Heavy flavor production in *pp* and *p*Pb collisions at LHCb

Matt Durham, on behalf of the LHCb collaboration
Los Alamos National Laboratory

19th International Conference on B-Physics at Frontier Machines, BEAUTY 2020

Outline

- Introduction: heavy flavor production in pp and pA collisions
- Charm/bottom dijet production
  - LHCb-PAPER-2020-018, in preparation
- Double charm production in pPb collisions
  - arXiv:2007.06945, submitted to PRL
- Prompt X(3872) suppression in high-multiplicity pp collisions
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Heavy Quark Production

$$d\sigma(Q^2, \sqrt{s})_{pA\to a+X} = \sum_{i,j=q,\bar{q},g} f_i^p(x_1, Q^2) \otimes A f_i^A(x_2, Q^2) \otimes d\hat{\sigma}(Q^2, x_1, x_2)_{i,j\to a+X}$$

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Measureable cross section

Calculable with pQCD

- Precision tests of perturbative QCD

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Linked by PDFs

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- Constrains parton distribution function in protons/nuclei

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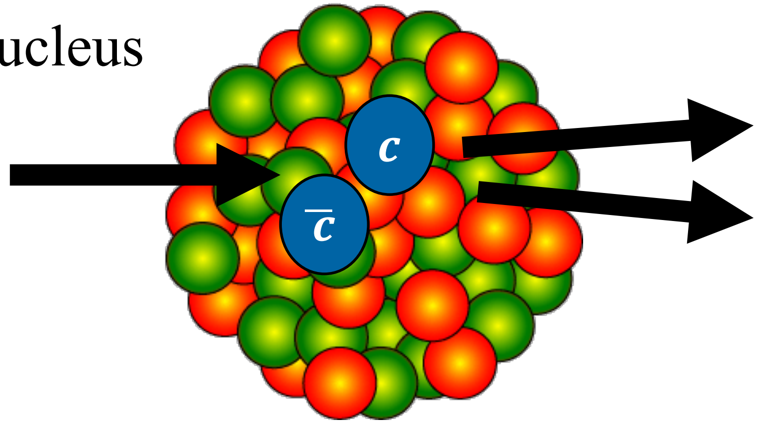

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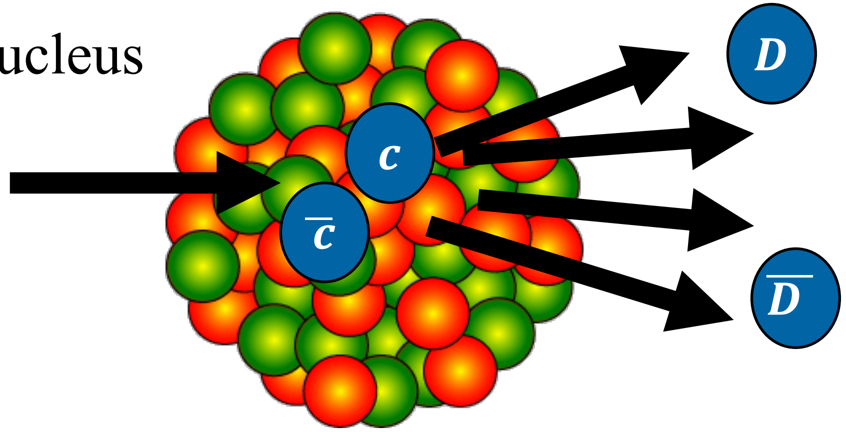
Measureable cross section — Linked by PDFs — Calculable with pQCD

- Precision tests of perturbative QCD
- Constrains parton distribution function in protons/nuclei
- Probes QCD energy loss and possible hydrodynamic effects in nucleus
- Quarkonia breakup is sensitive to binding energy of hadrons



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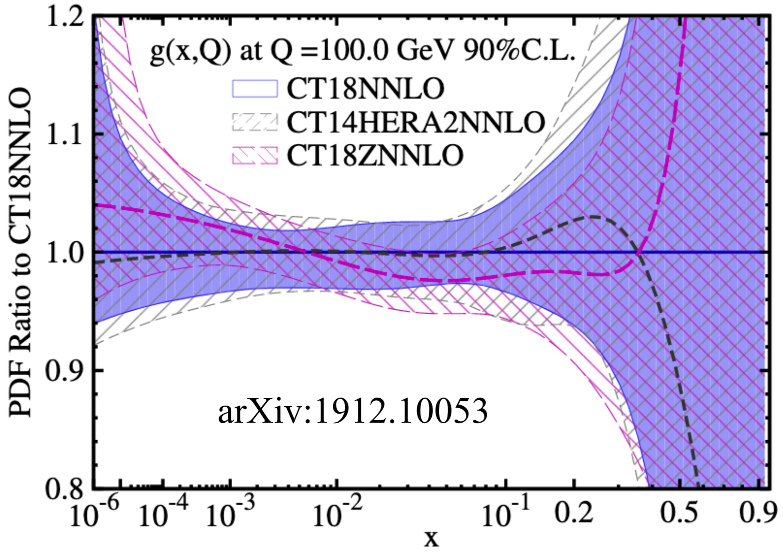
Charm and bottom dijet production



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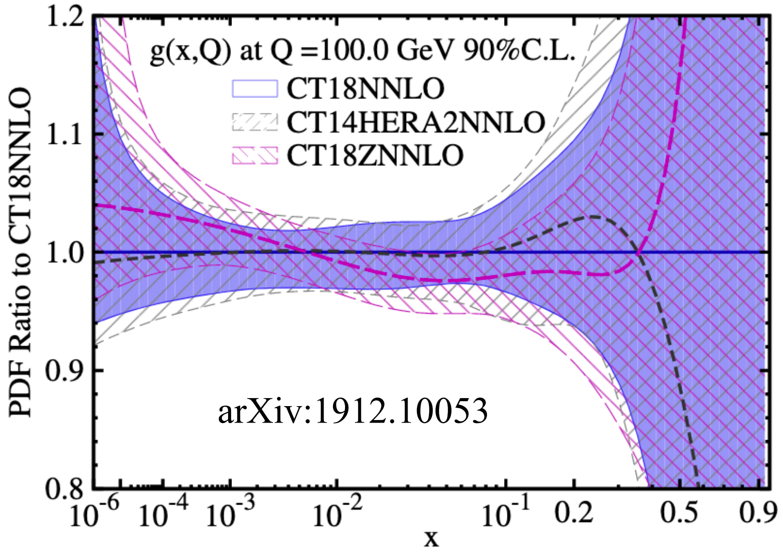
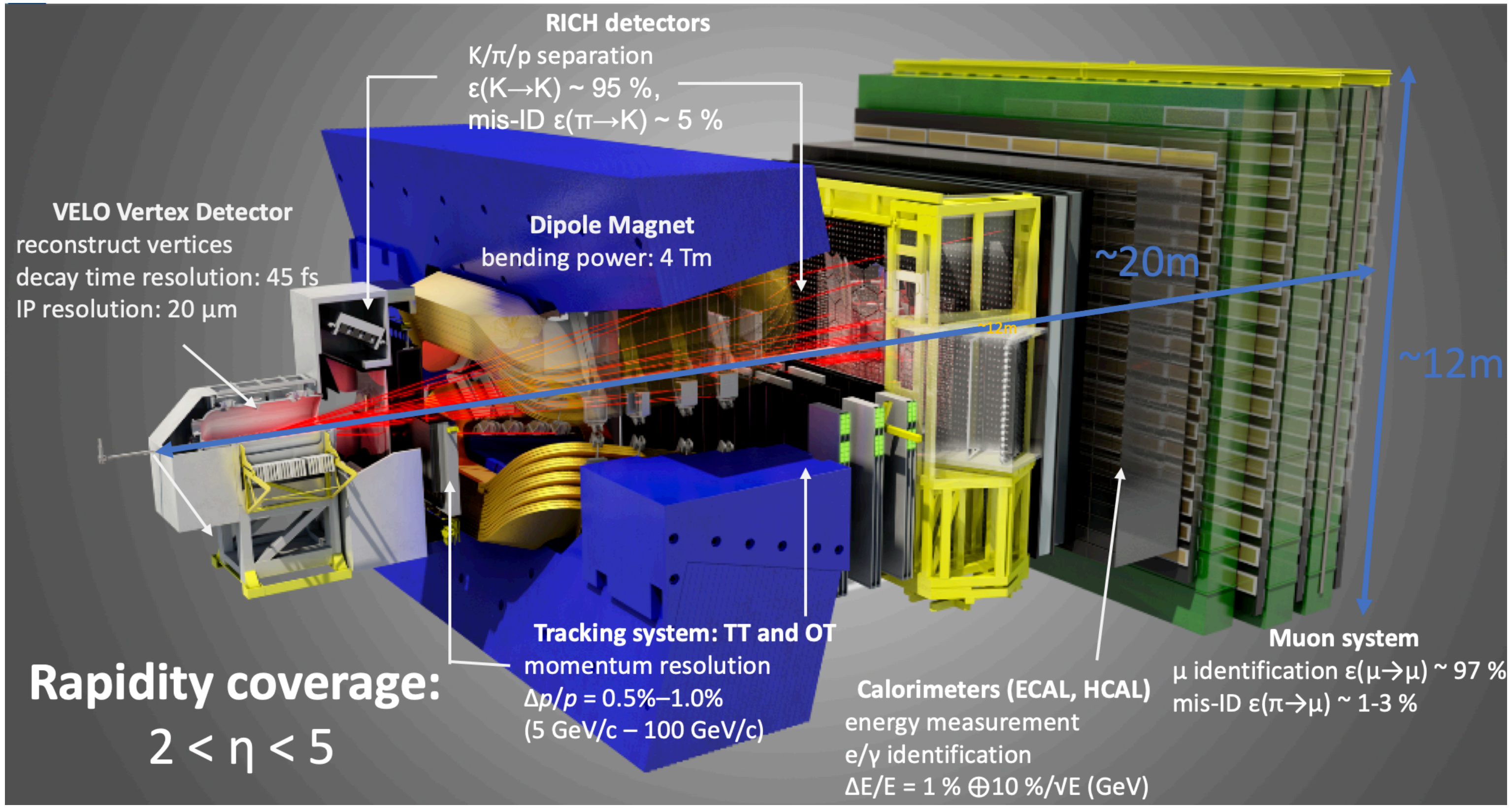


- LHCb has a unique forward acceptance: sensitive to high and low Bjorken-x values, where PDFs are not well constrained

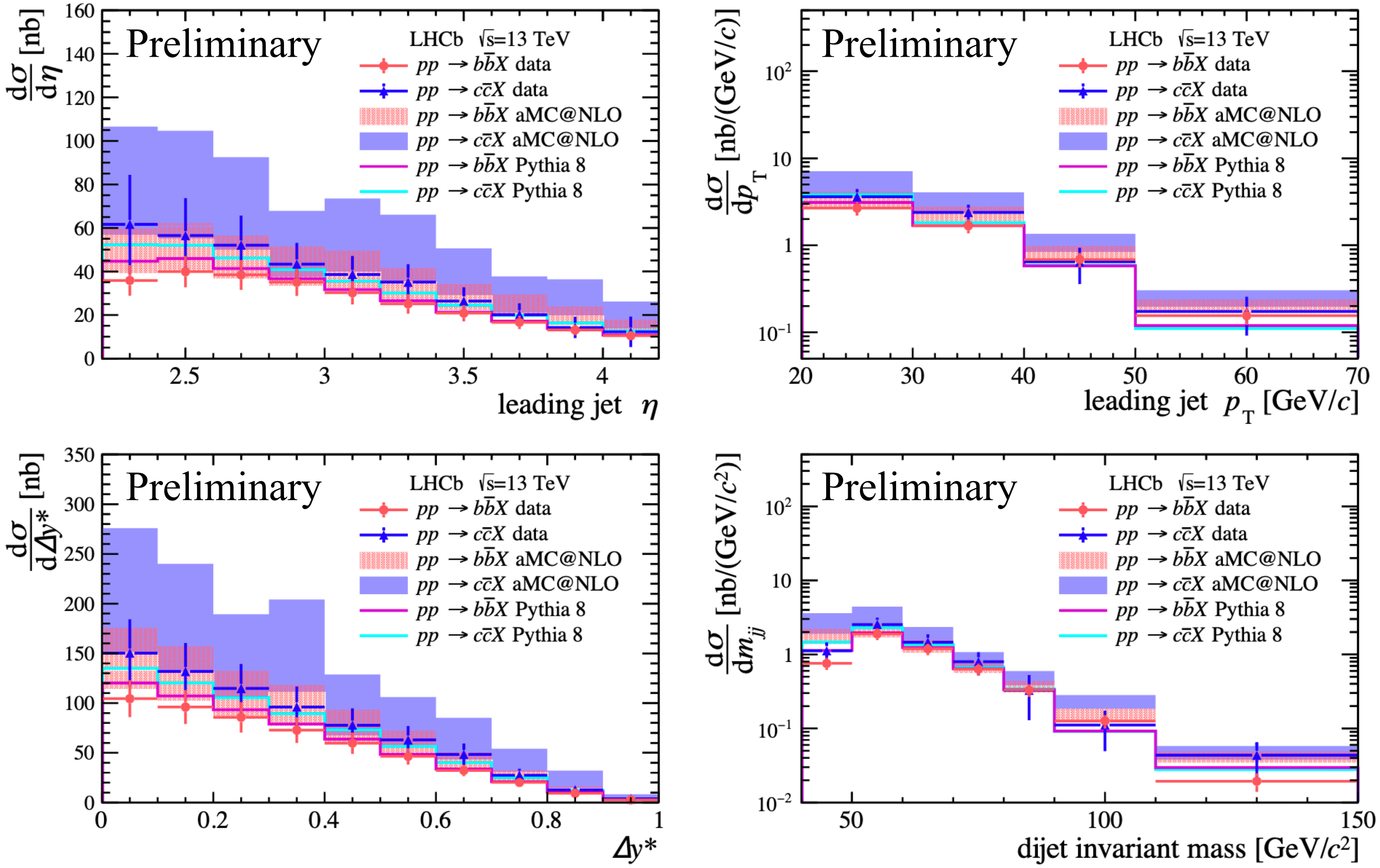
- Many new physics searches for massive particles look for decays to *b* and *c* jets; constraints from heavy quark measurements can clarify background contributions

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)



Charm and bottom dijet production

LHCb-PAPER-2020-018, in preparation



- Charm and bottom dijet yields measured as function of leading jet η, transverse momentum, rapidity difference, and invariant mass.
  - Anti-k_T algorithm with R= 0.5
- General agreement with shape of pQCD calculations, yields consistent with low edge
- Data uncertainties < pQCD uncertainties, dominated by uncertainties on renormalization and factorization scales, and PDF uncertainties.
- **Data provides new constraints**

Charm and bottom dijet production

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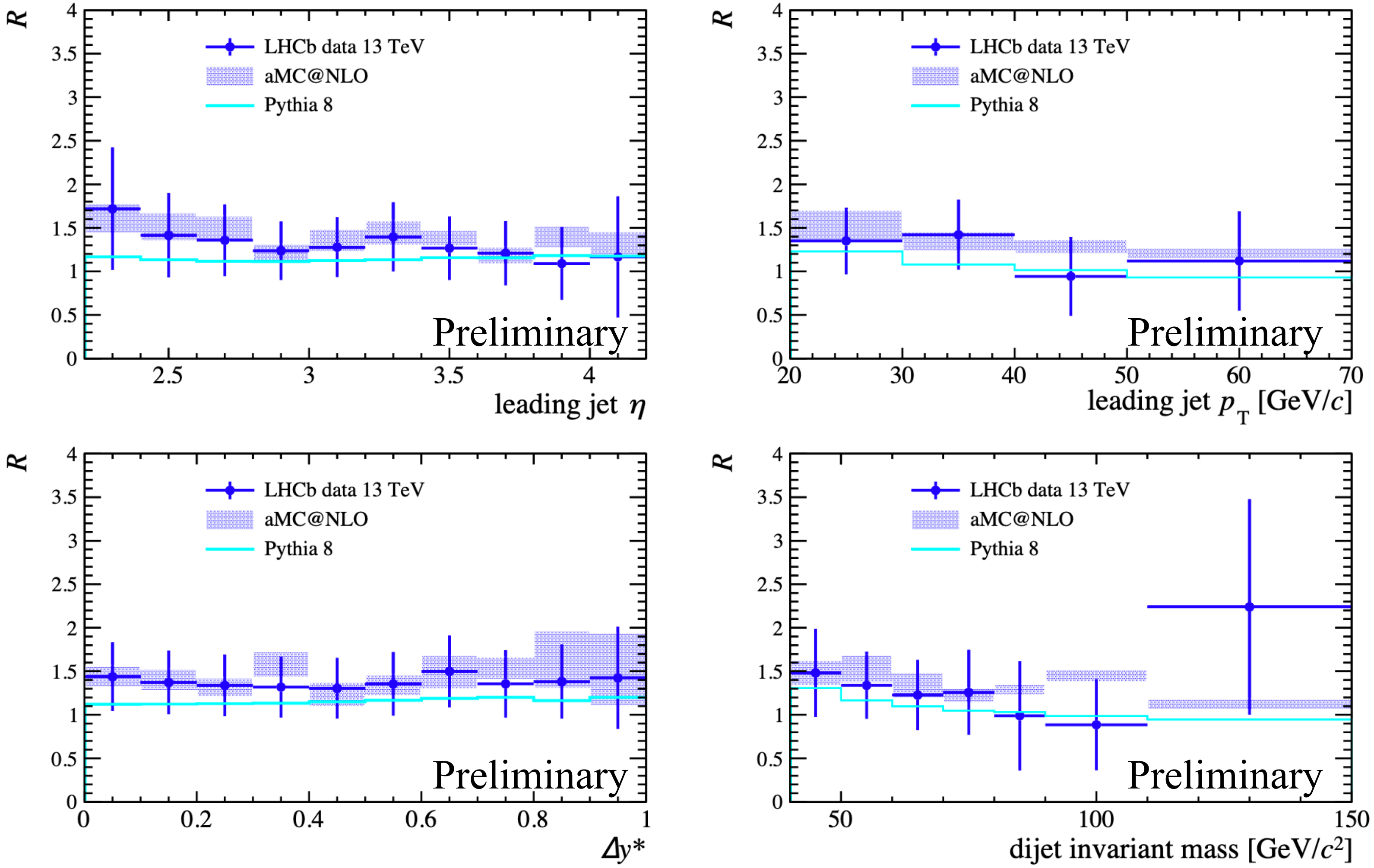

- Ratio of $c\bar{c}/b\bar{b}$ dijet cross sections
- Some uncertainties on predictions cancel in the ratio
- In general, good agreement with pQCD NLO calculations

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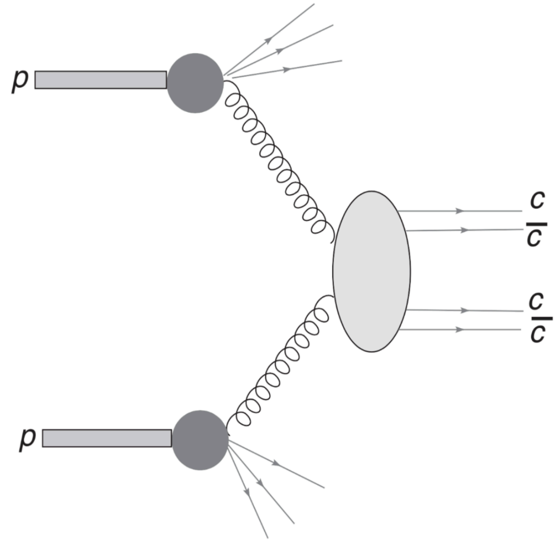
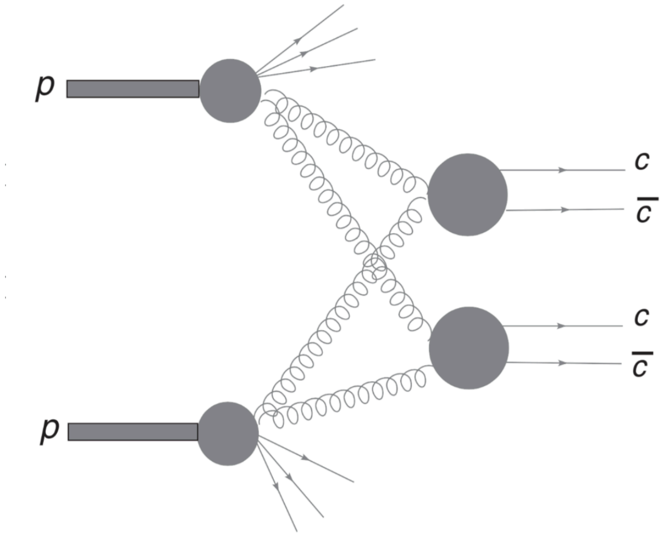


Single Parton Scattering



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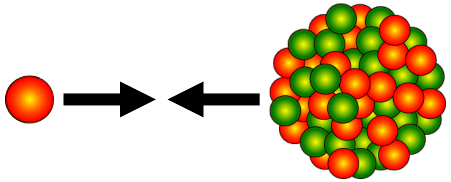


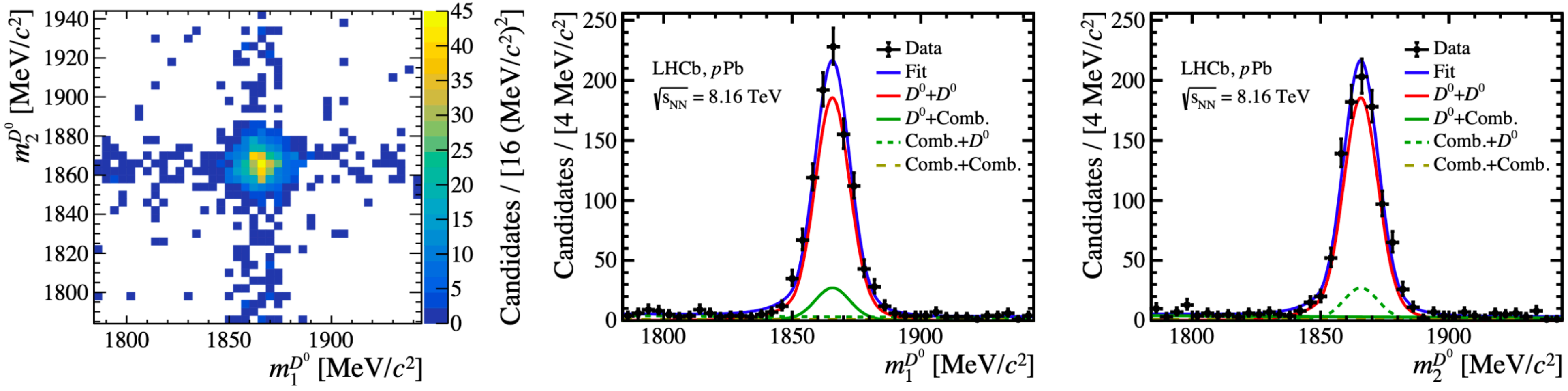
Enhancement of DPS is expected in pA relative to pp

Measure like-sign and opposite-sign pairs of D mesons (D^0, D^+,D_s^+) and J/ψD: correlated in SPS, uncorrelated in DPS

- Correlations can be modified relative to pp due to nuclear effects:
  - Modifications of the nuclear PDF (gluon saturation?)
  - Energy loss crossing nucleus, hydrodynamic effects?

Double charm production in *p*Pb collisions

arXiv:2007.06945



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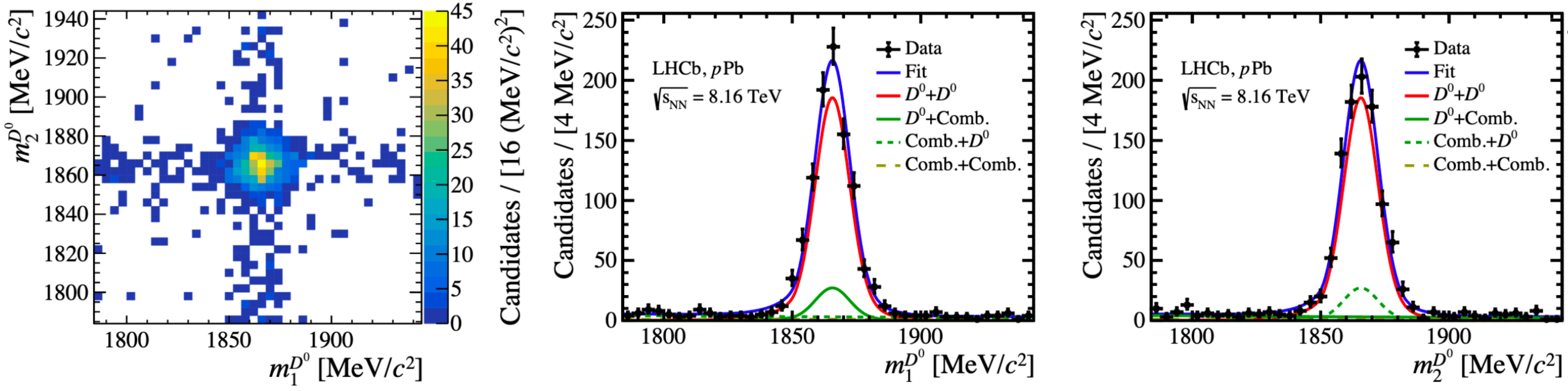

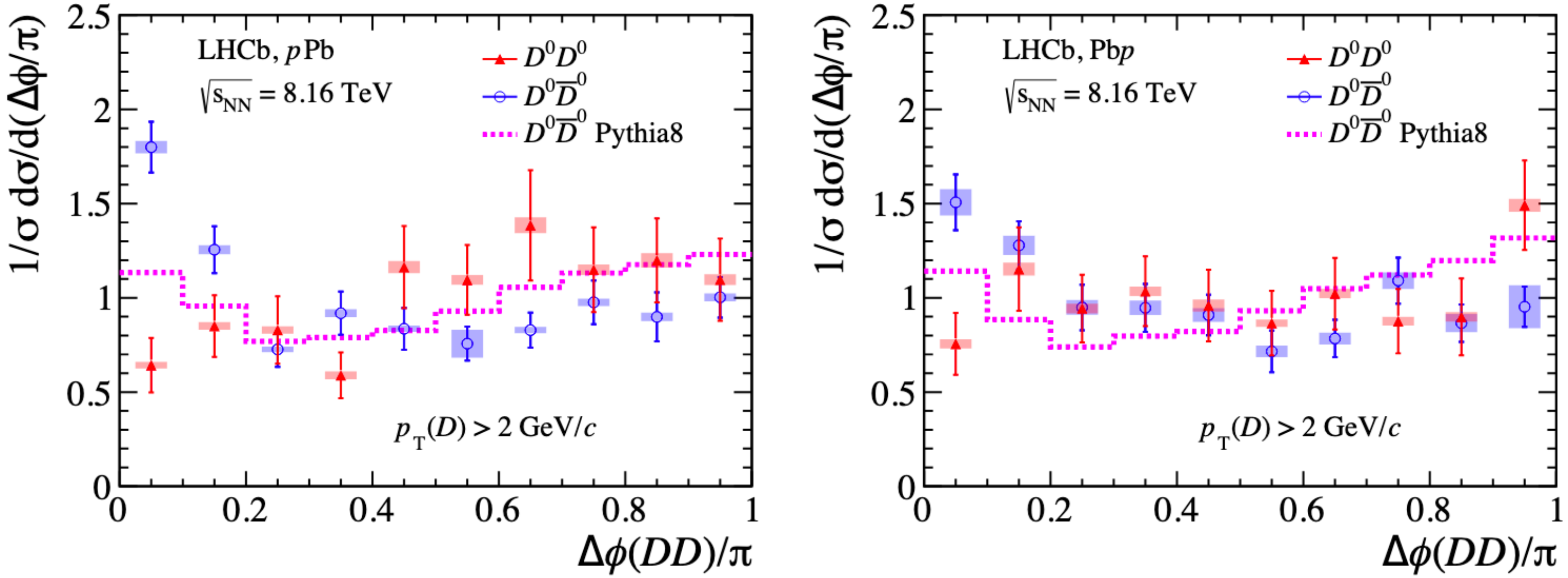

- Distribution of D^0D^0 consistent with flat
  - Uncorrelated pairs from DPS
- Distribution of $D\overline{D}$ rises at low $\Delta\phi$
  - Inconsistent with PYTHIA

Double charm production in pPb collisions

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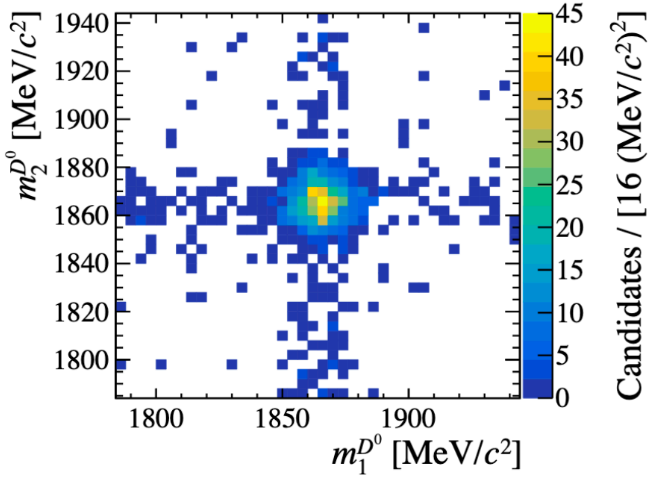

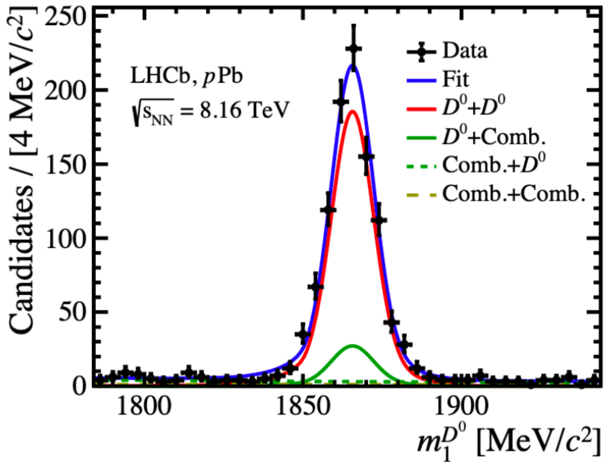

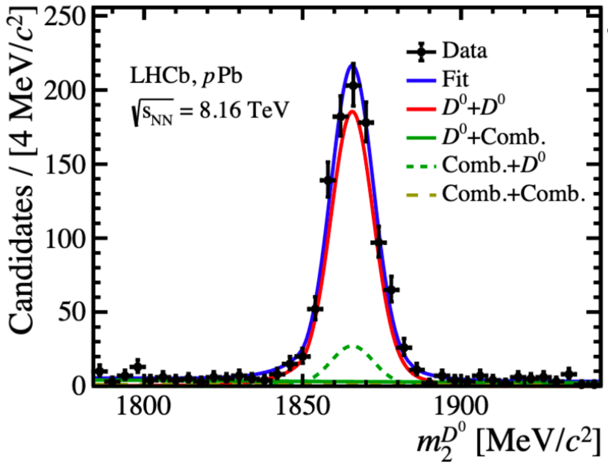

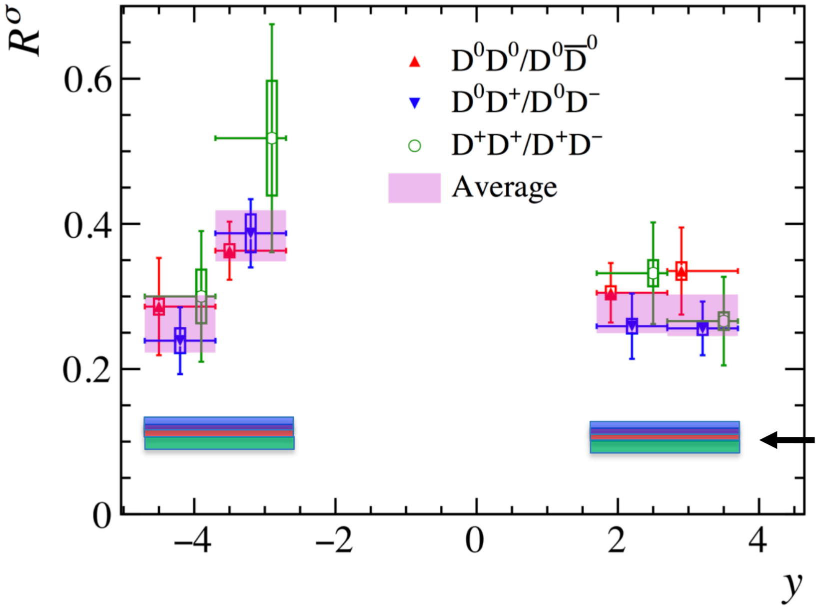

Results from pp collisions
JHEP 06 (2012) 141

- Significant increase in like-sign production cross sections compared to pp data (factor of ~3)
- Consistent with expectations for increased DPS in nuclear collisions

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X(3872) - a puzzle

Recently renamed $\chi_{c1}(3872)$ by PDG

- The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003, PRL 91 262001 (2003)
- Quantum numbers inconsistent with expected charmonium at measured mass, PRL 110 222001 2013

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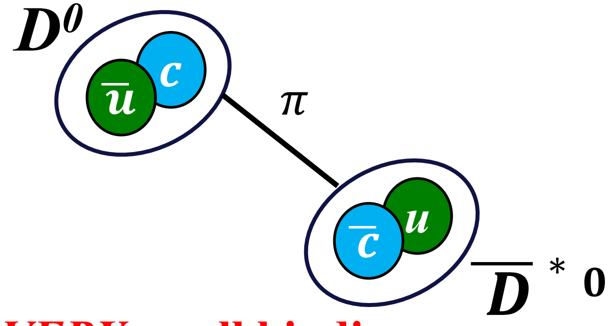
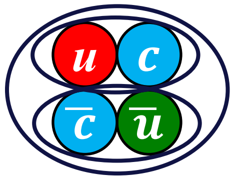
- In general, two different classes of X(3872) structure have been proposed:

$D^0\overline{D}^*$ Molecule



VERY **small binding energy**
VERY **large radius, ~7 fm**

Compact tetraquark



Tightly bound via color exchange between diquarks
Small **radius, ~1 fm**

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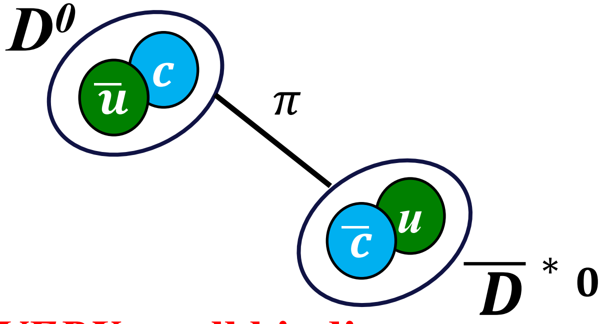

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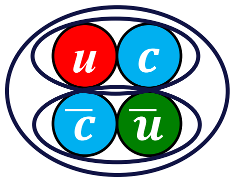

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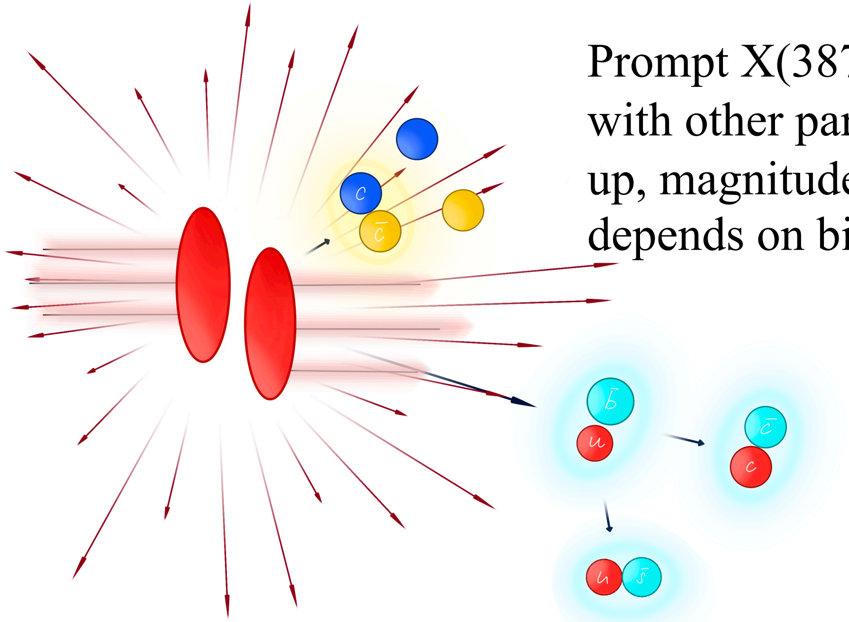
Technique from heavy ion collisions:



Prompt X(3872) can interact with other particles and break up, magnitude of disruption depends on binding energy

Invariant Mass Spectrum

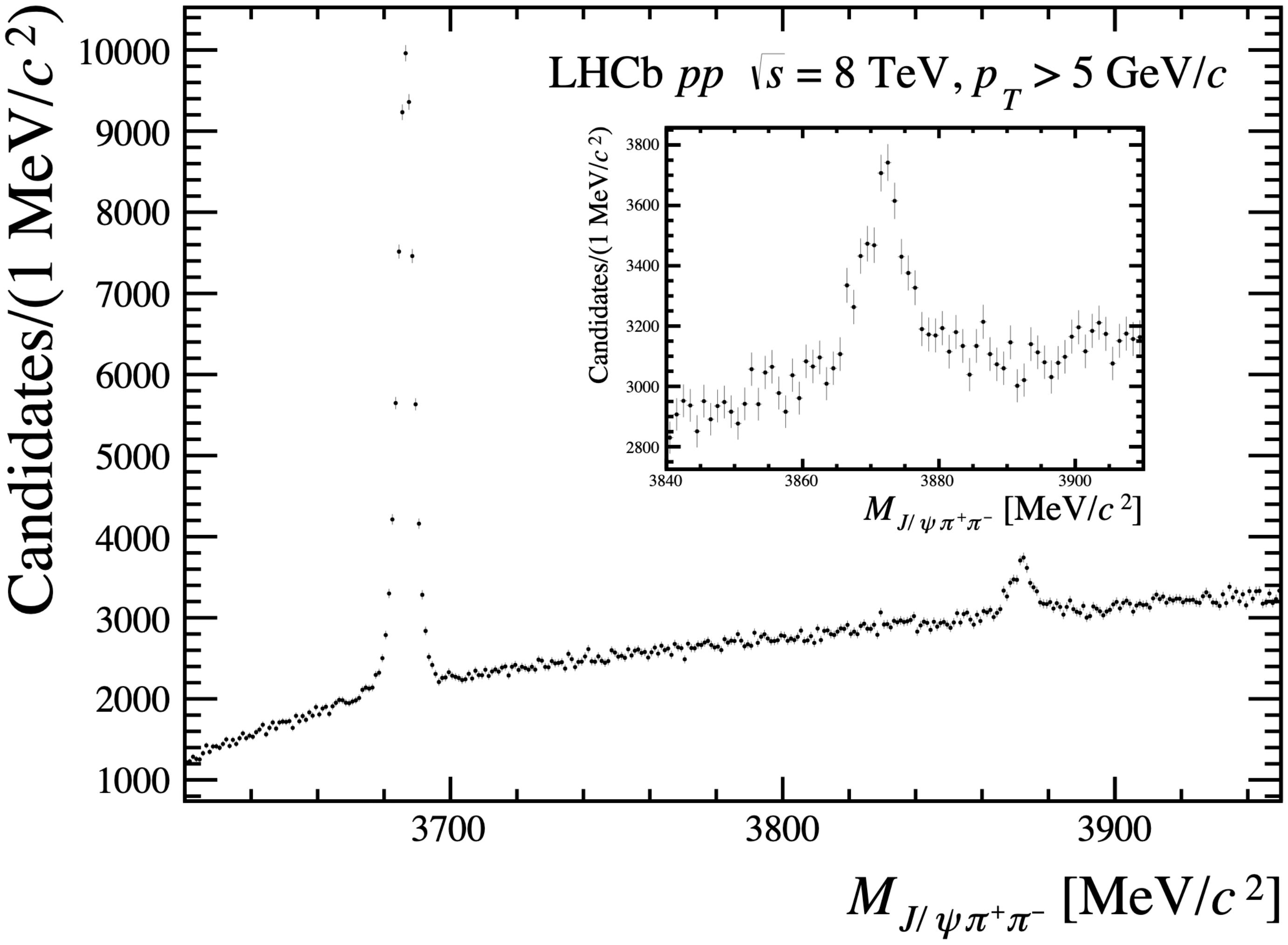
Reconstruct the $\mu^+\mu^-\ \pi^+\pi^-$ final state from the decays:

$$X(3872) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho(\rightarrow \pi^+\pi^-)$$

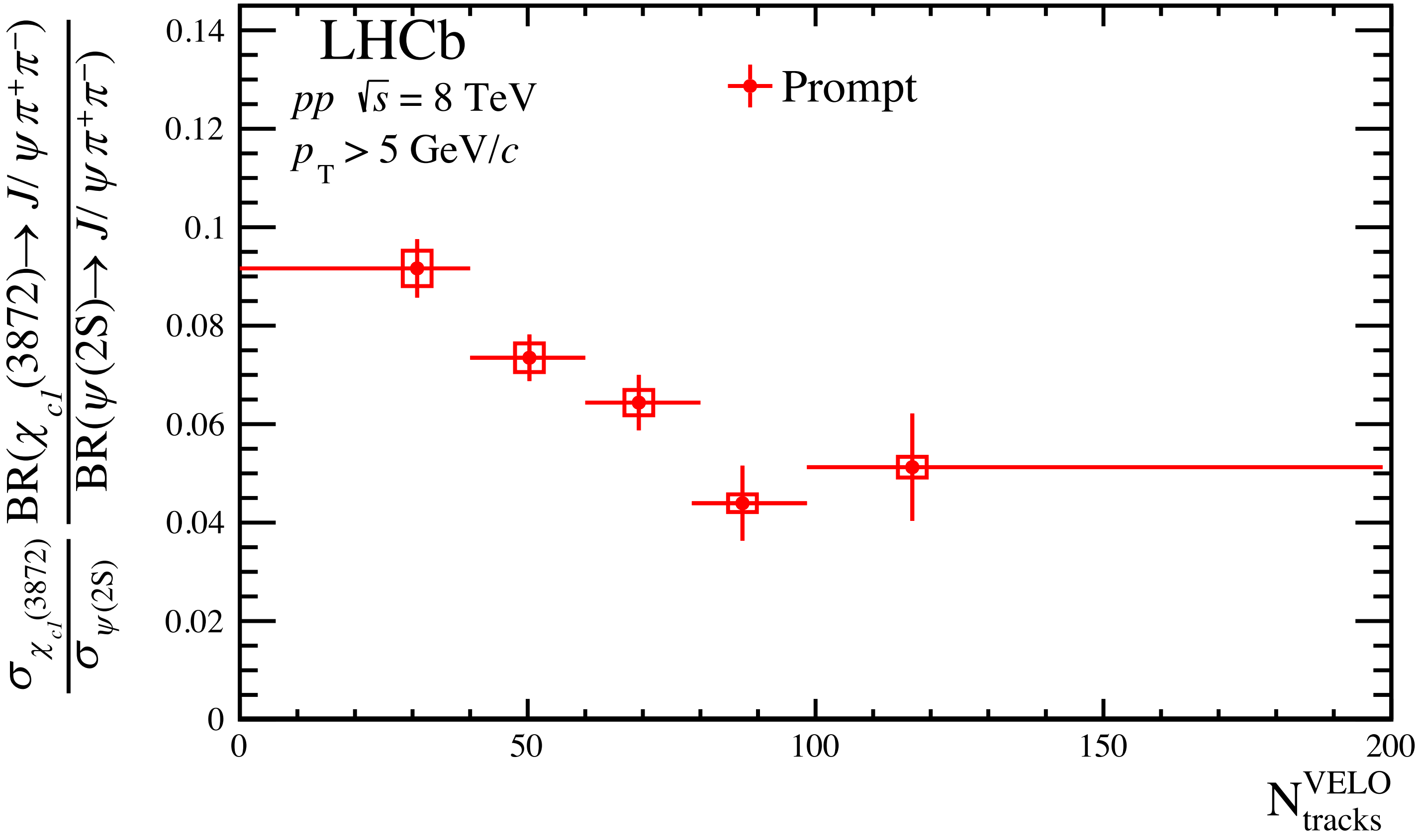
$$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$$

Direct comparison between conventional charmonium $\psi(2S)$ and exotic $X(3872)$ via ratio of cross sections:

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]}$$



X(3872)/ψ(2S)



Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

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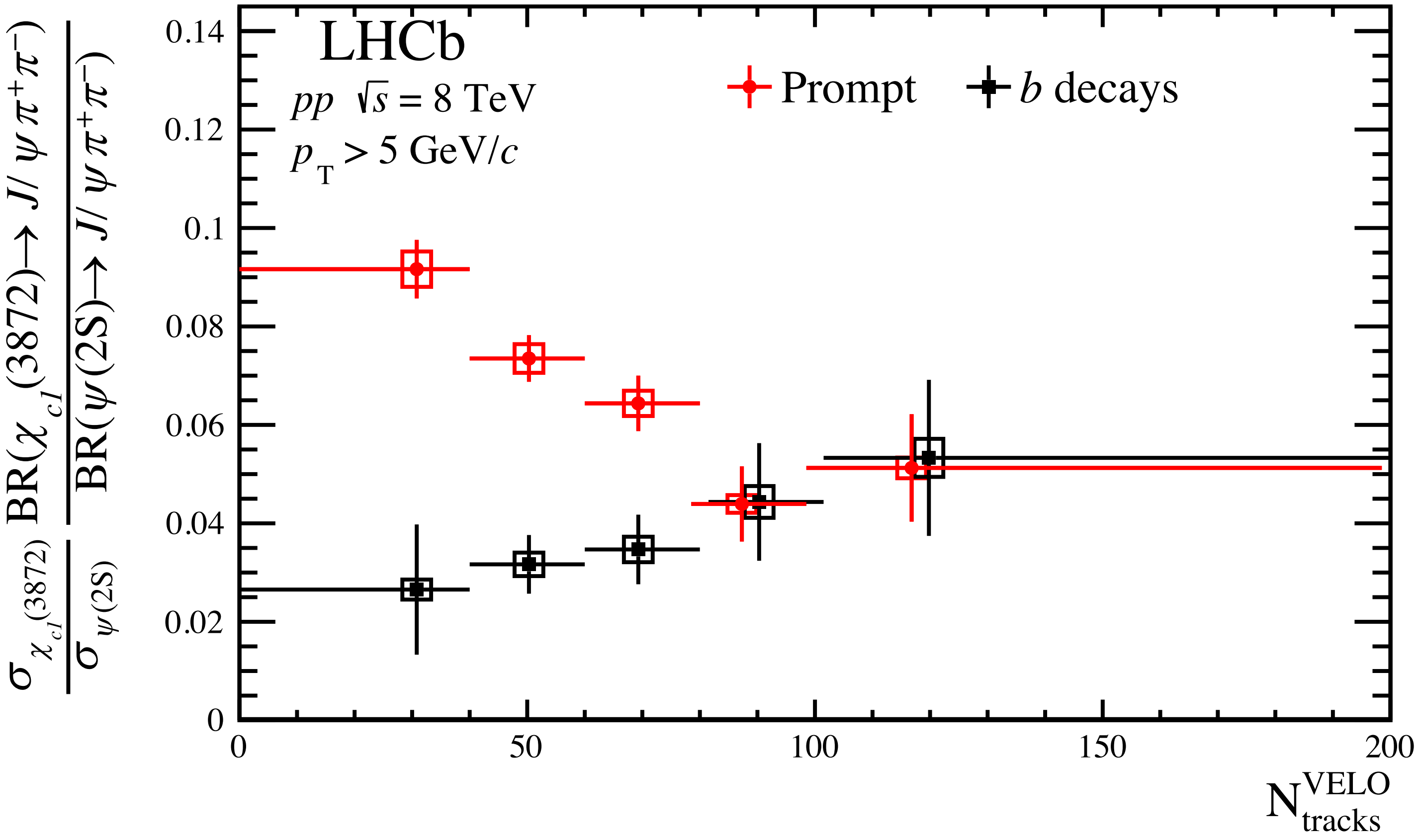

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Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.

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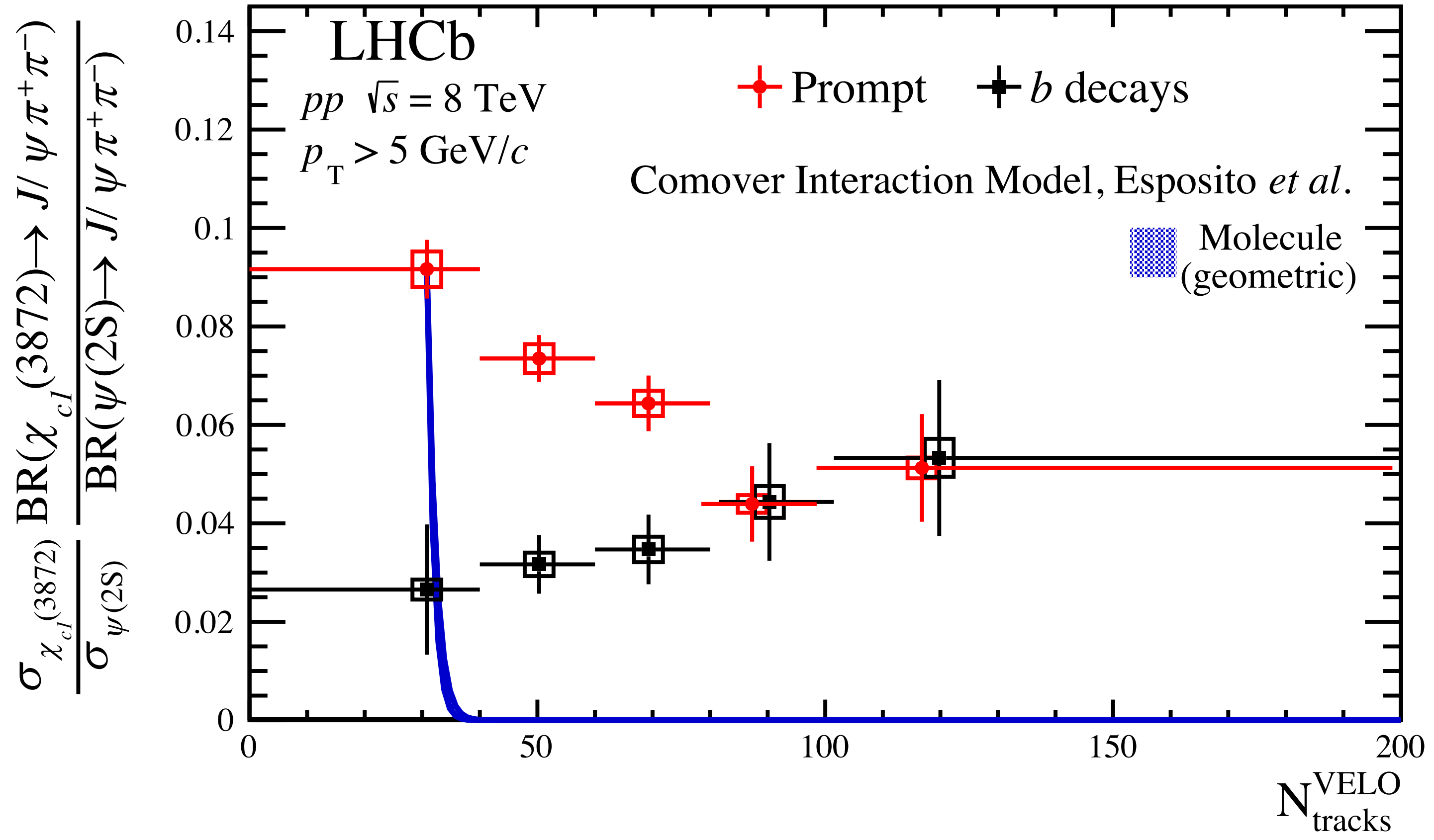

Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

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Calculations from arXiv:2006.15044

Break-up cross section:

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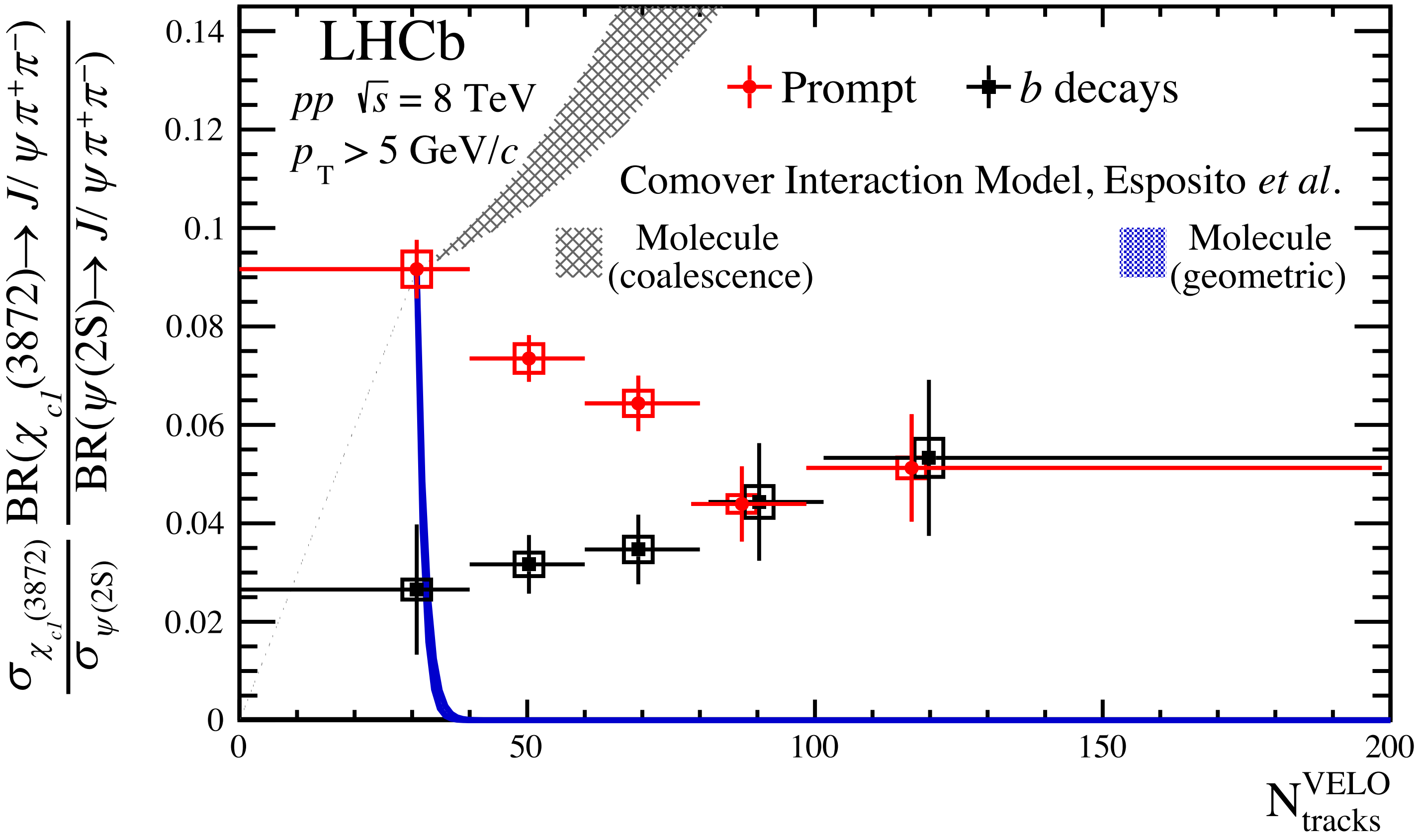

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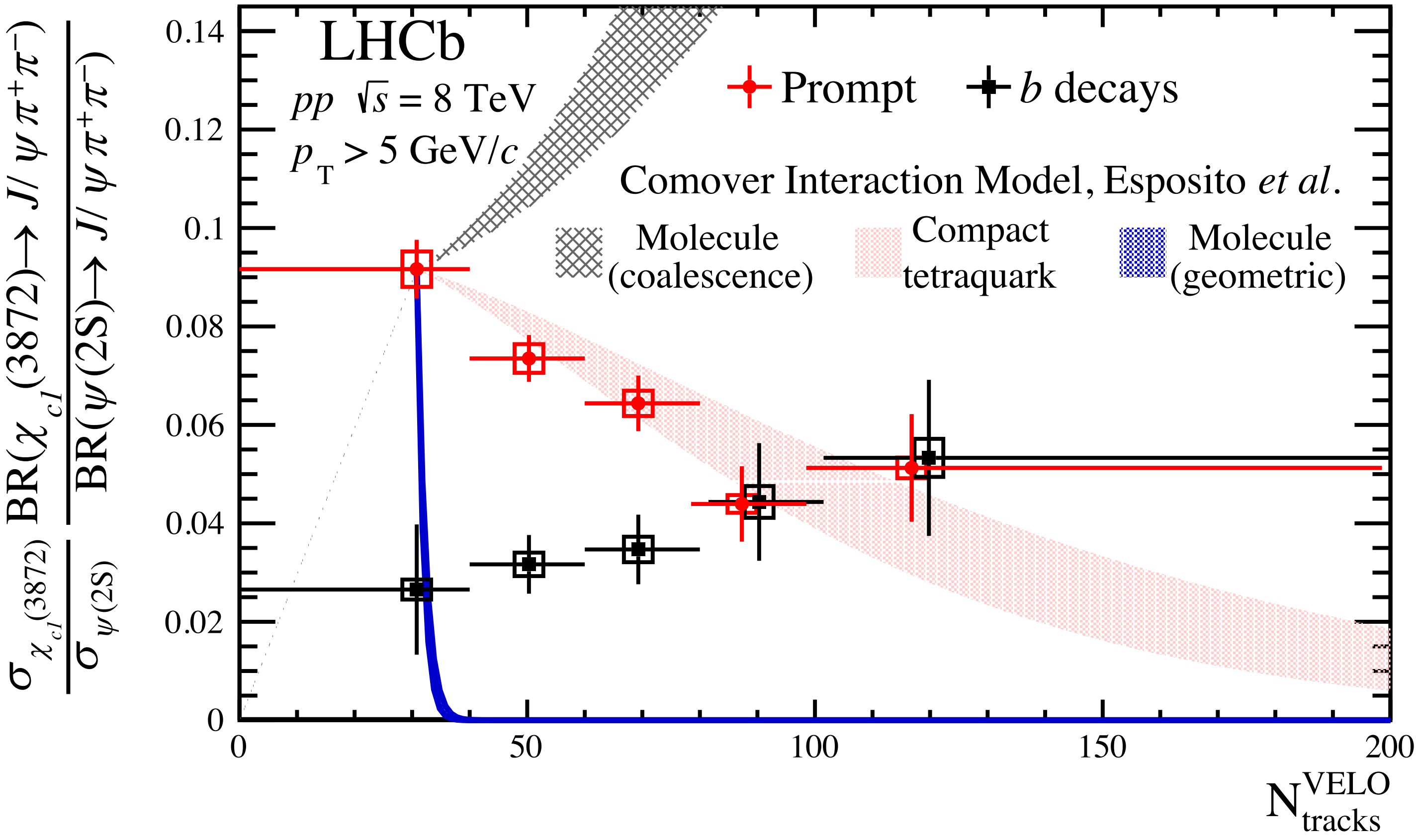

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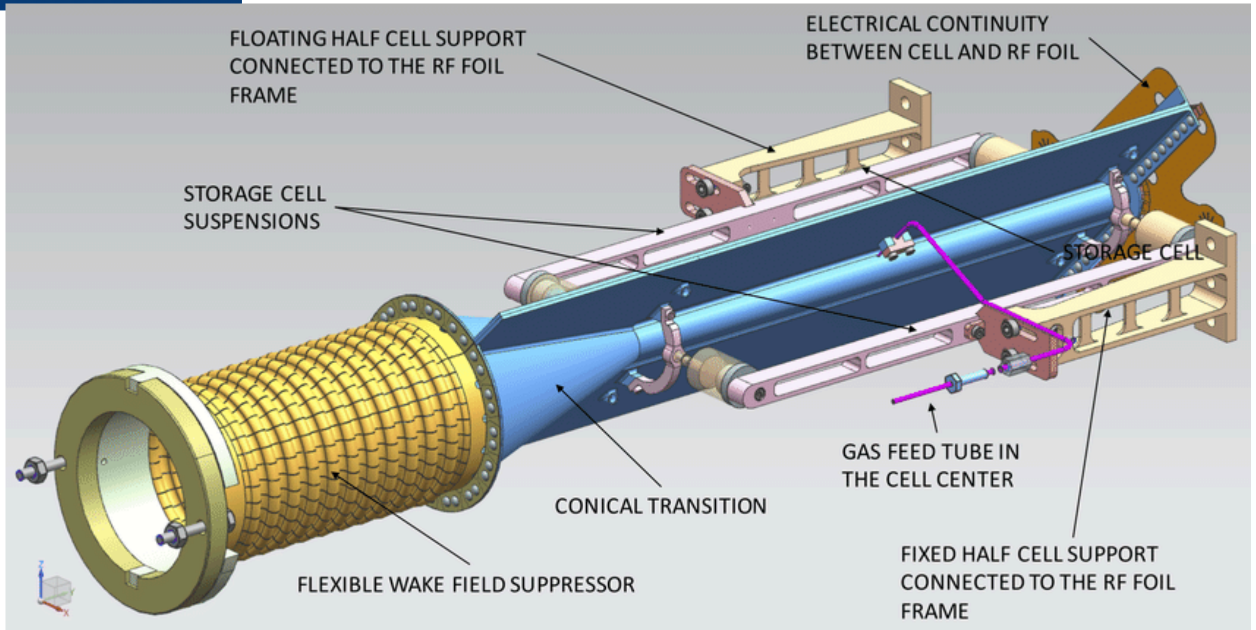
Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases

Fixed target at LHCb: SMOG II



https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

Installed last month!

Example SMOG2 pAr at 115 GeV for one year

Int. Lumi.		80 pb^{-1}
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

Upgraded SMOG system at LHCb allows greatly increased rates of beam+injected gas collisions

No centrality limitations in p+gas or Pb+gas at LHCb

Large heavy flavor samples
Access to exotic states near RHIC energies

Summary

- Heavy quark production at hadron colliders probes a range of phenomena:
  - Precision tests of pQCD
  - Constraints on nPDFs
  - Heavy quark production mechanisms
- LHCb is exploring new observables to constrain models of exotics
- Major upgrades to fixed target system, detector, and DAQ promise a rich heavy quark program at LHCb in the near future

BACKUPS

Probing X(3872) structure via interactions with the underlying event

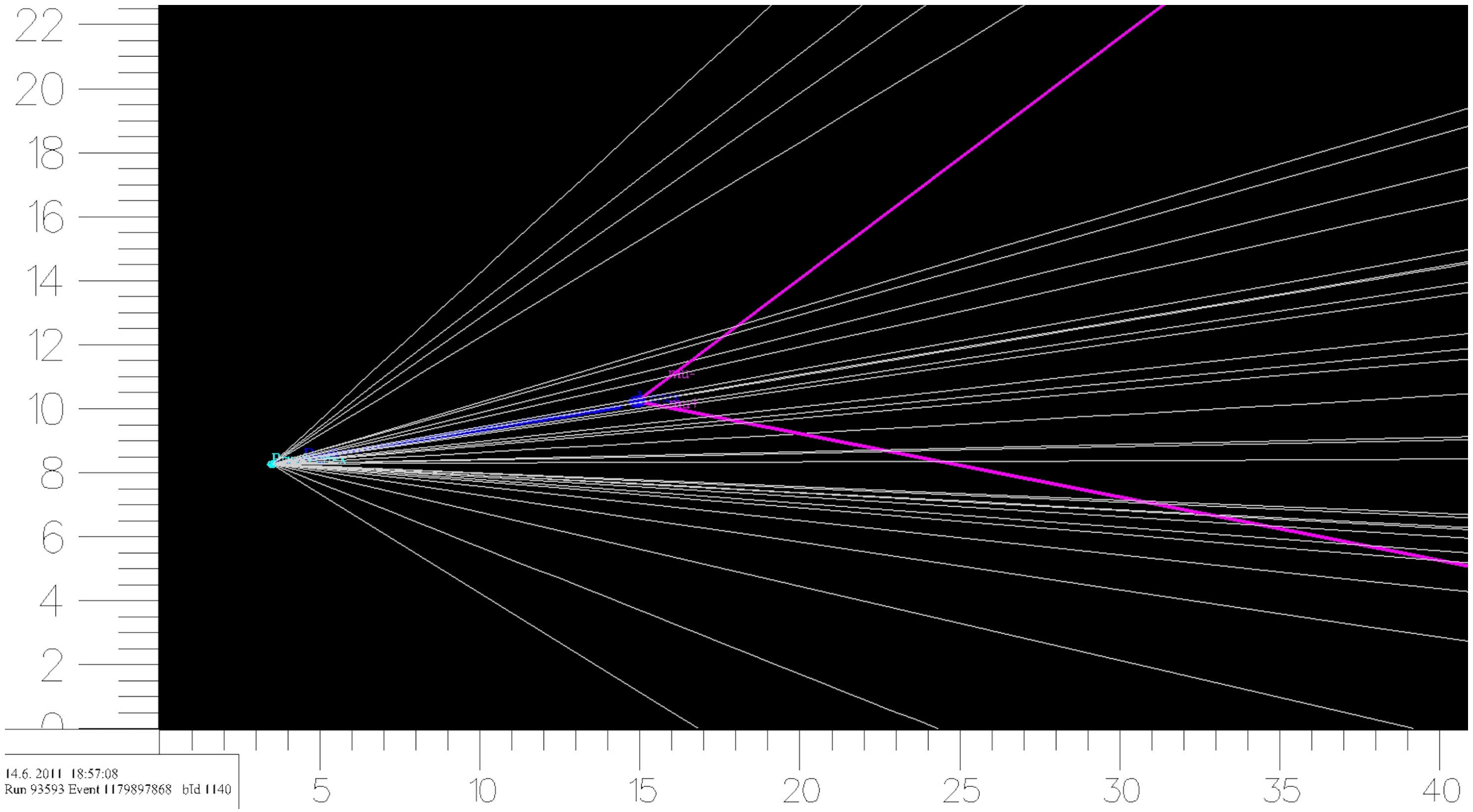
Prompt production:

- X(3872) produced at collision vertex can be subject to further interactions with co-moving particles (medium?) produced in the event
- Potentially subject to breakup effects

Production in ***b***-decays:

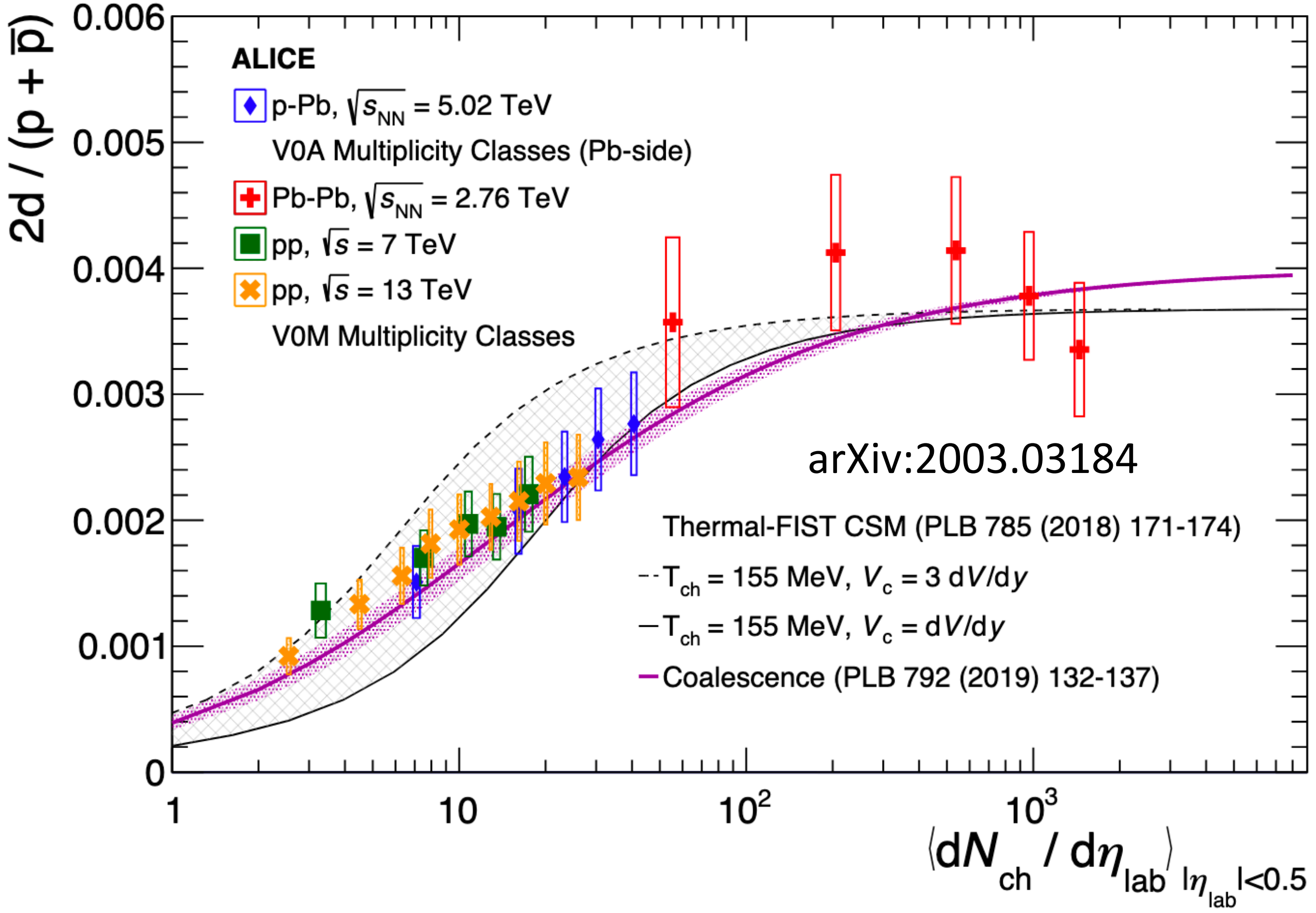
- Hadrons containing ***b*** travel down the beampipe and decay away from the primary vertex and decay in vacuum
- X(3872) from decays not subject to further interactions
- Control sample

Event display of $B_s^0 \to \mu^+\mu^-$ candidate, PRL 118 191801 (2017)

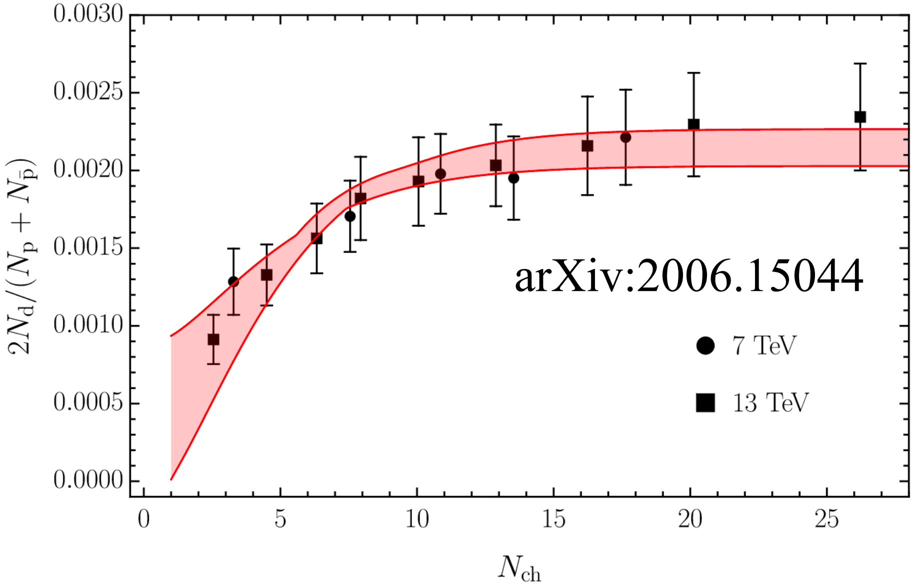


Deuteron production vs multiplicity

Deuterons – often considered a neutron+proton hadronic molecule



In contrast to X(3872)/ψ(2S), the d/p multiplicity dependence is well described by coalescence models



The LHCb Detector

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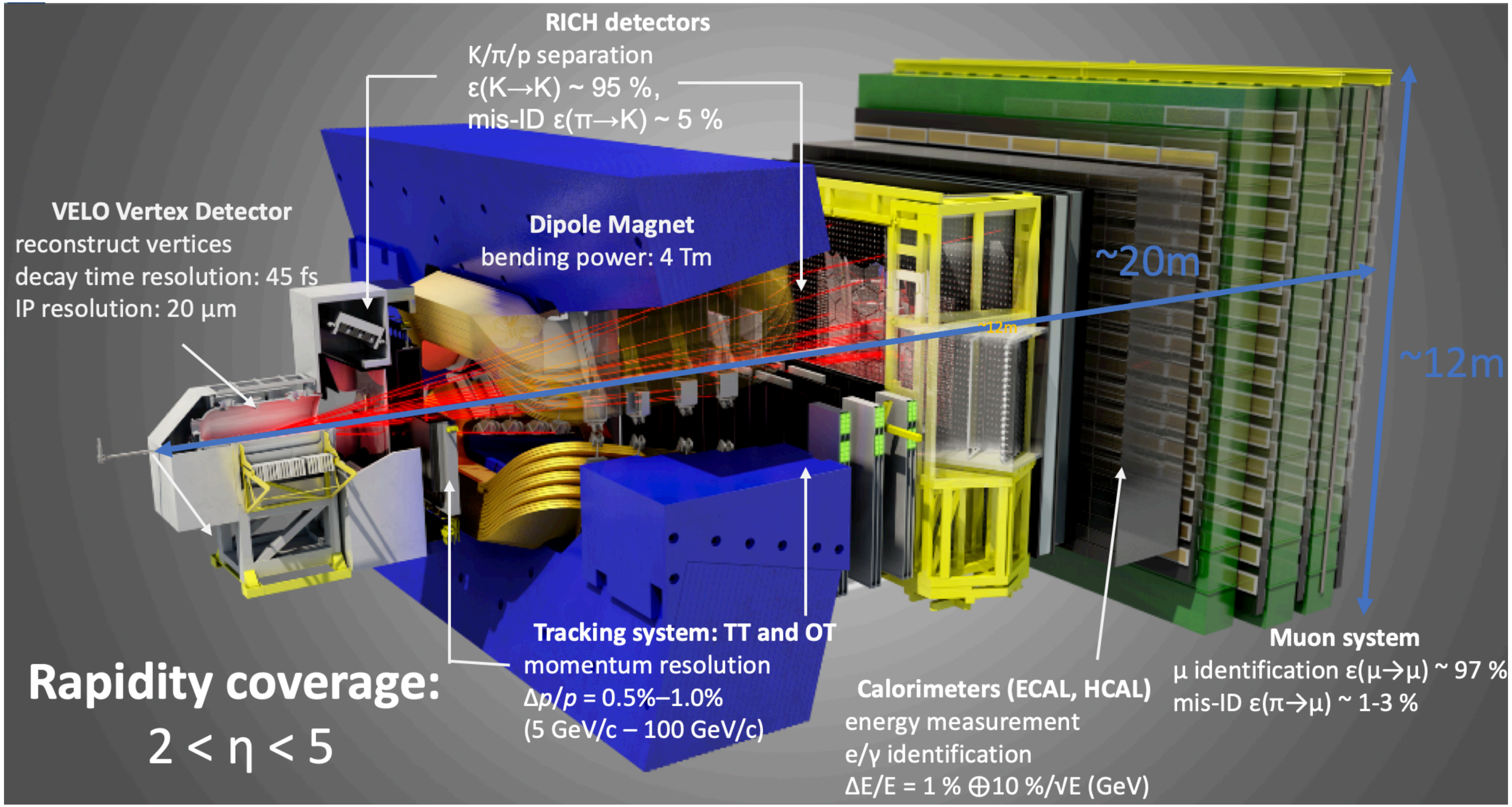
Int. J. Mod. Phys. A 30, 1530022 (2015)

$X(3872) \to J/\psi\pi^+\pi^-$

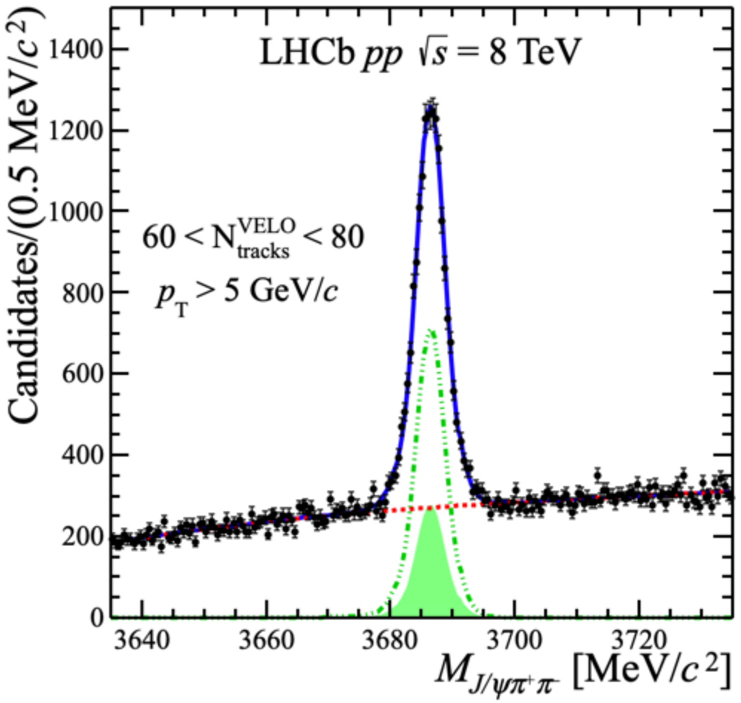
Vertex detector (VELO):
-Separation of prompt and ***b***-decay production
-Number of VELO tracks gives measure of event activity

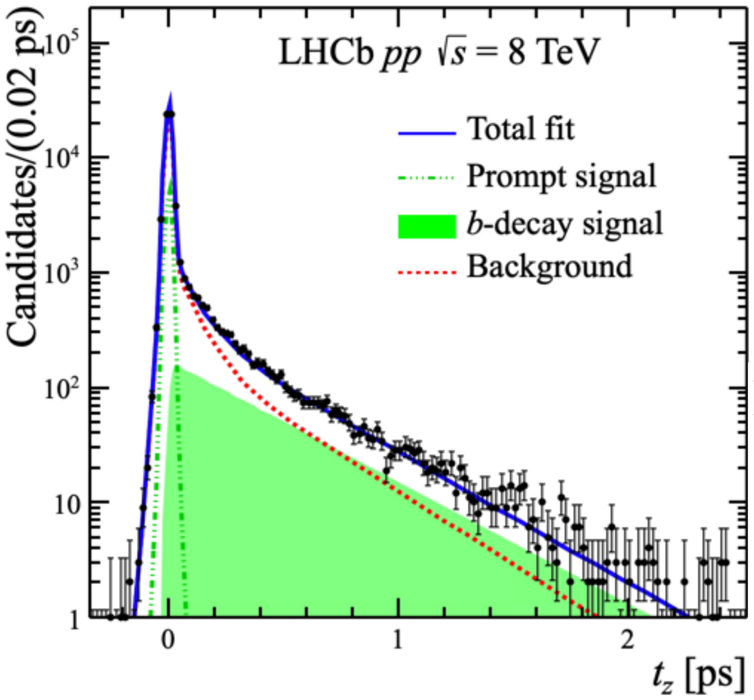
Two RICH detectors:
-Pion identification

Muon System:
-Layers of absorber/tracking
-Muon hardware trigger



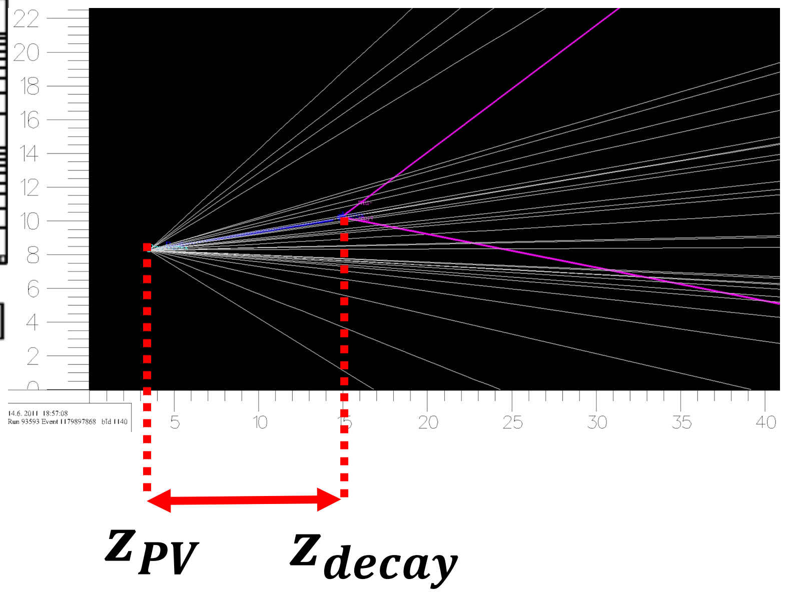
Prompt / *b*-decay separation





Simultaneous fit to invariant mass and pseudo proper time spectrum:

$$t_z = \frac{z_{decay} - z_{PV}}{p_z} M$$



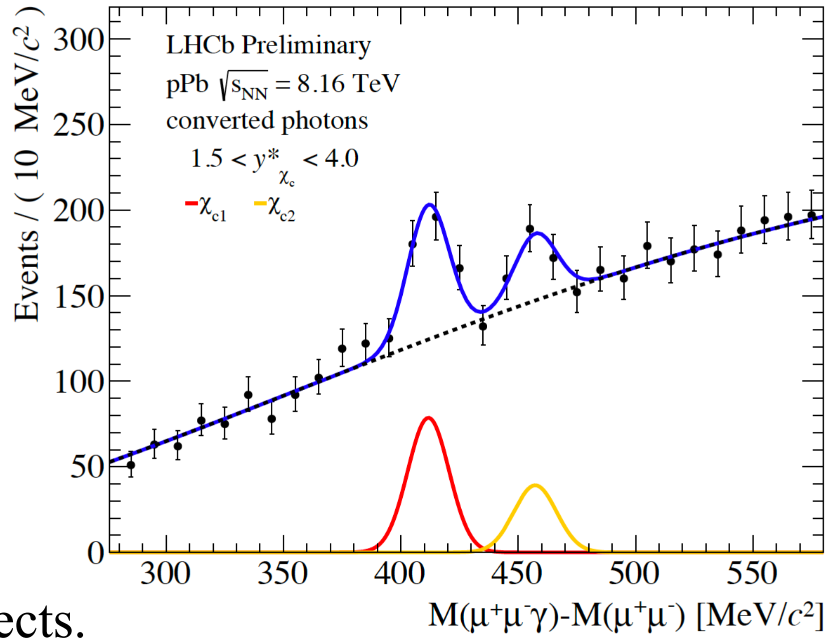
Fit to mass constrains S/B while fit to t_z constrains prompt fraction

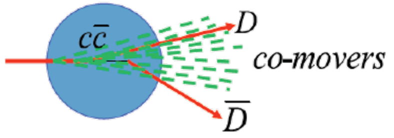
Effects of Binding Energy

- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
  - Ratios of $^{\psi(2S)}/_{J/\psi}$ and $^{\Upsilon(2S,3S)}/_{\Upsilon(1S)}$

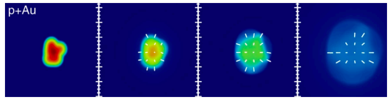
- In general, final state effects are required to explain difference in suppression between states
- Prevalent in regions with high particle multiplicity

- Weakly bound hadronic molecules may show similar effects.





cf. PLB 749 98 (2015)



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$D\bar{D}^*$ ***Molecule***

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

Satz, J. Phys. G 32 (3) 2006