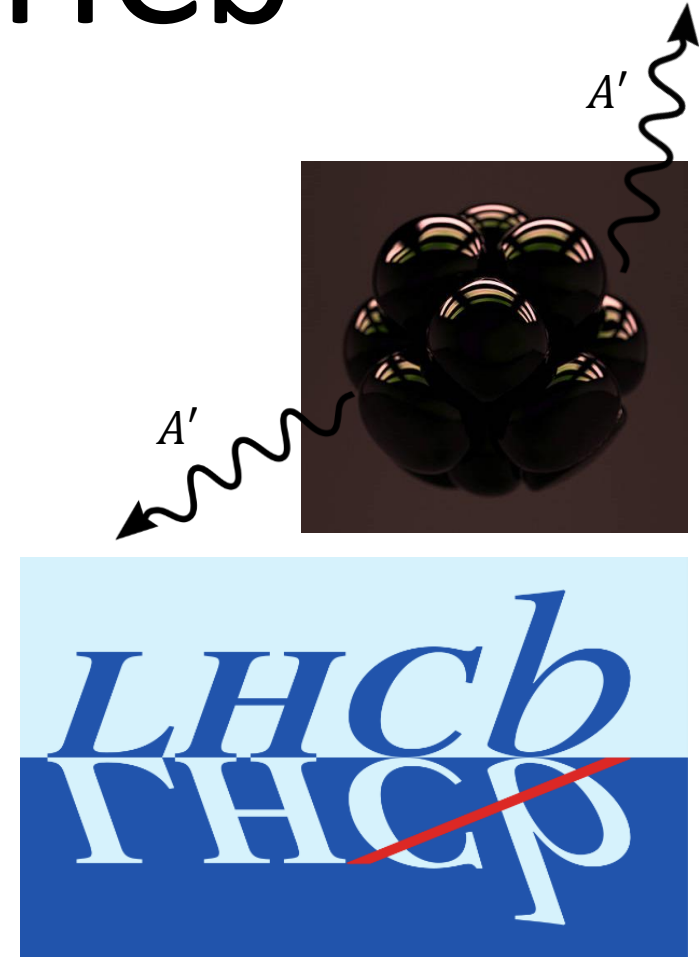
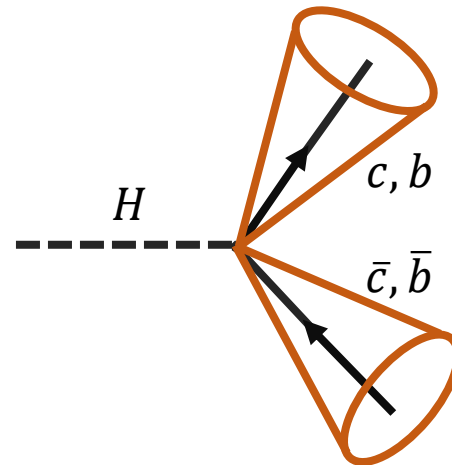
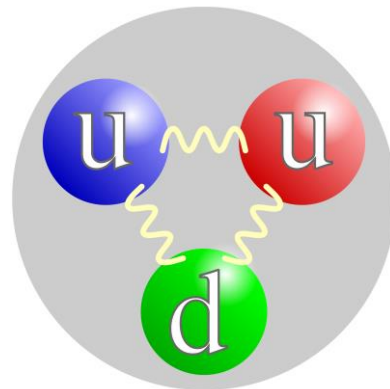


General introduction to QEE measurements at LHCb

Ezra D. Lesser (CERN)
on behalf of the LHCb Collaboration

25 October 2024



The QEE group at

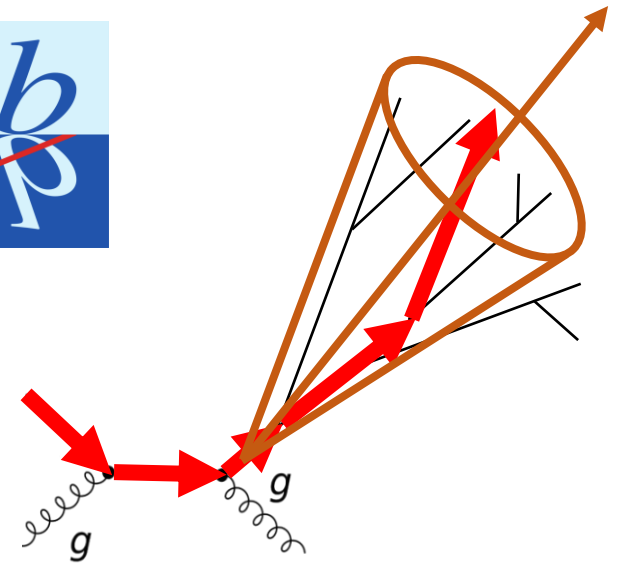


The QEE group at



- **Quantum chromodynamics**

- Jet substructure, hadronic production, ...

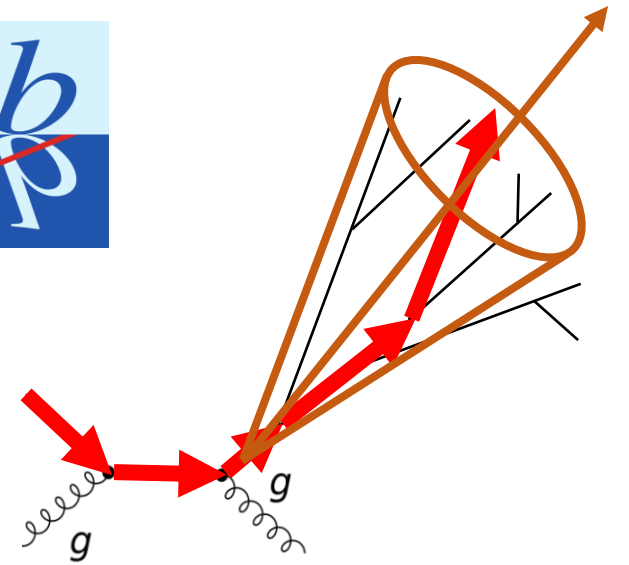


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- **Electroweak physics, Higgs, & top**

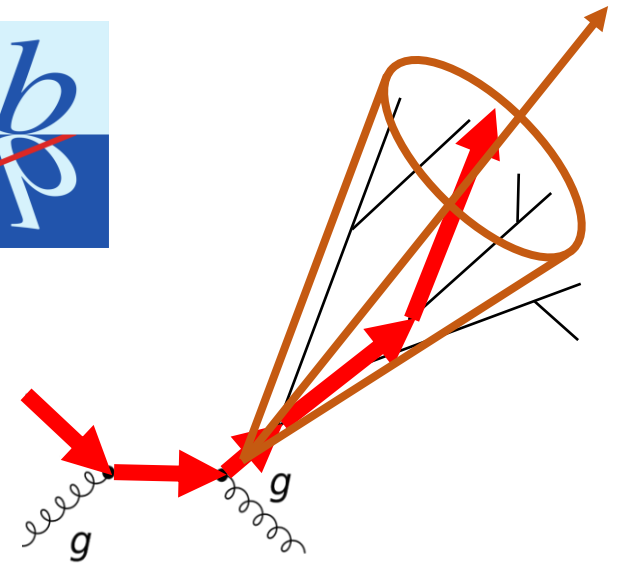
- W^\pm / Z^0 decays, precision measurements, cross sections, ...

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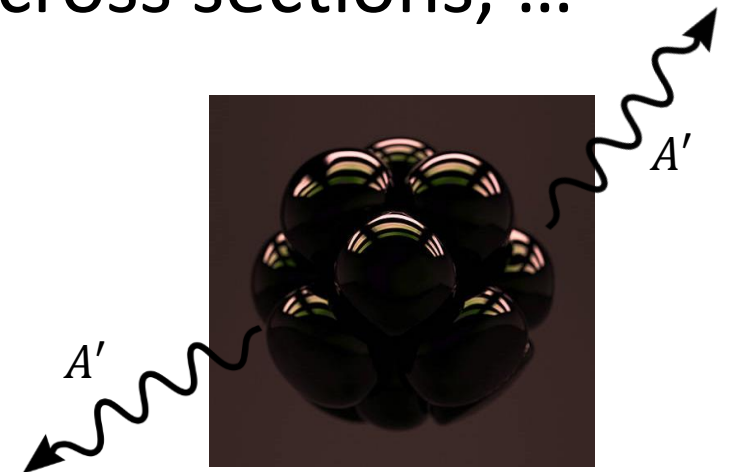


- **Electroweak physics, Higgs, & top**

- W^\pm / Z^0 decays, precision measurements, cross sections, ...

- **Exotica**

- Rare decays, beyond the SM searches, ...



The QEE group at



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- Jet substructure

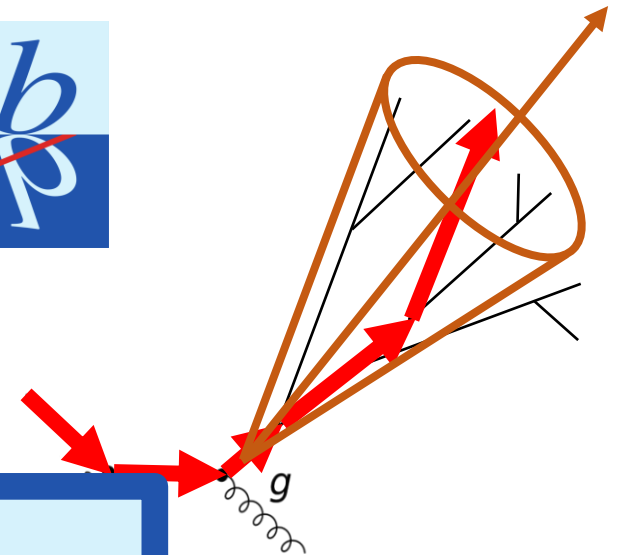
- **Electroweak**

- W^\pm / Z^0

- **Exotica**

- Rare decays, beyond the SM searches, ...

**Extremely diverse
group of physics
analyses!**



reactions, ...

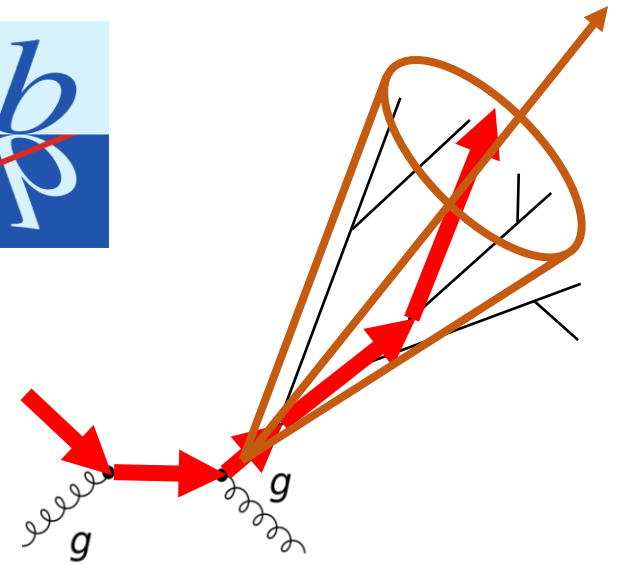


The QEE group at



- **Quantum chromodynamics**

- Jet substructure, hadronic production, ...

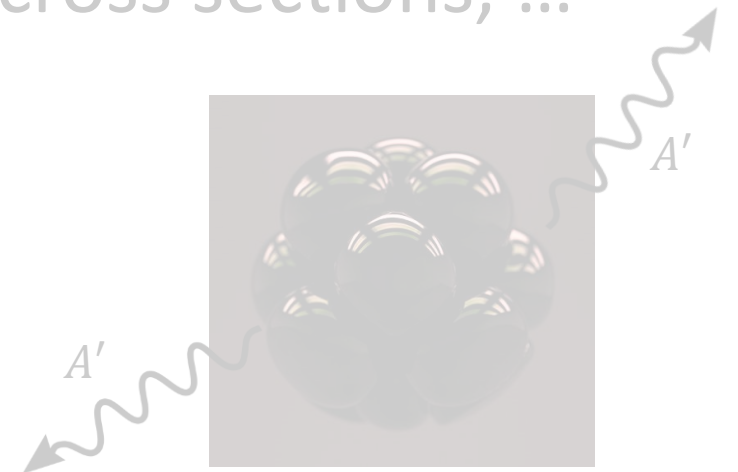


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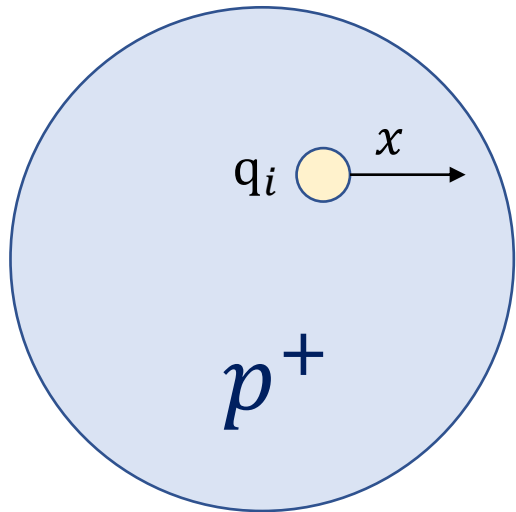
The many scales of QCD



The many scales of QCD



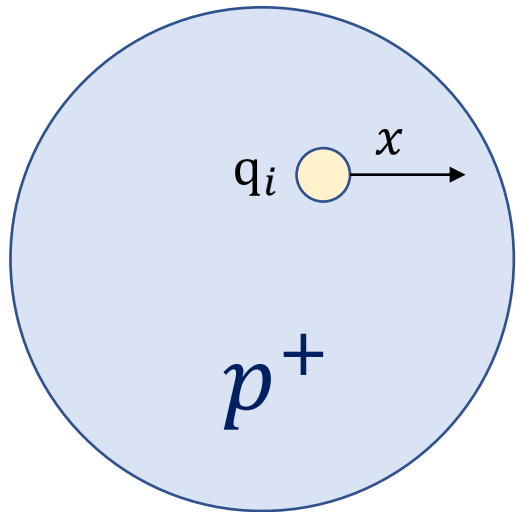
Parton Distribution Functions (PDFs)



The many scales of QCD

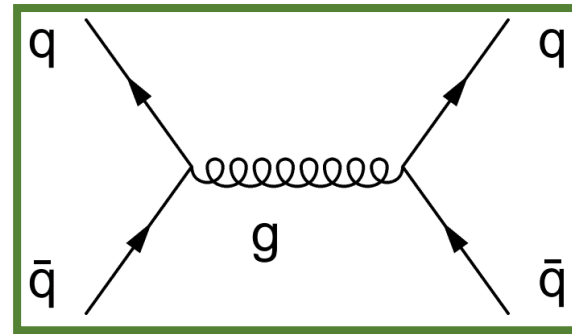


*Parton Distribution
Functions (PDFs)*



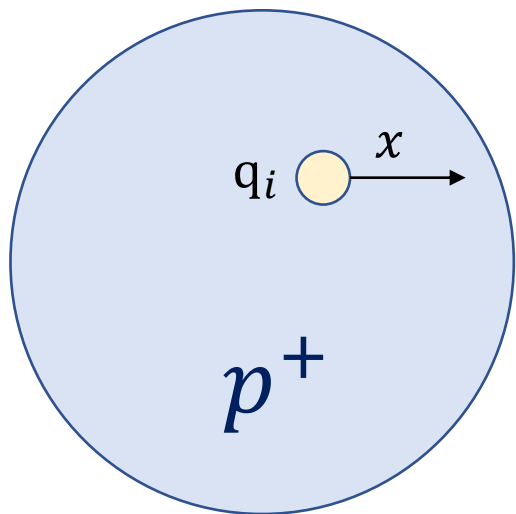
\otimes

*Hard scattering
process*



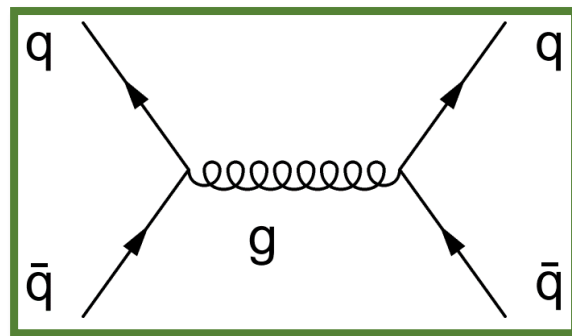
The many scales of QCD

Parton Distribution Functions (PDFs)



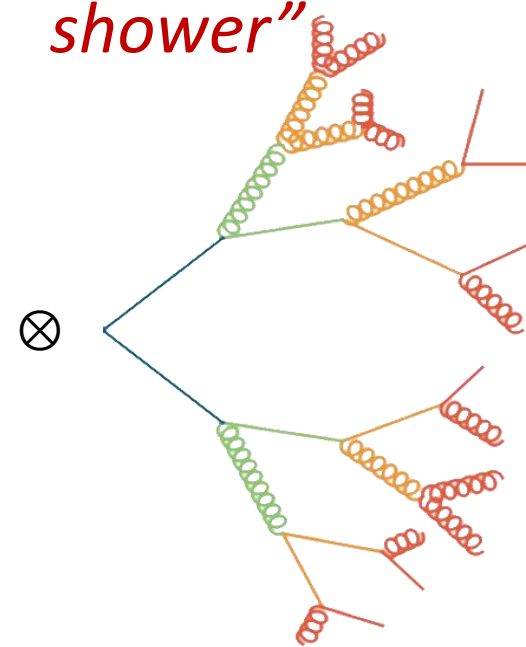
\otimes

Hard scattering process



\otimes

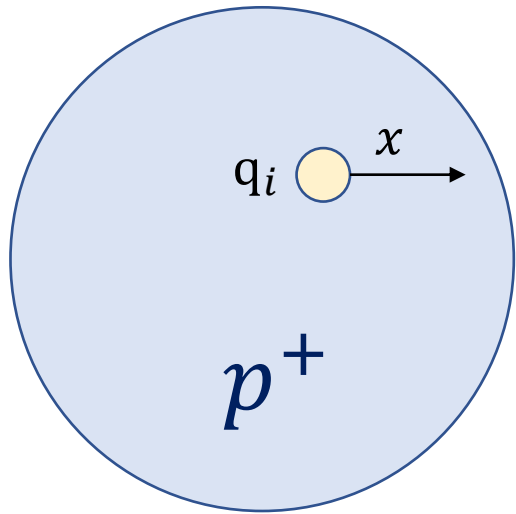
"Parton shower"



The many scales of QCD

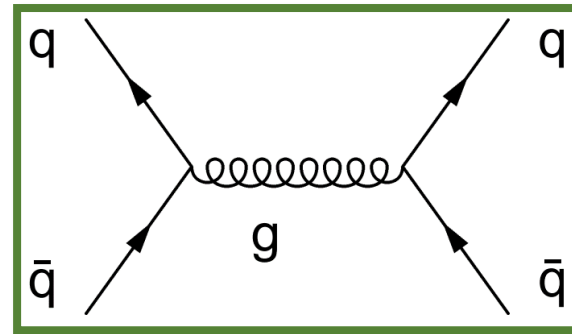


Parton Distribution Functions (PDFs)



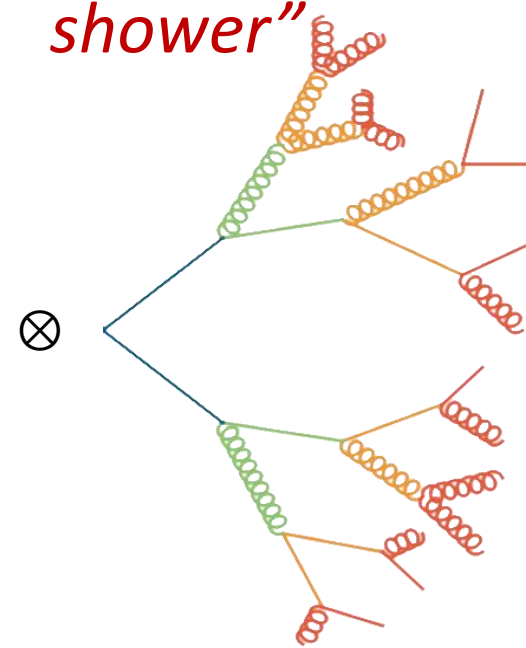
\otimes

Hard scattering process



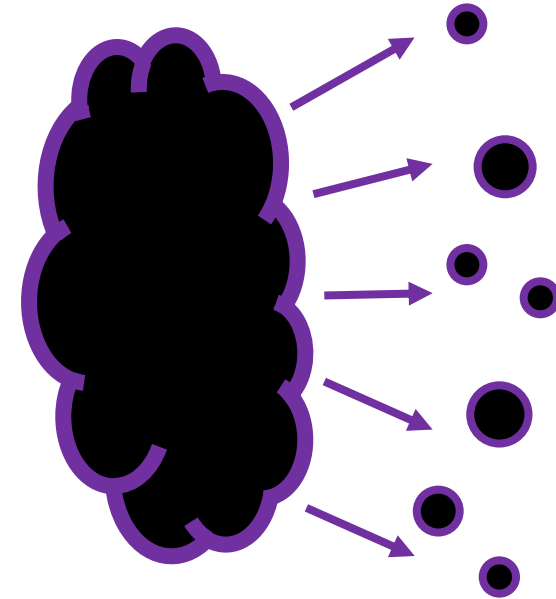
\otimes

"Parton shower"



\otimes

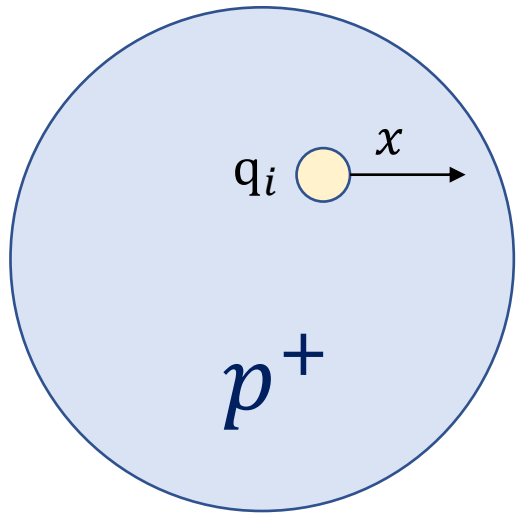
Hadronization



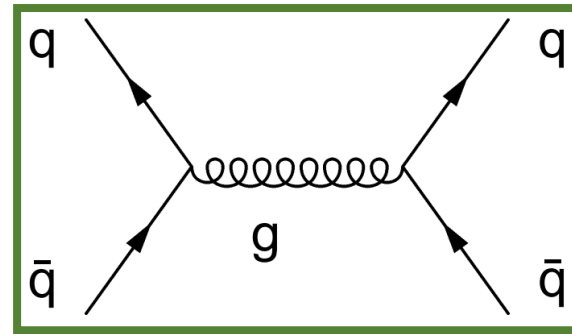
The many scales of QCD



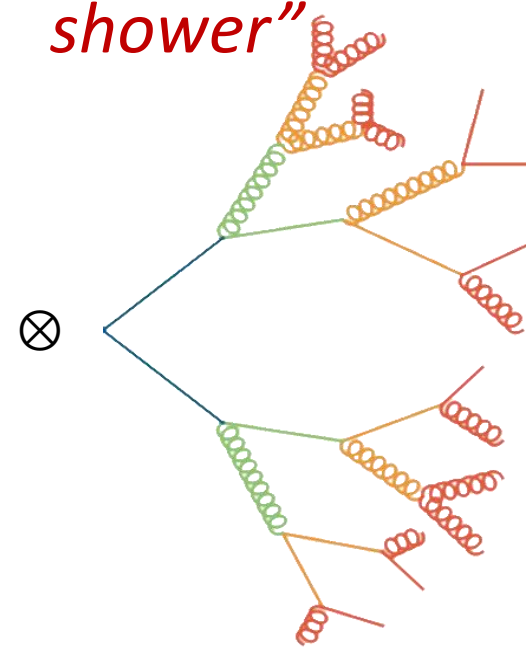
Parton Distribution Functions (PDFs)



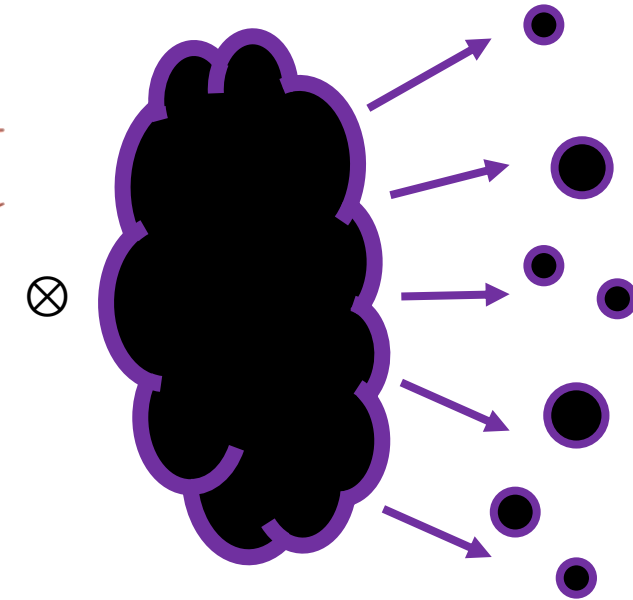
Hard scattering process



"Parton shower"

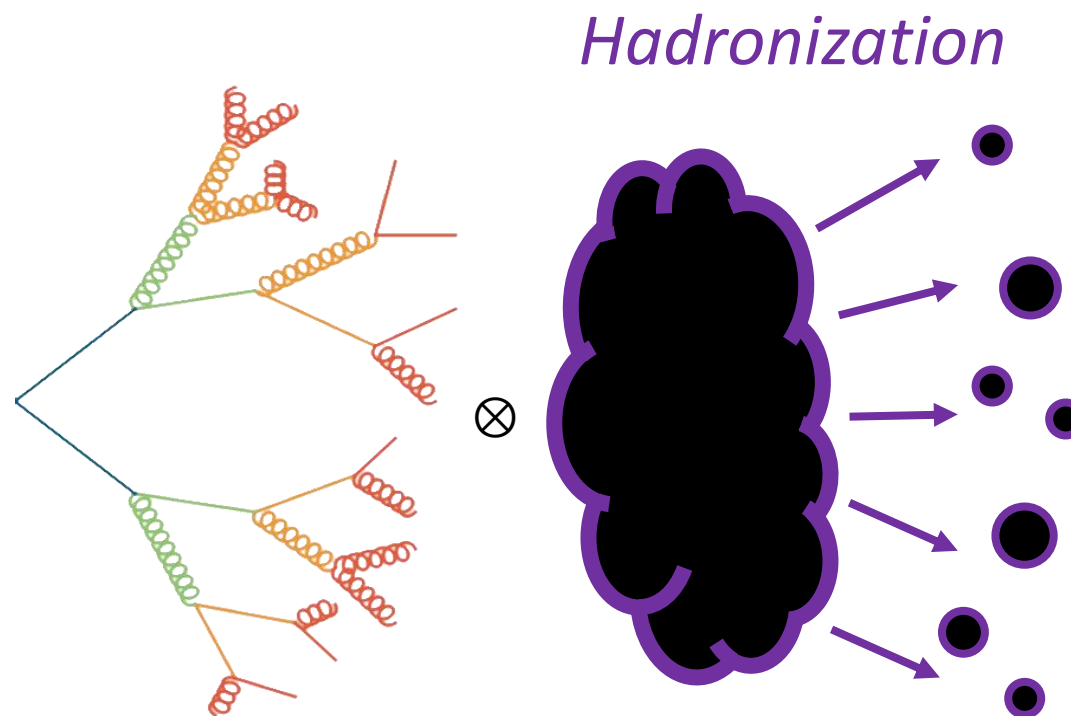


Hadronization

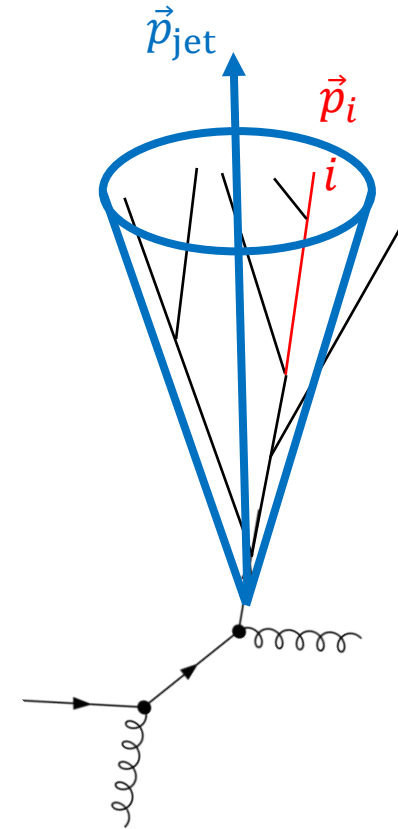
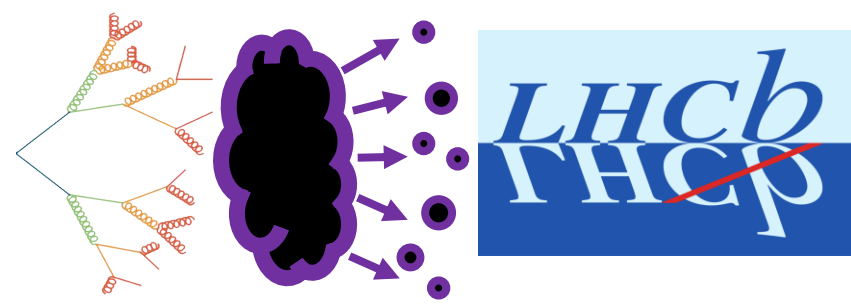


- Aim to **experimentally probe each stage** of jet formation

Jet fragmentation functions

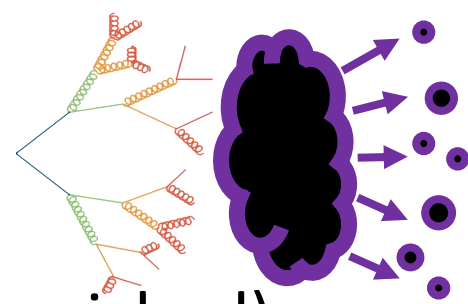


Jet fragmentation functions

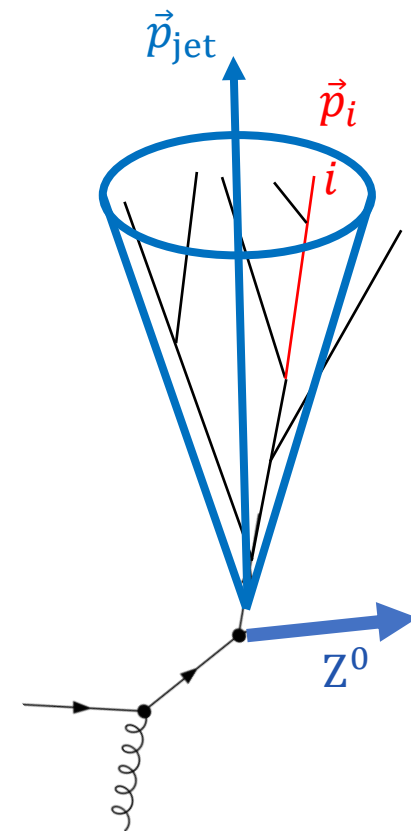


$$z = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_i}{|\vec{p}_{\text{jet}}|^2}$$

Jet fragmentation functions

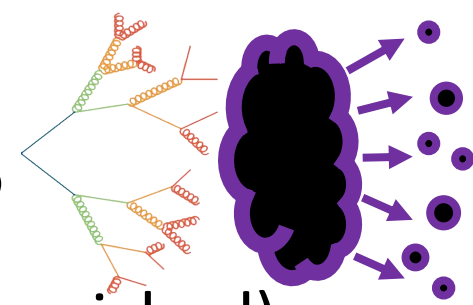


- Measurement for **inclusive Z^0 +jets** (light quark enriched)



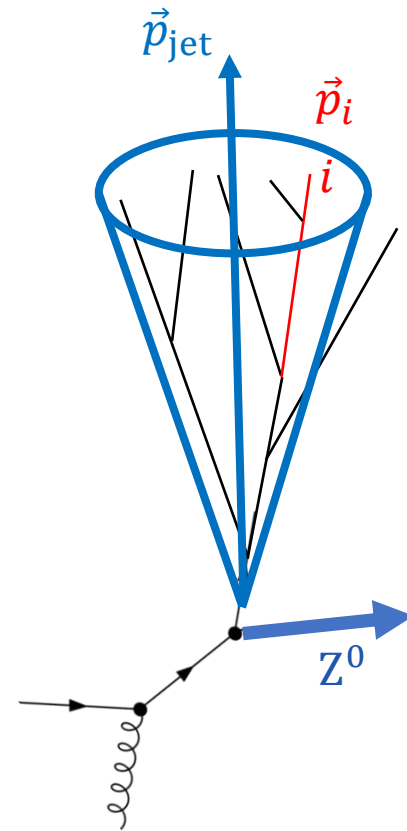
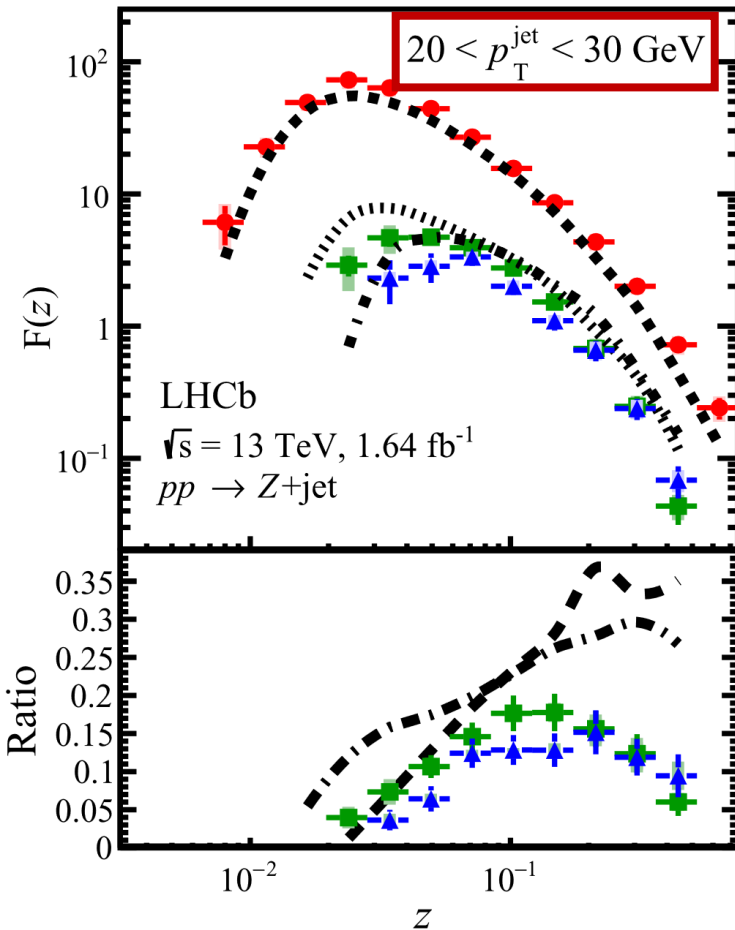
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Jet fragmentation functions



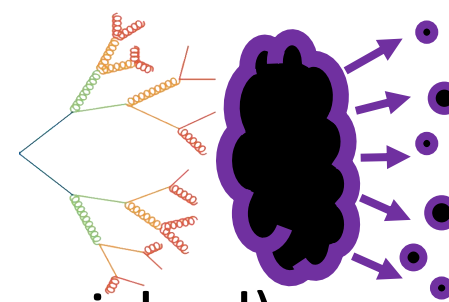
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low $\leftarrow p_T^{\text{jet}} \rightarrow$ high



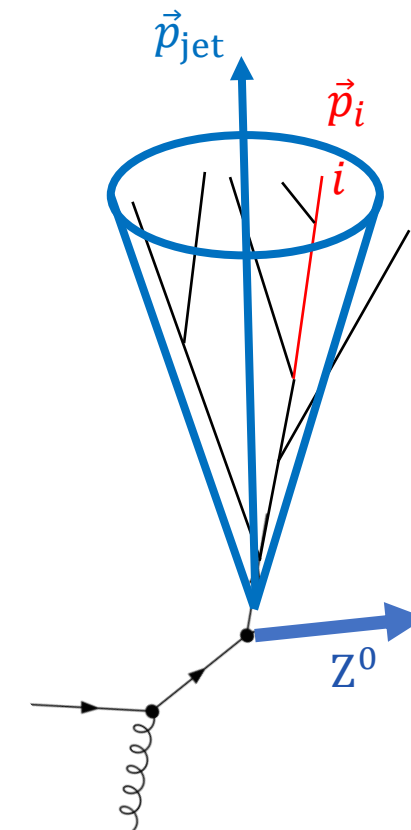
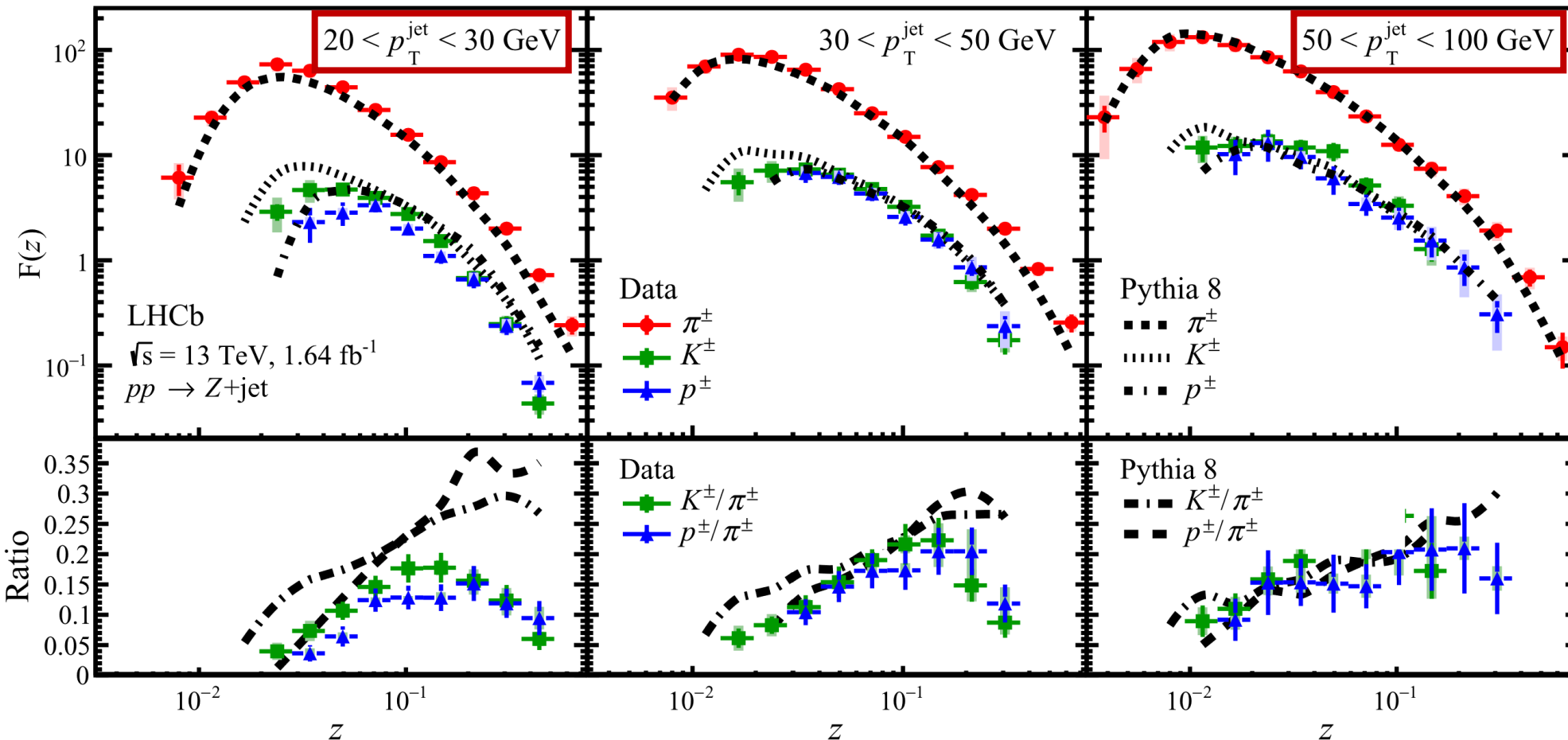
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Jet fragmentation functions



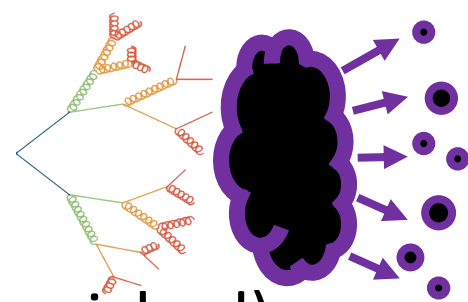
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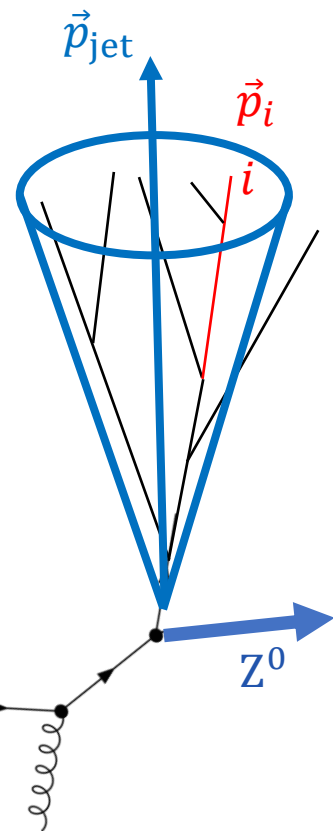
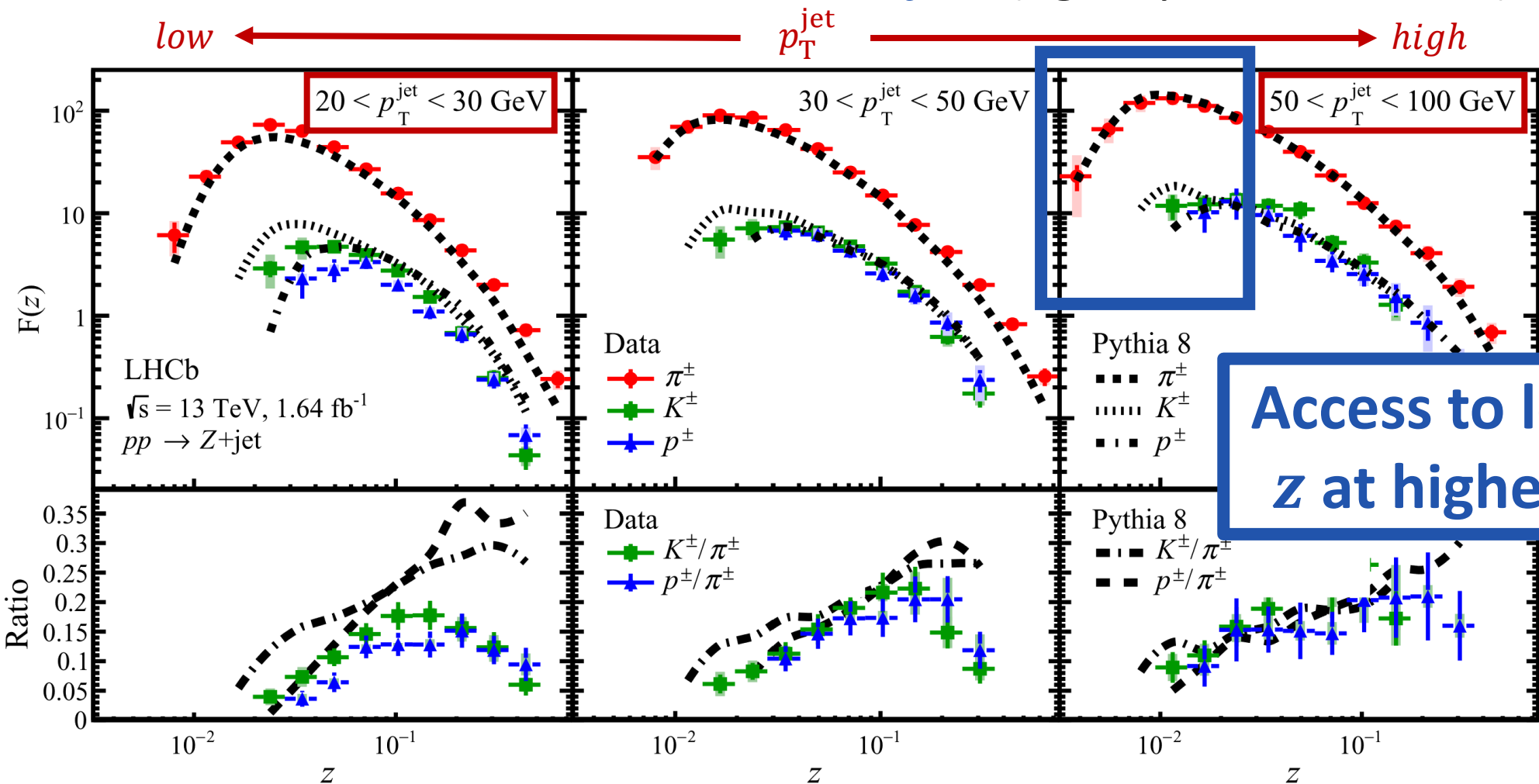


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Jet fragmentation functions

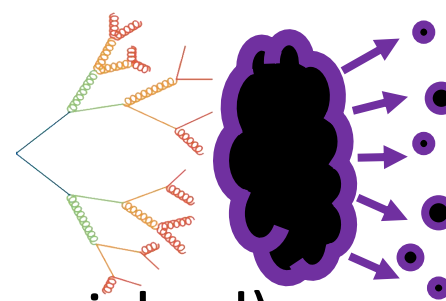


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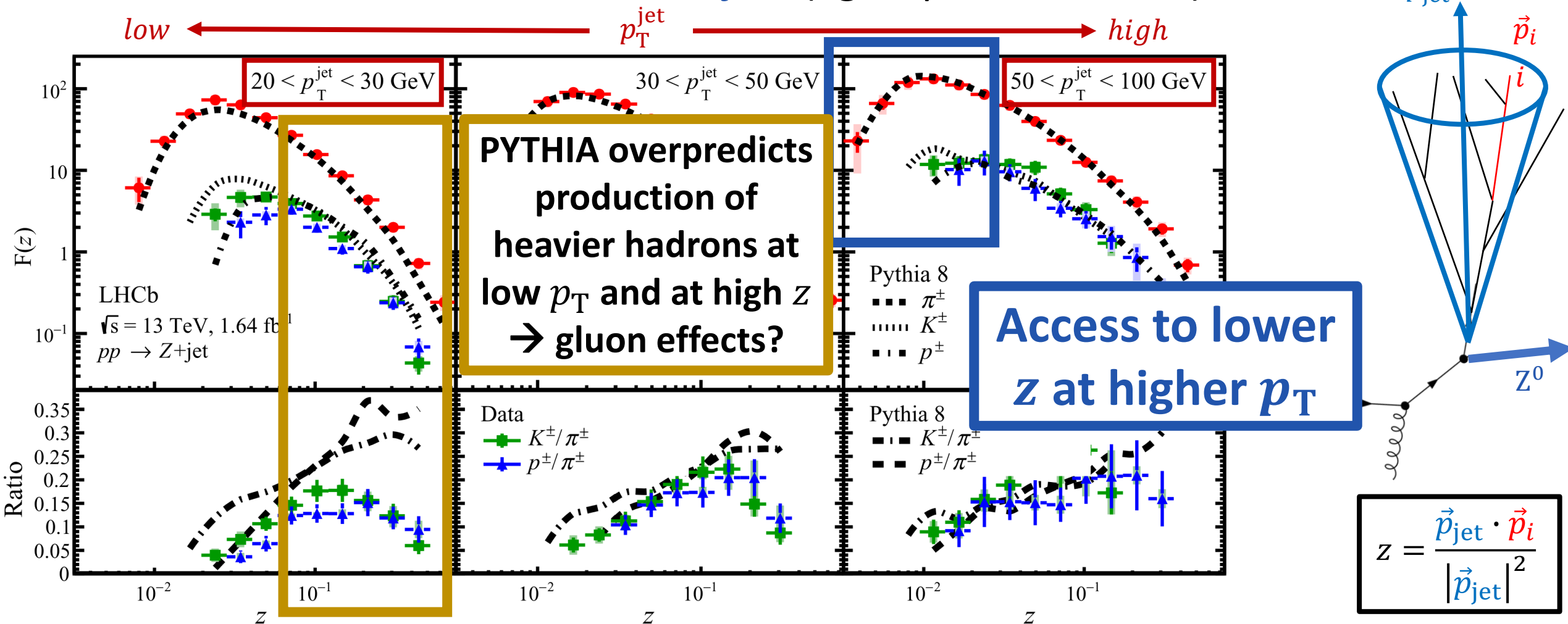


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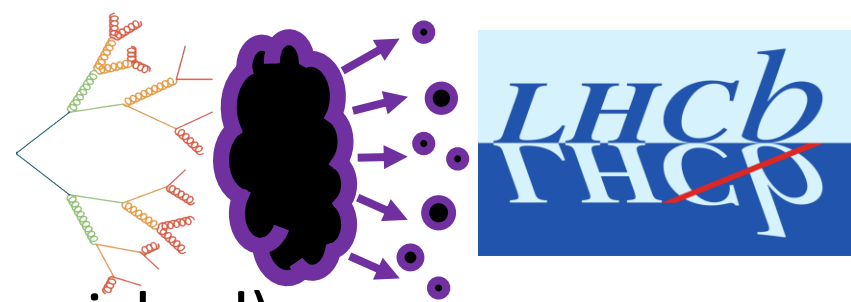
Jet fragmentation functions



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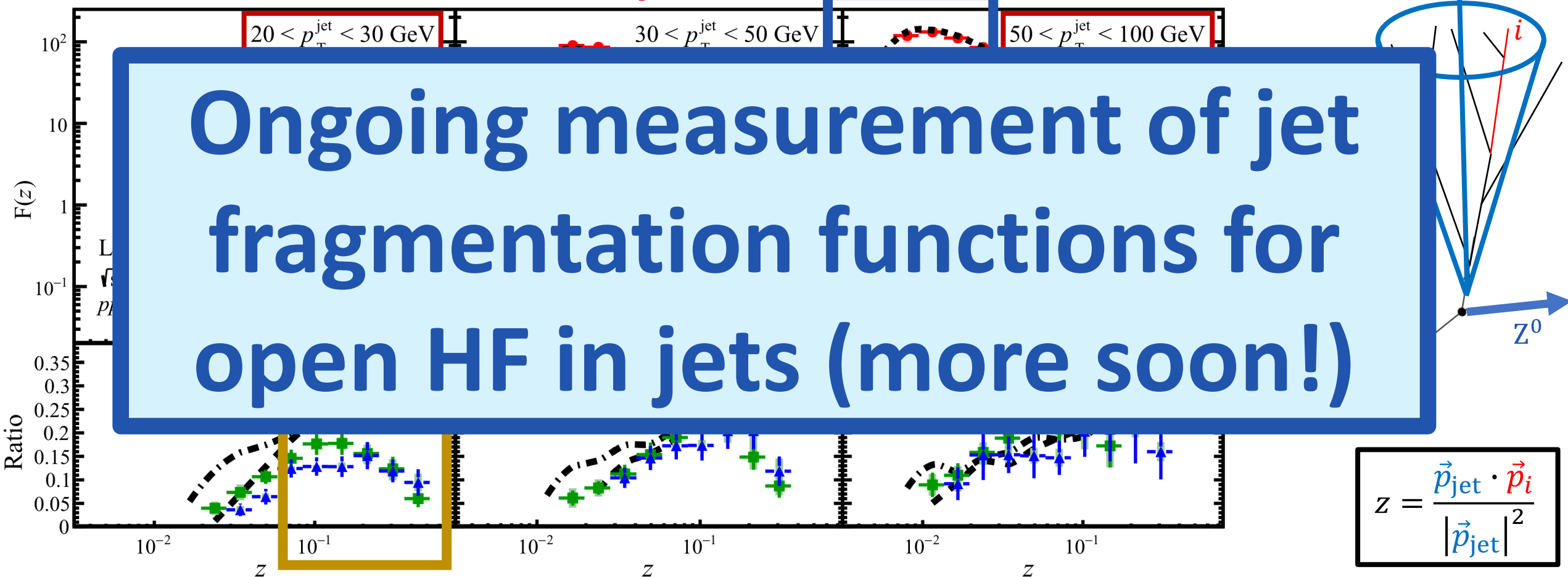
Jet fragmentation functions



- Measurement for **inclusive Z^0 +jets** (light quark enriched)

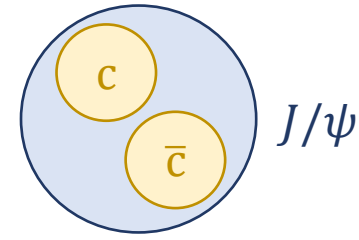
low ← p_T^{jet} → high

Ongoing measurement of jet fragmentation functions for open HF in jets (more soon!)



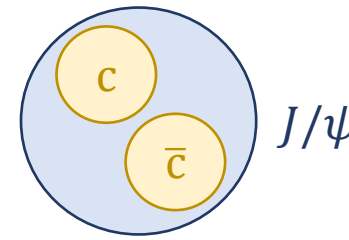
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Heavy quarkonium in jets

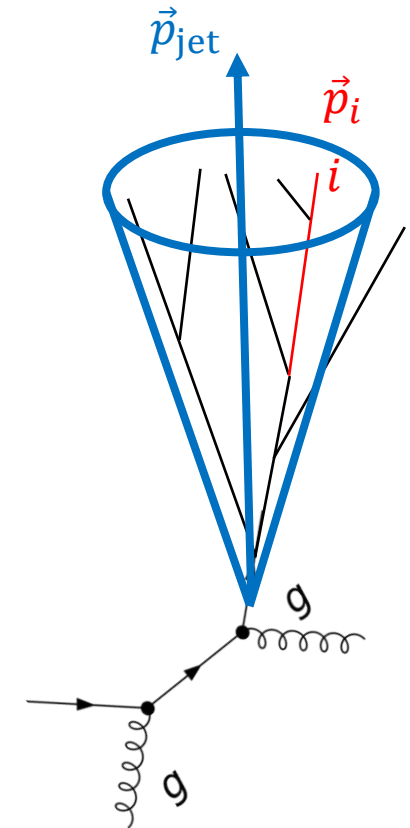


- How are heavy $q\bar{q}$ pairs (e.g. J/ψ) produced according to QCD?

Heavy quarkonium in jets



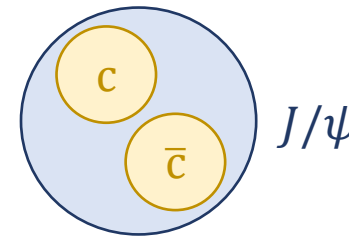
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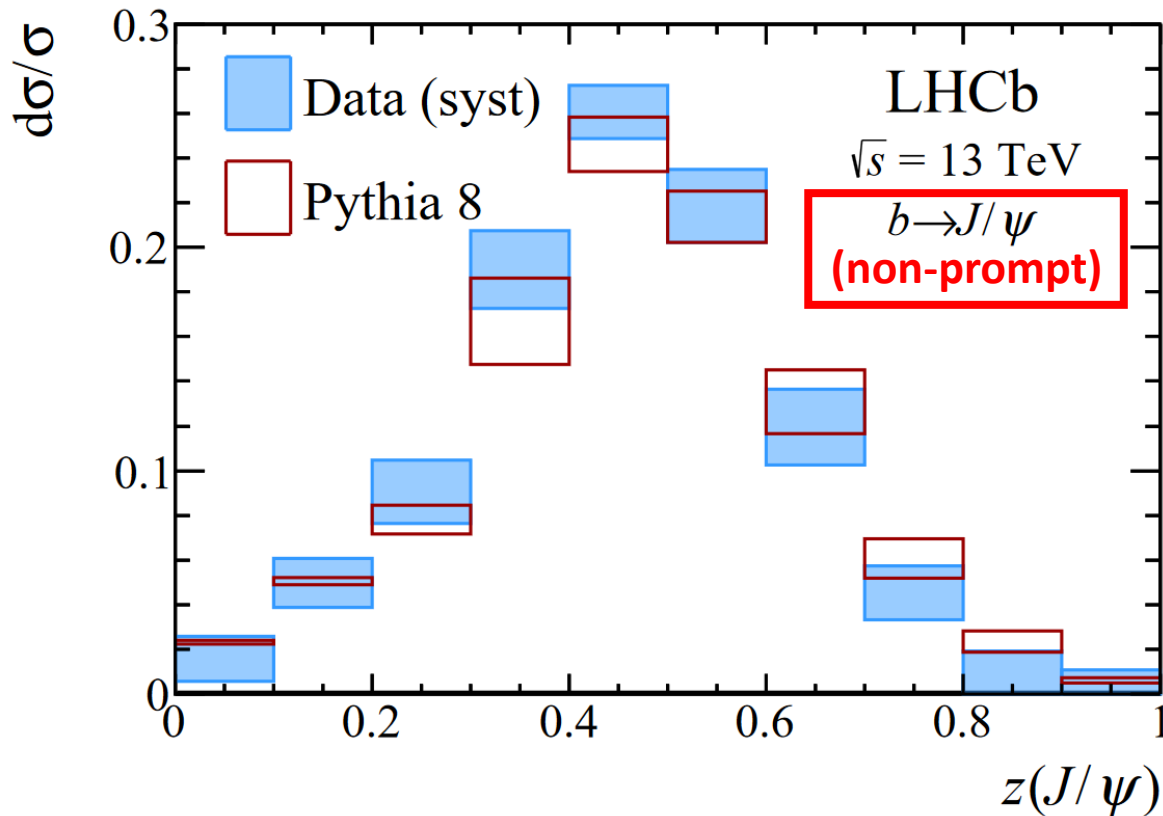
$$z = \frac{p_{T,i}}{p_{T,\text{jet}}}$$

particle momentum fraction

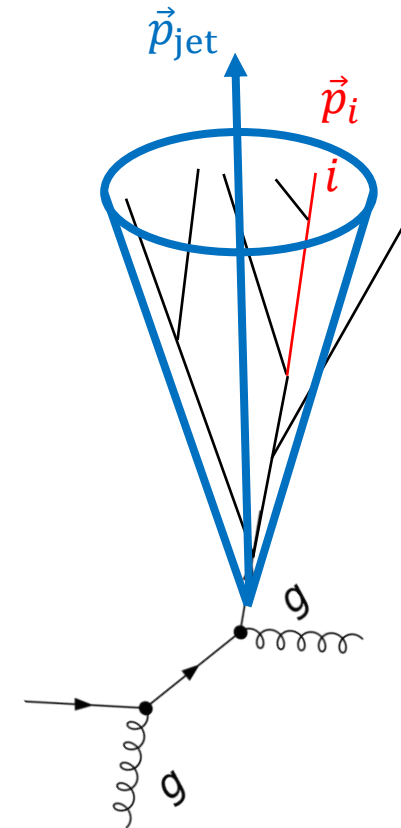
Heavy quarkonium in jets



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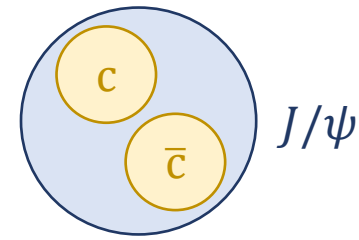
- Both **prompt** and **non-prompt (feed-down)** contributions



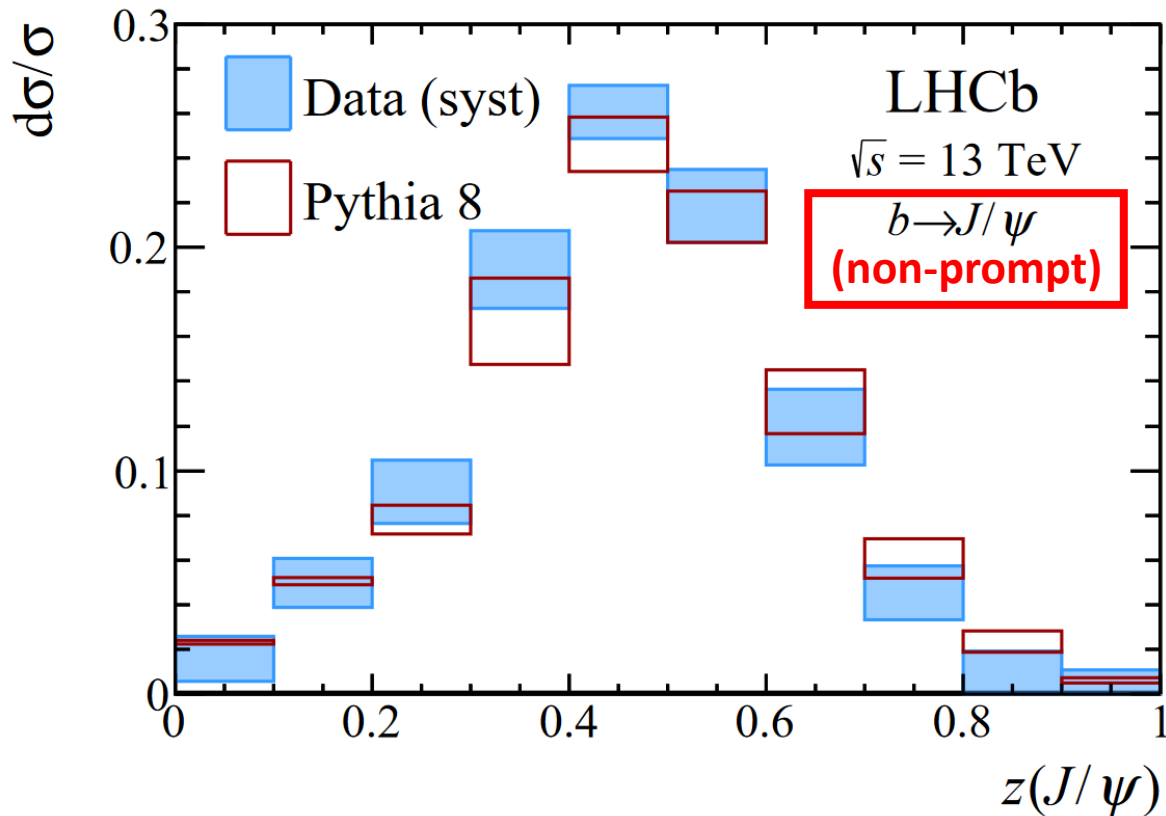
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particle momentum fraction

Heavy quarkonium in jets

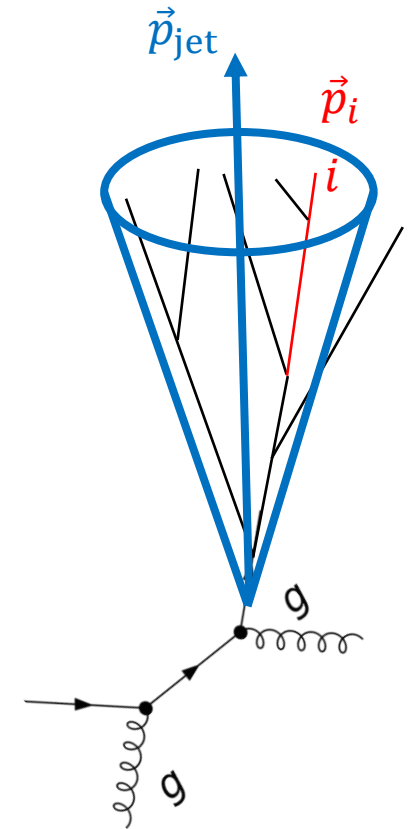


- How are heavy $q\bar{q}$ pairs (e.g. J/ψ) produced according to QCD?



- Both **prompt** and **non-prompt (feed-down)** contributions

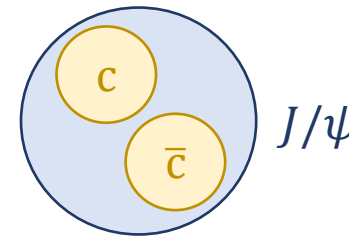
- Charmonium from b decays only carries $\sim 50\%$ of jet energy
 \rightarrow **surrounded by b -jet fragmentation**



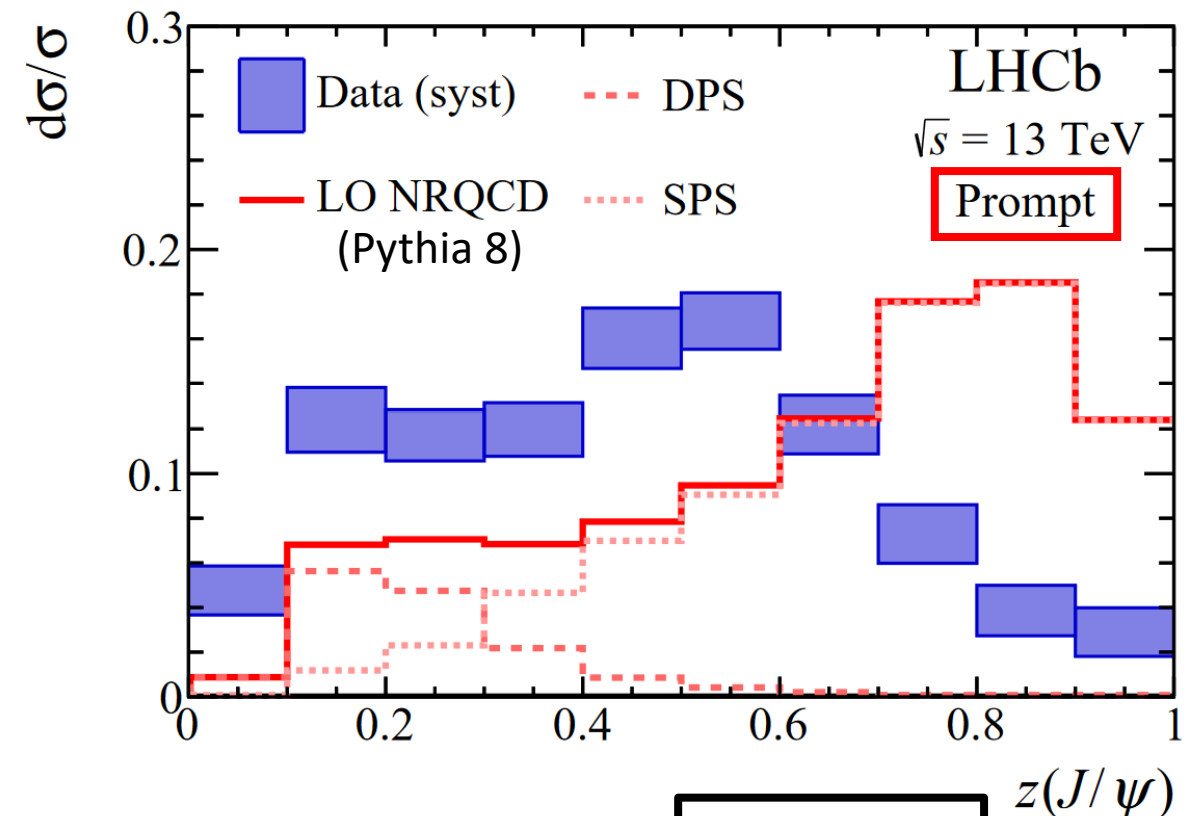
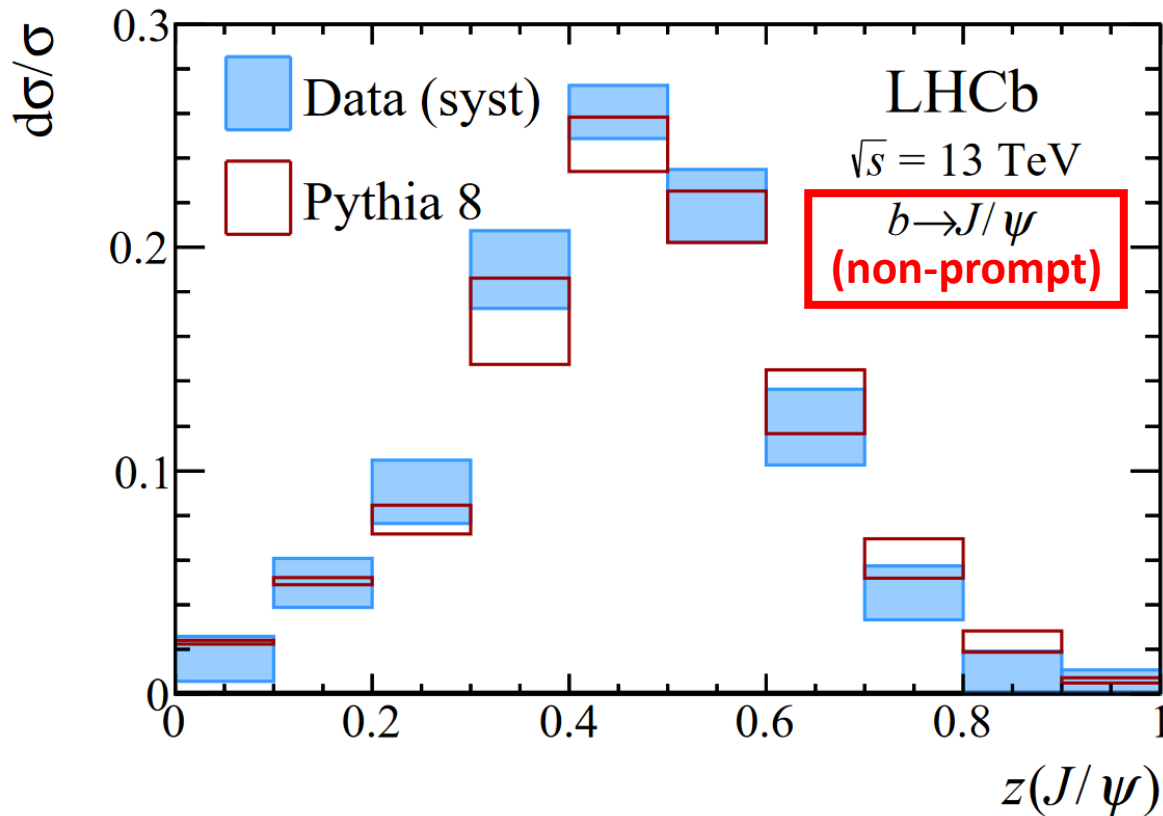
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Heavy quarkonium in jets



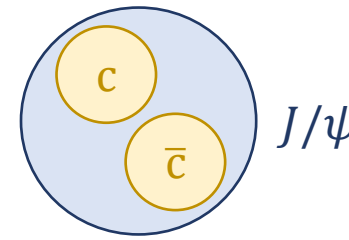
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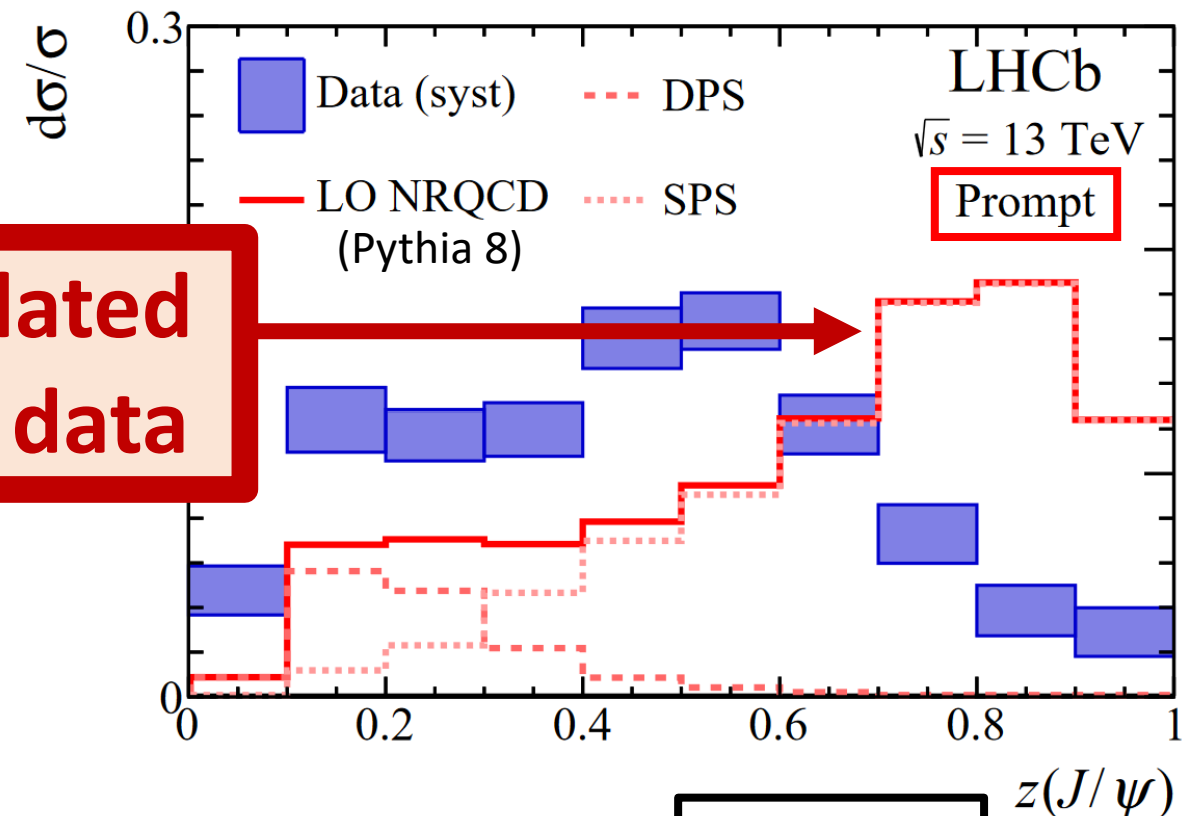
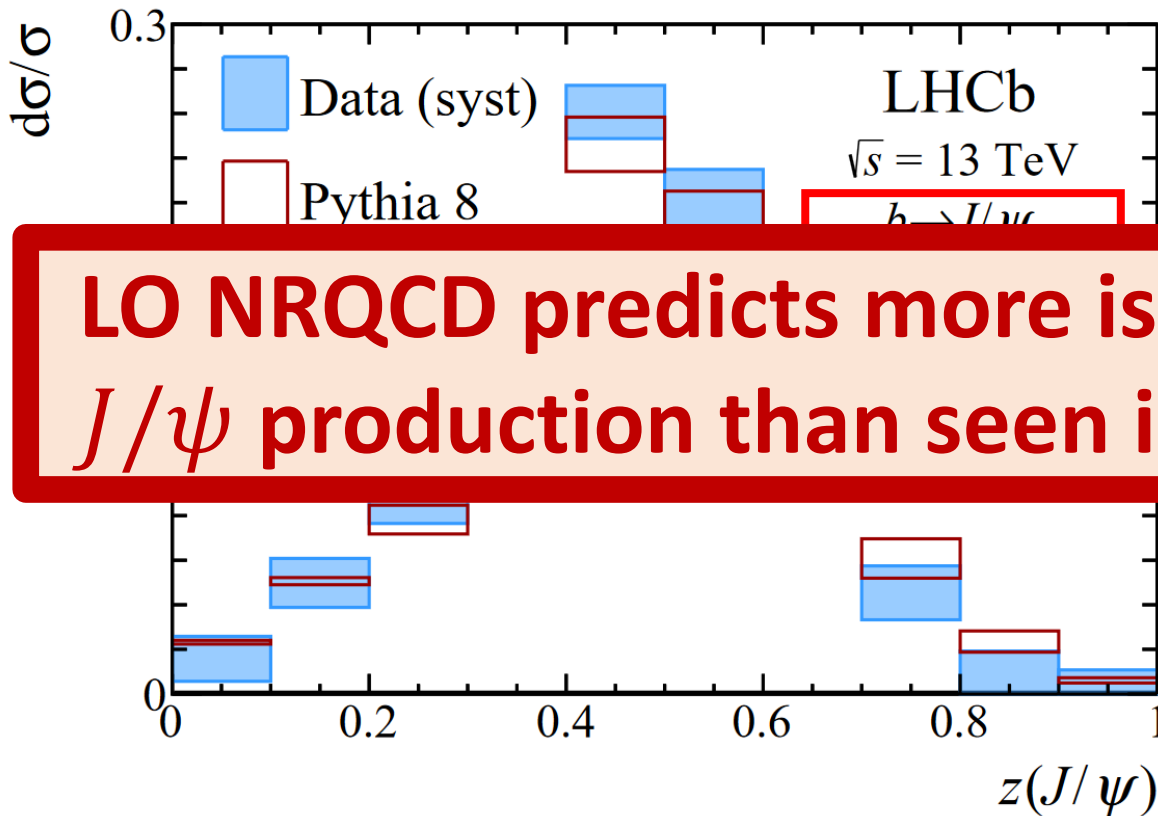
particle momentum fraction

$$Z = \frac{p_{T,i}}{p_{T,\text{jet}}}$$

Heavy quarkonium in jets

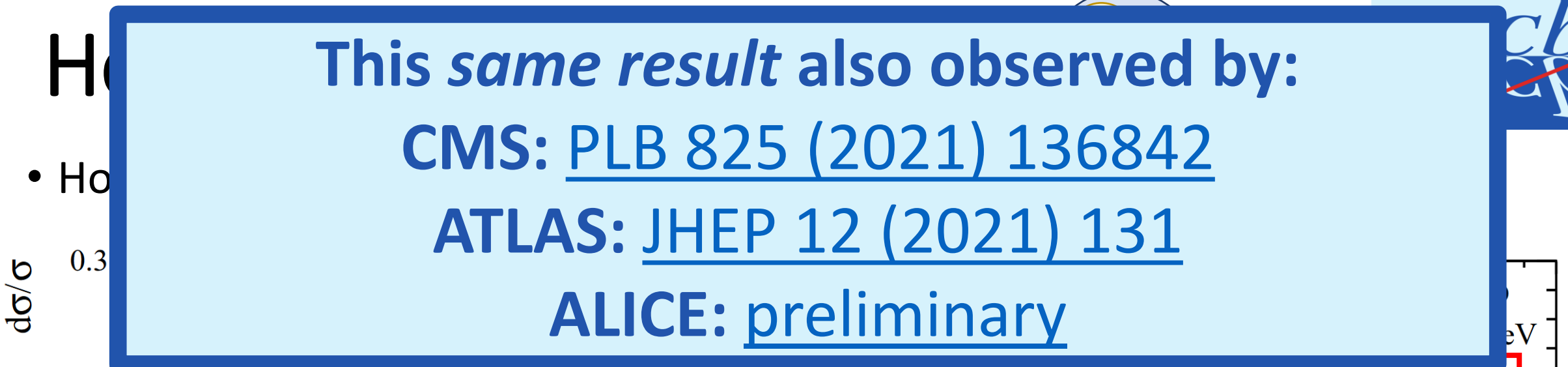


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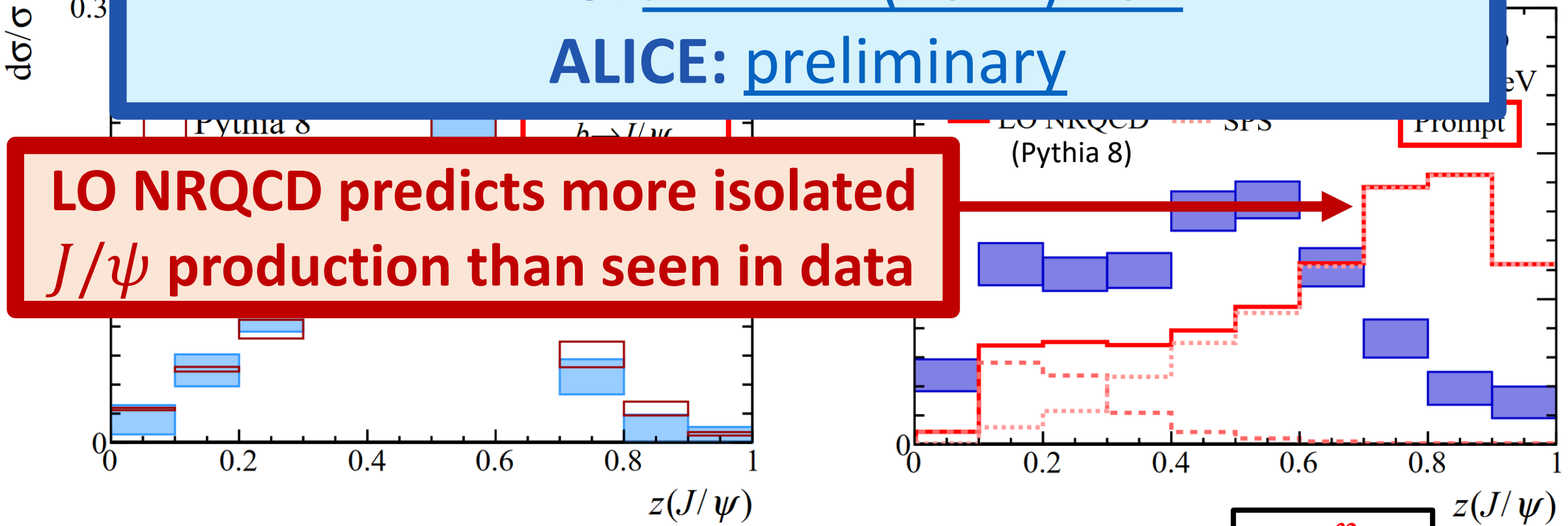


LO NRQCD predicts more isolated J/ψ production than seen in data

particle momentum fraction $Z = \frac{p_{T,i}}{p_{T,jet}}$



LO NRQCD predicts more isolated J/ψ production than seen in data



$$Z = \frac{p_{T,i}}{p_{T,jet}}$$

particle momentum fraction

Ho

• Ho

$d\sigma/\sigma$

0.2

0.1

0

1

(ψ)

$p_{T,jet}$

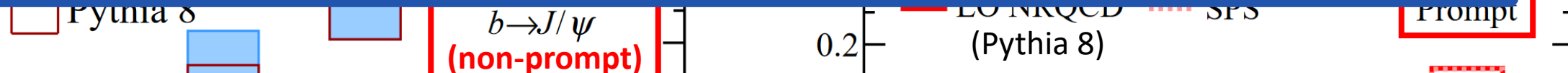
This same result also observed by:

CMS: [PLB 825 \(2021\) 136842](#)

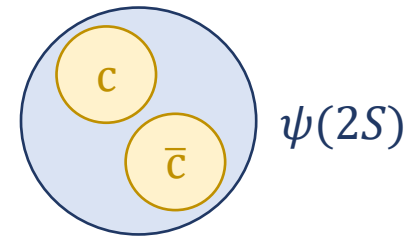
ATLAS: [JHEP 12 \(2021\) 131](#)

ALICE: [preliminary](#)

Production of heavy quark pairs is underestimated in the parton shower?

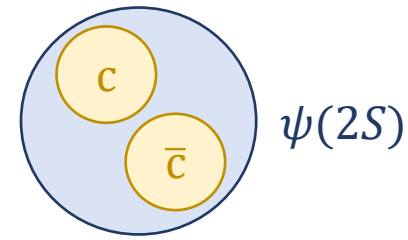


Higher mass states

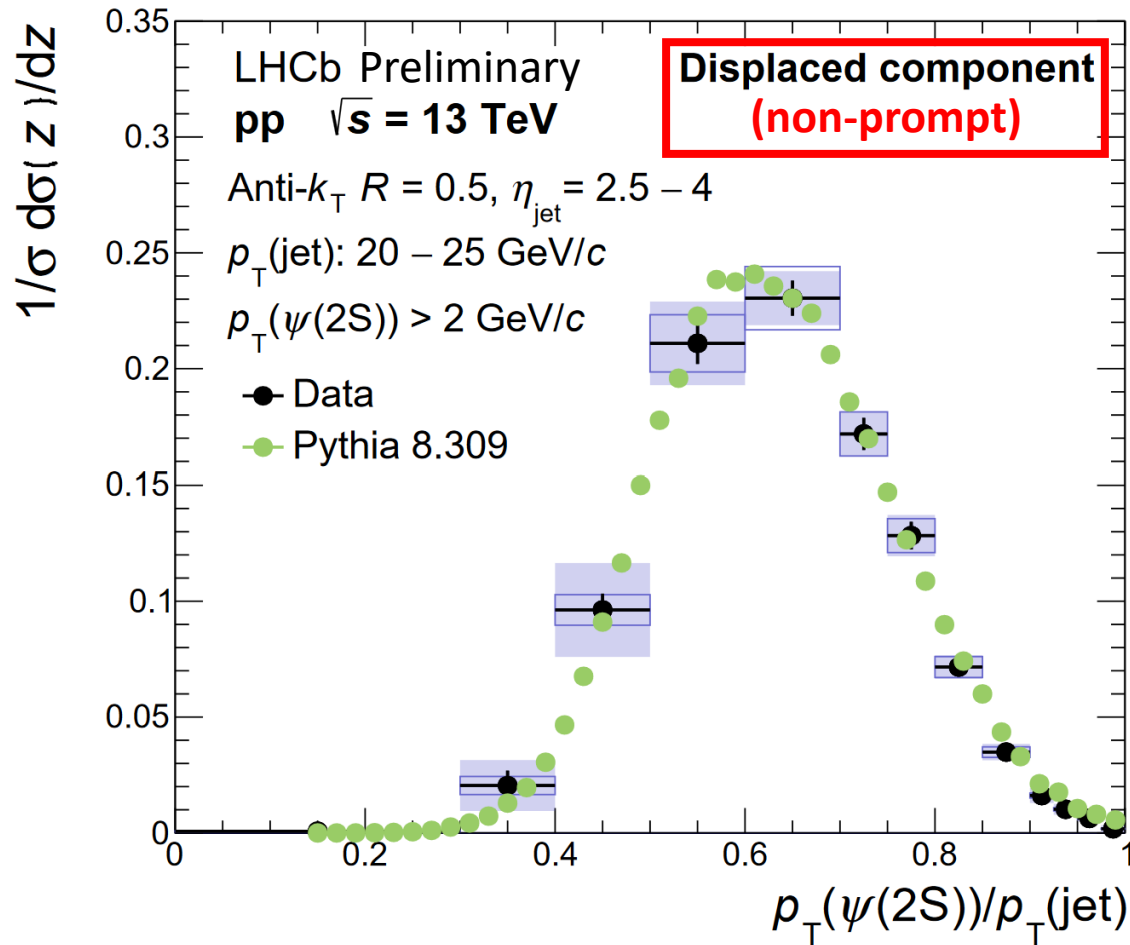


- What about heavier charmonium such as $\psi(2S)$ (less feed-down)?

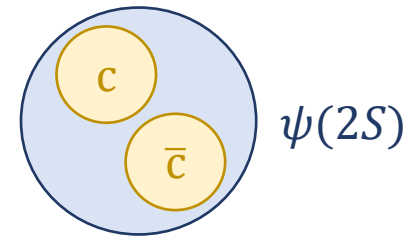
Higher mass states



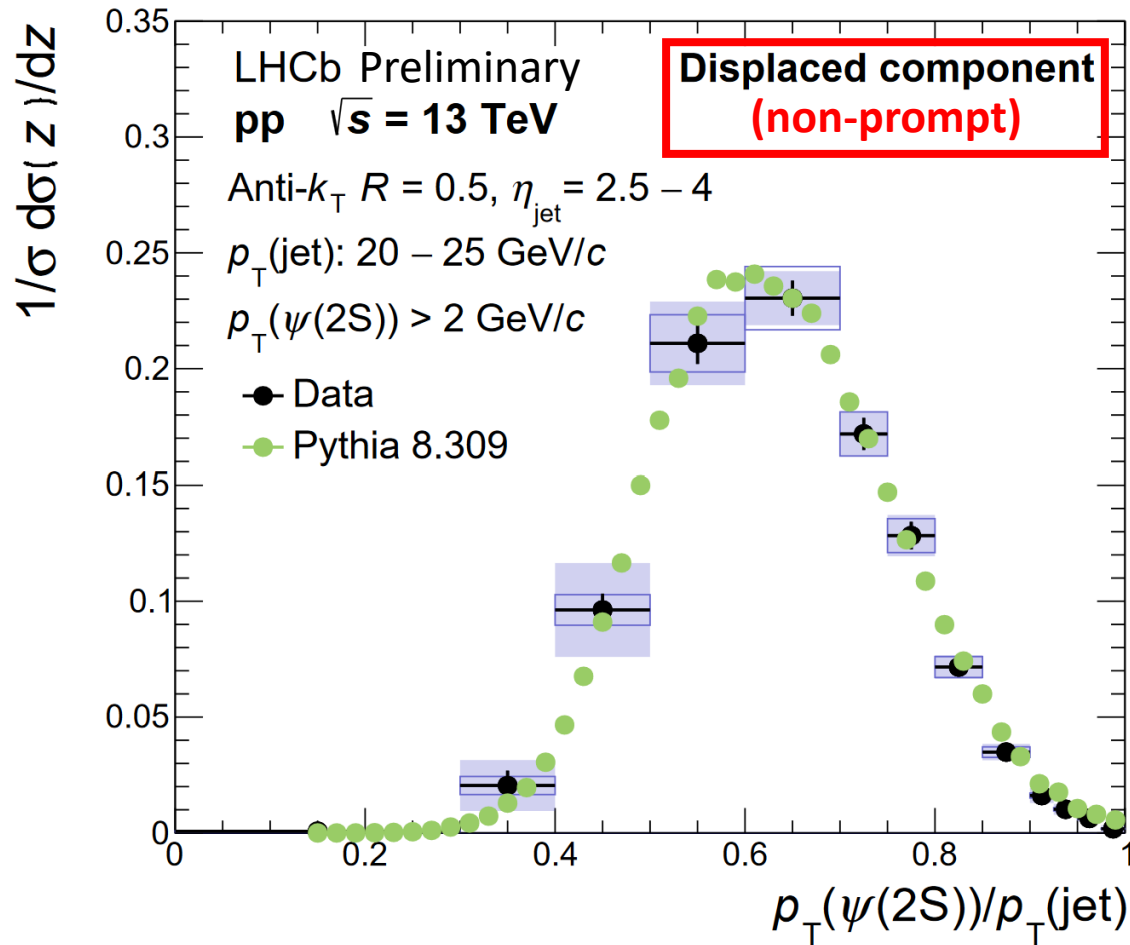
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Higher mass states

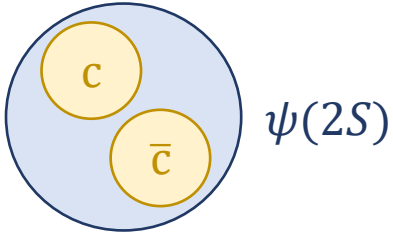


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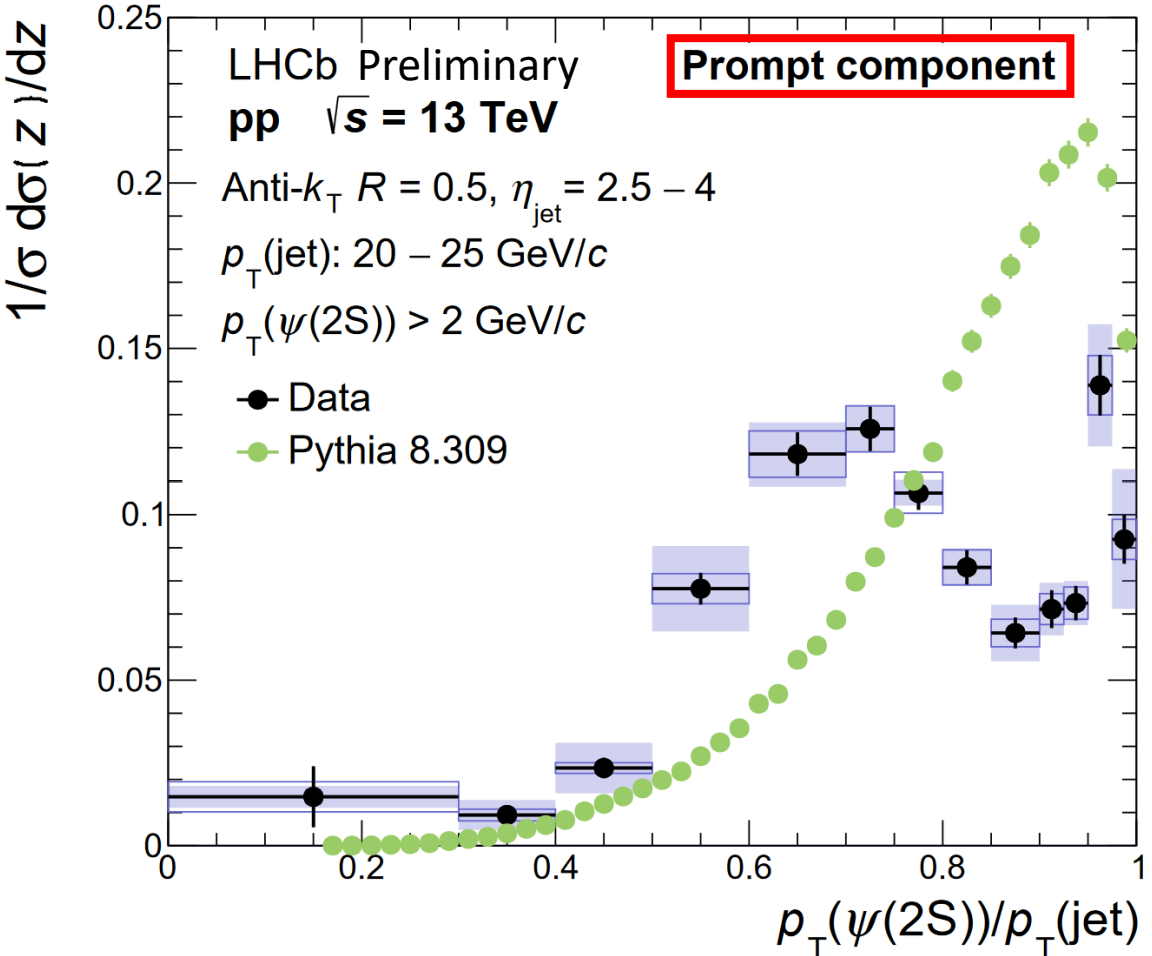
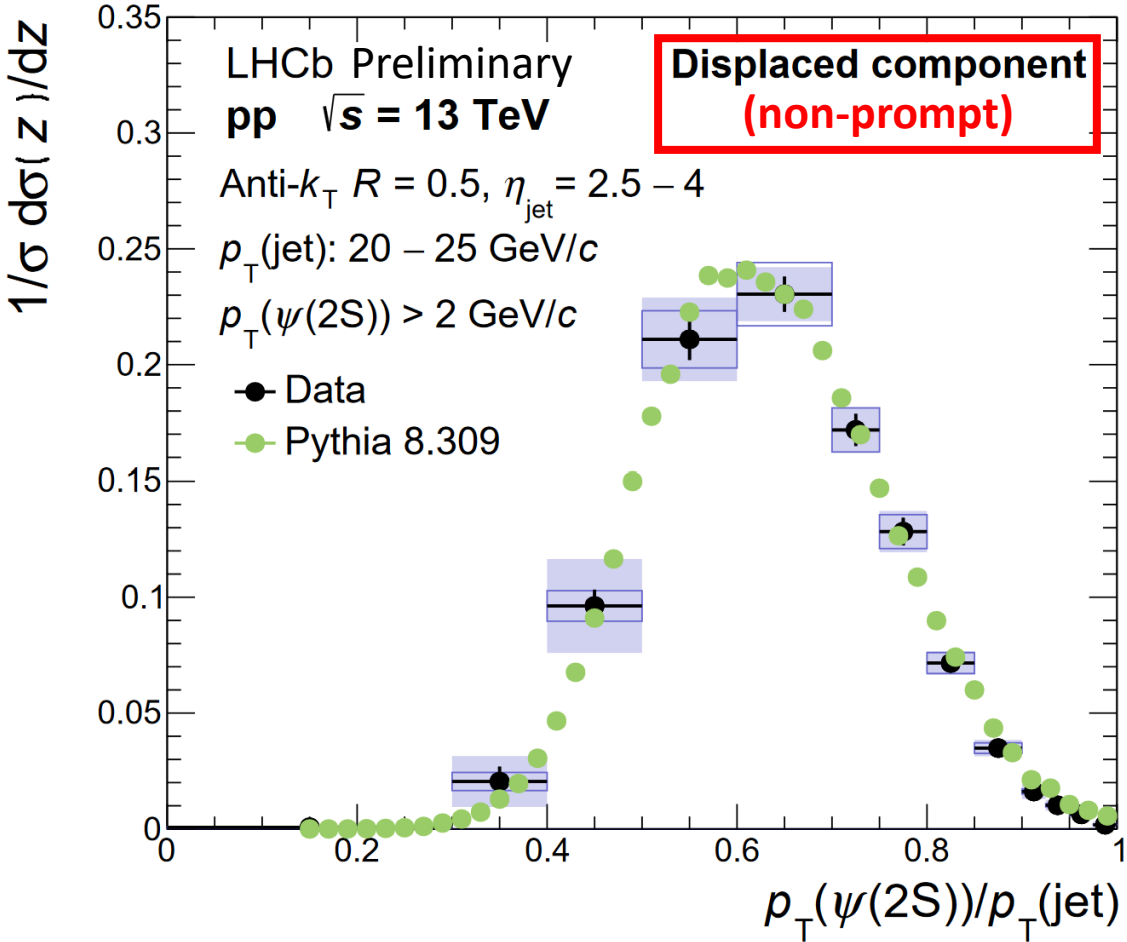


- **Good agreement** in non-prompt production (similar to J/ψ)
- Displaced $\psi(2S)$ carries $\sim 60\%$ of jet transverse momentum

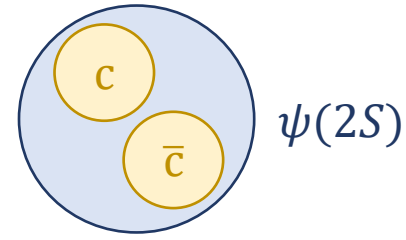
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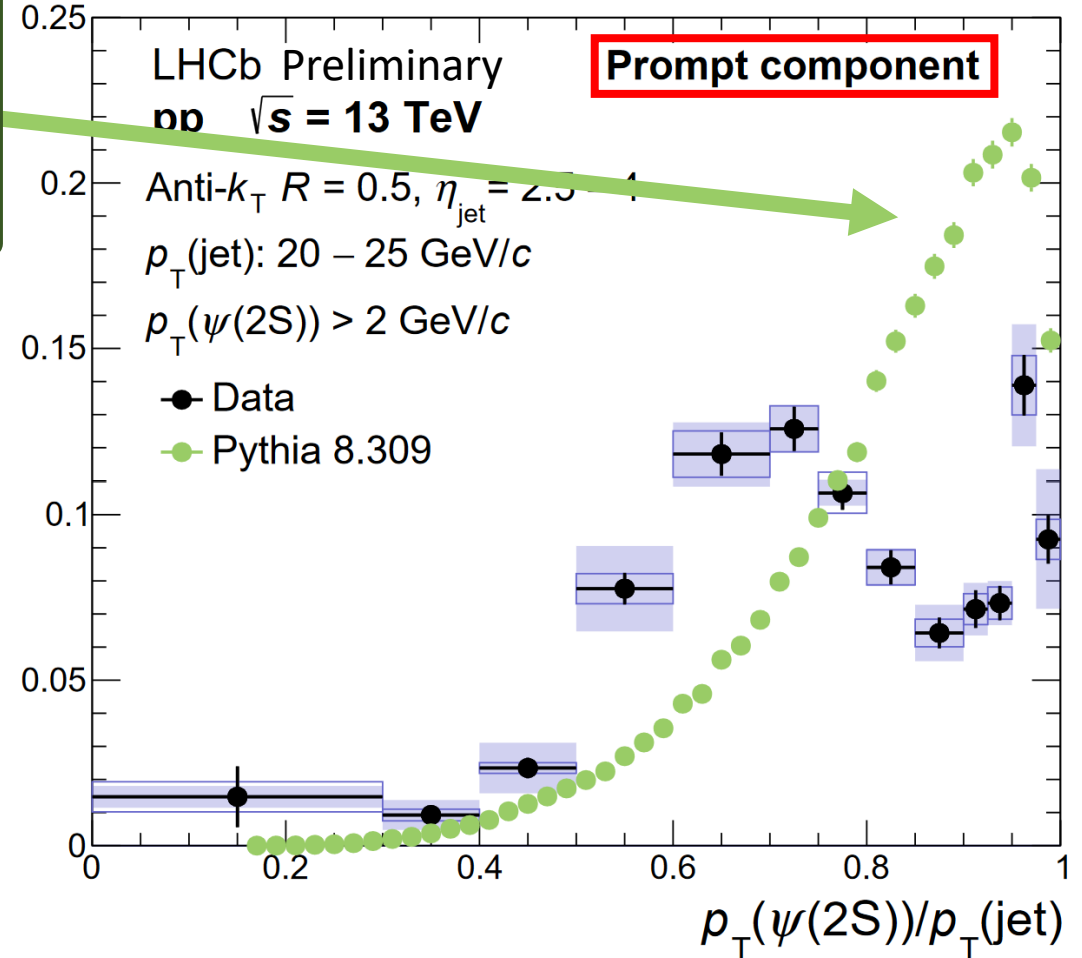
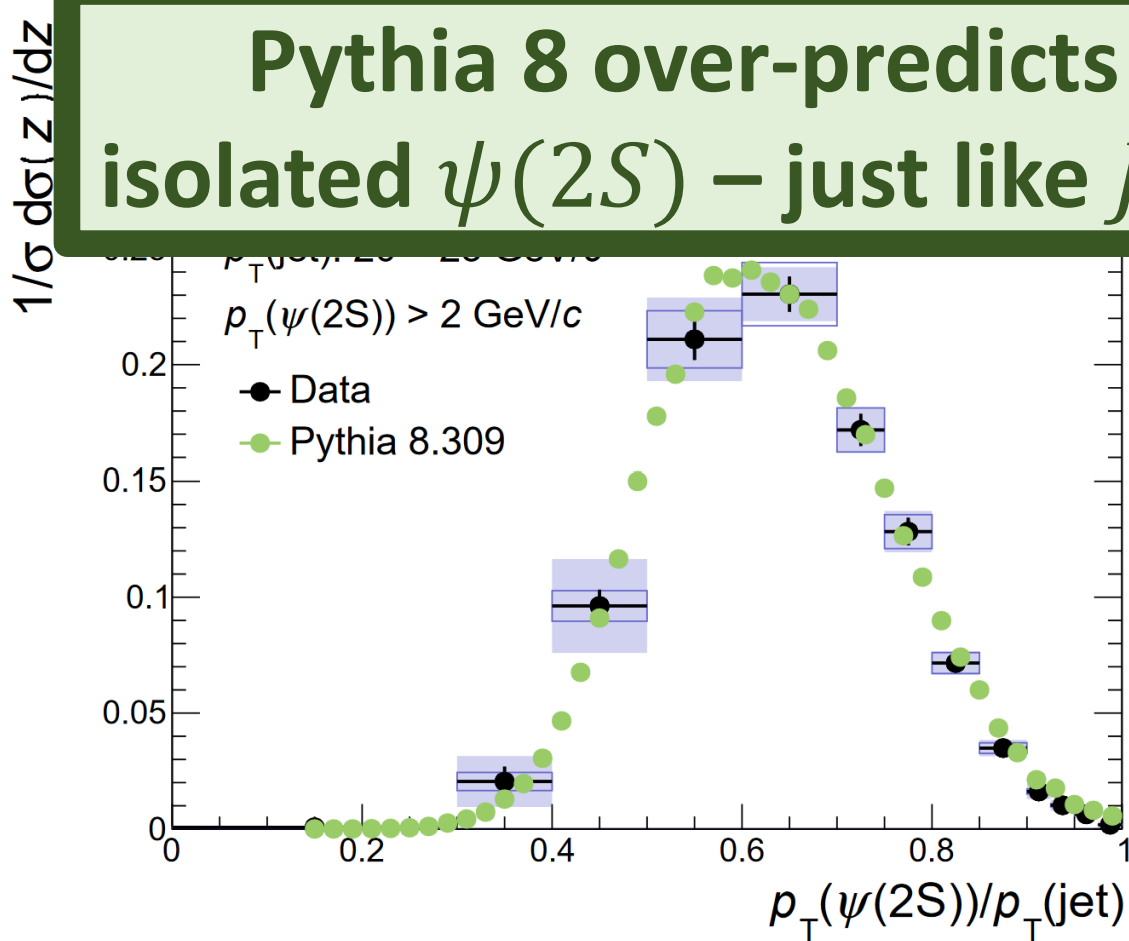


Higher mass states

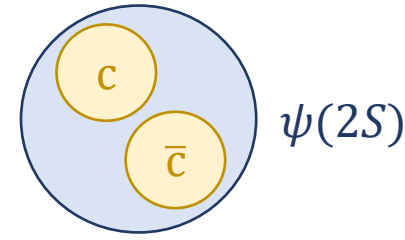


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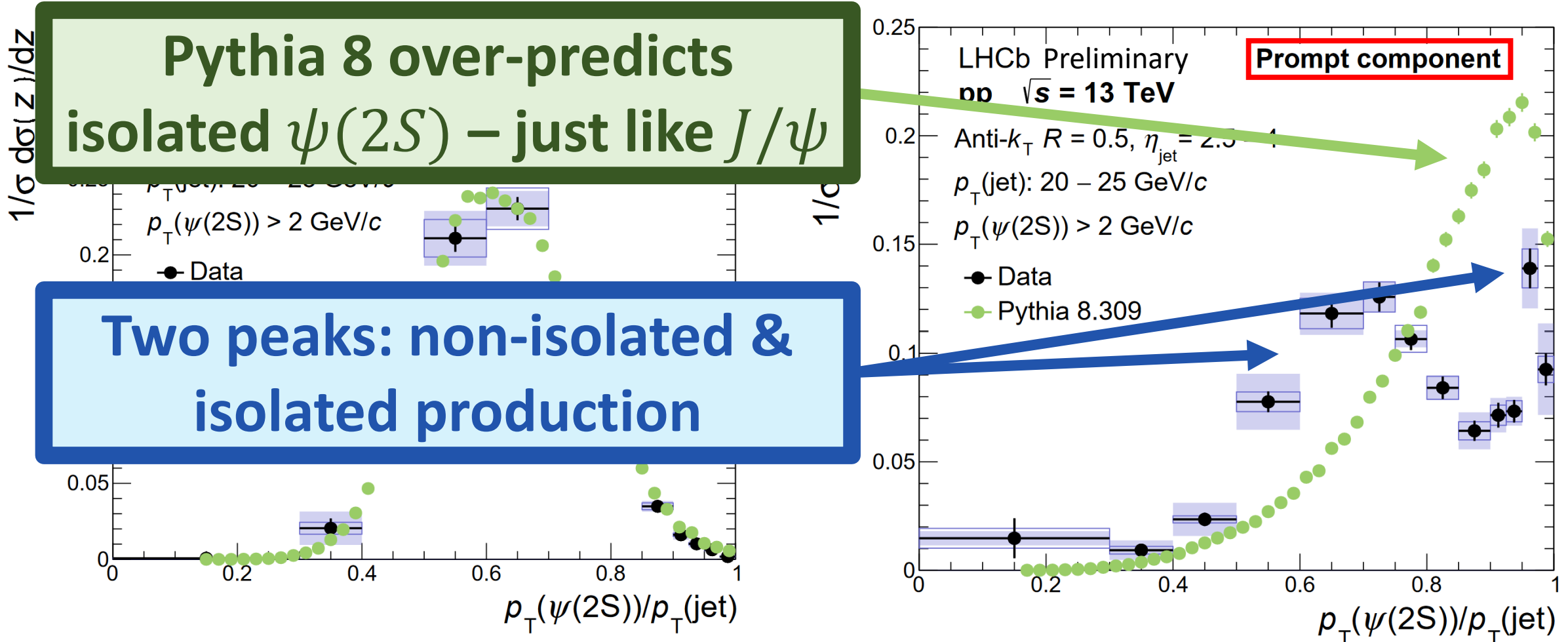
Pythia 8 over-predicts isolated $\psi(2S)$ – just like J/ψ



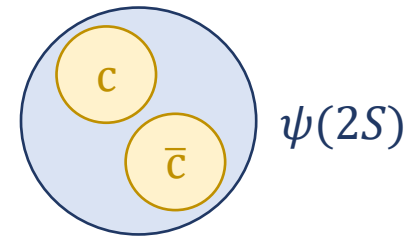
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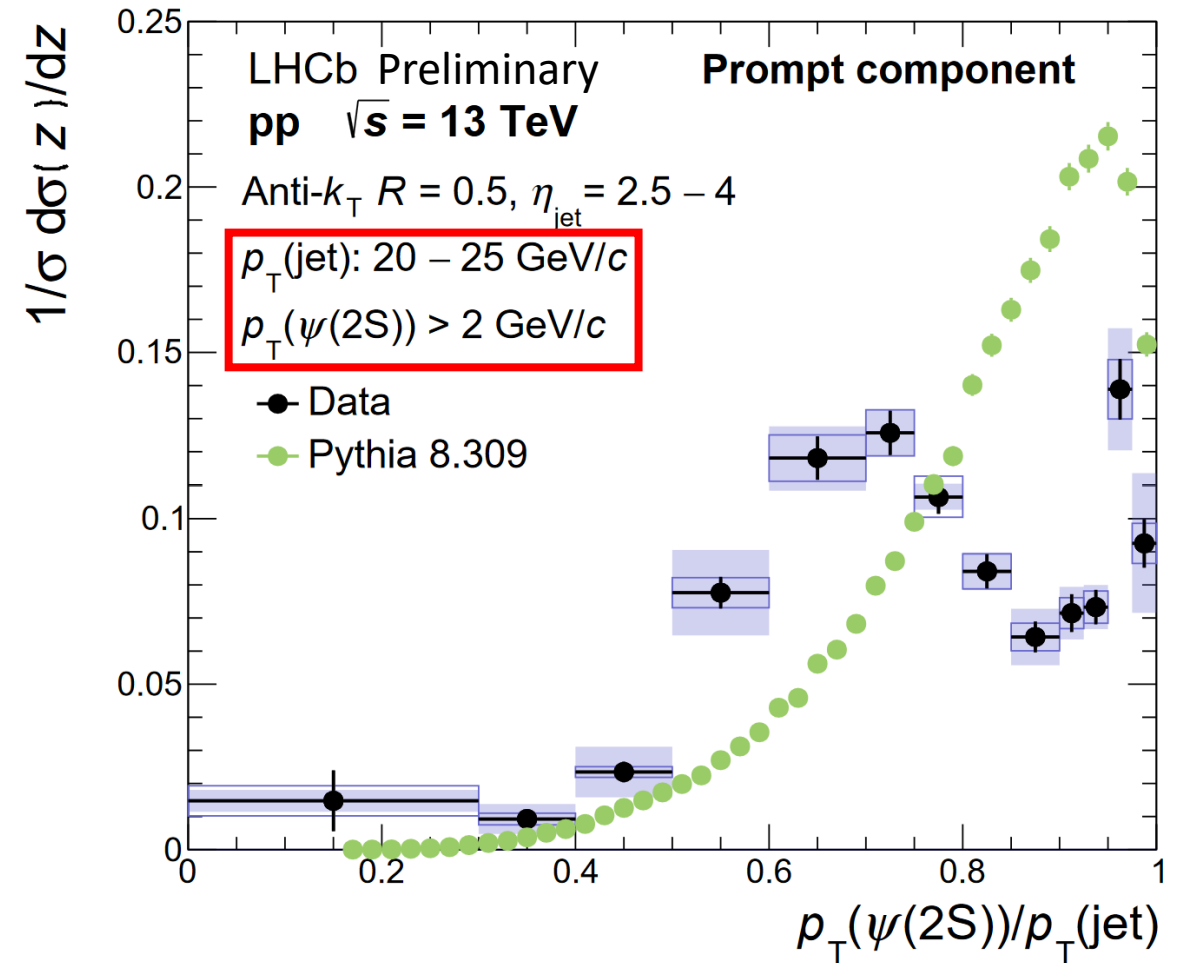


Higher mass states

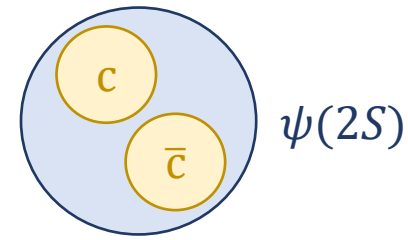


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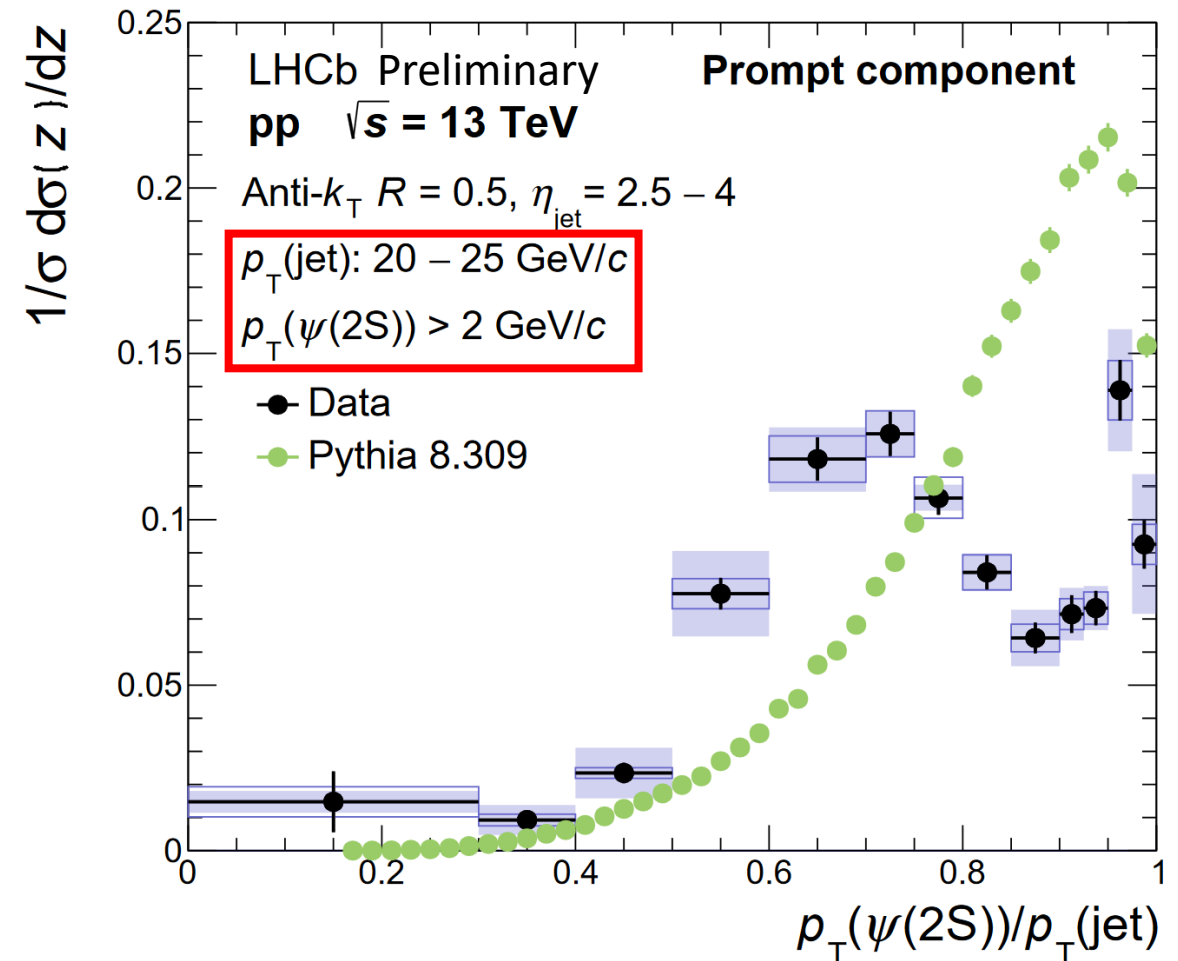
Higher mass states



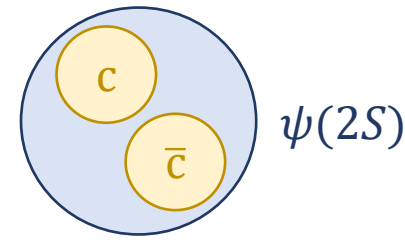
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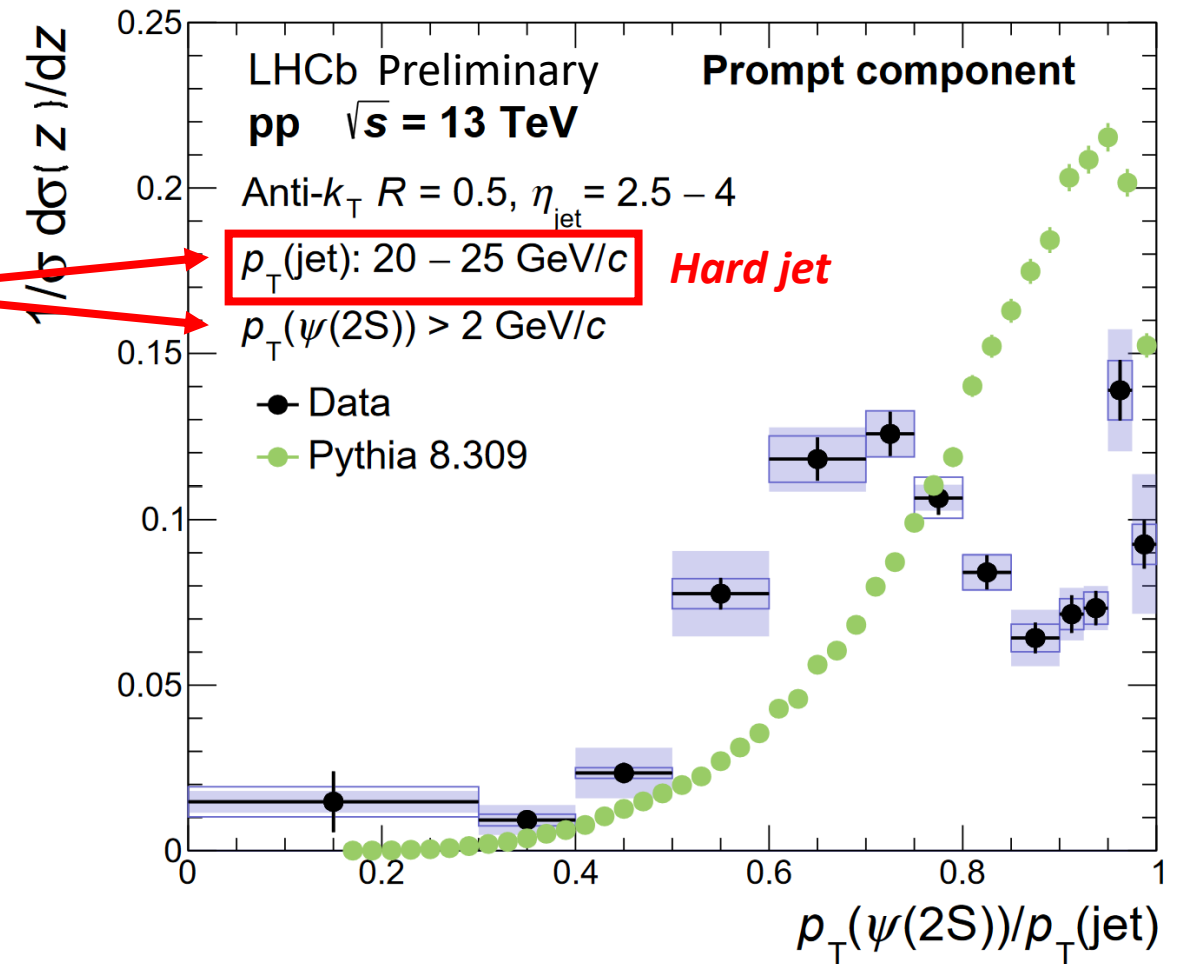
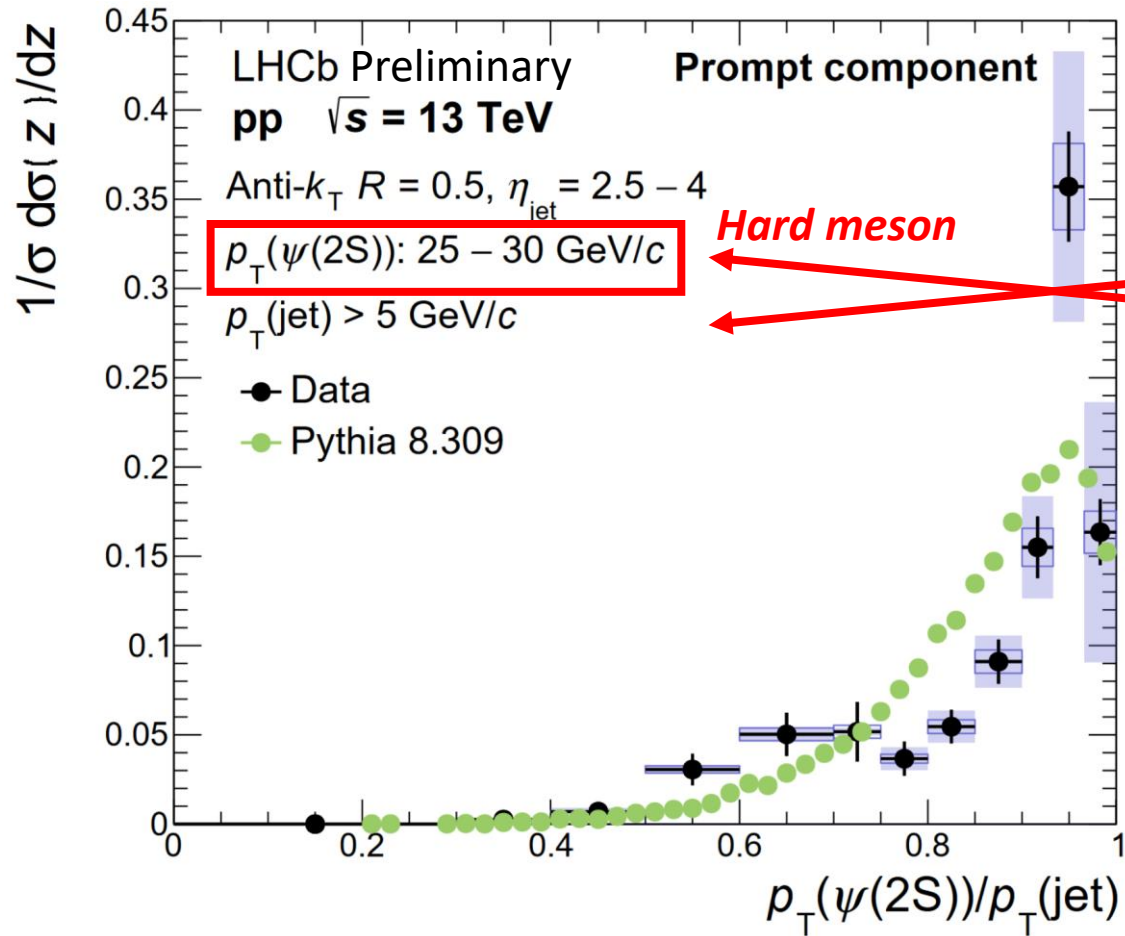
- What about harder $\psi(2S)$ in any jet momentum range?



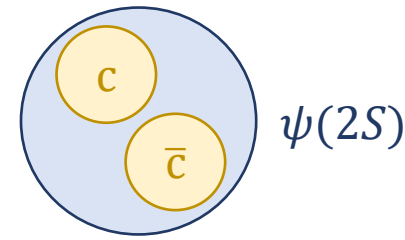
Higher mass states



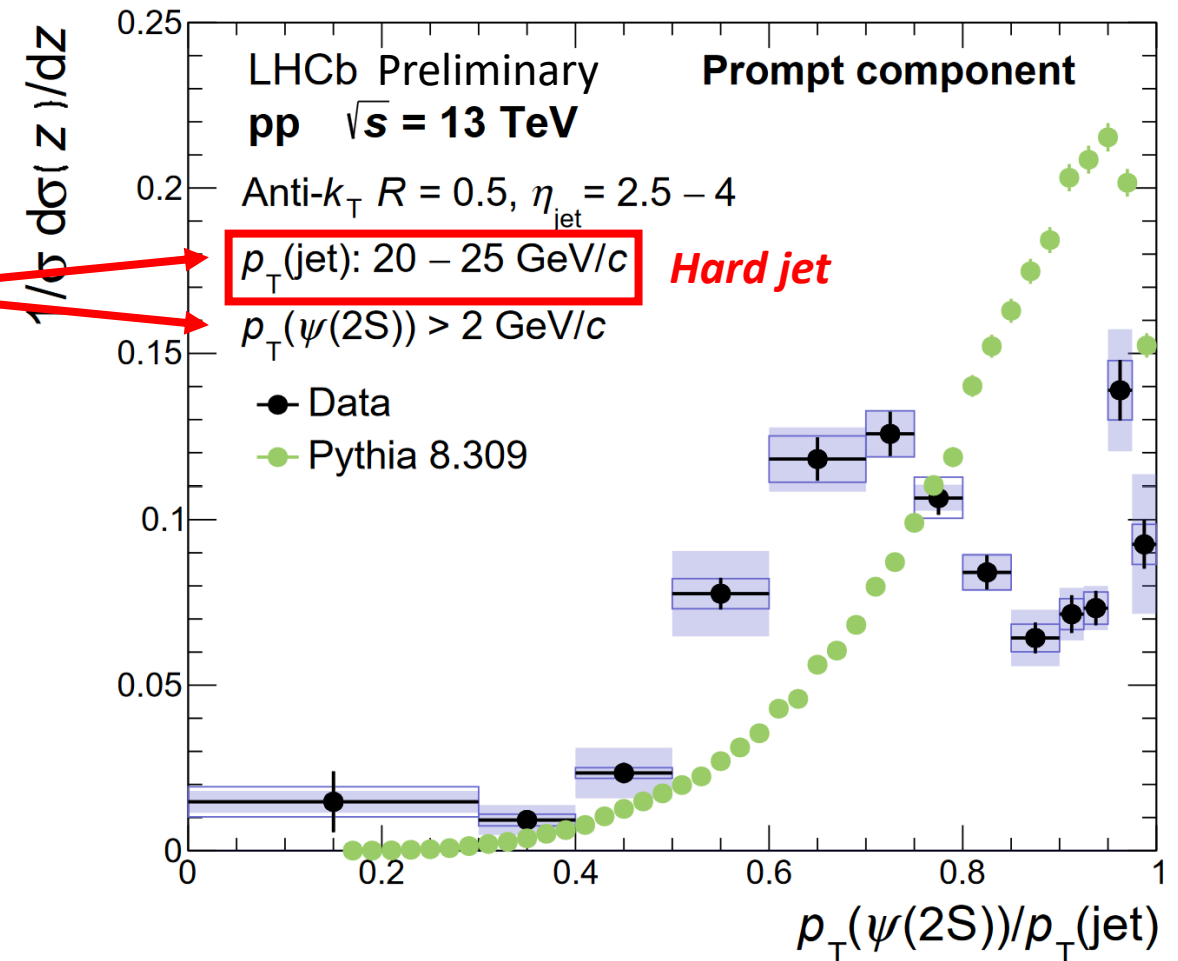
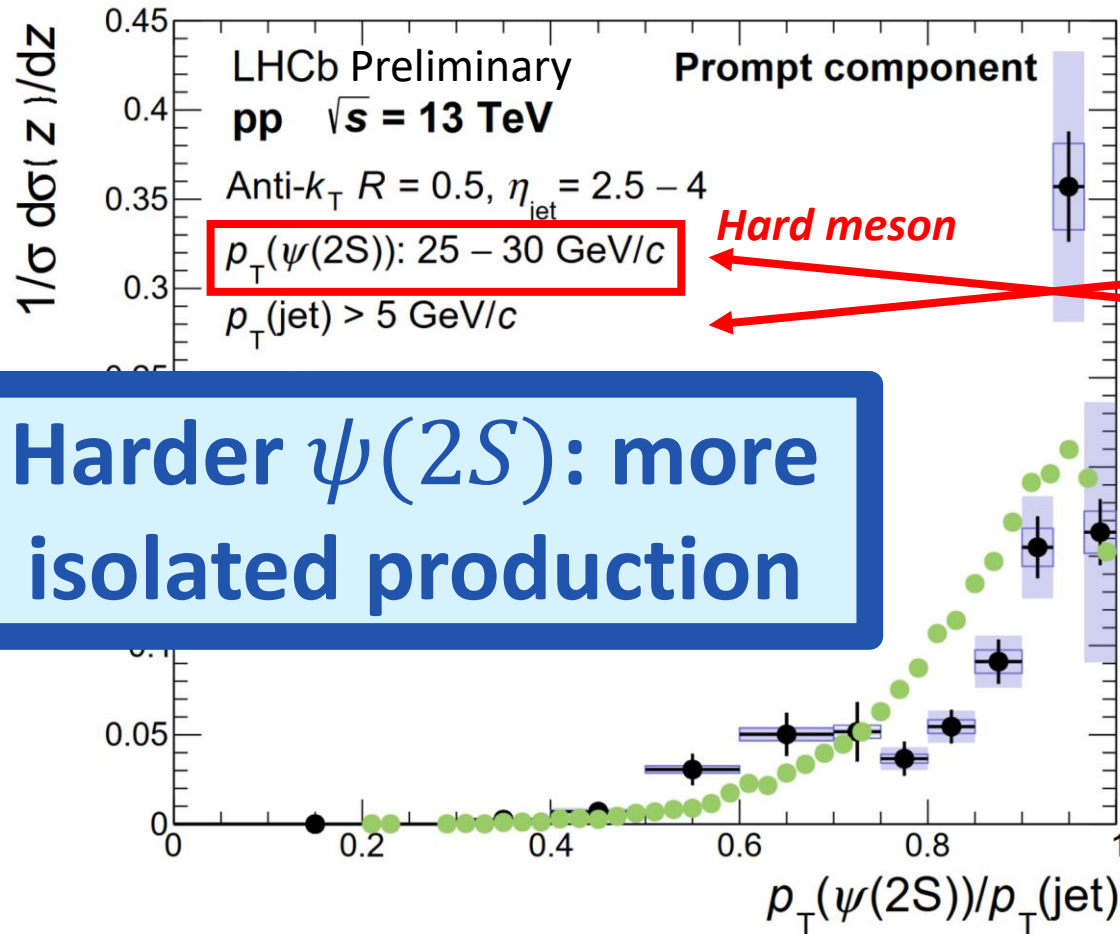
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Higher mass states

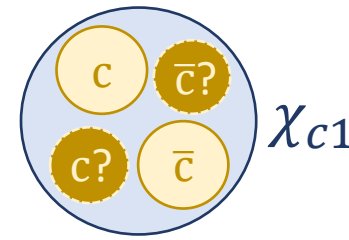


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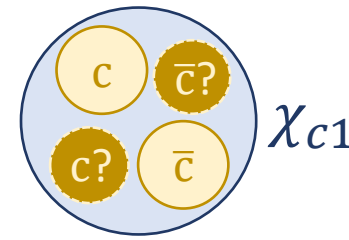
Harder $\psi(2S)$: more isolated production

(Even) Higher mass states

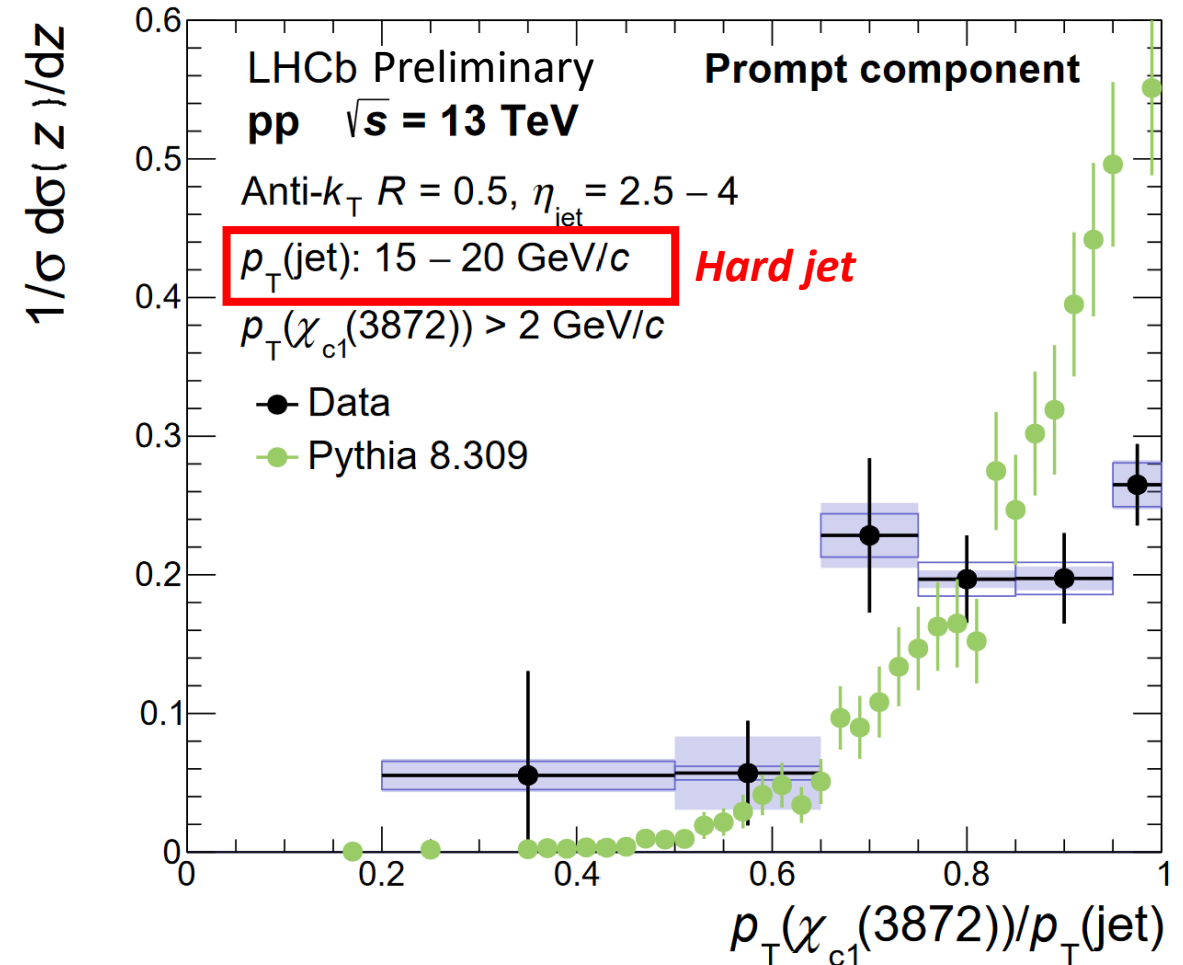


- How is **tetraquark / $D\bar{D}^*$ molecule candidate $\chi_{c1}(3872)$** produced?

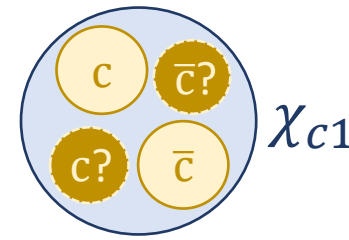
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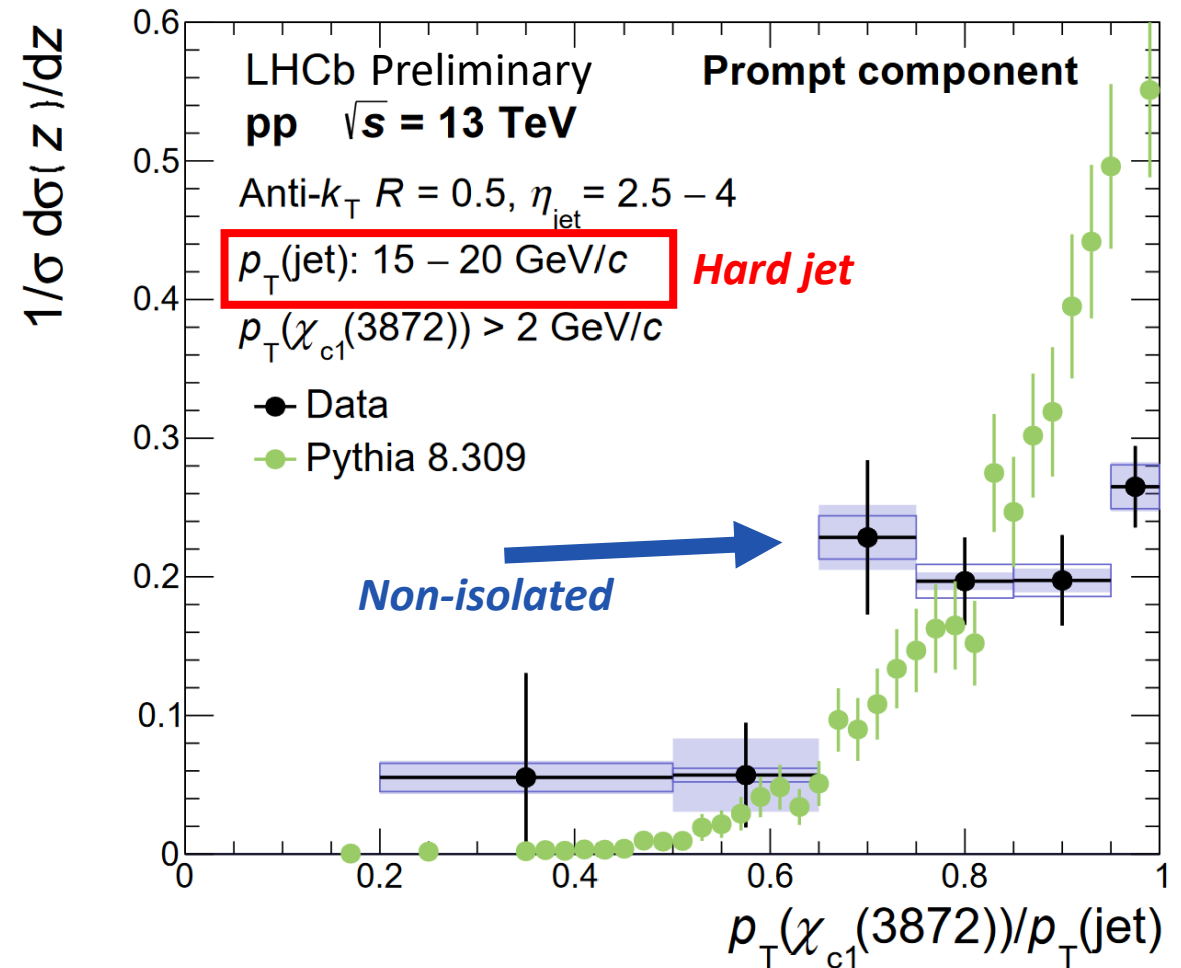
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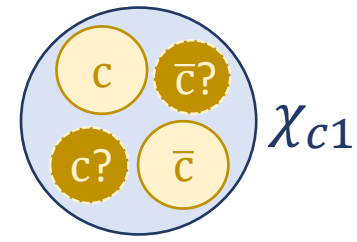
(Even) Higher mass states



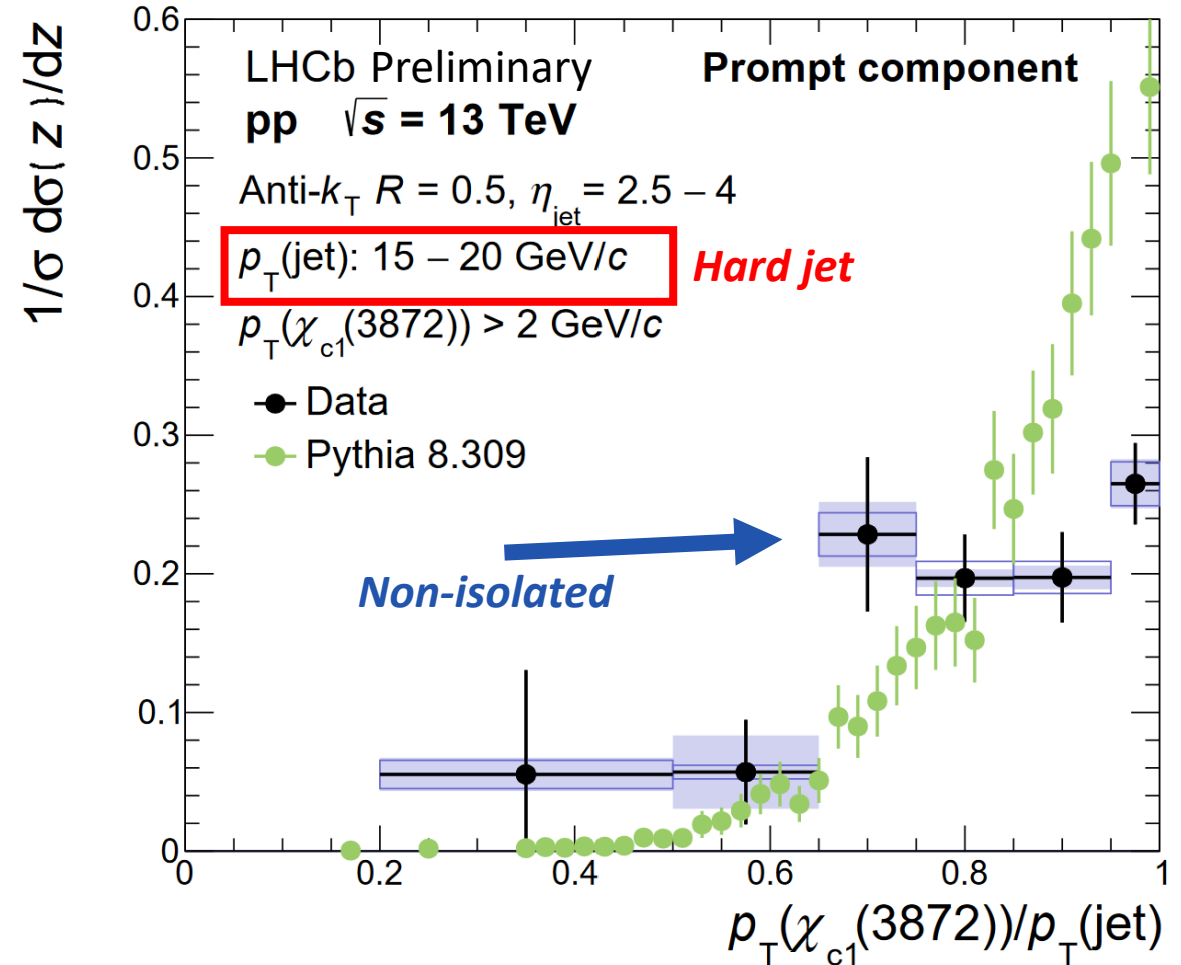
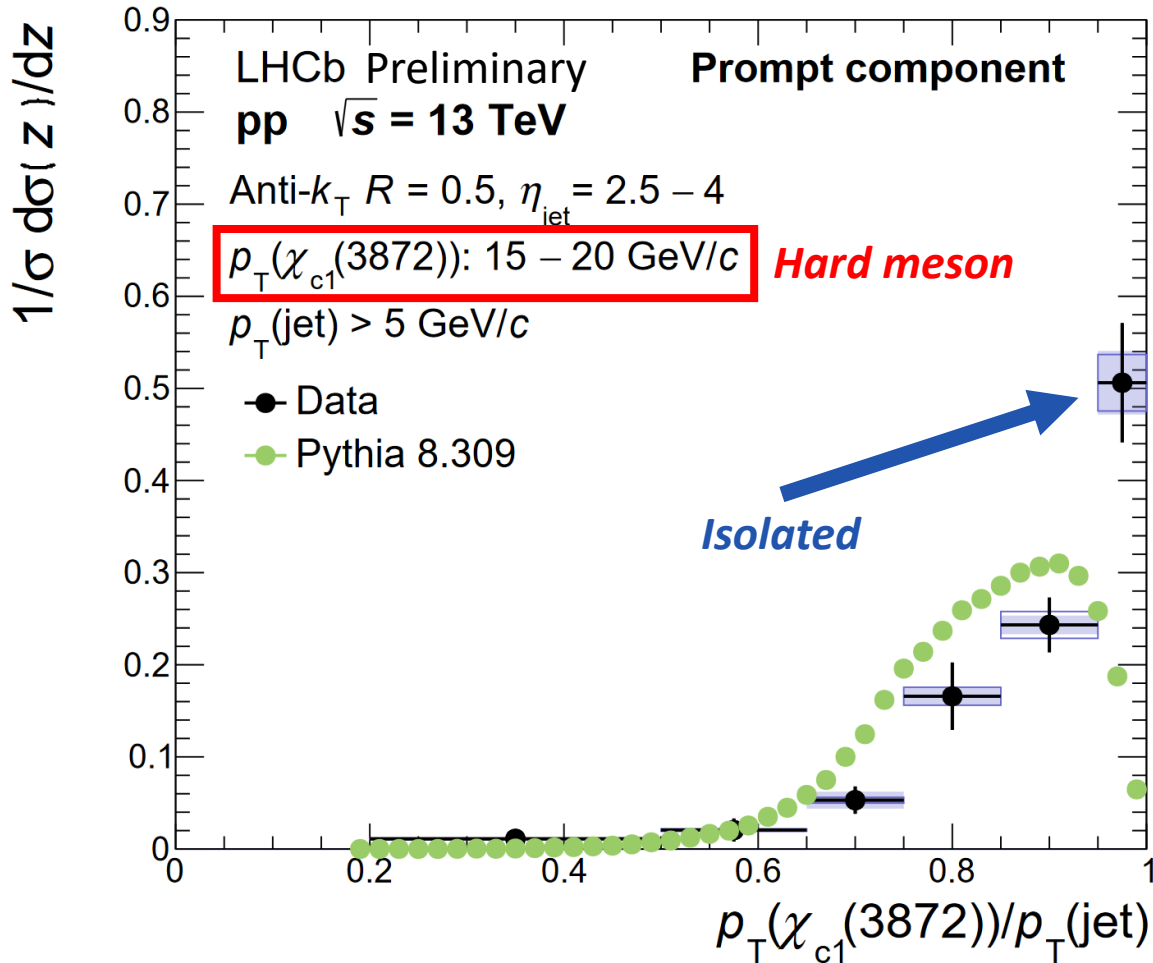
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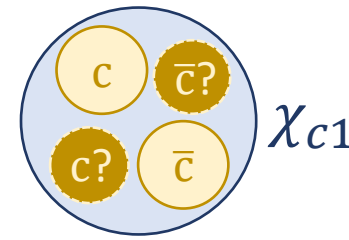
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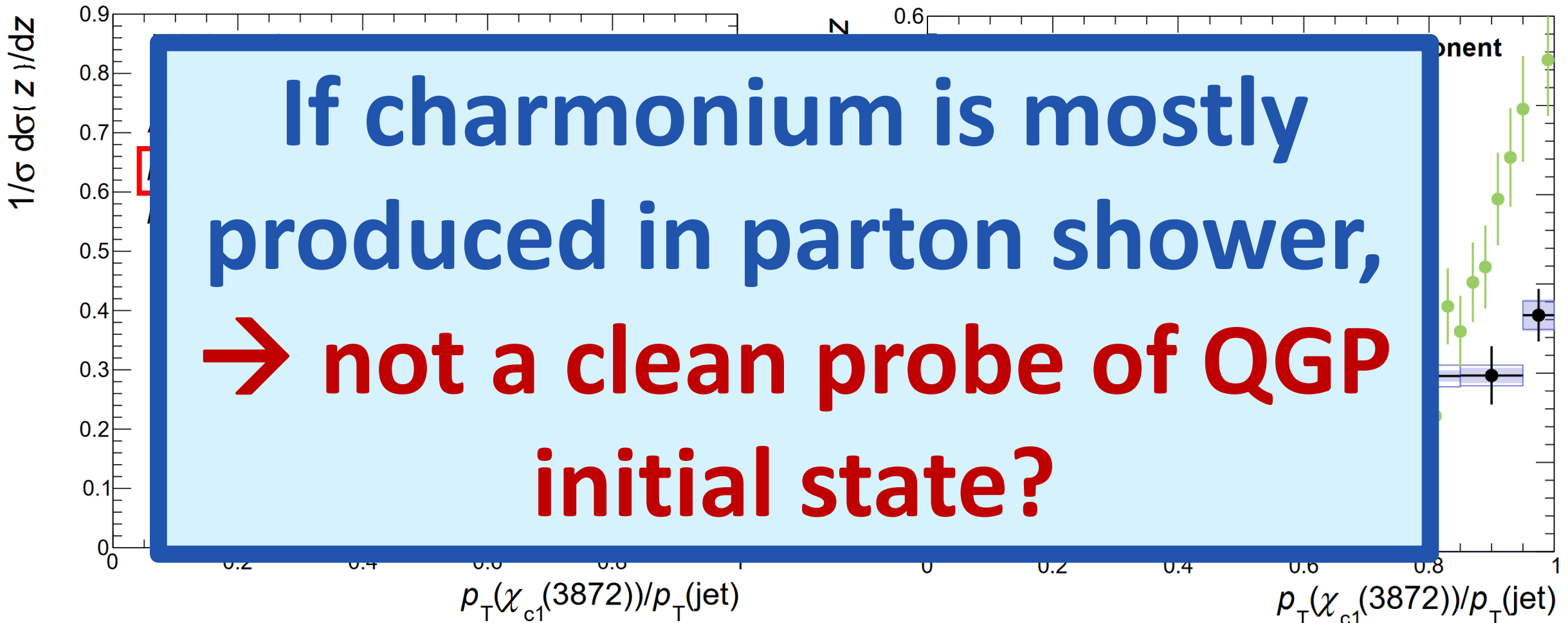
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(Even) Higher mass states



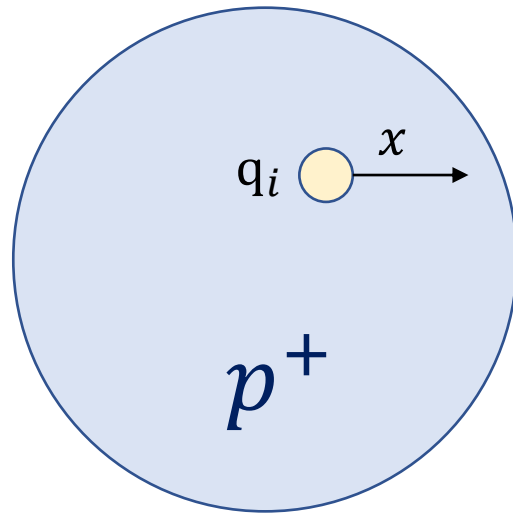
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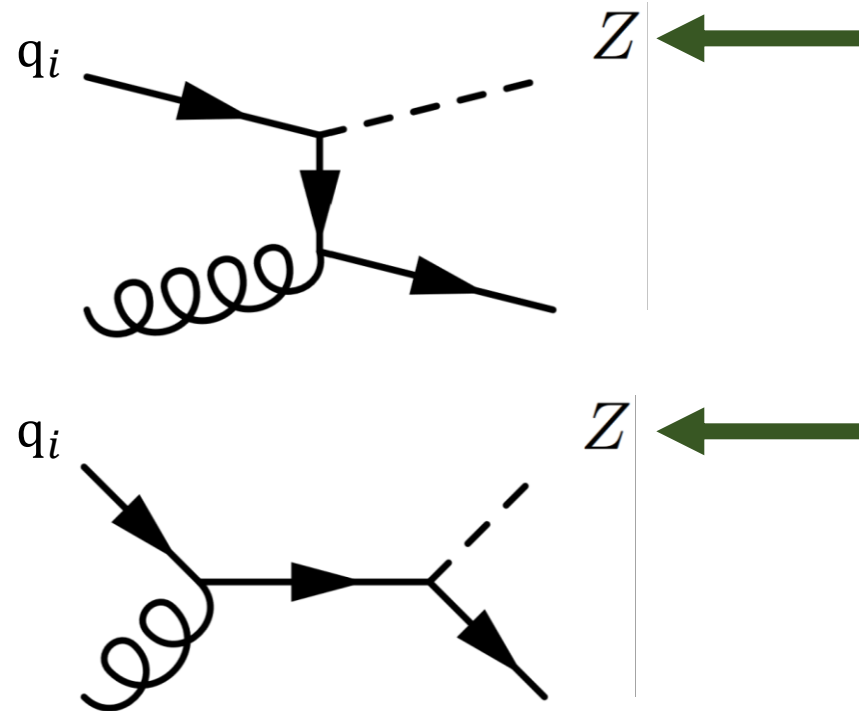
EW-tagged heavy flavor production



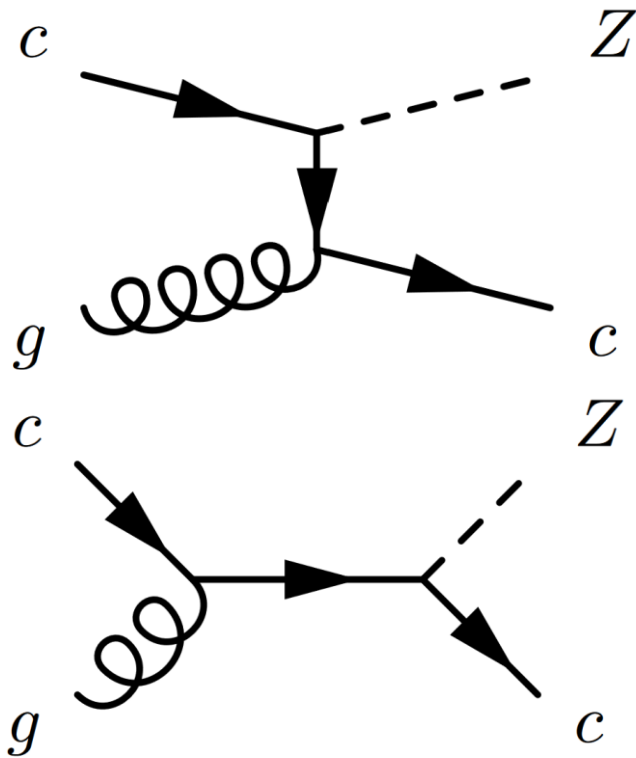
Parton Distribution
Functions (PDFs)



\otimes

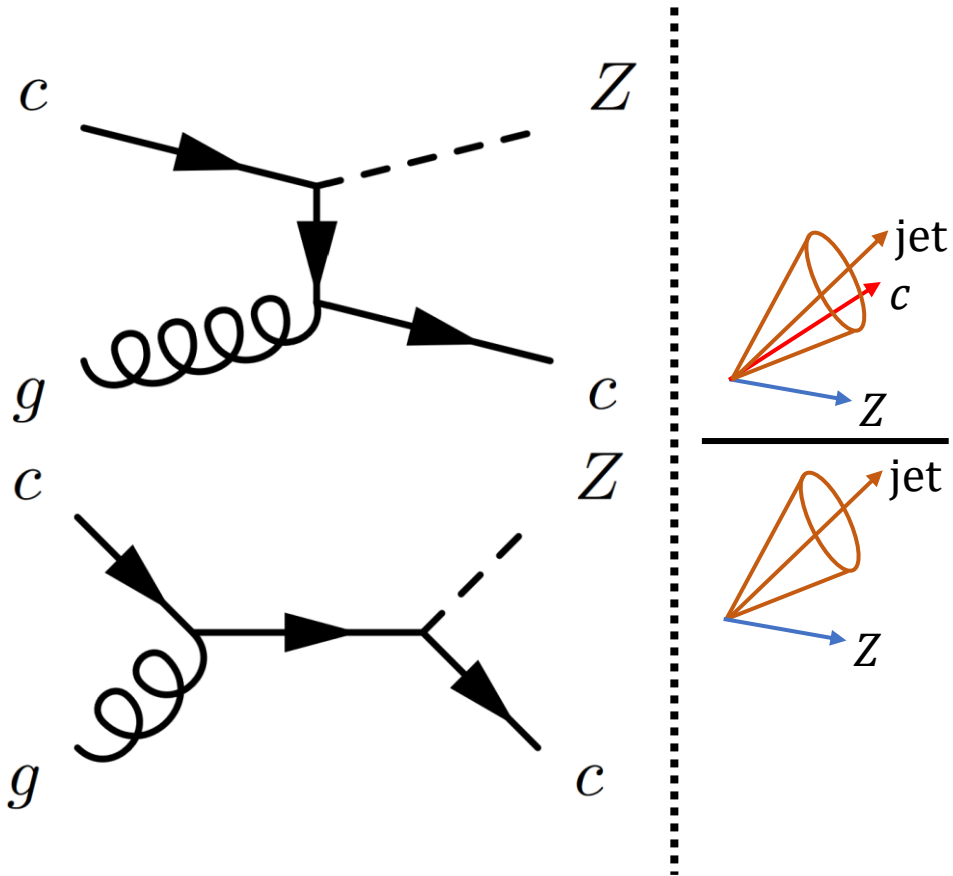


EW-tagged heavy flavor production



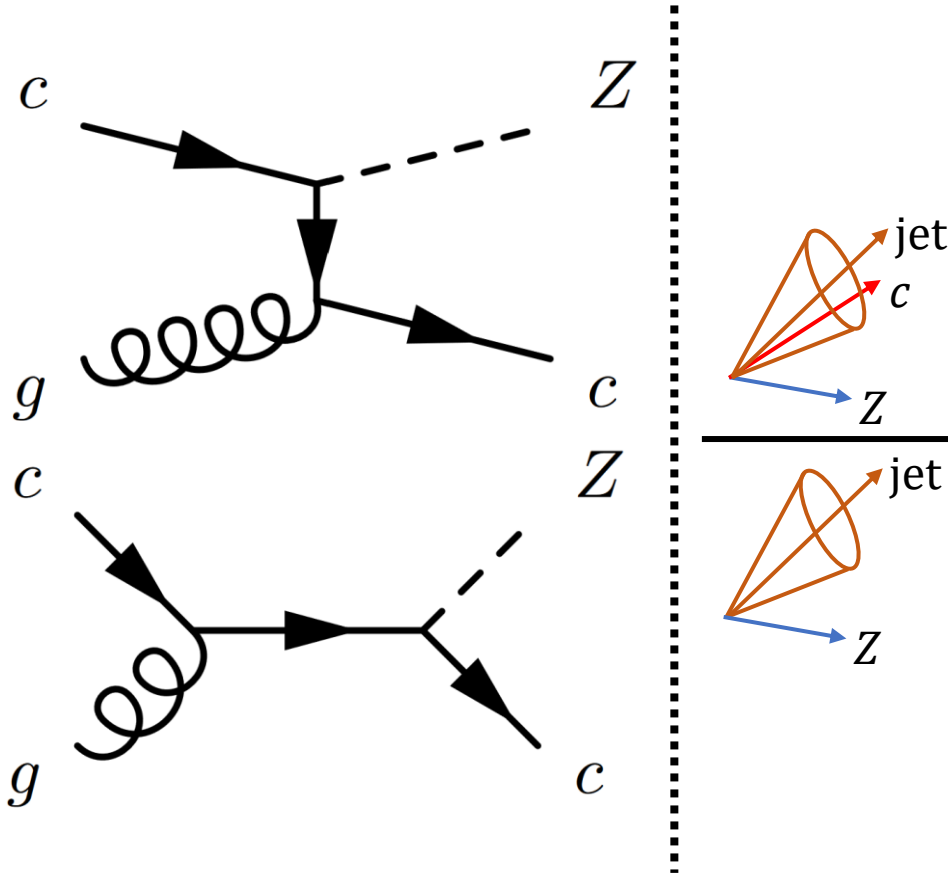
- Search for intrinsic charm

EW-tagged heavy flavor production

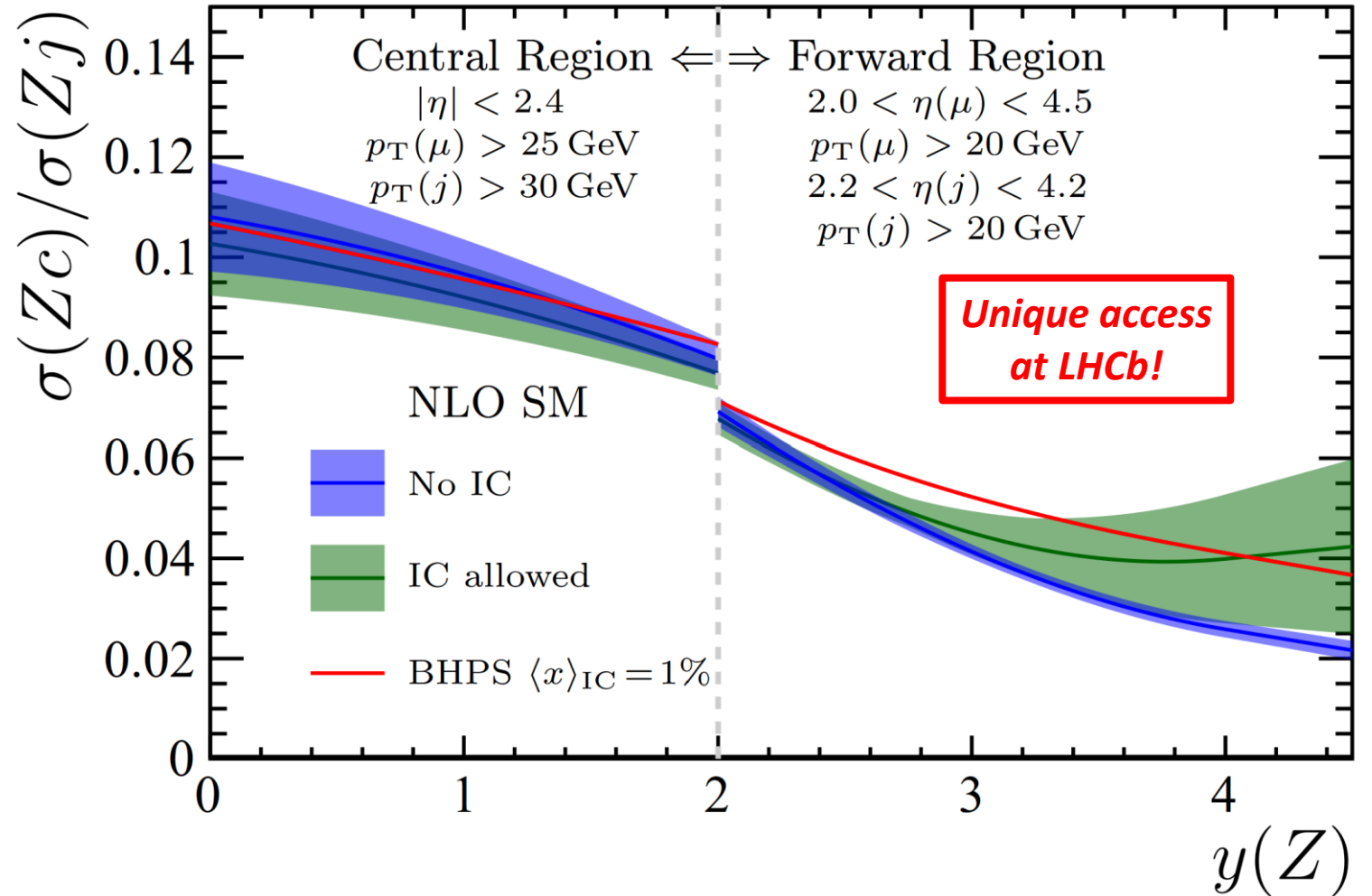


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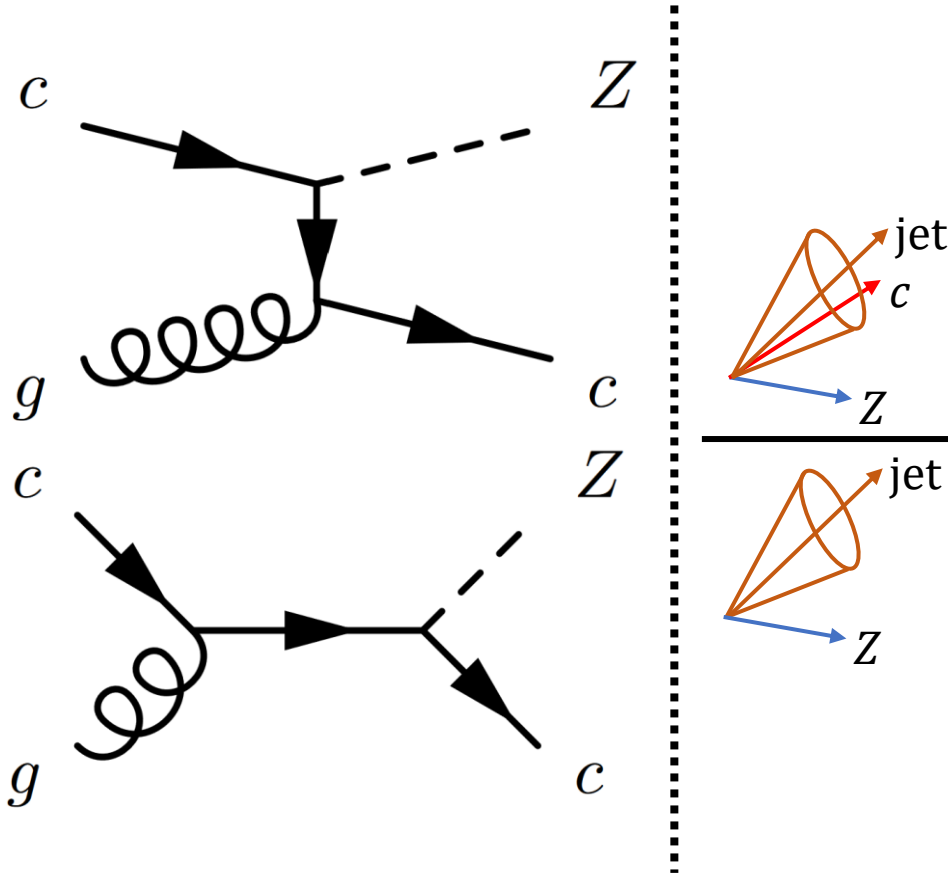
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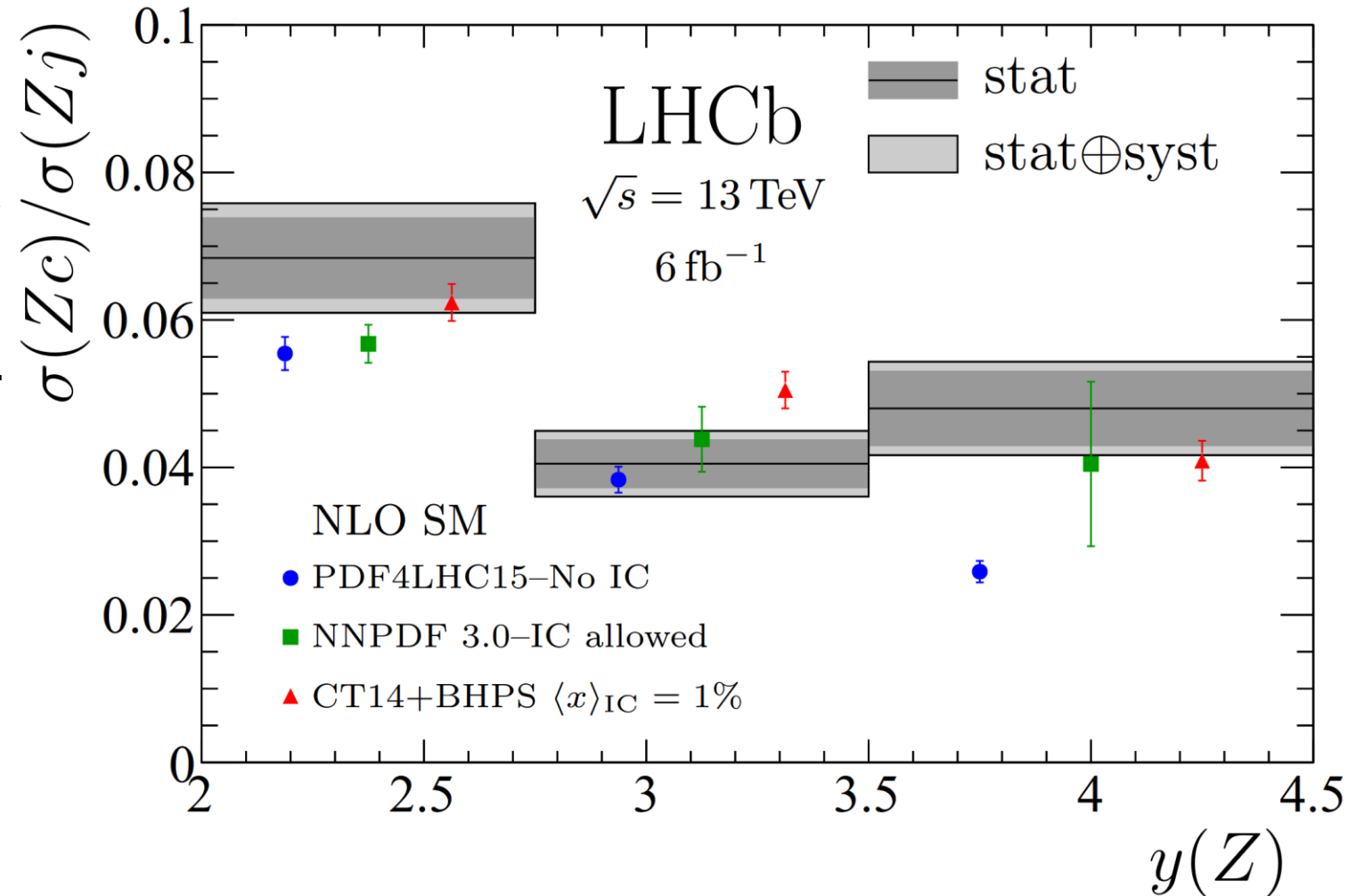
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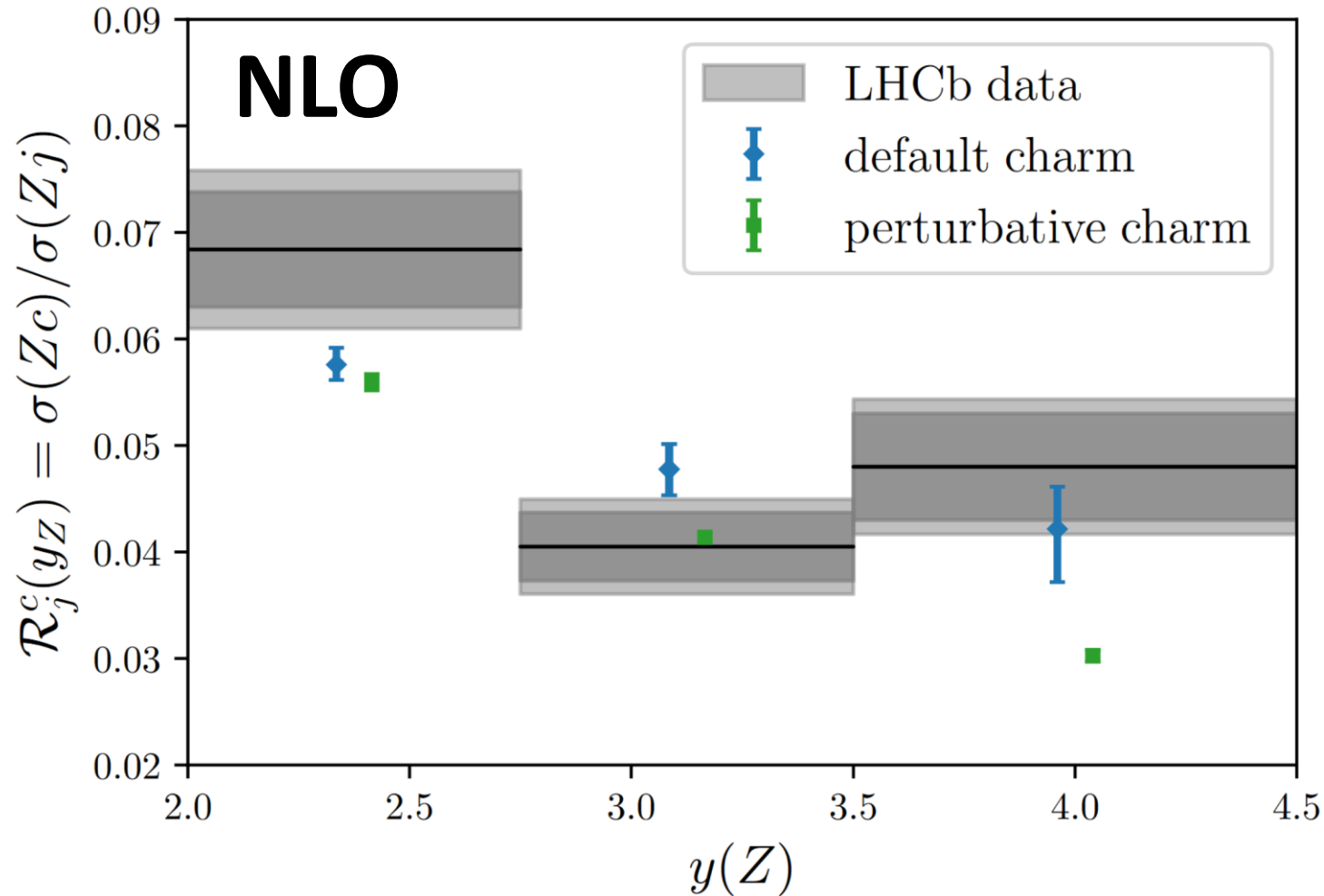
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• Search for intrinsic charm

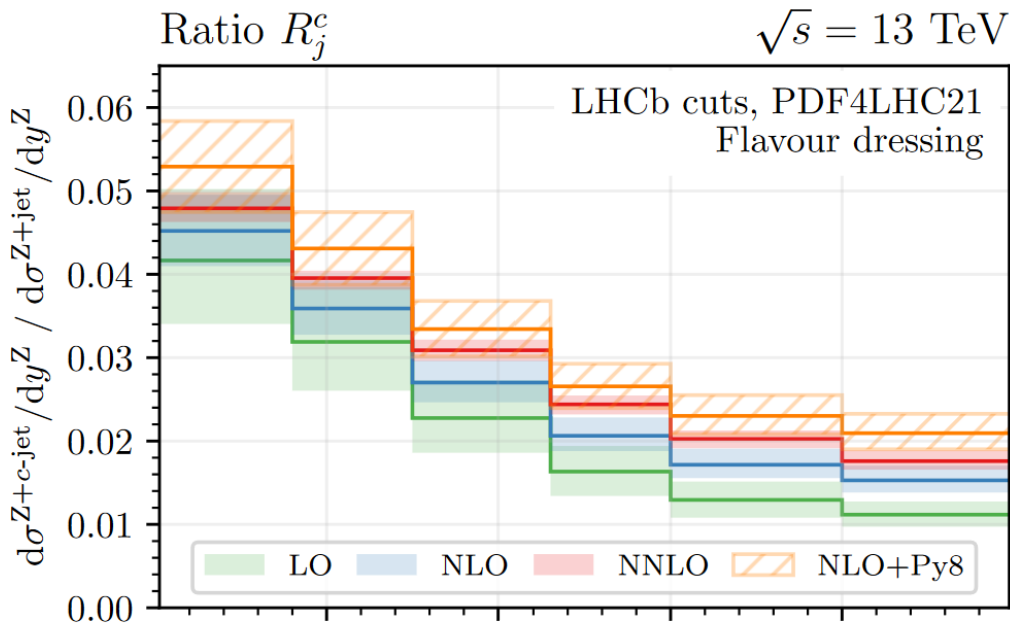


EW-tagged heavy flavor production



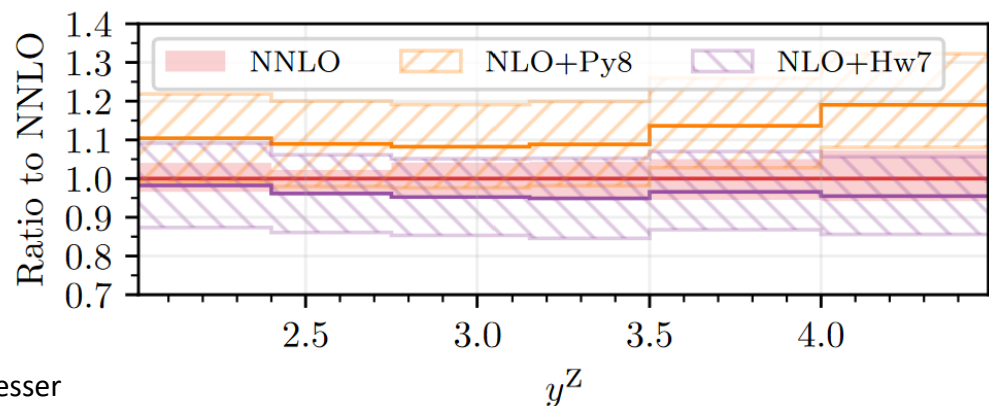
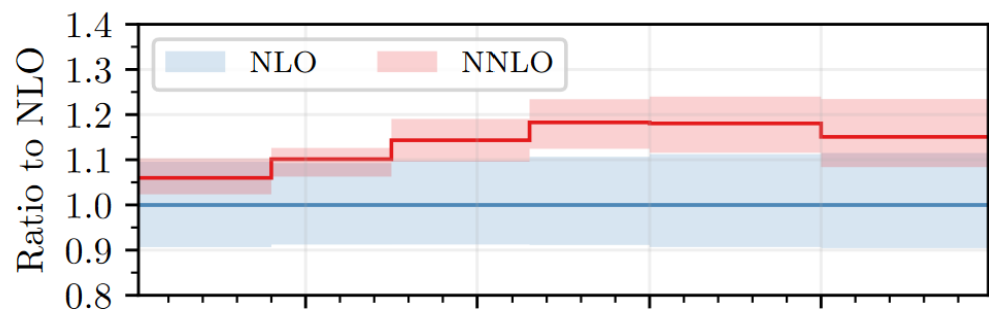
NNPDF Collab.
[Nature 608 \(2022\) 483-487](#)

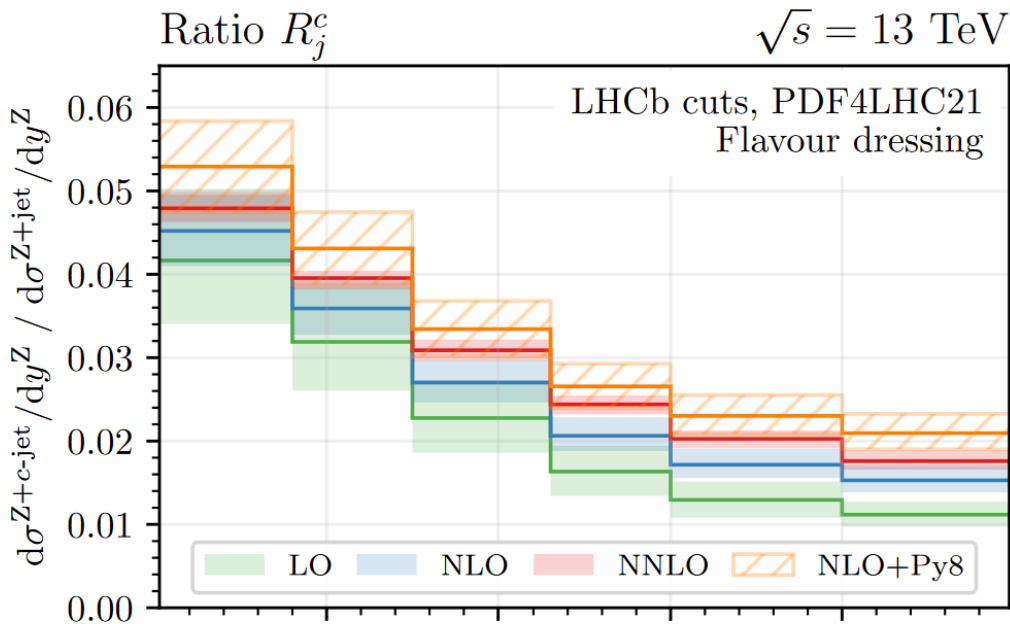
“We establish
the existence of
intrinsic charm
at the **3 σ** level”



**Repeat with Run 3 data
(better statistics)?**

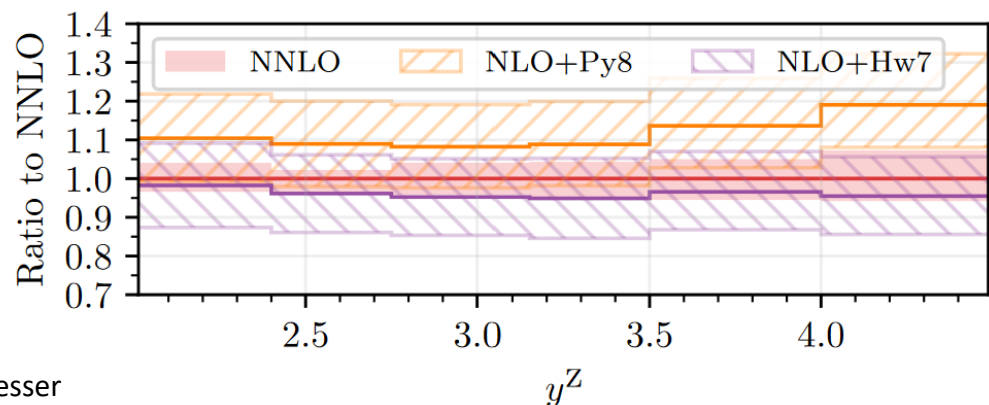
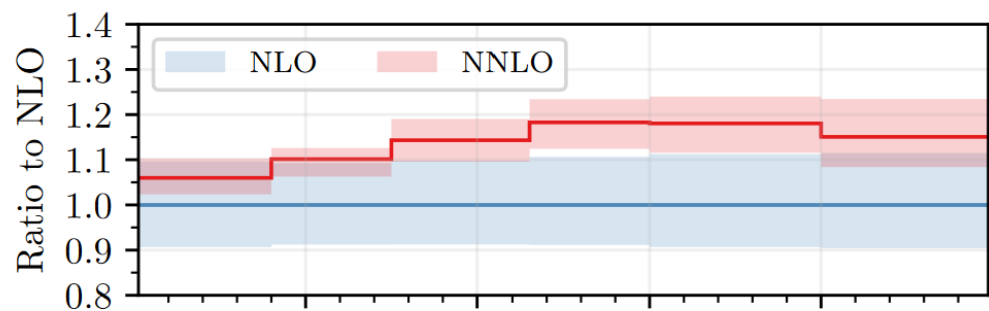
- NNLO predictions now available
 - Requires use of **IRC-safe flavor tagging algorithm**

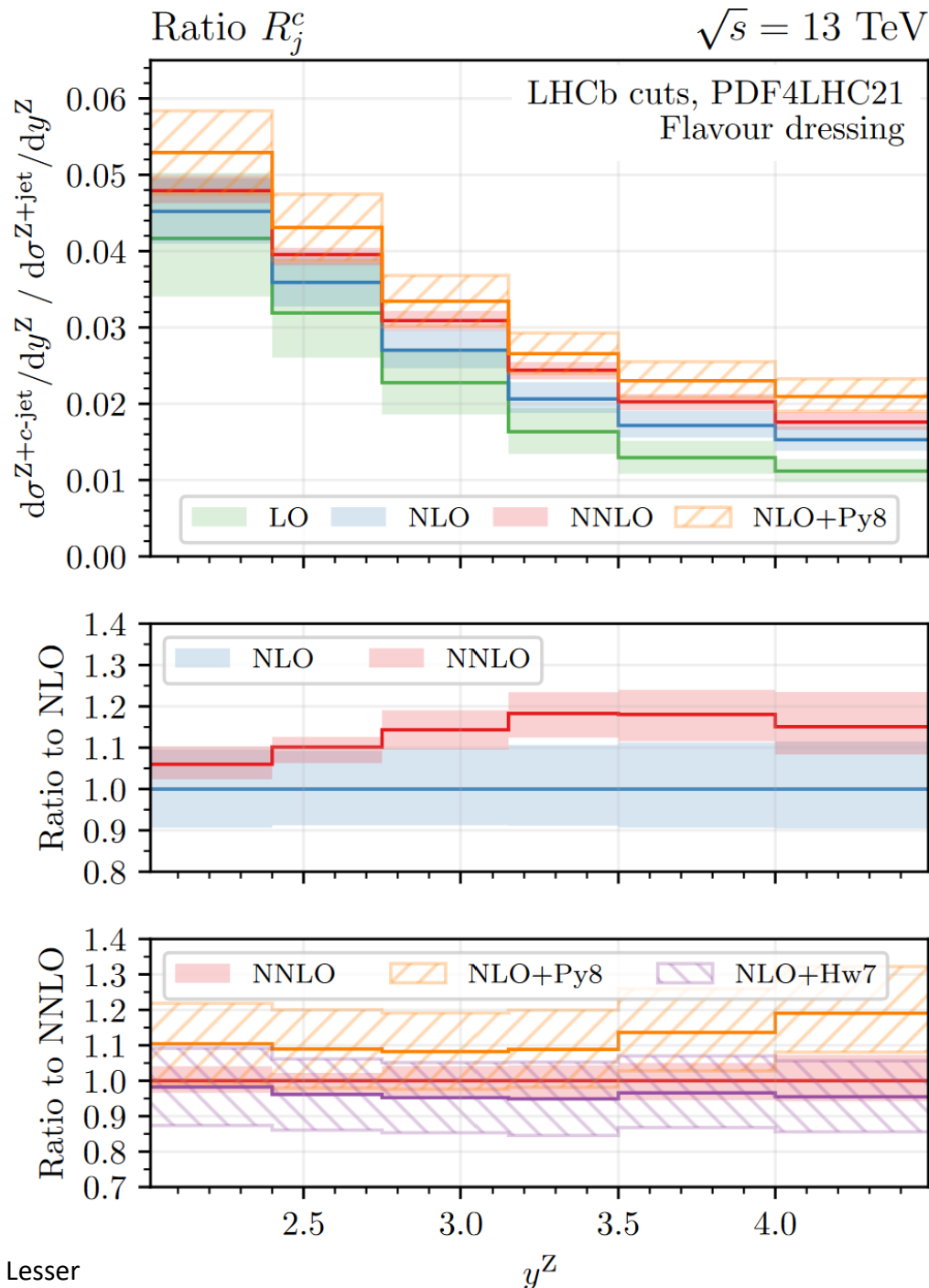




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 - See *LHCb public meeting on jet flavor algorithms* (hosted by QEE):
<https://indico.cern.ch/event/LHCb-jet-flavor>





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- Possibility to **resolve the 3σ discrepancy** with a new Run 3 measurement, using **higher-precision experimental & theoretical methods**

Exciting QCD prospects for Run 3



- Studies of hadronic structure (e.g. **intrinsic charm**)

Exciting QCD prospects for Run 3



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Exciting QCD prospects for Run 3



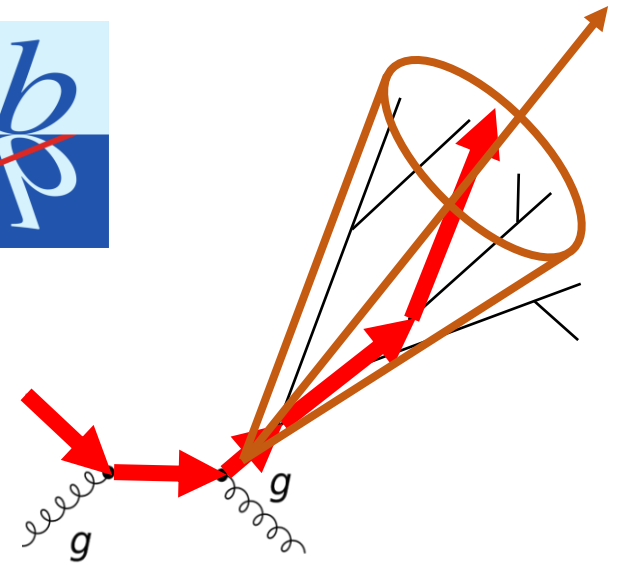
- Studies of hadronic structure (e.g. **intrinsic charm**)
- Inclusive/HF **jet and hadron cross sections**
 - Also an important QCD background to constrain for searches
- High-precision measurements of **jet substructure**
 - *Jet mass & angularities, energy-energy correlators, Lund jet plane, N-subjettiness, ...*

The QEE group at



- **Quantum chromodynamics**

- Jet substructure, hadronic production, ...

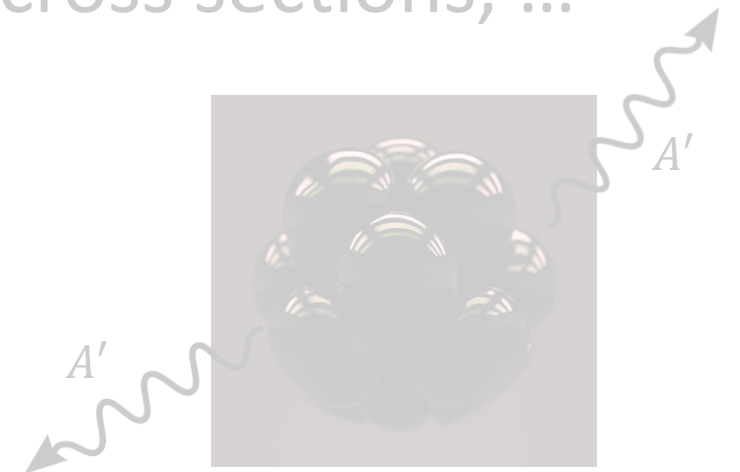


- **Electroweak physics, Higgs, & top**

- W^\pm / Z^0 decays, precision measurements, cross sections, ...

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- Rare decays, beyond the SM searches, ...

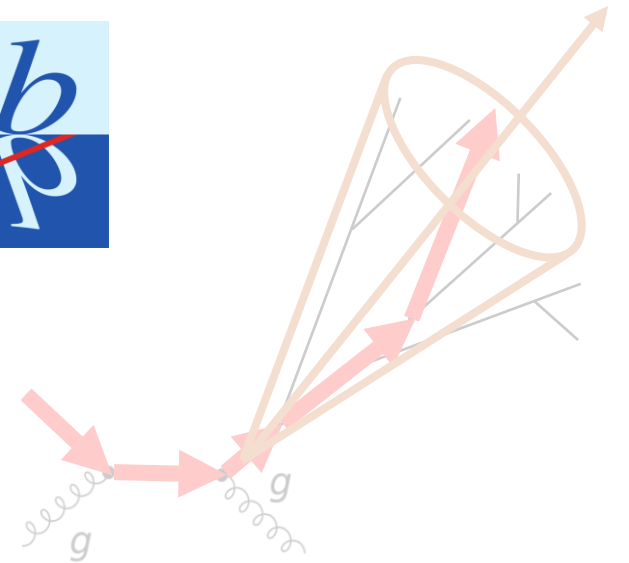


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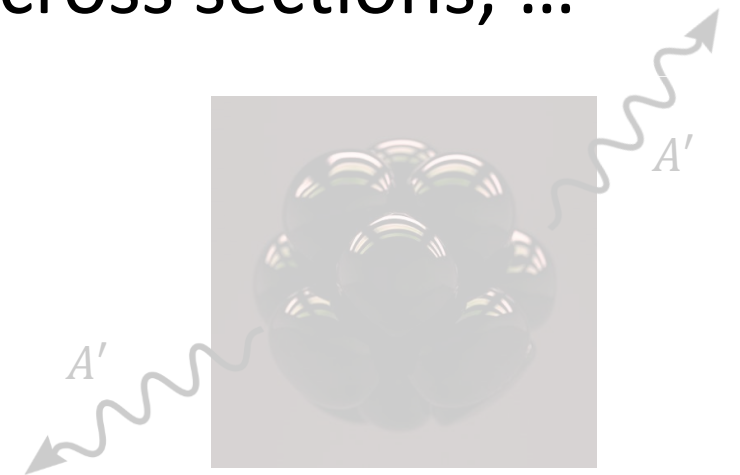


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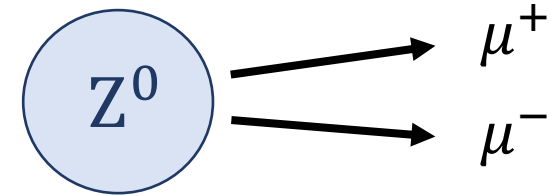
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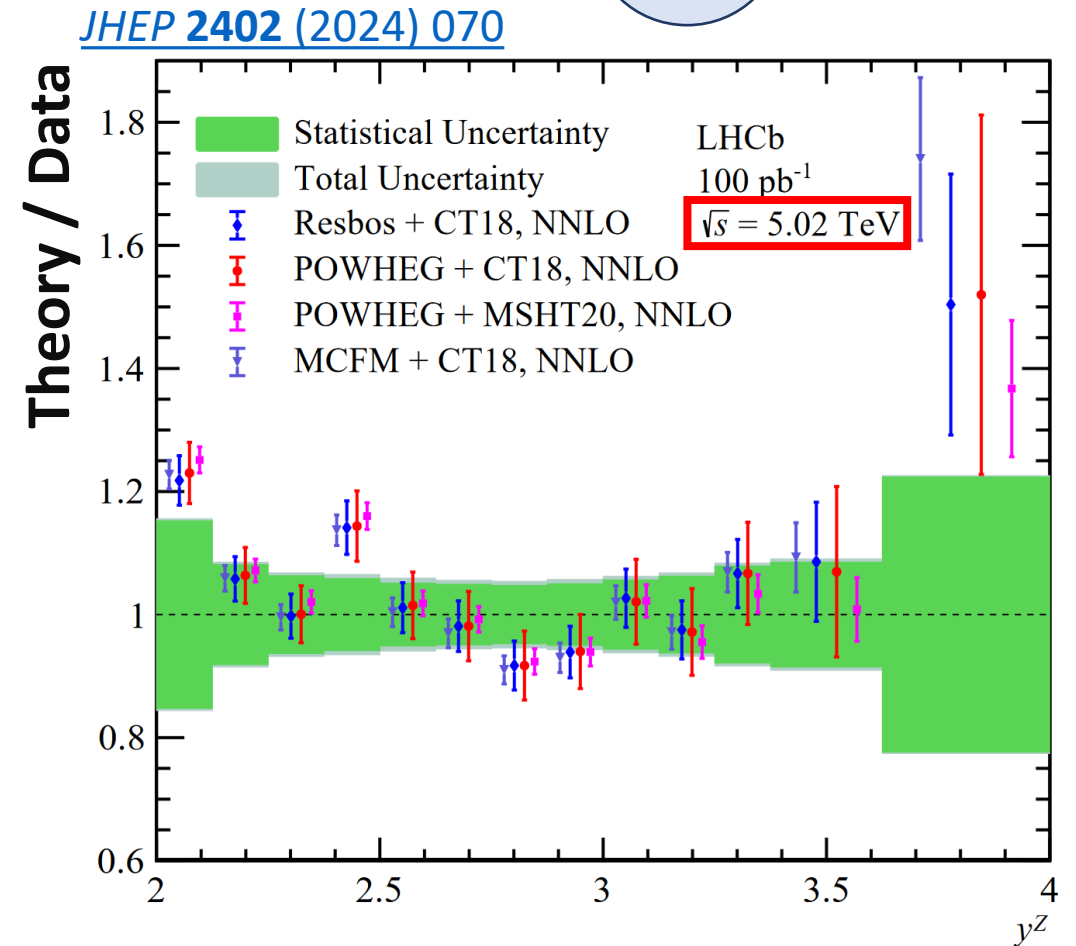
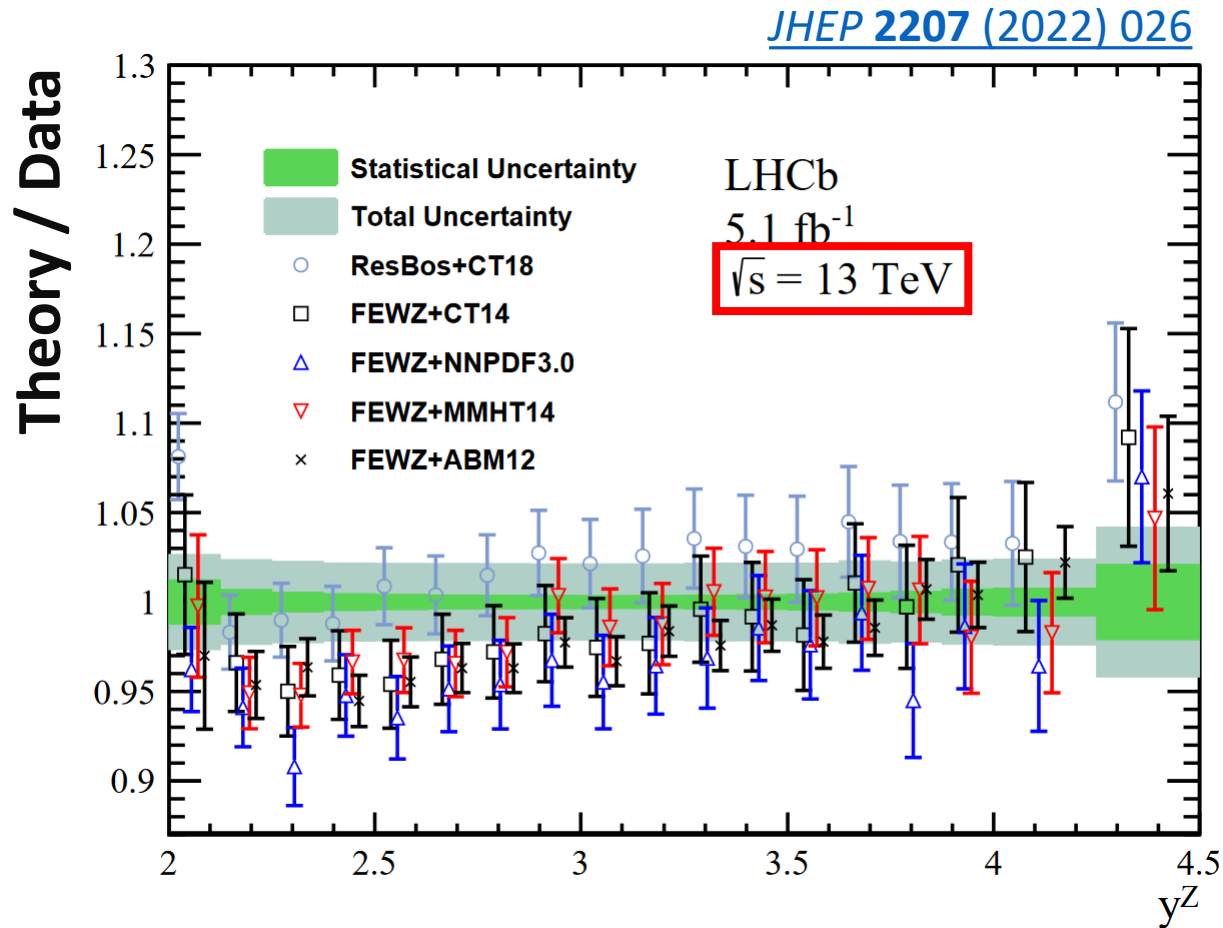
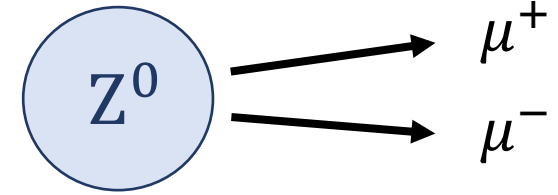
Precision Z^0 boson cross section



Precision Z^0 boson cross section



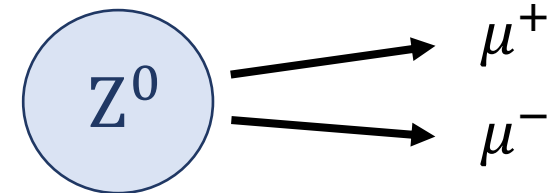
- Differential in \sqrt{s} , rapidity y



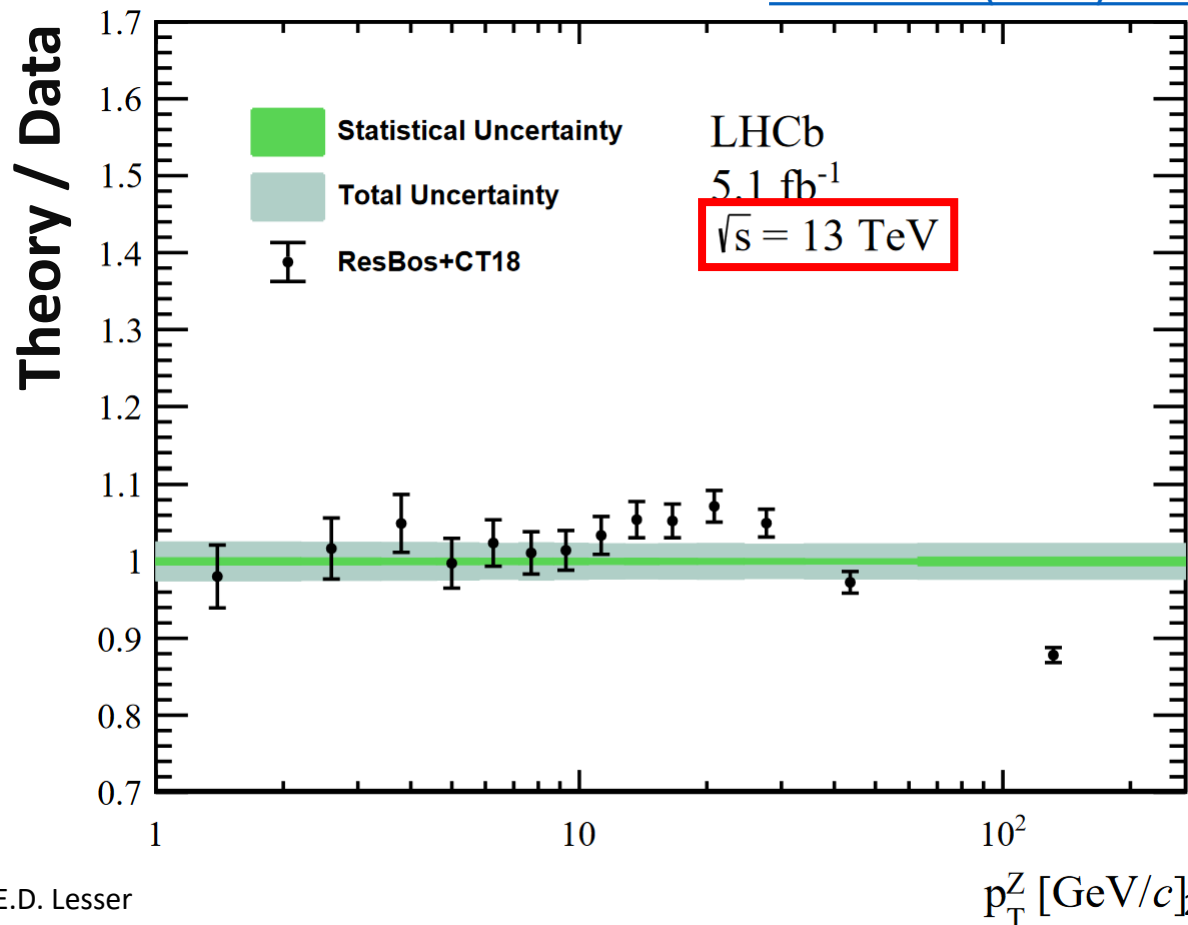
Precision Z^0 boson cross section



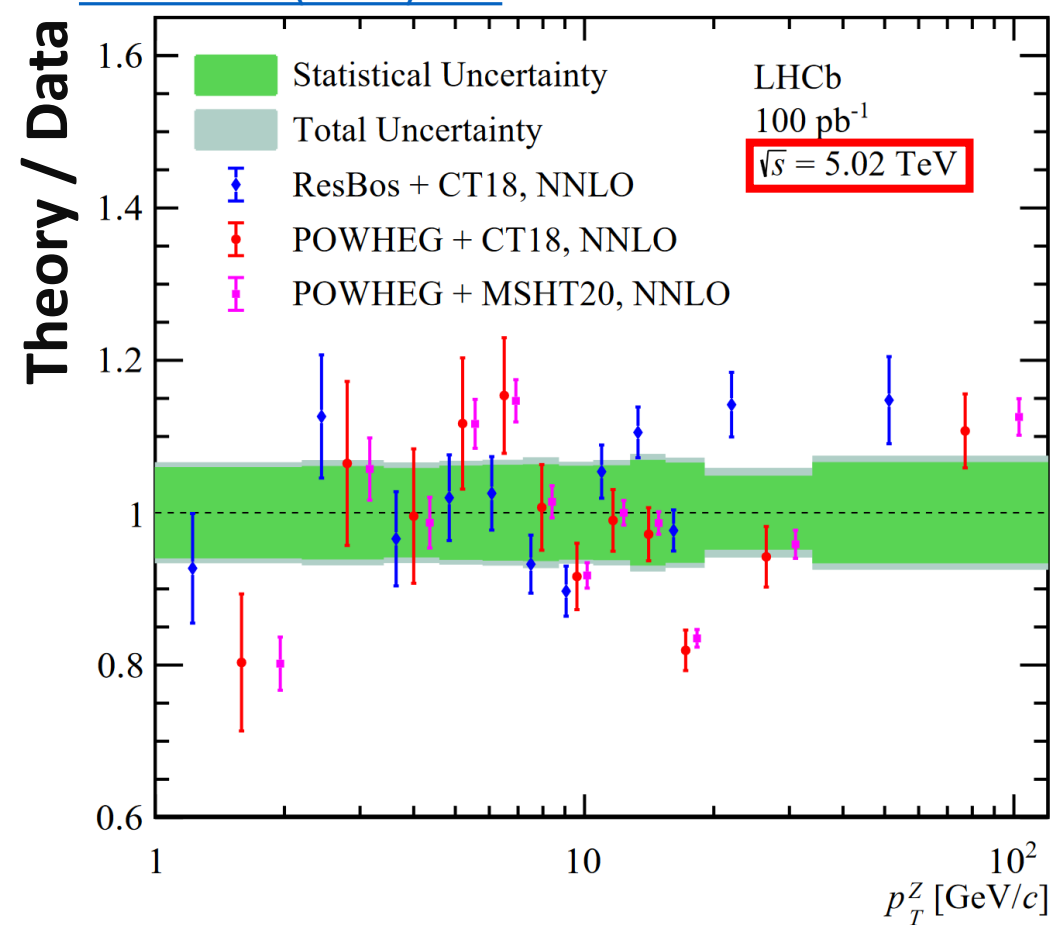
- Differential in \sqrt{s} , rapidity y , transverse momentum p_T



[JHEP 2207 \(2022\) 026](#)



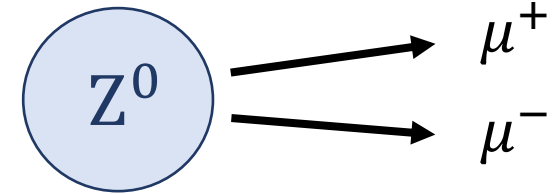
[JHEP 2402 \(2024\) 070](#)



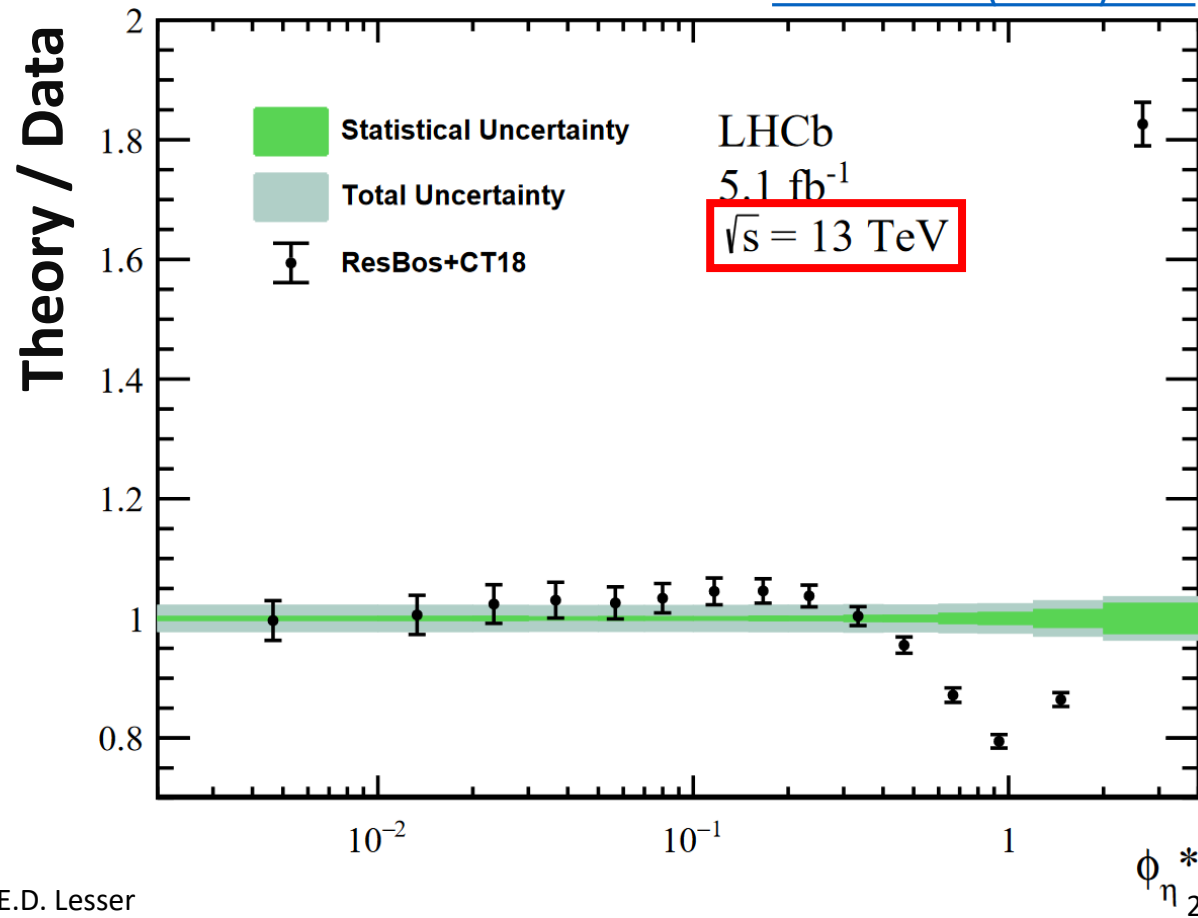
Precision Z^0 boson cross section



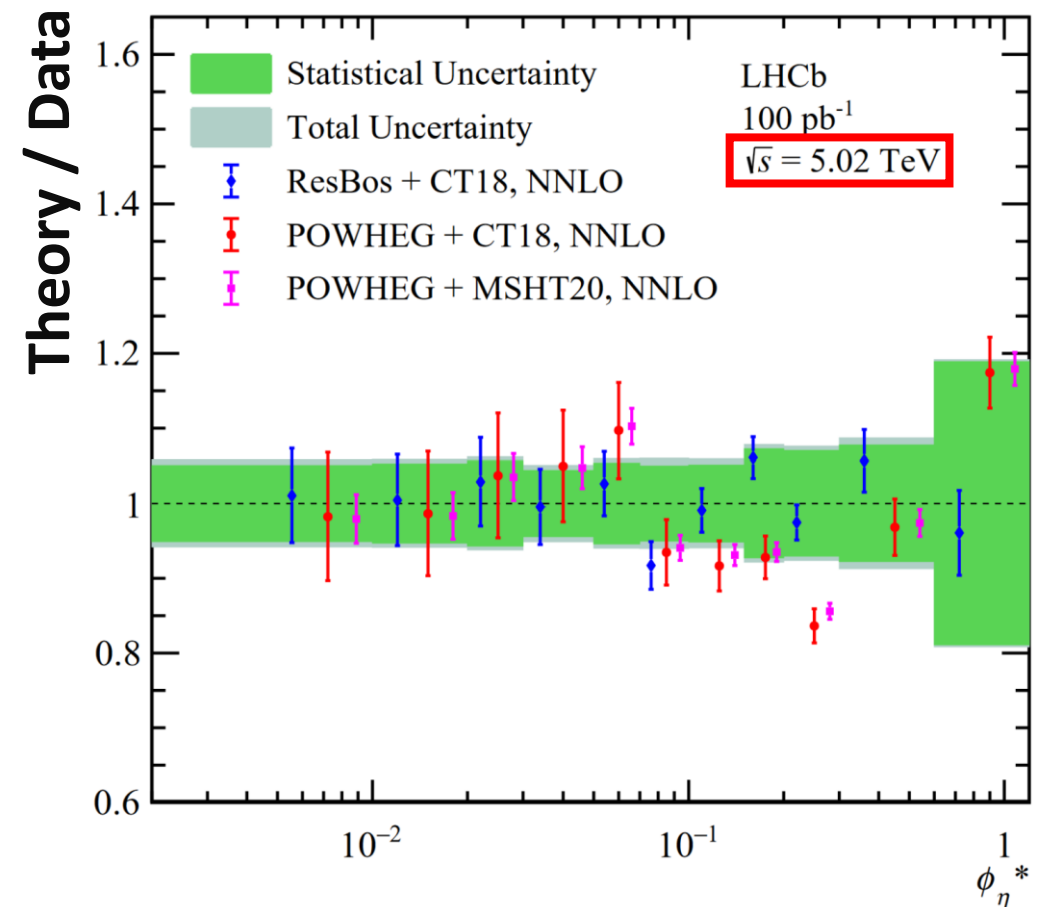
- Differential in \sqrt{s} , rapidity y , transverse momentum p_T , “idealized” variable ϕ_η^* (similar physics as p_T)



[JHEP 2207 \(2022\) 026](#)



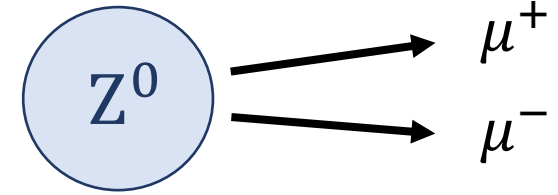
[JHEP 2402 \(2024\) 070](#)



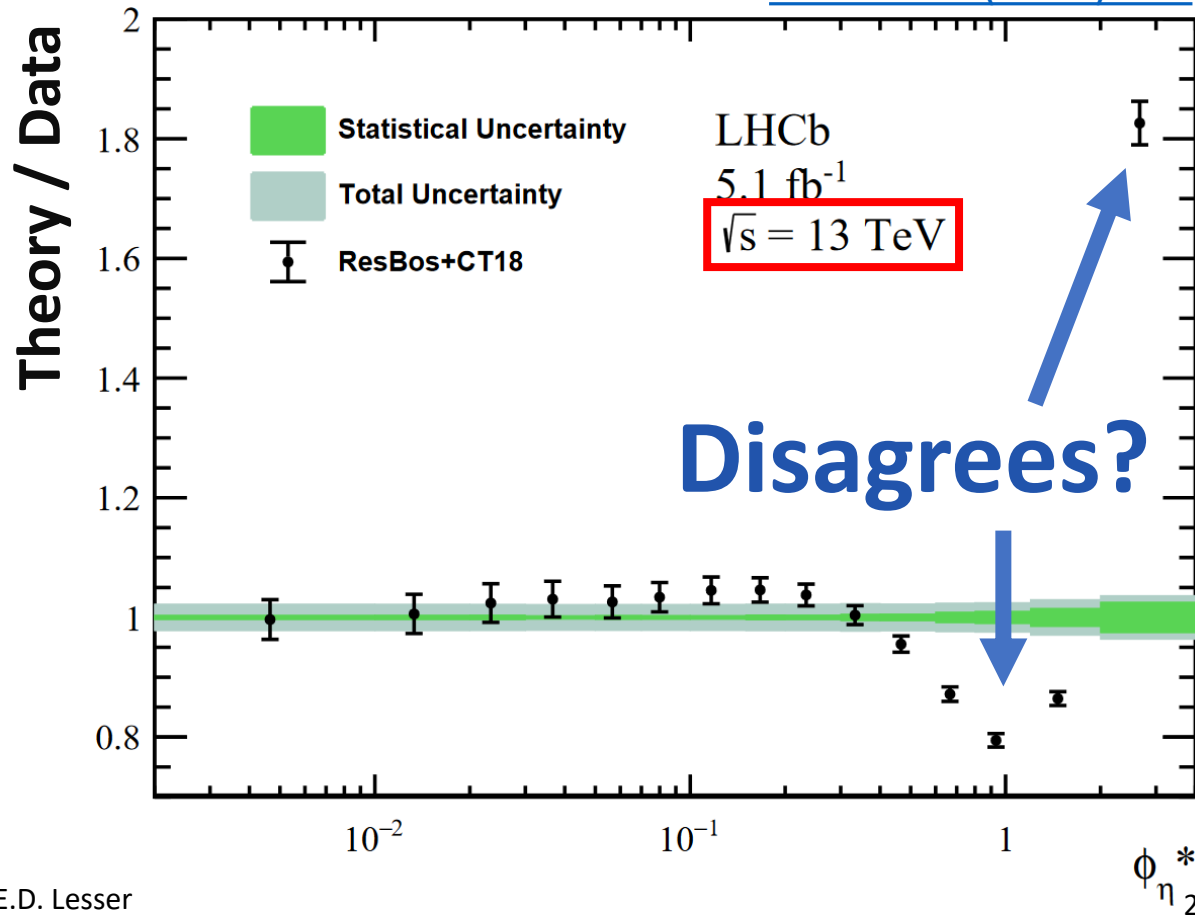
Precision Z^0 boson cross section



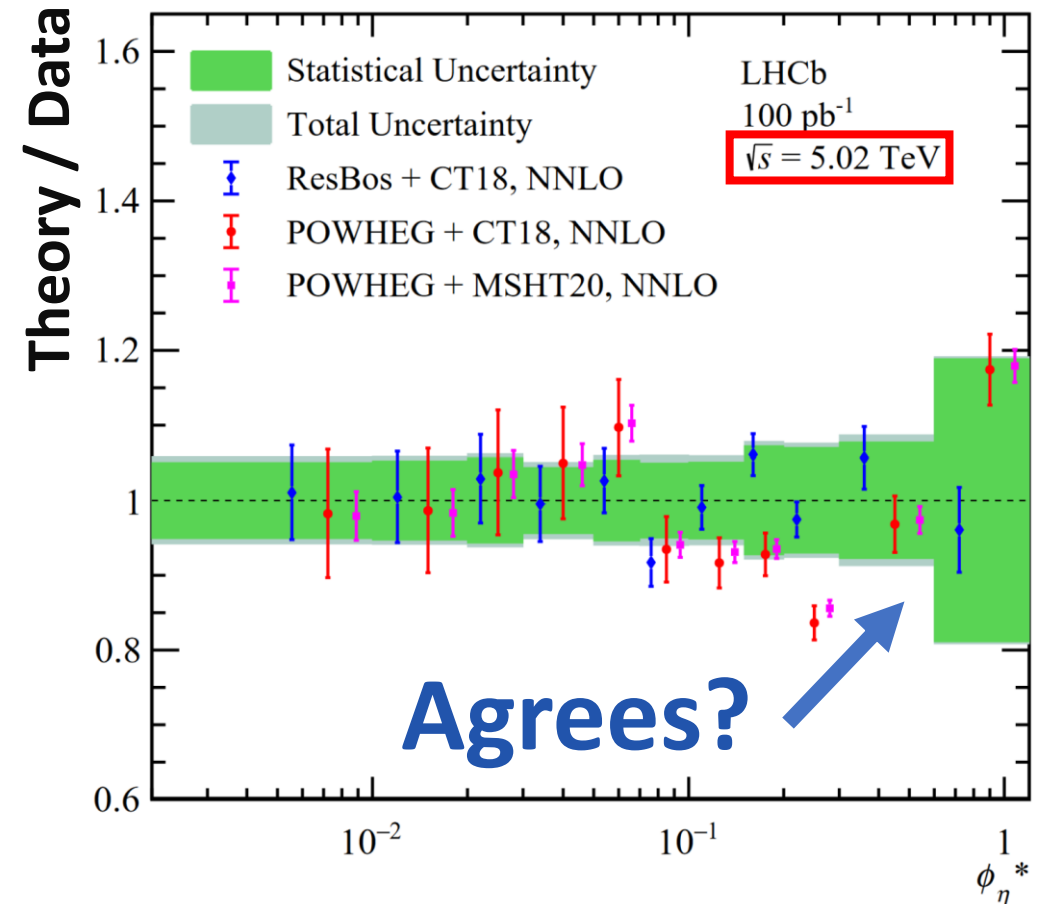
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[JHEP 2207 \(2022\) 026](#)



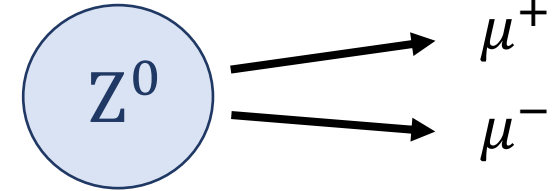
[JHEP 2402 \(2024\) 070](#)



Precision Z^0 boson cross section

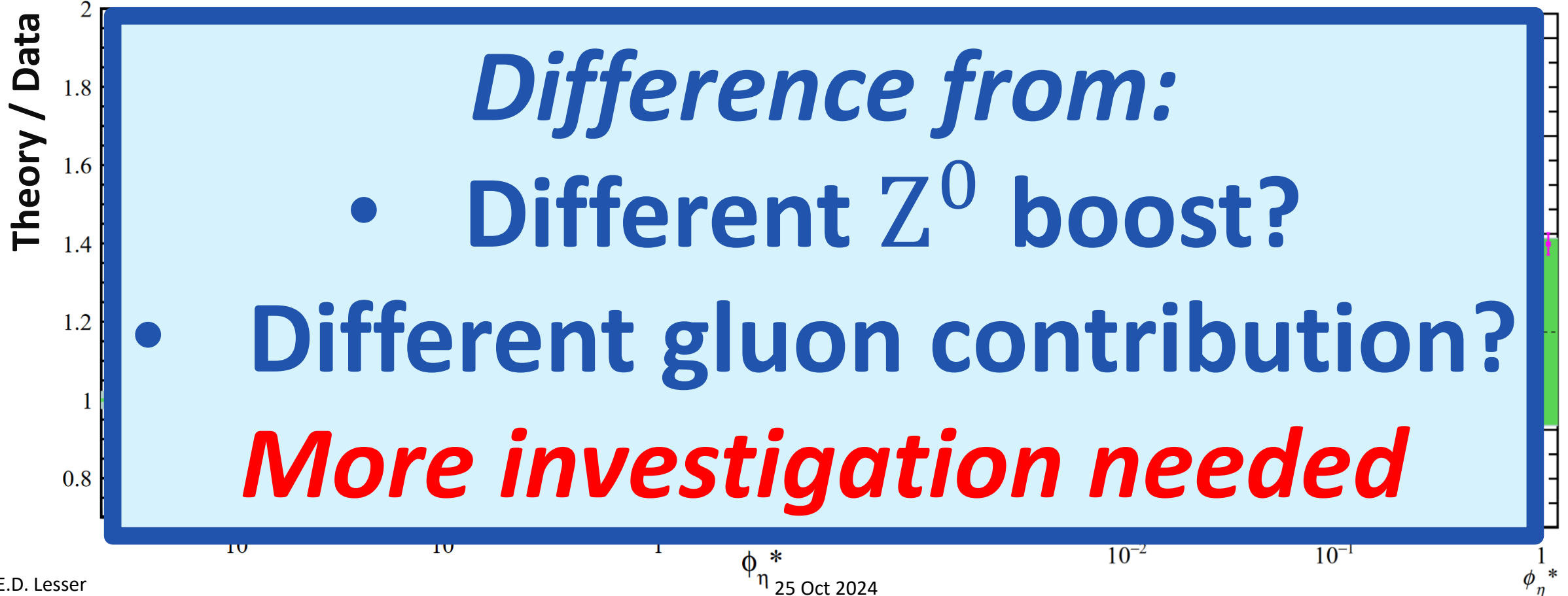


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[JHEP 2207 \(2022\) 026](#)

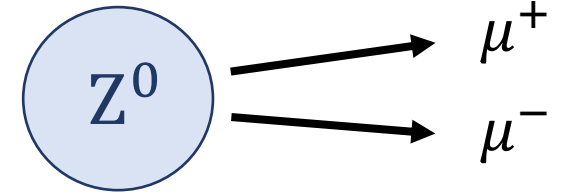
[JHEP 2402 \(2024\) 070](#)



Precision Z^0 angular coefficients



$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1 + \cos^2\theta) + \frac{1}{2}A_0(1 - 3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi \\ + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$

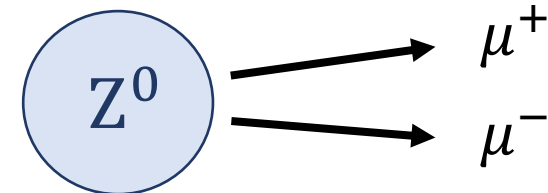


θ, ϕ of μ^+ in the Collins-Soper frame

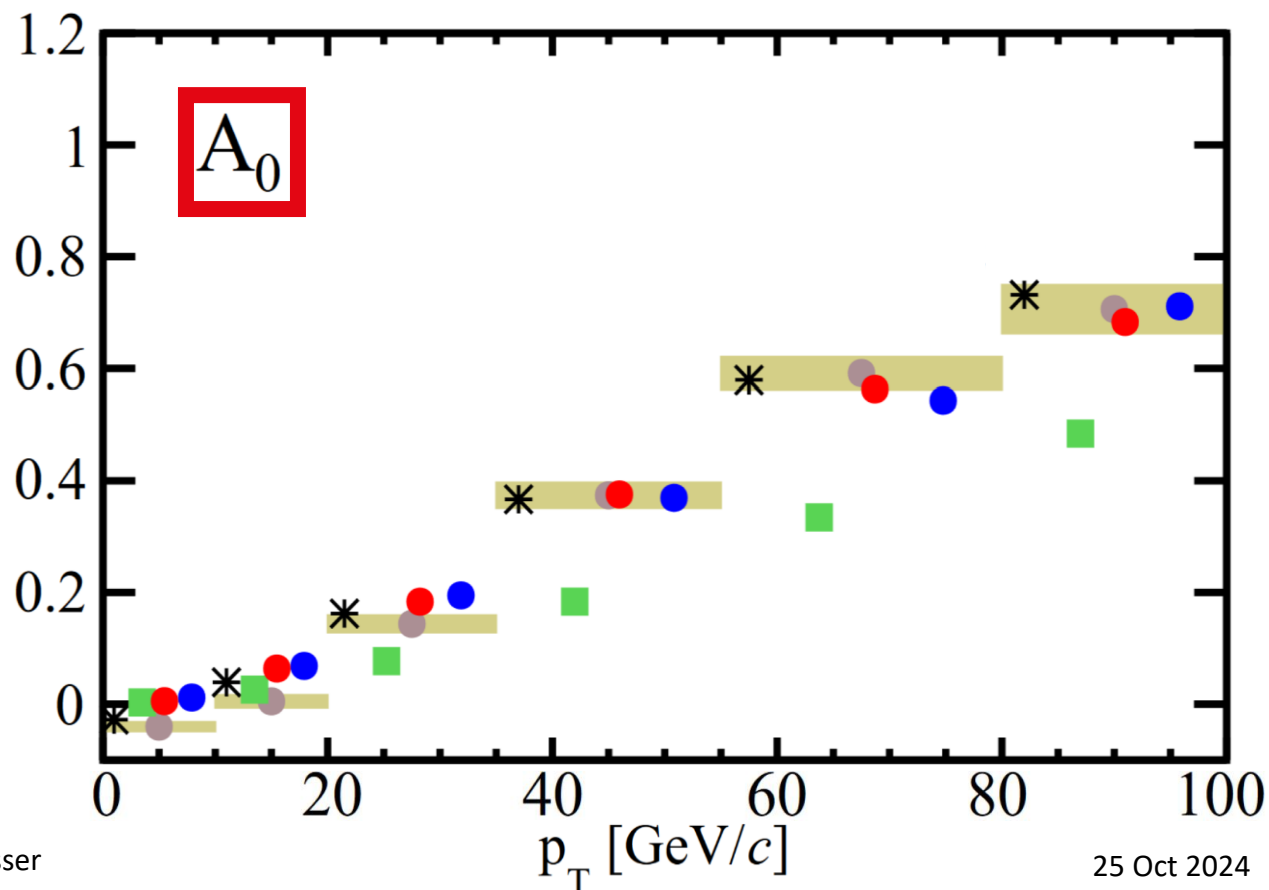
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θ, ϕ of μ^+ in the Collins-Soper frame



LHCb

$\sqrt{s} = 13 \text{ TeV}, 5.1 \text{ fb}^{-1}$

$y > 2, 75 < M_{\mu\mu} < 105 \text{ GeV}/c^2$

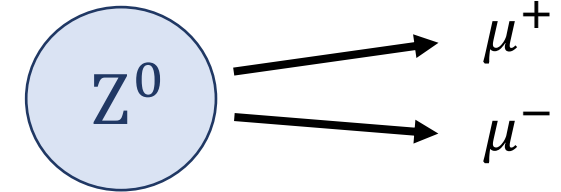
- Measurement + Uncertainty
- POWHEG+PYTHIA
- Pythia8, LHCb tune
- DYTURBO
- ResBos

[Phys. Rev. Lett. 129 \(2022\) 091801](https://arxiv.org/abs/2108.07350)

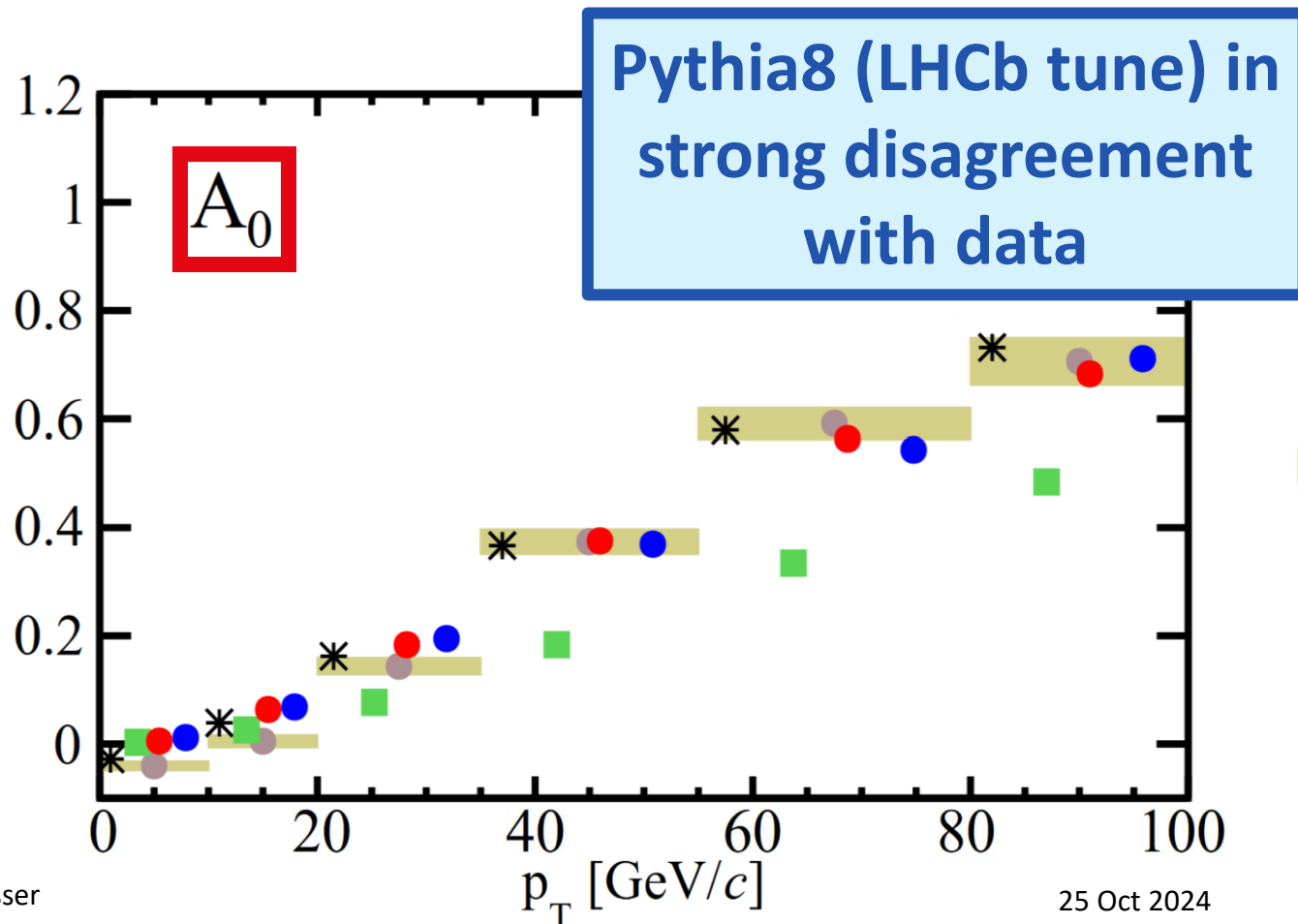
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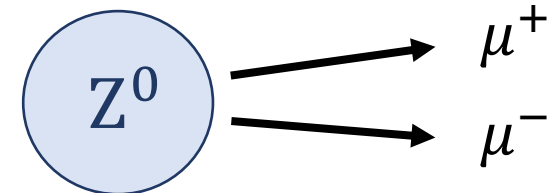
- Measurement + Uncertainty
- POWHEG+PYTHIA
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- ResBos

[Phys. Rev. Lett. 129 \(2022\) 091801](https://arxiv.org/abs/2205.00001)

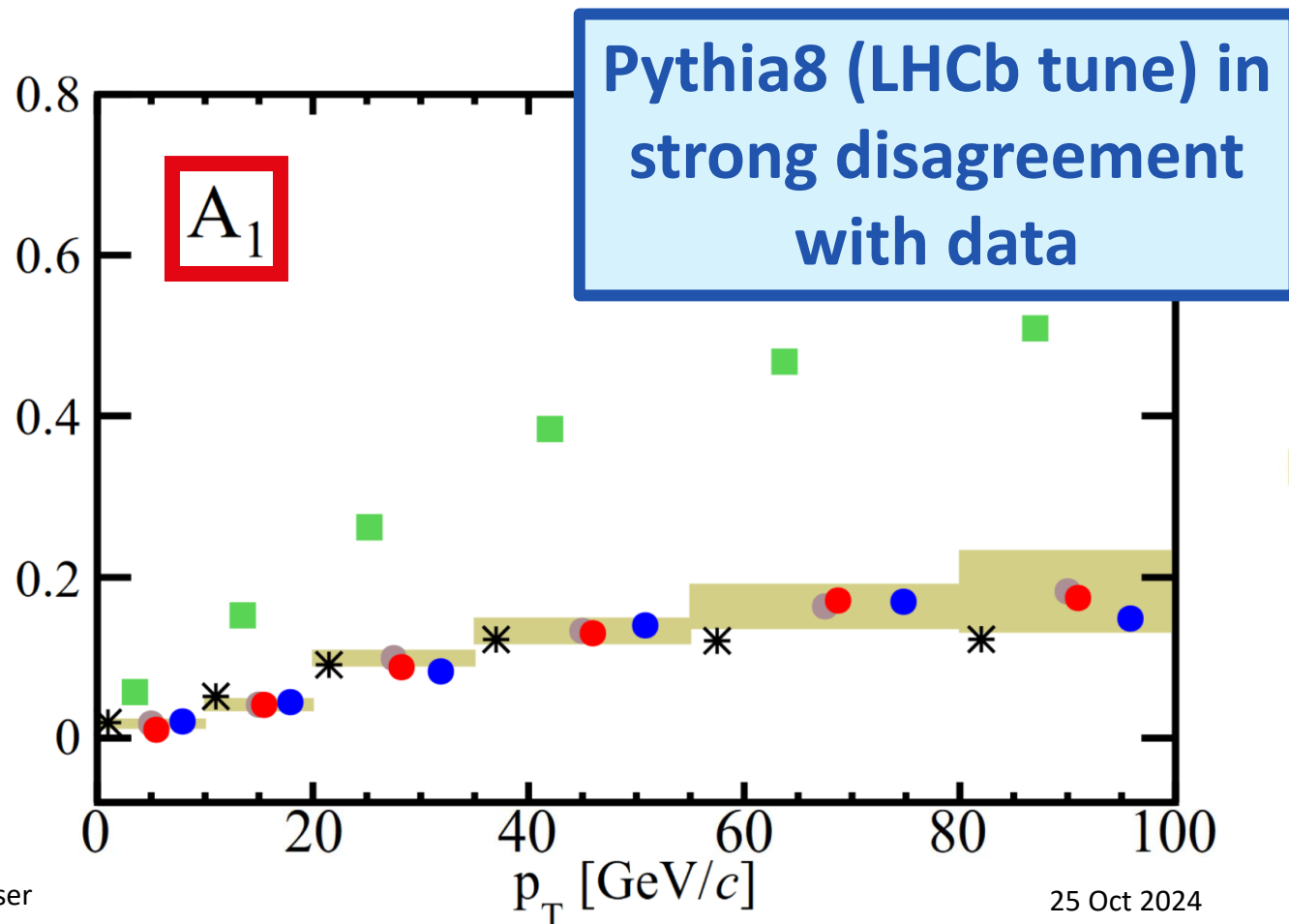
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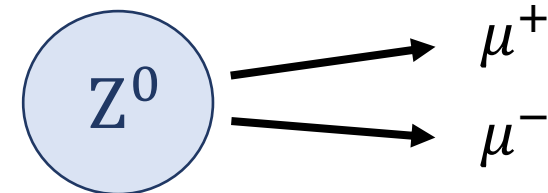
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[Phys. Rev. Lett. 129 \(2022\) 091801](https://arxiv.org/abs/2108.07354)

Precision Z^0 angular coefficients

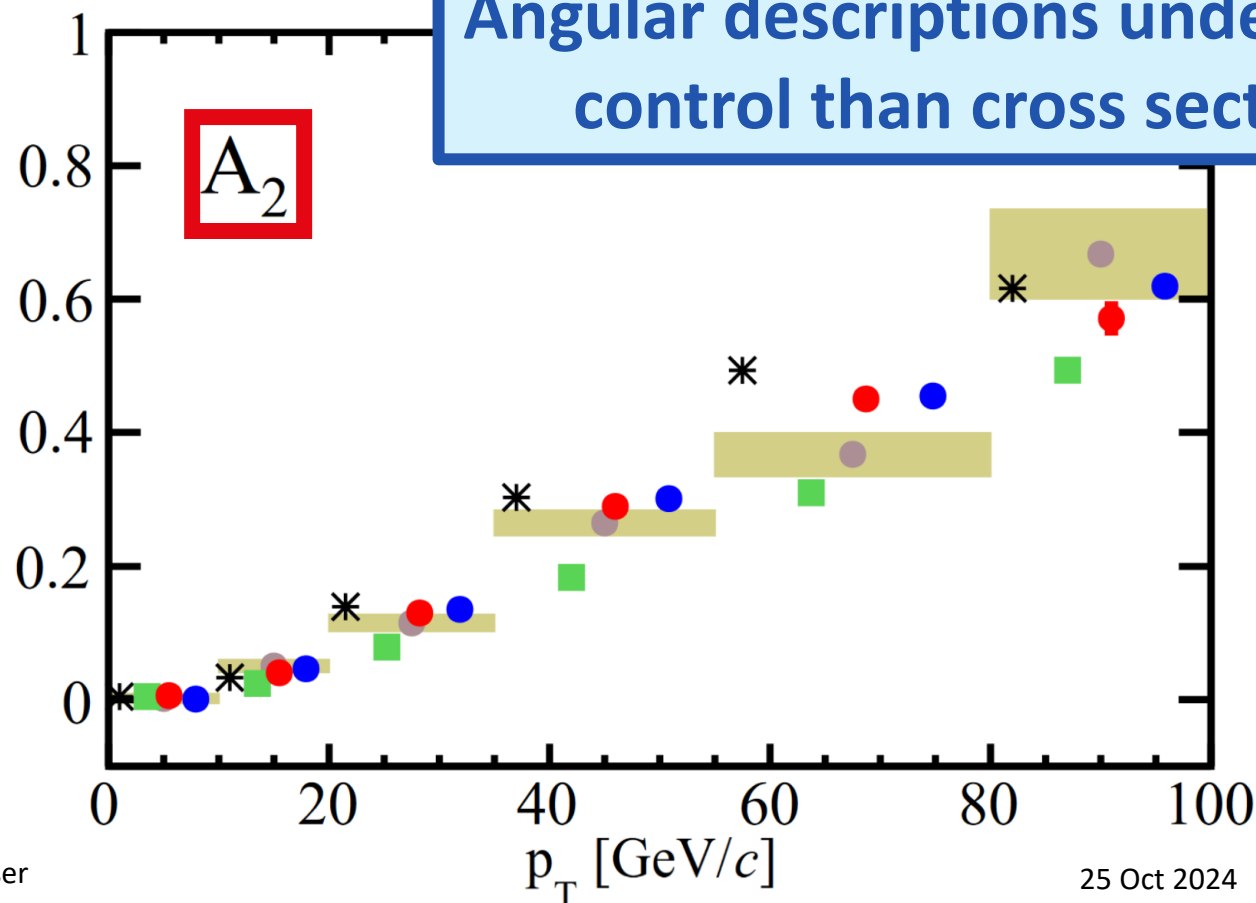


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θ, ϕ of μ^+ in the Collins-Soper frame

Angular descriptions under worse control than cross sections



$\sqrt{s} = 13 \text{ TeV}, 5.1 \text{ fb}^{-1}$
 $y > 2, 75 < M_{\mu\mu} < 105 \text{ GeV}/c^2$

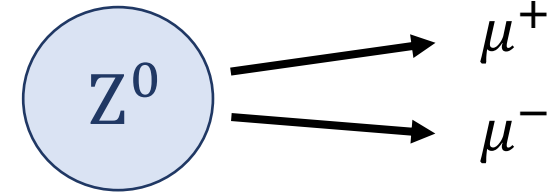
- Measurement + Uncertainty
- POWHEG+PYTHIA
- Pythia8, LHCb tune
- DYTurbo
- ResBos

[Phys. Rev. Lett. 129 \(2022\) 091801](https://arxiv.org/abs/2108.07554)

Precision Z^0 angular coefficients

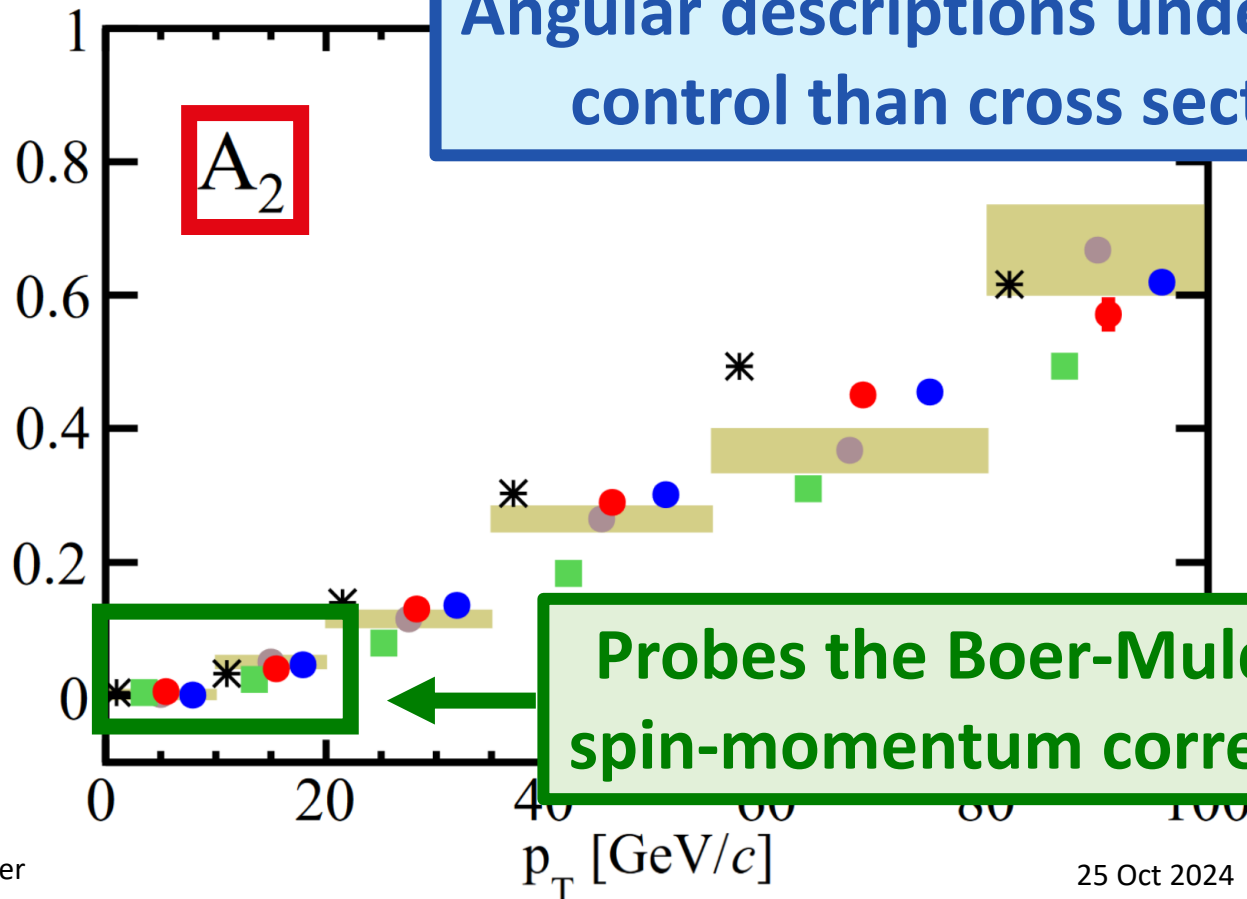


$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1 + \cos^2\theta) + \frac{1}{2}A_0(1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$



θ, ϕ of μ^+ in the Collins-Soper frame

Angular descriptions under worse control than cross sections



$\sqrt{s} = 13 \text{ TeV}, 5.1 \text{ fb}^{-1}$
 $y > 2, 75 < M_{\mu\mu} < 105 \text{ GeV}/c^2$

- Measurement + Uncertainty
- * POWHEG+PYTHIA
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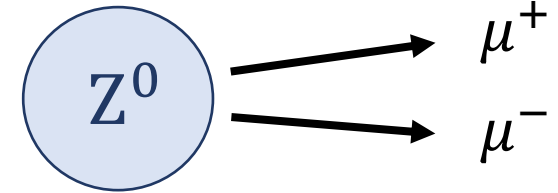
Probes the Boer-Mulders TMD PDF: spin-momentum correlations in p^+ ?

*(see backup)

Precision Z^0 angular coefficients

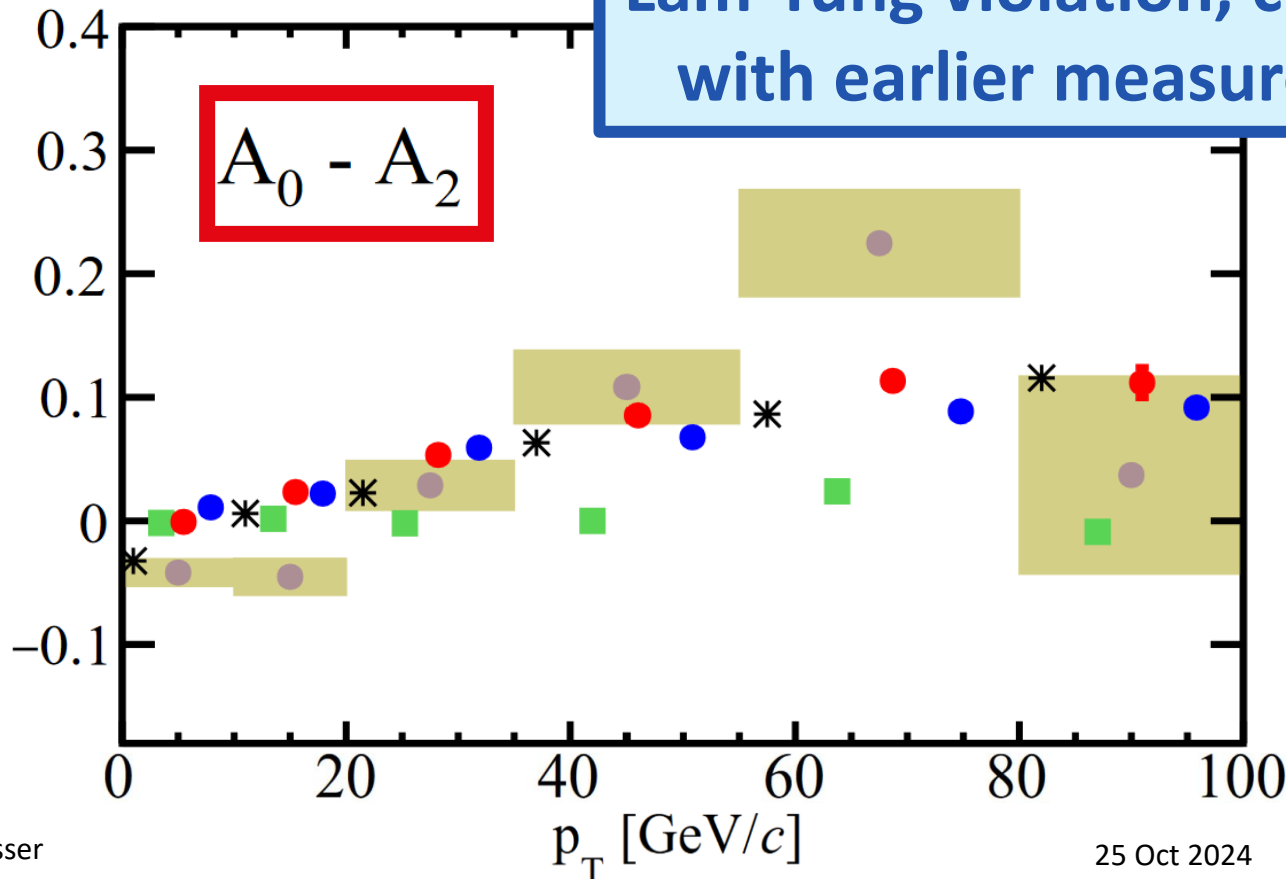


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θ, ϕ of μ^+ in the Collins-Soper frame

Lam-Tung violation, consistent with earlier measurements



$\sqrt{s} = 13 \text{ TeV}, 5.1 \text{ fb}^{-1}$
 $y > 2, 75 < M_{\mu\mu} < 105 \text{ GeV}/c^2$

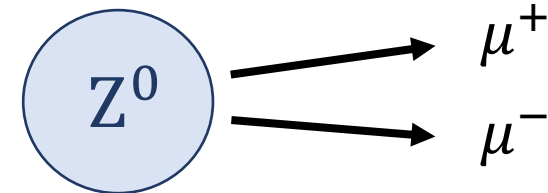
- Measurement + Uncertainty
- * POWHEG+PYTHIA
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[Phys. Rev. Lett. 129 \(2022\) 091801](https://arxiv.org/abs/2108.07158)

Precision Z^0 angular coefficients



$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1 + \cos^2\theta) + \frac{1}{2}A_0(1 - 3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi \\ + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$



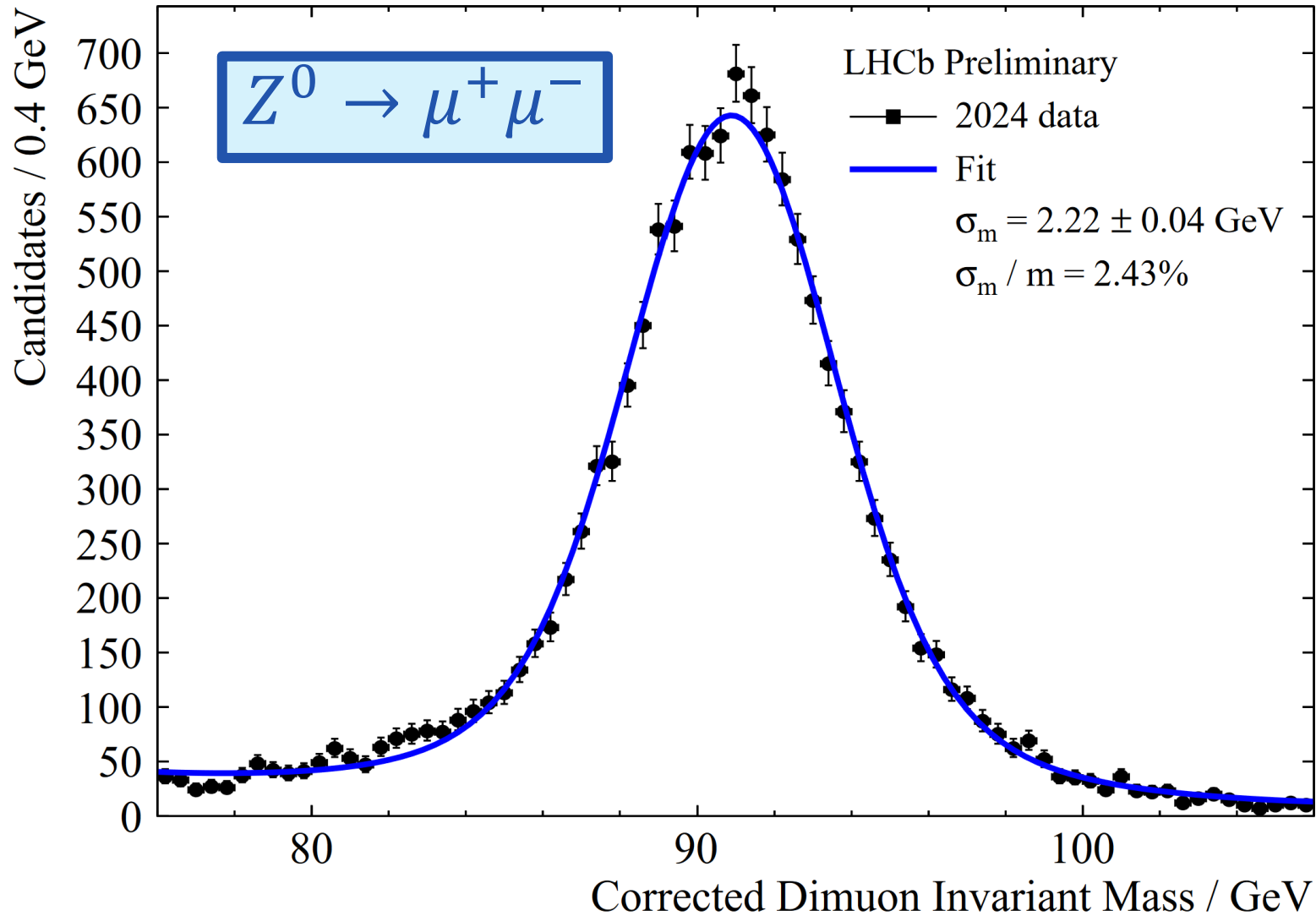
**Data awaiting in-depth precision
theoretical exploration!**

*Ongoing studies with Run 1 data
to cross-check Run 2 results*

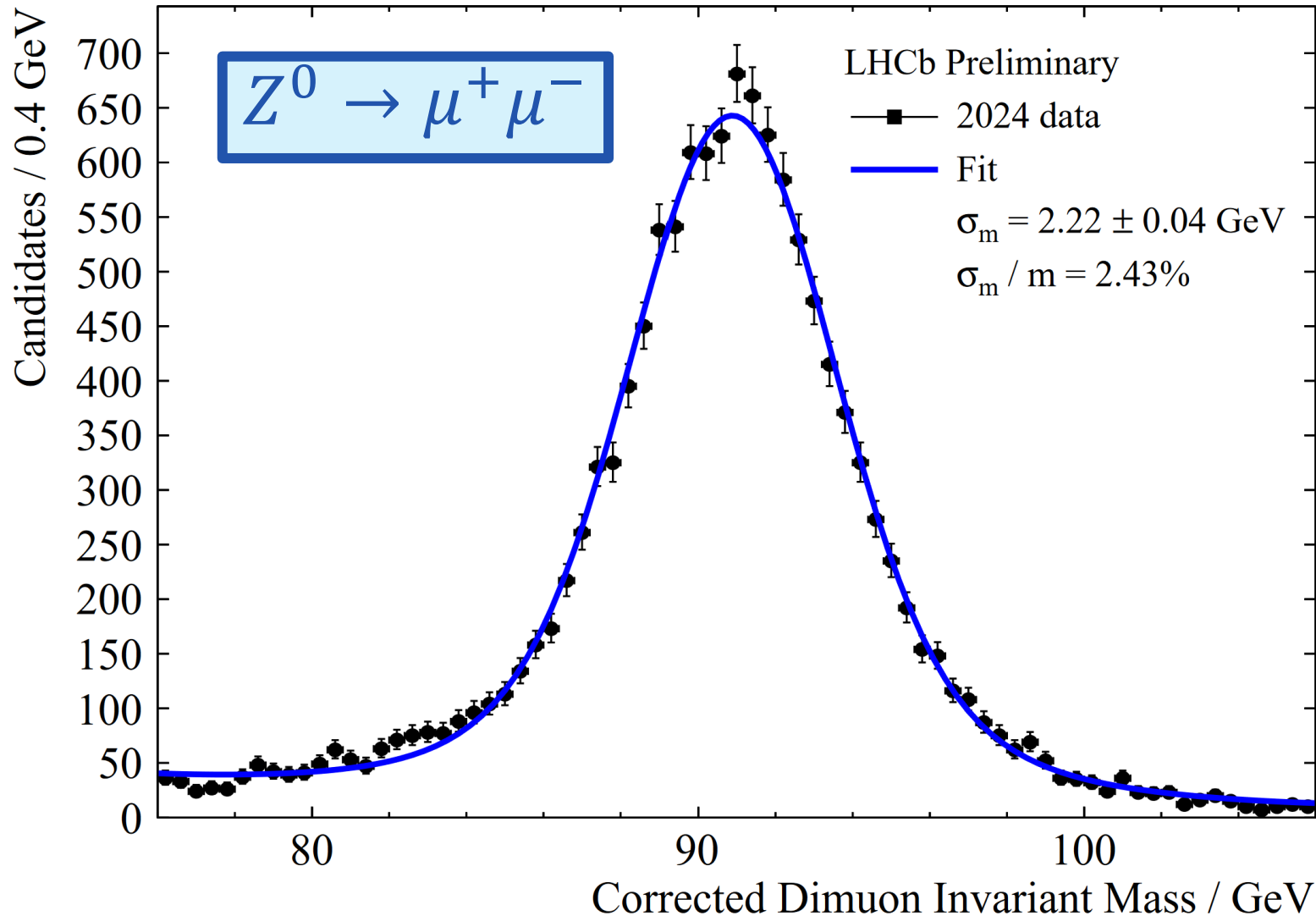
0 20 40 60 80 100

p_T [GeV/c]

Exciting prospects with Run 3 data



Exciting prospects with Run 3 data



- Enhanced Run 3 statistics offer **unprecedented opportunity** for **future EW measurements!**

Studying elusive Higgs decays

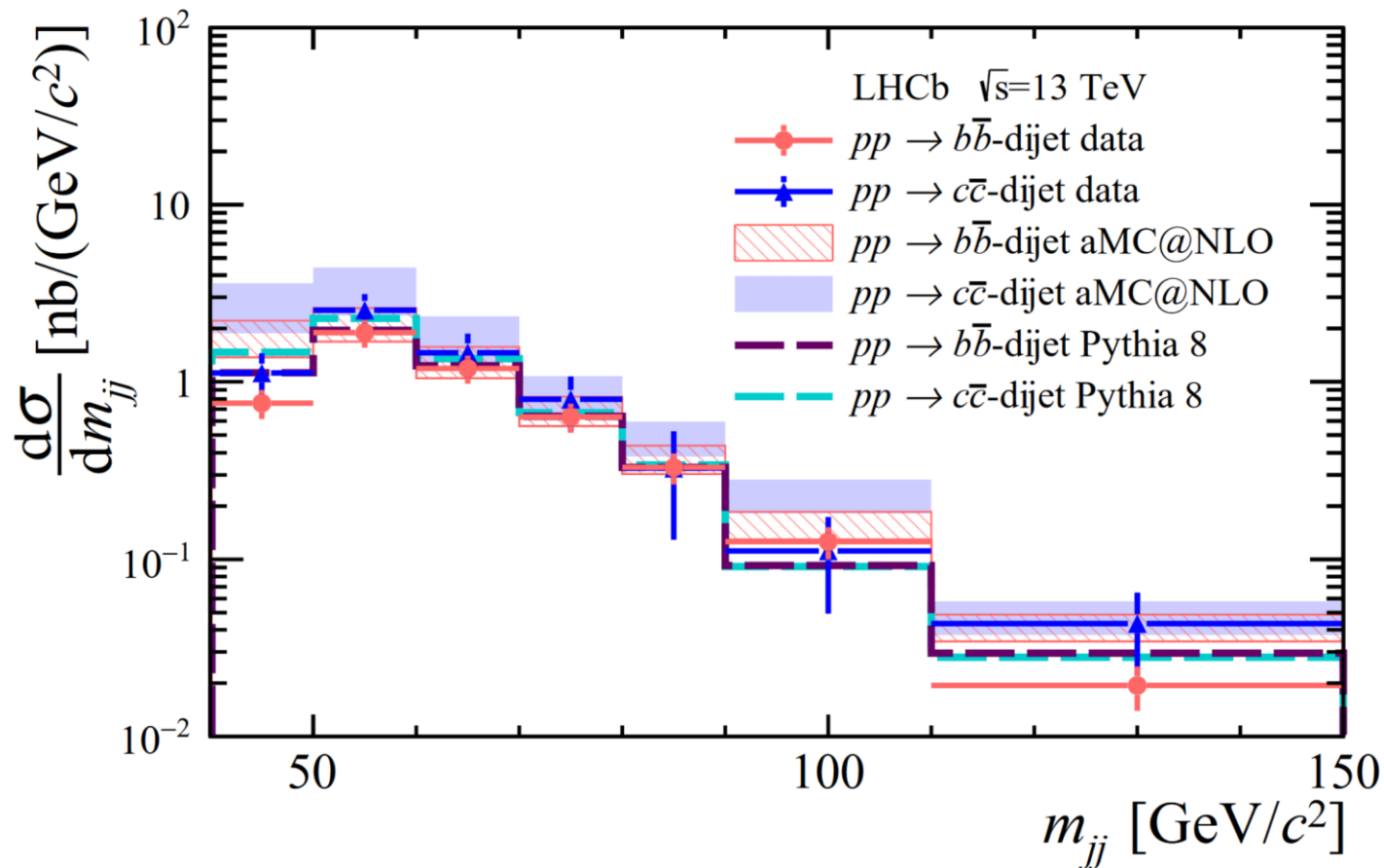


- How well does **the SM predict** $H \rightarrow b\bar{b}, c\bar{c}$?

Studying elusive Higgs decays



- How well does the SM predict $H \rightarrow b\bar{b}, c\bar{c}$?

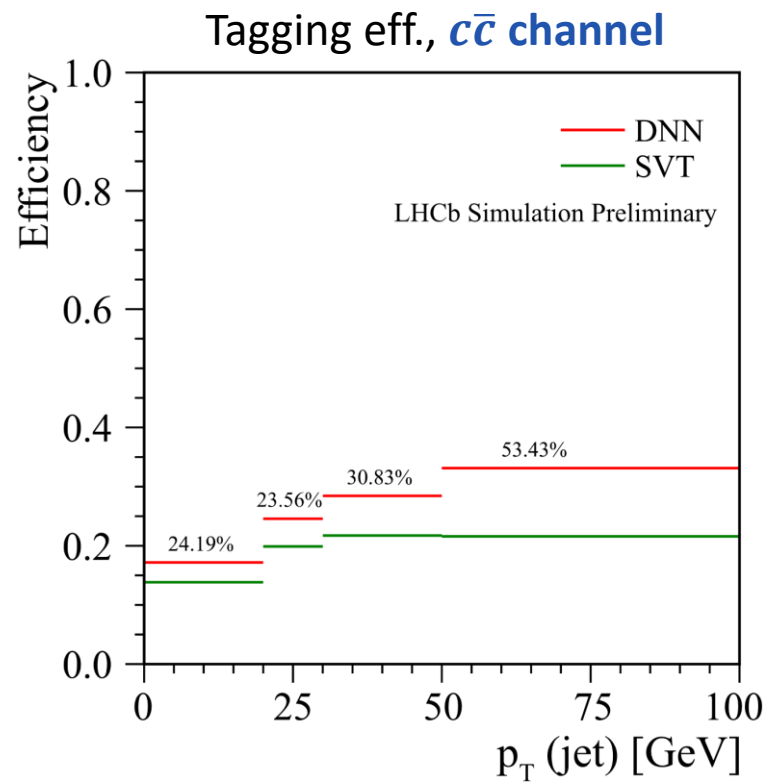
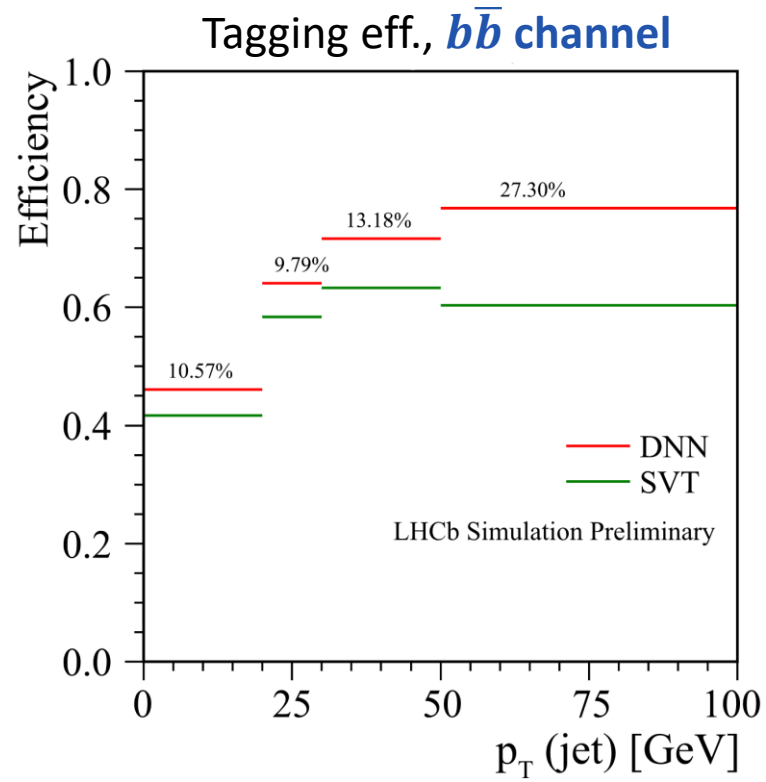


- **Dijet invariant mass**
 m_{jj} : QCD background for these Higgs decays

Studying elusive Higgs decays



- How well does the SM predict $H \rightarrow b\bar{b}, c\bar{c}$?

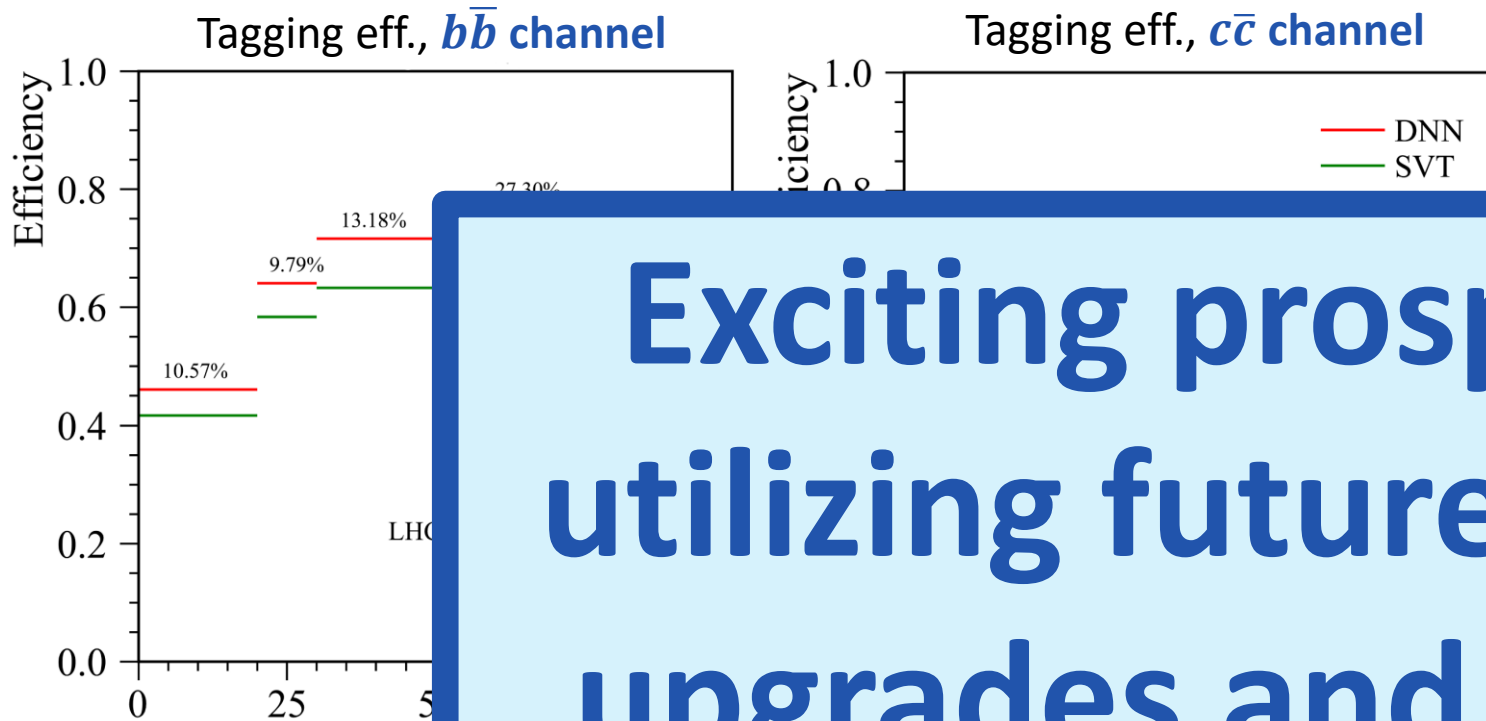


- **Dijet invariant mass**
 m_{jj} : QCD background for these Higgs decays
- Use modern **Deep Neural Network (DNN) approach** to improve heavy-flavor tagging (vs. **Secondary Vertex Tag**)

Studying elusive Higgs decays



- How well does the SM predict $H \rightarrow b\bar{b}, c\bar{c}$?



- **Dijet invariant mass**

m_{jj} : QCD background

Higgs decays

**Exciting prospects
utilizing future LHCb
upgrades and data!**

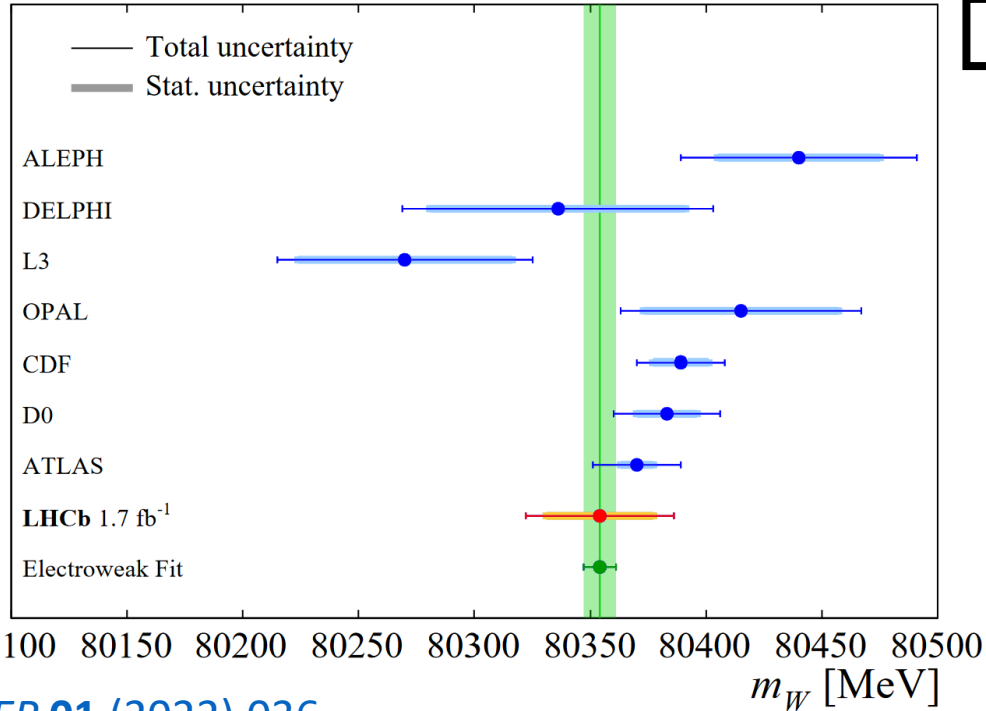
Deep
work (DNN)

to improve
tagging (vs.
Vertex Tag)

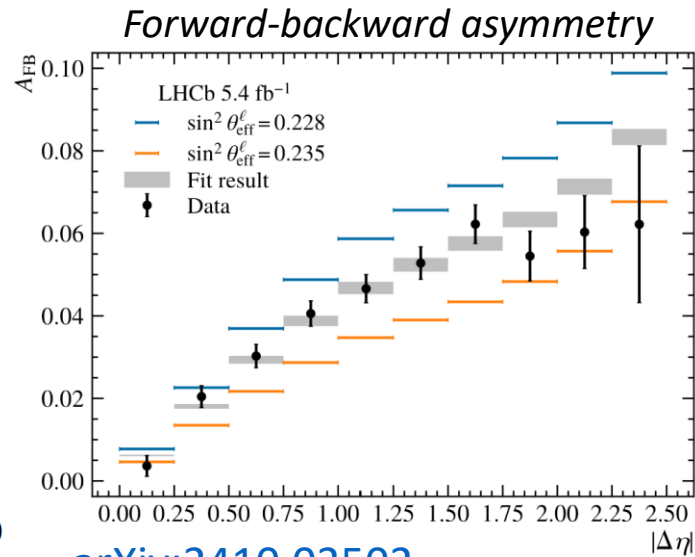
Many more exciting EW results!



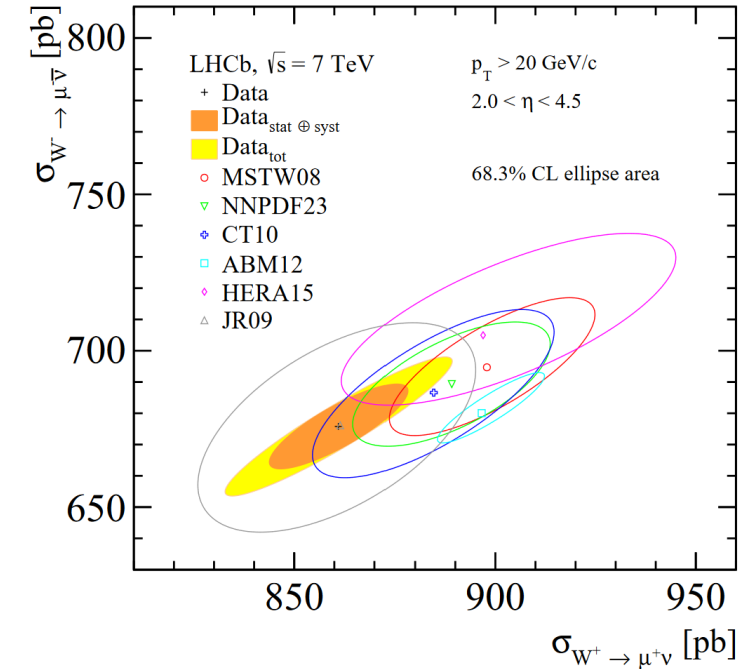
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$



[JHEP 01 \(2022\) 036](#)



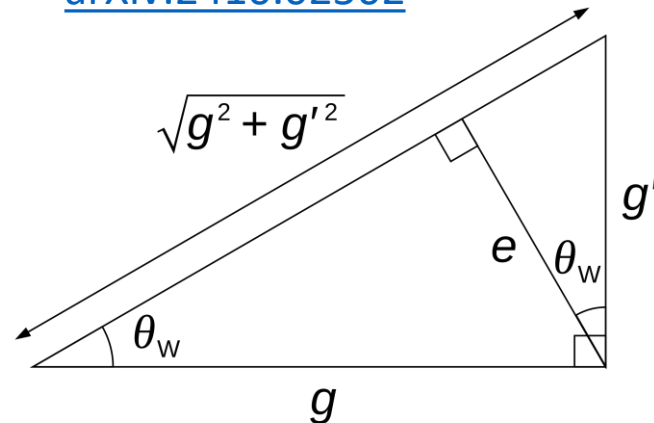
[arXiv:2410.02502](#)



$$\sigma_{W^+ \rightarrow \mu^+ \nu} = 861.0 \pm 2.0 \pm 11.2 \pm 14.7 \text{ pb}$$

$$\sigma_{W^- \rightarrow \mu^- \bar{\nu}} = 675.8 \pm 1.9 \pm 8.8 \pm 11.6 \text{ pb}$$

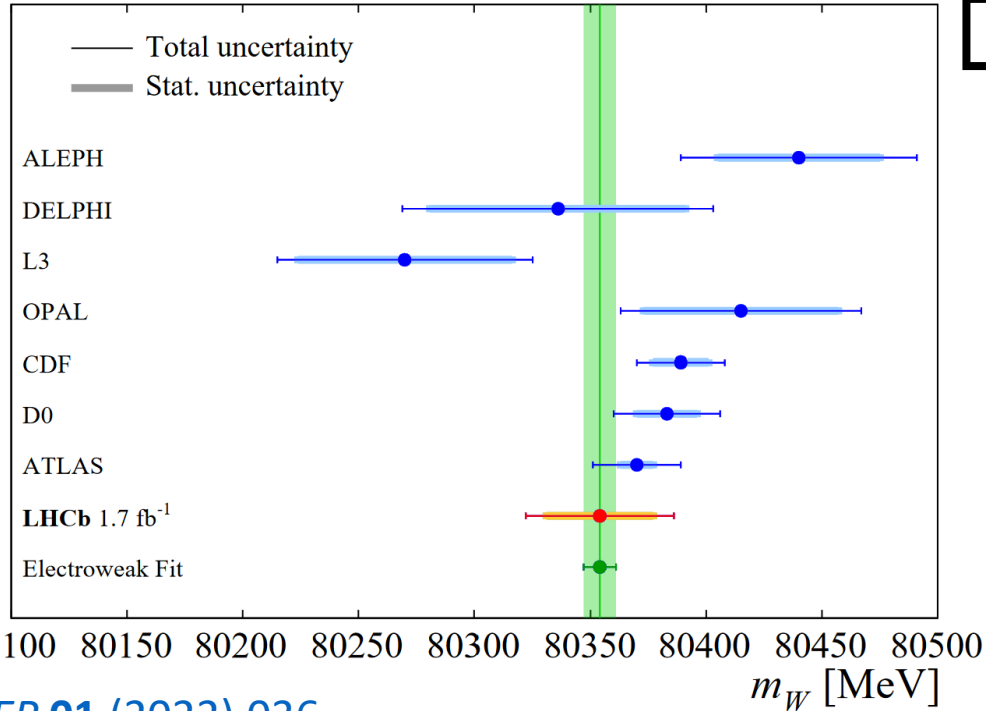
[JHEP 12 \(2014\) 079](#)



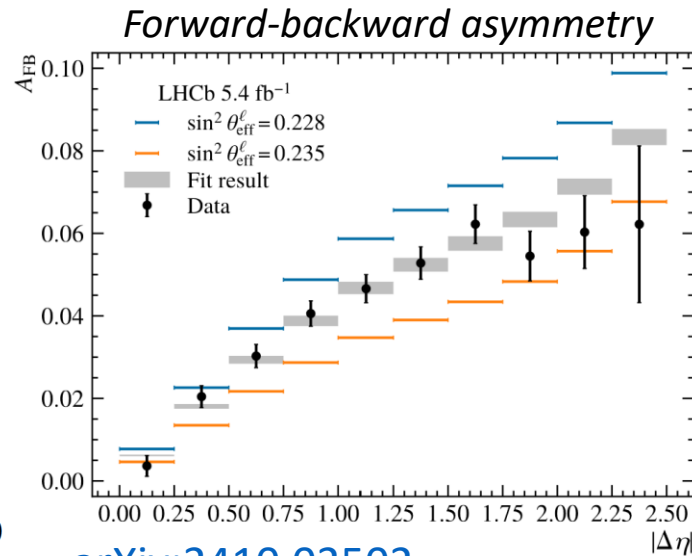
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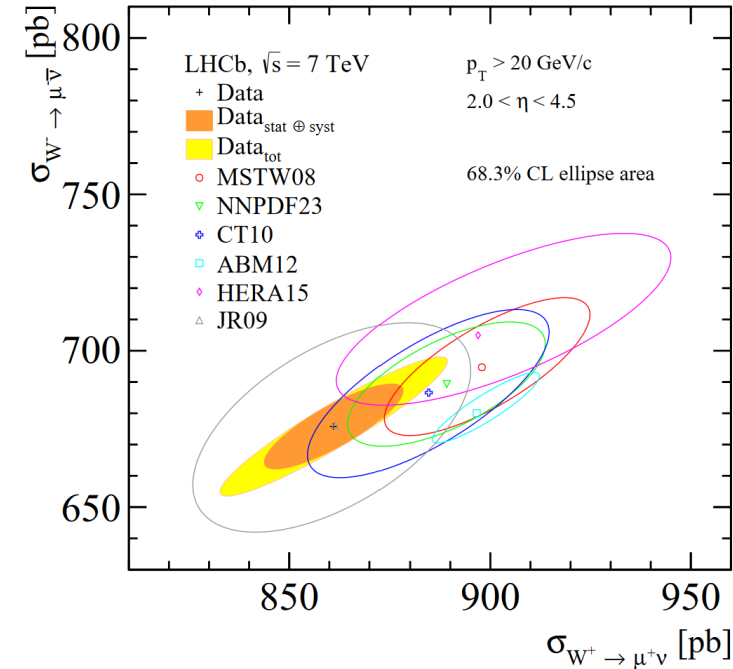
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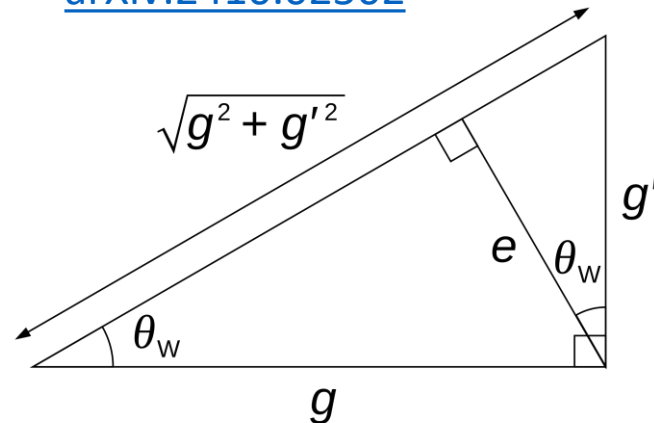
[JHEP 01 \(2022\) 036](#)



[arXiv:2410.02502](#)



See talk by Nate Grieser:
[Weak-mixing angle, cross-sections and W mass](#)



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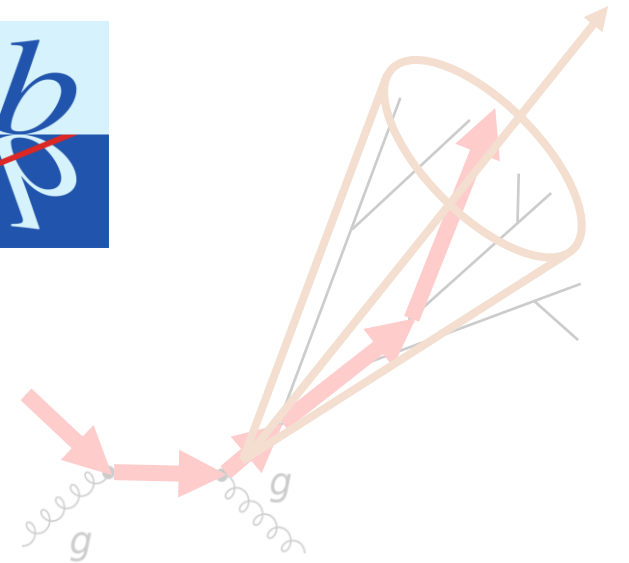
[JHEP 12 \(2014\) 079](#)

The QEE group at



- **Quantum chromodynamics**

- Jet substructure, hadronic production, ...

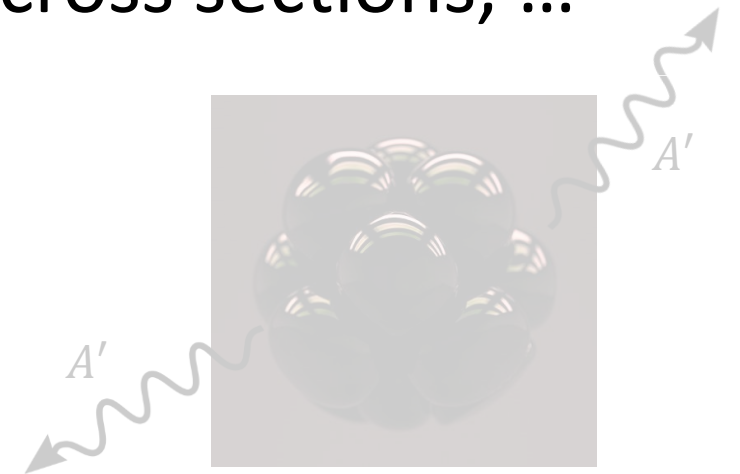


- **Electroweak physics, Higgs, & top**

- W^\pm / Z^0 decays, precision measurements, cross sections, ...

- **Exotica**

- Rare decays, beyond the SM searches, ...

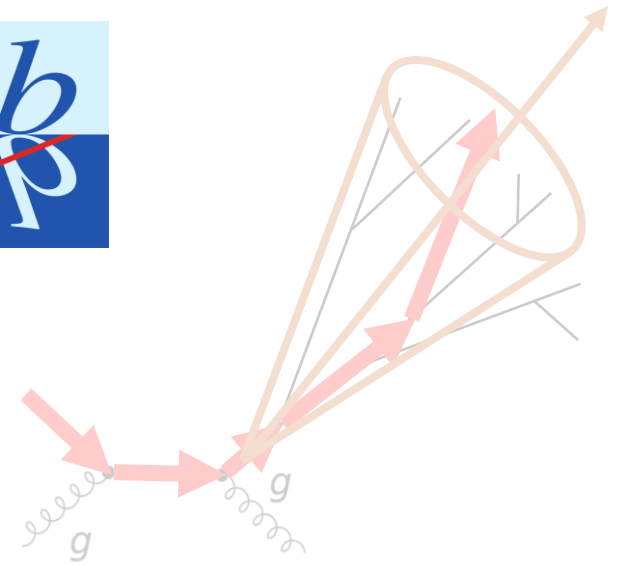


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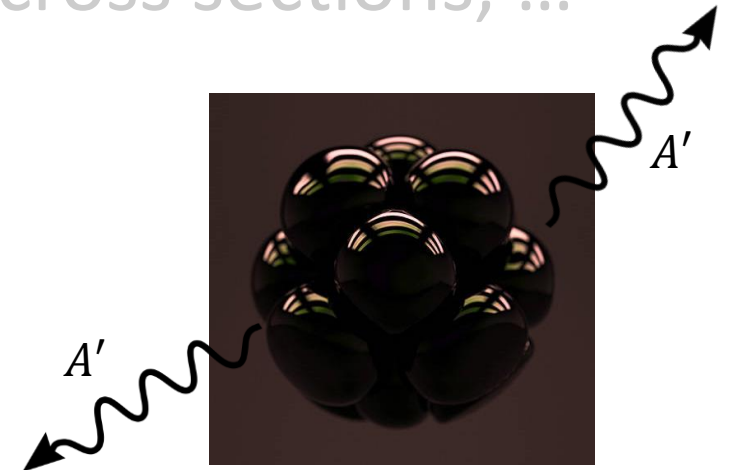


- **Electroweak physics, Higgs, & top**

- W^\pm / Z^0 decays, precision measurements, cross sections, ...

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Search:



Search:

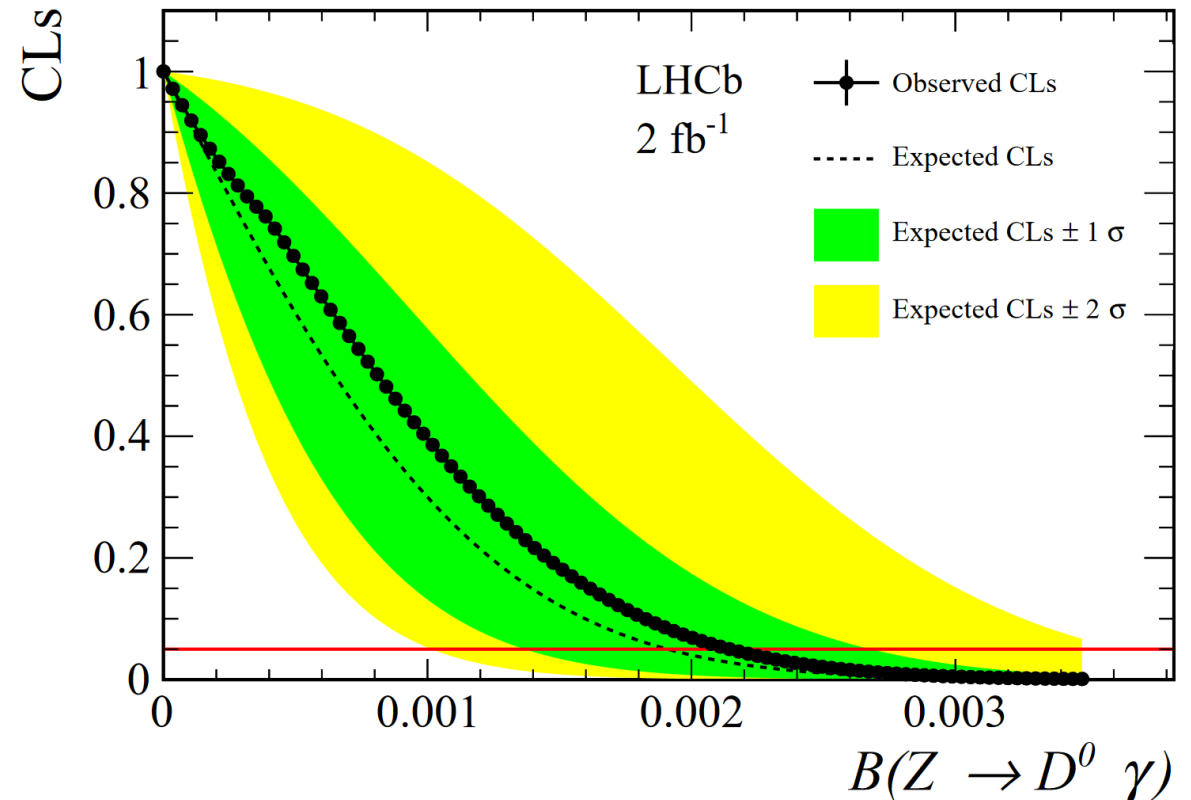
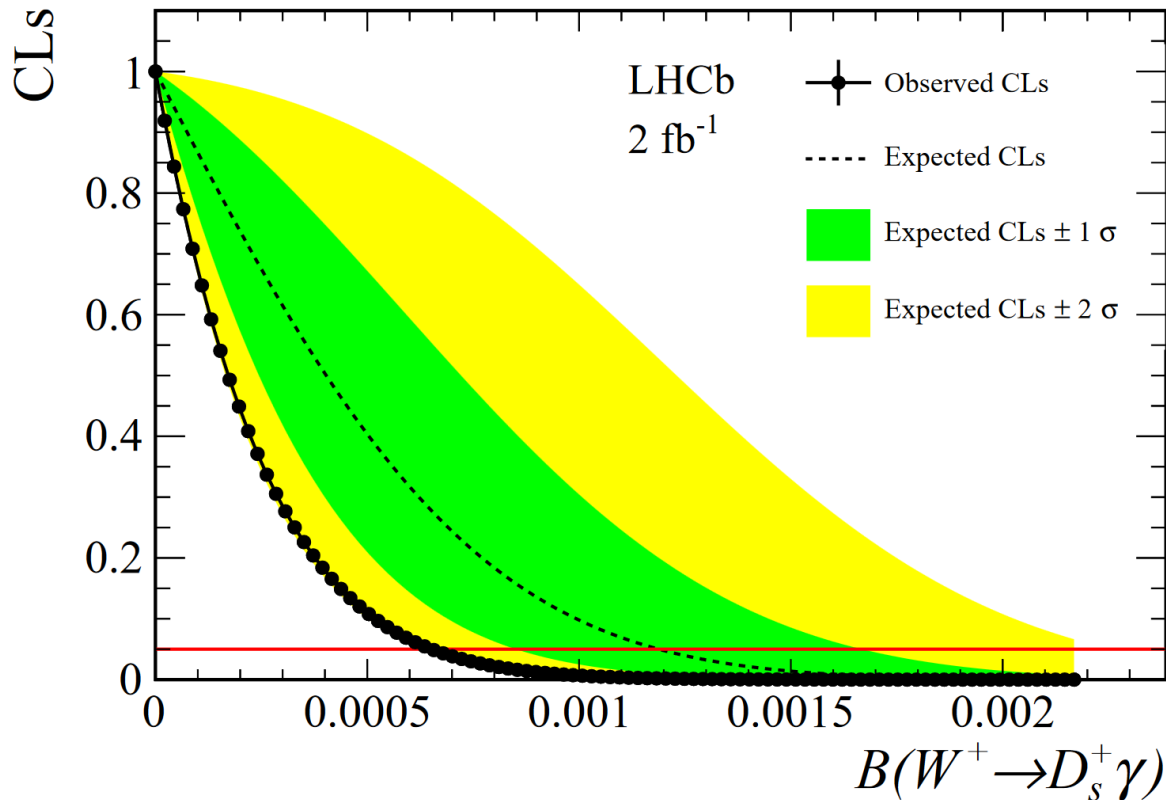


- How well do calculations within the **QCD factorization formalism** describe the **rare radiative decays of W^\pm and Z^0** bosons?

Search: rare EW radiative decays



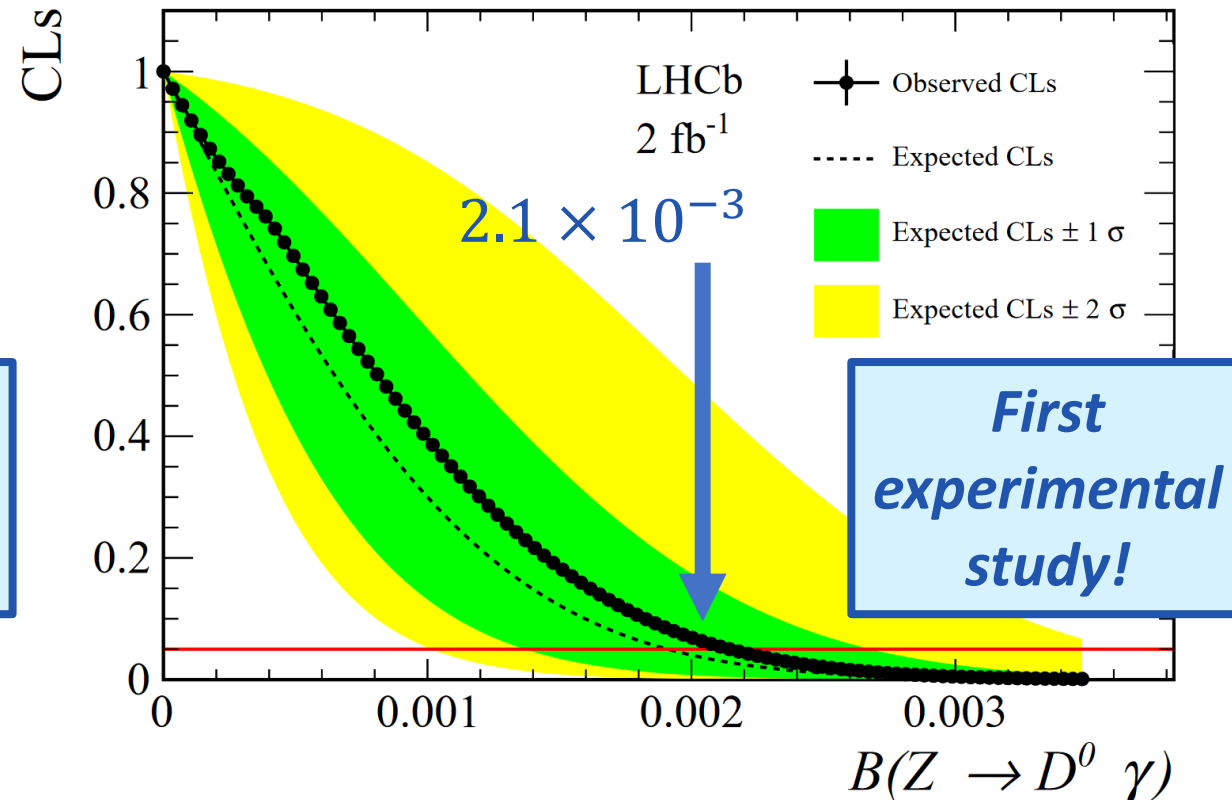
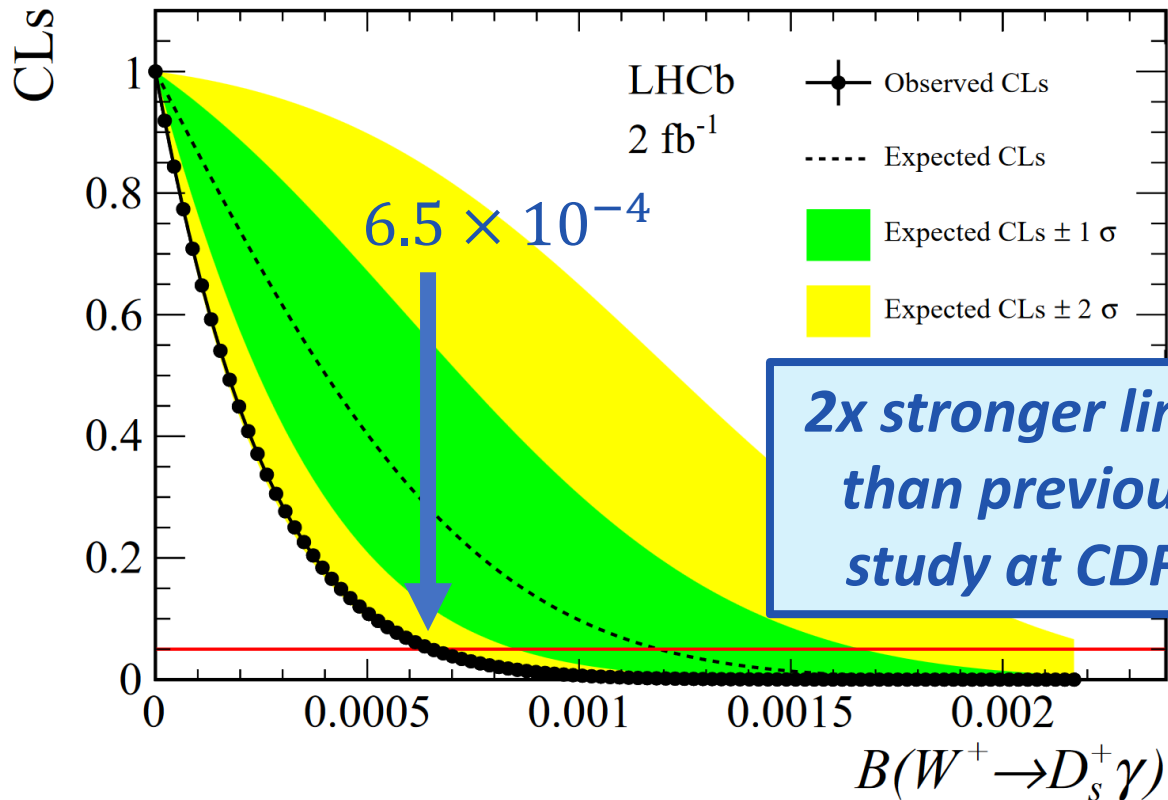
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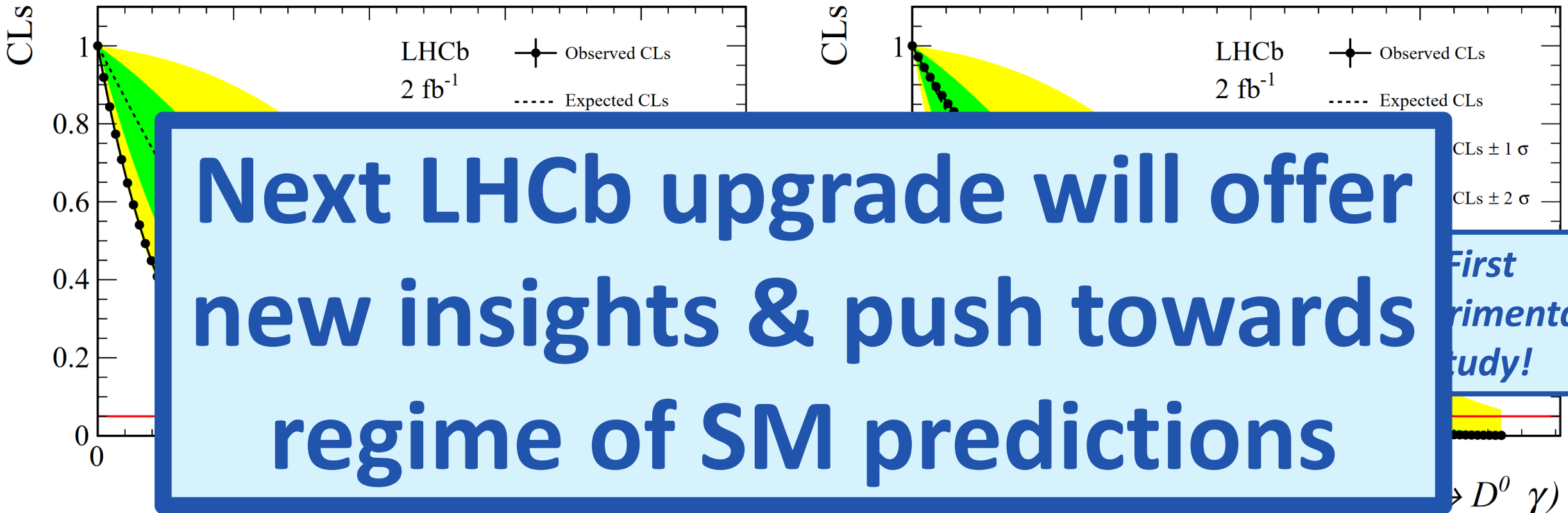
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Search: rare EW radiative decays



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Search:



Search:

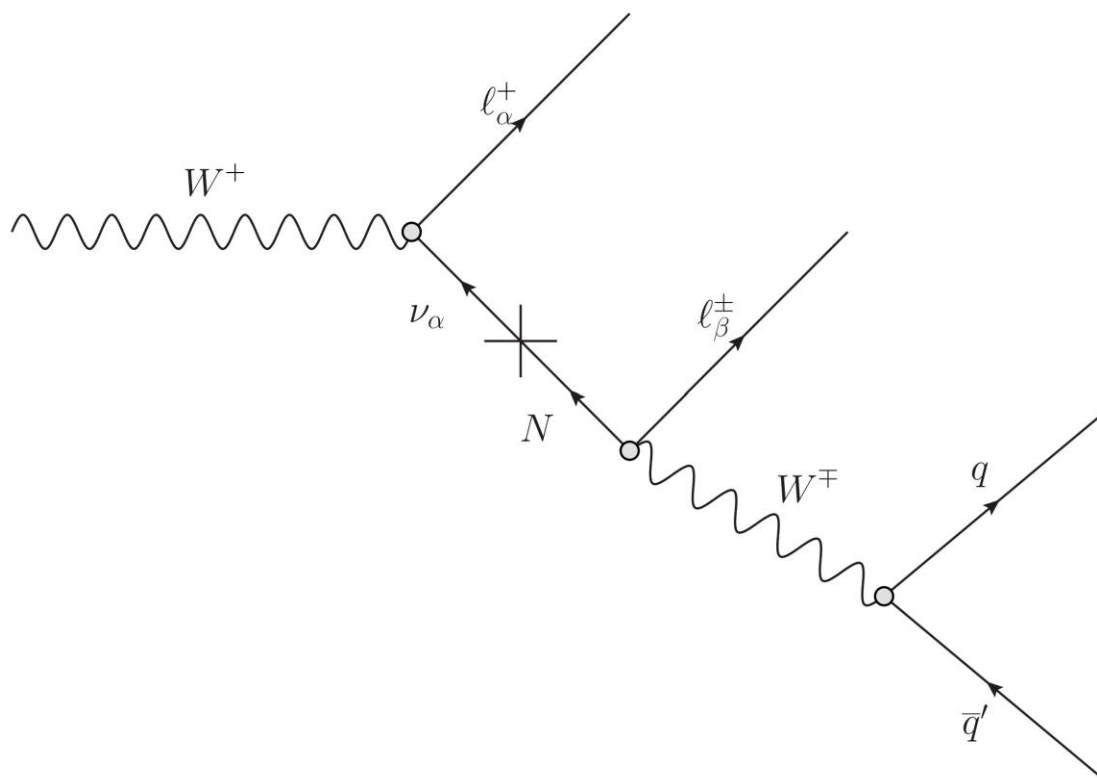


- Is there a **heavy neutral lepton (HNL)** to explain small neutrino masses?

Search: heavy neutrinos in W^\pm decays



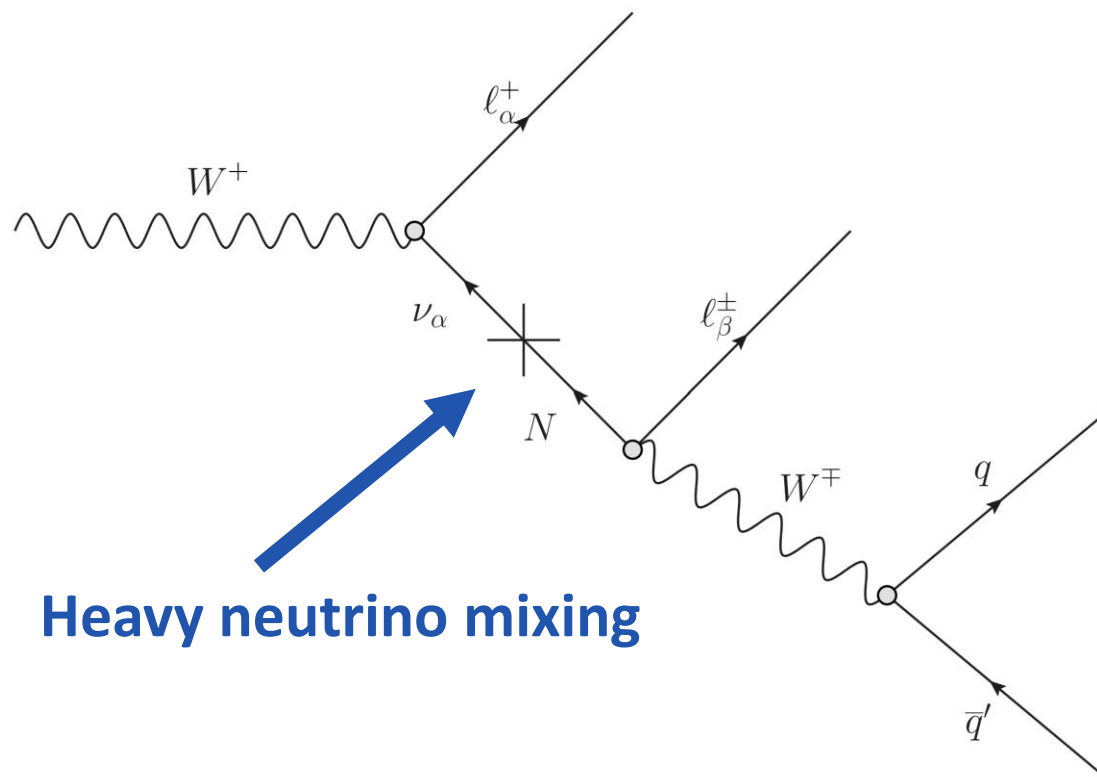
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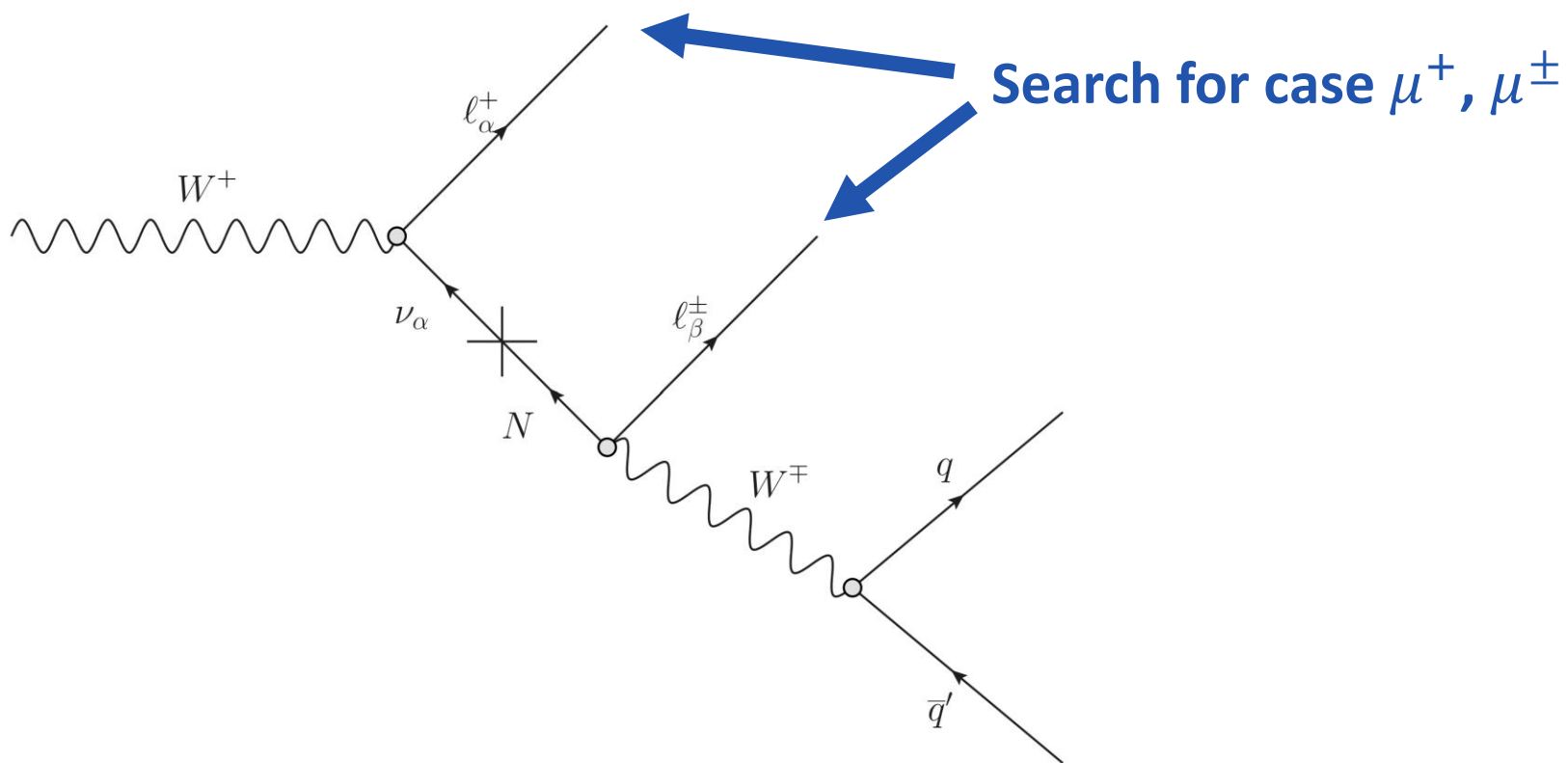
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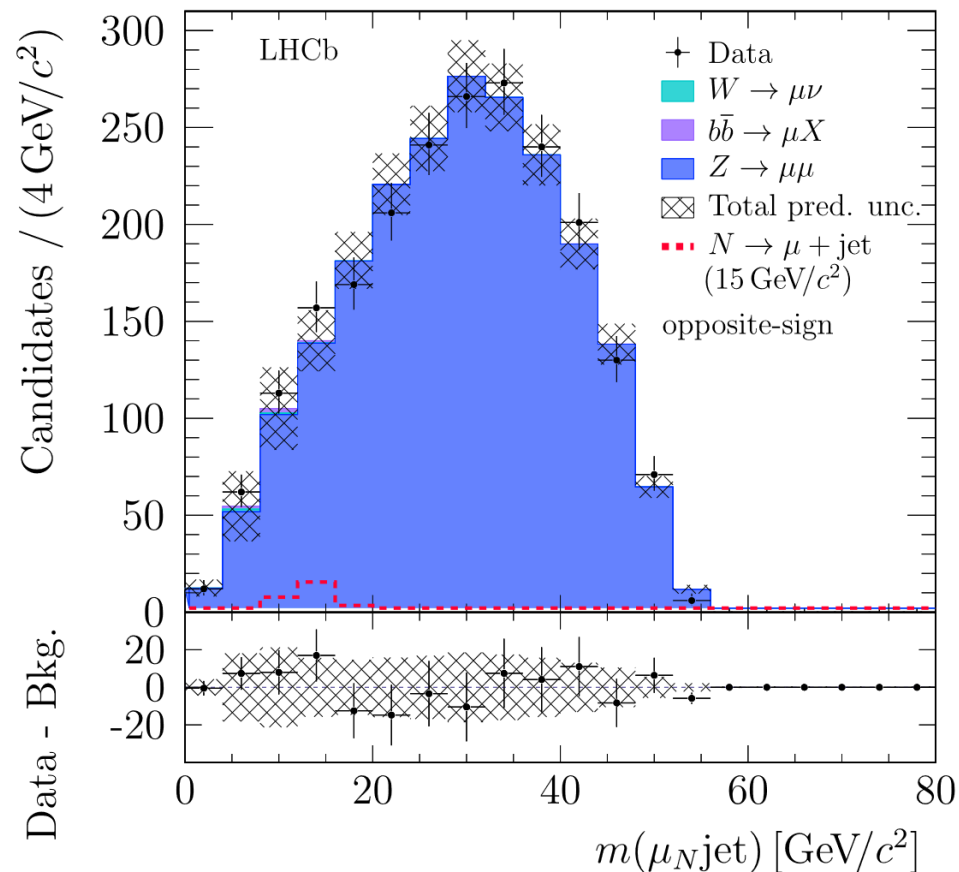
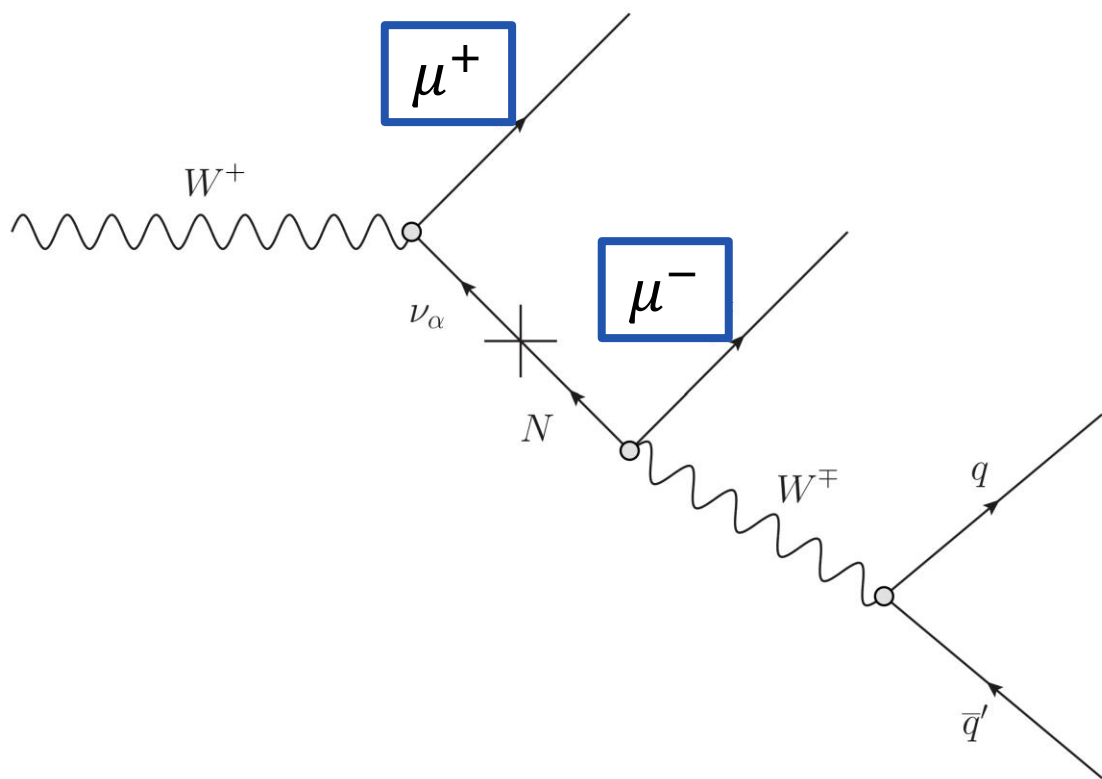
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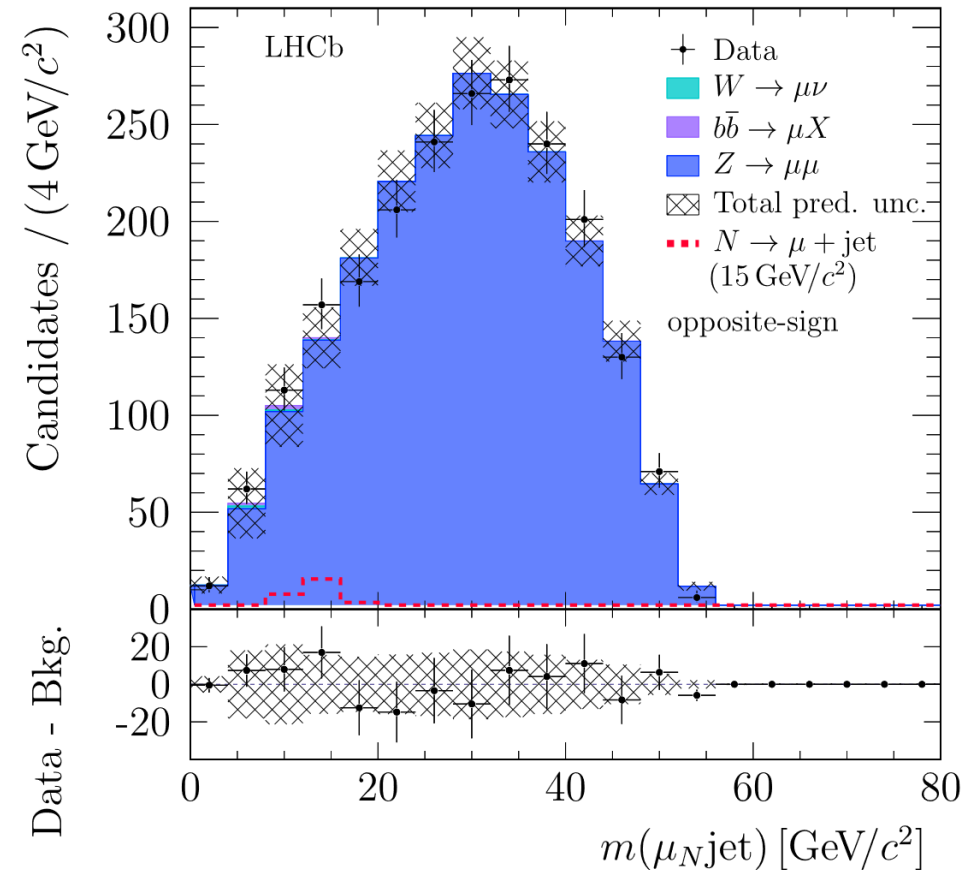
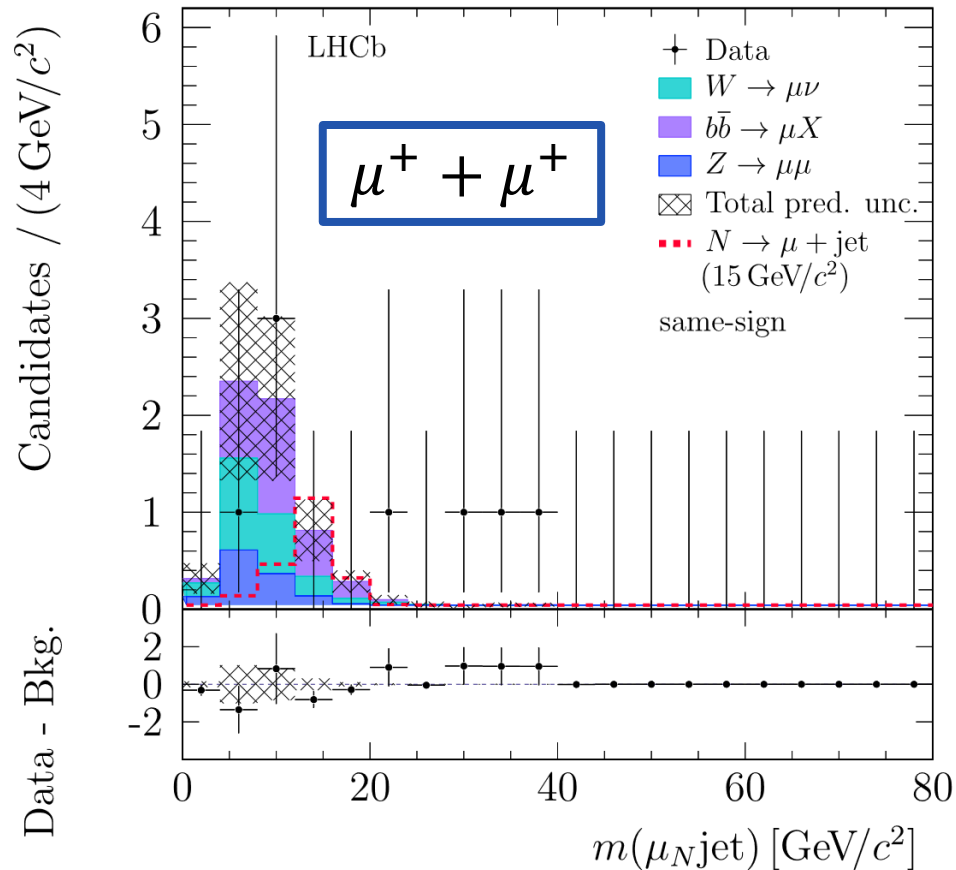


$\mu^+ + \mu^-$

Search: heavy neutrinos in W^\pm decays



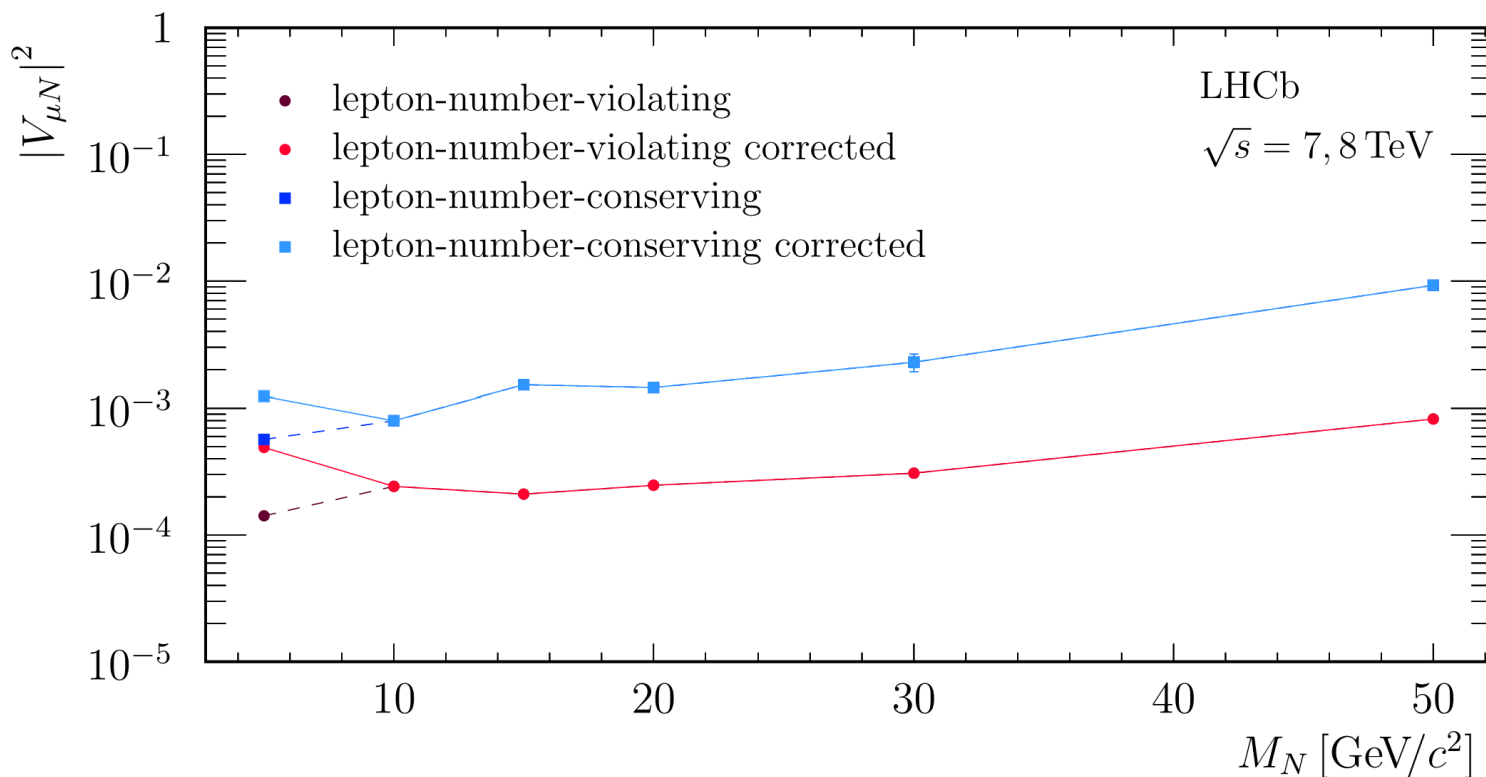
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Search: heavy neutrinos in W^\pm decays



- Is there a **heavy neutral lepton (HNL)** to explain small neutrino masses?



**Data consistent
with SM
predictions**

- *New competitive limits
in $5 < M_N < 50 \text{ GeV}/c^2$*

Search for other neutral particles



Search for other neutral particles



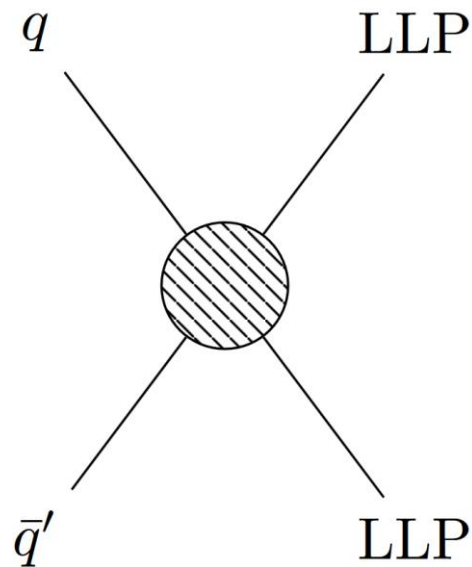
- Are there **Long Lived Particles (LLPs)** coming from beyond the Standard Model?

Search for other neutral particles



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Direct Pair Production (DPP)

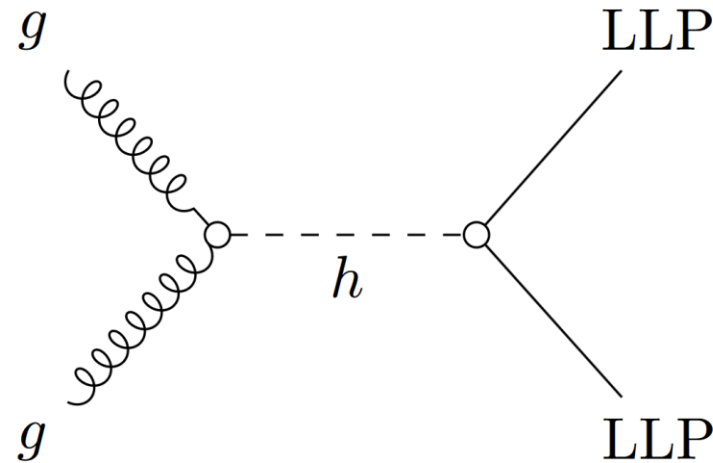
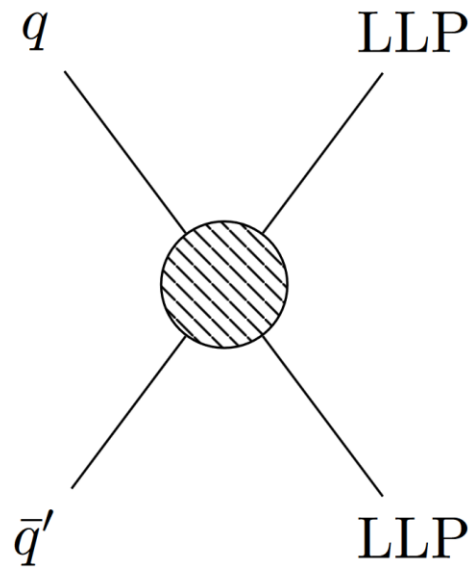


Search for other neutral particles



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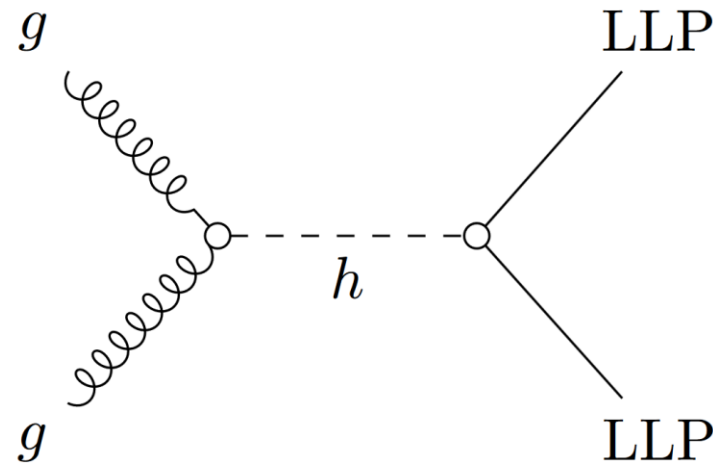
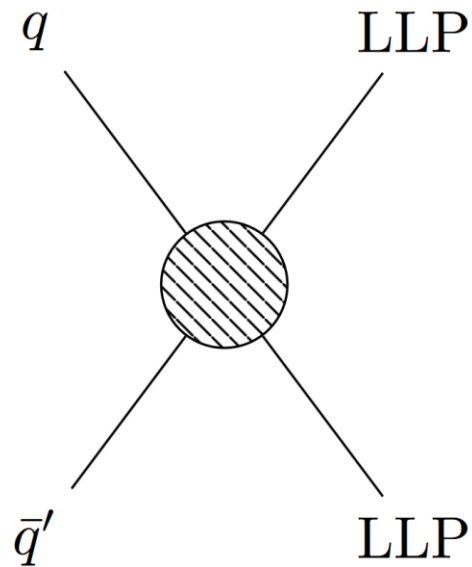
**gg fusion → Higgs decay
(HIG)**

Search for other neutral particles



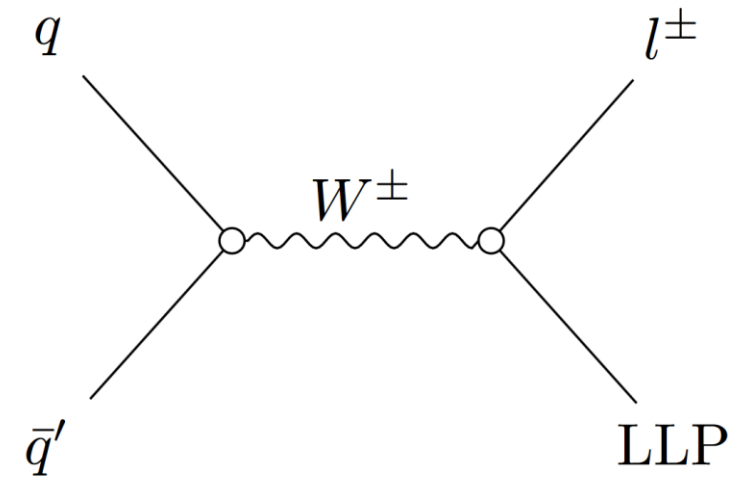
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Direct Pair Production (DPP)



gg fusion \rightarrow Higgs decay
(HIG)

Charged current (CC)

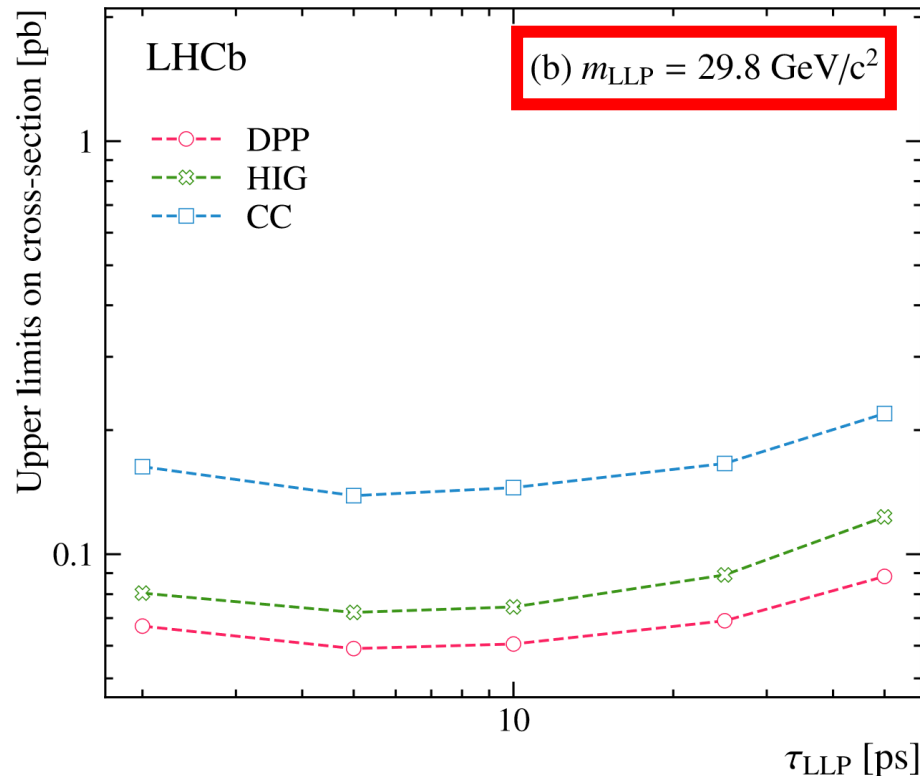
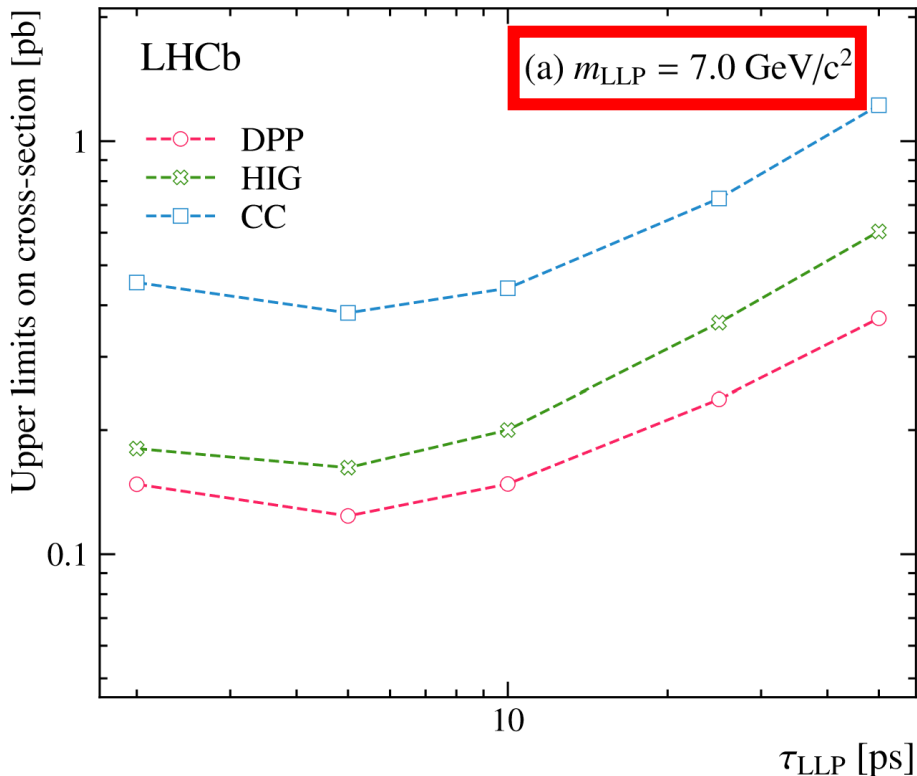


Search for other neutral particles



- Are there **Long Lived Particles (LLPs)** coming from beyond the Standard Model?

New limits as a function of LLP lifetime τ_{LLP} for different mass assumptions

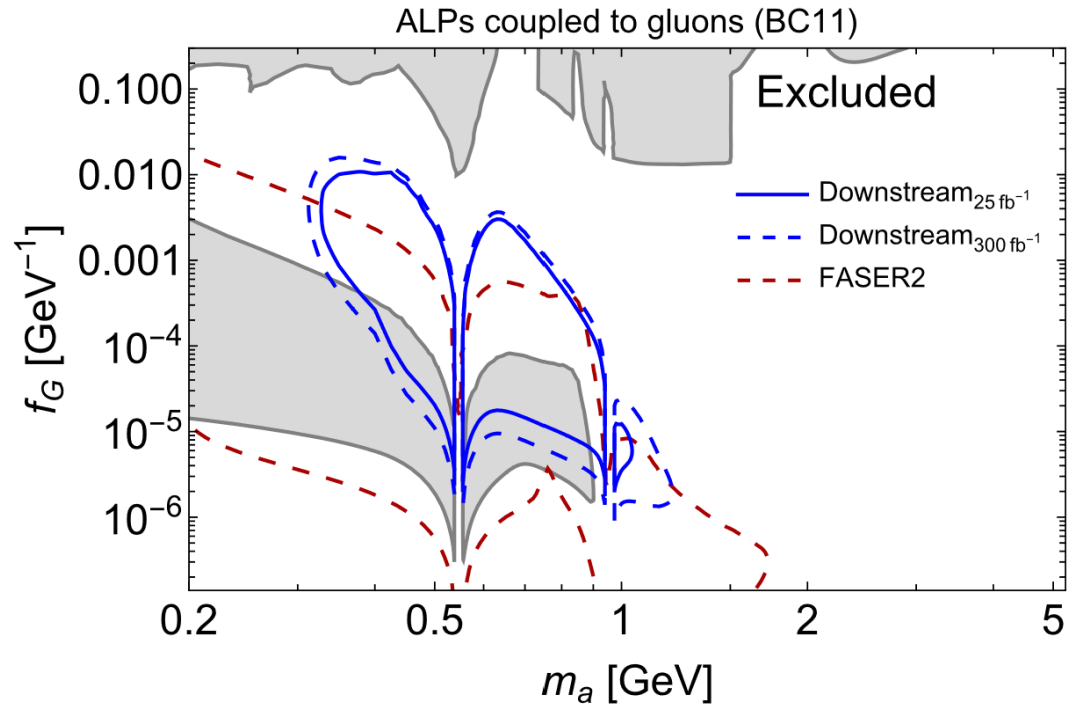


- BDT used to separate heavy hadron background
- Strongest limits are for DPP

Many more exotica results...

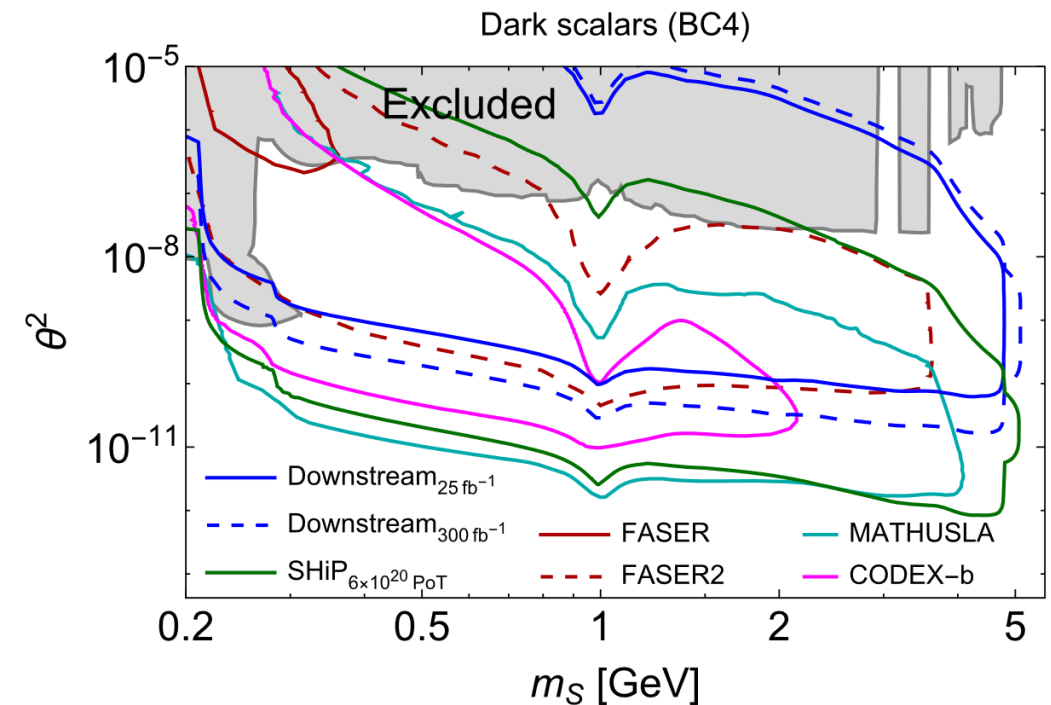


- ... & exciting possibilities coming in future searches soon!



LHCb potential to discover long-lived new physics particles with lifetimes above 100 ps

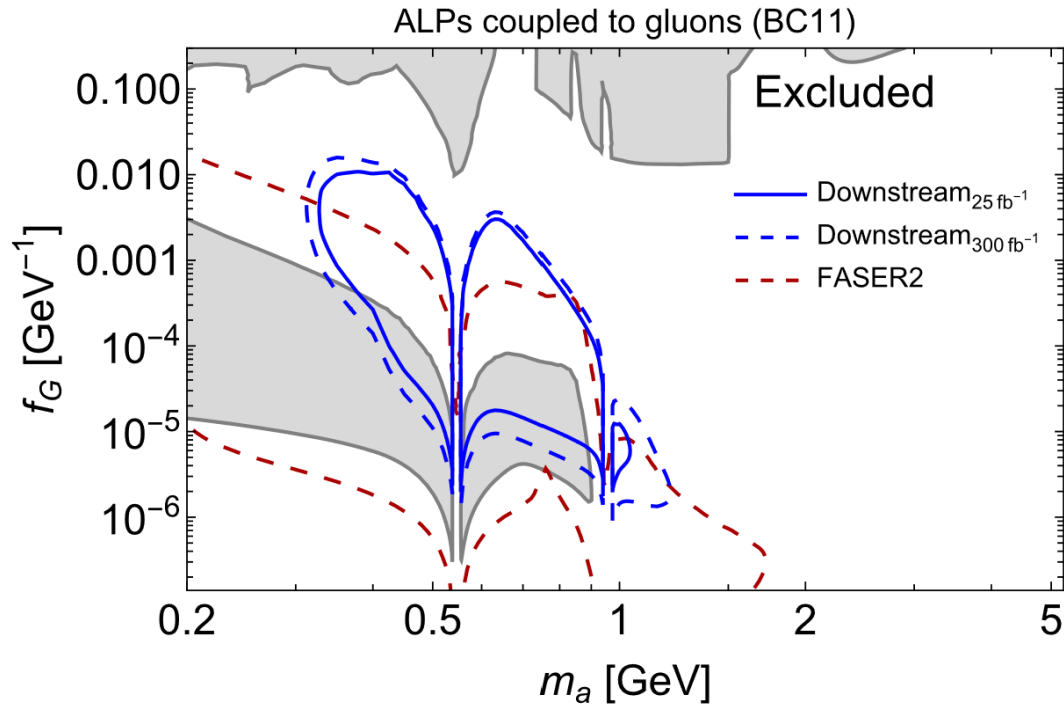
[EPJC 84 \(2024\) 608](#)



Many more exotica results...

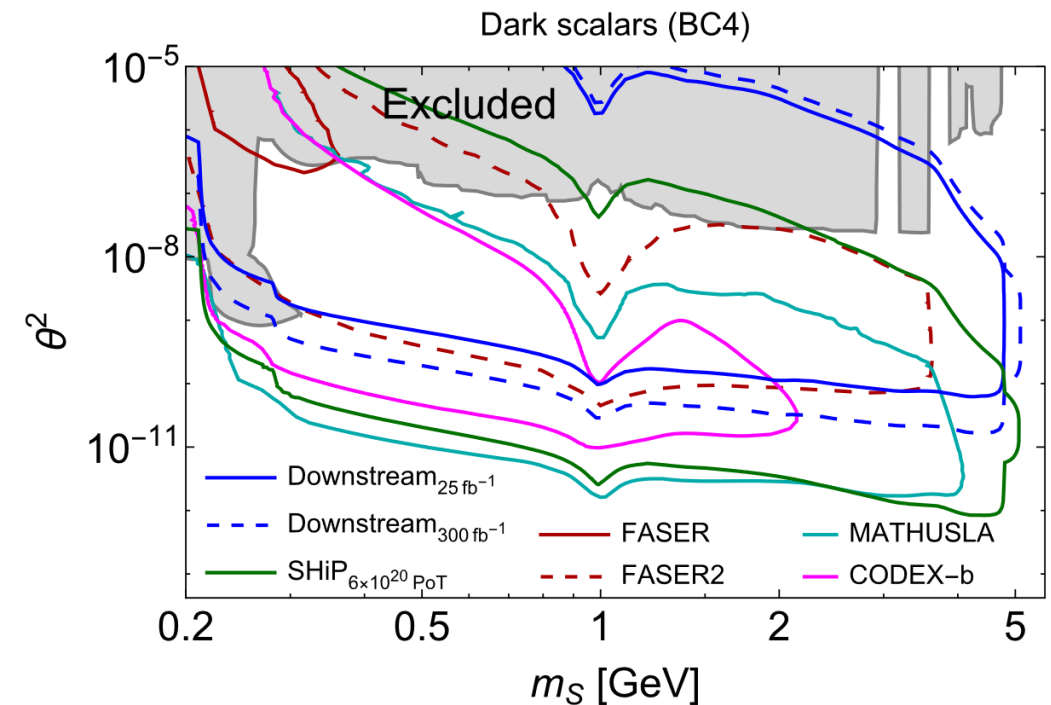


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LHCb potential to discover long-lived new physics particles with lifetimes above 100 ps

[EPJC 84 \(2024\) 608](#)



See talk by Felicia Volle:
[Searches for exotic particles](#)

Lots of new measurements!

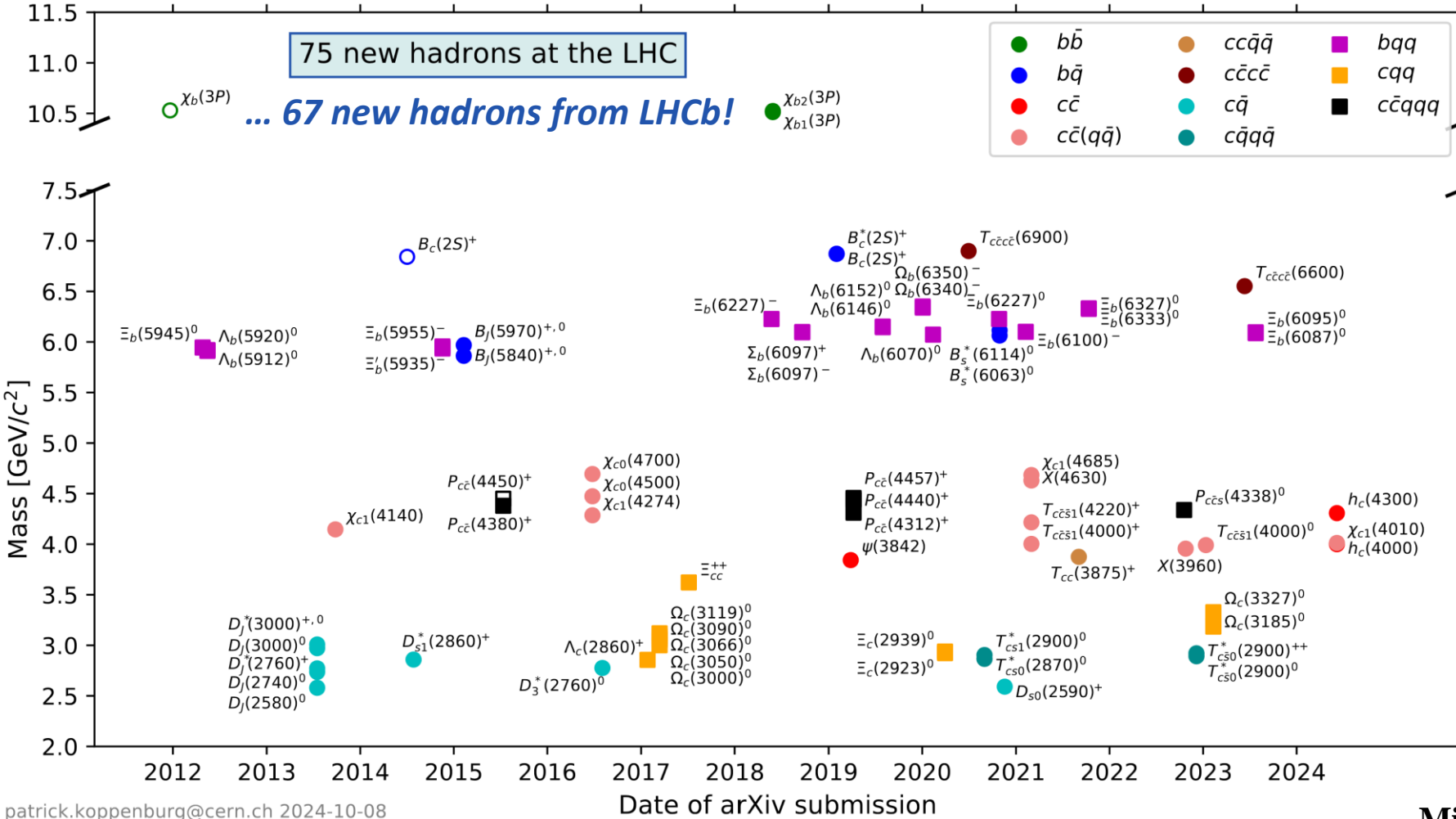


- ... & more soon!
- LHCb papers are available from [this link](#)
- **QEE working group** is the **most diverse on LHCb**, encompassing the entire Standard Model and searches beyond
- ***Feel free to contact us for discussion or collaboration!***

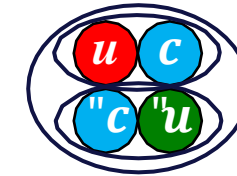


Backup

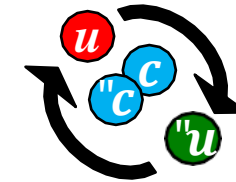
New hadrons discovered at the LHC



Compact tetraquark/pentaquark

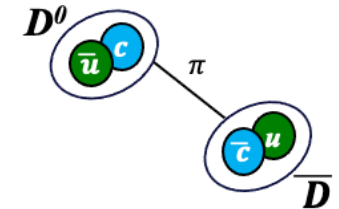


Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/
adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

Mixtures

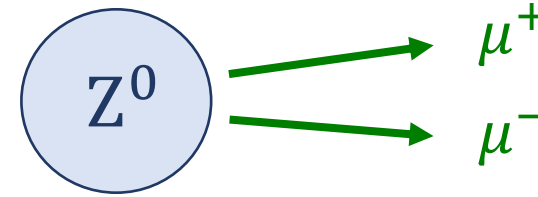
$$X = a |c\bar{c}\rangle + b |c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

~90% of the new particles were discovered by LHCb

Credit for this slide: Matt Durham (LANL), [Hard Probes 2024](#)

The ϕ_{η}^* observable



- Proposed as a **high-precision angular observable** for cross section measurements, encoding the same physics as $p_T^{Z^0}$

A. Banfi et al.

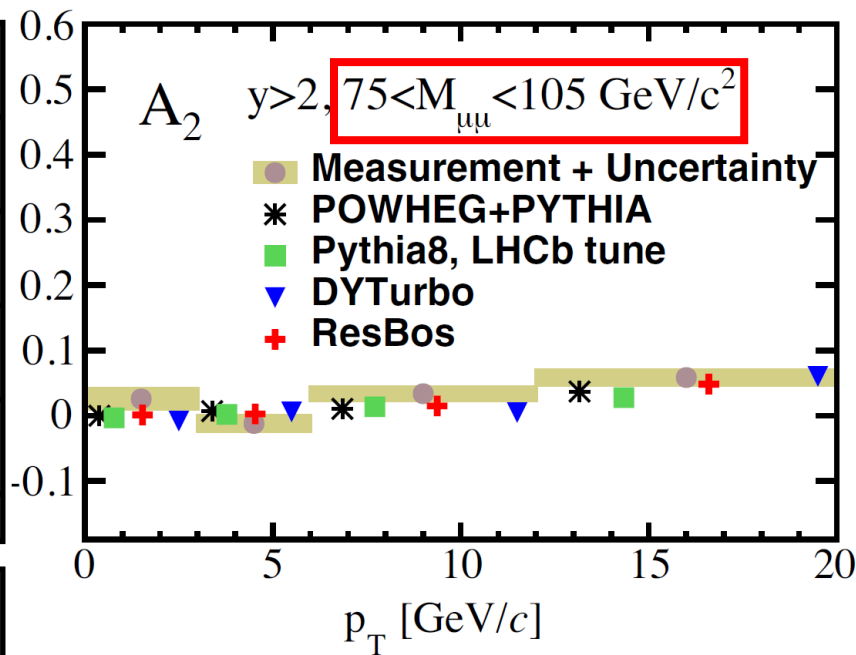
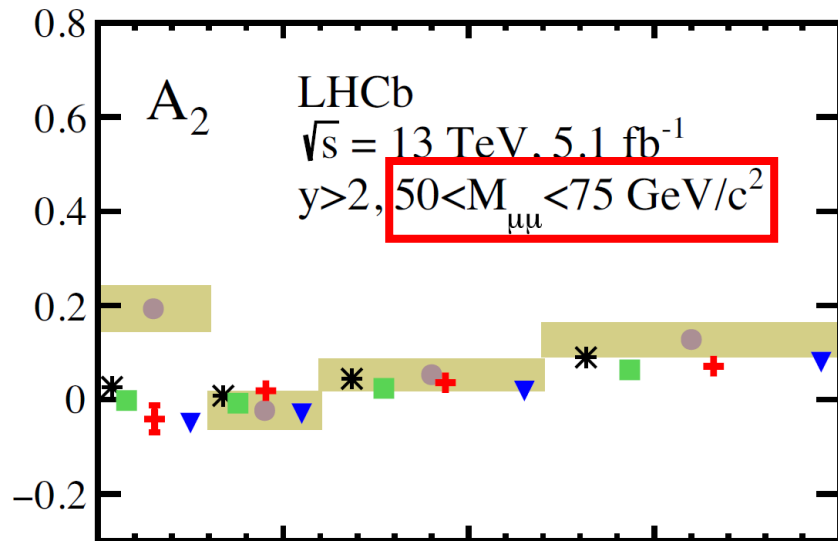
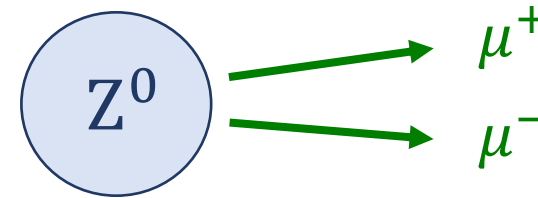
[EPJC 71 \(2011\) 1600](#)

$$\phi_{\eta}^* = \tan[(\pi - \Delta\phi^{\mu\mu})/2] \sin(\theta_{\eta}^*)$$

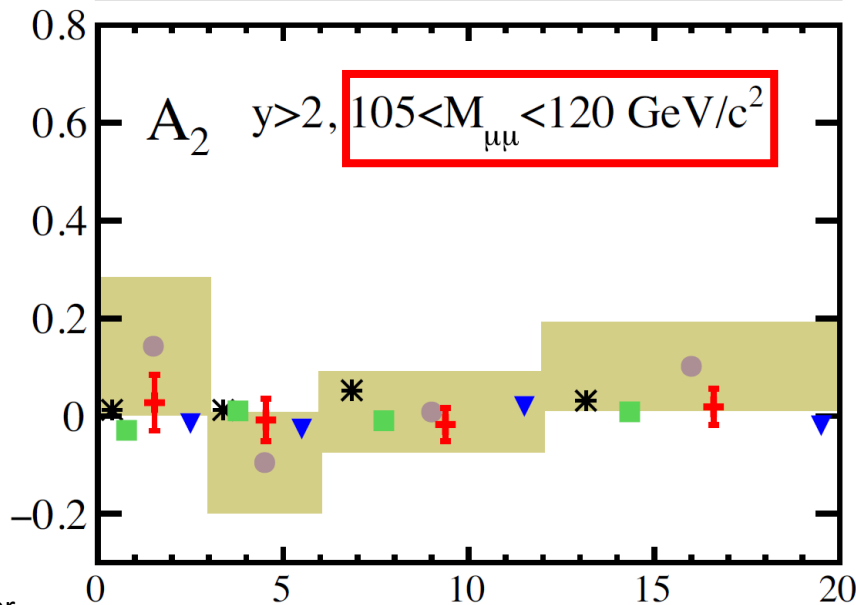
where: $\Delta\phi^{\mu\mu}$ is azimuthal angle between μ^+ and μ^- , and:

$$\cos(\theta_{\eta}^*) = \tanh[(\eta^{\mu^-} - \eta^{\mu^+})/2]$$

A_2 : three mass regions

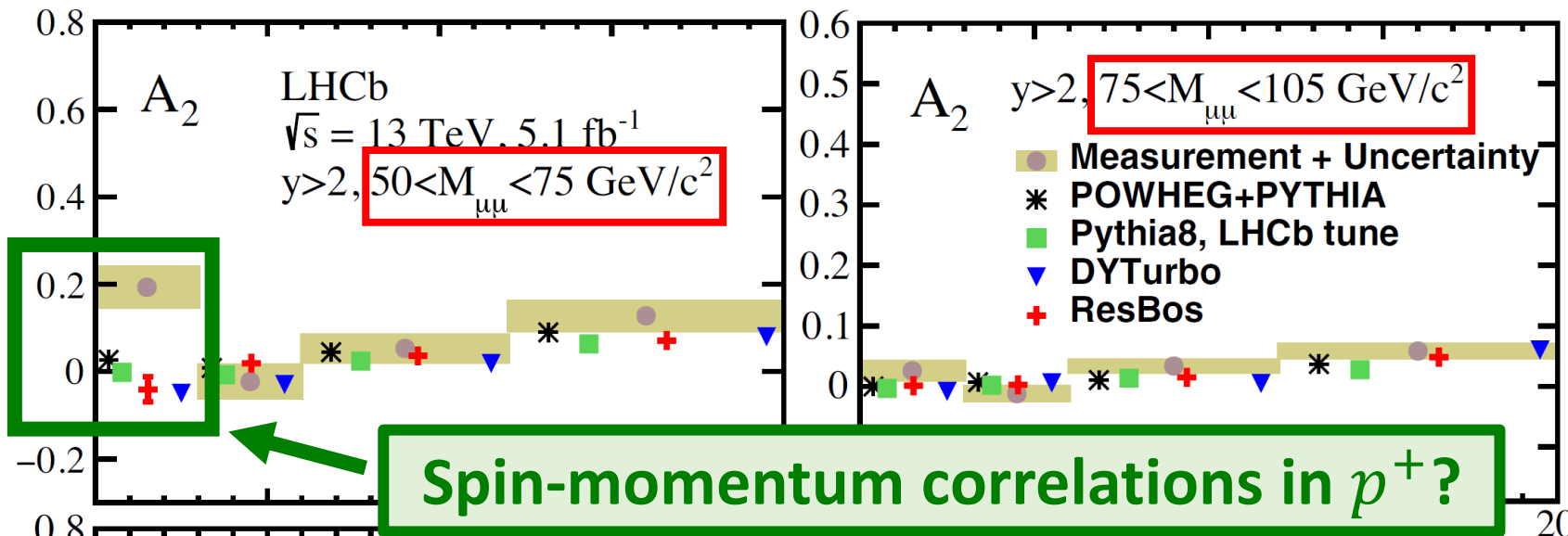
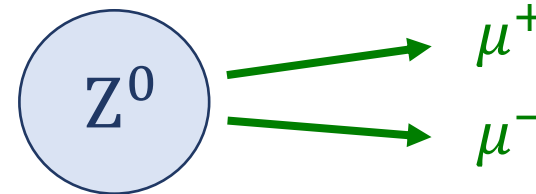


$M_{\mu\mu} = \text{dimuon invariant mass}$

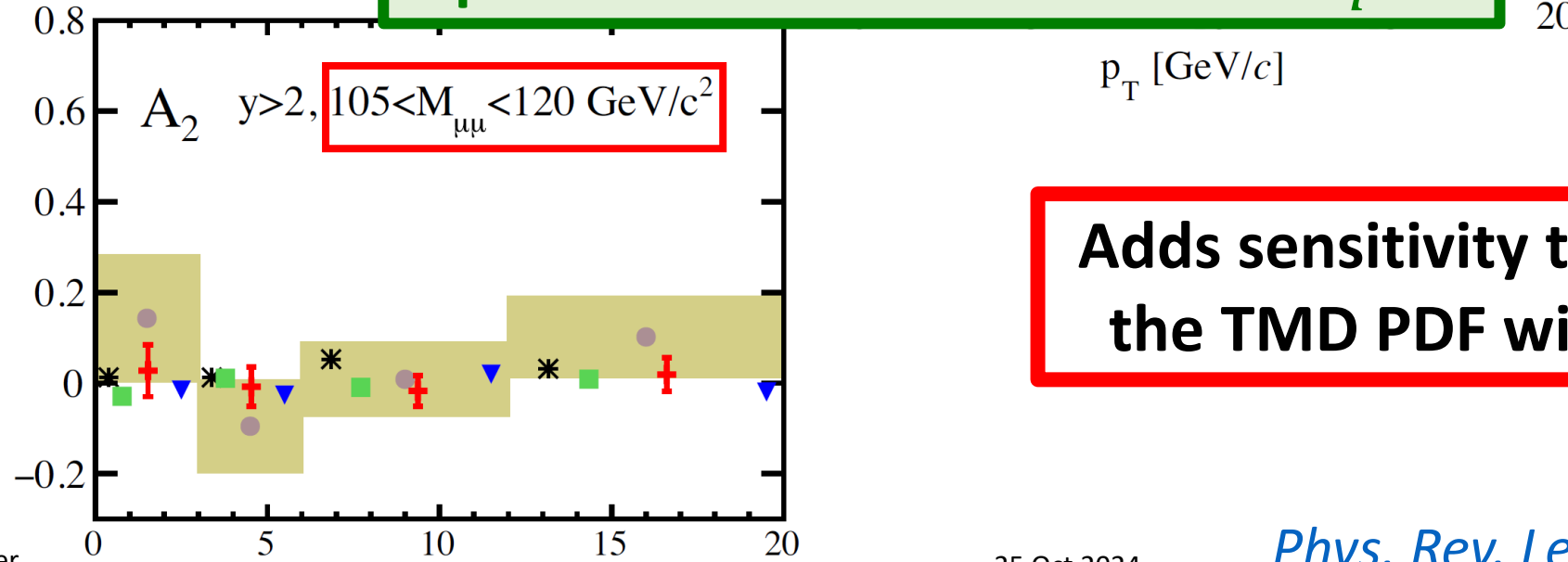


Adds sensitivity to the evolution of the TMD PDF with the hard scale

A_2 : three mass regions



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Adds sensitivity to the evolution of the TMD PDF with the hard scale