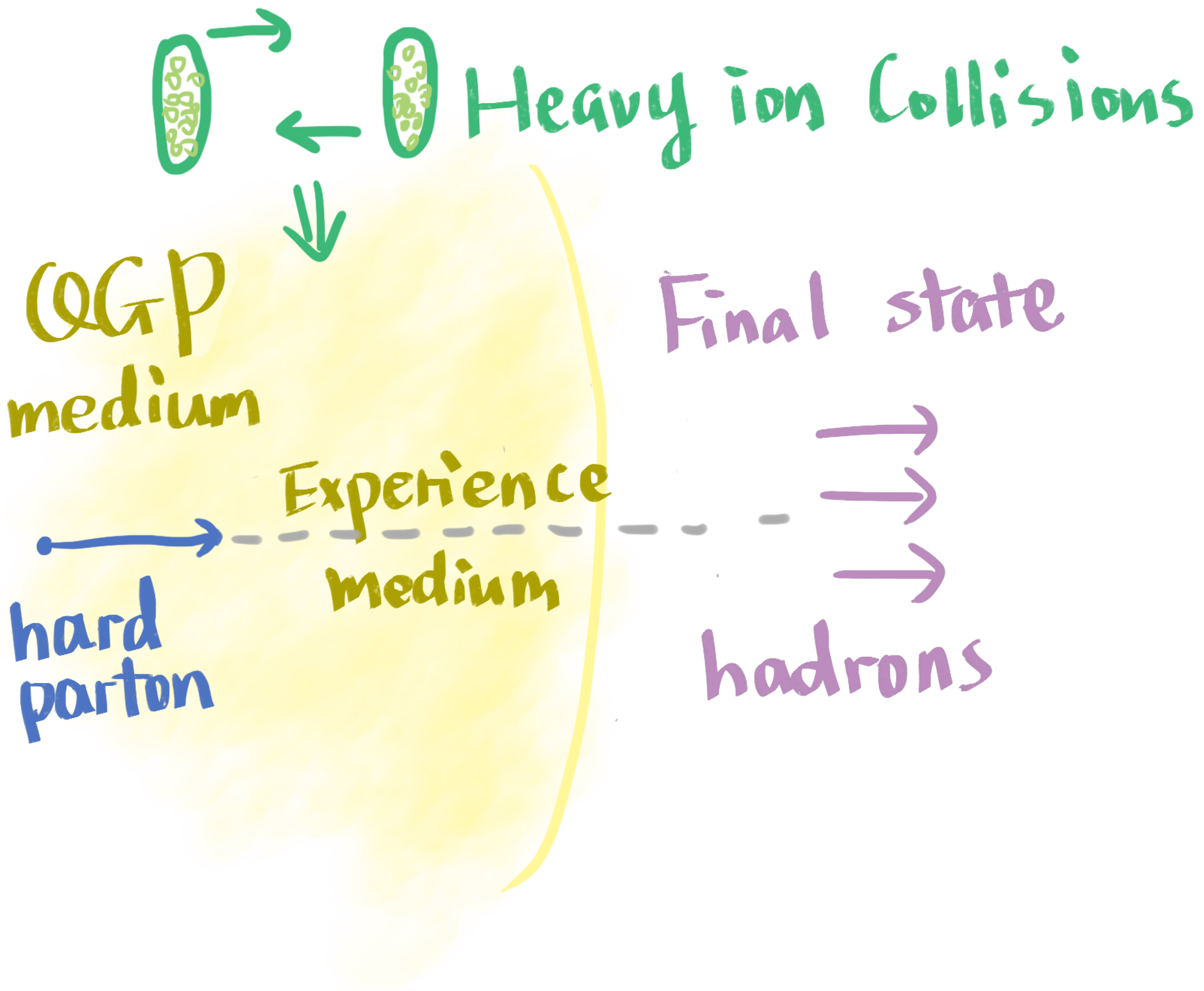
- **Medium** produced by **heavy-ion collisions**

  Predicted by QCD
  - Quark Gluon Plasma (QGP)
  - Exciting properties
    - ➡ Extremely dense and hot
    - ➡ Strongly interacting
    - ➡ Asymptotic freedom
    - ➡ Behaves like liquid
    - ➡ Existing short time

How?

- Want to understand QGP!

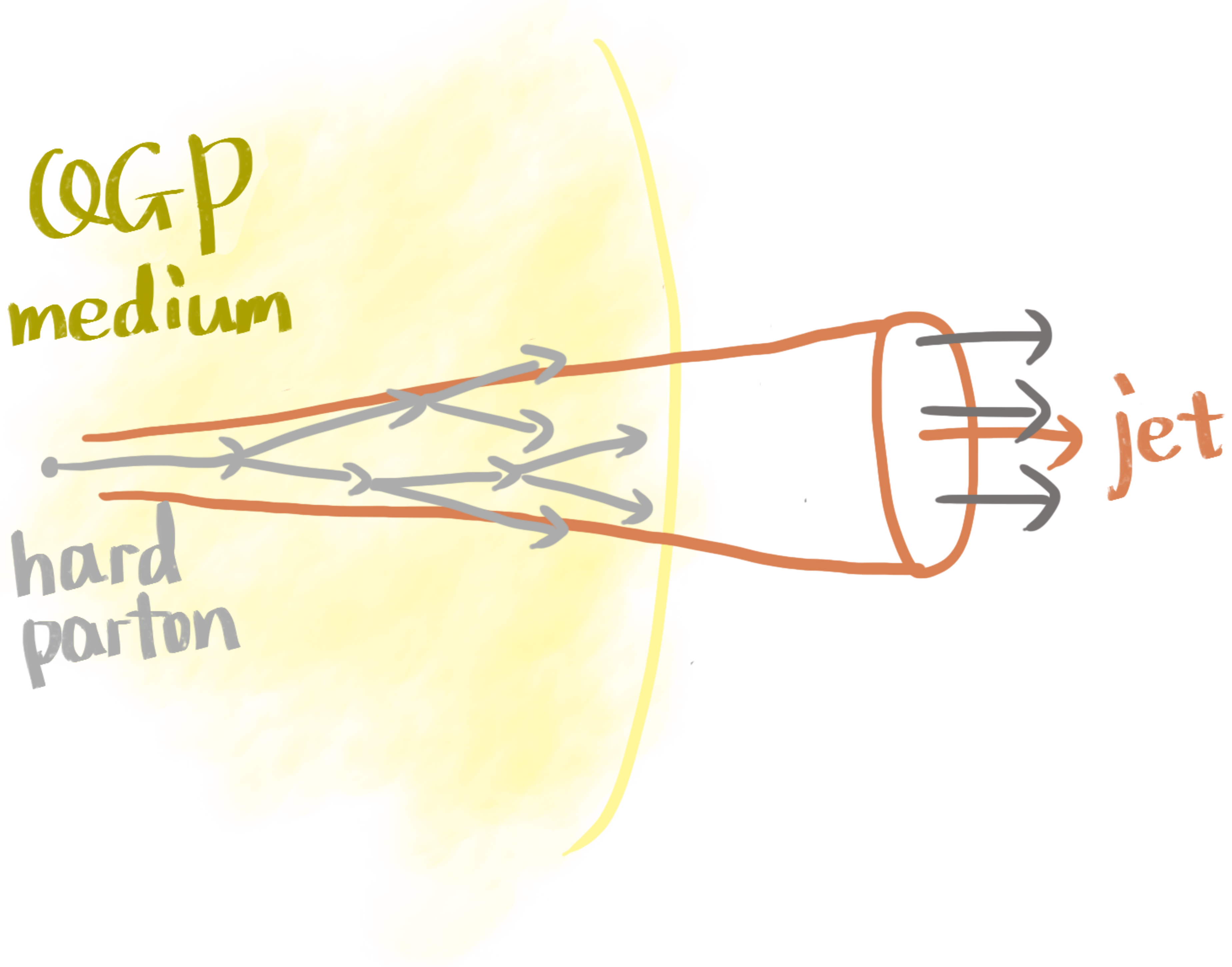
Probe Quark Gluon Plasma



- Probe QGP
  - **Partons** generated by hard scatterings in Heavy-ion collisions as probes
  - Color-charged partons:
    ➡ Interact with the medium
    ➡ Final state carries information of QGP

- Ordinary probes of QGP
  - Jets
  - Heavy flavors (charm, beauty)
  - Quarkonia
  - Electroweak bosons
  - Flow/Correlation

Jets as Probes of Quark Gluon Plasma



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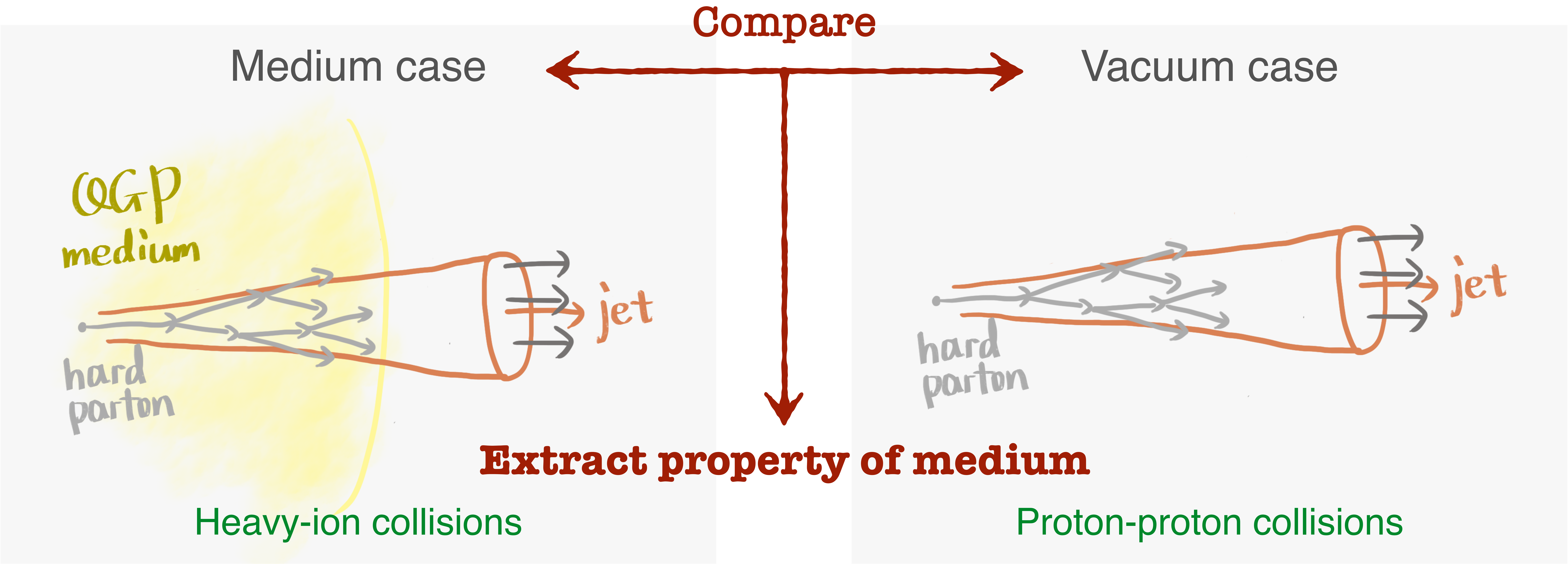
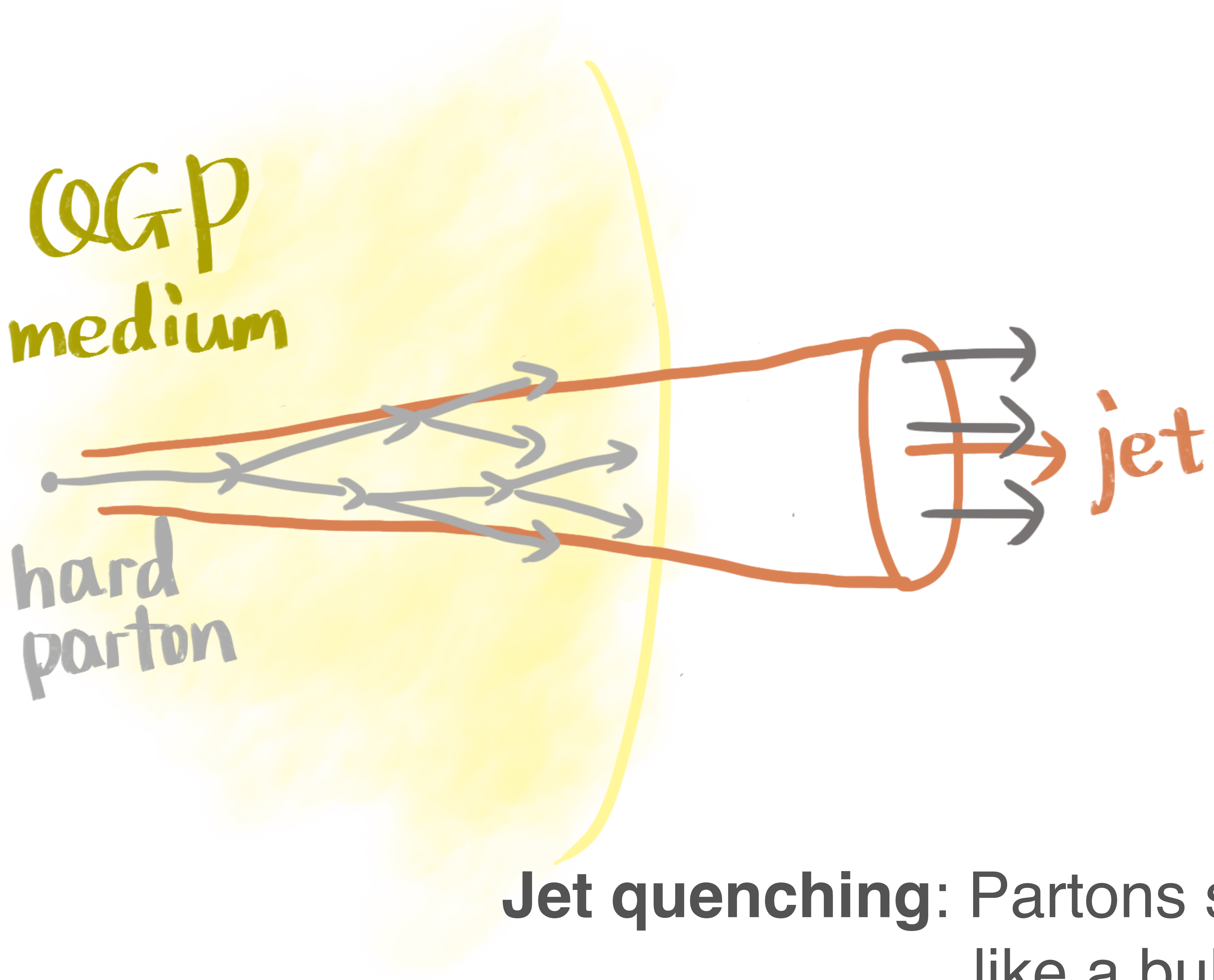
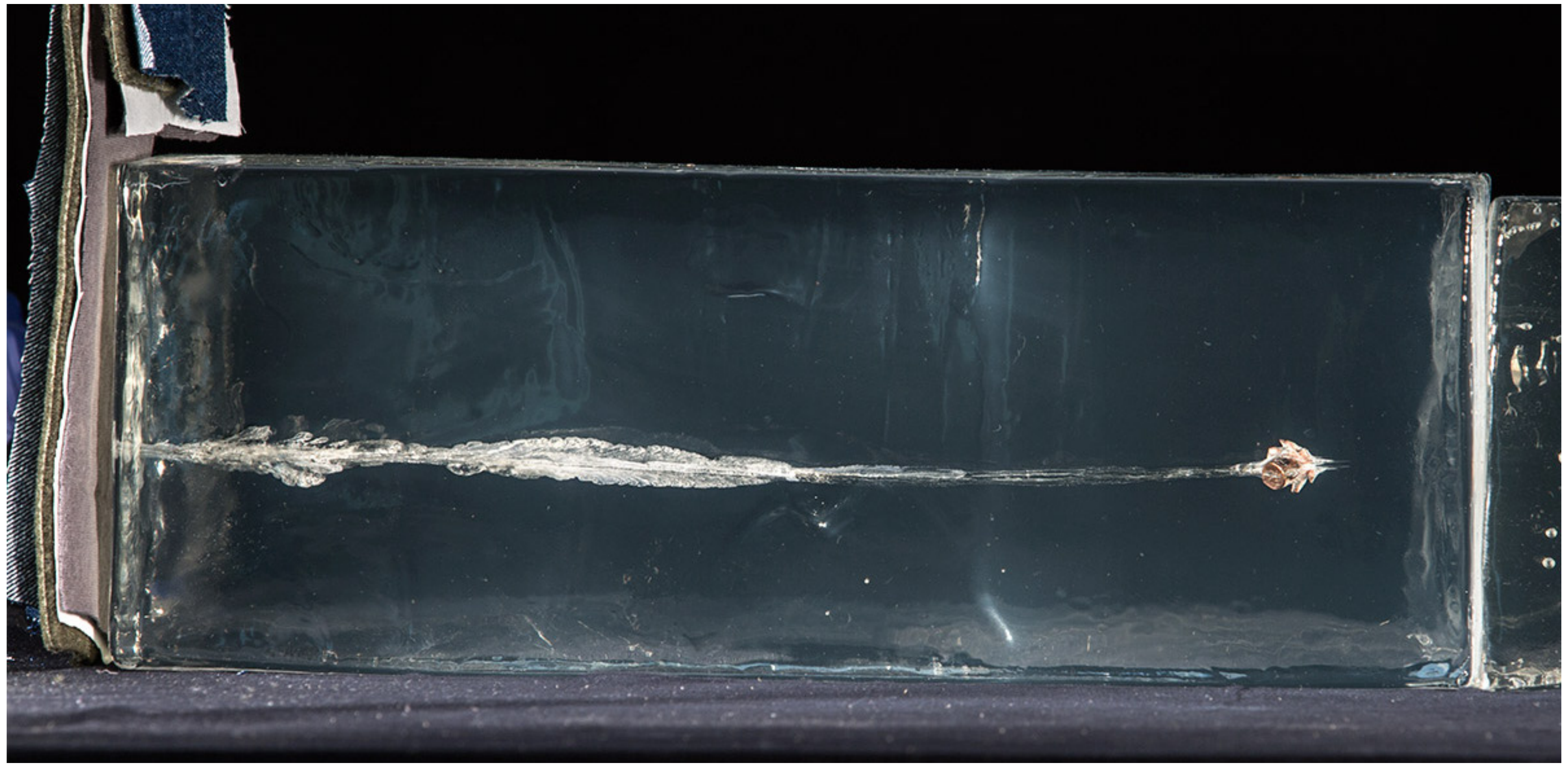


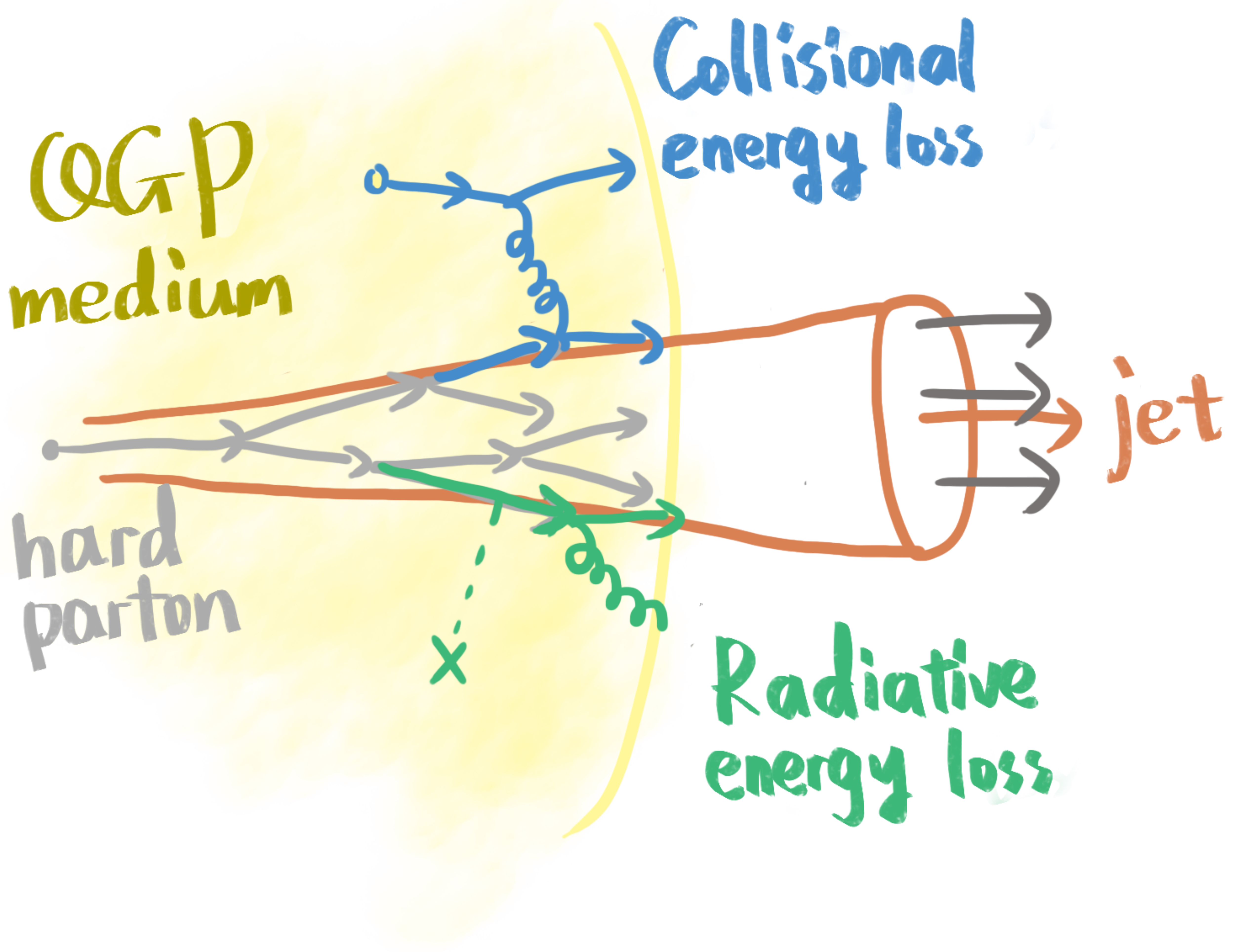
Jet quenching: Energy loss





Jet quenching: Partons slowed down in produced medium, like a bullet passing through ballistics gel

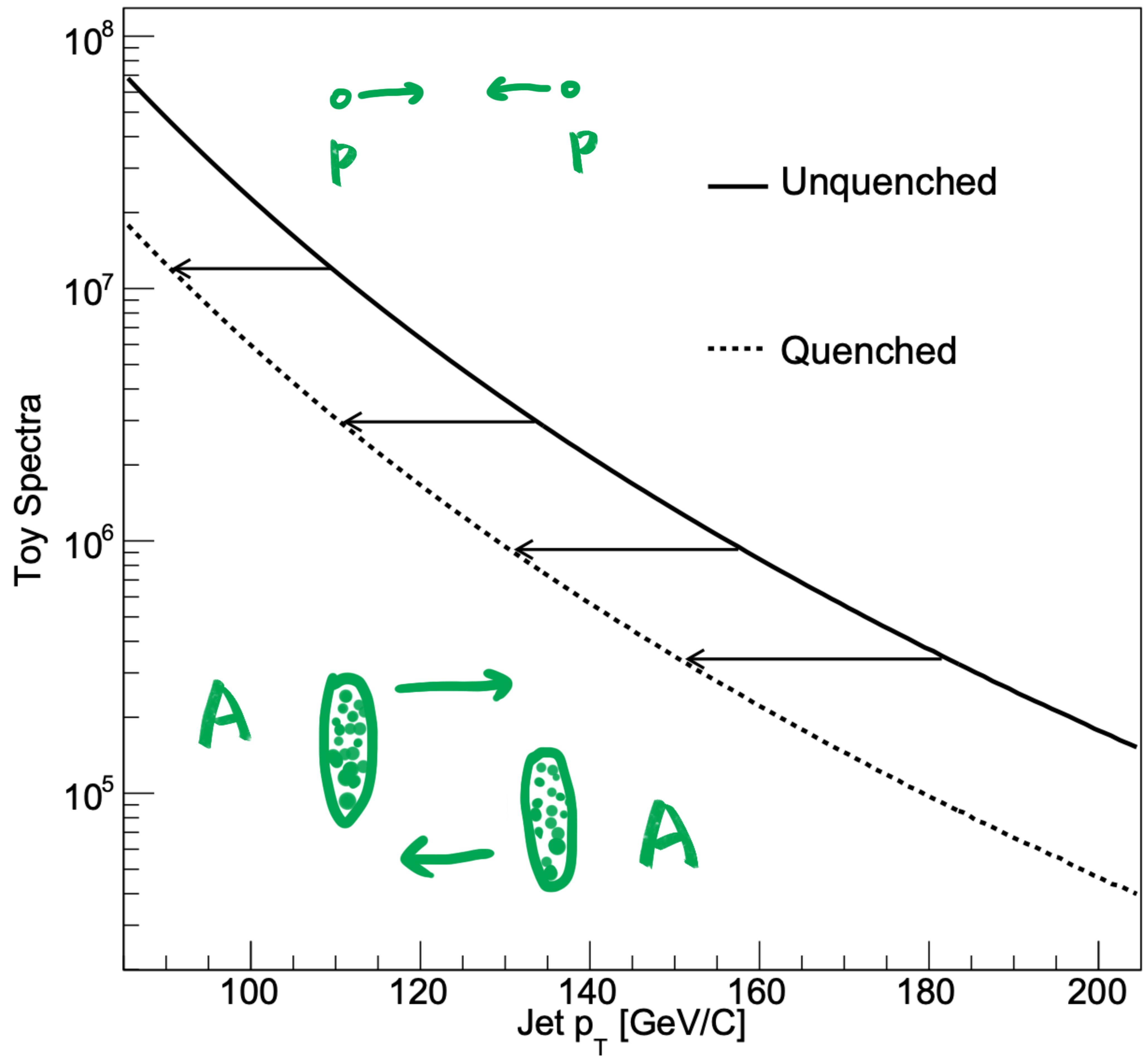
Jet quenching: Energy loss



- **pQCD based (weak coupling)**
  - Mechanism
    - ➡ Collisions
    - ➡ Medium-induced radiations
  - Various quenching formalisms
    - ➡ AMY, HT, BDMPS-Z, SCET$_G$
- **AdS/CFT based (strong coupling)**
  - Anti-de Sitter/Conformal Field Theory
  - Mechanism: Drag force

Nuclear modification factor R_{AA}

Jet spectra

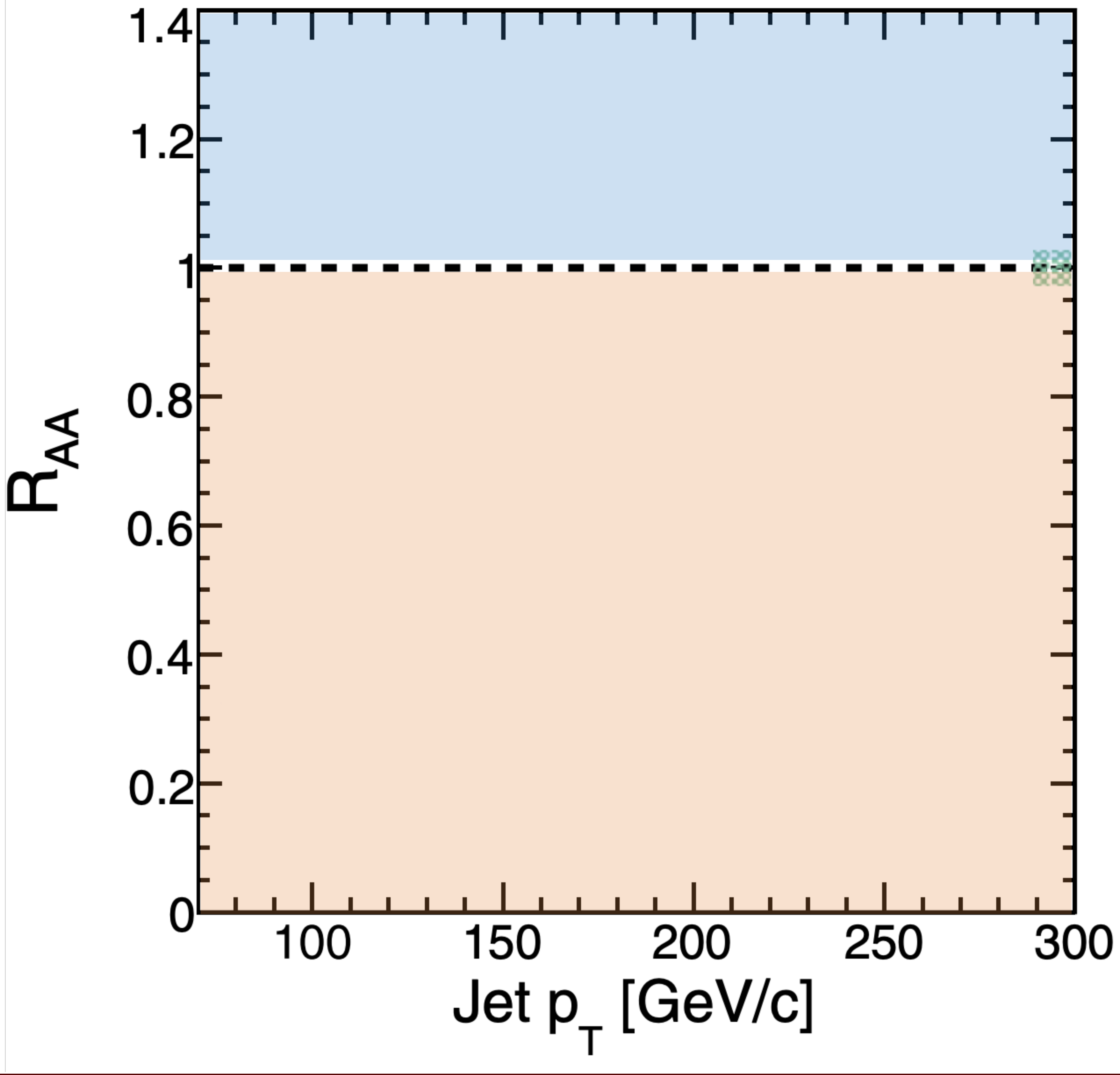


- To quantify the quenching, define R_{AA}:

$$R_{AA} = \frac{dN^{AA}/dp_T}{T_{AA} dN^{pp}/dp_T} \rightarrow \frac{\text{Heavy-ion:}}{\text{Proton-proton:}}$$

- Jet quenching
  - ➡ Jet spectra shift to left due to energy loss
  - ➡ Jets not disappear

R_{AA}



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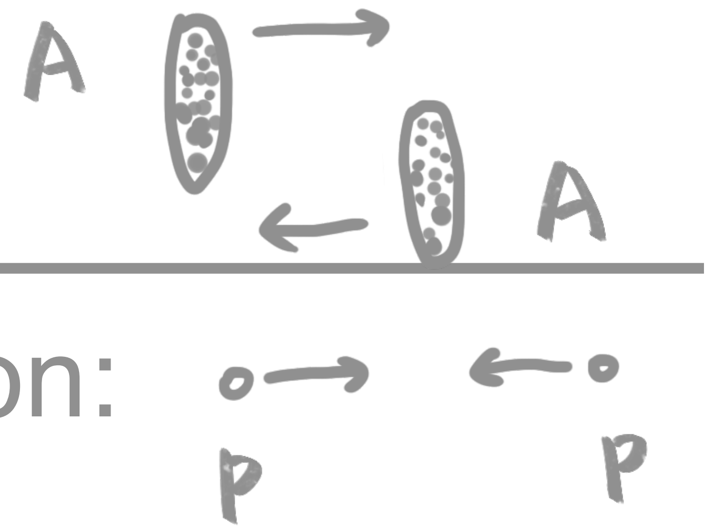
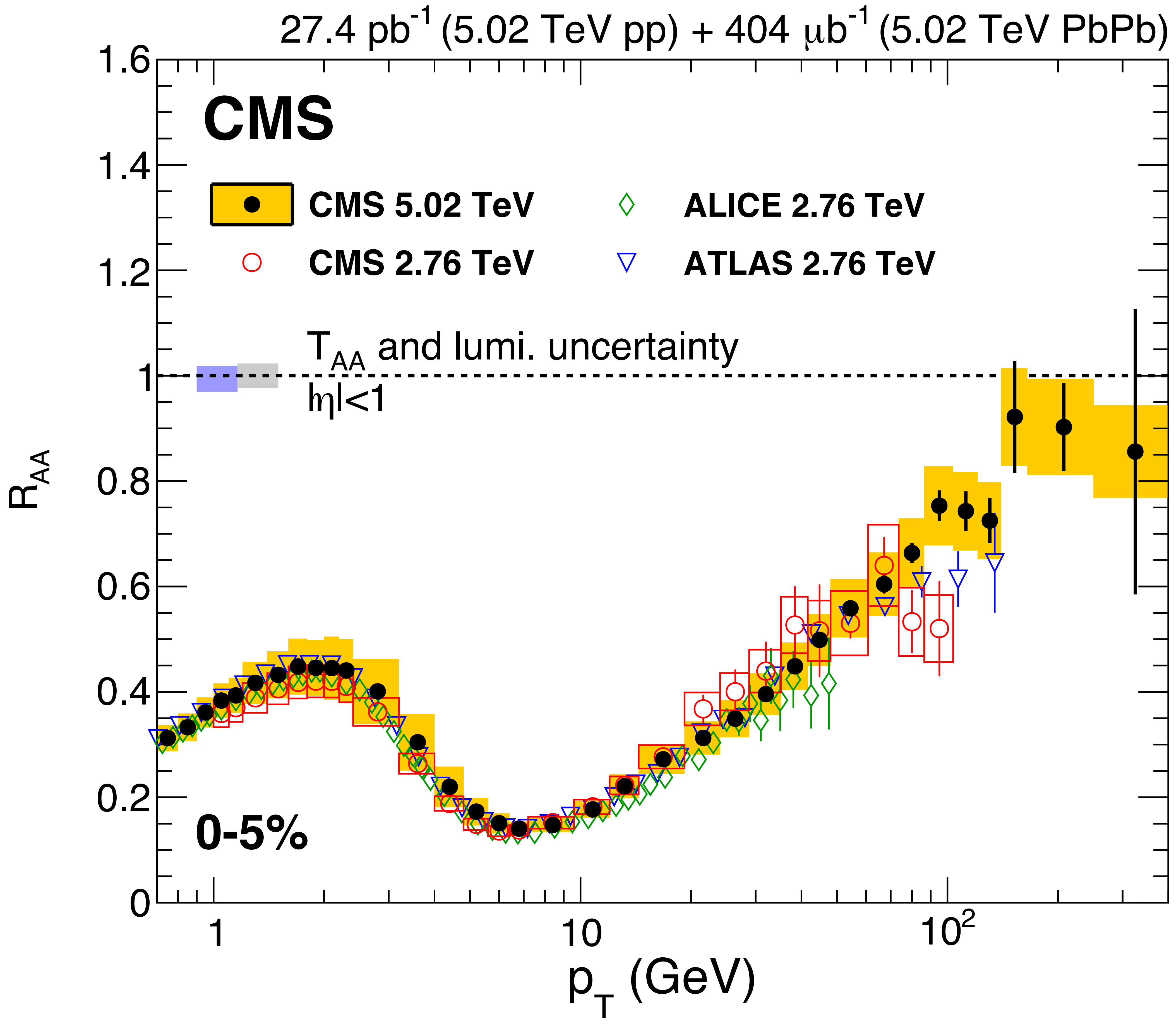


If ➜

- $R_{AA} > 1$: enhanced by medium
- $R_{AA} = 1$: no modification
  - AA collision like incoherent superposition of nucleon-nucleon scatterings
- $R_{AA} < 1$: suppressed by medium

Charged particle R_{AA}



- Color-charged probes strongly suppressed in AA collisions ⇠ Charged particles

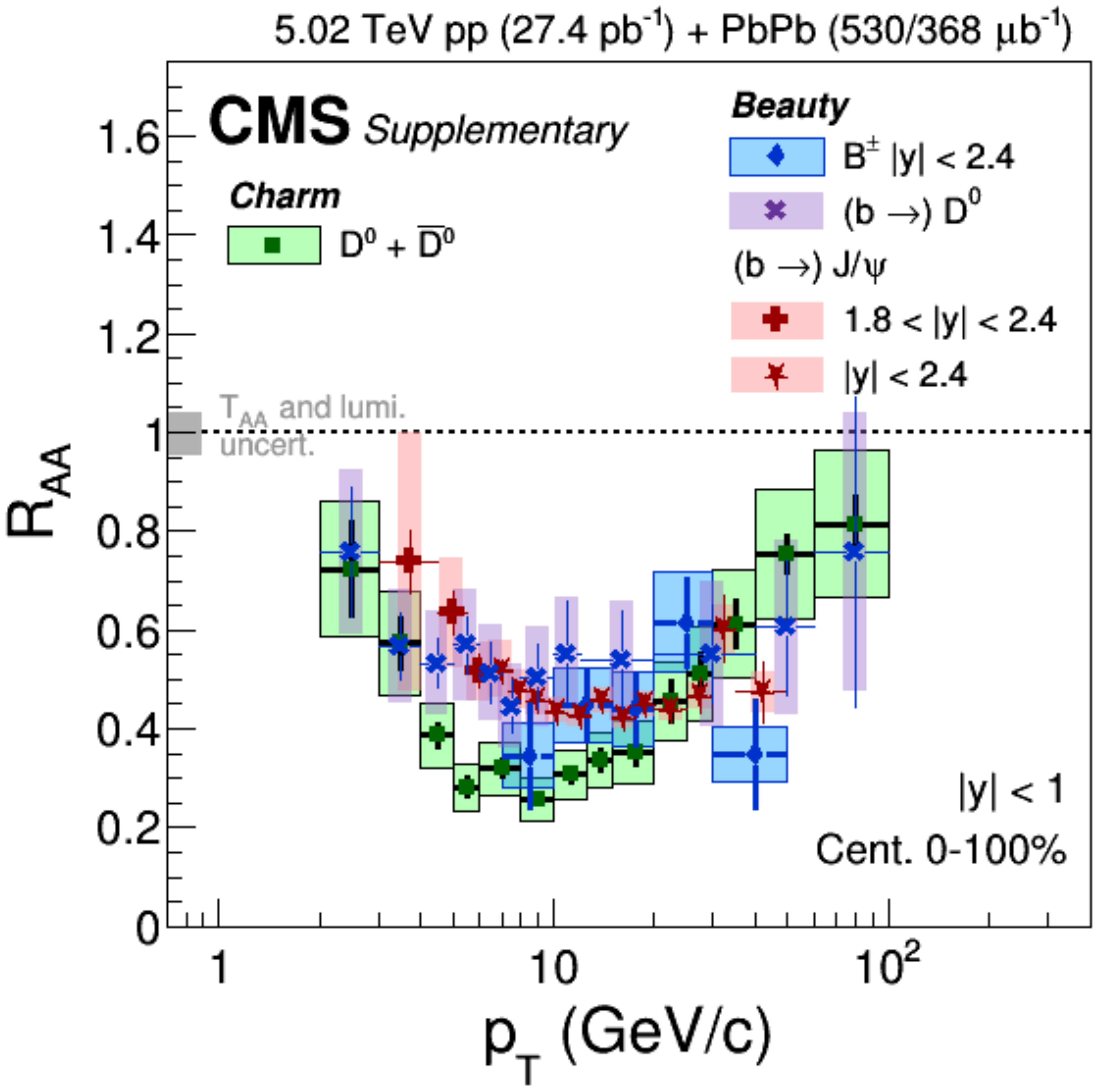
Data says ➜

- R_{AA} > 1: enhanced by medium
- R_{AA} = 1: no modification
  - AA collision like incoherent superposition of nucleon-nucleon scatterings
- R_{AA} < 1: suppressed by medium

JHEP 04 (2017) 039

Color-charged R_{AA}: Heavy flavors

Heavy-flavor R_{AA}



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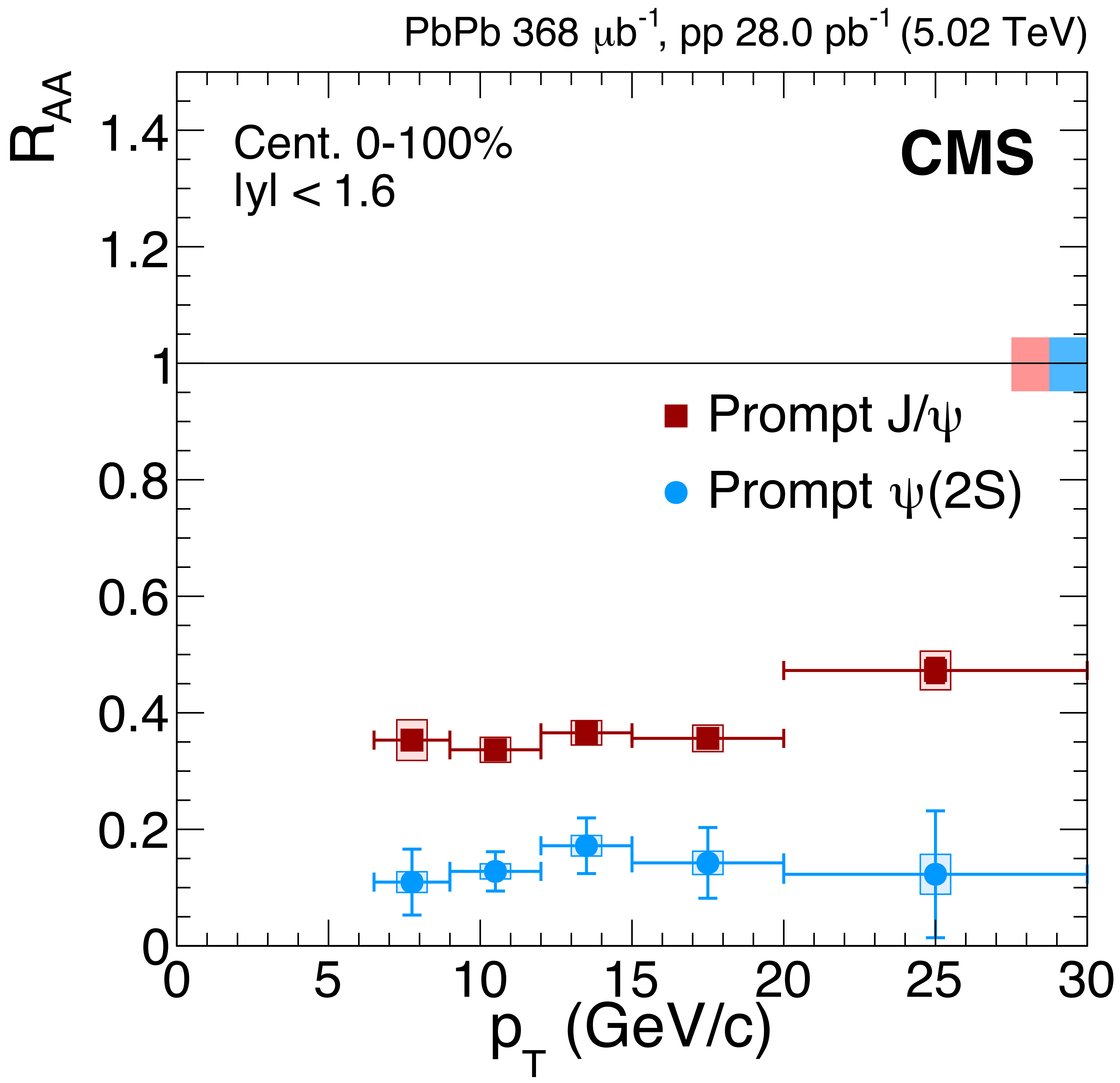
PLB 782 (2018) 474
PRL 119 (2017) 152301
EPJC 78 (2018) 509
PRL 123 (2019) 022001

Quarkonion R_{AA}



- Color-charged probes strongly suppressed in AA collisions ⇠ Quarkonia

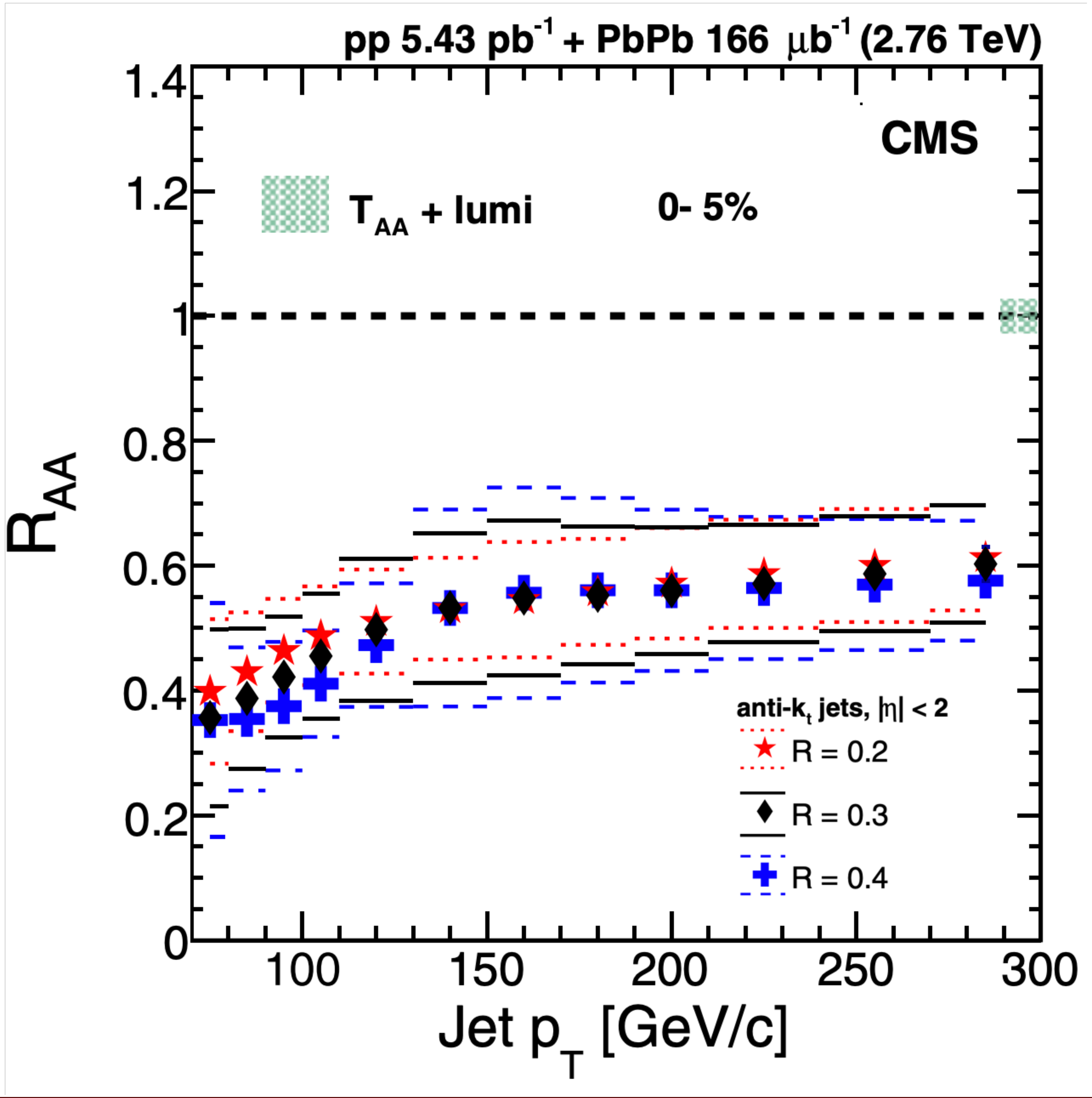
Data says ➜

- R_{AA} > 1: enhanced by medium
- R_{AA} = 1: no modification
  - **AA collision like incoherent superposition of nucleon-nucleon scatterings**
- R_{AA} < 1: suppressed by medium

EPJC 78 (2018) 509

Color-charged R_{AA}: Jets

Jet R_{AA}



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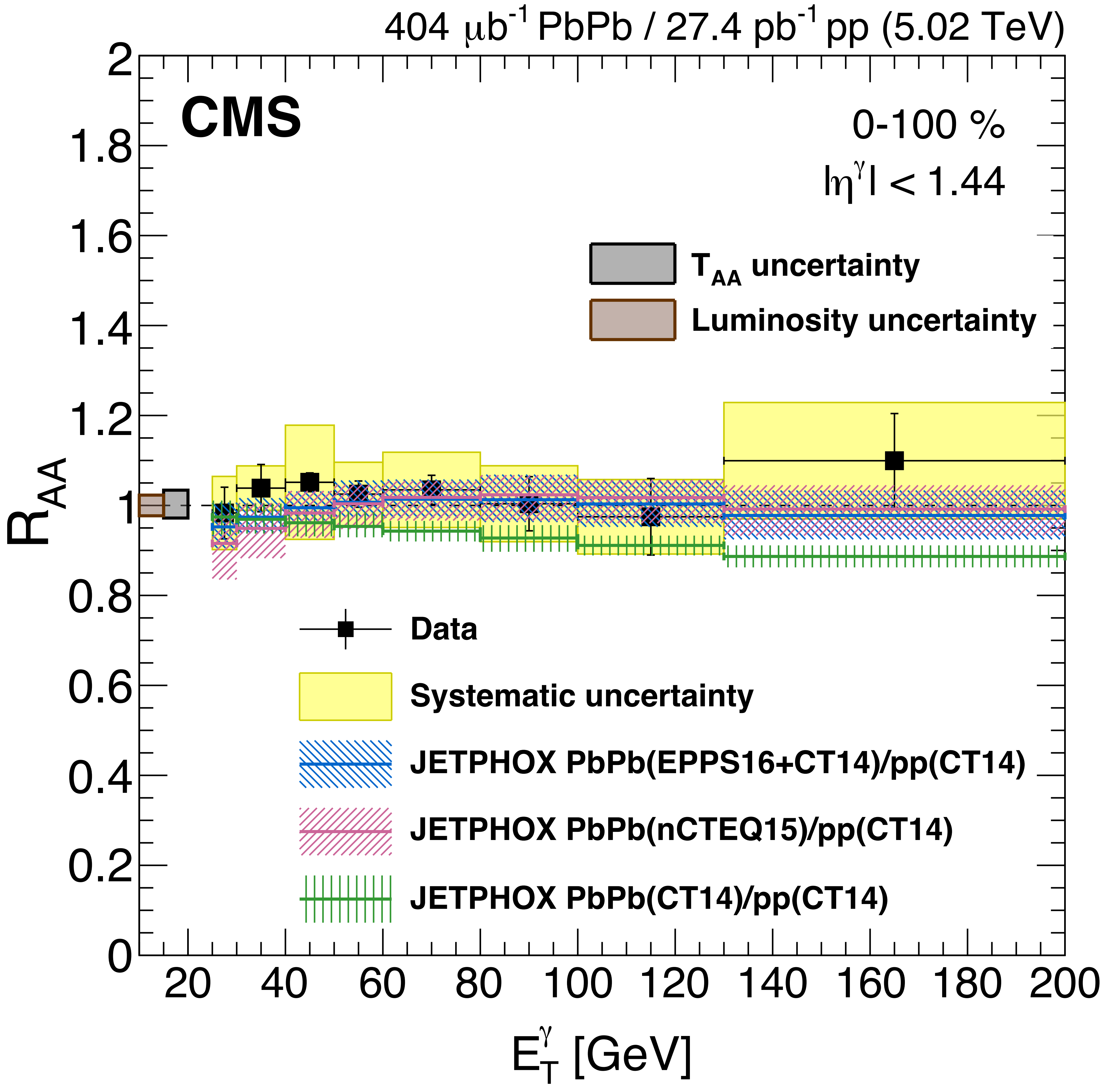
PRC 96 (2017) 015202

Colorless R_{AA}: Direct photons

Photon R_{AA}

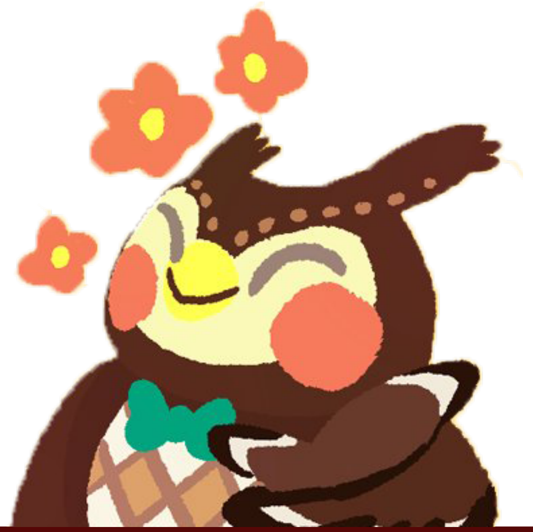


- Color-charged probes strongly suppressed in AA collisions
- Colorless probes experience no modification

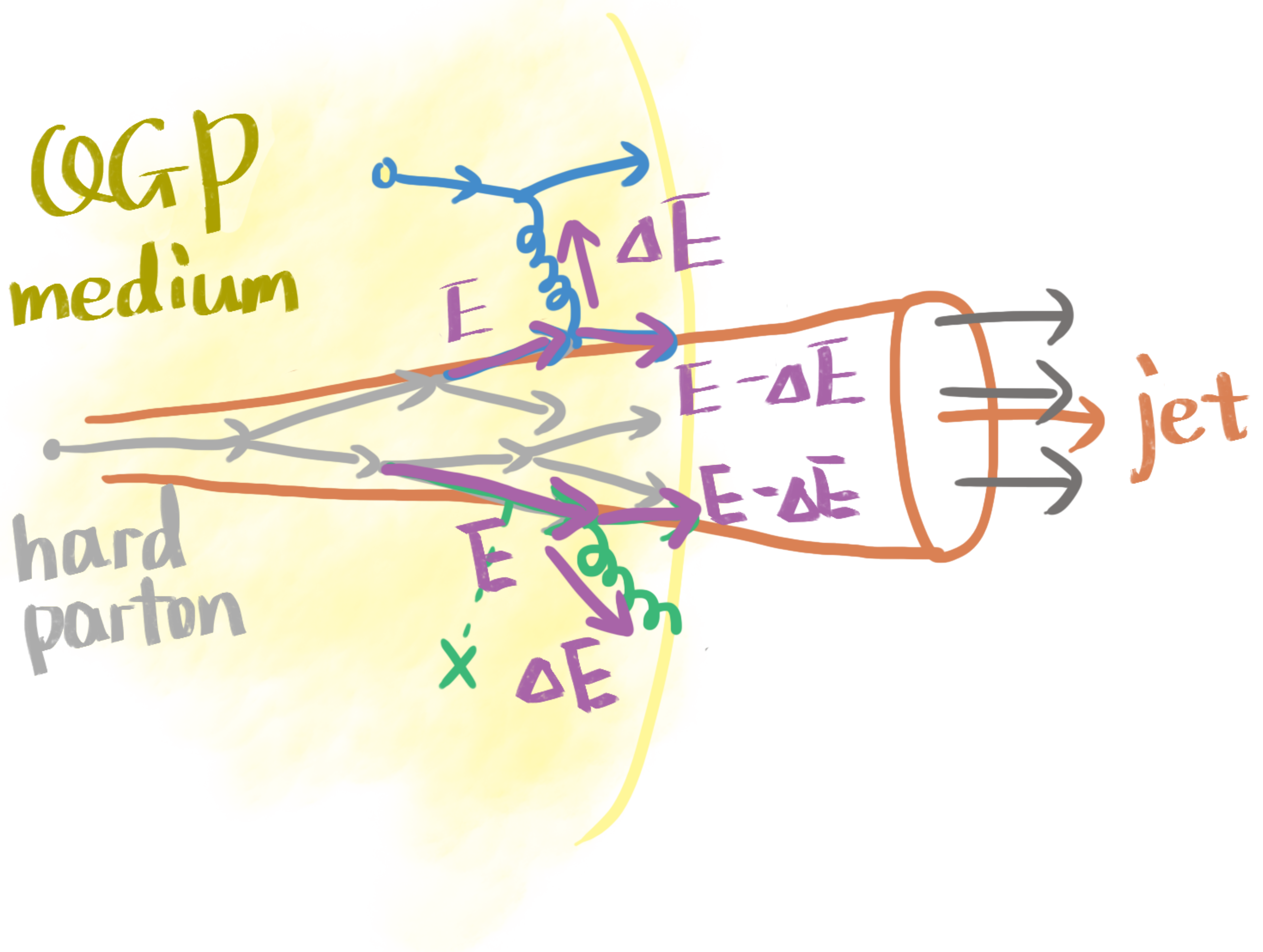
Data says ➜

- R_{AA} > 1: enhanced by medium
- R_{AA} = 1: no modification
  - AA collision like incoherent superposition of nucleon-nucleon scatterings
- R_{AA} < 1: suppressed by medium

arXiv:2003.12797

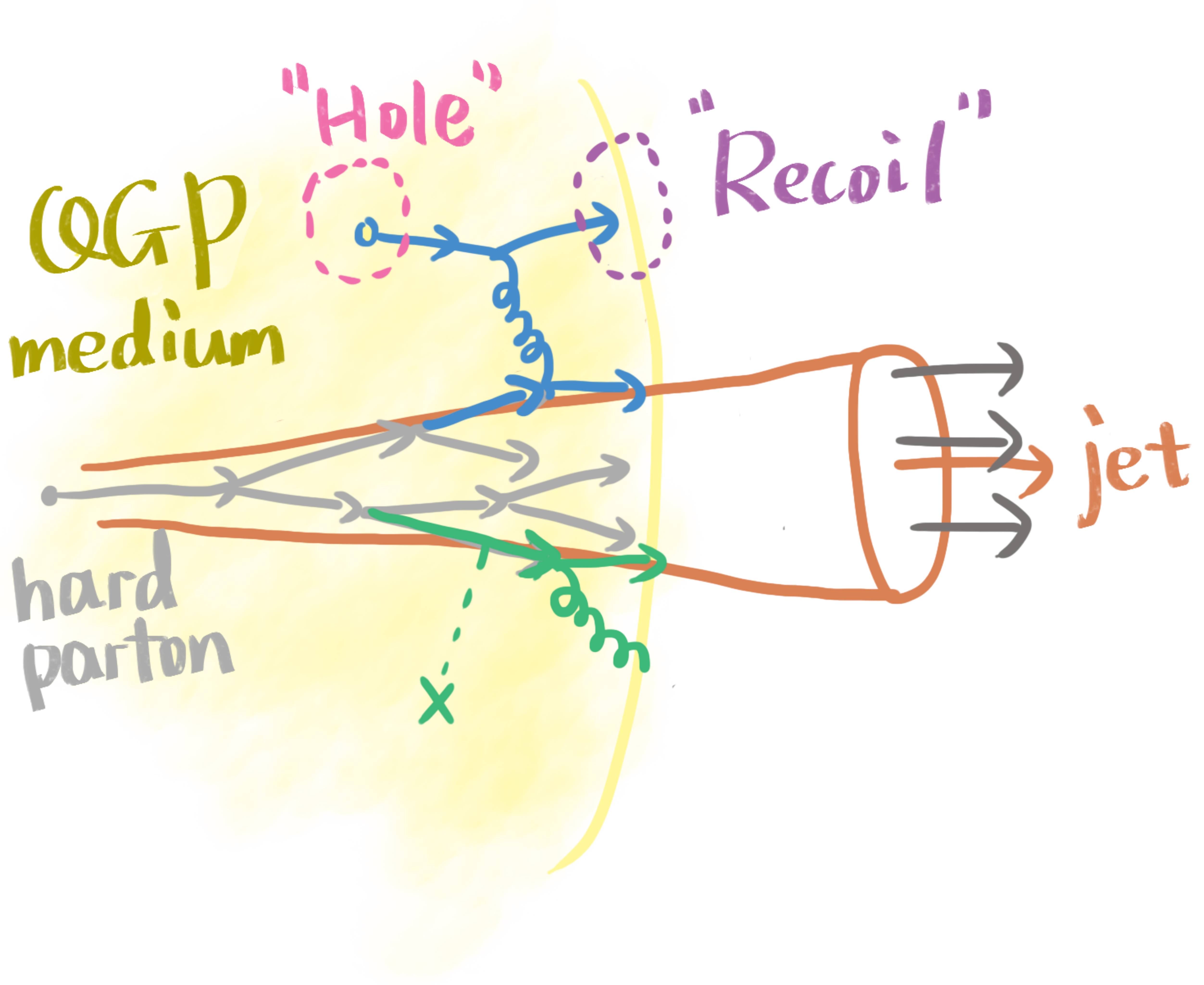


Medium response



Medium response (to jets)

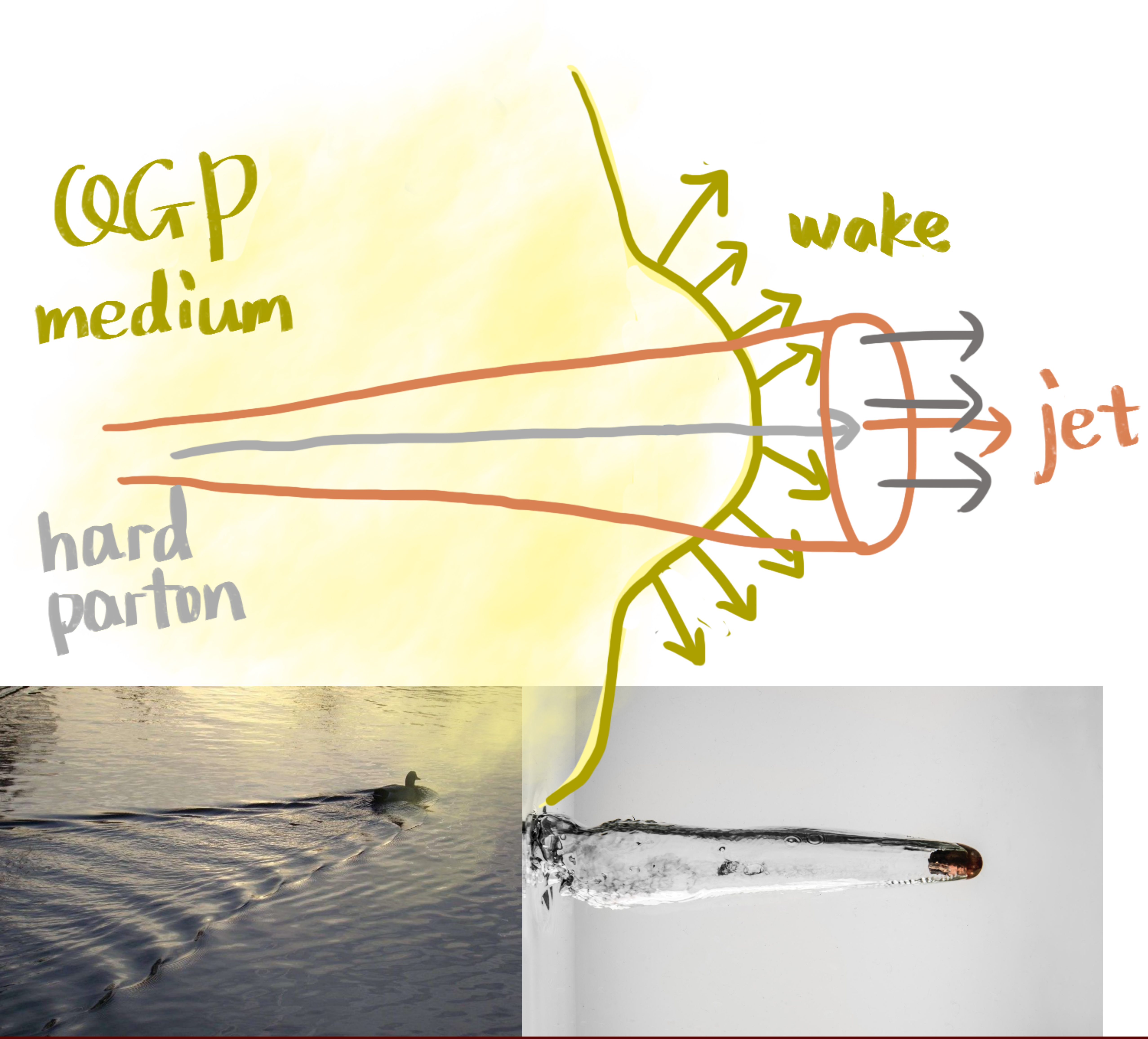
- Energy deposited into medium
- Medium excitation induced by jets



Two descriptions:

- **Recoils** (weakly coupled)
  Kinetic theory based approach
  - Medium partons picking energy scattered off from medium
  - Remain a "hole" where the parton was

Describe Medium response (II): Hydro



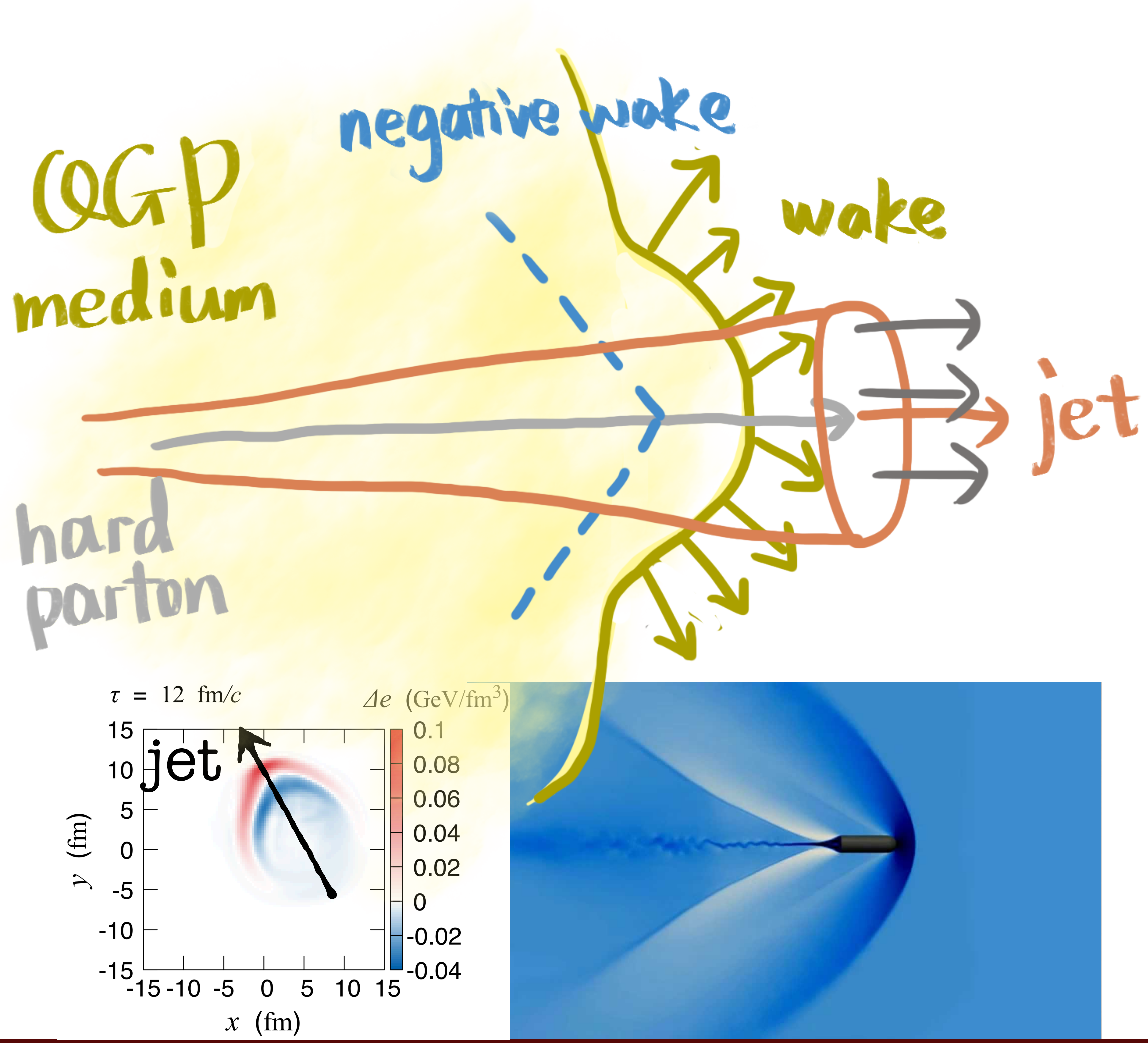
Two descriptions:

- **Recoils** (weakly coupled)
  Kinetic theory based approach

Multiple interactions among many medium particles ➜ Thermalized

- **Hydro response** (strongly coupled)
  Hydrodynamics based approach
  - Evolution as part of bulk medium
  - Diffusion wake

Describe Medium response (II): Hydro

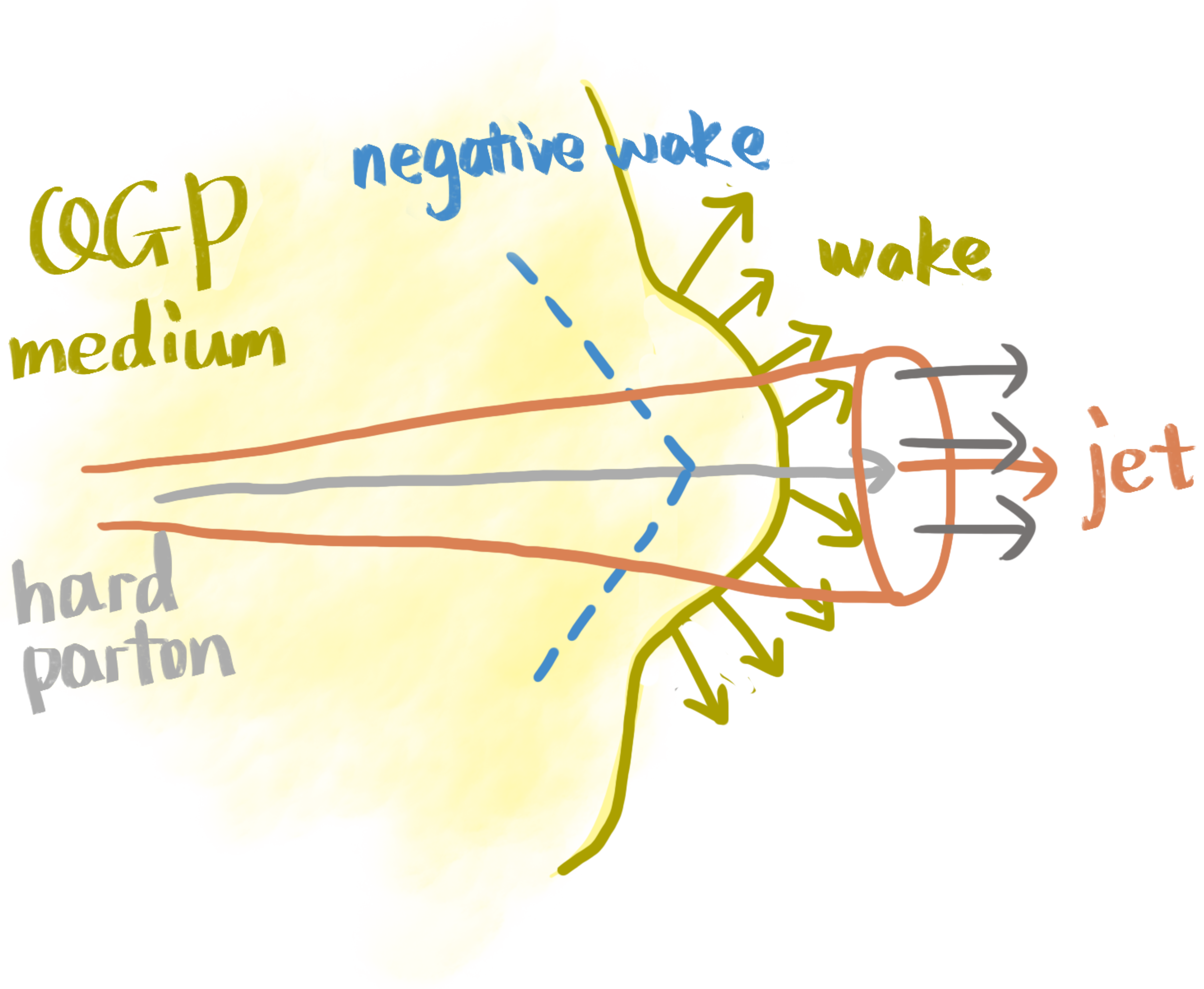


Two descriptions:

- **Recoils** (weakly coupled)
  Kinetic theory based approach

- **Hydro response** (strongly coupled)
  Hydrodynamics based approach
  - Evolution as part of bulk medium
  - Diffusion wake
  - Negative wake at back of hard parton
    ➡ “Holes” in hydro language

Describe Medium response



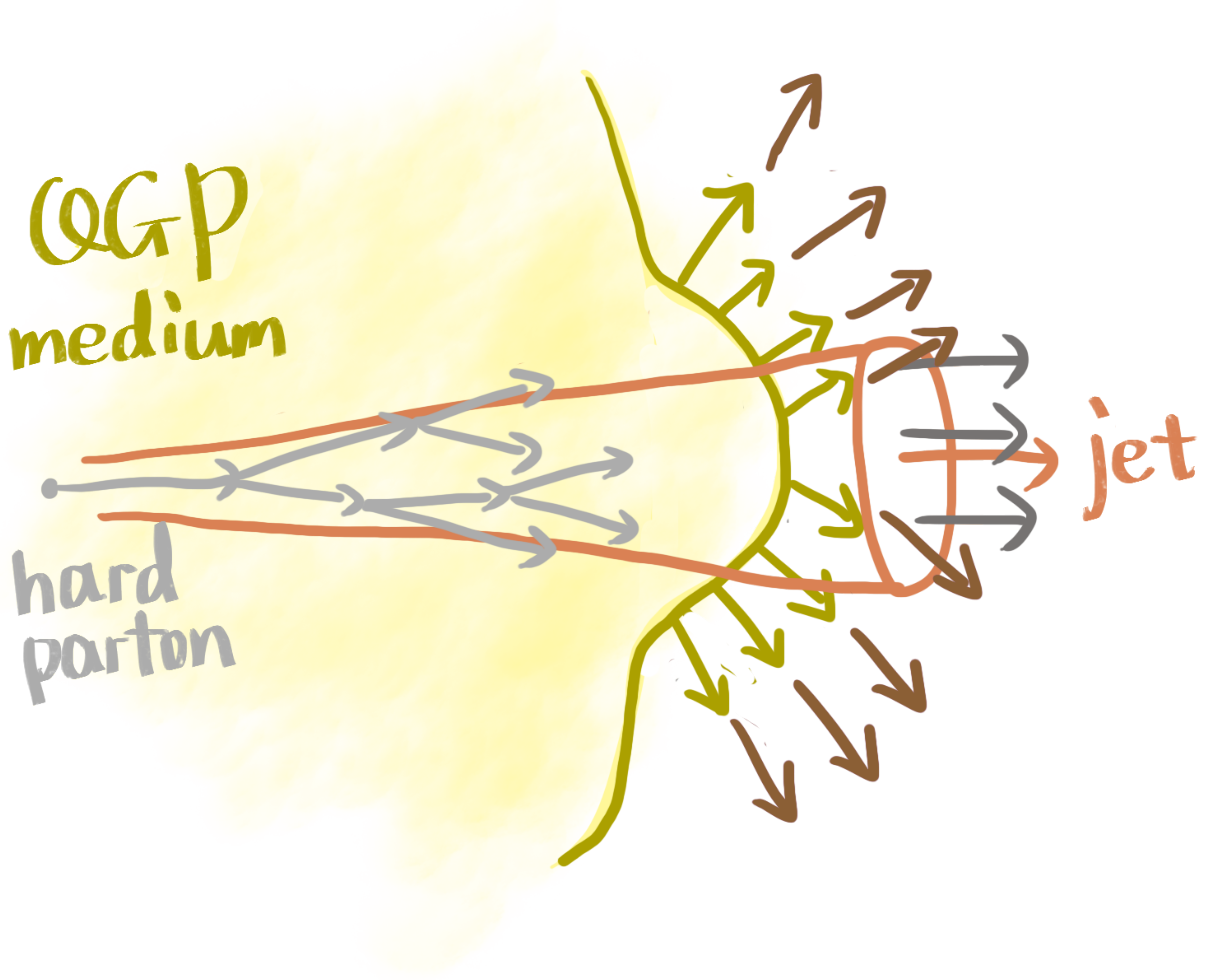
Two descriptions:

- **Recoils** (weakly coupled)
  Kinetic theory based approach

Models consider different thermalization level

- **Hydro response** (strongly coupled)
  Hydrodynamics based approach

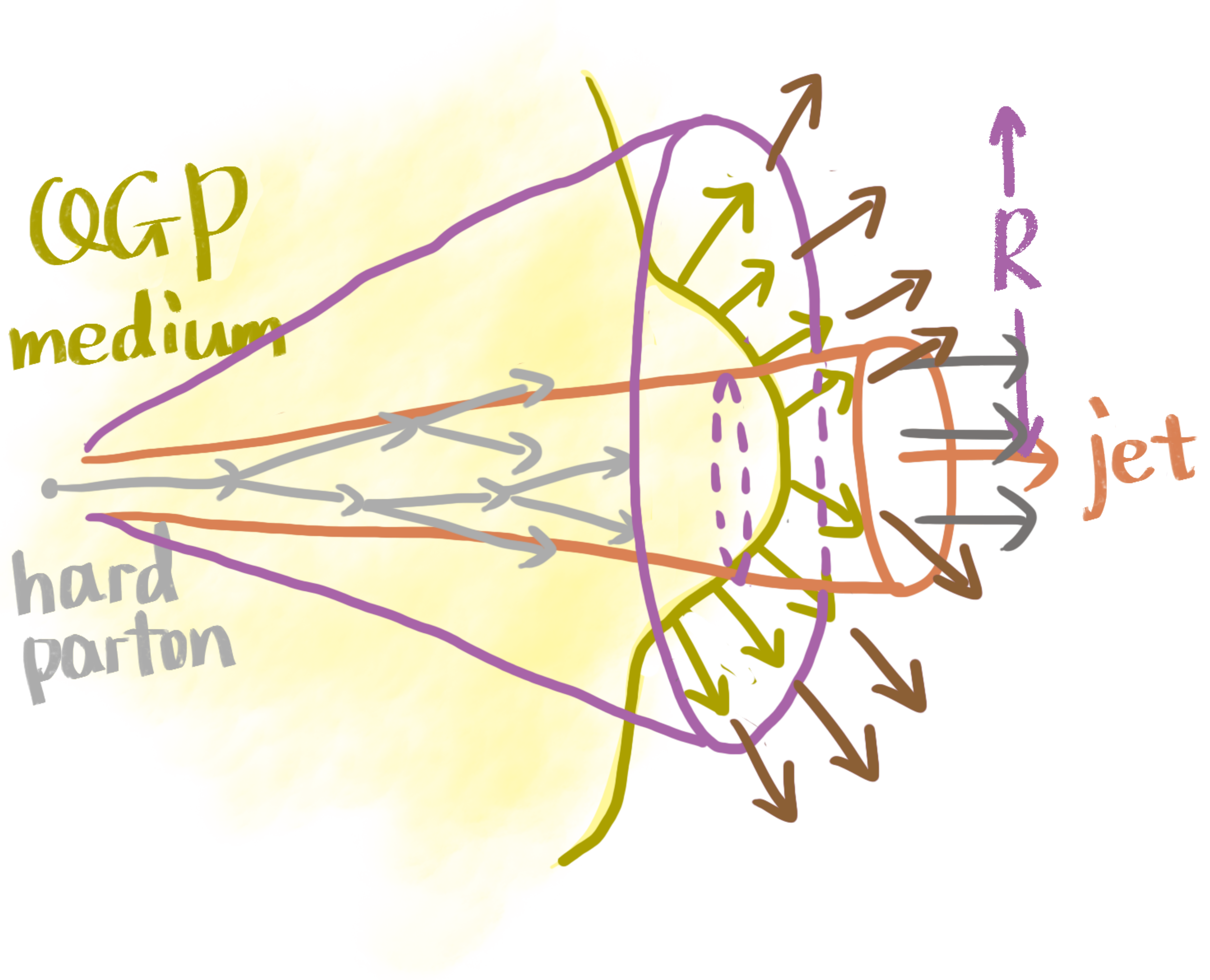
Medium response effects



Excited medium partons

- Added to jet shower
- Spread out: large angle
- Particle emission near jet modified
- Correlated with jet: will not be subtracted as background

Large radius



Scan through increasing R

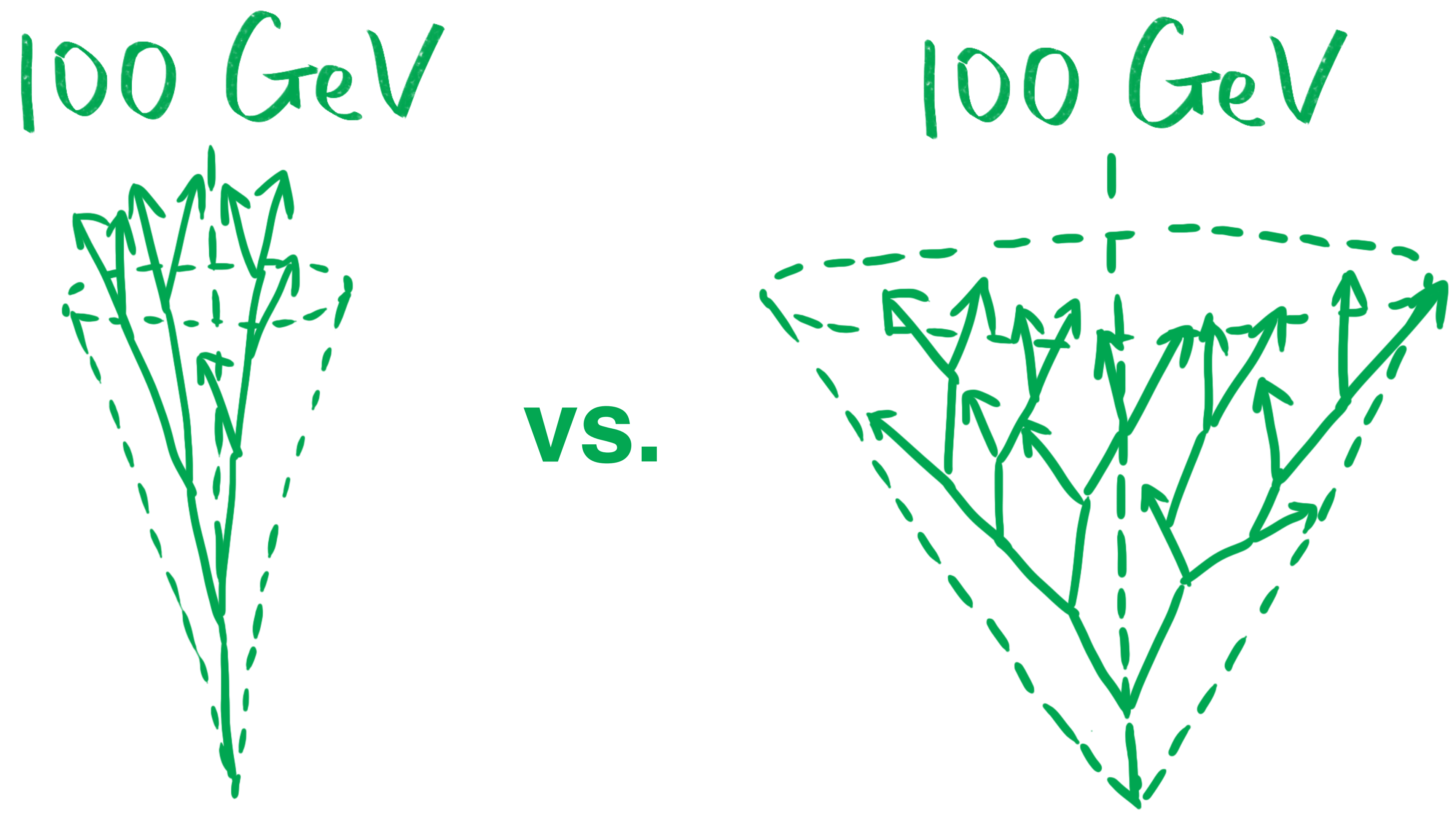
➡ **Recover energy**

- Sensitive to medium response

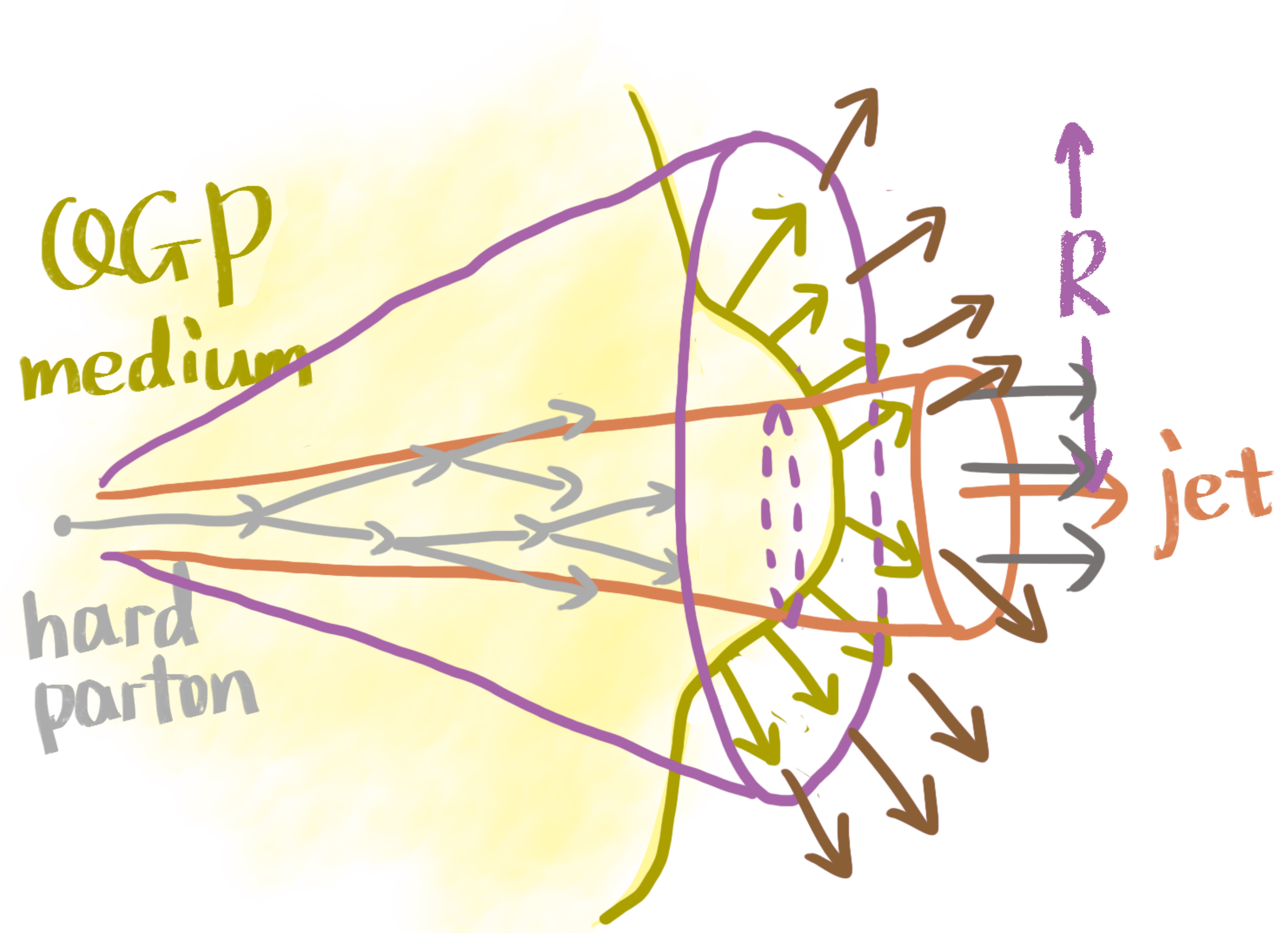
➡ **Select different jet population**

- Different shower structure quenched differently

➜ R-dependence reflects abundant effects



Large radius



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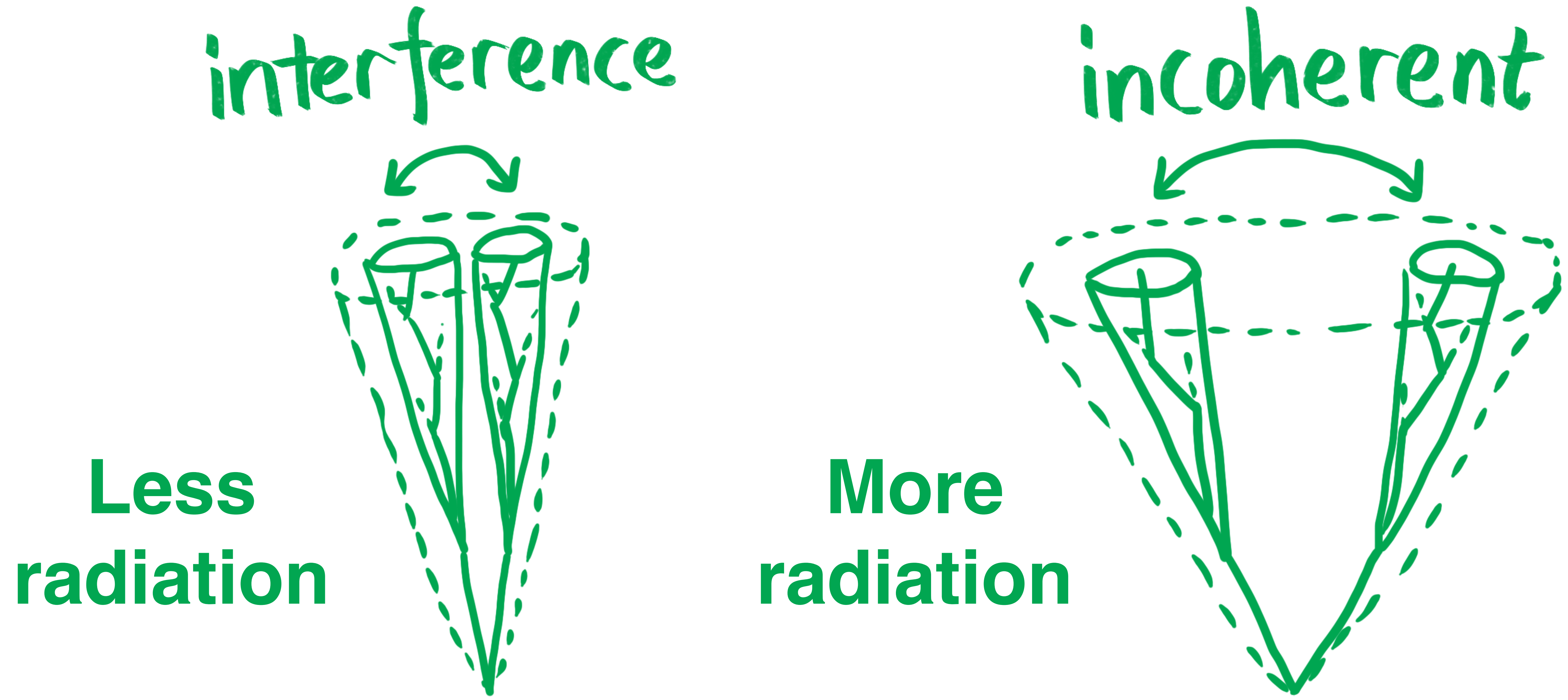


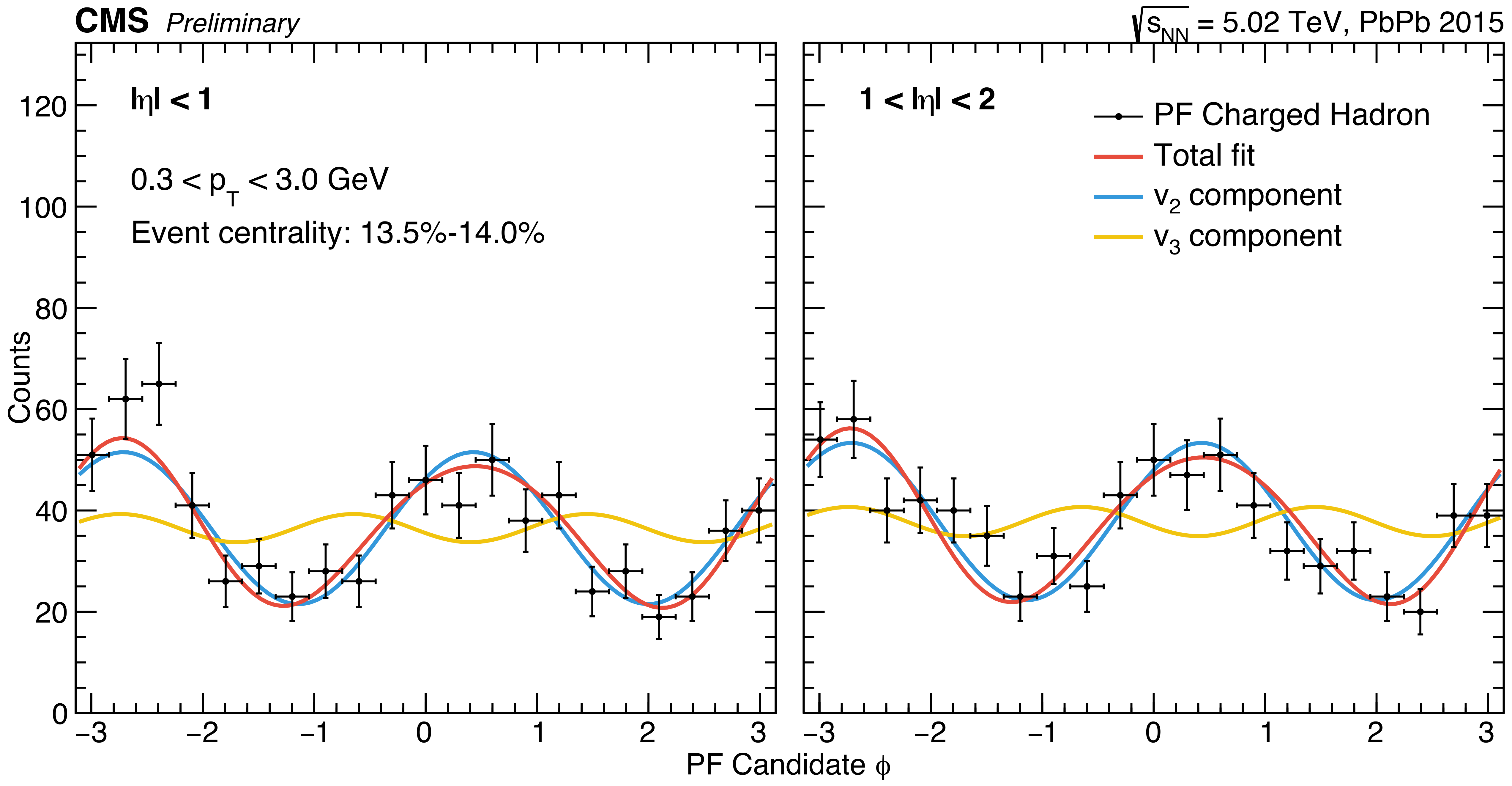
Jet R_{AA} with large radius in PbPb

[CMS-PAS-HIN-18-014]

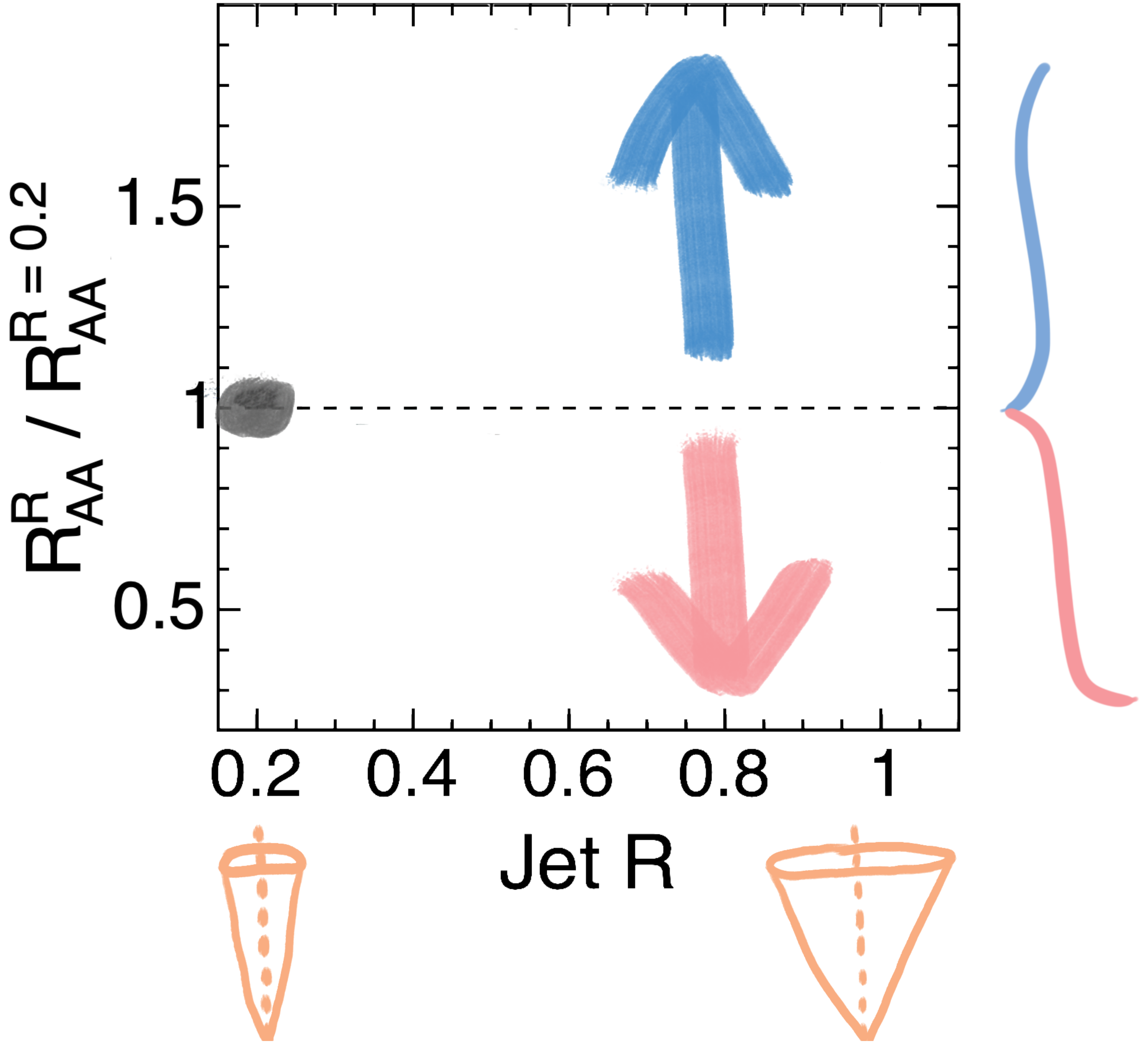
2015 data

Jet R_{AA}: Analysis Strategy

- Reconstruct jets from particle-flow candidates with anti-k_T algorithm using $R = 0.2$, 0.3, 0.4, 0.6, 0.8, 1.0
- Subtract underlying event (UE) background in an iterative procedure
  - Azimuthal structure of this UE
- Correct energy scales
- Unfolding follows D'agostini iterative method as implemented in rooUnfold



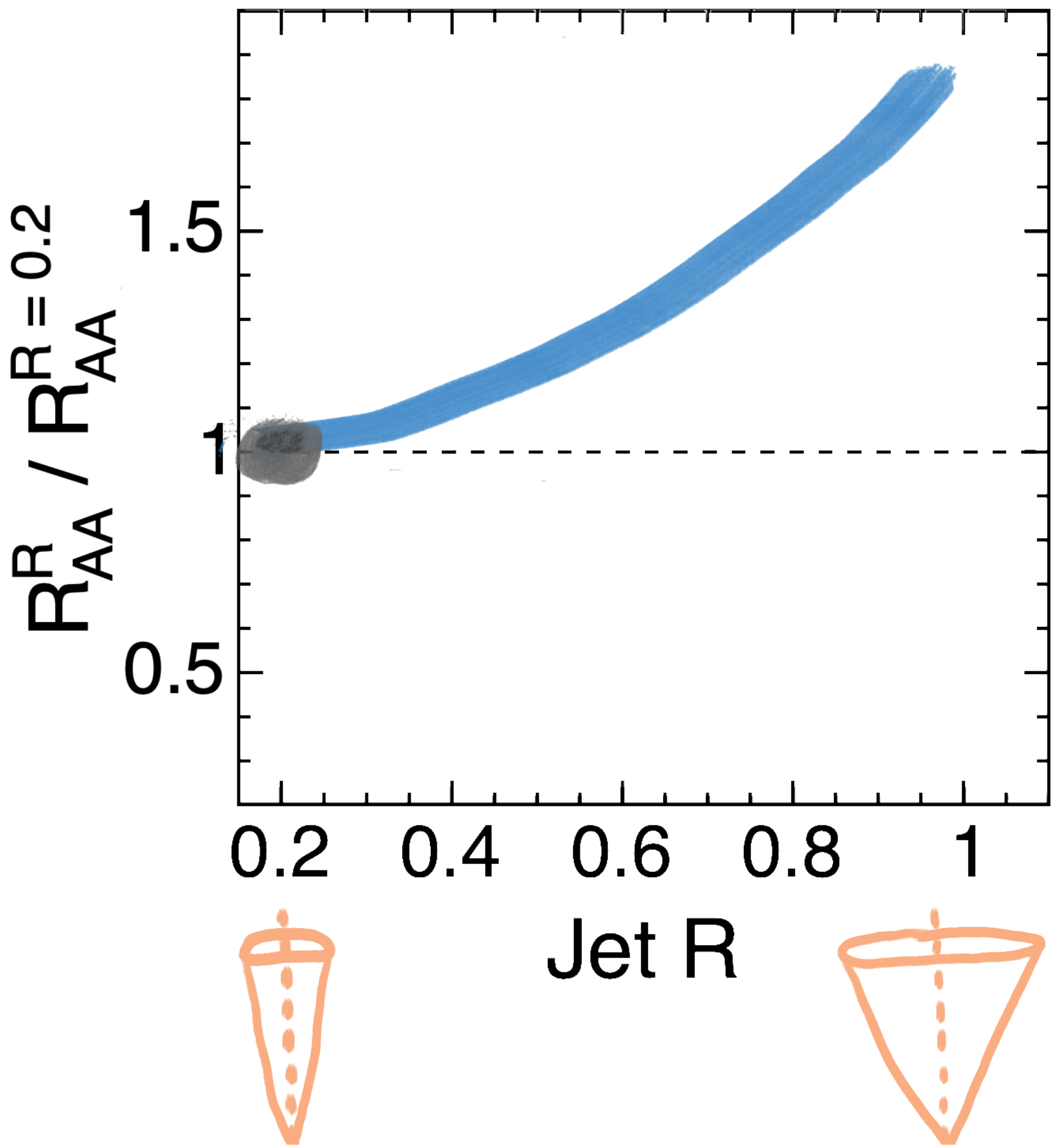
R dependence: Imagine



Less suppressed than R = 0.2

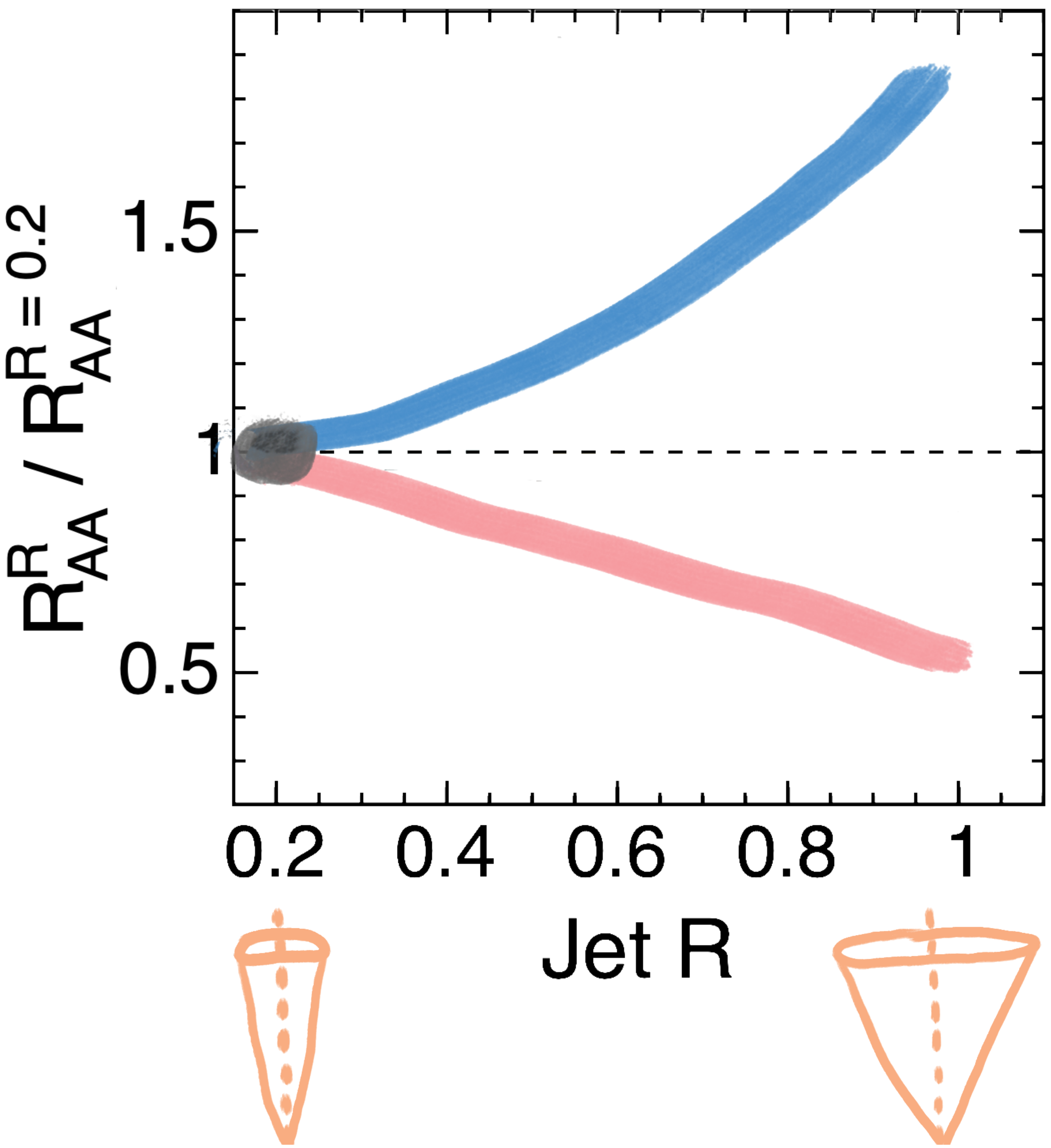
More suppressed than R = 0.2

R dependence: Imagine



- Quenched energy recoverery
  ➡ Large angle spread out

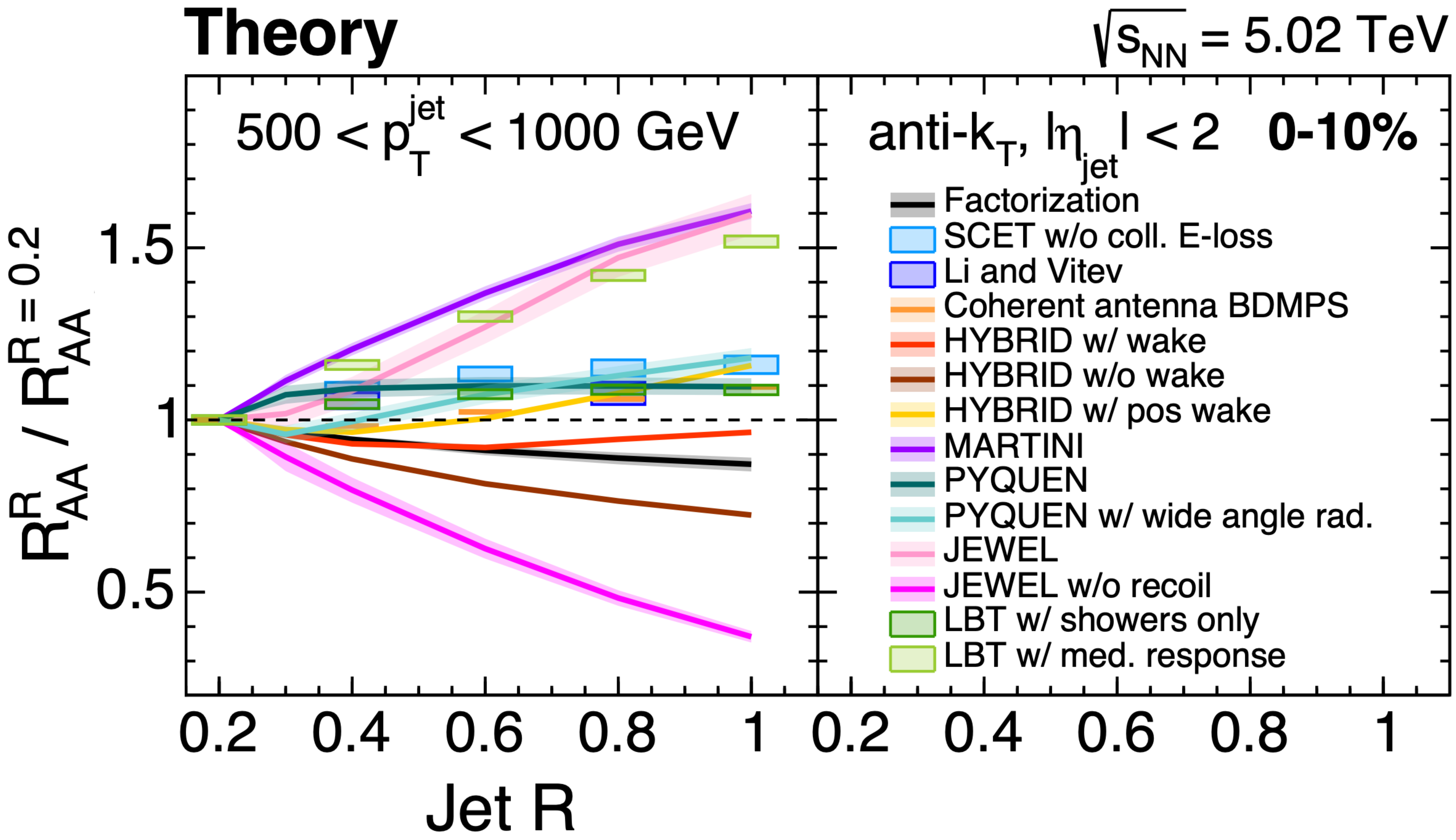
R dependence: Imagine



Competing effects

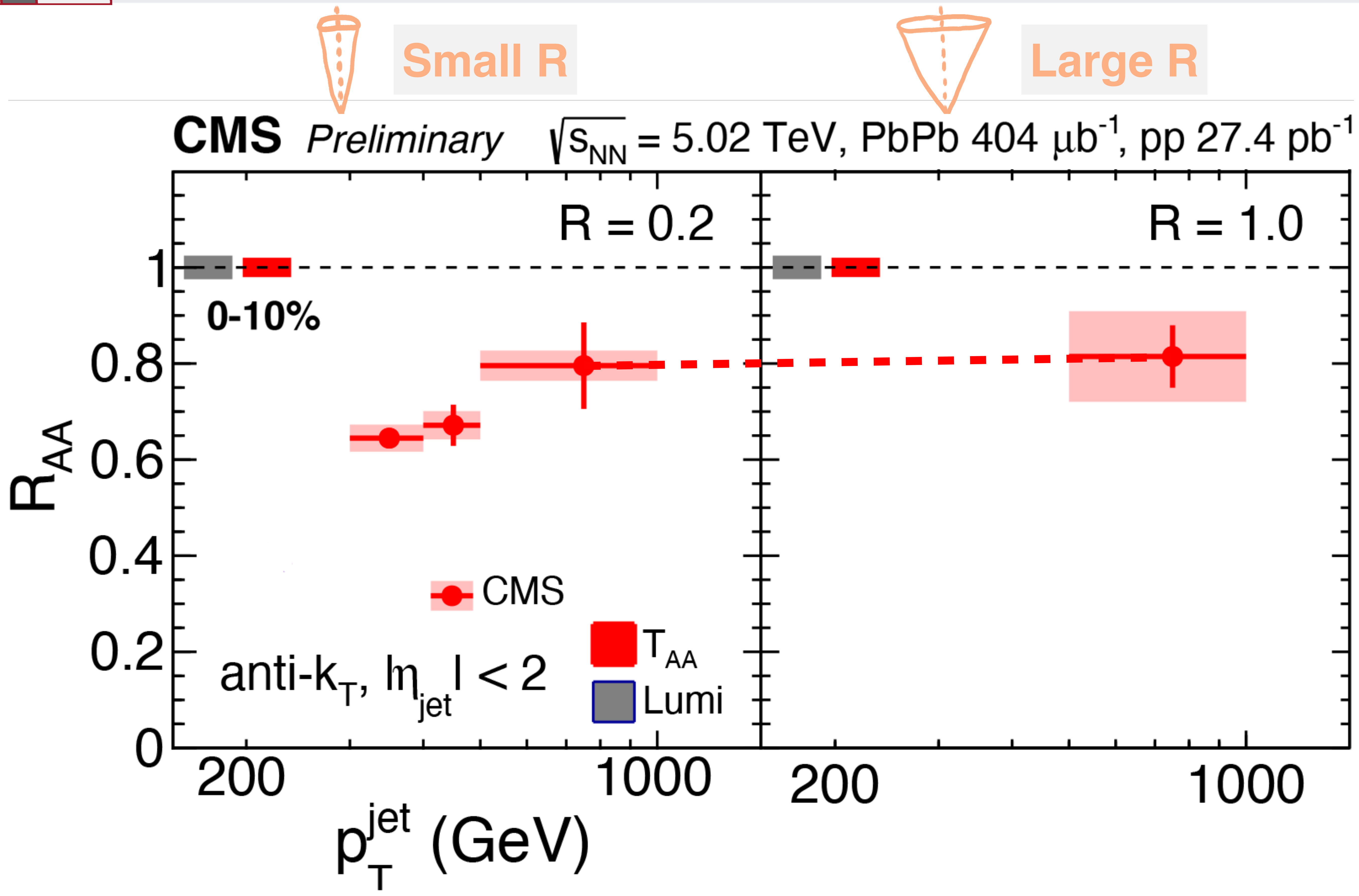
- Quenched energy recoverery
  ➡ Large angle spread out
- Different jet population
  ➡ Increase R: wider jet
  Wider jets suppressed more

R dependence: Theory



- Great discrimination power for models!

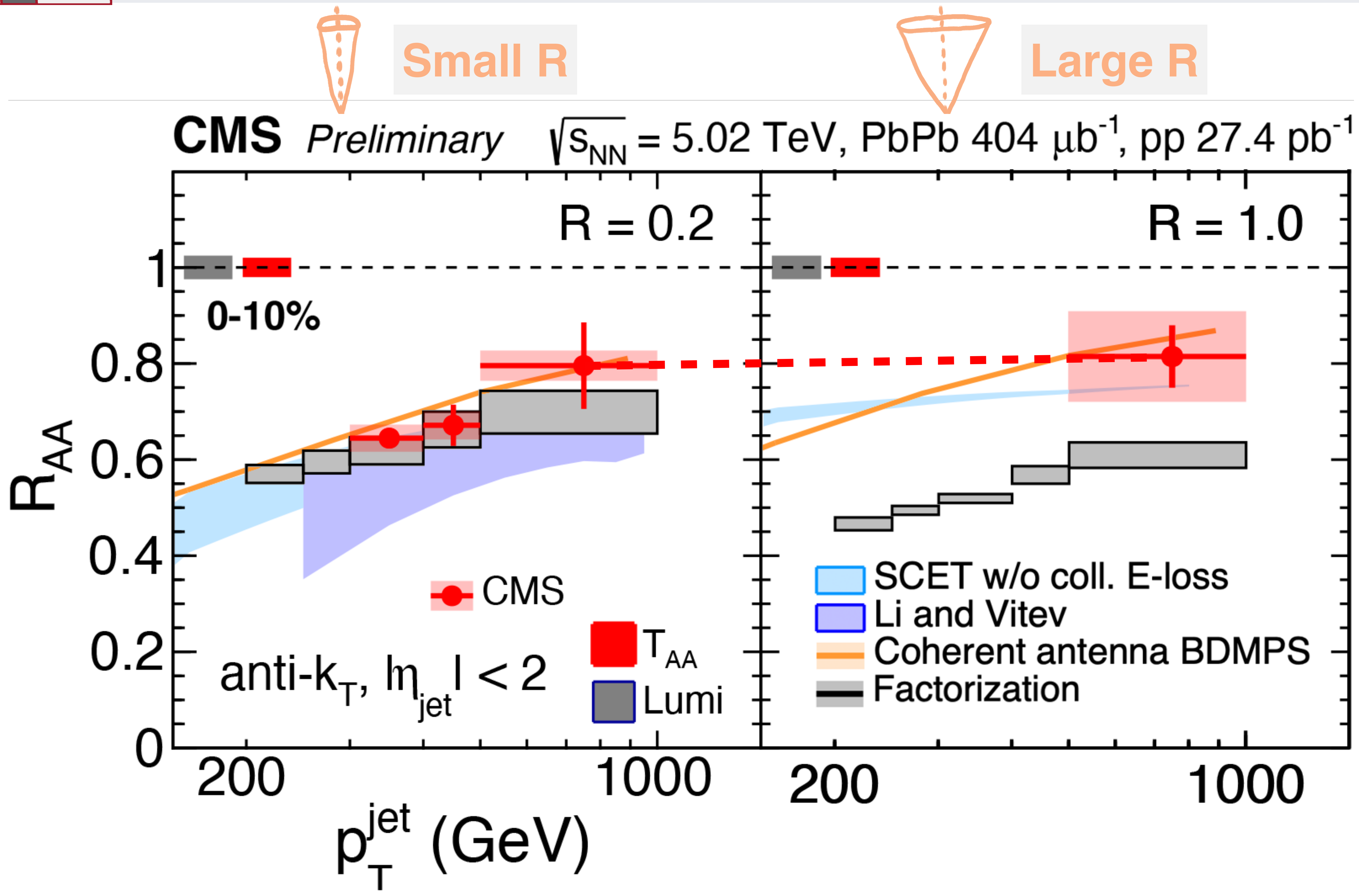
R dependence: Data



Results with other R values and centrality classes see backup slides

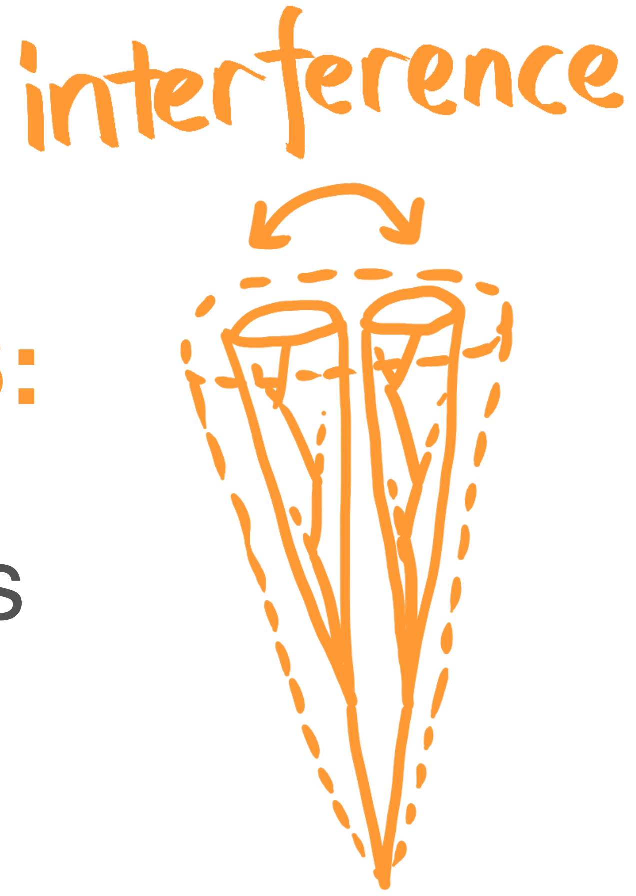
- First measurement to large radius up to R = 1.0
- Very mild R dependence

Data vs. Model (I)



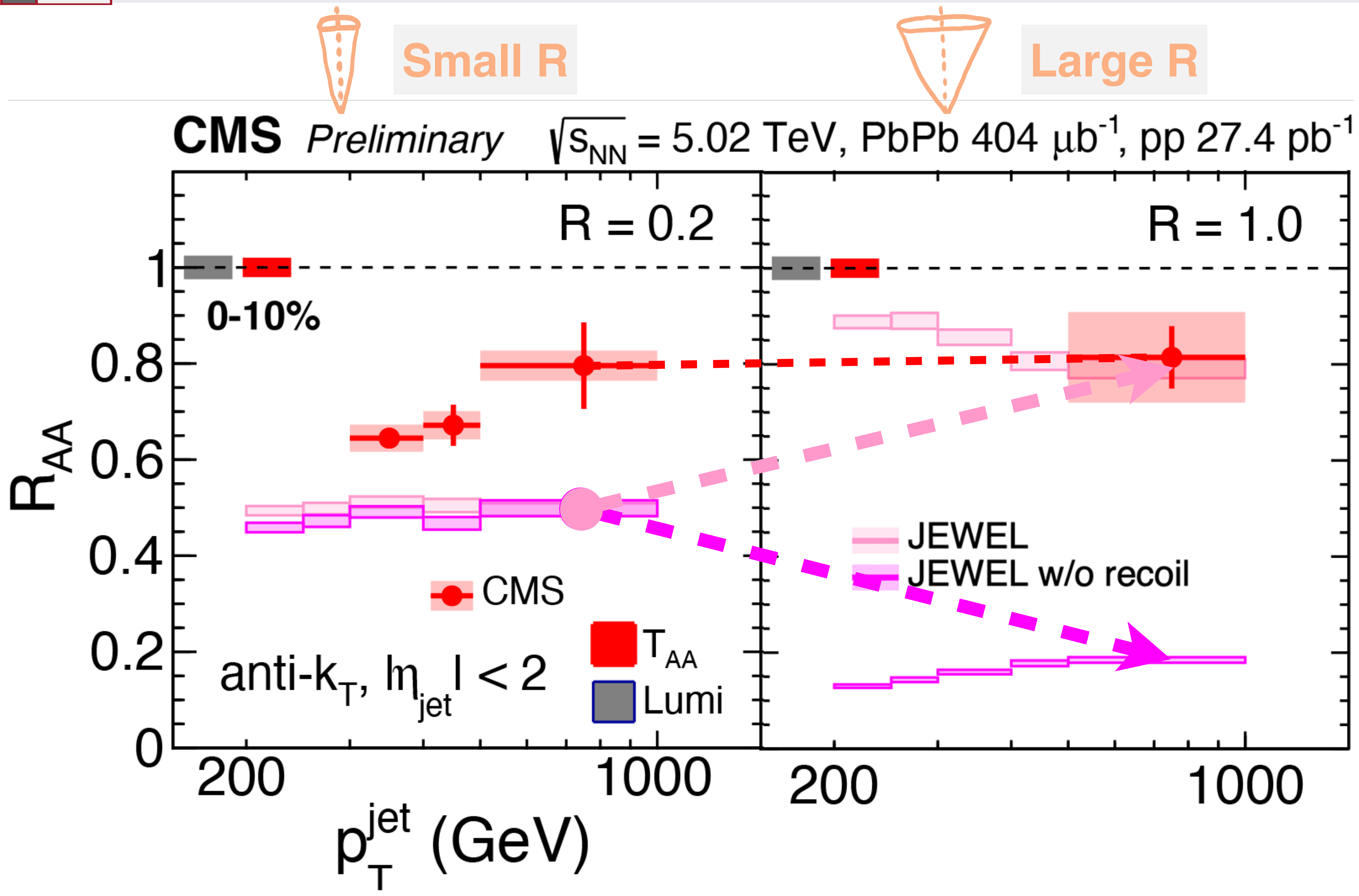
	SCET$_G$	Li & Vitev	BDMPS	Factorization
Quench	SCET	SCET	BDMPS-Z	-
Medium Response	No response			

- **SCET$_G$:** w/o collisional energy loss
  JHEP 05 (2016) 023
- **Li, Vitev:** built on SCET$_G$ w/ coll. Eloss
  JHEP 07 (2019) 148, PLB 795 (2019) 502
- **Coherent antenna BDMPS:**
  PRD 98 (2018) 5, 051501
  Interference between emitters

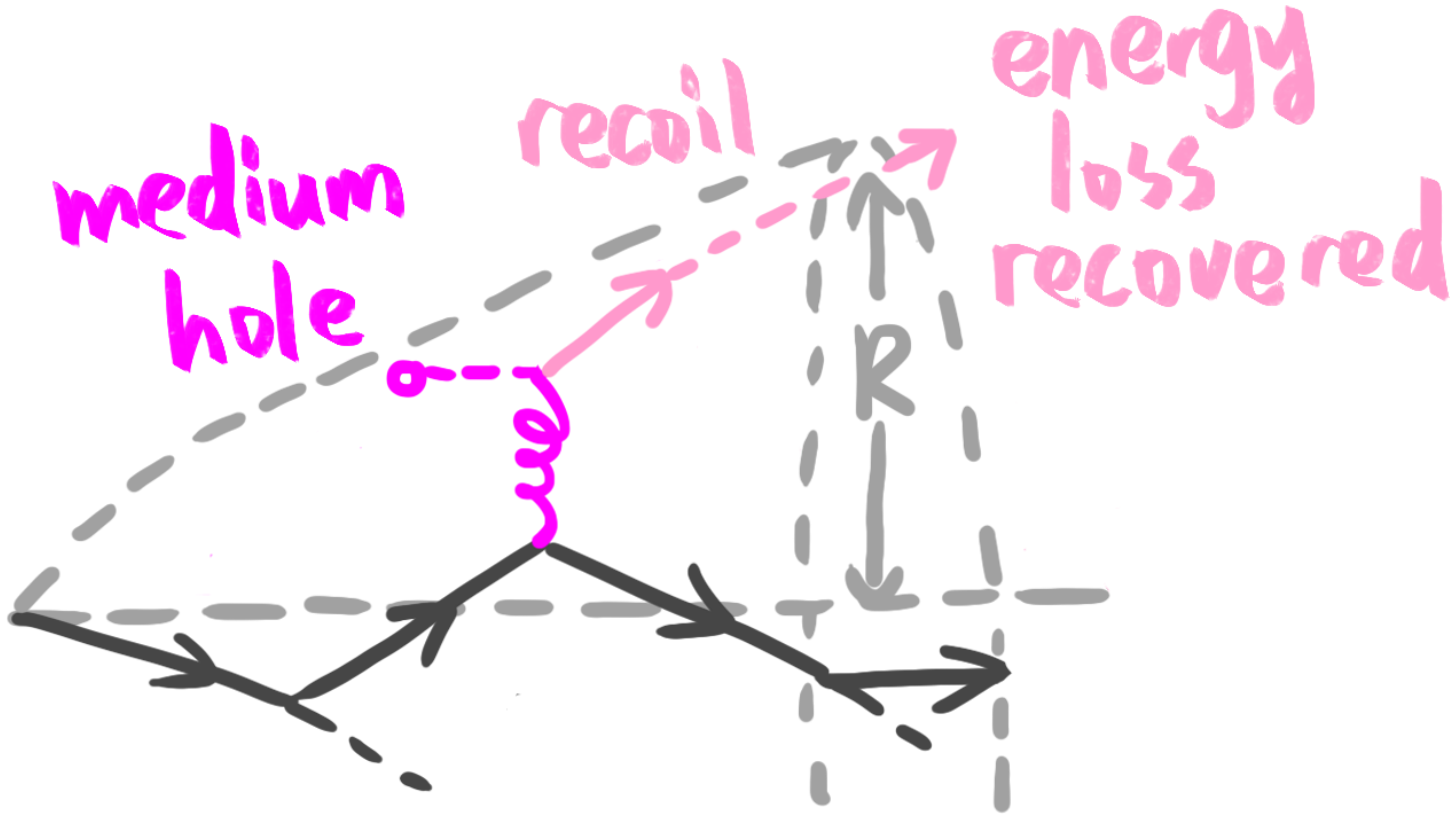


- **Factorization:** miss magnitude at large R
  PRL 122 (2019) 252301
  Assume universal fragmentation function, extrapolate to large R from small R data

Data vs. Model (II)



- Recoil parton no multi-scattering
➜ Response too collimated to jet axis

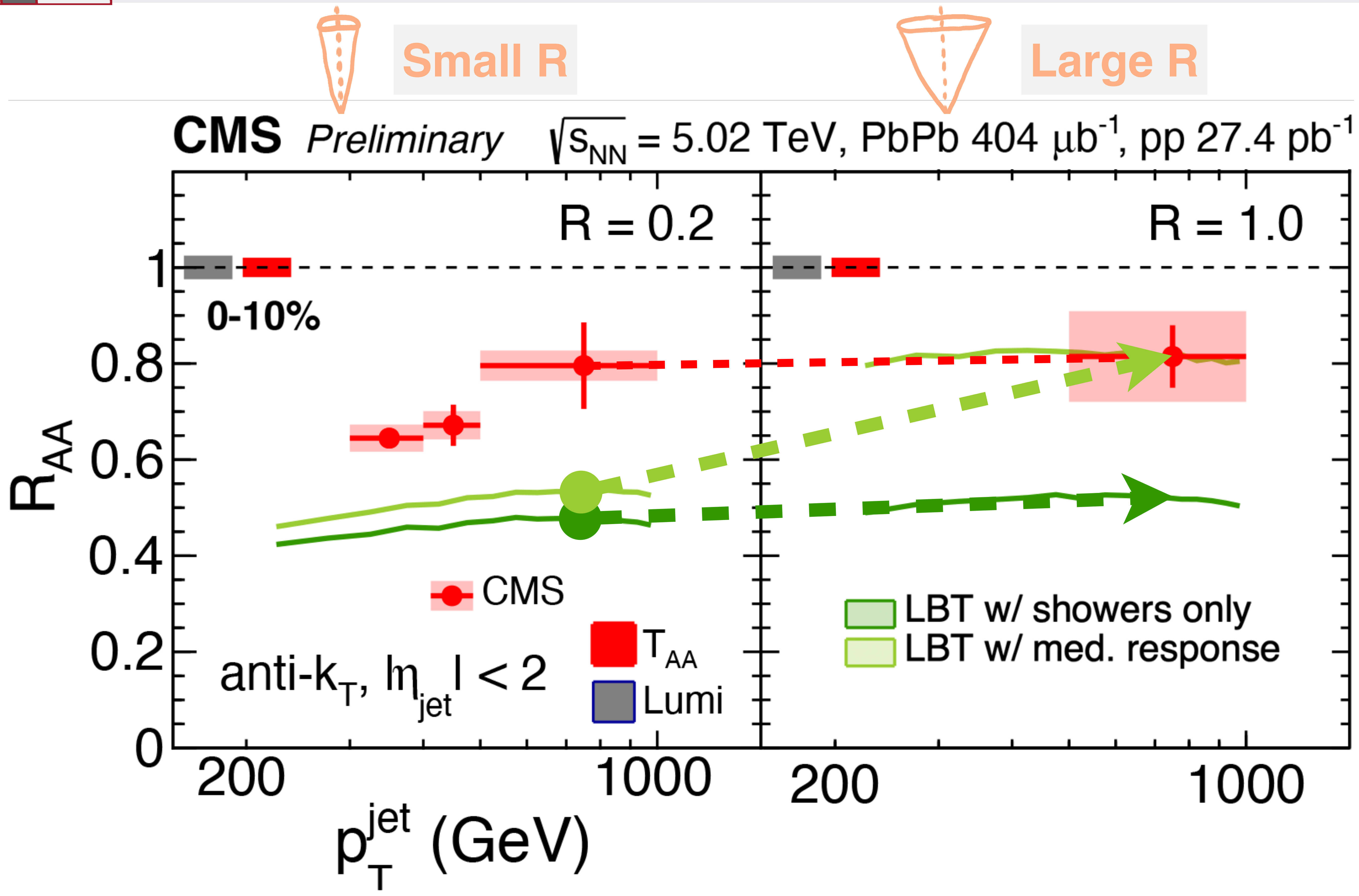


JEWEL JHEP 1707 (2017) 141

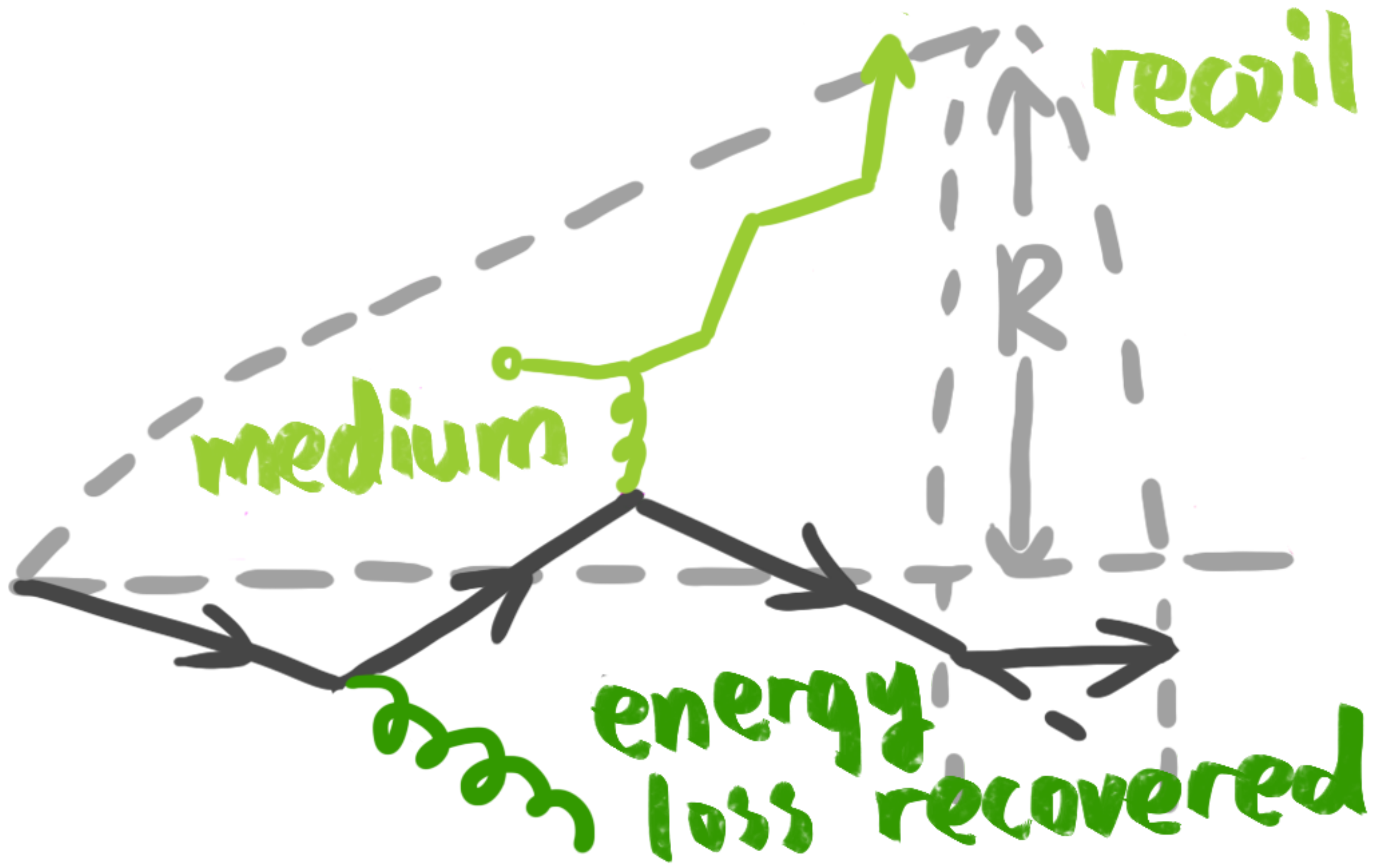
- **w/o recoils:** unphysical, misses R behavior completely
- **w/ recoils:** Overestimate R dependence

JEWEL	
Quench	BDMPS-Z
Medium Response	Recoils

Data vs. Model (III)



- Effective strong coupling constant extracted from fitting ATLAS data
- Medium evolves independently of recoil partons in linear approximation

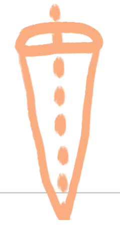


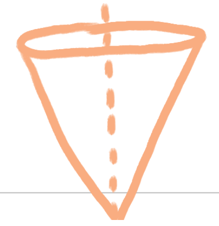
LBT PRC 99 (2019) 054911

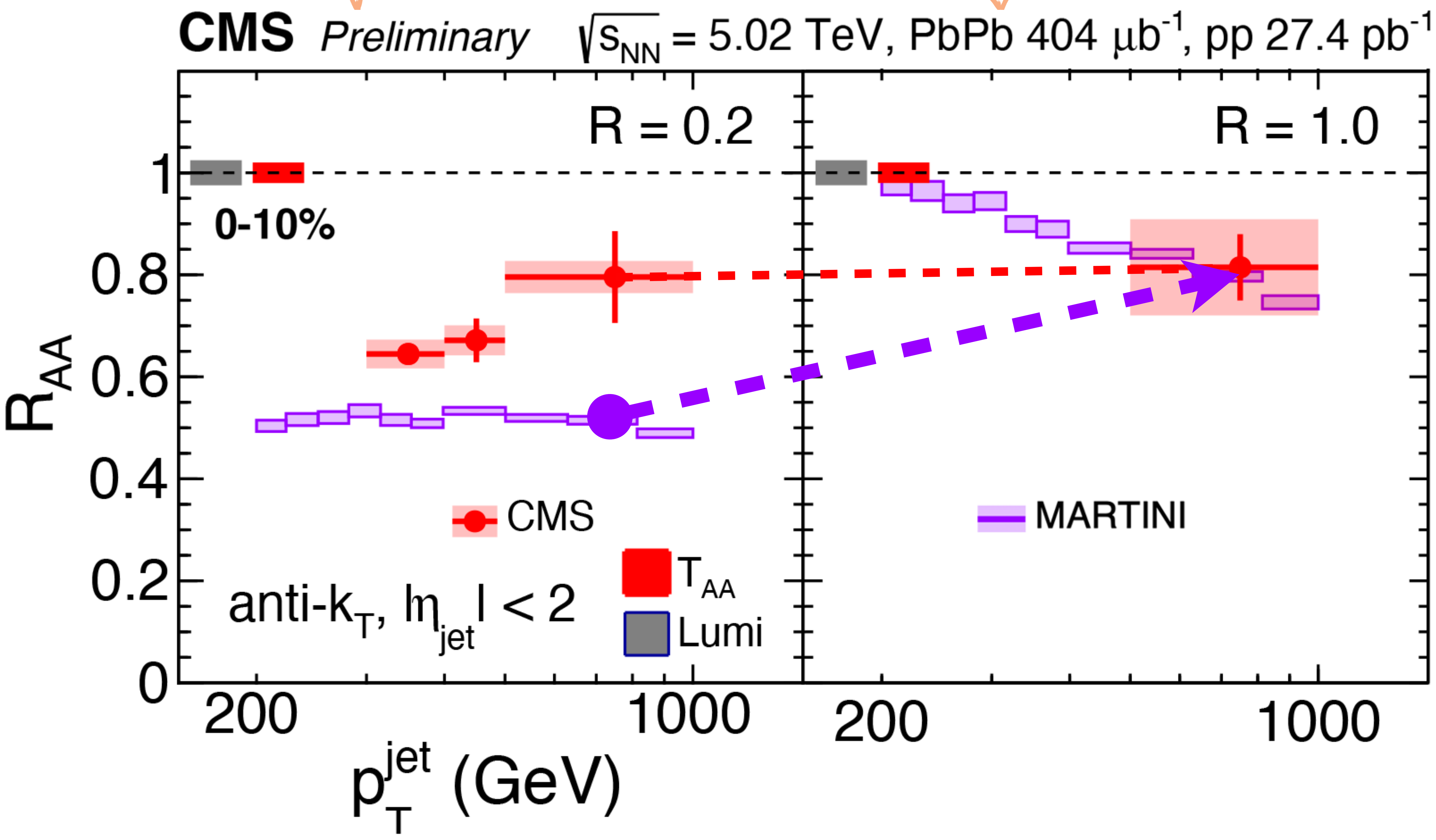
- **w/o response:** Shower only, misses R_{AA} magnitude
- **w/ response:** Overestimate R dependence

LBT	
Quench	HT
Medium Response	Recoils

Data vs. Model (IV)


Small R


Large R



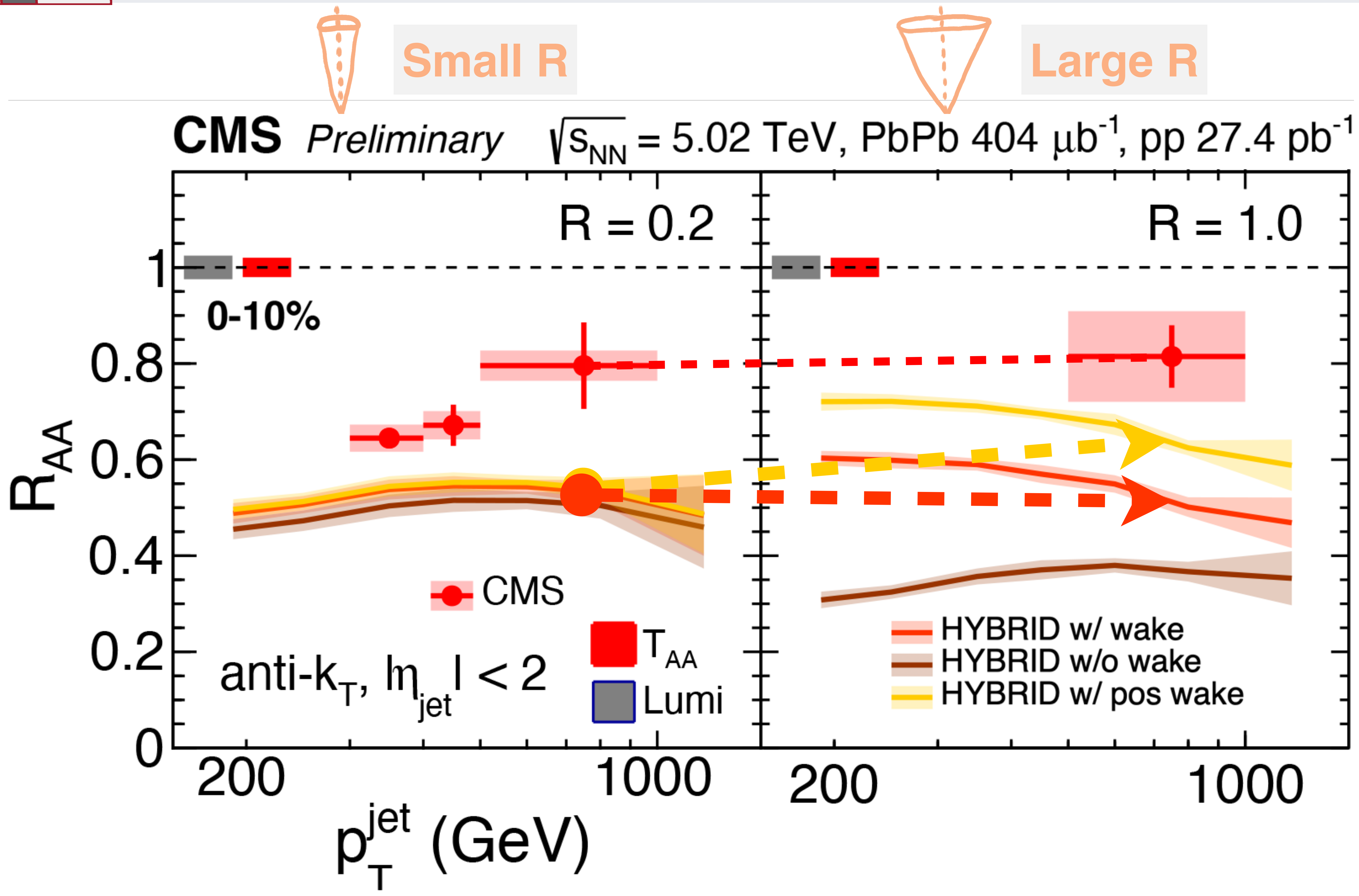
- Recoil based models all overestimate R dependence

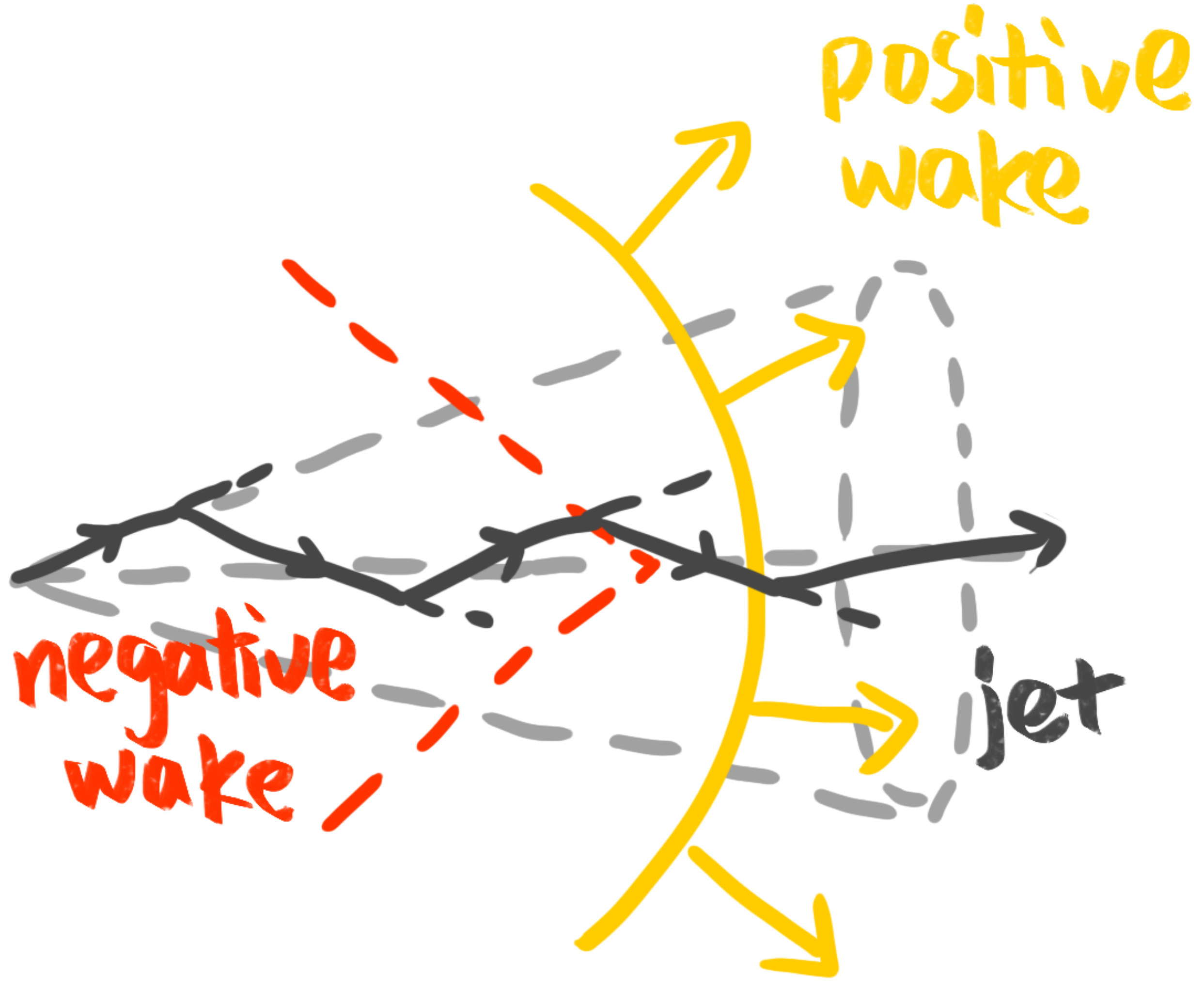
MARTINI PRC 80 (2019) 054913

- Misses R_{AA} magnitude at small R

MARTINI	
Quench	AMY
Medium Response	Recoils

Data vs. Model (V)



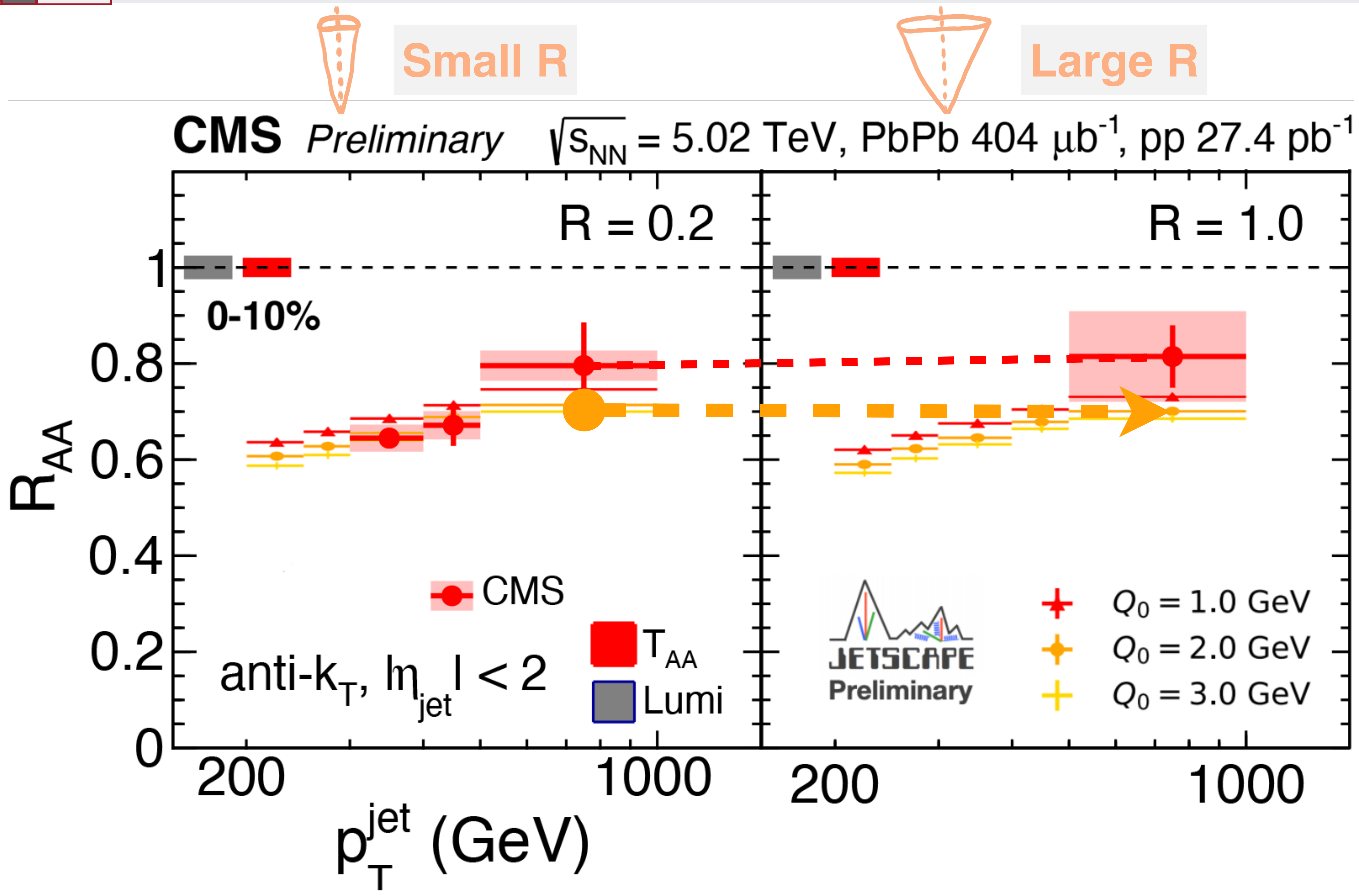


At large R
- Positive wake increases R_{AA}
- Adding negative wake decreases R_{AA}

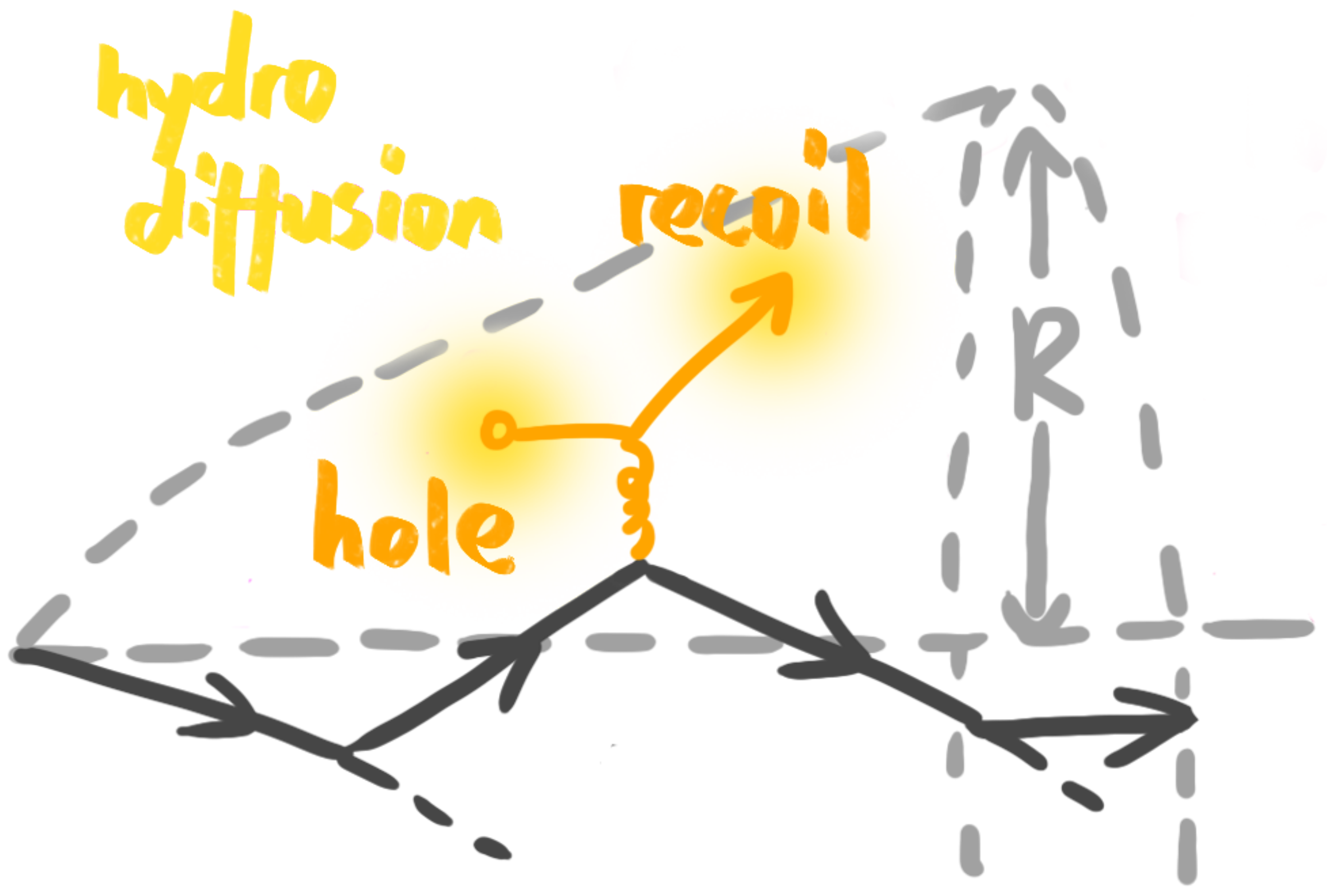
HYBRID JHEP 03 (2017) 135
- **No wake** vs. **positive wake only** vs. **w/ full wake**
- Data disfavors all variations (but capture mild R dependence)

HYBRID	
Quench	AdS/CFT
Medium Response	Hydro

Data vs. Model (VI)



- Medium response: Recoil + Hydro

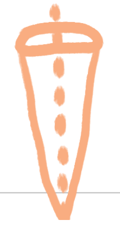


JETSCAPE arXiv:1903.07706

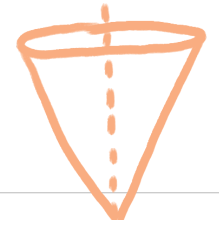
- General agreement with data (a bit underestimate R_{AA})
- Q_0: Virtuality switching between MATTER and LBT shower

JETSCAPE	
Quench	HT/AMY
Medium Response	Recoil + Hydro

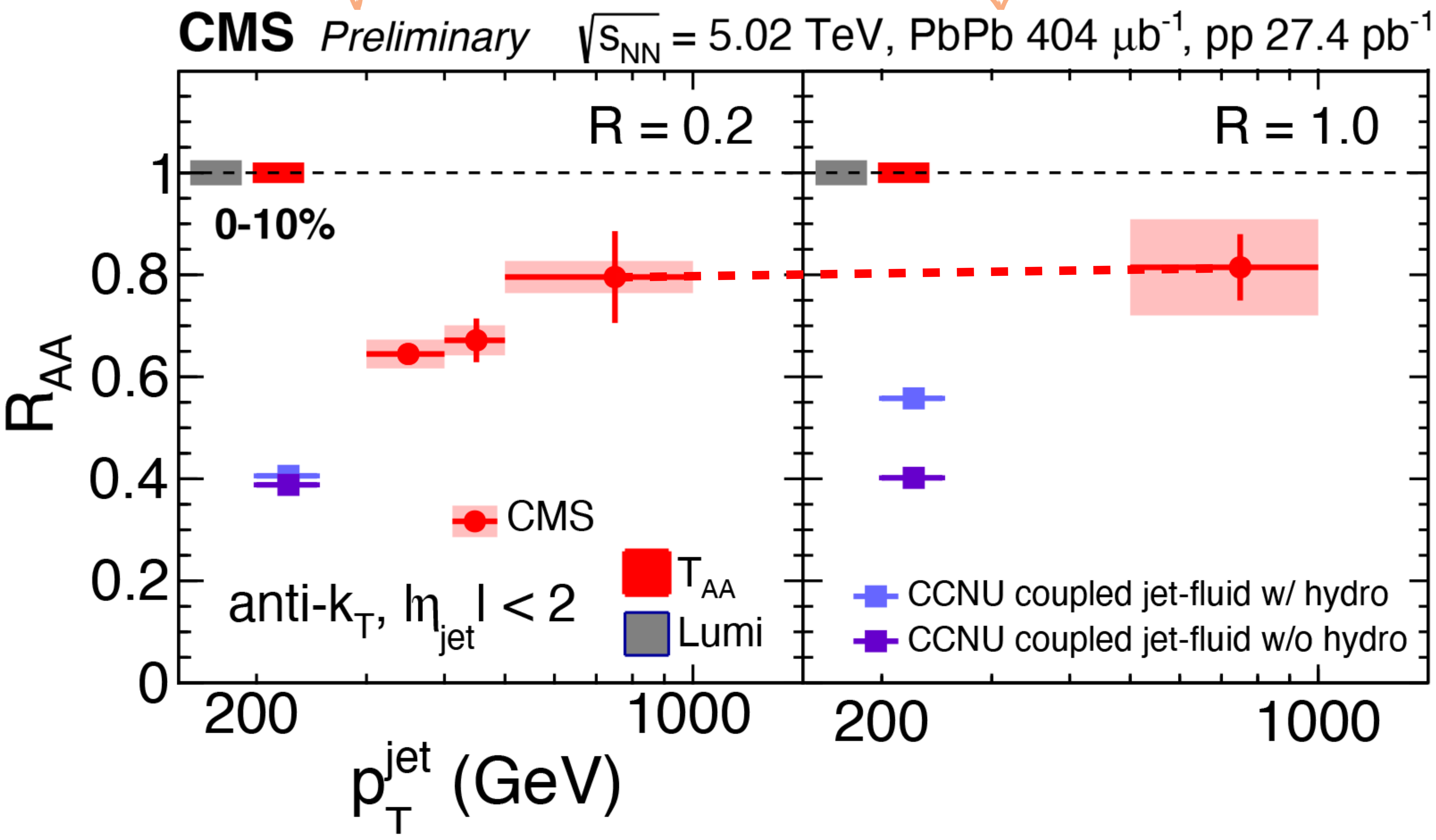
Data vs. Model (VII)

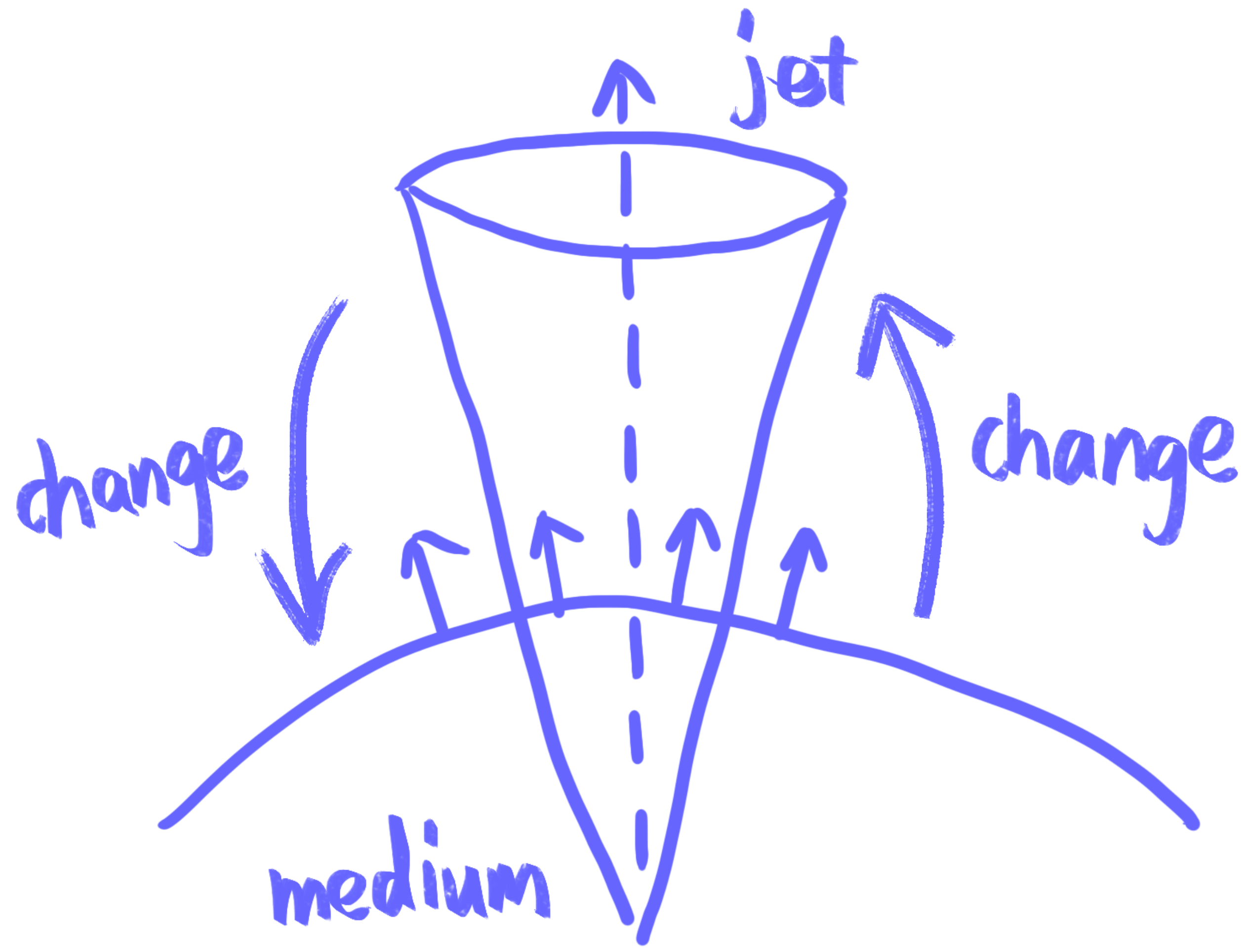


Small R



Large R





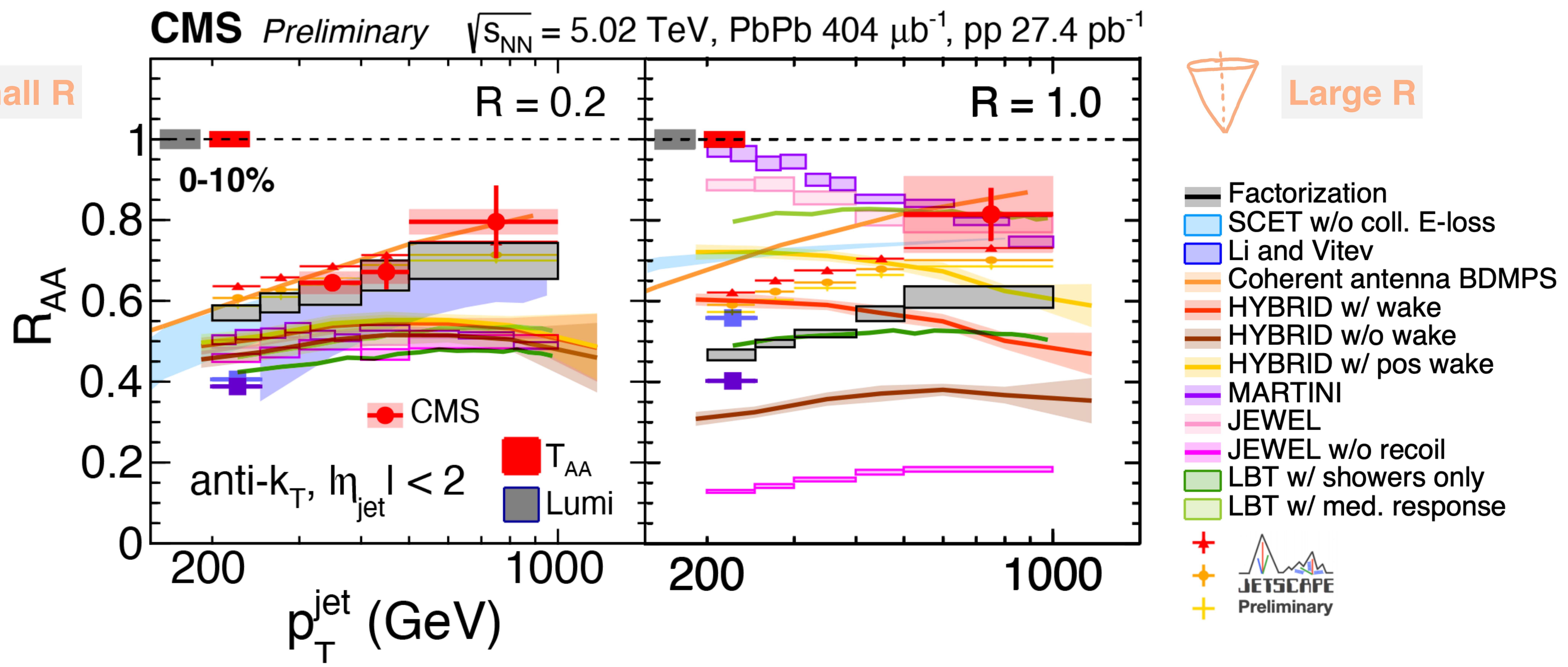
CCNU PRC 94 (2016) 024902, PRC 95 (2017) 044909, arXiv:1906.09562

- **w/o hydro** and **w/ hydro**
- Recursive treatment for effects b/w jets and medium

CCNU	
Quench	HT
Medium Response	Hydro

Small R

Large R



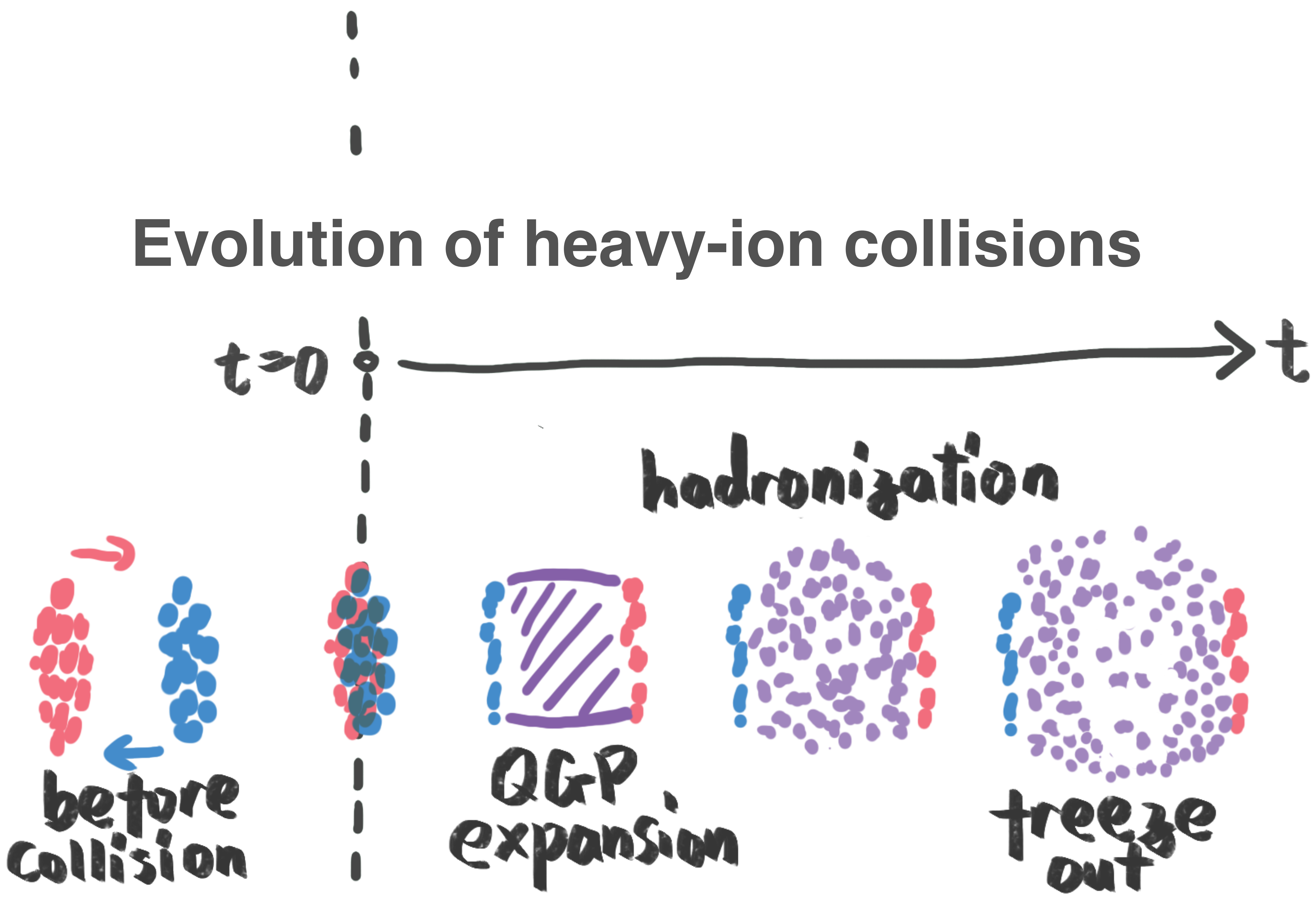
- No full model describes R dependence very well

➡ We do not know well:

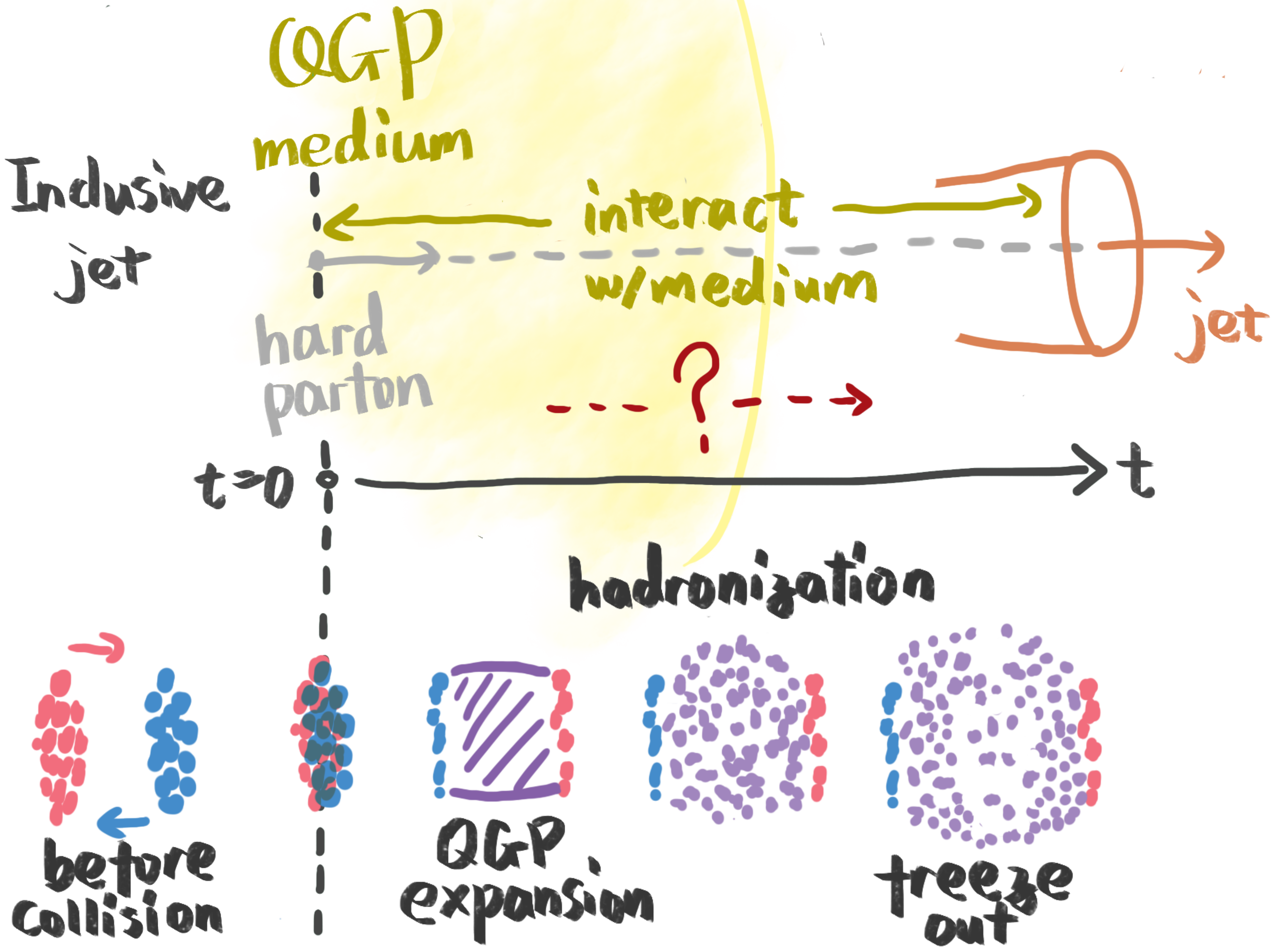
- How correlated is medium response to jet axis?
- How fragmentation function changes from narrow to wide jets?

Time structure of evolution

Evolution of heavy-ion collisions

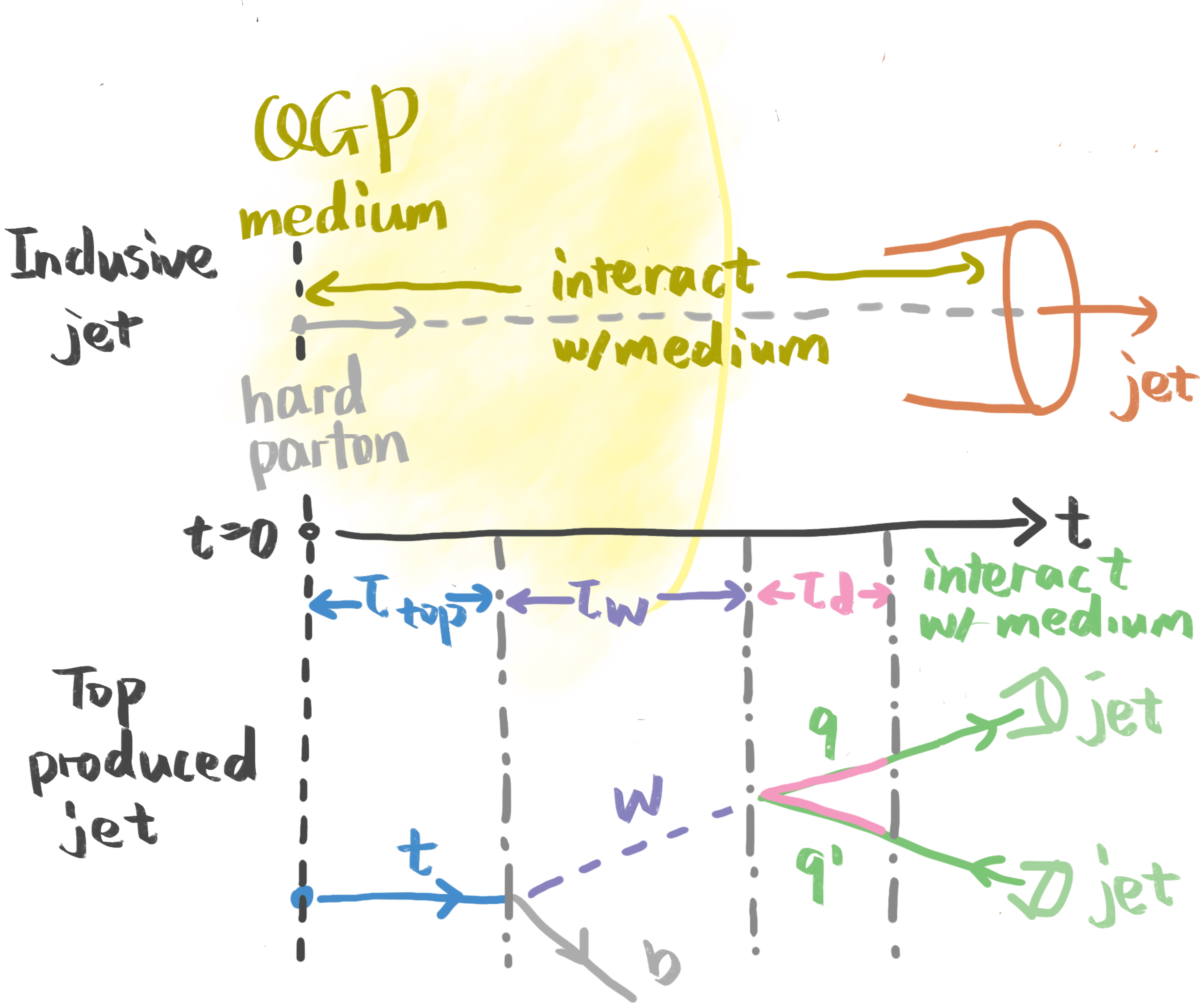


Time structure of evolution



- **Inclusive jet R_{AA}**
  - Experience the whole evolution
  - Only see accumulated effect
  - How to study time dependence?

Time structure of evolution: Top quark



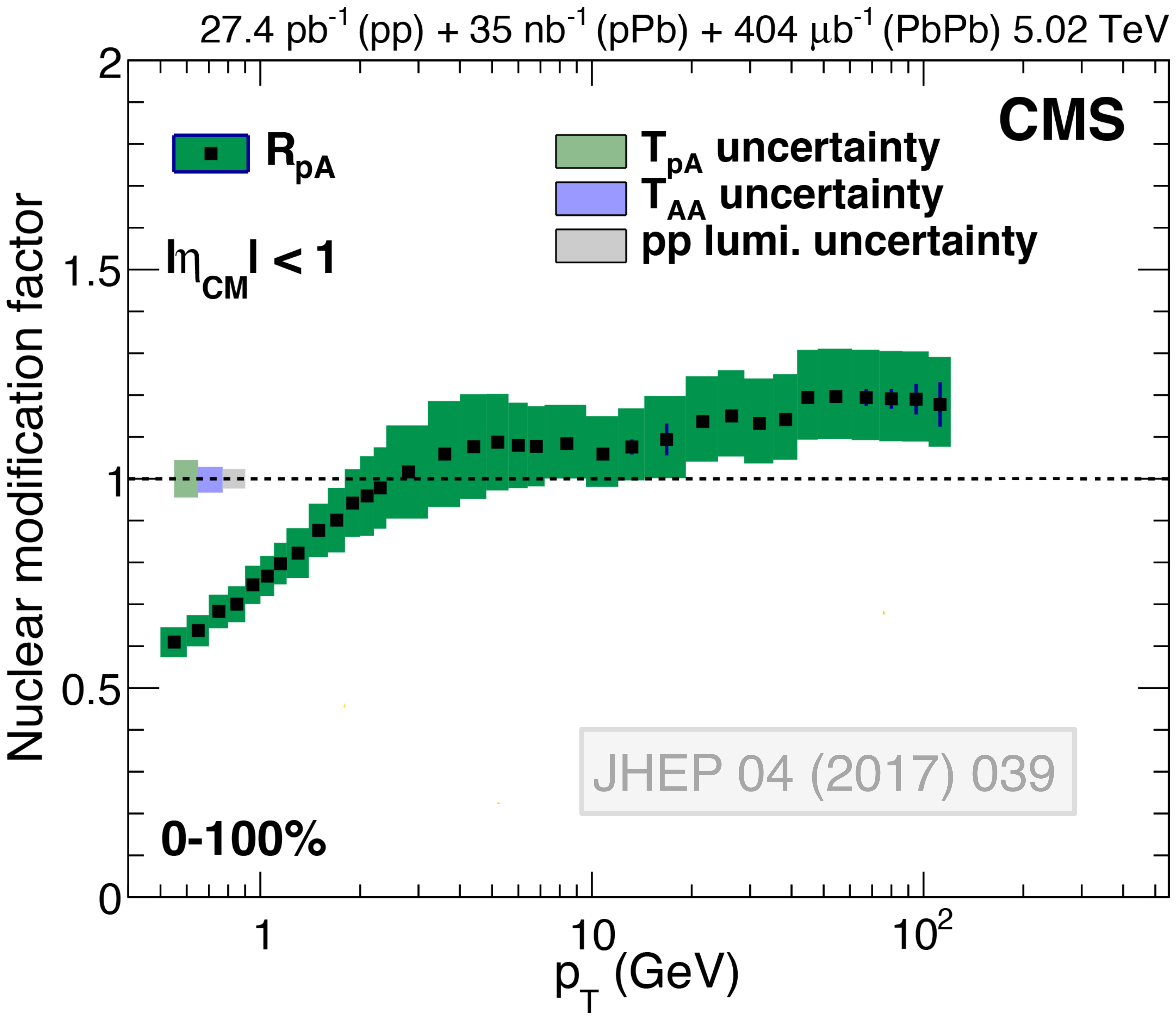
- Inclusive jet R_{AA}
  - Experience the whole evolution
  - Only see accumulated effect
  - How to study time dependence?

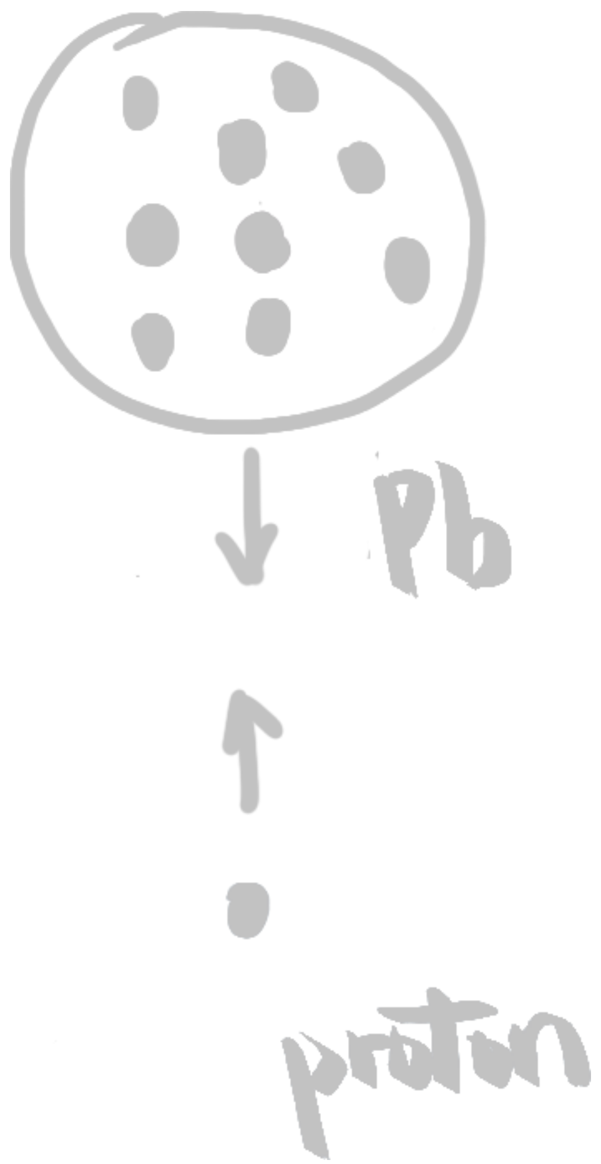
PRL 120 (2018) 23, 232301

- Top-produced jet
  - Interaction delayed by
    - ➡ τ_{top}: top lifetime
    - ➡ τ_W: W lifetime
    - ➡ τ_d: de-coherence time
  - Study top production helps understand evolution time structure

nuclear Parton Distribution Function

R_{pA}: "R_{AA}" in p-Pb collisions

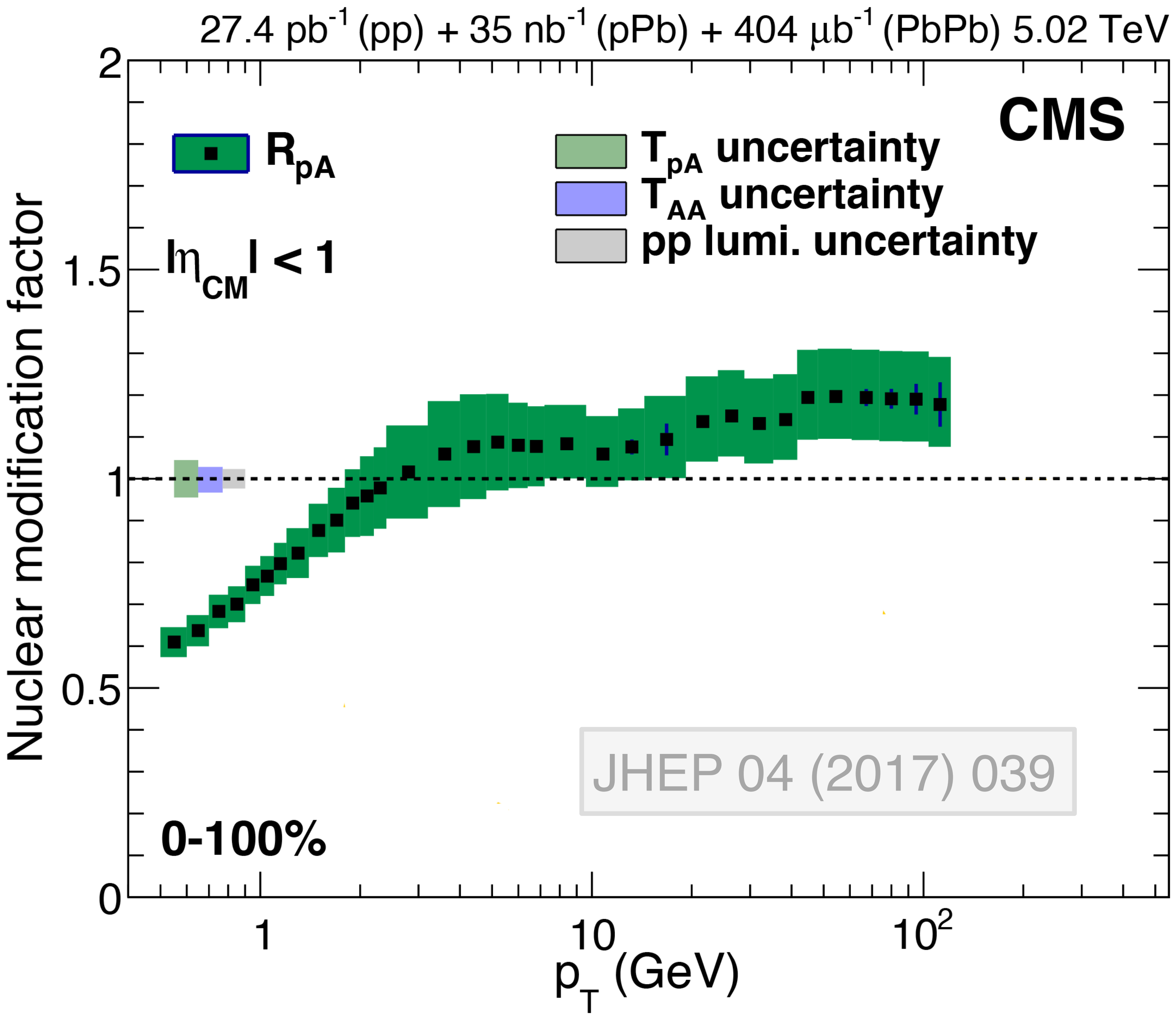




- **p-Pb collision**
  - ➡ No medium production expected
  - ➡ Why $R_{pA} \neq 1$?

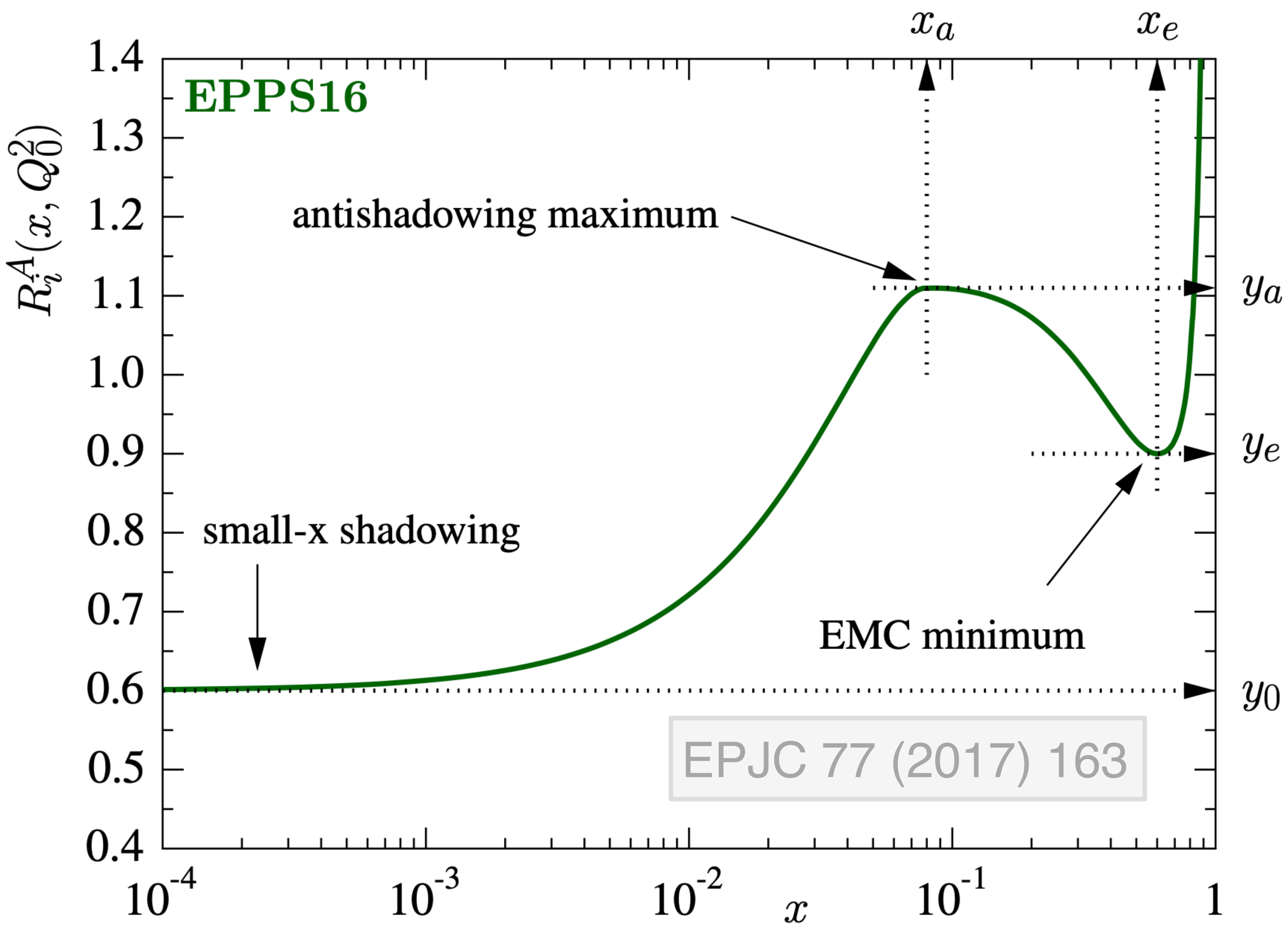
nuclear Parton Distribution Function

R_{pA}: "R_{AA}" in p-Pb collisions



One reason …

nuclear PDF modification



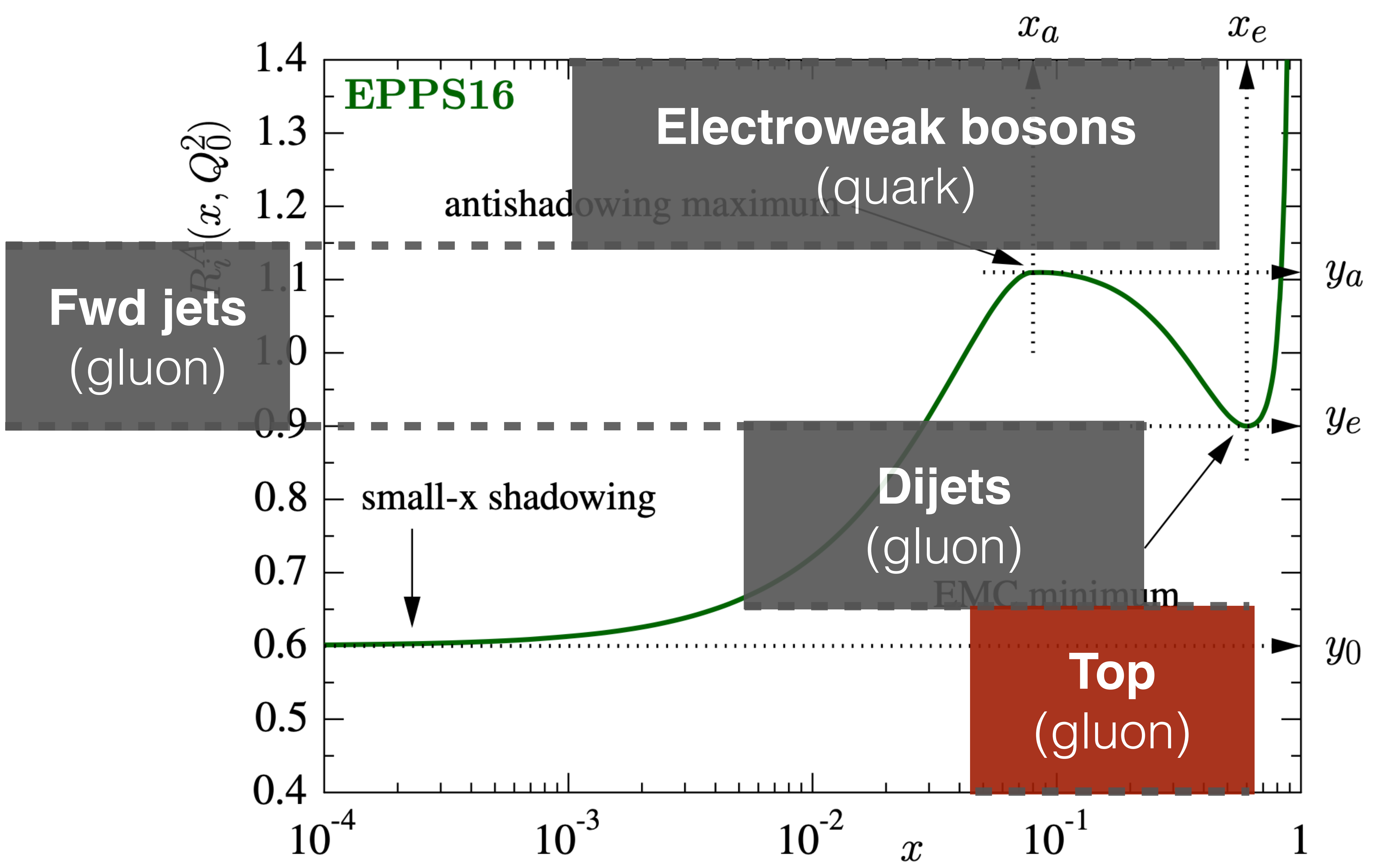
- PDF of proton in nuclei different from free proton

$$R_i^A(x, Q^2) = \frac{f_i^{p/A}(x, Q^2)}{f_i^p(x, Q^2)} = \frac{\text{proton PDF (mass number A)}}{\text{free-proton PDF}}$$

Probe nPDF: Top quark

- Probes sensitive to different (x, Q^2) region
- Nuclear modification on top production probes gluon nPDF at high (x, Q^2)

nuclear PDF modification

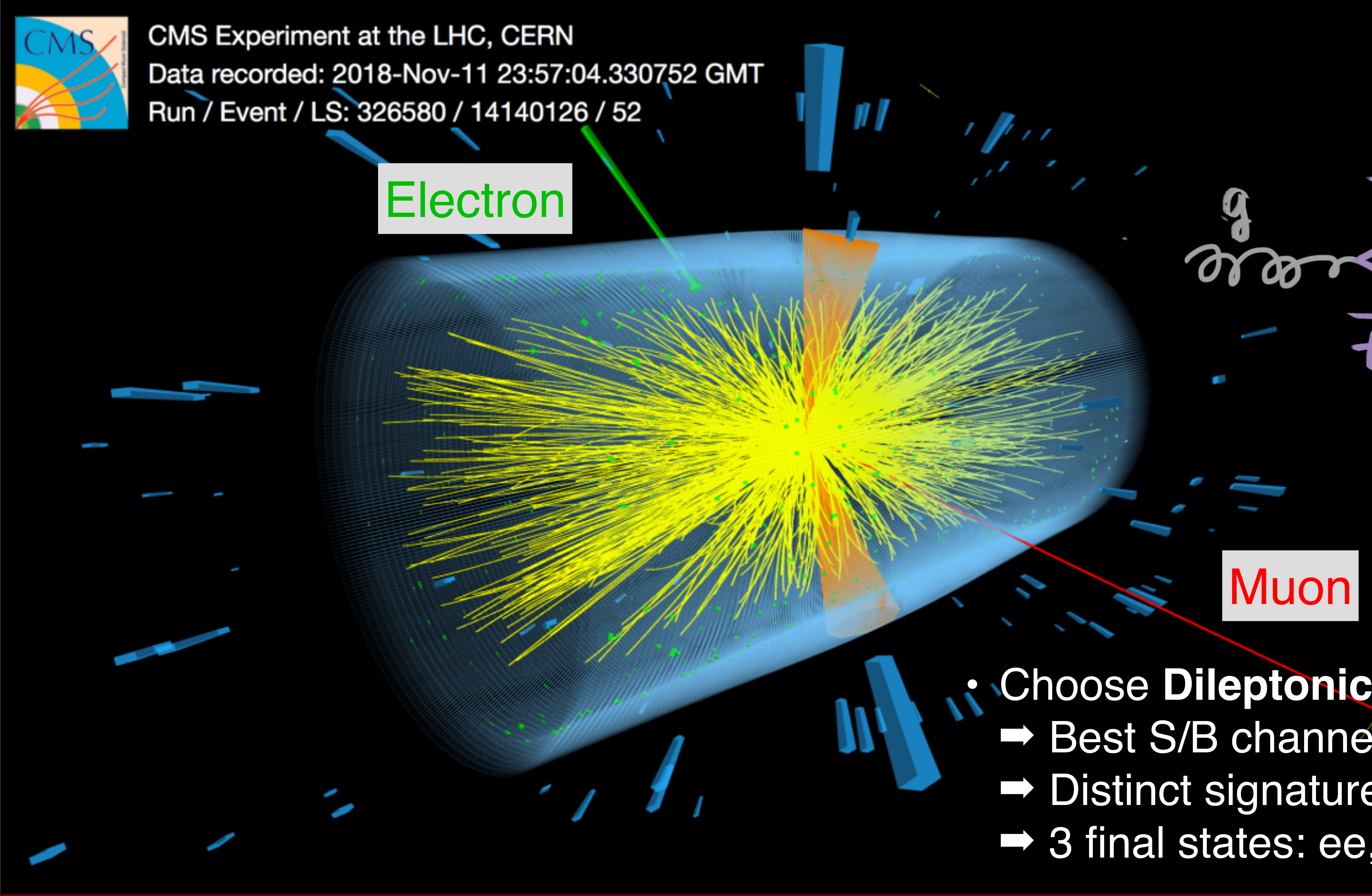


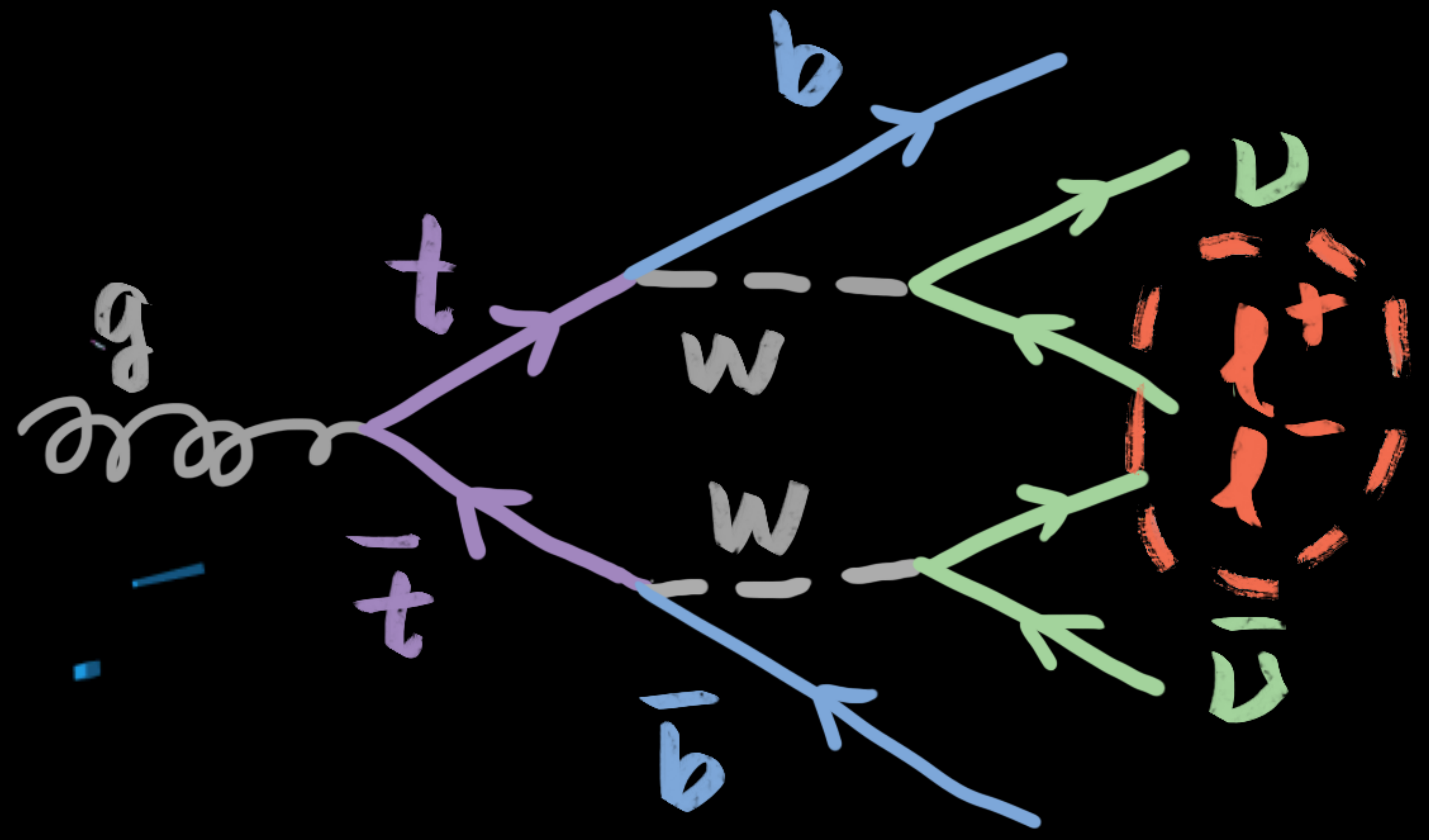
$t\bar{t}$ Cross-section in PbPb

[arXiv:2006.11110, Submitted to Nature Physics]

2018 data

Search $t\bar{t}$ events in Heavy-ion collisions

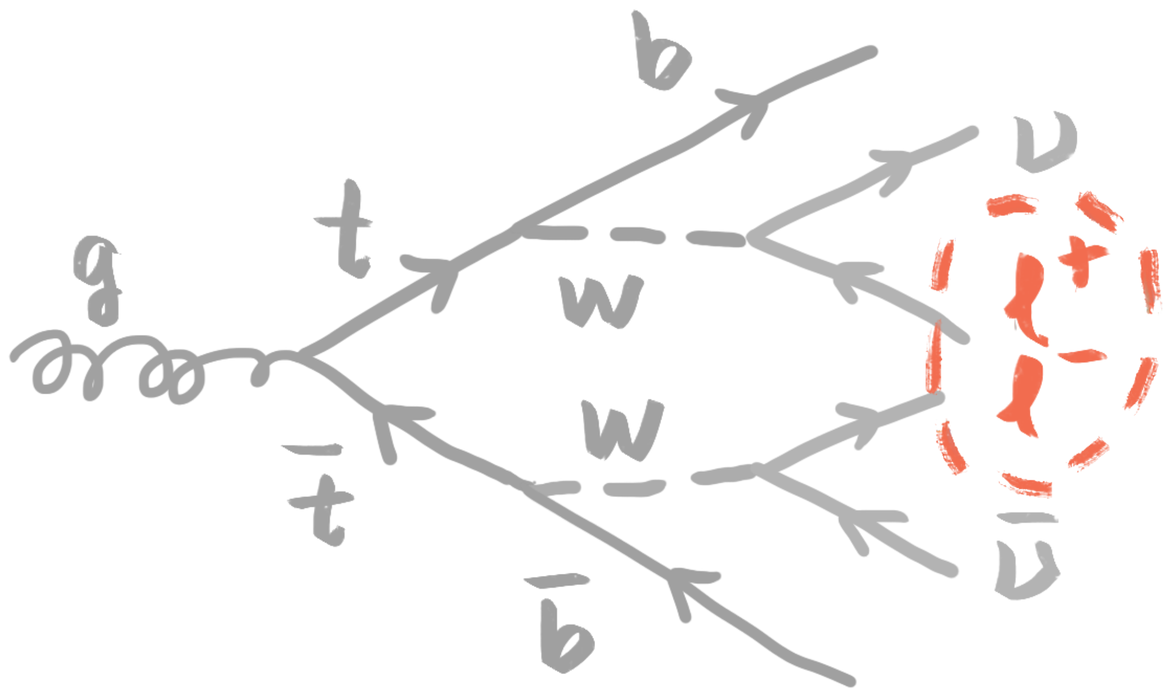




- Choose **Dileptonic final states**
  - ➡ Best S/B channel for high event count
  - ➡ Distinct signature: high-p_T, isolated leptons
  - ➡ 3 final states: ee, μμ, eμ

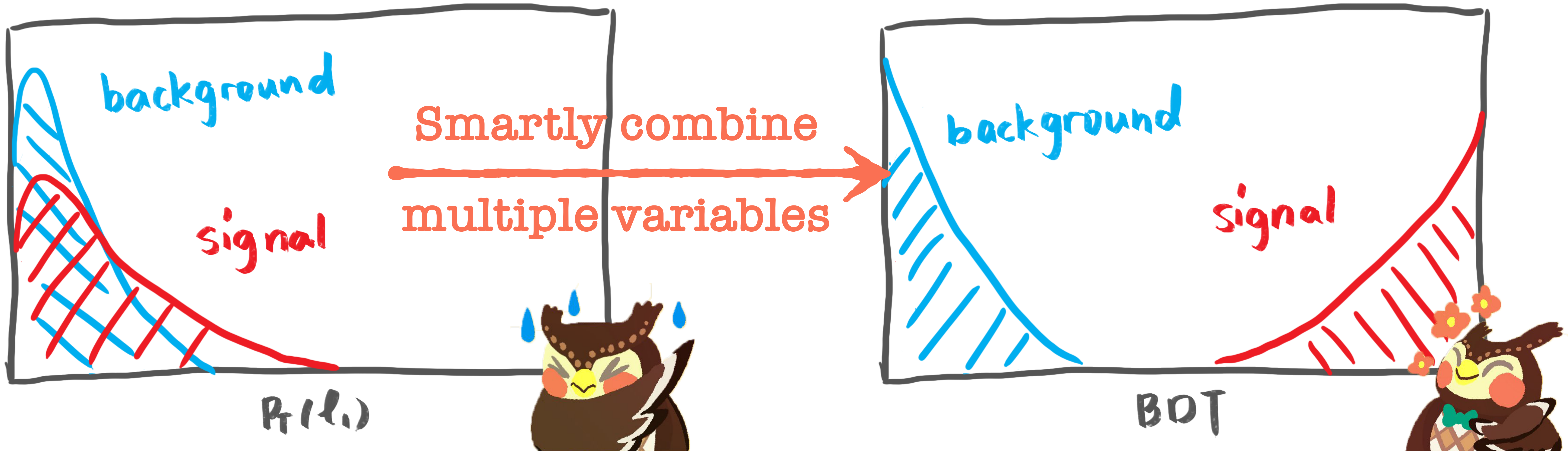
Separate signal and background

- Use lepton kinematics to separate signal and background
  ➡ Optimize signal extraction with BDT algorithm
  ➡ The more different between signal and bkg, the better



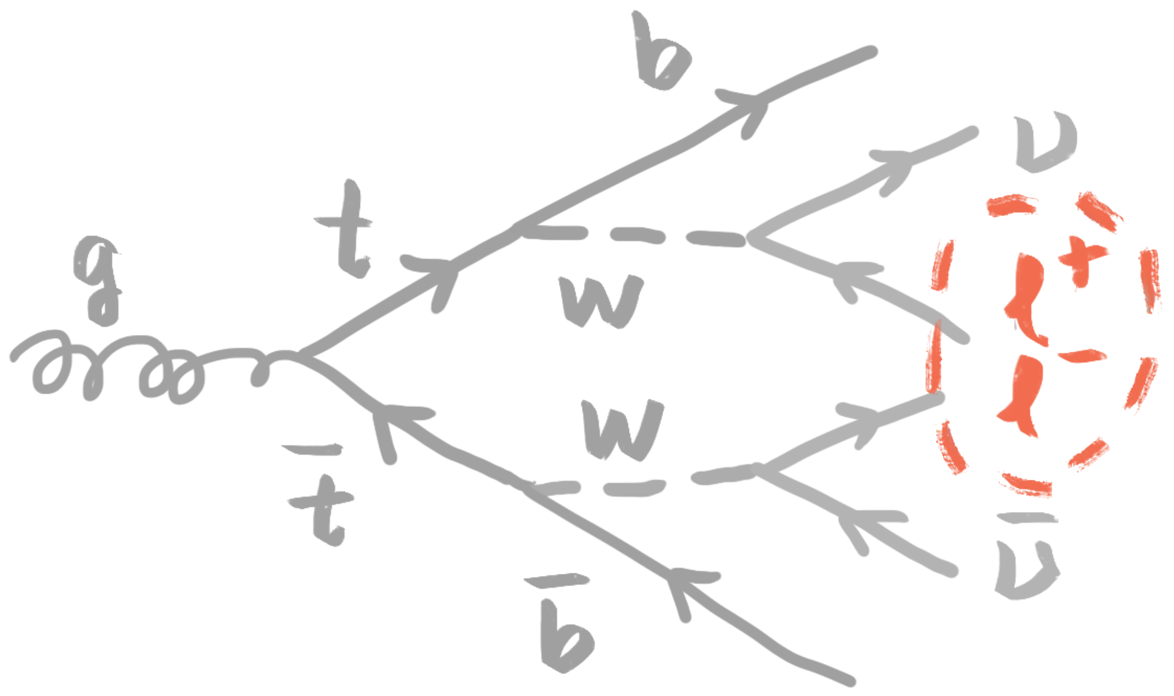
Single variable

Multiple variables: BDT

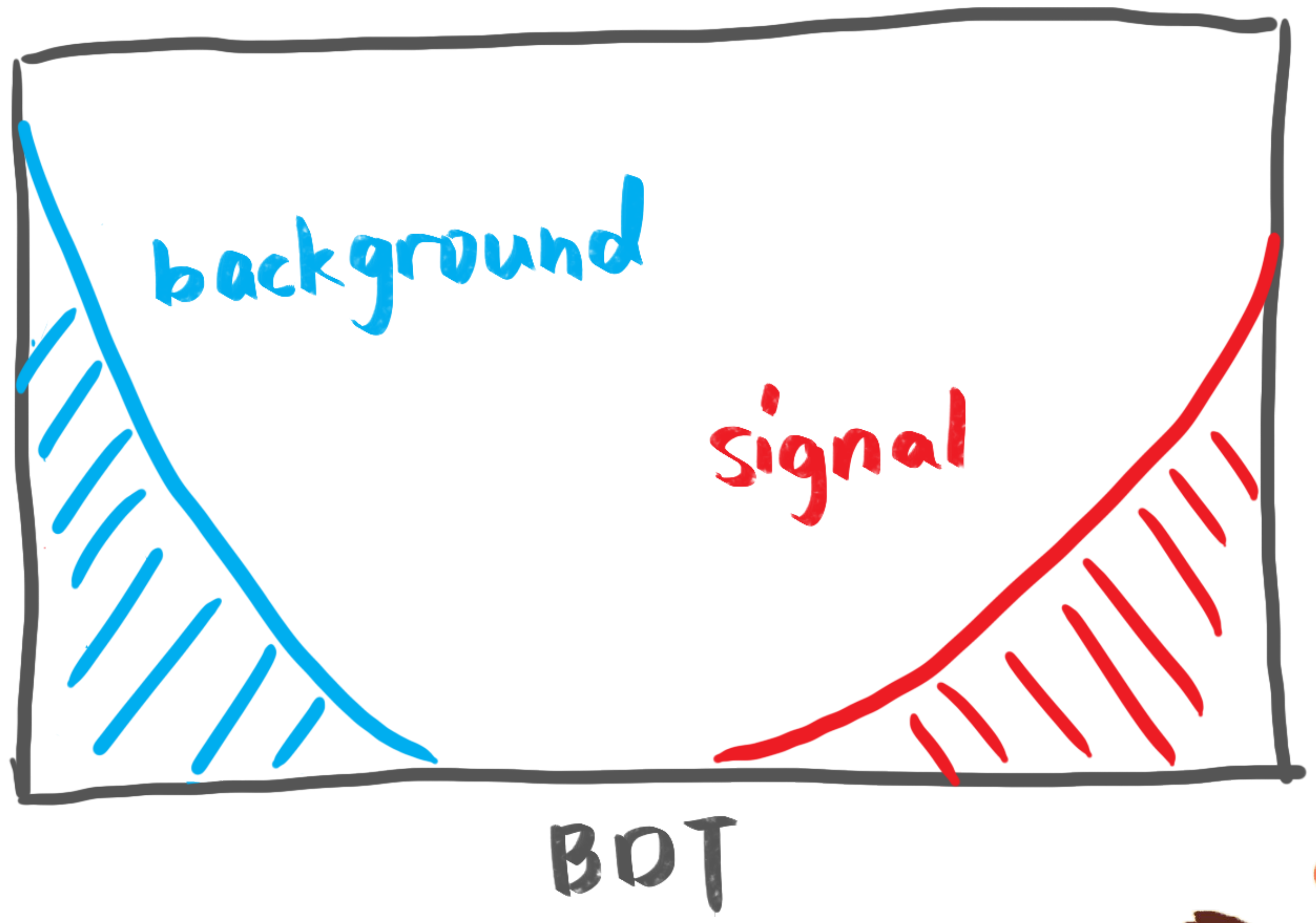


Separate signal and background

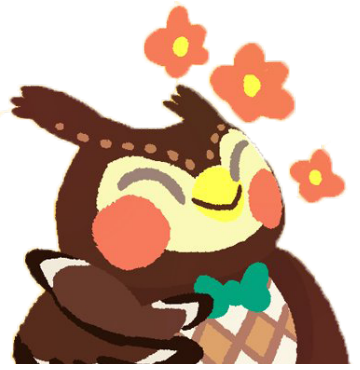
- Use lepton kinematics to separate signal and background
  ➡ Optimize signal extraction with BDT algorithm
  ➡ Very good discrimination between $t\bar{t}$ signal and background

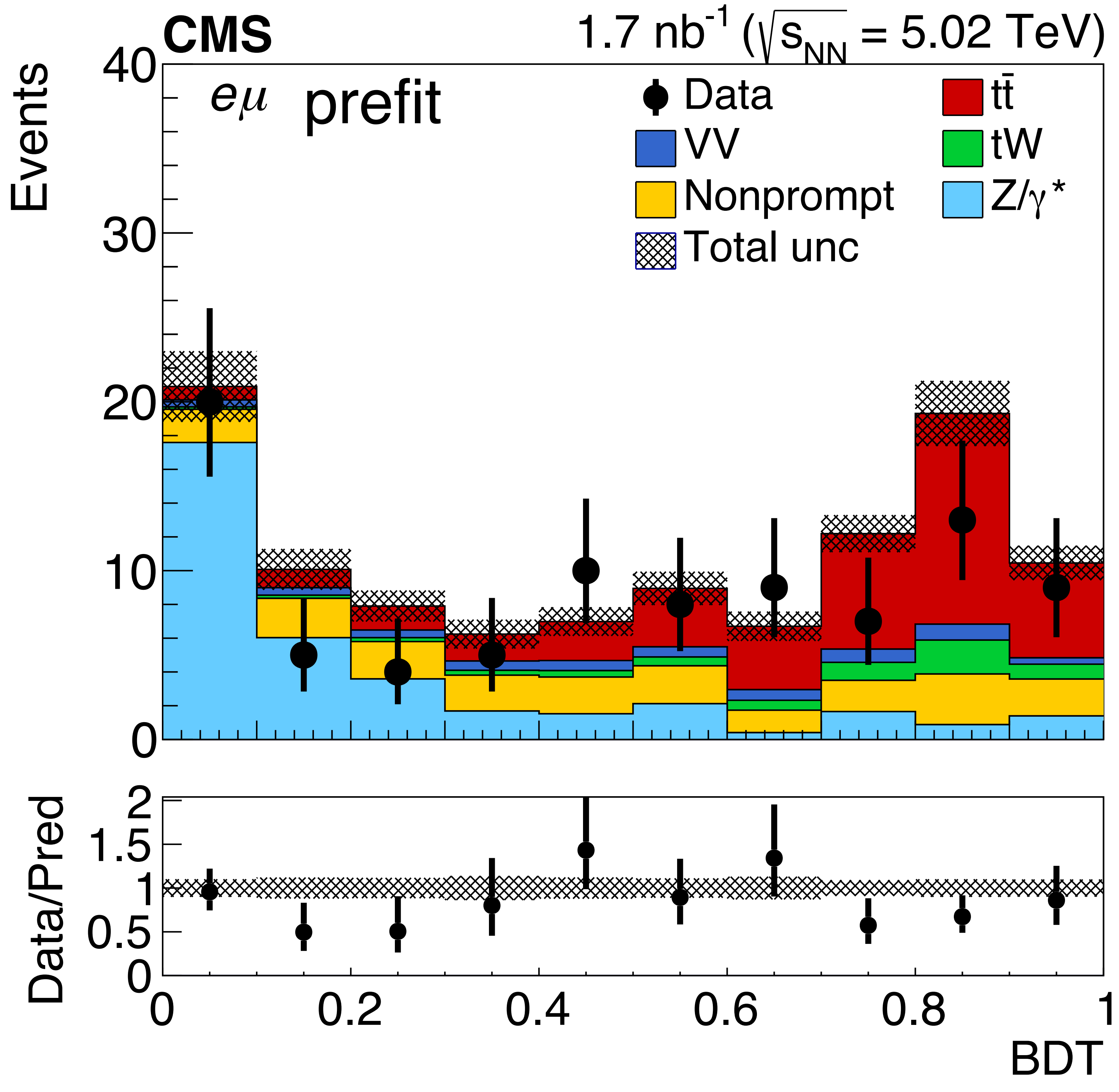


Multiple variables: BDT



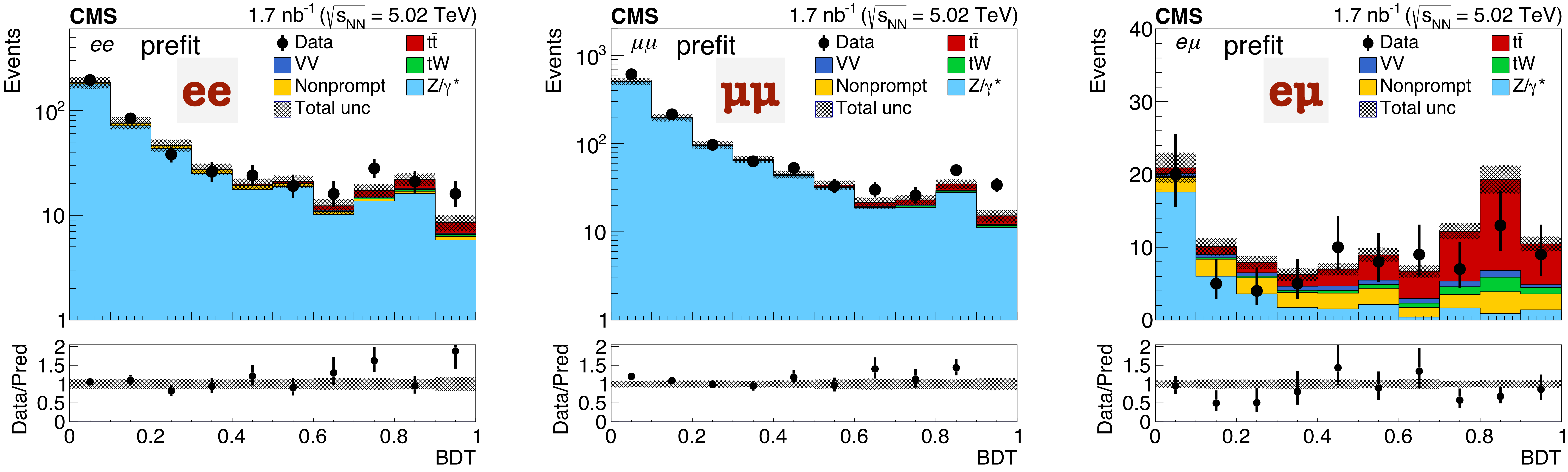
➜ Modeling of signal and background see backup slides





Result: $t\bar{t}$ Cross-section (lepton only)

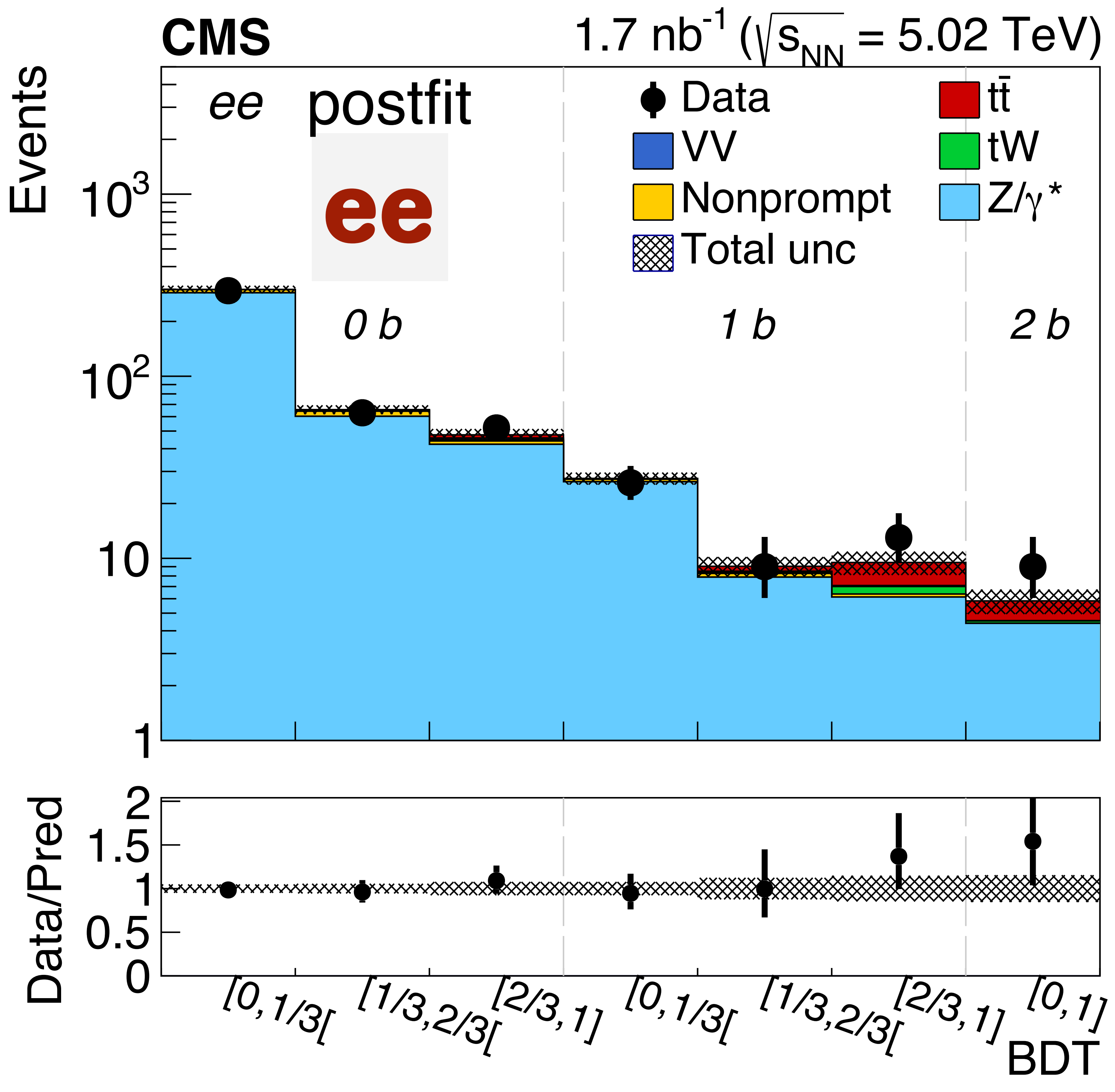
- Fit BDT distribution simultaneously in all three final states
- The cross section is measured σ = 2.54 +0.84 -0.74 μb
- Bkg-only hypothesis is excluded at 3.8σ

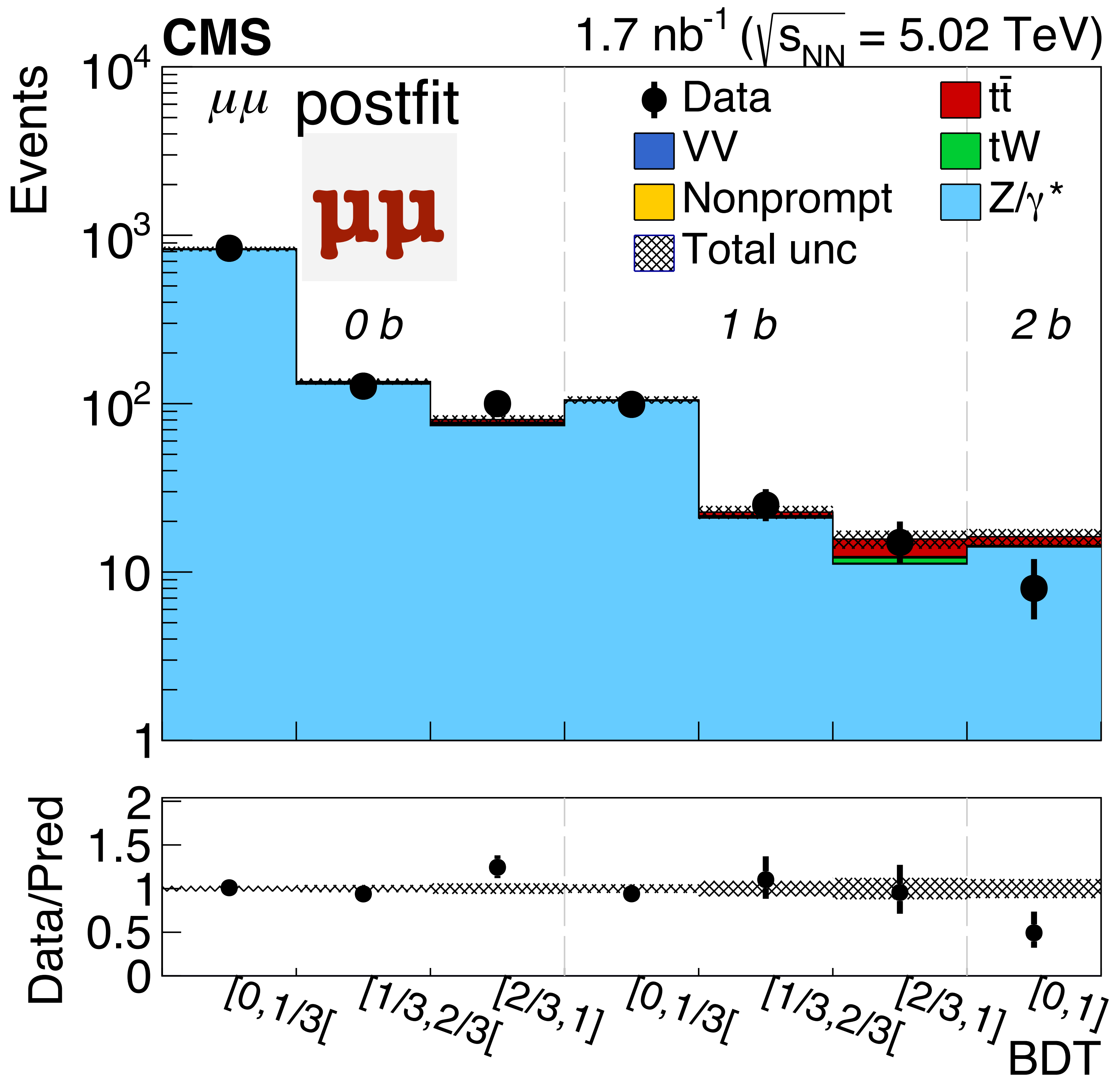


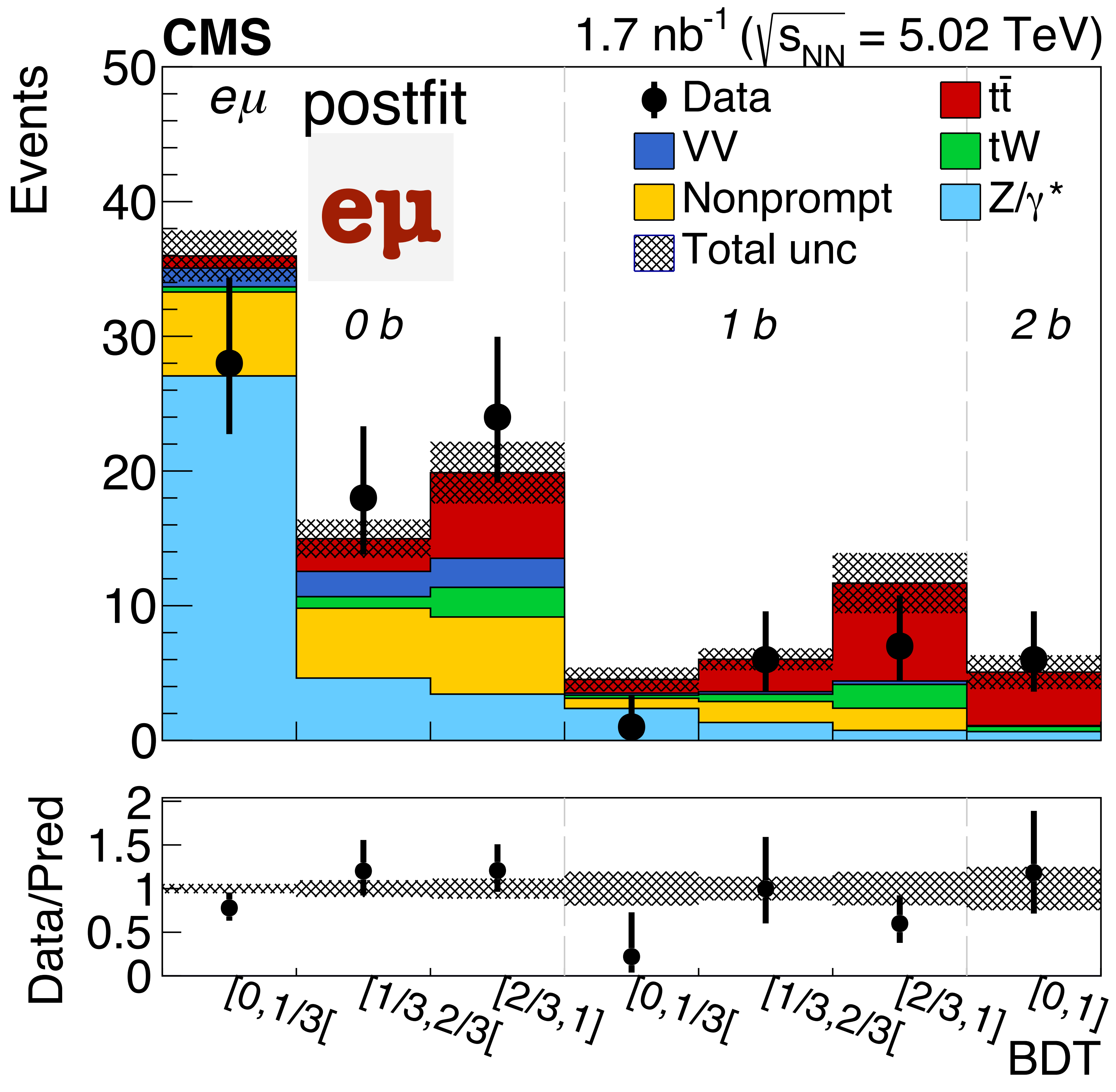
Include information from b-jet

Result: $t\bar{t}$ Cross-section (lepton & b-tags)

- Fit BDT distribution correlating b-jet multiplicity
- The cross section is measured σ = 2.03 +0.71 -0.64 µb (w/o b-jet multiplicity selection)
- Bkg-only hypothesis is excluded at 4.0σ

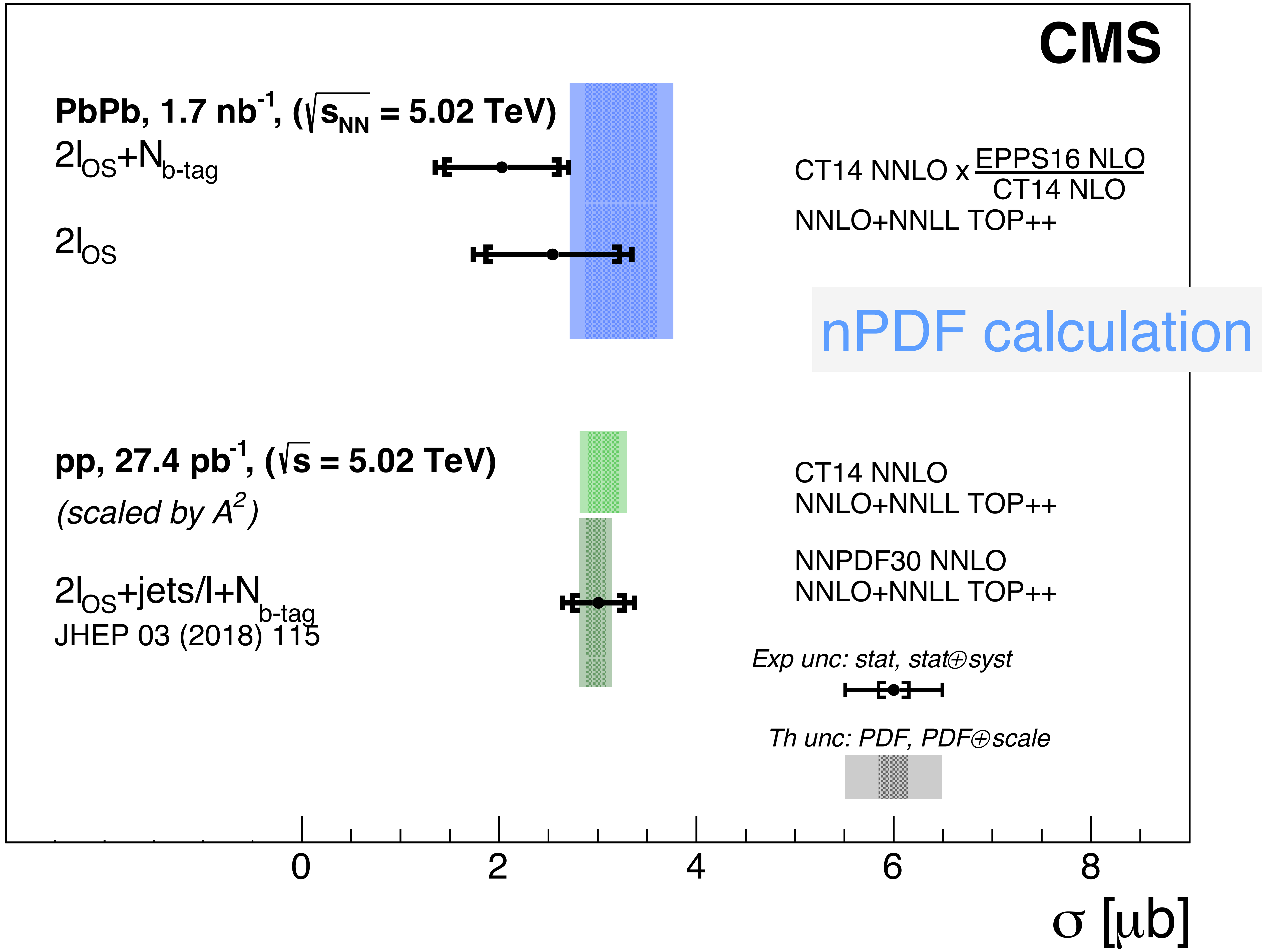






Comparison with nPDF models

PbPb



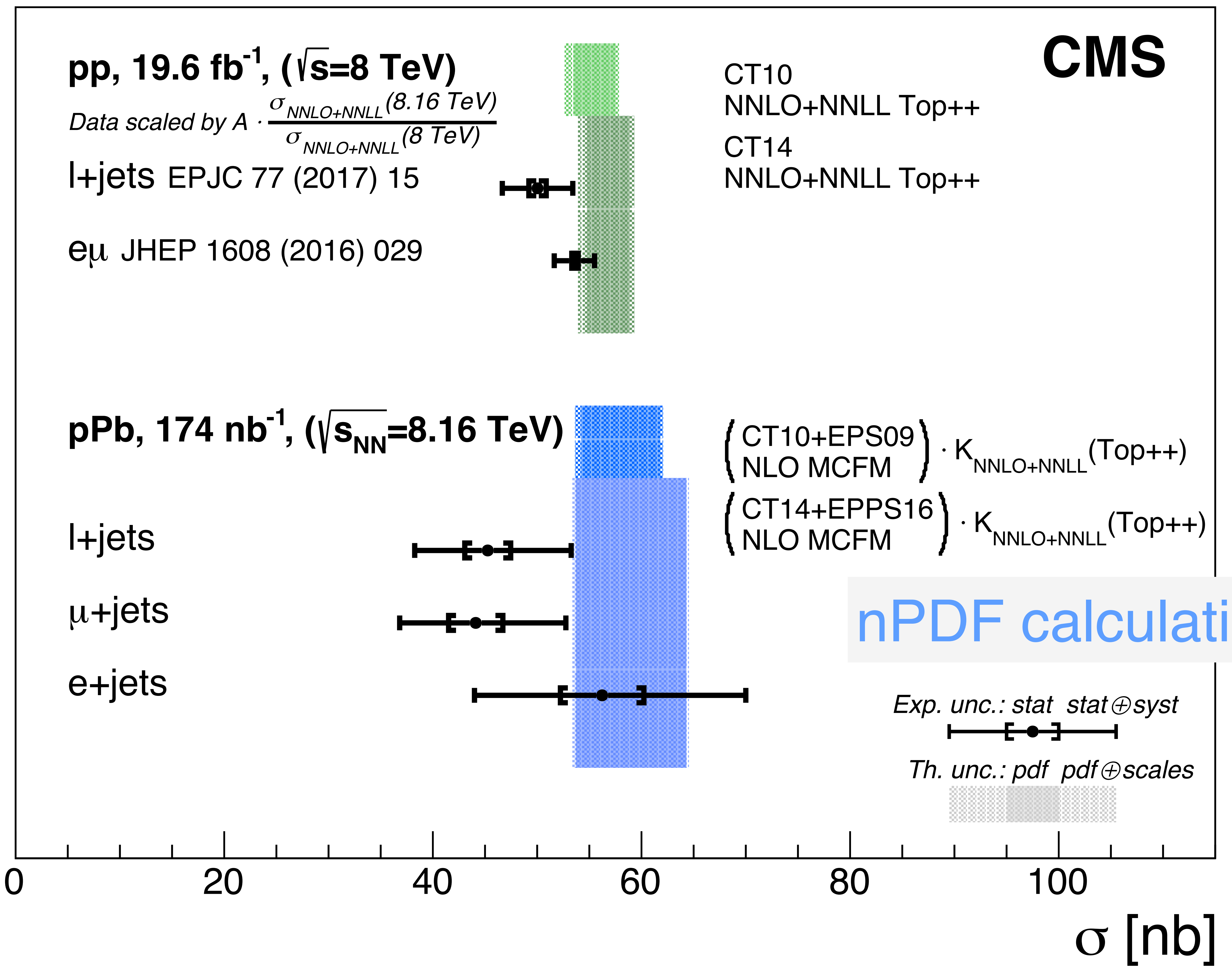
pp

- First experimental evidence of the top quark in nucleus-nucleus collisions
- Establish a new tool for probing nPDFs

$t\bar{t}$ cross-section in pPb

pp

pPb



nPDF calculation

PRL 119 (2017) 242001

- $t\bar{t}$ cross-section has been measured in all 3 systems

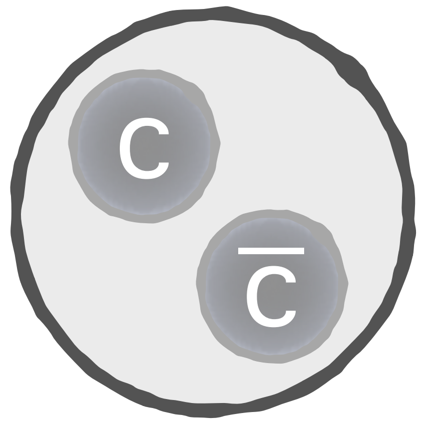
X(3872)/ψ(2S) Ratio in PbPb

[CMS-PAS-HIN-19-005]

2018 data

X(3872)

- 2003: X(3872), also known as χ_{c1}(3872), discovered by BELLE
  ➡ ~~Charmonium state~~: Abandoned ⬅ predict wrong mass
  ⬆
- 2013: Quantum number determined by LHCb data: $J^{PC}=1^{++}$
- Today: Internal structure is still under debate



PRL 91 (2003) 262001

PRL 110 (2013) 222001

X(3872)

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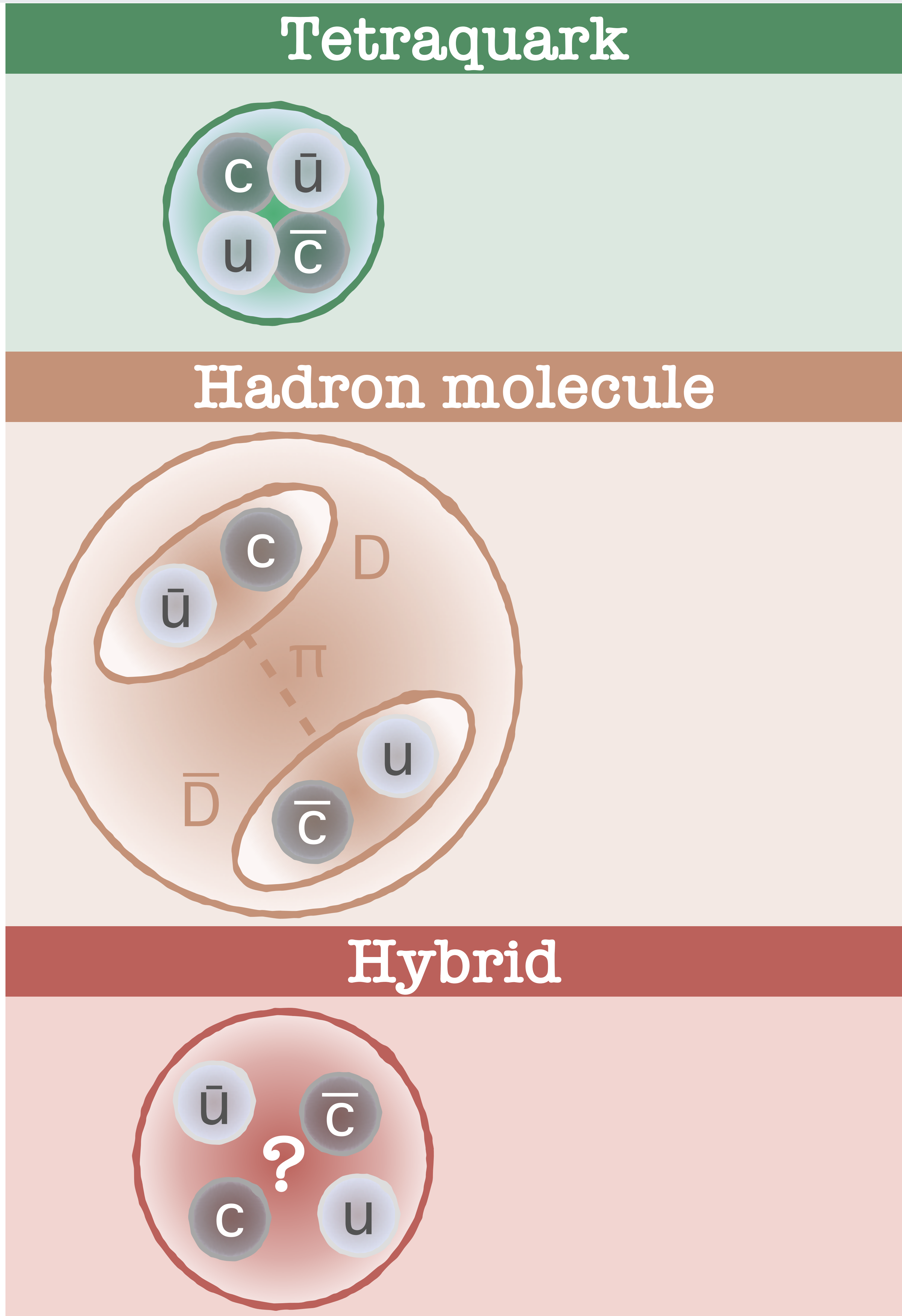
  ➡ ~~Charmonium state: Abandoned~~ ⬅ predict wrong mass
  ⬆
- 2013: Quantum number determined by LHCb data: $J^{PC}=1^{++}$

- Today: Internal structure is still under debate
  Remaining possibilities:
  ➡ **Tetraquark (4q)**: Compact four quark state
  ➡ **D-D̄* hadron molecule**: mass X(3872) ≈ D(1875)D̄*(2007)
  ➡ **Hybrid**: mixed molecule-charmonium state

- All can explain measured mass/decay width

⇒ Any way to distinguish those models?

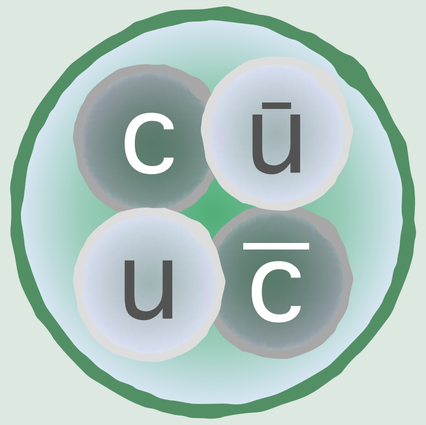


X(3872) in Heavy-ion Collisions

- X(3872) production yield in QGP strongly reflects internal structure
  - ➡ **Interact** with other hadrons: produced + absorbed:
    $\pi X \rightleftharpoons D\bar{D}, D\bar{D}^*$ & $\rho X \rightleftharpoons D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$
  - ➡ Different behaviors due to **radius** $r_{4q} \ll r_{mol}$:
    Molecule easier to be produced and destroyed than **tetraquark**

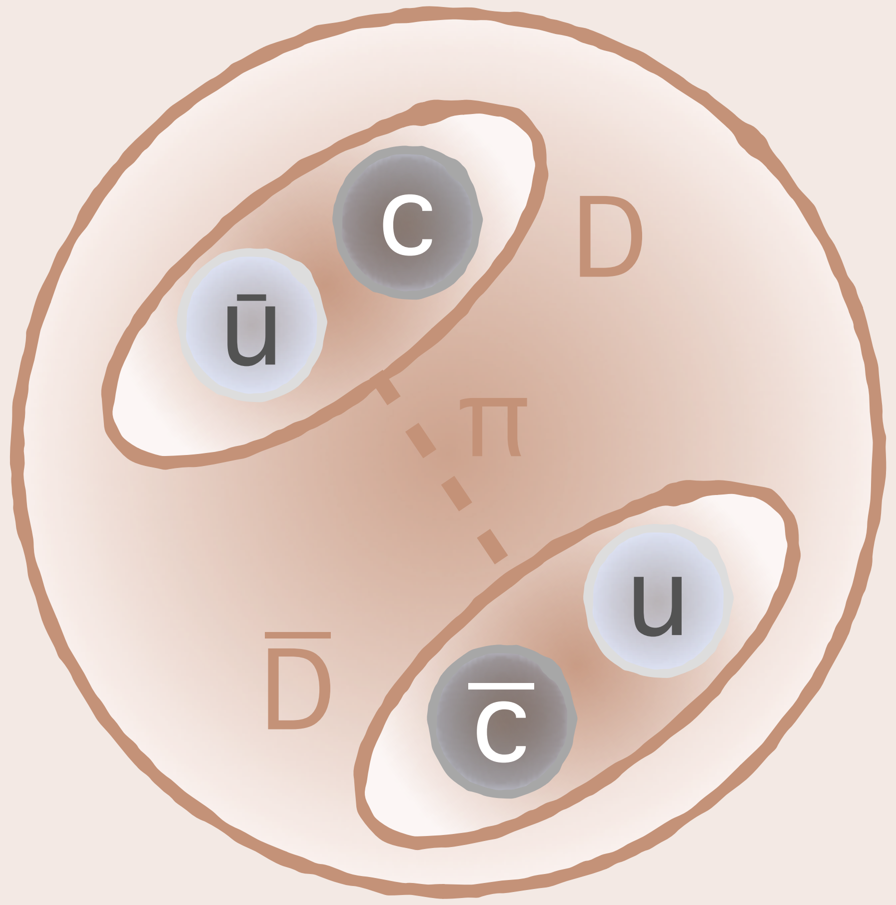
⇒ Help reveal the nature of X(3872)!

Tetraquark



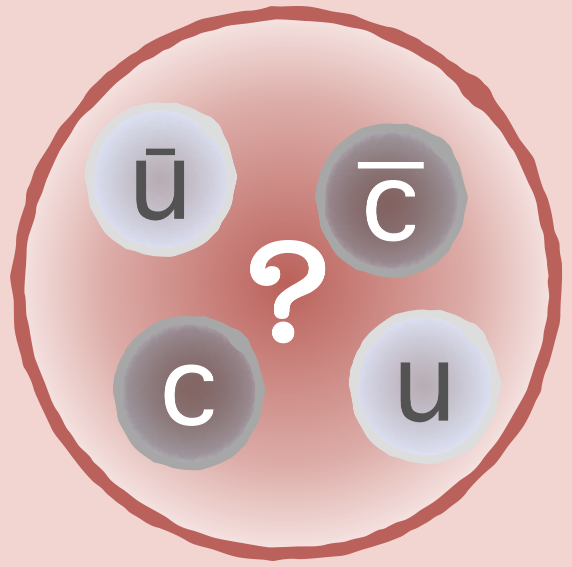
- Small $r_{4q} \approx r_{c\bar{c}} \approx 0.3$ fm
- Tight bound

Hadron molecule



- Large $r_{mol} \approx 5$ fm
- Loose bound

Hybrid



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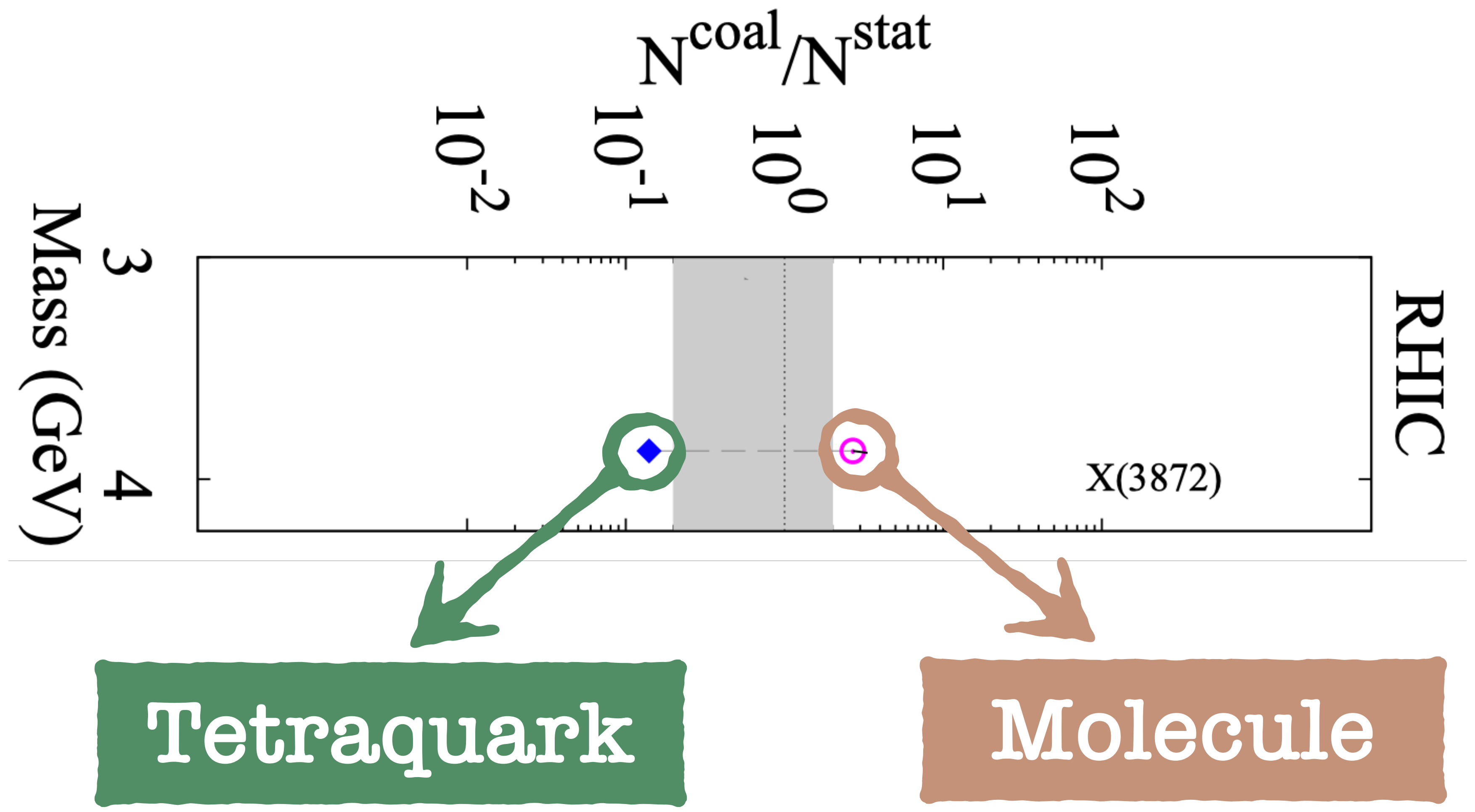
  - ➡ Different behaviors due to **radius** $r_{4q} \ll r_{mol}$:
    Molecule easier to be produced and destroyed than **tetraquark**

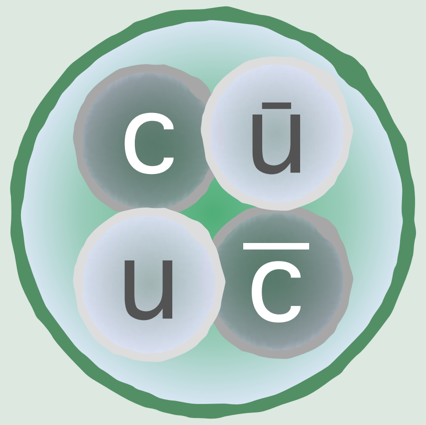
⇒ Help reveal the nature of X(3872)!

- **Coalescence model** PRL 106 (2011) 212001



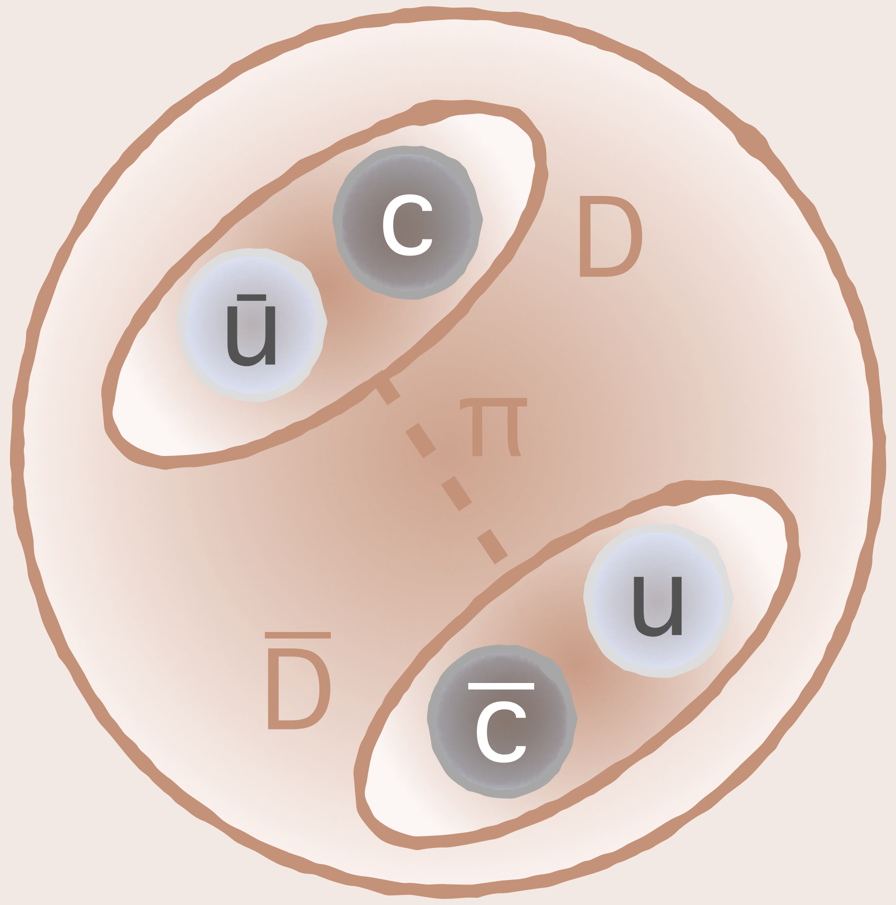
➡ Orders of yield difference

Tetraquark



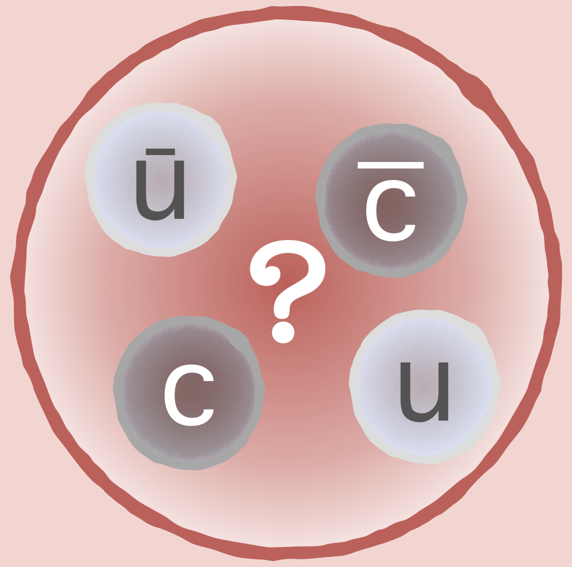
- Small $r_{4q} \approx r_{c\bar{c}}$ ≈ 0.3 fm
- Tight bound

Hadron molecule



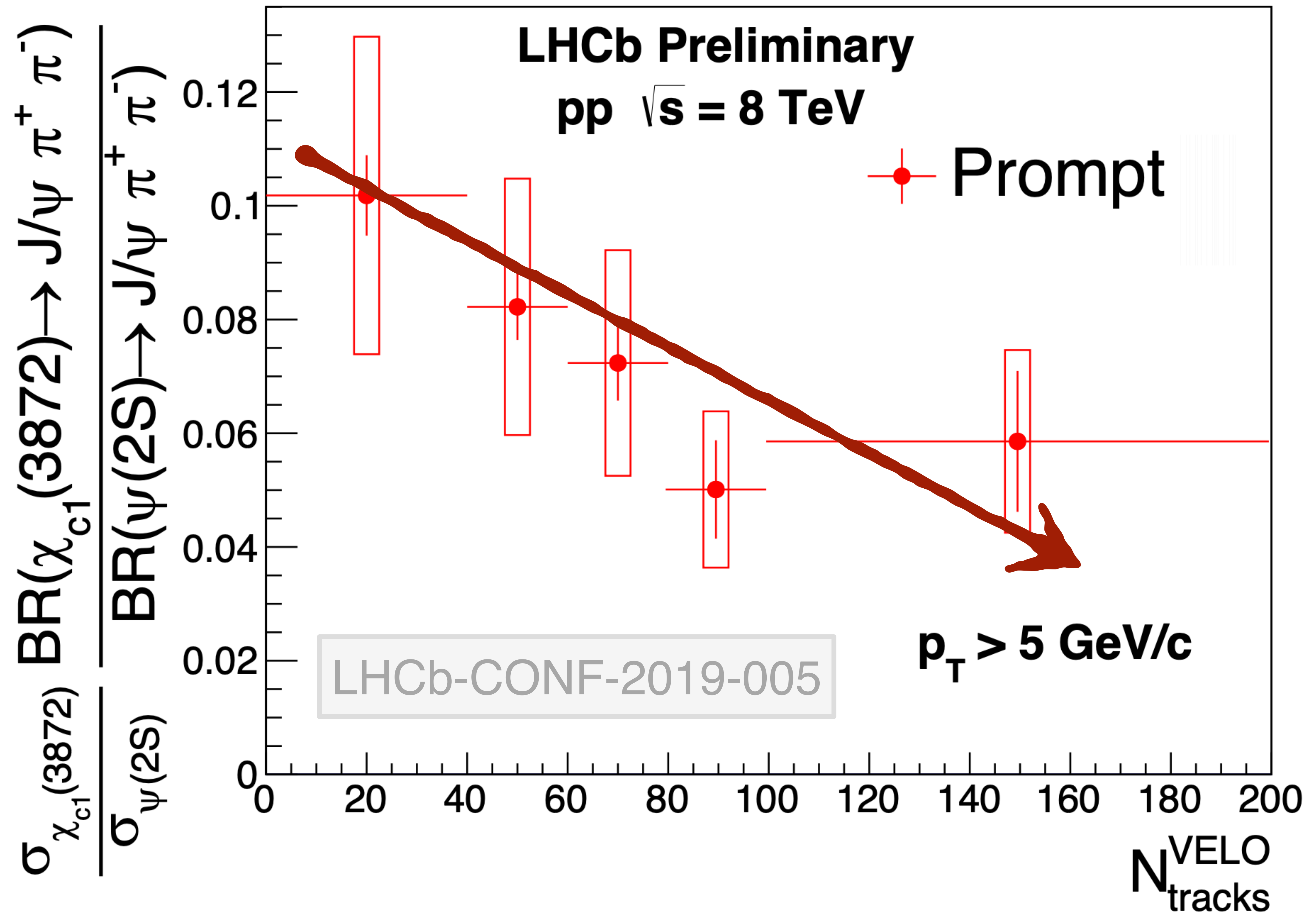
- Large r_{mol} ≈ 5 fm
- Loose bound

Hybrid



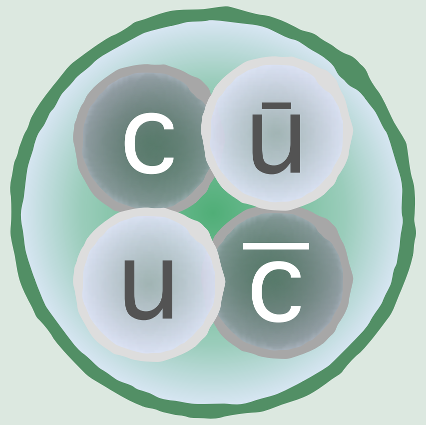
X(3872) in Heavy-ion Collisions

Prompt X(3872)/ψ(2S) vs. multiplicity in pp



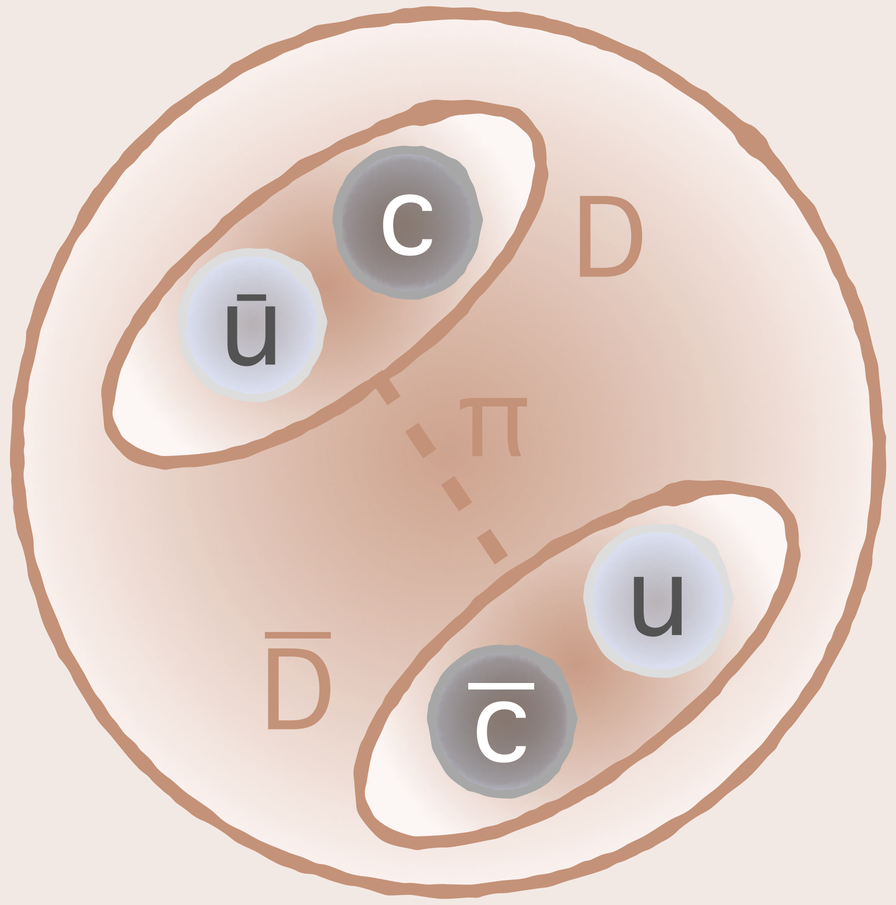
- Destroyed by interactions with other hadrons due to smaller binding energy?

Tetraquark



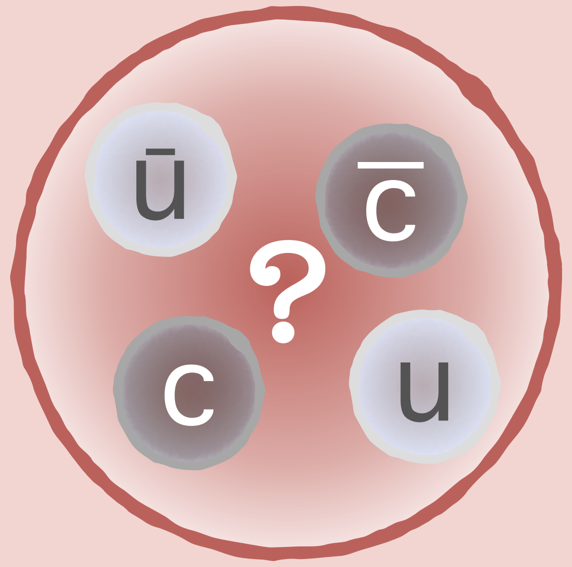
- Small $r_{4q} \approx r_{c\bar{c}}$ ≈ 0.3 fm
- Tight bound

Hadron molecule



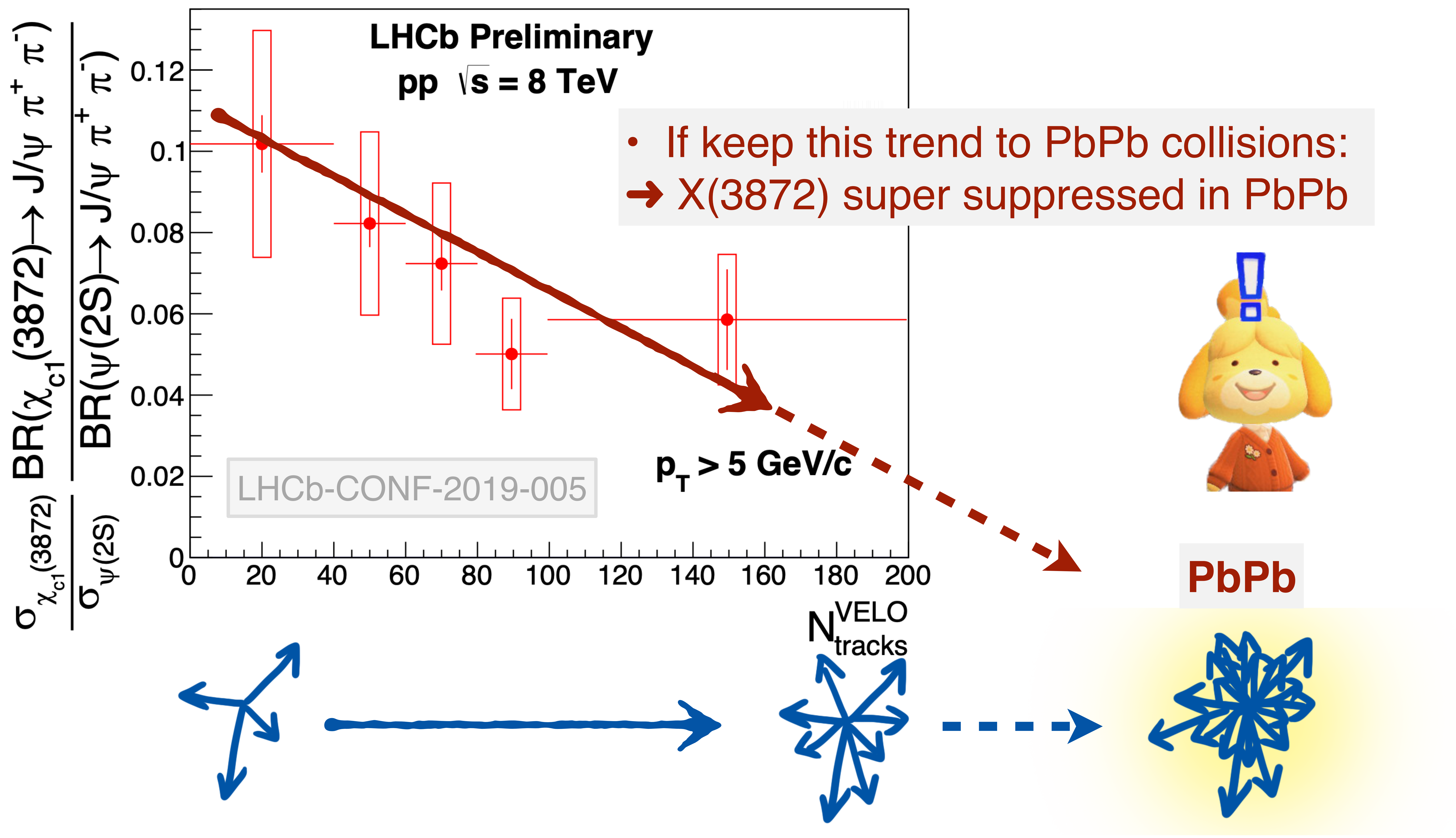
- Large r_{mol} ≈ 5 fm
- Loose bound

Hybrid



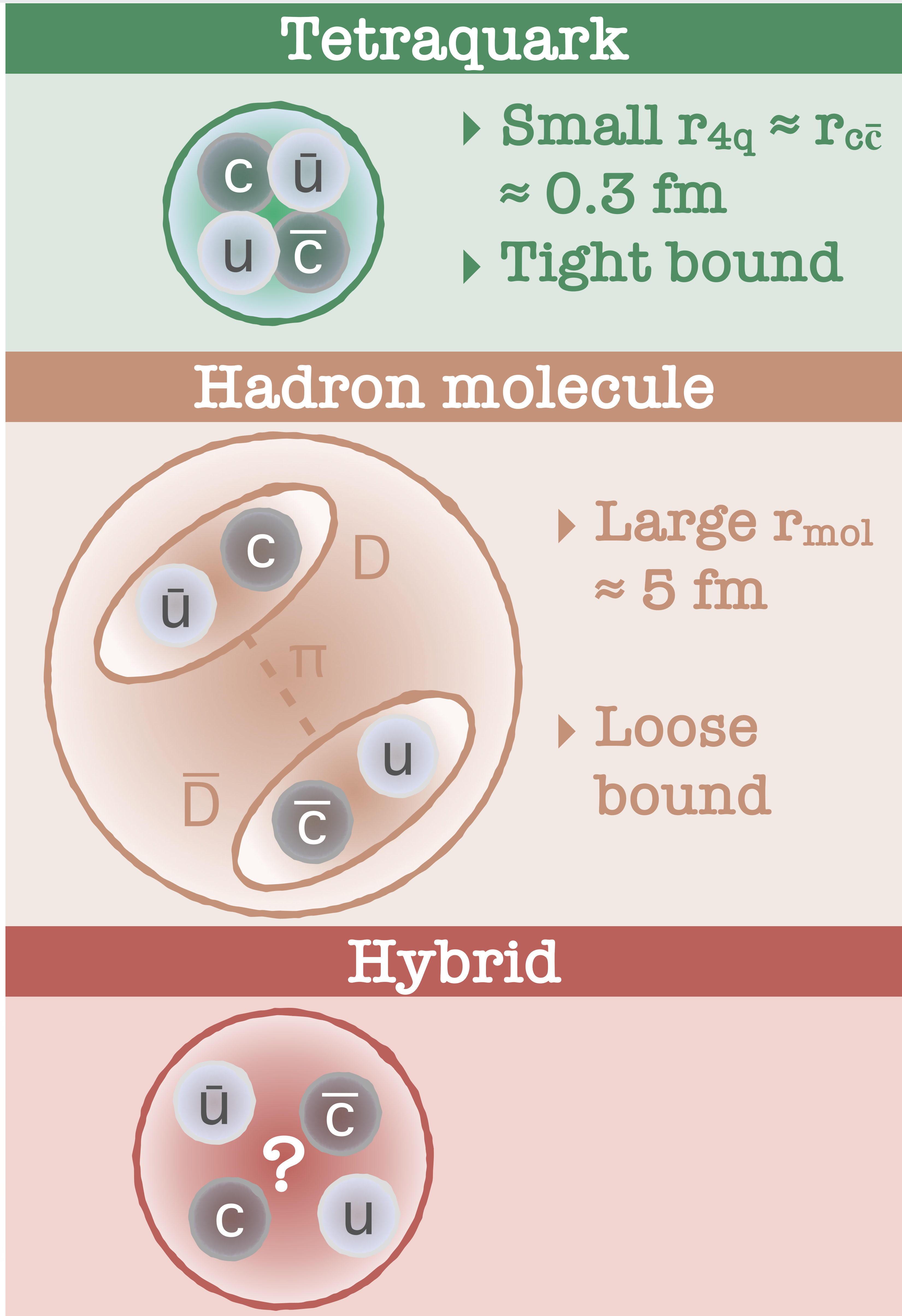
X(3872) in Heavy-ion Collisions

Prompt X(3872)/ψ(2S) vs. multiplicity in pp



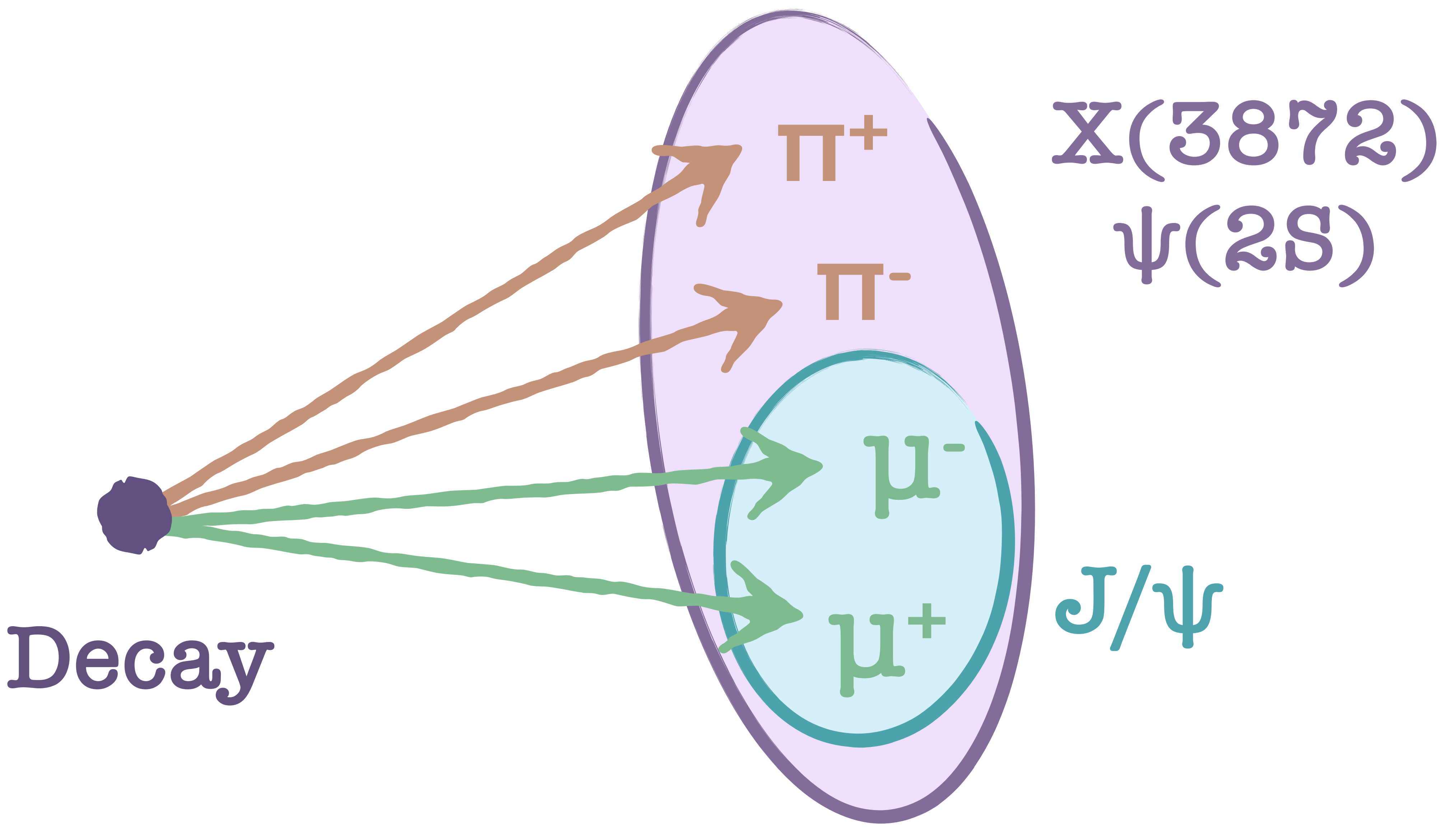
- If keep this trend to PbPb collisions:

➜ X(3872) super suppressed in PbPb



X(3872) and ψ(2S) Reconstruction

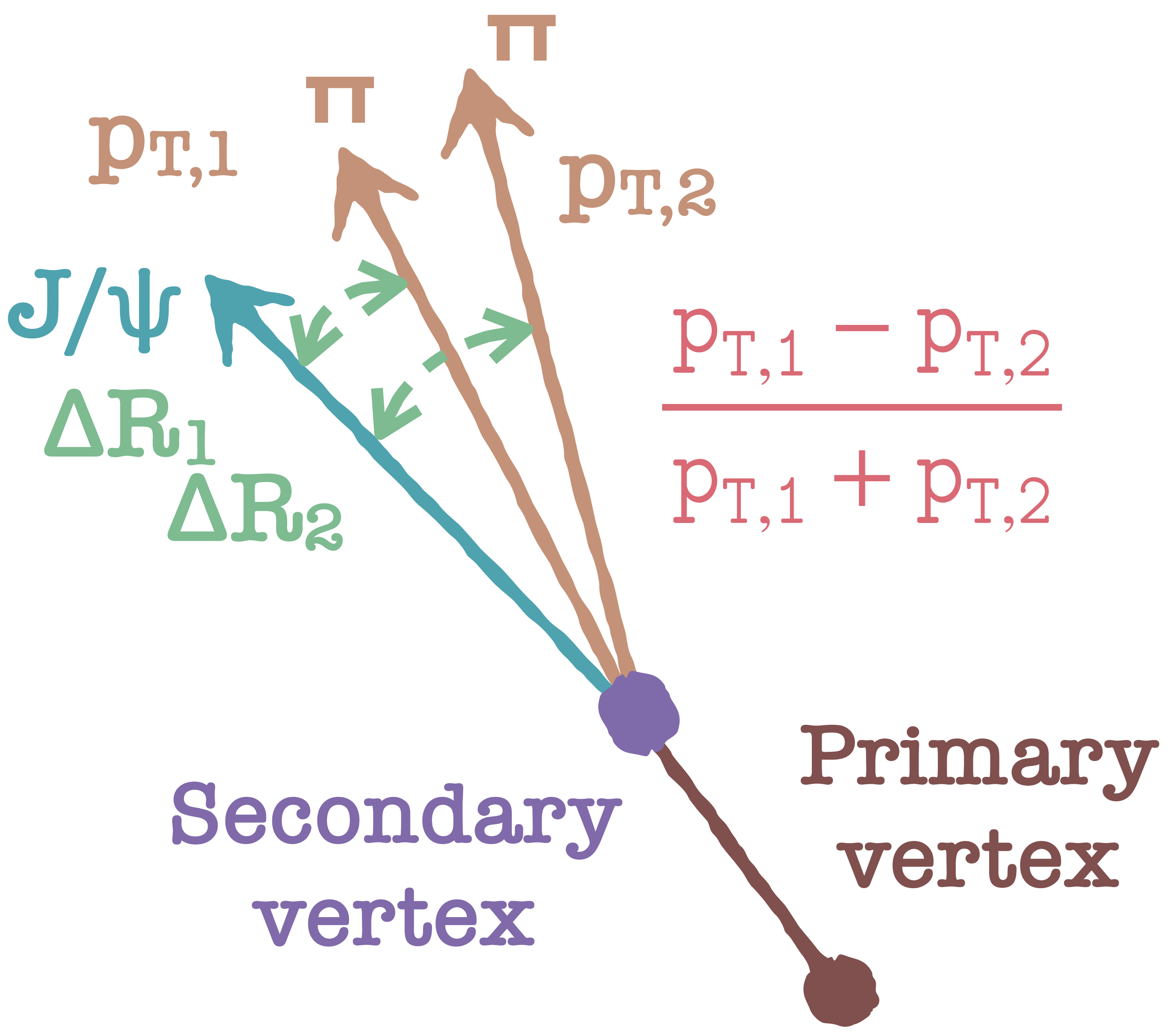
- Di-muon trigger sample in **PbPb** collisions at 5 TeV (LHC 2018 Run)
- X(3872) and ψ(2S) fully reconstructed with same hadronic decay chain **$J/\psi(\mu\mu)\pi^+\pi^-$**
- No constraints on invariant mass $m(\pi^+\pi^-)$



Observable: $R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$, $N^{(Corr)} = N^{(Raw)} \times f_{prompt} / \left(\alpha \times \epsilon_{reco} \times \epsilon_{sel}\right)_{prompt}$

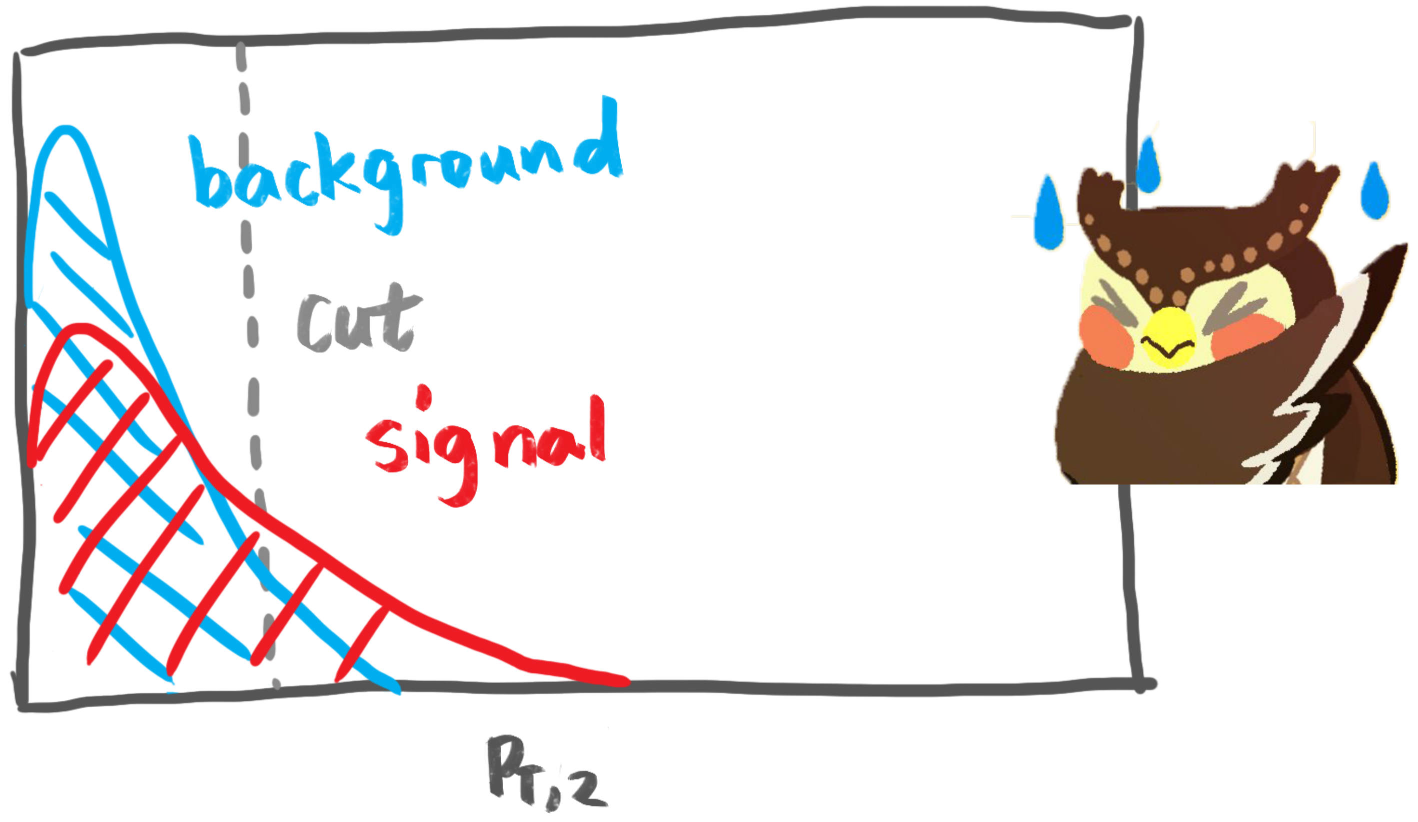
Combinatorial Background Suppression

- A boosted decision tree (**BDT**) algorithm used to suppress the combinatorial background

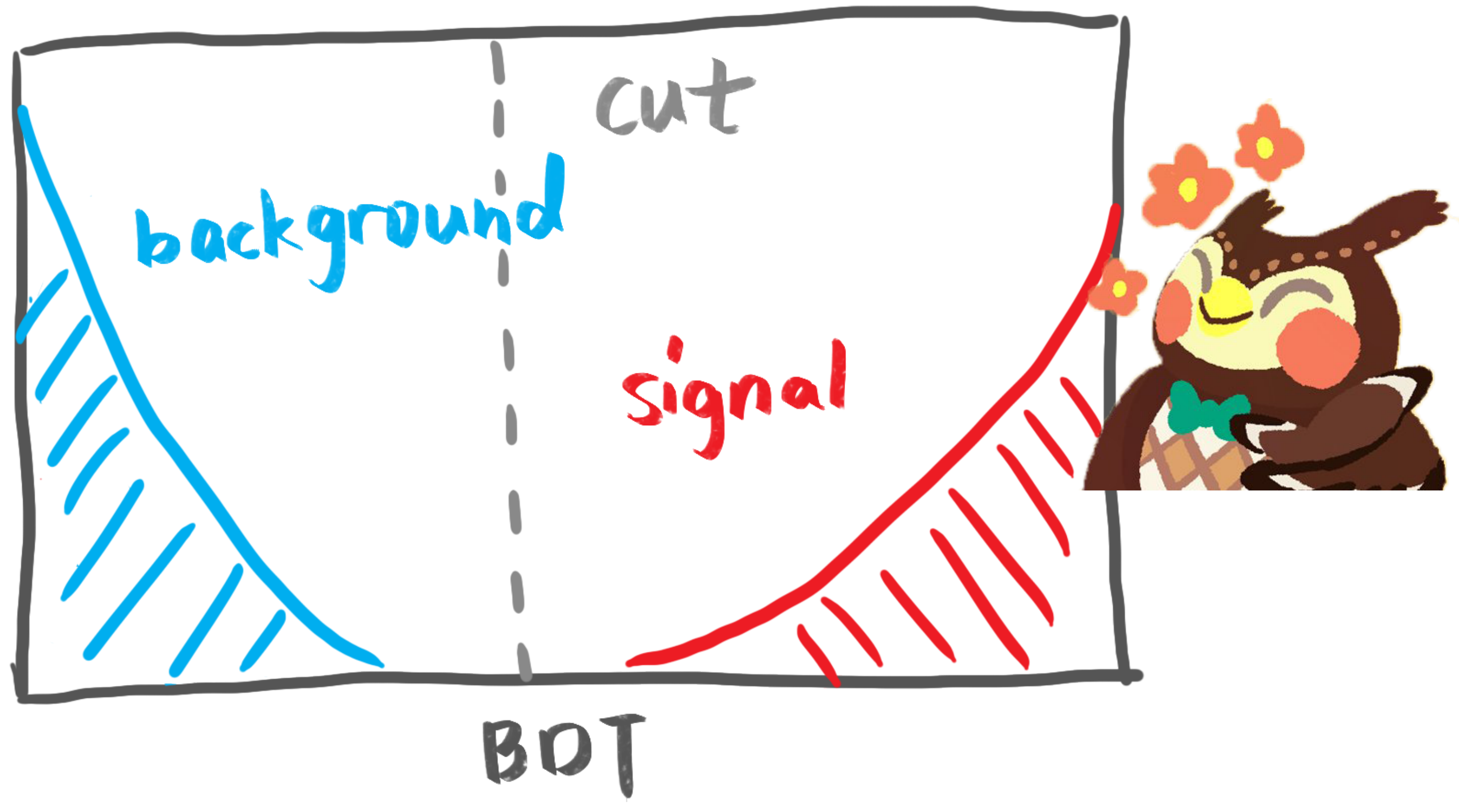


- 5 variables input to BDT
  - ➡ Secondary vertex probability
  - ➡ π p_T imbalance
  - ➡ Slow π $p_{T,2}$
  - ➡ Opening angle between J/ψ and π: ΔR_1, ΔR_2
- Additional cut on $Q = m_{\mu\mu\pi\pi} - m_{\mu\mu} - m_{\pi\pi}$

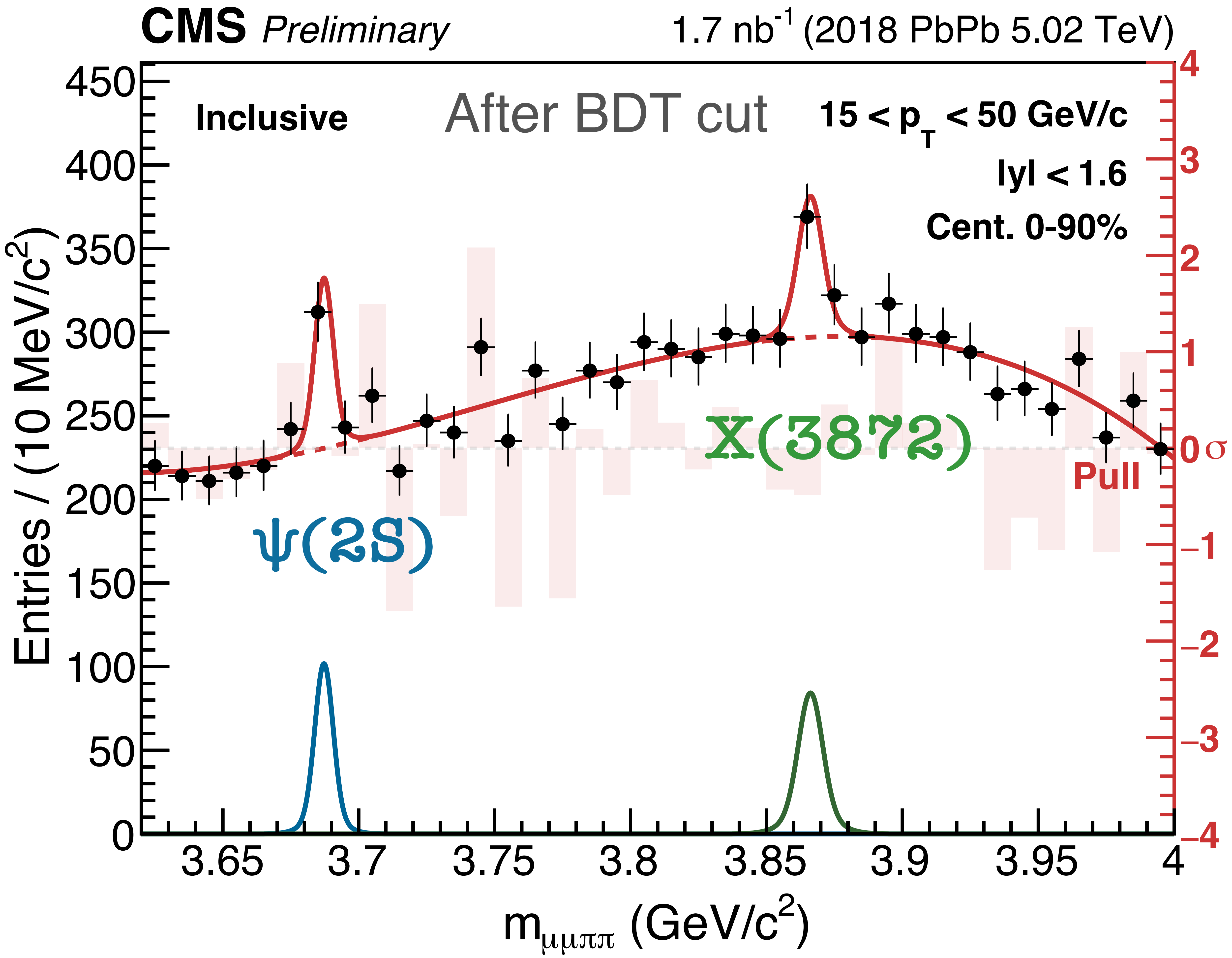
Single variable



Multiple variables: BDT



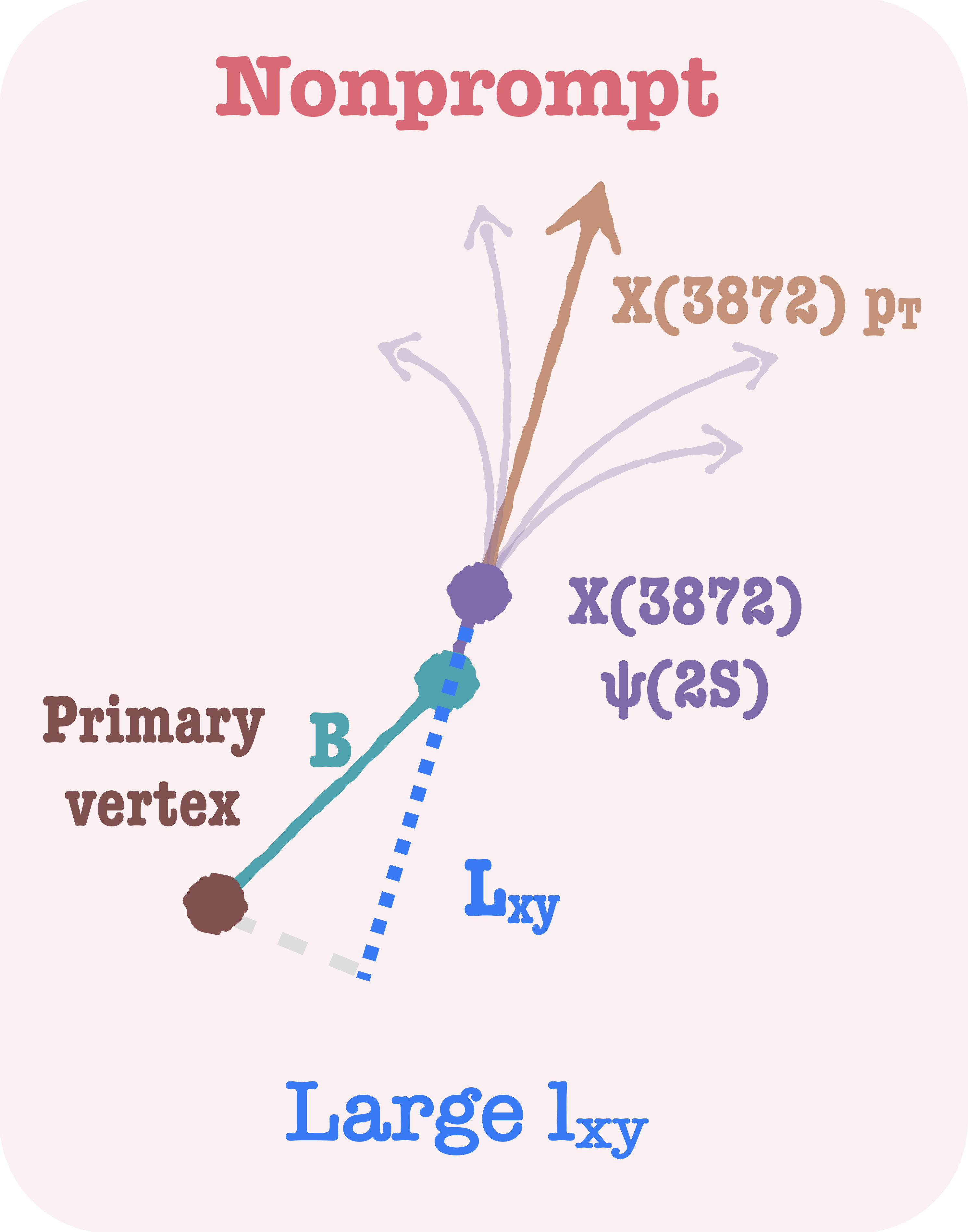
Raw Yield Extraction

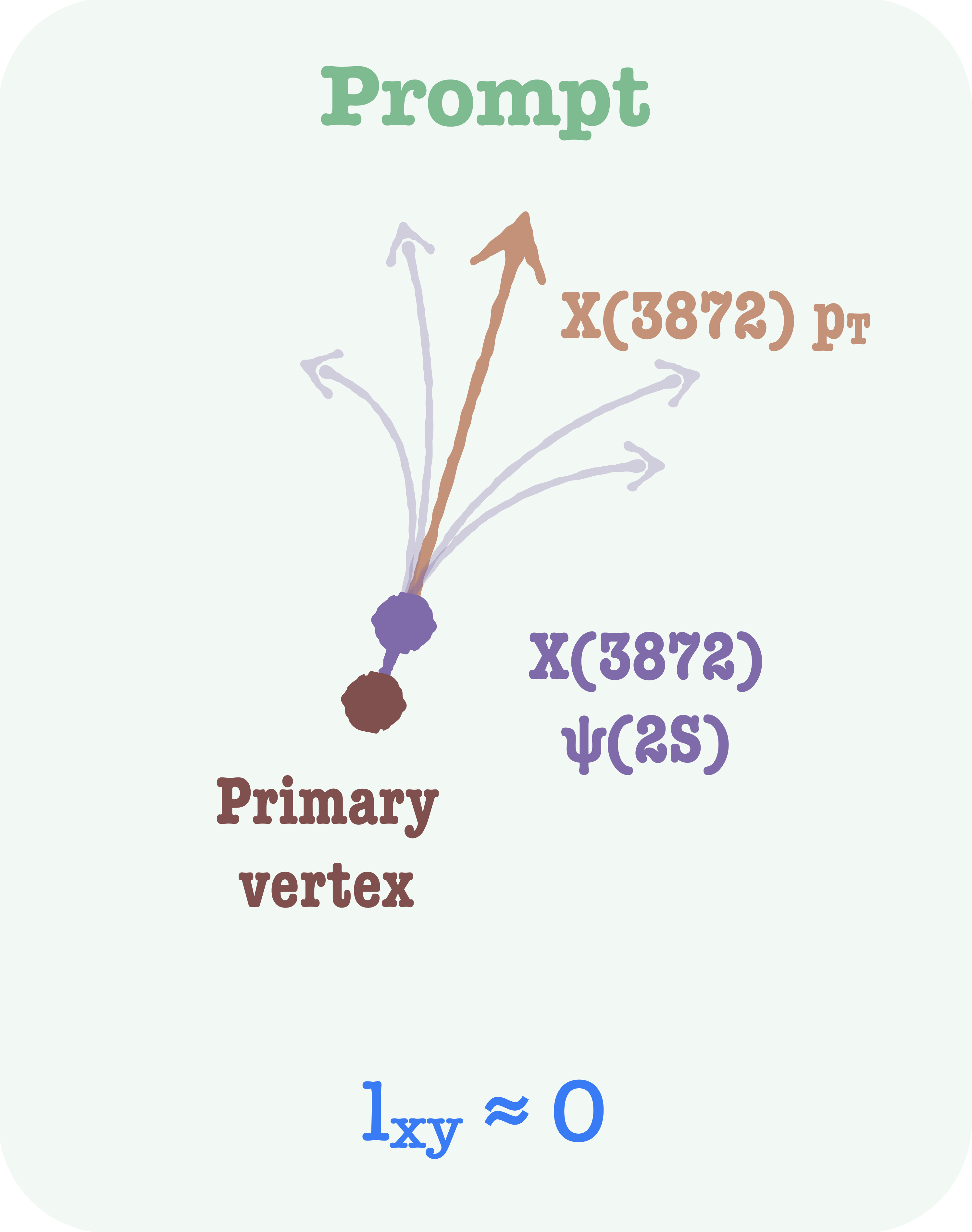


- First evidence of **X(3872)** production in heavy ion collisions!
  - ➡ Statistical **significance > 3σ**
- Clear **ψ(2S)** signal is also observed under same selections
- **Raw yield** extracted with unbinned likelihood fit of invariant mass spectra

Observable: $R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$, $N^{(Corr)} = N^{(Raw)} \times f_{prompt} / (\alpha \times \epsilon_{reco} \times \epsilon_{sel})_{prompt}$

Separate Nonprompt Component





- Inclusive:
  ✔ Prompt: c-quark fragmentation
  ✘ Nonprompt: b-hadron decays
- Pseudo-proper decay length $\mathbf{l_{xy}}$

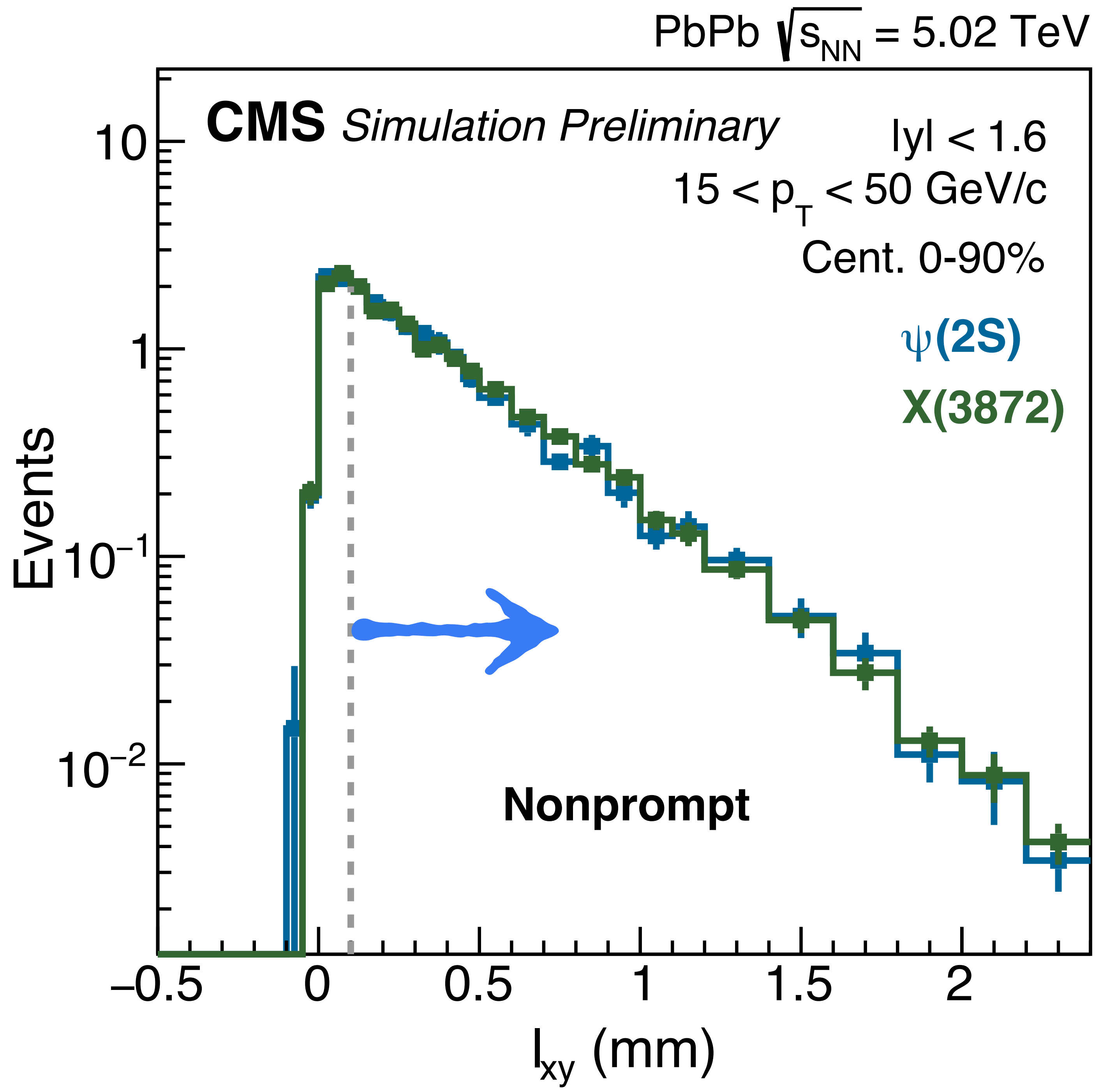
$$l_{xy} = \frac{L_{xy} \cdot m}{|\vec{p}_T|}$$

- Separate nonprompt with l_{xy}

Observable: $R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$, $N^{(Corr)} = N^{(Raw)} \times f_{prompt} / \left(\alpha \times \epsilon_{reco} \times \epsilon_{sel}\right)_{prompt}$

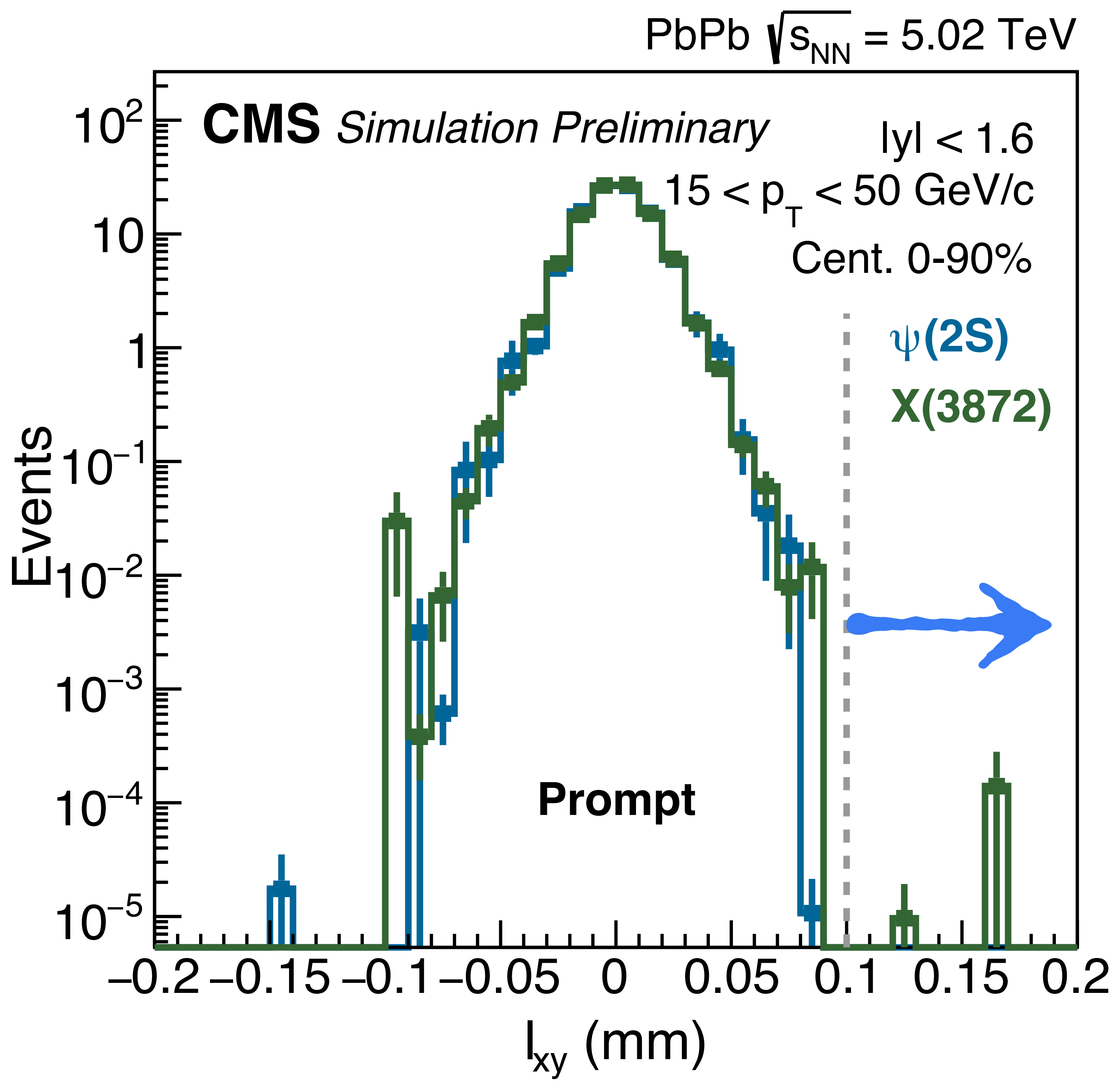
Extract f_{prompt}: B-enrich method

Nonprompt



l_{xy}

Prompt



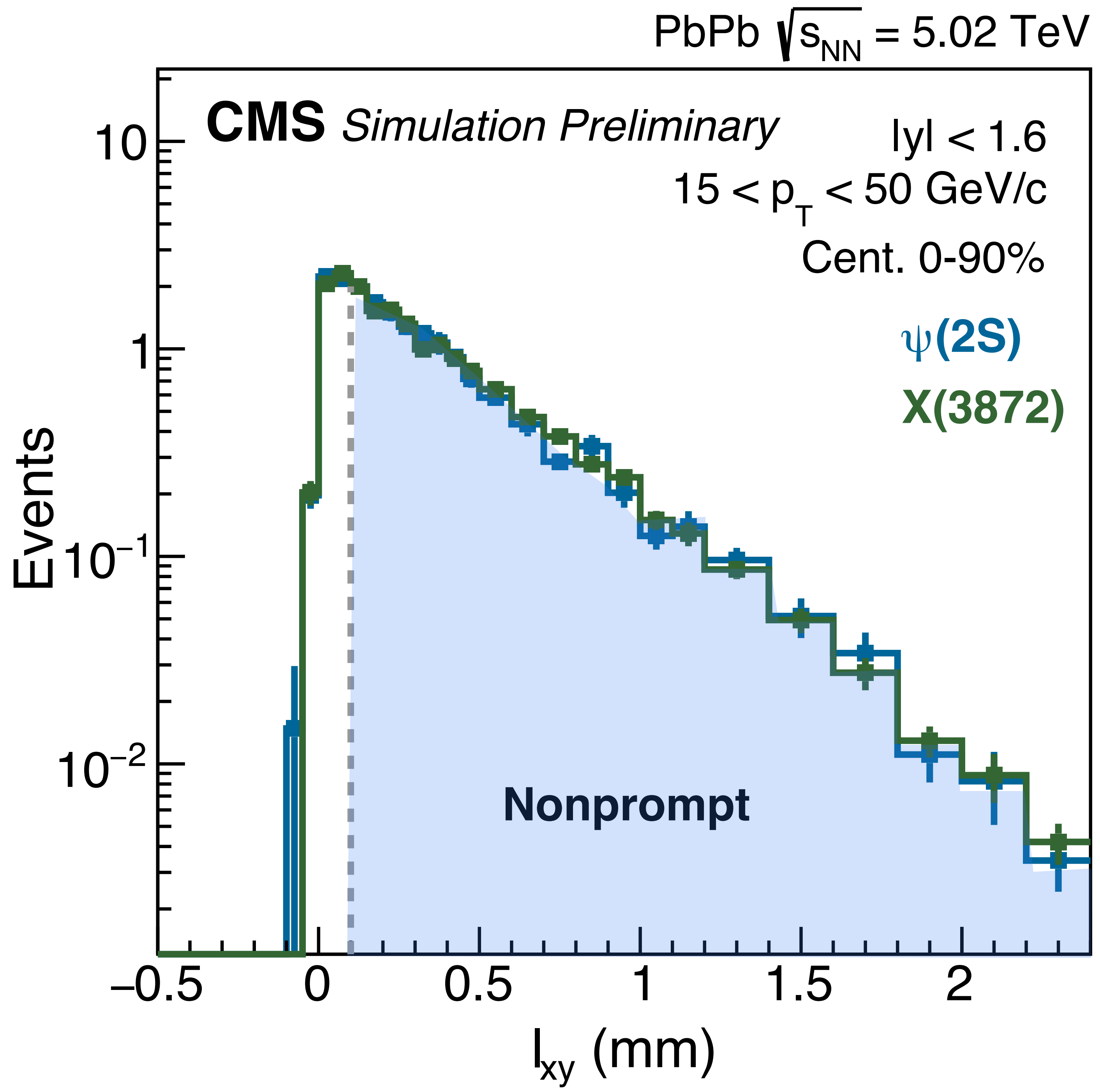
l_{xy}

- Inclusive:
  ✔ Prompt: c-quark fragmentation
  ✘ Nonprompt: b-hadron decays
- B-enriched sample:
  ➡ Pure nonprompt in l_{xy} > 0.1mm

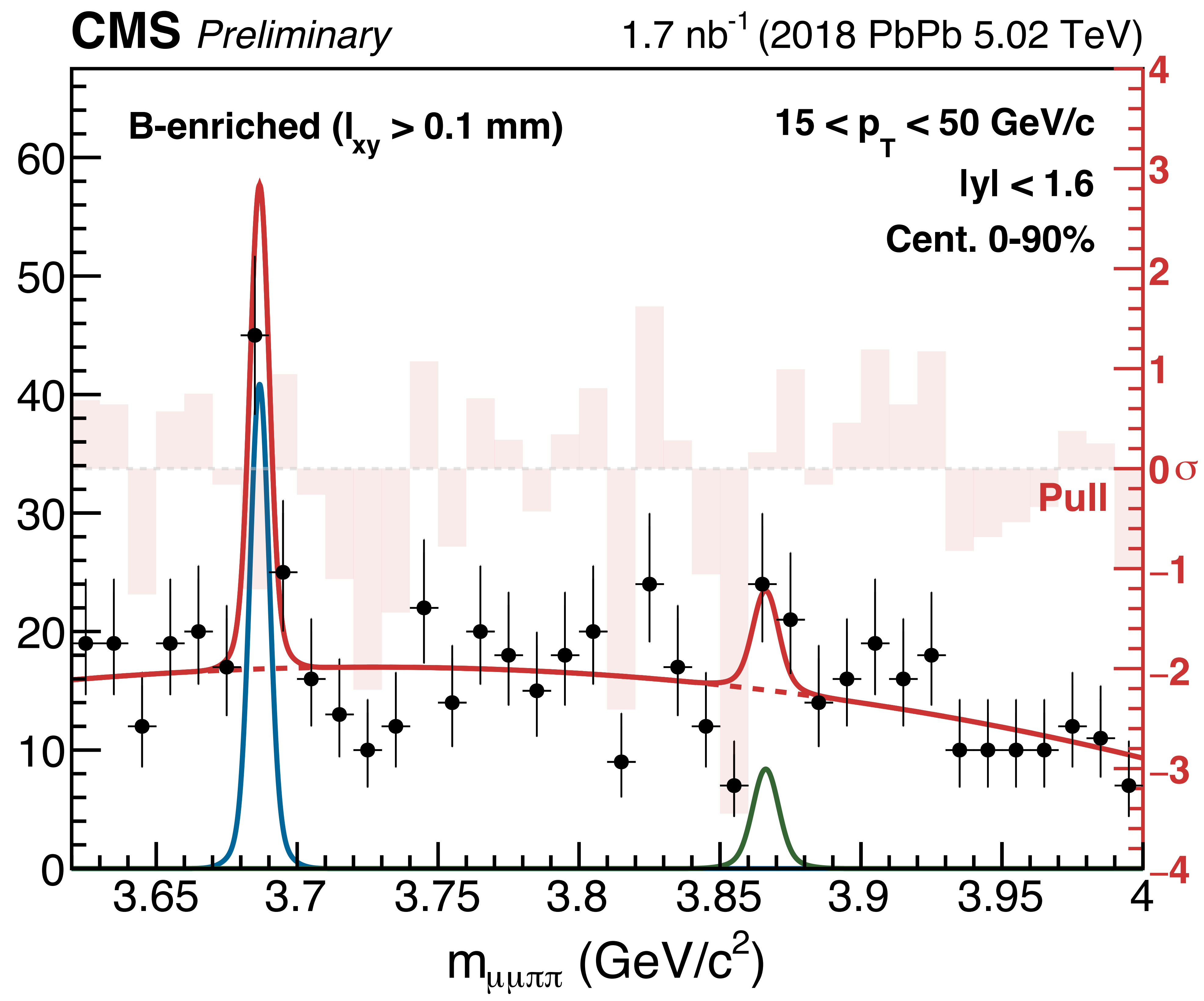
Observable: $R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$, $N^{(Corr)} = N^{(Raw)} \times f_{prompt} / (\alpha \times \epsilon_{reco} \times \epsilon_{sel})_{prompt}$

Extract f_{prompt}: B-enrich method

Nonprompt



B-enriched: pure nonprompt



- Prompt fraction:

$$f_{prompt} = 1 - \frac{N^{data}_{B-enr} \cdot N^{NP\ MC}_{Inclusive}}{N^{NP\ MC}_{B-enr} \cdot N^{data}_{Inclusive}}$$

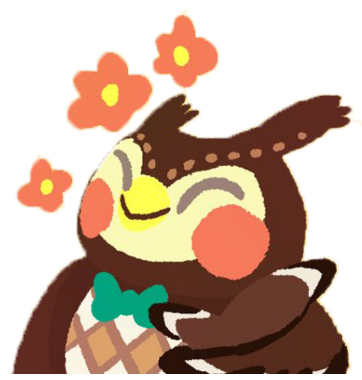
- Cross-check with l_{xy} template fit method

Observable: $R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$, $N^{(Corr)} = N^{(Raw)} \times f_{prompt} / (\alpha \times \epsilon_{reco} \times \epsilon_{sel})_{prompt}$

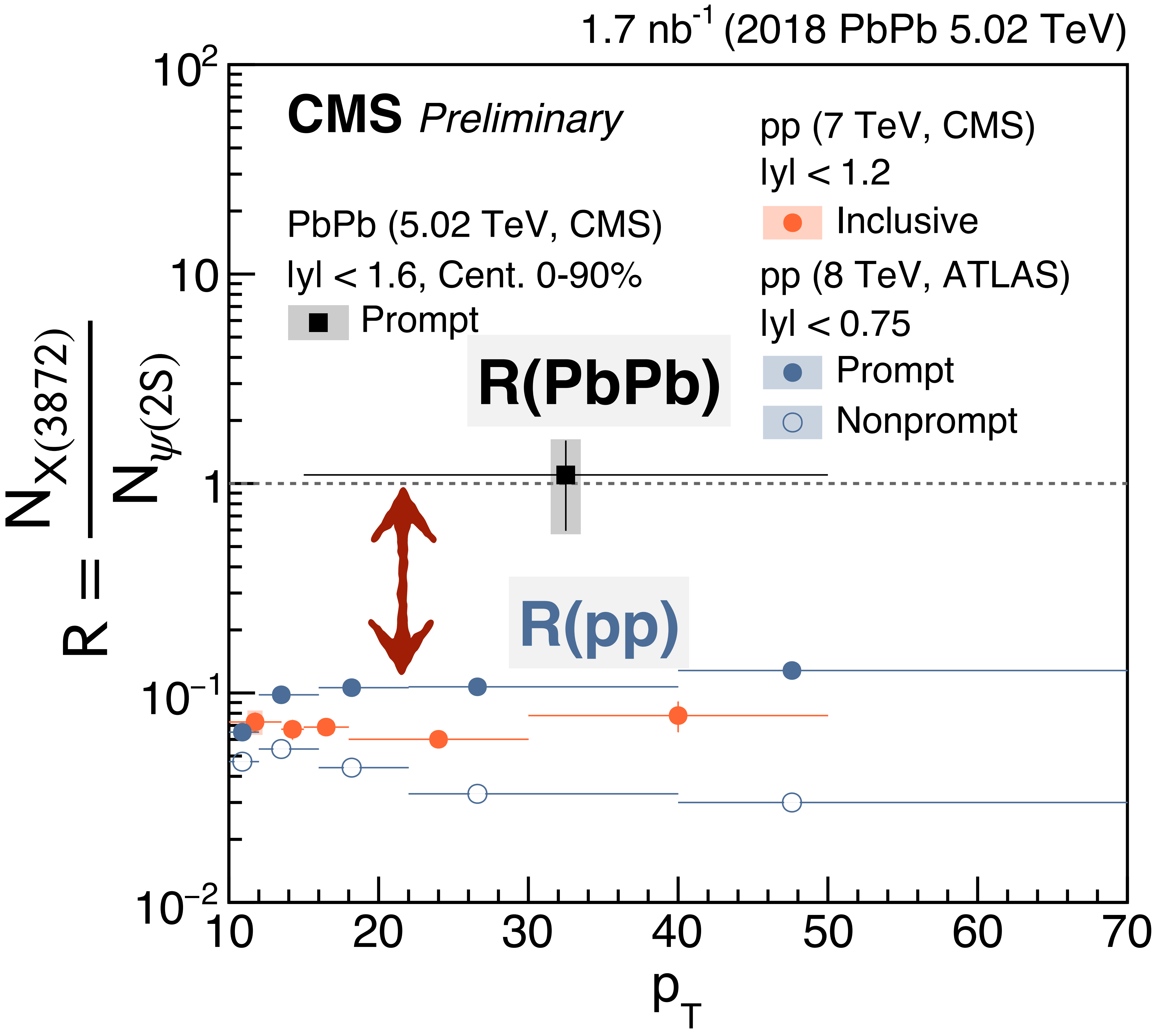
Result: X(3872)/ψ(2S) Ratio in PbPb

- In PbPb collisions
  ➡ R = 1.10 ± 0.51 (stat.) ± 0.53 (syst.)

- Indication of R enhancement in PbPb collisions with respect to pp at 8 TeV
  ➡ R(pp) ~ 0.04-0.1



- Better precision needed to draw conclusion



Observable: $R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$, $N^{(Corr)} = N^{(Raw)} \times f_{prompt} / (\alpha \times \epsilon_{reco} \times \epsilon_{sel})_{prompt}$

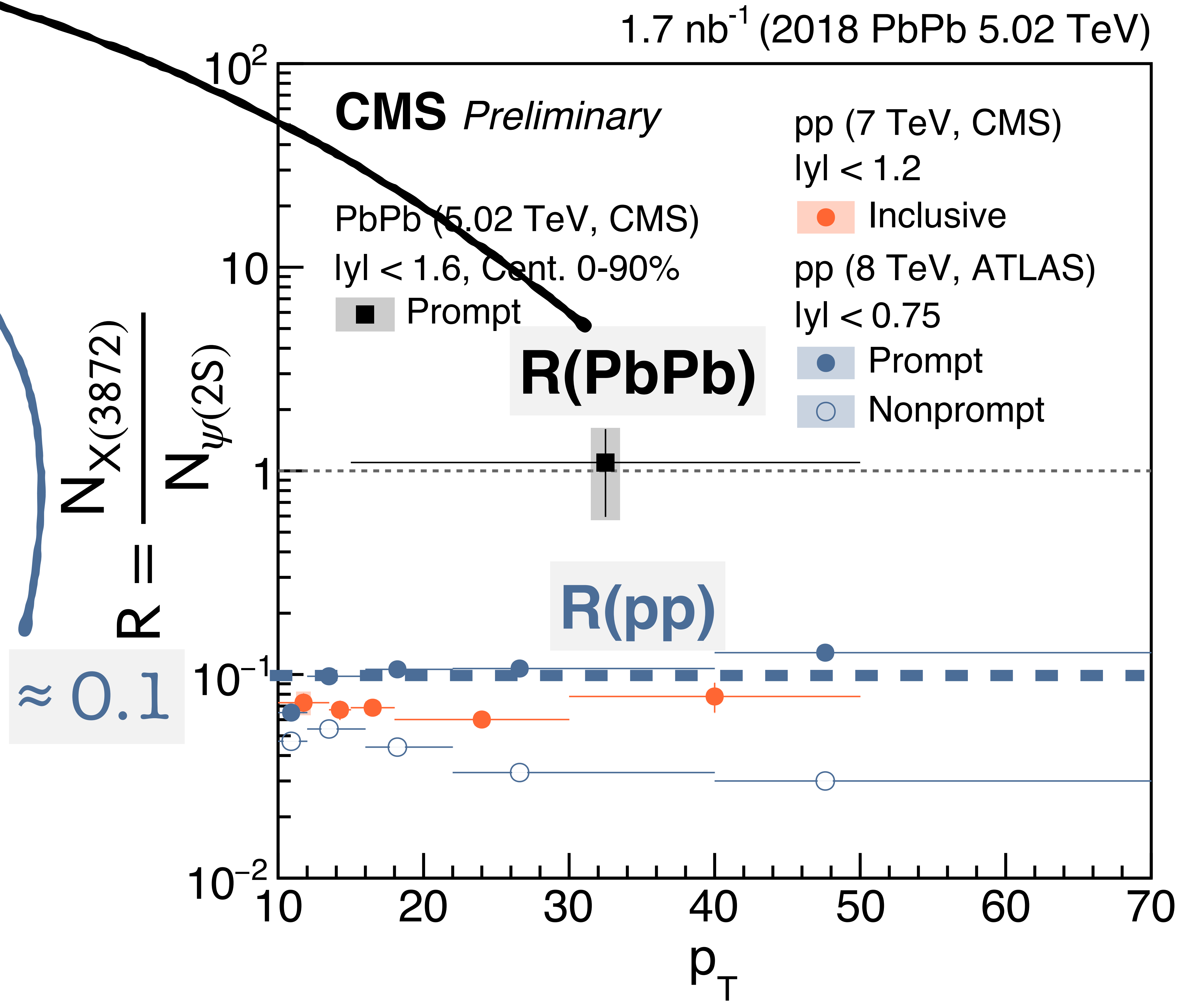
Result: X(3872)/ψ(2S) Ratio in PbPb

$$R_{AA}^{X(3872)} = \frac{N_{X(3872)}(PbPb)}{N_{X(3872)}(pp)} = \frac{R(PbPb)}{R(pp)} \cdot R_{AA}^{\psi(2S)}$$

$R(PbPb) \approx 1.1$

$R(pp) \approx 0.1$

- ψ(2S) as reference suppressed in PbPb

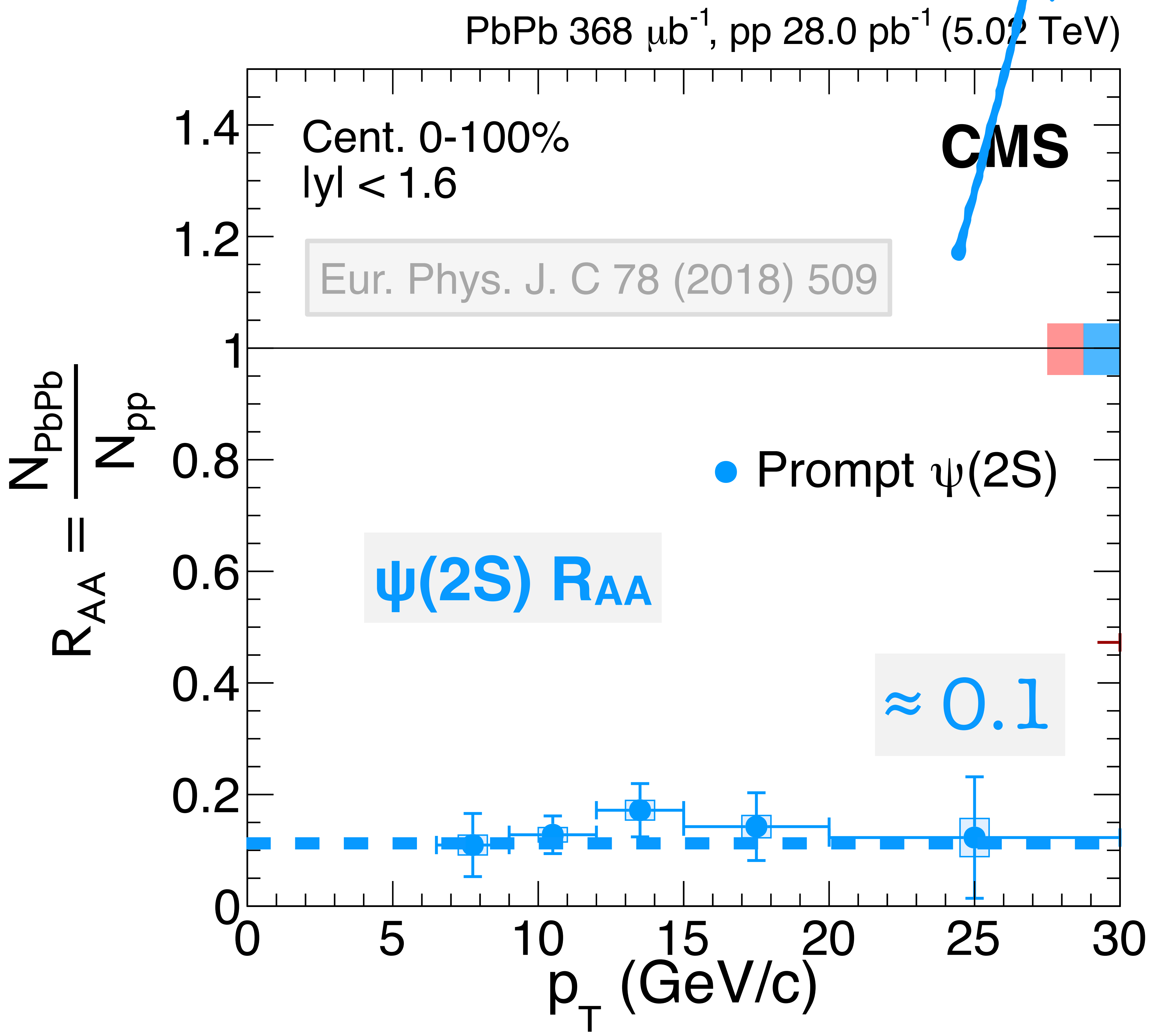


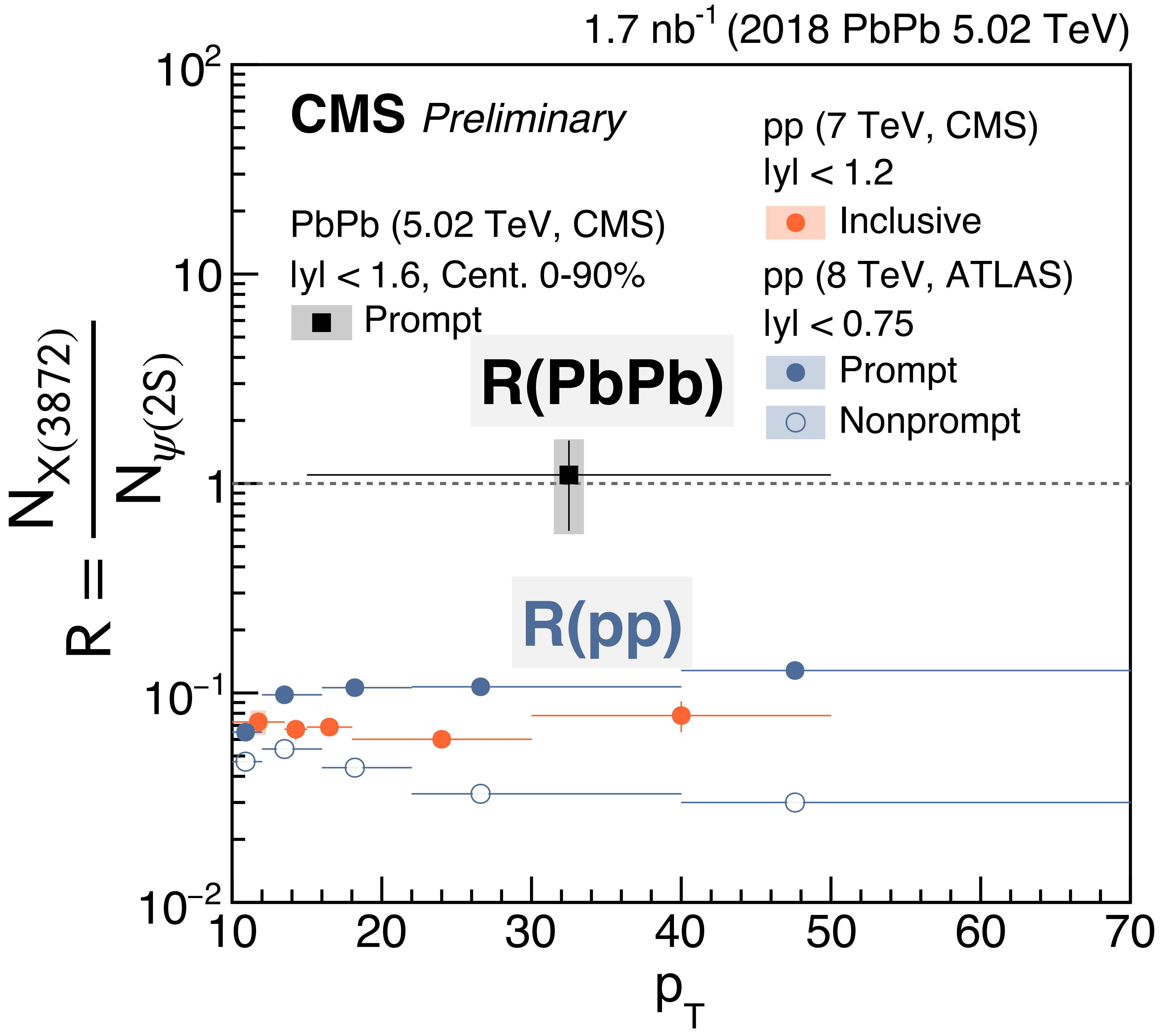
- R enhancement:
  ➜ X(3872) less suppressed than ψ(2S)

Result: X(3872)/ψ(2S) Ratio in PbPb

$$R_{AA}^{X(3872)} = \frac{N_{X(3872)}(PbPb)}{N_{X(3872)}(pp)} = \frac{\simeq 1.1}{\simeq 0.1} \cdot R_{AA}^{\psi(2S)} \simeq 1.1$$

≈ 0.1

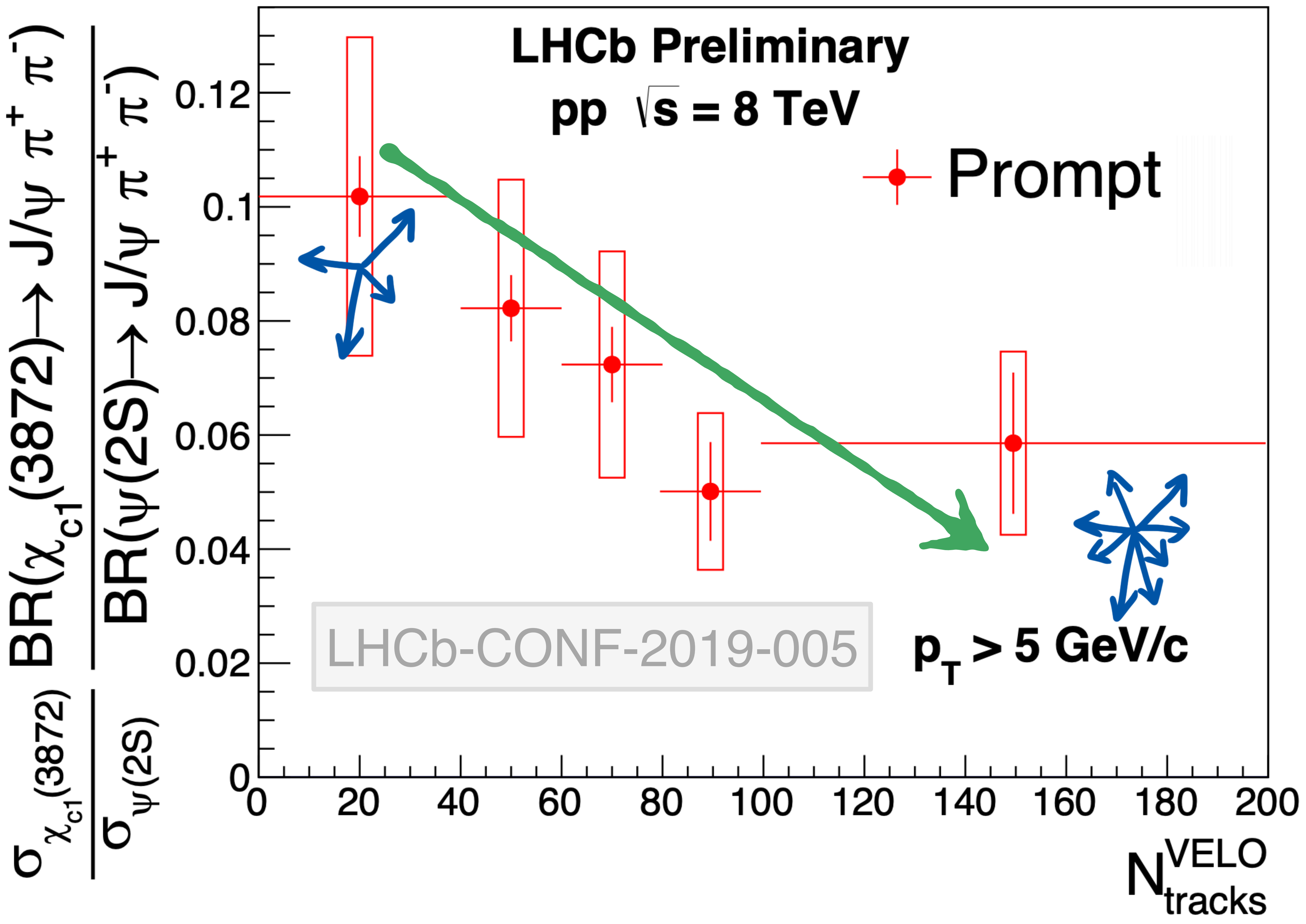


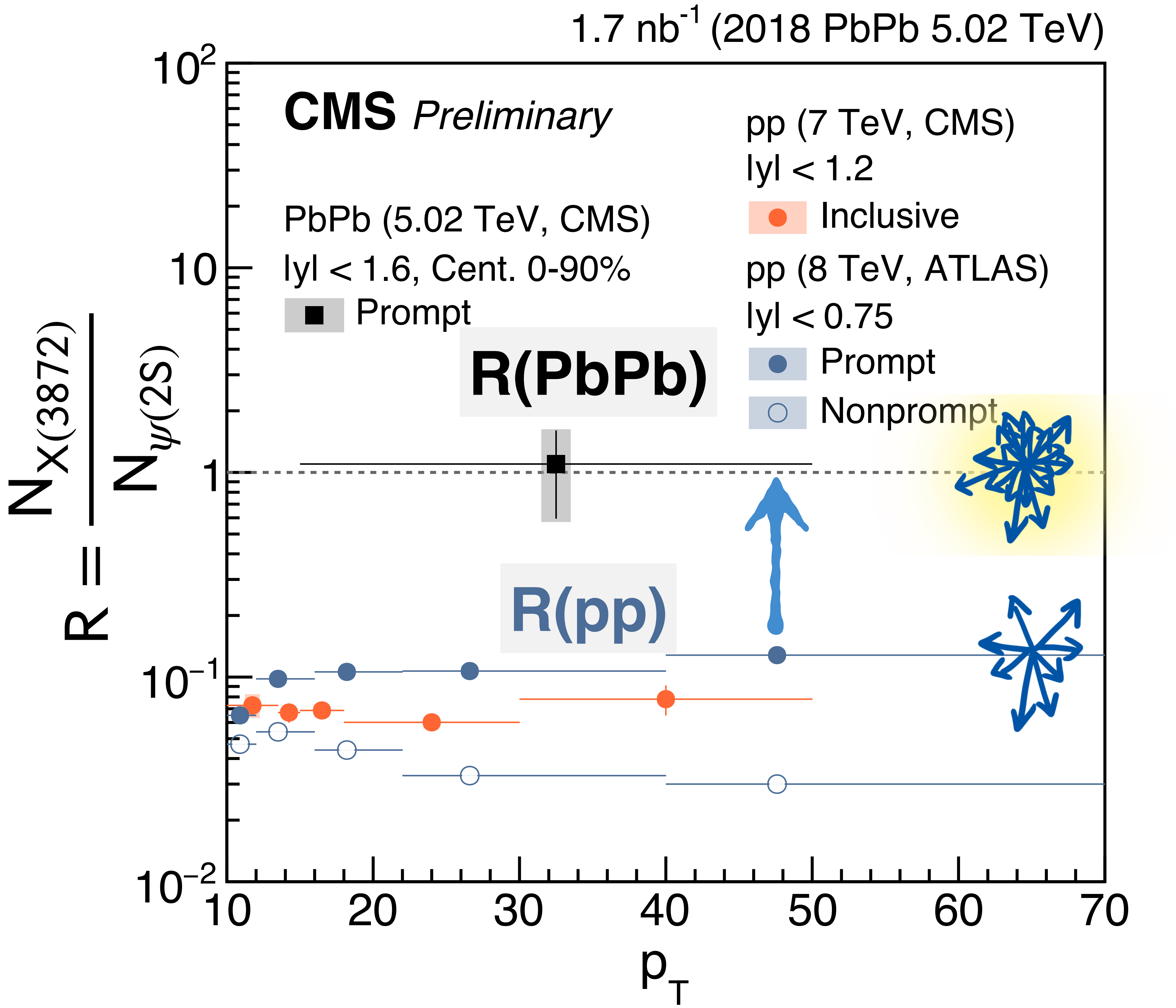


- X(3872) very weak suppressed or even enhance?

Result: Compare to pp

R vs. multiplicity in pp





- From low to high-multiplicity pp:
  ➜ X(3872) more suppressed than ψ(2S)?
- From pp to PbPb:
  ➜ X(3872) less suppressed than ψ(2S)?

Tetra-quark or Molecule?

Tetra-quark or Molecule?

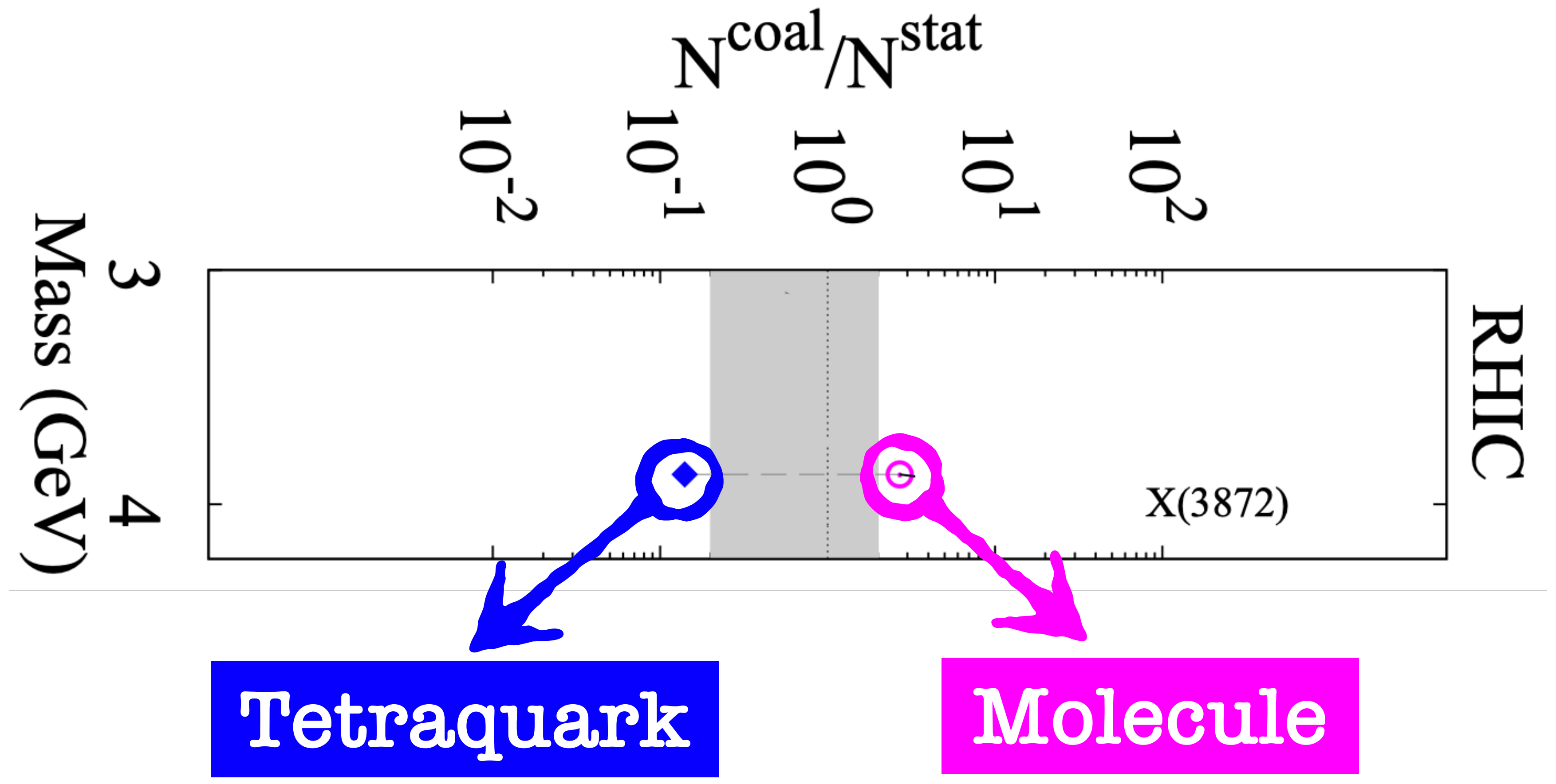
We don't know…

- No yet direct comparison to theory
- Disagreement among models

Tetra-quark or Molecule?

Status of current X(3872) theoretical calculations in heavy-ion collisions

Coalescence model



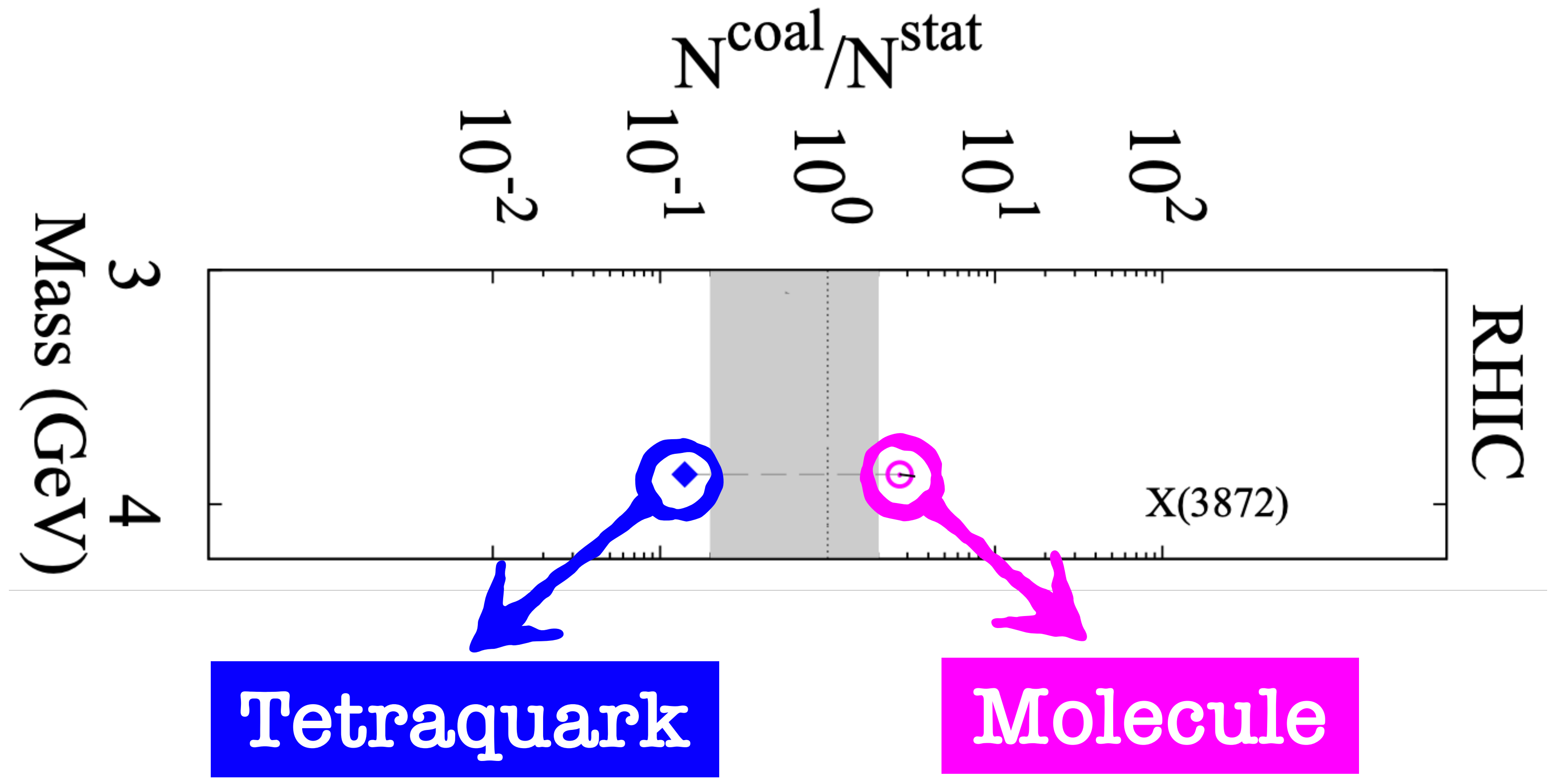
PRL 106 (2011) 212001

- Molecule easier to be produced w/ recombination of quarks in medium
- $N_{Molecule} > N_{Tetraquark}$

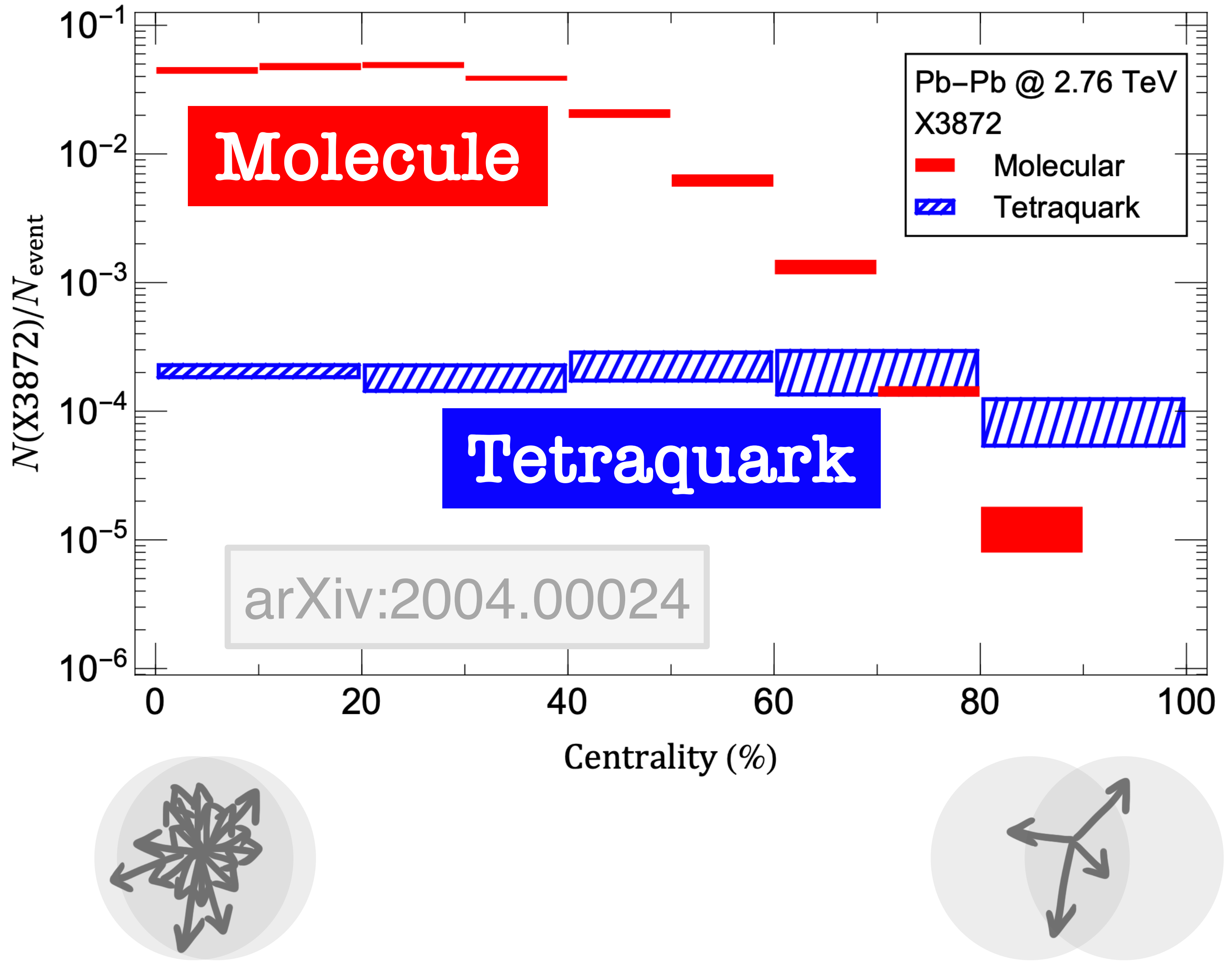
Tetra-quark or Molecule?

Status of current X(3872) theoretical calculations in heavy-ion collisions

Coalescence model | **AMPT transport model**



PRL 106 (2011) 212001



arXiv:2004.00024

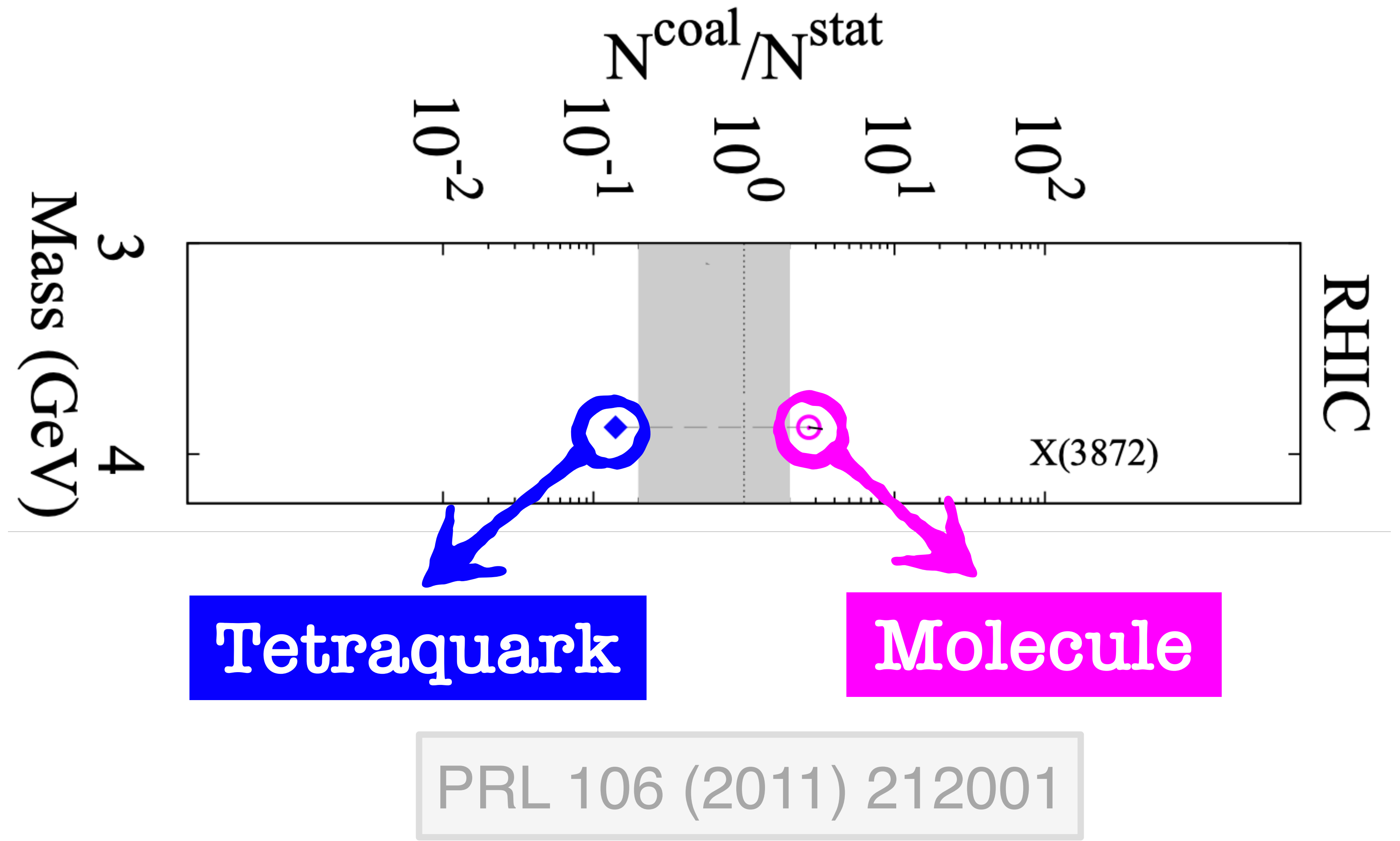
- Molecule easier to be produced w/ recombination of quarks in medium
- $N_{Molecule} > N_{Tetraquark}$

- Molecule production per event decreases from central to peripheral
- Tetraquark no centrality dependence
- $N_{Molecule} > N_{Tetraquark}$

Tetra-quark or Molecule?

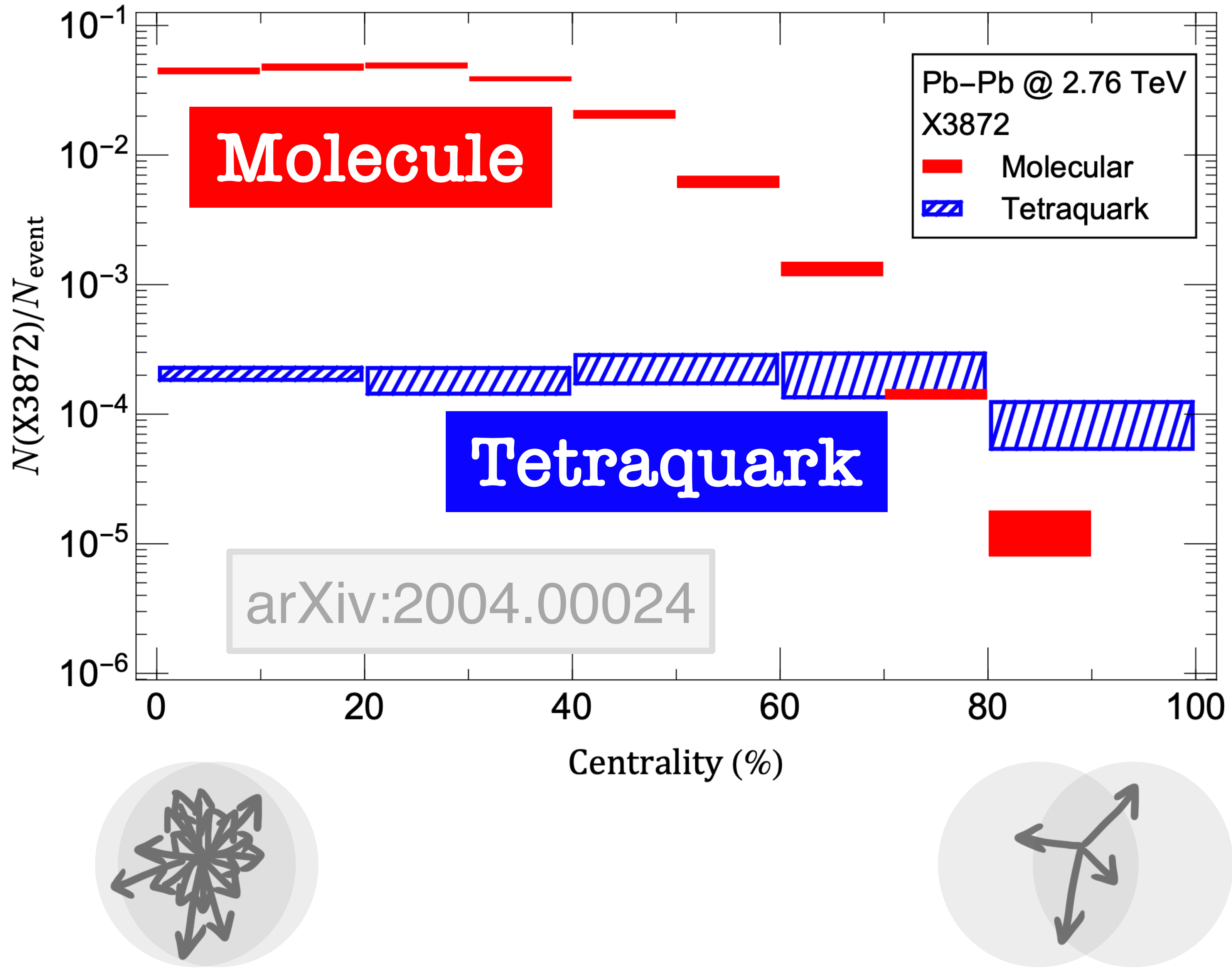
Status of current X(3872) theoretical calculations in heavy-ion collisions

Coalescence model



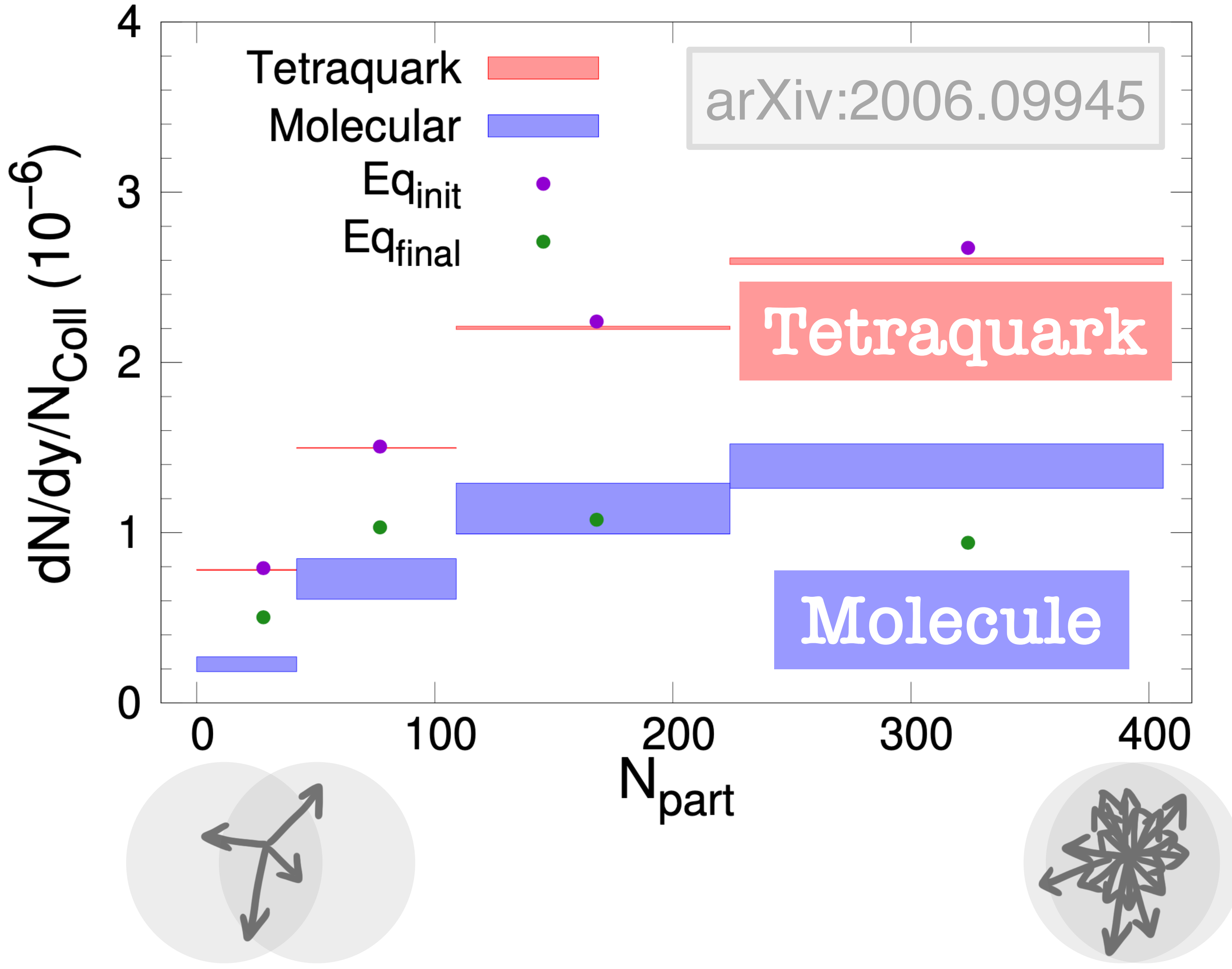
- Molecule easier to be produced w/ recombination of quarks in medium
- $N_{Molecule} > N_{Tetraquark}$

AMPT transport model



- Molecule production per event decreases from central to peripheral
- Tetraquark no centrality dependence
- $N_{Molecule} > N_{Tetraquark}$

TAMU transport model



- Molecule (more loosely bound) regenerated later in the evolution compared to tetraquark
- $N_{Molecule} < N_{Tetraquark}$

Summary (I): We have learnt a lot before

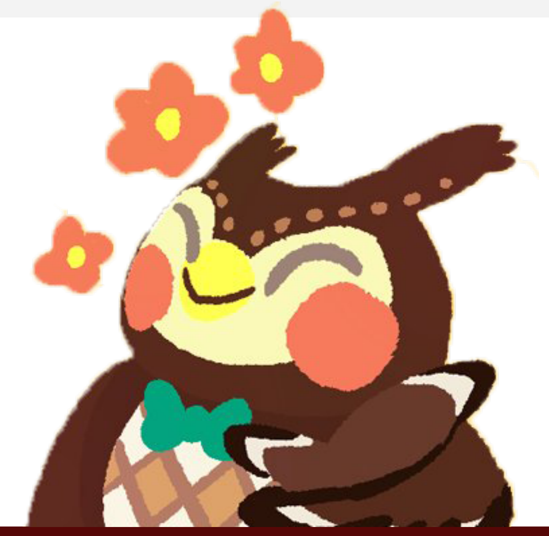
Only from publications w/ Run II data…

nPDF arXiv:2003.12797 PLB 800 (2020) 135048 PRL 121 (2018) 062002	**Initial stage** arXiv:1910.08789 PRC 100 (2019) 064908 PLB 799 (2019) 135049 PLB 789 (2019) 643 PRC 97 (2018) 044912 JHEP 01 (2018) 045 PRL 119 (2017) 242001	**Jet quenching** JHEP 10 (2018) 138 PLB 785 (2018) 14 PRL 119 (2017) 082301 JHEP 04 (2017) 039	**Jet substructure** arXiv:2005.14219 arXiv:2004.00602 PRL 122 (2019) 152001 JHEP 10 (2018) 161 JHEP 05 (2018) 006 PRL 121 (2018) 242301 PRL 120 (2018) 142302	**Collective dynamics** PRC 100 (2019) 044902 PRC 98 (2018) 044902 PLB 776 (2017) 195
Small system arXiv:1910.04812 PRC 101 (2020) 014912 PLB 791 (2019) 172 PRL 121 (2018) 082301 PRL 120 (2018) 092301	**Heavy flavors** arXiv:1911.01461 PRL 123 (2019) 022001 JHEP 03 (2018) 181 PLB 782 (2018) 474 PRL 120 (2018) 202301 PRL 119 (2017) 152301	**Quarkonion prod.** PLB 790 (2019) 270 PLB 790 (2019) 509 EPJC 78 (2018) 509 PRL 120 (2018) 142301 EPJC 77 (2017) 269 PRL 118 (2017) 162301	**Hadronization** PLB 803 (2020) 135328 PLB 796 (2019) 168	More preliminary results in queue…

→ CMS Heavy-ion Publications

→ CMS Heavy-ion Preliminary

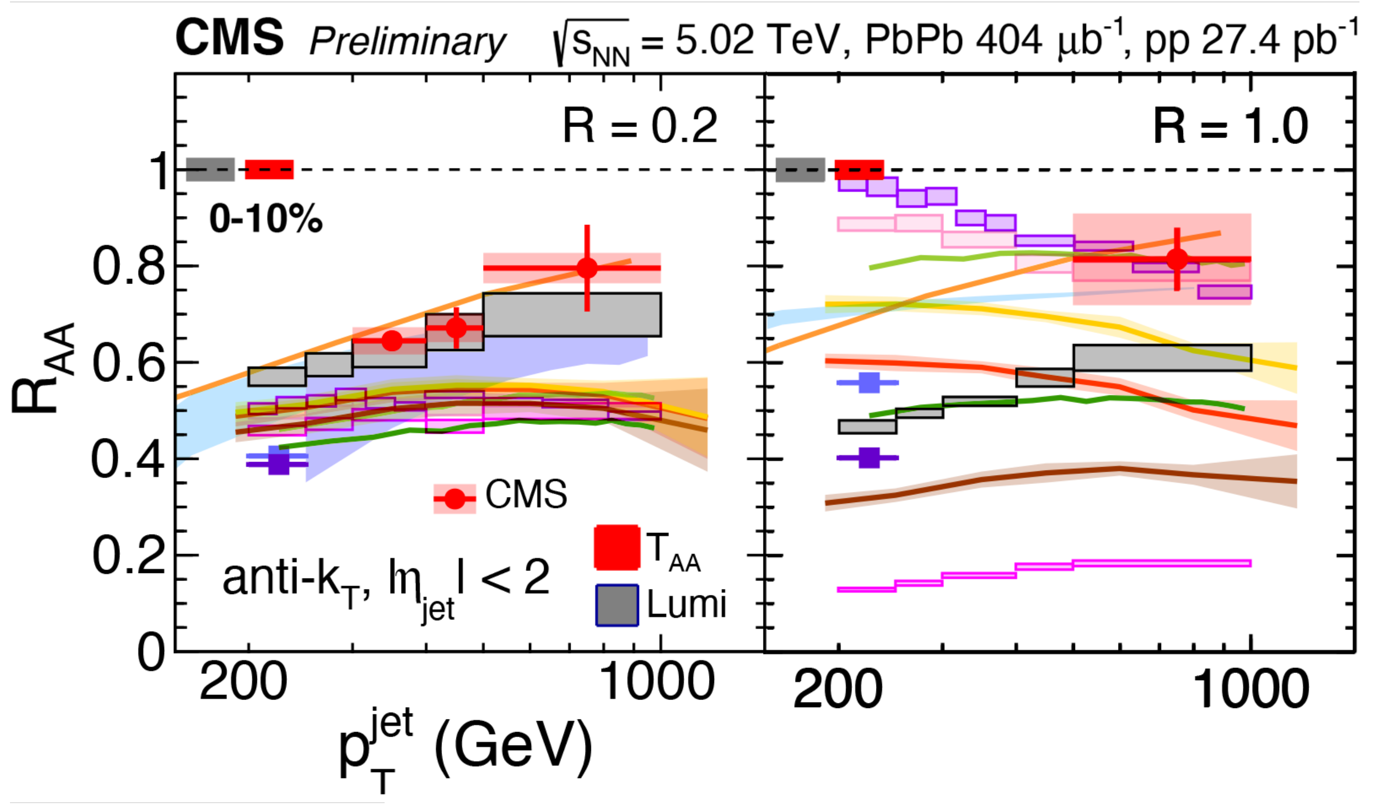
Look into what you are interested in!



Summary (II): Develop new probes

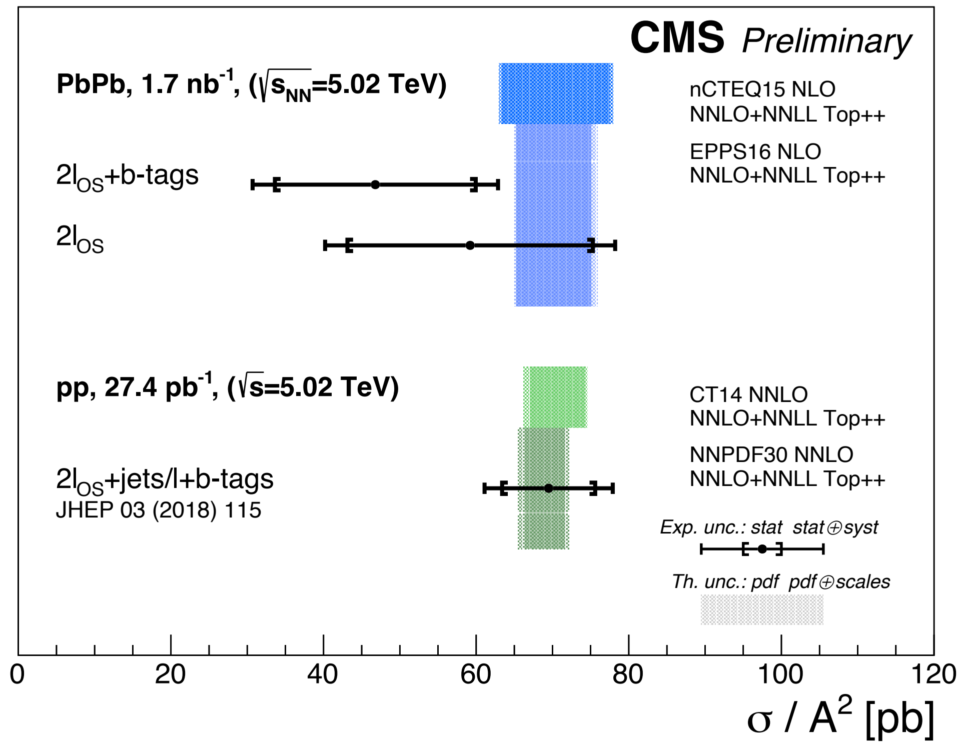
CMS-PAS-HIN-18-014

- First jet R_{AA} measurement with R up to 1.0
  - ➡ Mild R dependence of R_{AA}
  - ➡ Great discrimination power for models to study energy loss and medium response mechanisms



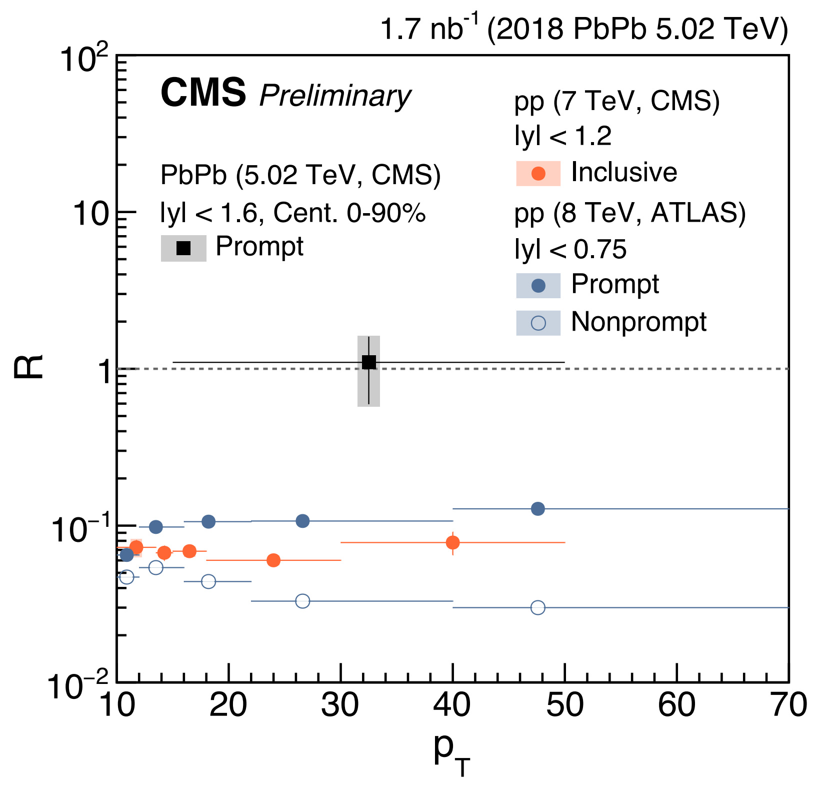
arXiv:2006.11110

- First experimental evidence of top quark in heavy-ion collisions
  - ➡ $t\bar{t}$ cross-section in PbPb measured
  - ➡ Establish a new tool for probing nPDFs



CMS-PAS-HIN-19-005

- First experimental evidence of X(3872) in heavy-ion collisions
  - ➡ Indication of prompt X(3872) to ψ(2S) ratio enhancement in PbPb
  - ➡ Potential new constraints on the inner structure of X(3872)!




Isabelle
Thanks for your attention!

Back up

Thanks for your attention!

Heavy-ion data in CMS

	Collision System	Energy	CMS Recorded	Scale to pp
		Run 1		
2011	Pb-Pb	2.76 TeV	174.3 μb^{-1}	7.5 pb^{-1}
2013	p-Pb	5.02 TeV	35.5 nb^{-1}	7.4 pb^{-1}
		Run2		
2015	p-p	5.02 TeV	28.1 pb^{-1}	28.1 pb^{-1}
2015	Pb-Pb	5.02 TeV	0.55 nb^{-1}	23.8 pb^{-1}
2016	p-Pb	8.16 TeV	180.2 nb^{-1}	37.5 pb^{-1}
2017	Xe+Xe	5.44 TeV	6.0 μb^{-1}	99.8 nb^{-1}
2017	p-p	5.02 TeV	316.3 pb^{-1}	316.3 pb^{-1}
2018	Pb-Pb	5.02 TeV	1.71 nb^{-1}	74.0 pb^{-1}

Top: Modelling signal and background

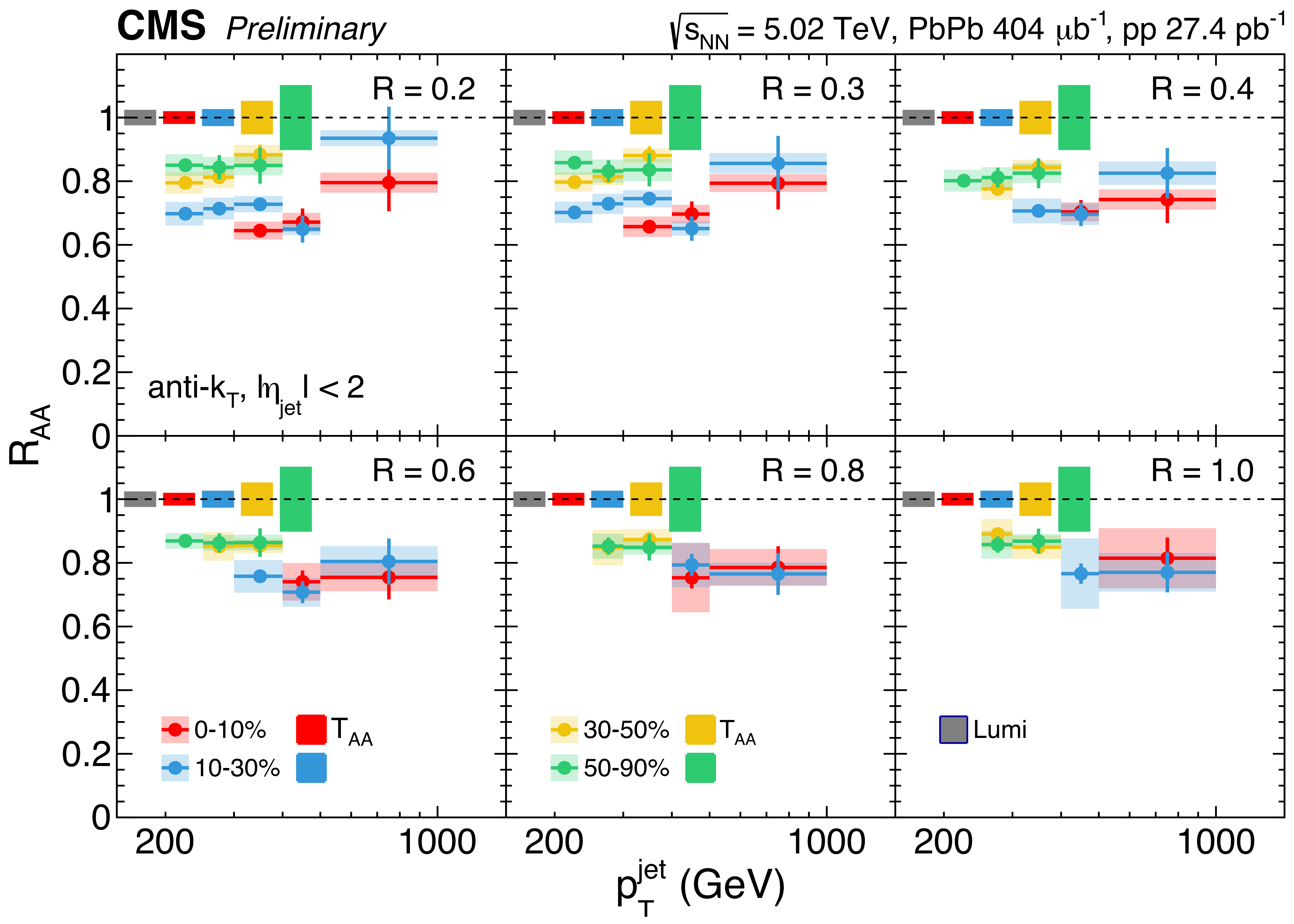
	Shape	Normalization	Shower Hadronize
$t\bar{t}$	MadGraph5_aMC@NLO, NLO POWHEG (v2) (EPPS16 NLO nPDF, CT14 NLO PDF, $\alpha_S(m_Z)$, m_t) p_T modeling scale: Correct low p_T where multi-gluon emission dominates with data	QCD NNLO+NNLL σ	PYTHIA8
Z/γ^*	MadGraph5_aMC@NLO + p_T modeling scale: Correct low p_T where multi-gluon emission dominates with data	NNLO σ from FEWZ (v3.1.rc) + number in m_Z mass region	
VV	NLO POWHEG	NLO σ from MCFM (v8.0)	
tW	NLO POWHEG	approximate NNLO σ	
Nonprompt	Event mixing	Same-sign control	-

➜ back

Top analysis uncertainties

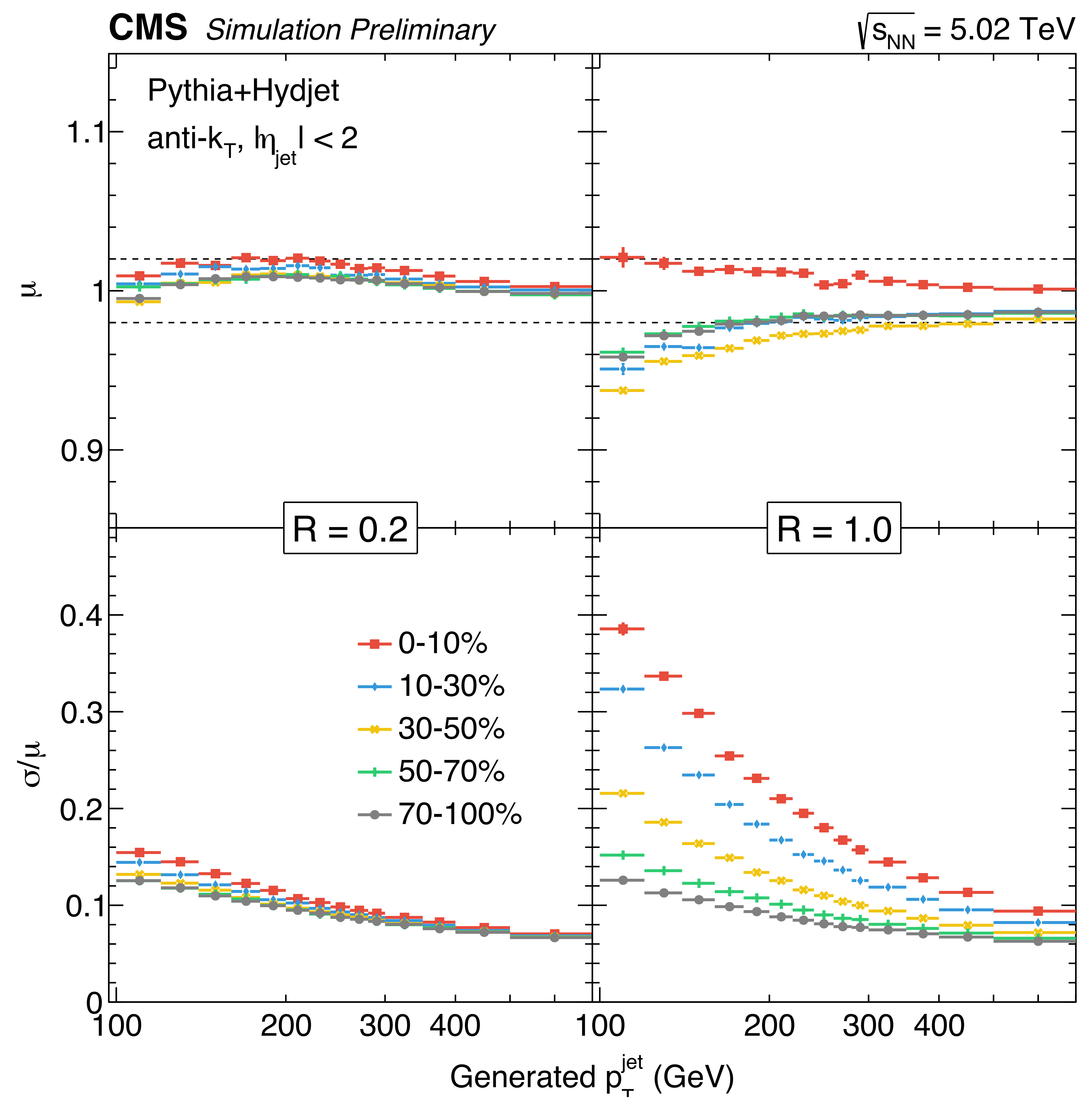
Source	$\Delta\mu/\mu$ Dilepton only	Dilepton plus b-tagged jets
Total statistical uncertainty	0.27	0.28
Total systematic experimental uncertainty	0.17	0.19
Background normalization	0.12	0.12
Background and $t\bar{t}$ signal distribution	0.07	0.08
Lepton selection efficiency	0.06	0.06
Jet energy scale and resolution	—	0.02
b jet identification (ε_b)	—	0.06
Integrated luminosity	0.05	0.05
Total theoretical uncertainty	0.05	0.05
nPDF, μ_R, μ_F scales, and $\alpha_S(m_Z)$	<0.01	<0.01
Top quark and Zboson p_T modelling	0.05	0.05
Top quark mass	<0.01	<0.01
Total uncertainty	0.32	0.34

All R_{AA} (centrality, R)



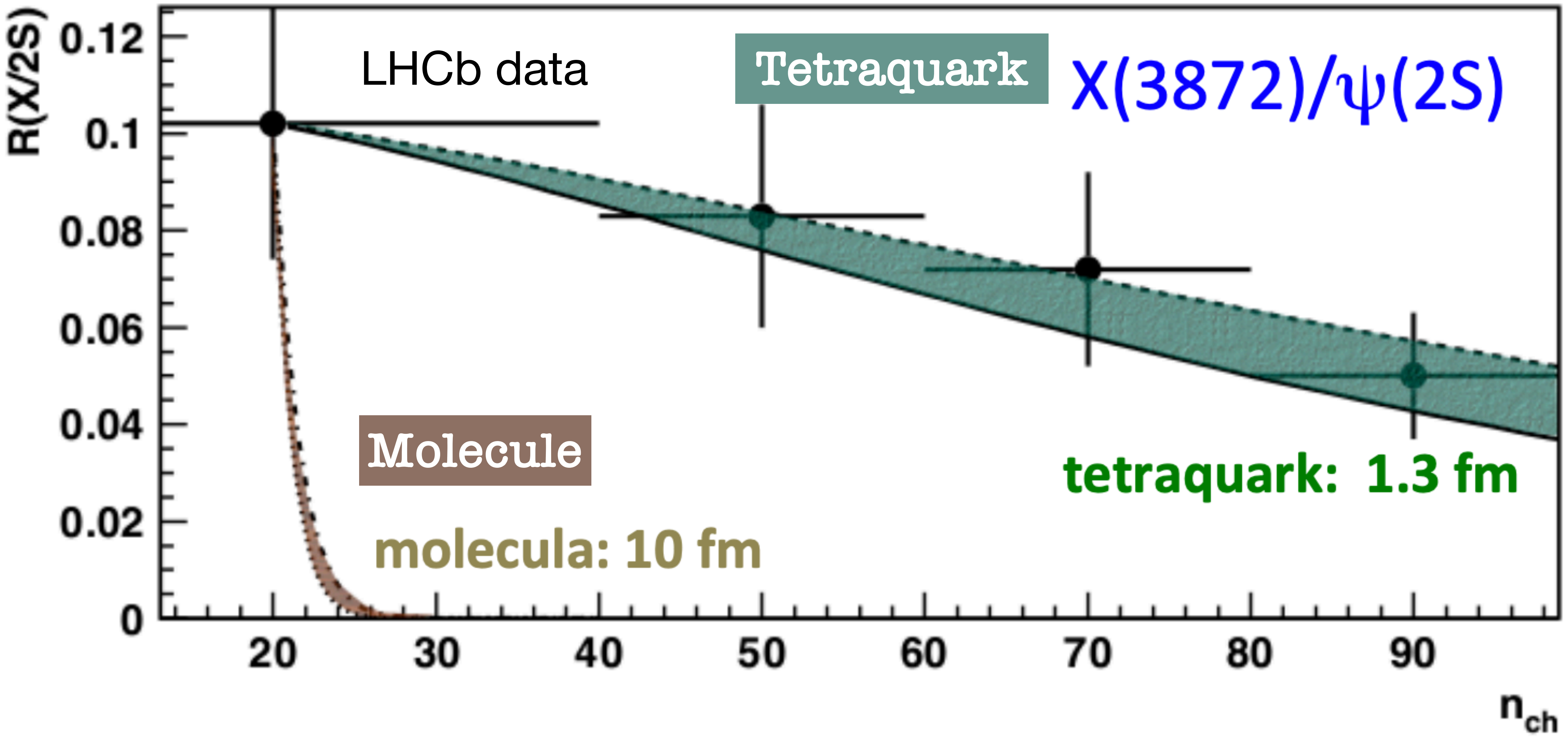
➜ back

Jet response



Tetra-quark or Molecule?

Status of current X(3872) theoretical calculations (pp)



From Elena HP talk

- Destroyed by comover
- Recombination not included
  - Implementing recombination leads to opposite trend

Jet quenching models

- Multi-gluon final states
  - Coherent antenna: Interference between emitters accounted in
  - Others: repeated application of a single-gluon emission

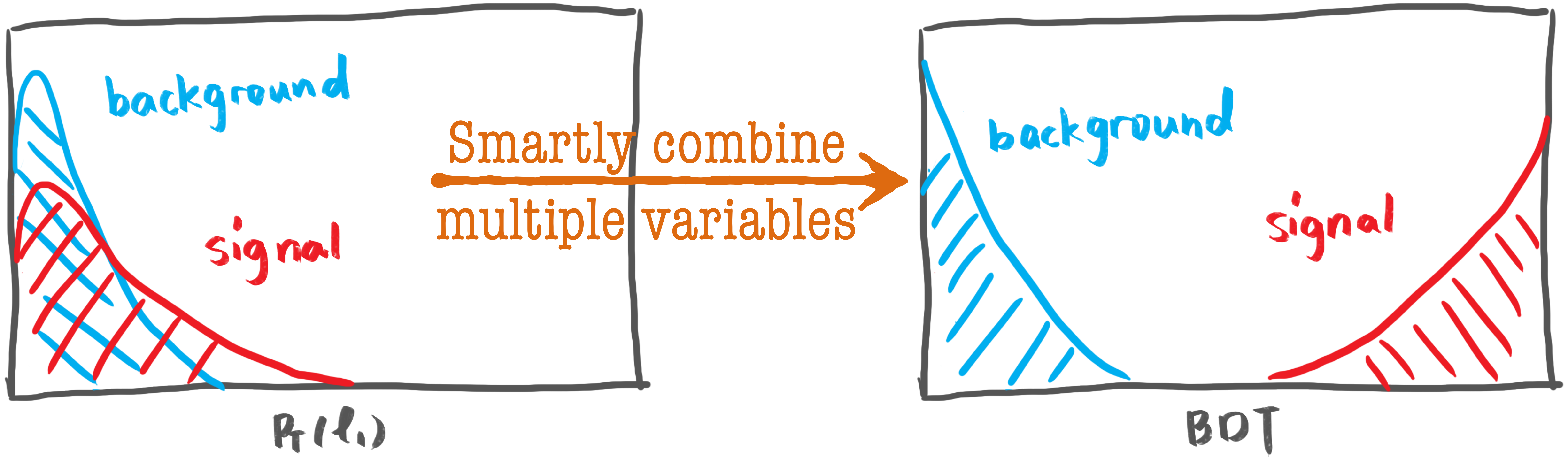
- Between formalisms
  - Virtuality and branching of hard partons
  - Medium modeling
    - BDMPS-Z (ASW-SH, DGLV): medium as collection of static scattering centers
    - HT: medium properties enter calculation in terms of higher-twist matrix elements
    - AMY: medium as a thermal equilibrium, perturbative state
  - Kinematical approximation

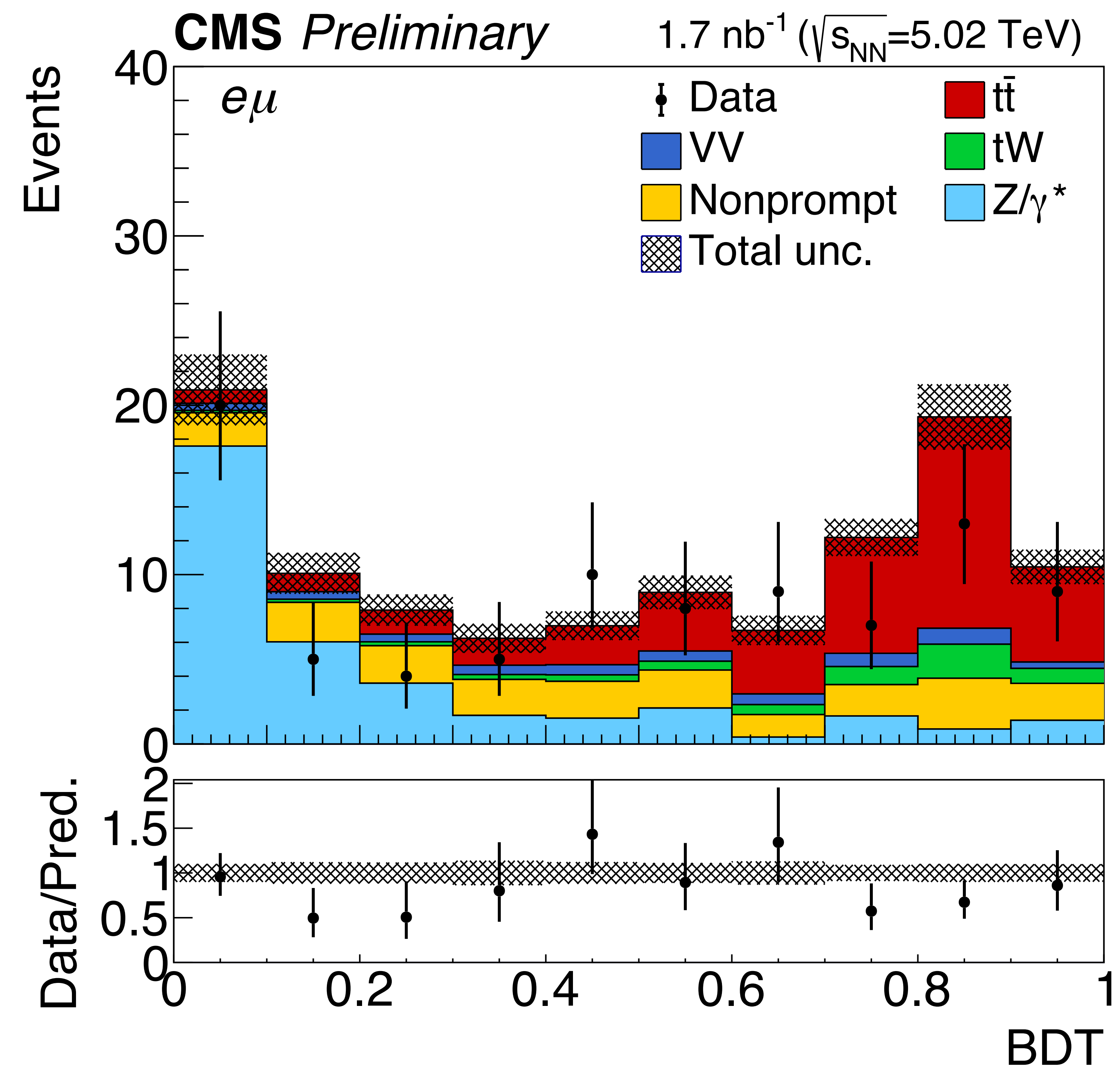
Separate signal and background

Use lepton kinematics to separate signal and background

- $p_T(l_1)$: p_T of the highest-p_T lepton
- A_{p_T}: asymmetry in the lepton-p_T's
- $p_T(ll)$: p_T of the dilepton system
- $|\eta(ll)|$: absolute η of the dilepton system
- $|\Delta\Phi(ll)|$: separation in ϕ of the two leptons
- $\sum|\eta_i|$: sum of the absolute η's of the leptons

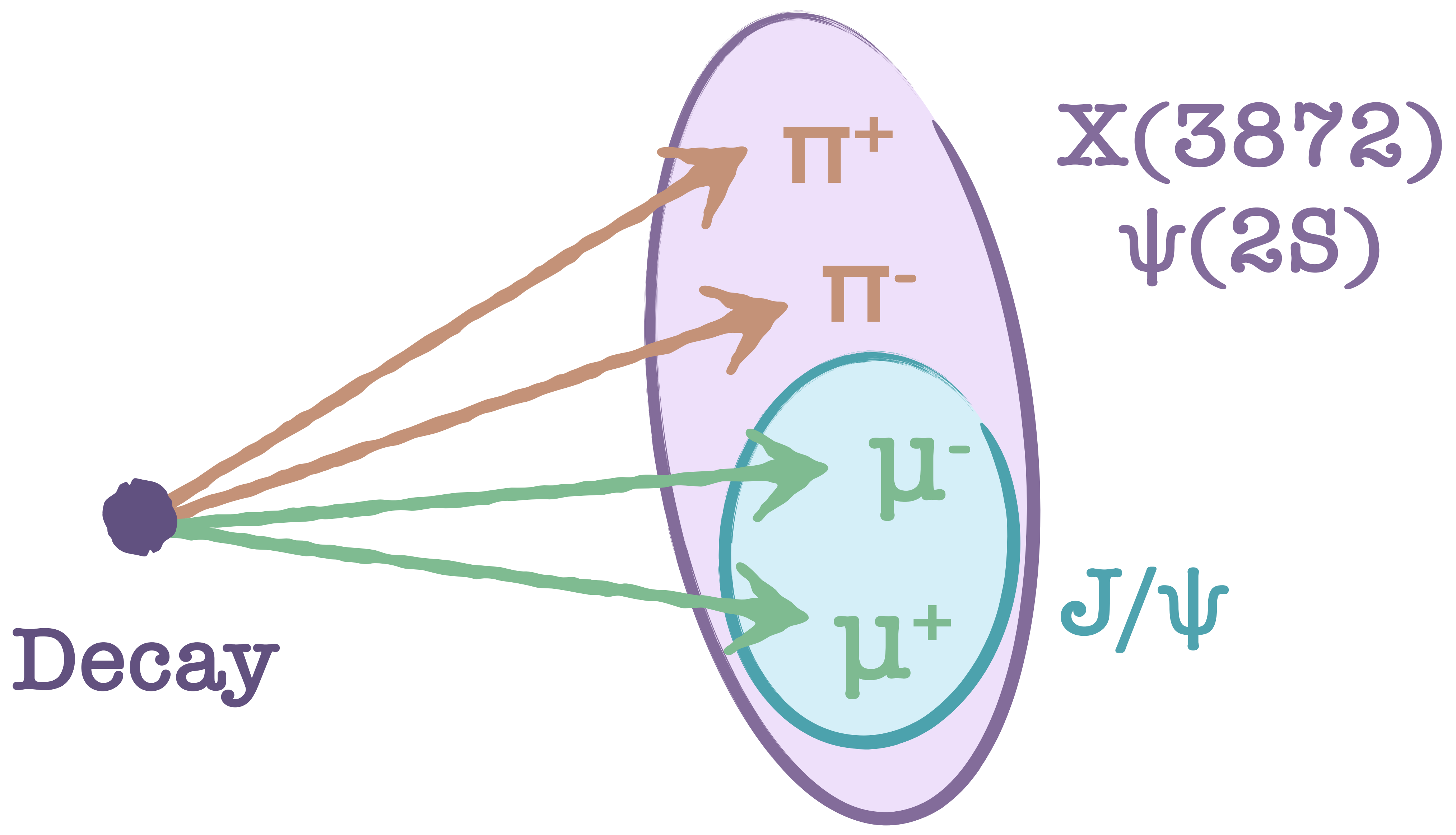
Single variable | **Multiple variables: BDT**





Monte-Carlo Simulation

- Di-muon trigger sample in **PbPb** collisions at 5 TeV (LHC 2018 Run)
- X(3872) and ψ(2S) fully reconstructed with same hadronic decay chain **J/ψ(μμ)π⁺π⁻**
- No constraints on invariant mass $m(\pi^+\pi^-)$

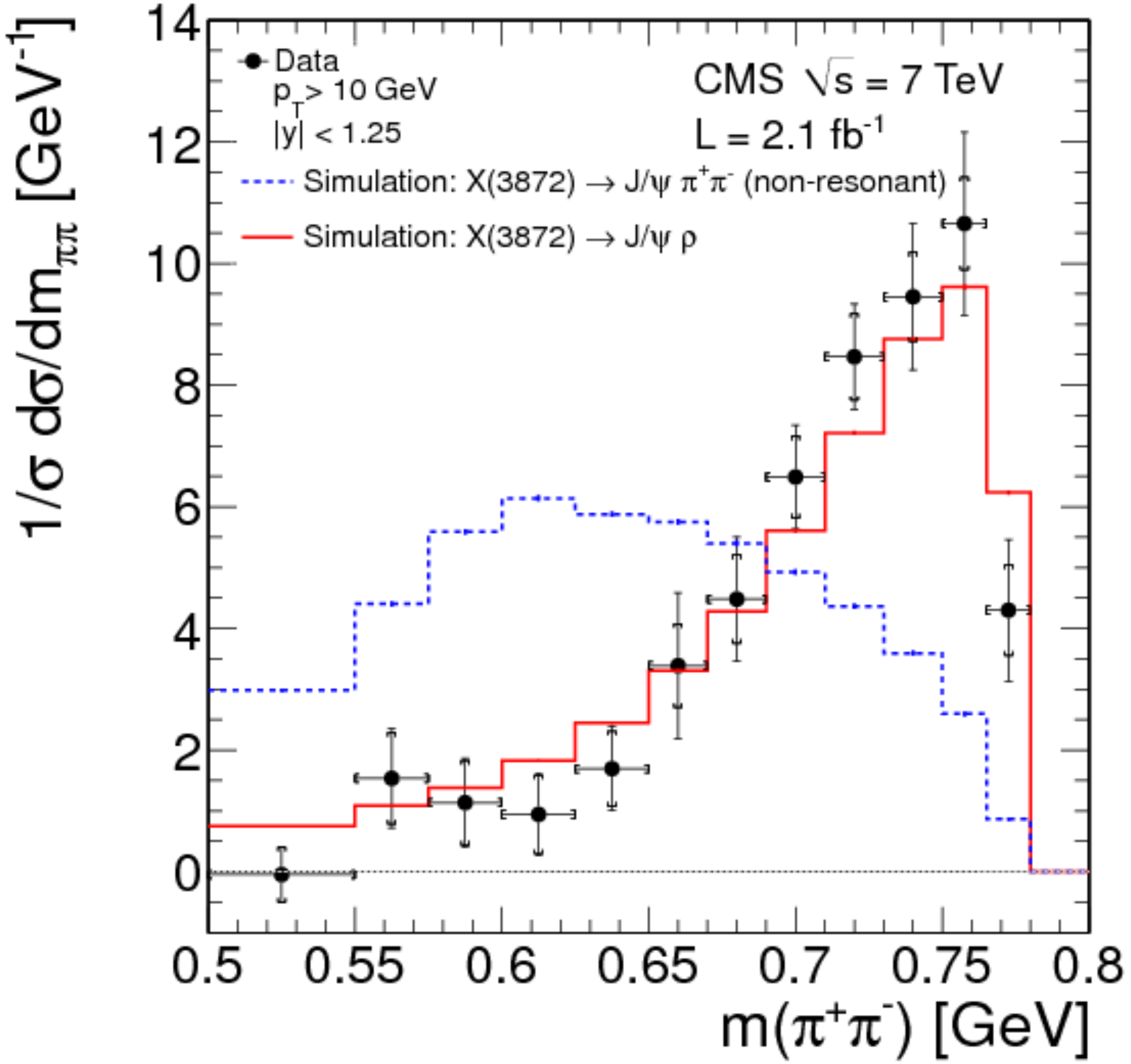


- PYTHIA8 simulation embedded in HYDJET PbPb events used for acceptance and efficiency correction
- Simulation: X(3872)→ρ(ππ)J/ψ(μμ)
  - ➡ $m(\pi^+\pi^-)$ distribution from simulation w/ ρ resonance agrees better to pp data
  - ➡ Cross-check with non-resonance simulation

Observable: $R = N^{(Corr)}_{X(3872)} / N^{(Corr)}_{\psi(2S)}$, $N^{(Corr)} = N^{(Raw)} \times f_{prompt} / (\alpha \times \epsilon_{reco} \times \epsilon_{sel})_{prompt}$

ρ(ππ) Resonance

JHEP 04 (2013) 154



Result: X(3872)/ψ(2S) Ratio in PbPb

$$R_{AA}^{X(3872)} = \frac{N_{X(3872)}(PbPb)}{N_{X(3872)}(pp)} = \frac{N_{X(3872)}(PbPb)/N_{\psi(2S)}(PbPb)}{N_{X(3872)}(pp)/N_{\psi(2S)}(pp)} \cdot \frac{N_{\psi(2S)}(PbPb)}{N_{\psi(2S)}(pp)}$$