Physics with Heavy Ions and Exotic Hadrons at LHCb

Matt Durham

Los Alamos National Laboratory

BNL Nuclear Physics Seminar 7 Jan 2020

Outline

- LHCb Physics program
- Apparatus
- Heavy Ions at LHCb
  - Collider Mode
  - Fixed Target Mode (SMOG)
- Exotics at LHCb
- Upgrades

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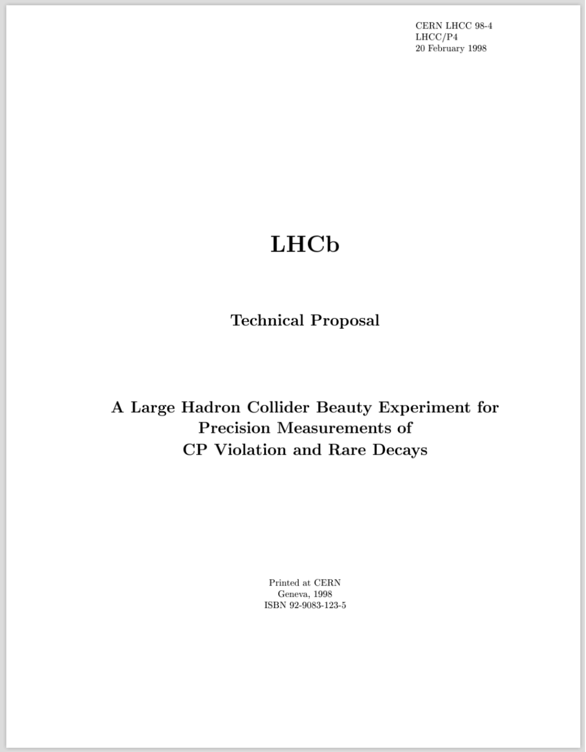
LHCb Physics Program


CERN LHCC 98-4
LHCC/P4
20 February 1998

LHCb

Technical Proposal

A Large Hadron Collider Beauty Experiment for
Precision Measurements of
CP Violation and Rare Decays

Printed at CERN
Geneva, 1998
ISBN 92-9083-123-5

1998 Technical Proposal:
“Beauty Experiment for
CP Violation and Rare Decays”

LHCb Physics Program

PHYSICAL REVIEW LETTERS **122,** 211803 (2019)

Editors' Suggestion | Featured in Physics

Observation of *CP* Violation in Charm Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

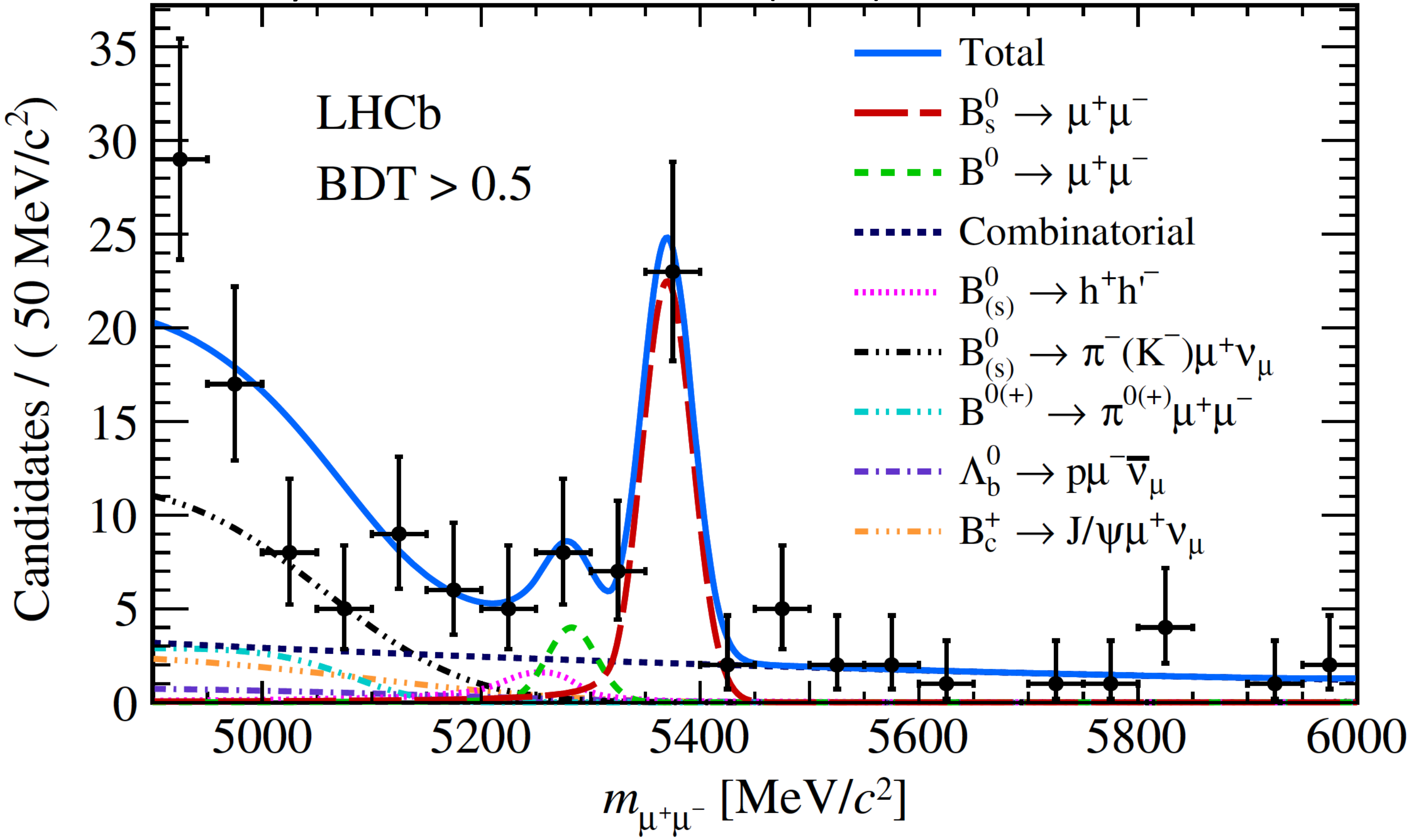
(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

A search for charge-parity (CP) violation in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is reported, using pp collision data corresponding to an integrated luminosity of 5.9 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the charm meson is inferred from the charge of the pion in $D^*(2010)^+ \to D^0 \pi^+$ decays or from the charge of the muon in $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$ decays. The difference between the CP asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2(\mathrm{stat}) \pm 0.9(\mathrm{syst})] \times 10^{-4}$ for π-tagged and $\Delta A_{CP} = [-9 \pm 8(\mathrm{stat}) \pm 5(\mathrm{syst})] \times 10^{-4}$ for μ-tagged D^0 mesons. Combining these with previous LHCb results leads to $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than 5 standard deviations. This is the first observation of CP violation in the decay of charm hadrons.

- CKM Mechanism and CP violation
  - First observation of CP violation in the charm sector

LHCb Physics Program

Phys. Rev. Lett. 118 191801 (2017)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

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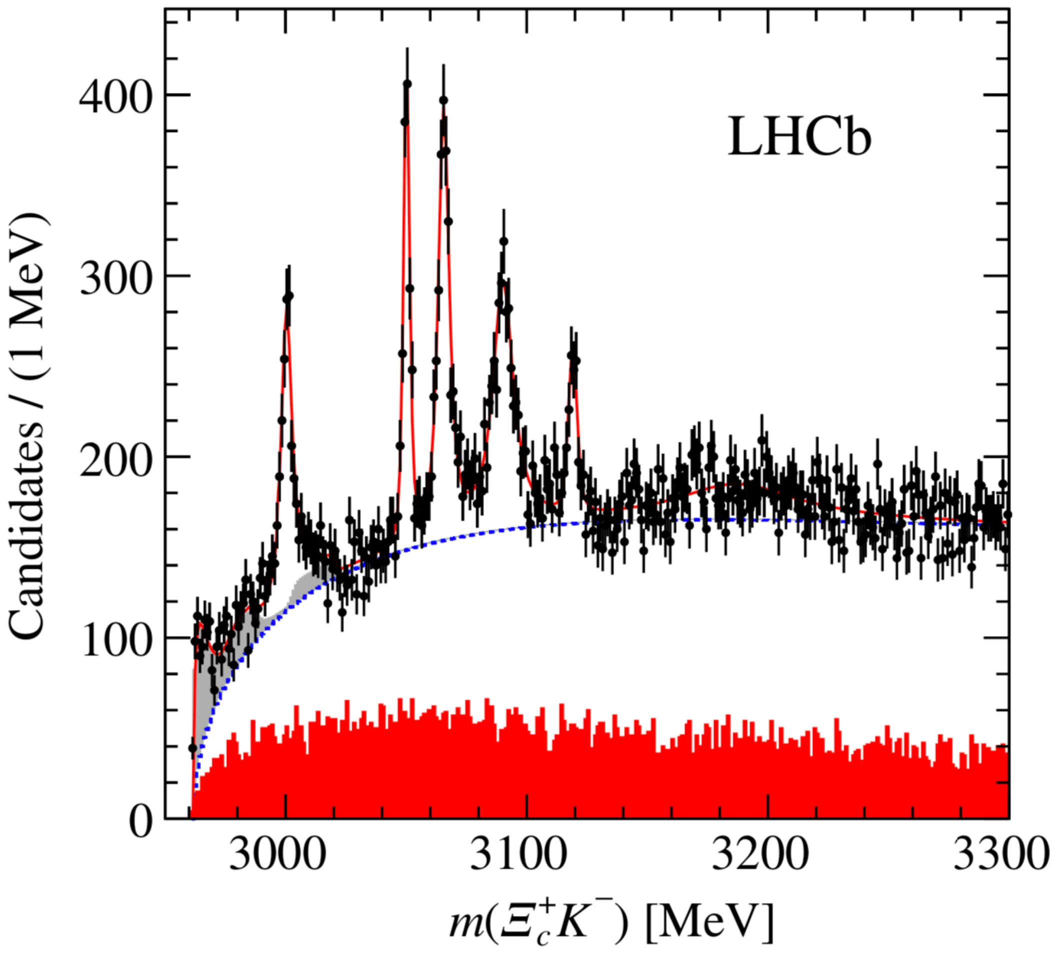
  - First observation of CP violation in the charm sector

Rare decays

- $B_s \to \mu\mu$, $b \to s\, \ell^+\ell^-$

LHCb Physics Program



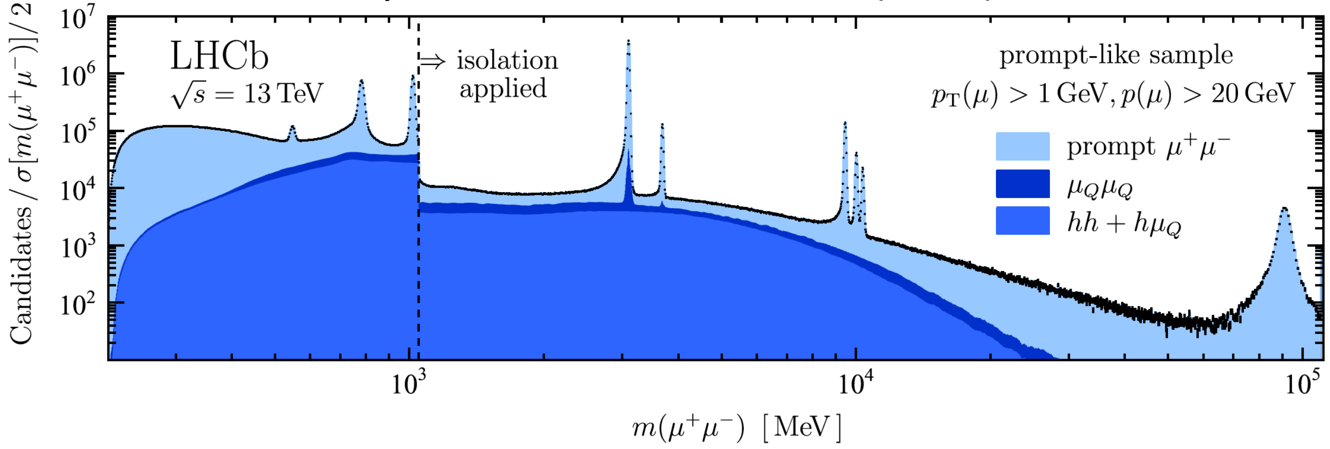
$\Xi_c^+ \rightarrow pK^-\pi^+$

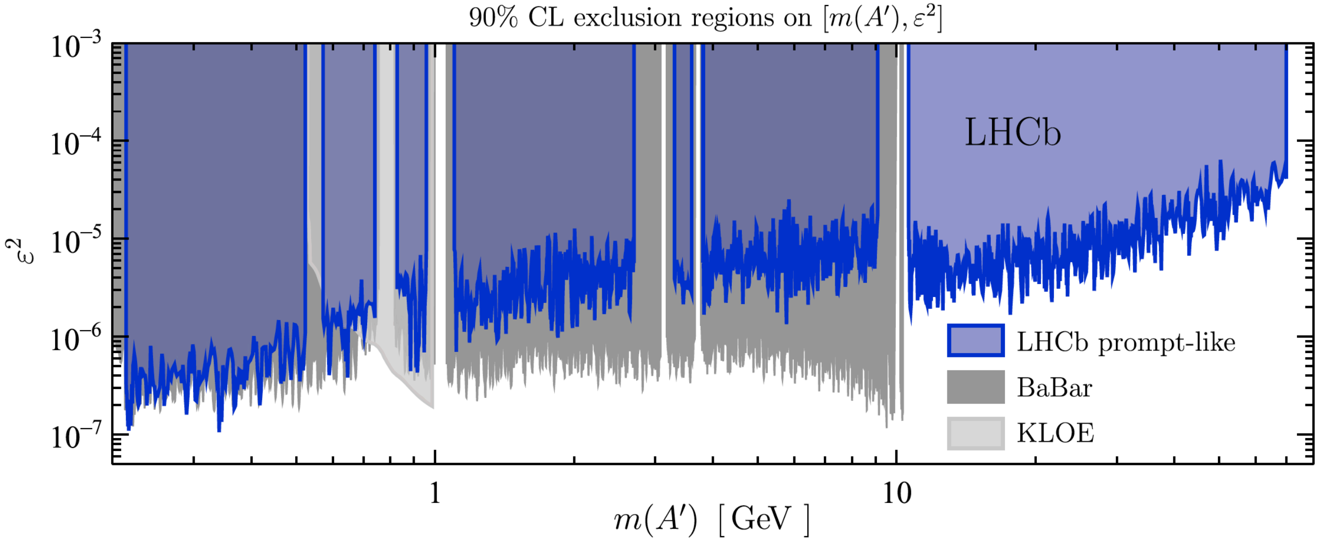
Phys. Rev. Lett. 118 182001 (2018)

- CKM Mechanism and CP violation
  - First observation of CP violation in the charm sector
- Rare decays
  - $B_s \rightarrow \mu\mu$, $b \rightarrow s\, \ell^+\ell^-$
- Spectroscopy
  - Observation of 5 new Ω_c baryons

LHCb Physics Program

Phys. Rev. Lett. 120 061801 (2018)





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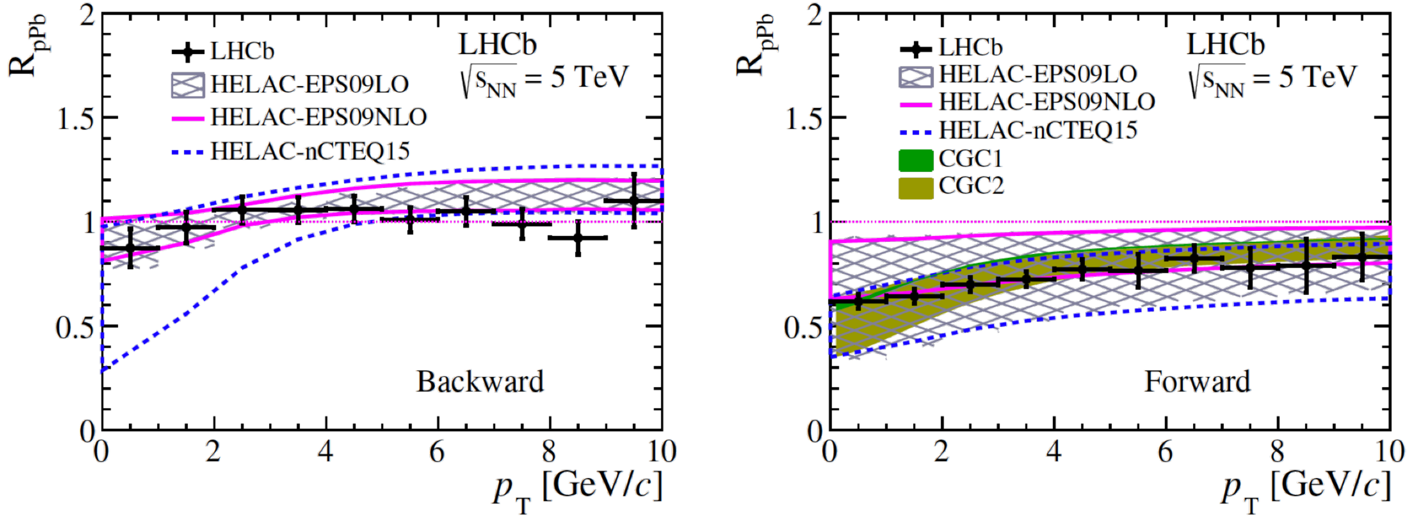
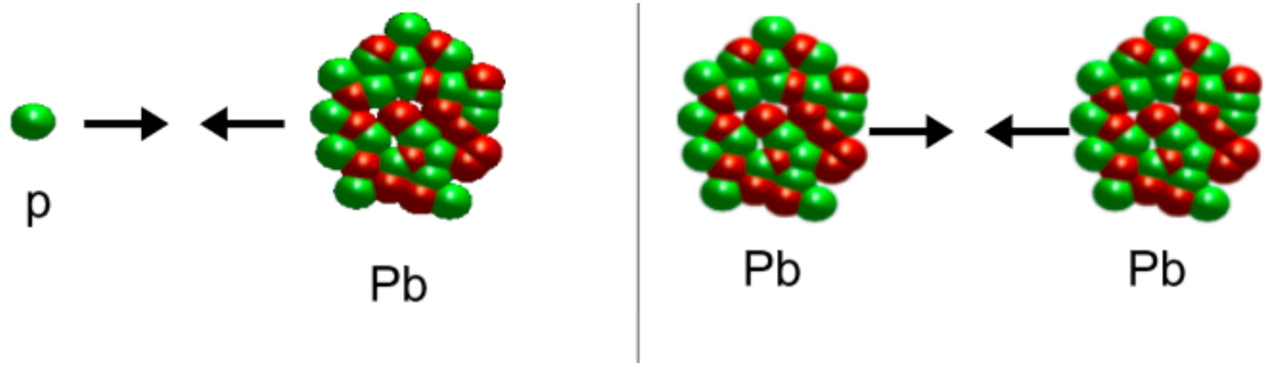
  - Limits on $A' \to \mu\mu$ decays

LHCb Physics Program

JHEP10 (2017) 090





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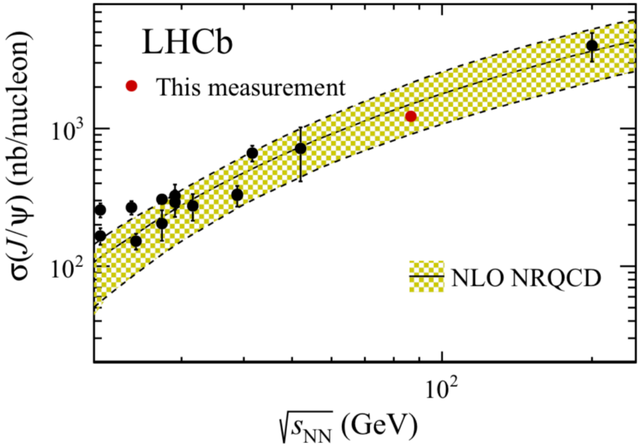
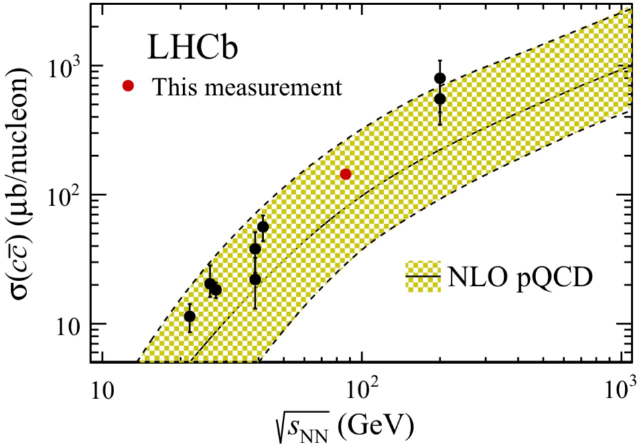
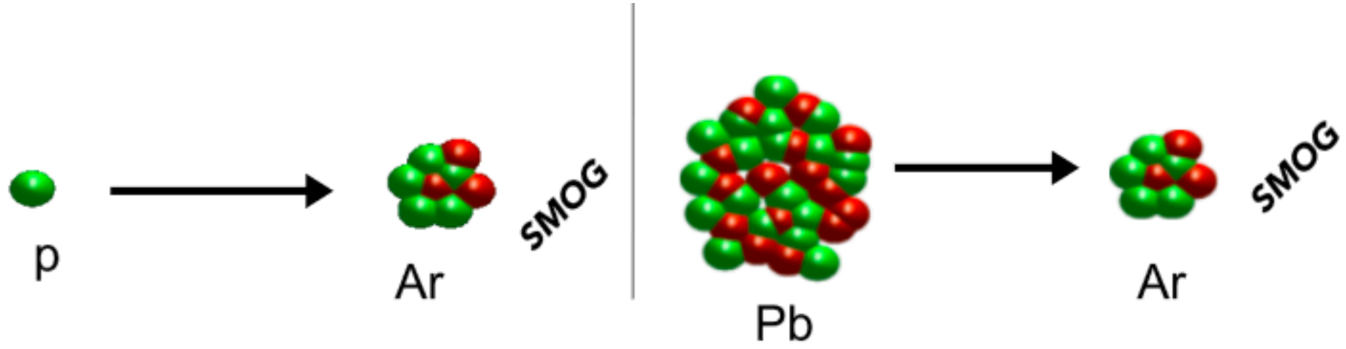
- Heavy ion collisions
    - Heavy flavor in pPb, PbPb collisions

LHCb Physics Program

Phys. Rev. Lett. 122, 132002 (2019)







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- Fixed target collisions
  - pHe, pNe, pAr, PbNe, PbAr, etc accessible by injecting gas into beampipe

LHCb Physics Program

Huge evolution in physics program:

LHCb is a *general purpose* detector covering forward rapidity

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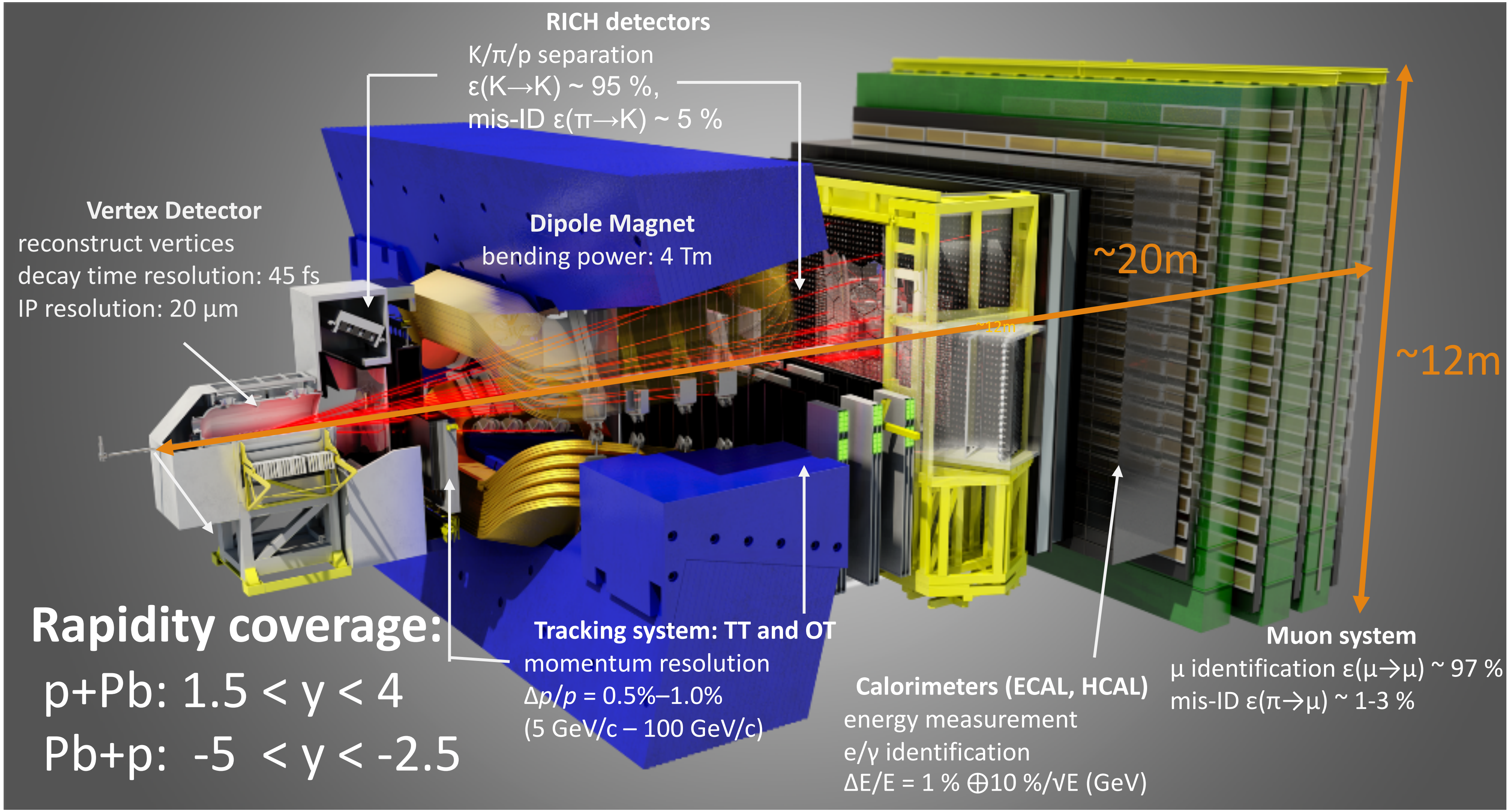
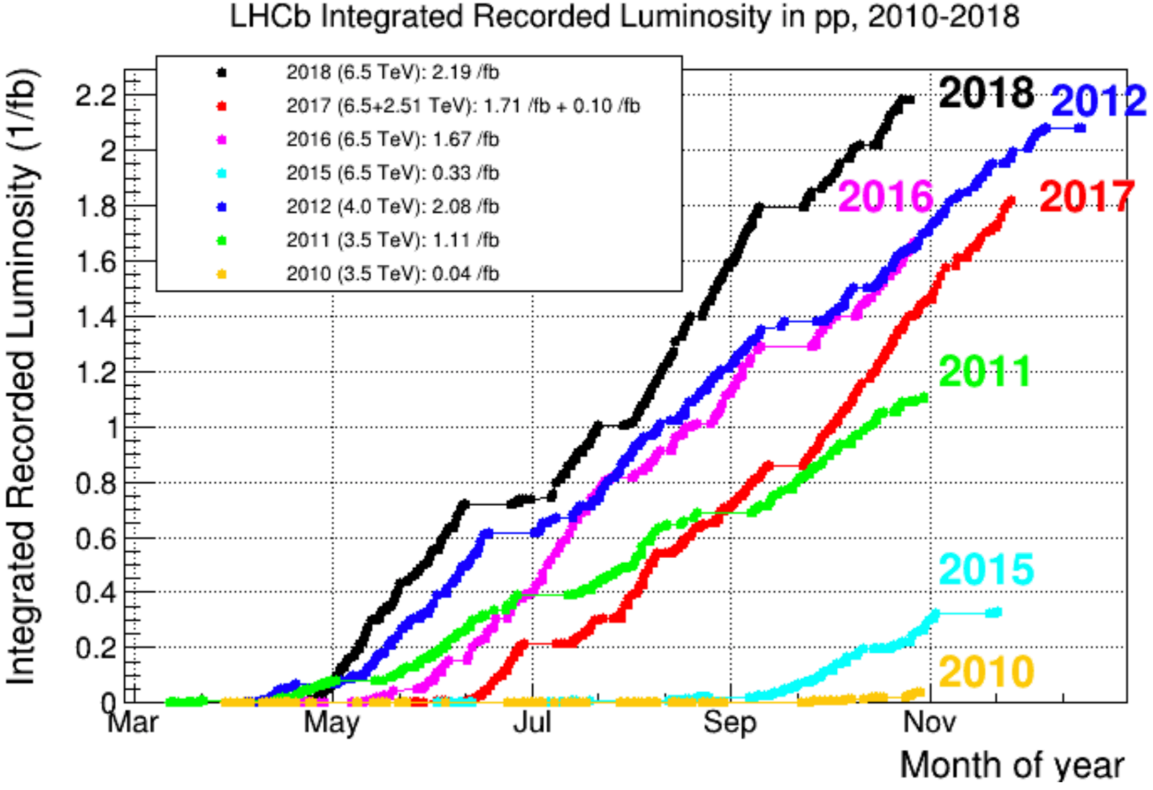
The LHCb Detector

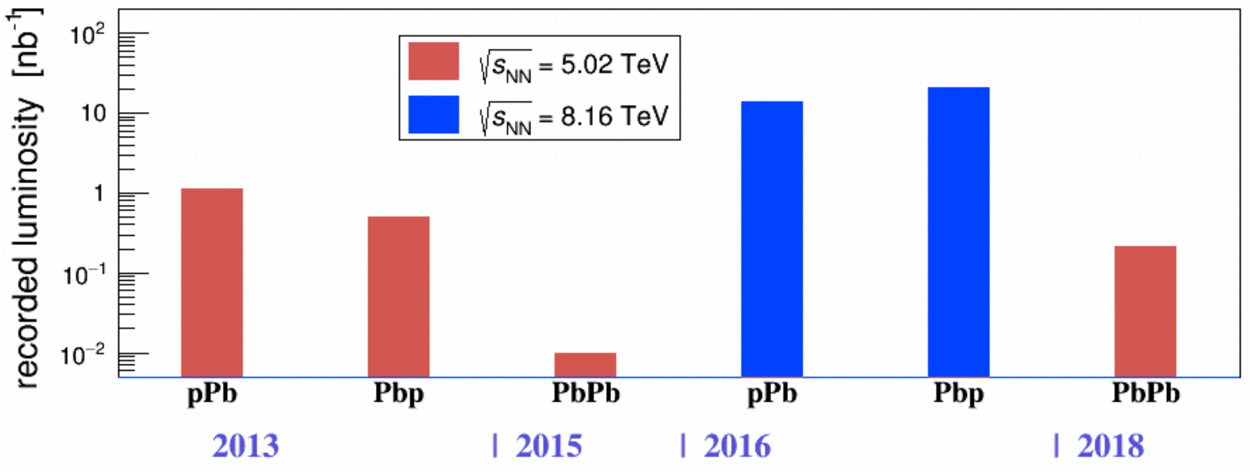
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

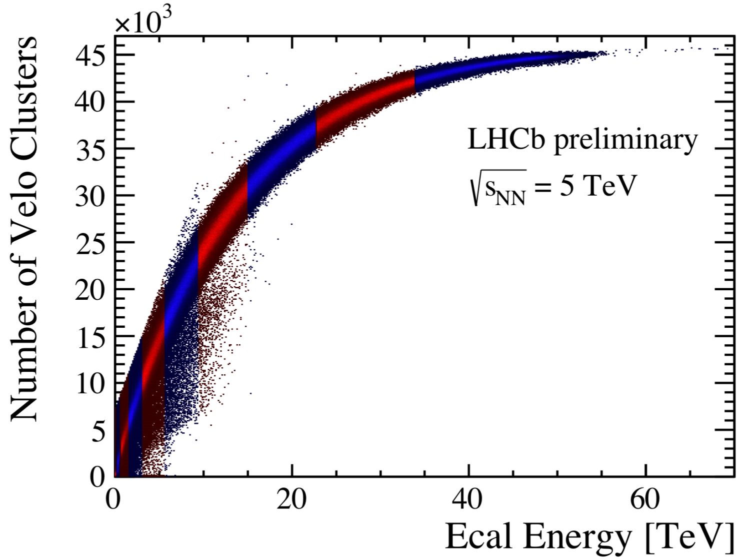


Tracking detector granularity designed for *pp* collisions is not optimal for measurements in central PbPb collisions → upgrade ongoing

Data on Tape







First heavy ion data recorded: 2013 pPb

Tracking works well in full pPb centrality

…limited in PbPb to >60% centrality

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The nuclear PDF

Generic cross section for heavy quark production:

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

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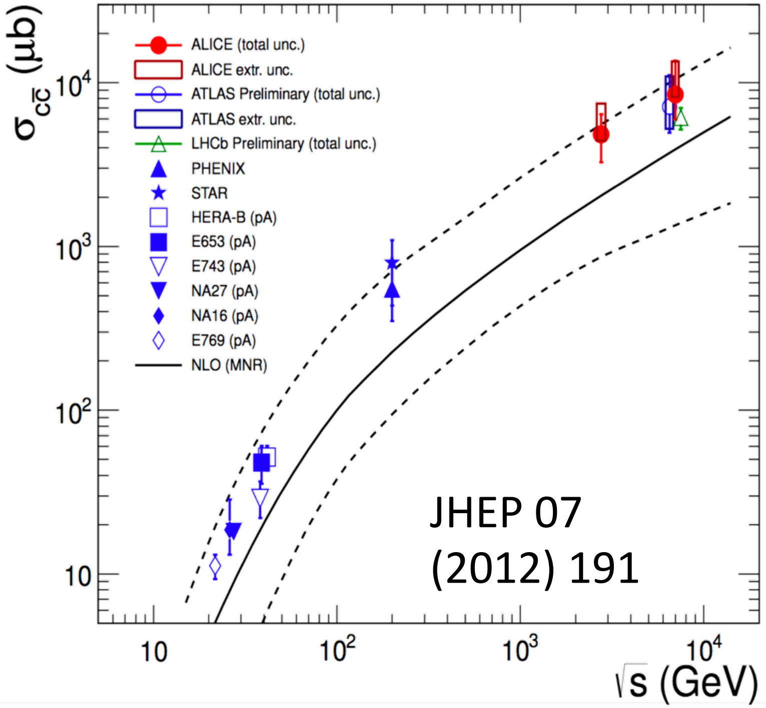

JHEP 07 (2012) 191

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Measurable at experiments

Well constrained HERA and other data

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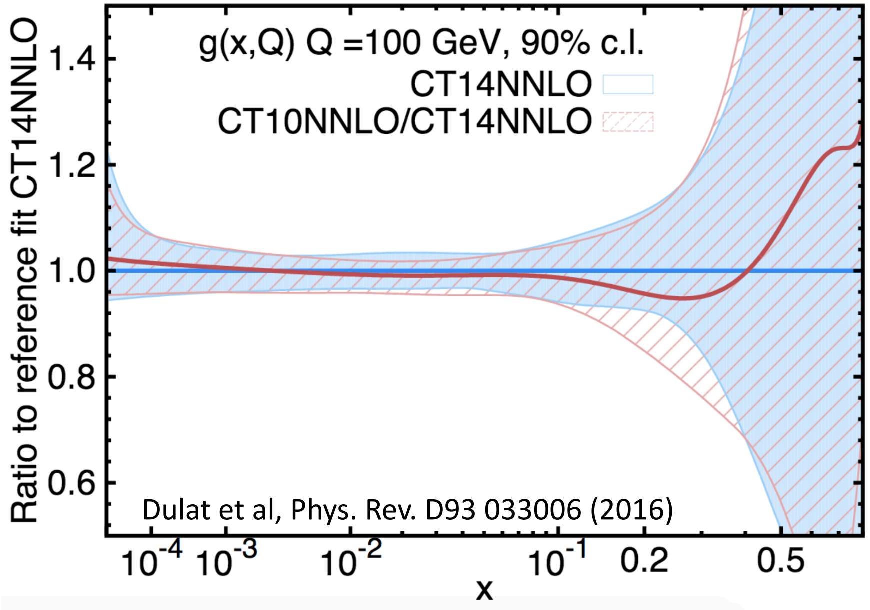
Due to incredible effort, proton PDF is reasonably well known

A sample of some recent work:
NNPDF3.1: EPJ C77 663 (2017)
CT14: Phys. Rev. D93 033006 (2016)
MMHT 2014: EPJ C75 204 (2015)
CJ15: Phys. Rev. D93, 114017 (2016)
ABMP16: Phys. Rev. D96, 014011 (2017)
Boughezal et al JHEP (2017) 130



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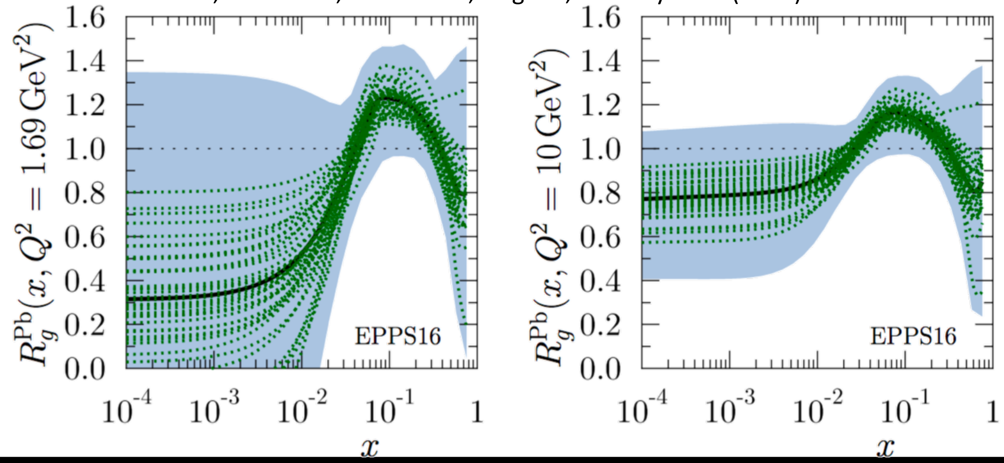
Despite incredible effort, nuclear PDF is not well constrained, esp gluons at low x

Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C (2017) 77: 163



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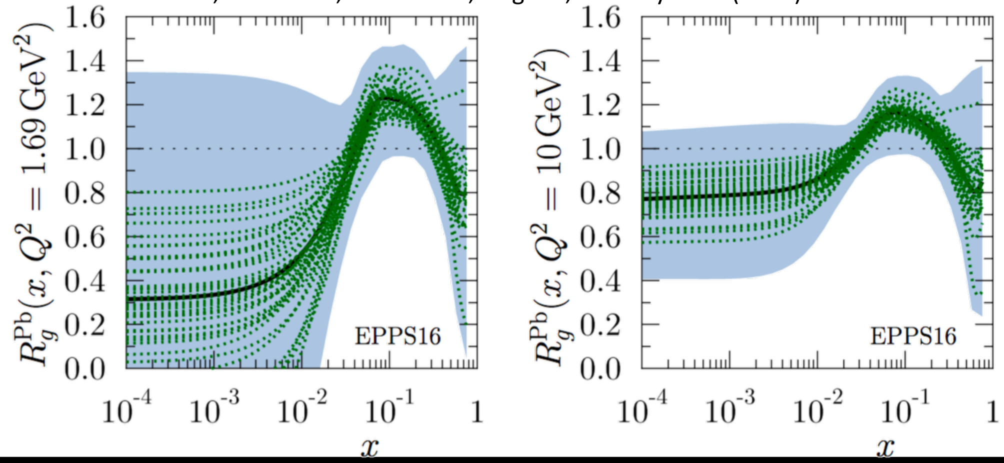


Solution: constrain fits with data at low x with probes that are sensitive to gluon distribution

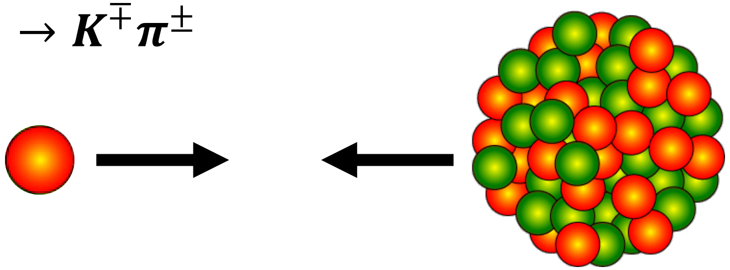
->Heavy quarks at forward rapidity

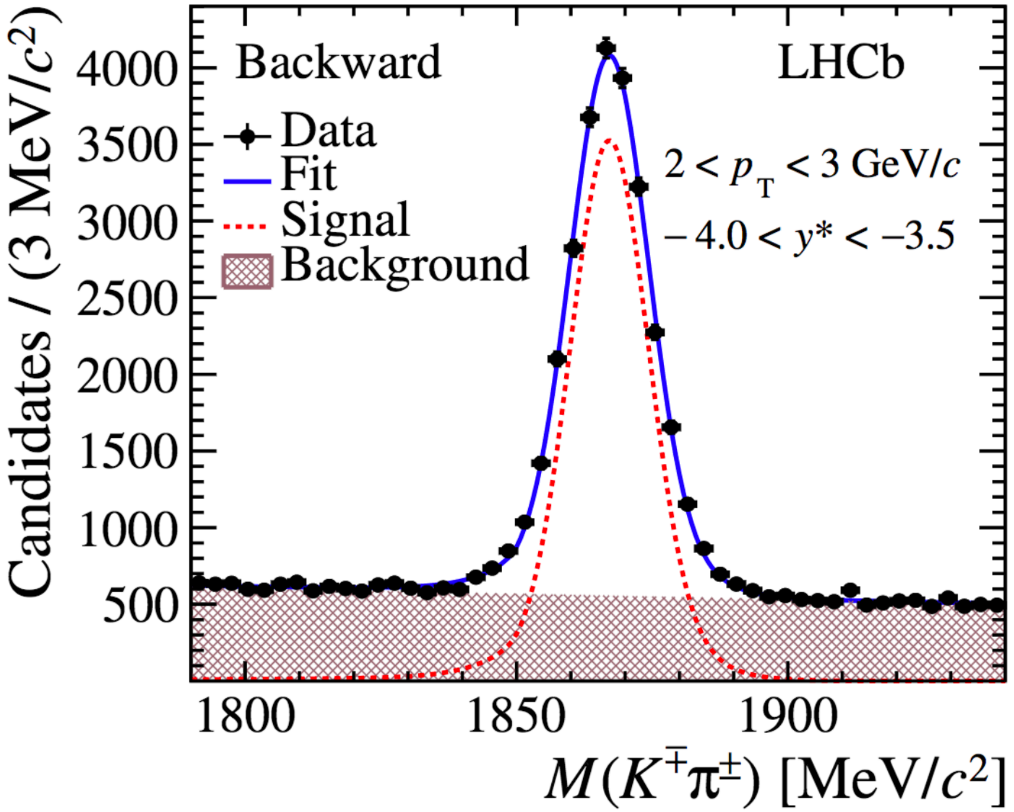
Open Charm Mesons in *p*Pb collisions: D^0

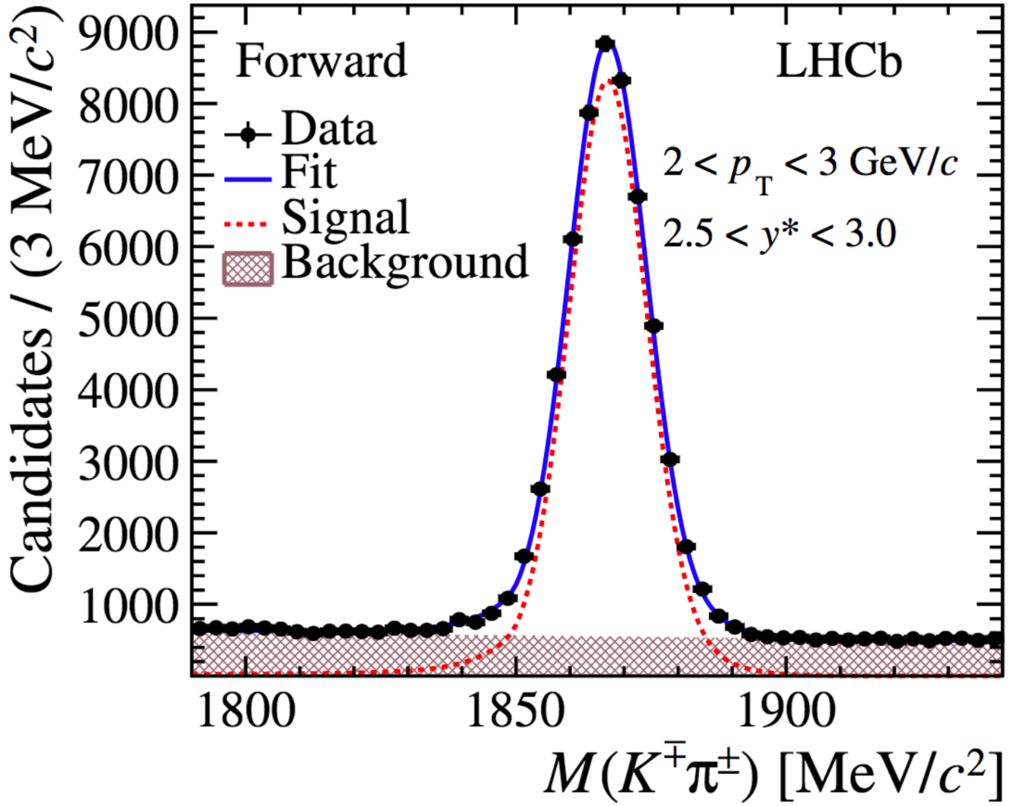
Fully reconstructed through decay channel $D^0 \rightarrow K^{\mp}\pi^{\pm}$

J. High Energ. Phys. 10 (2017) 90

$\sqrt{s_{NN}}$ **= 5 TeV**







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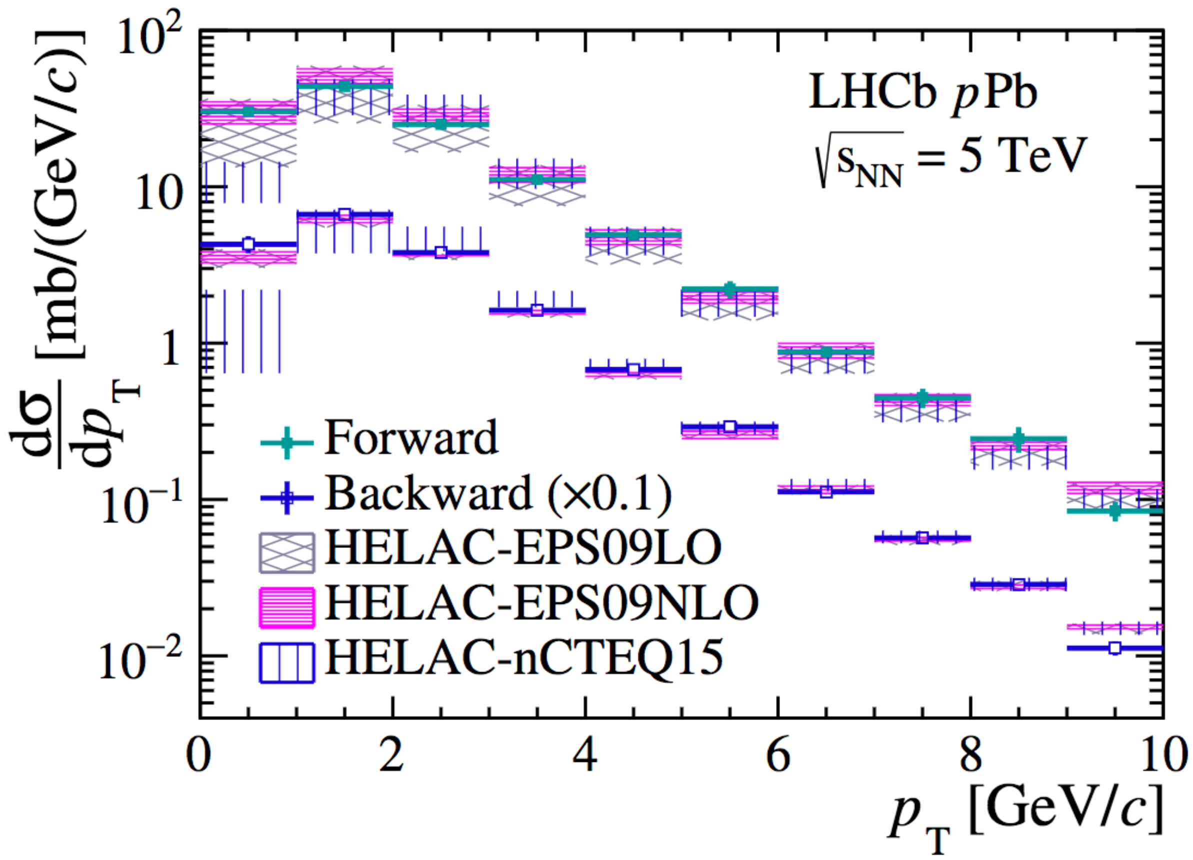

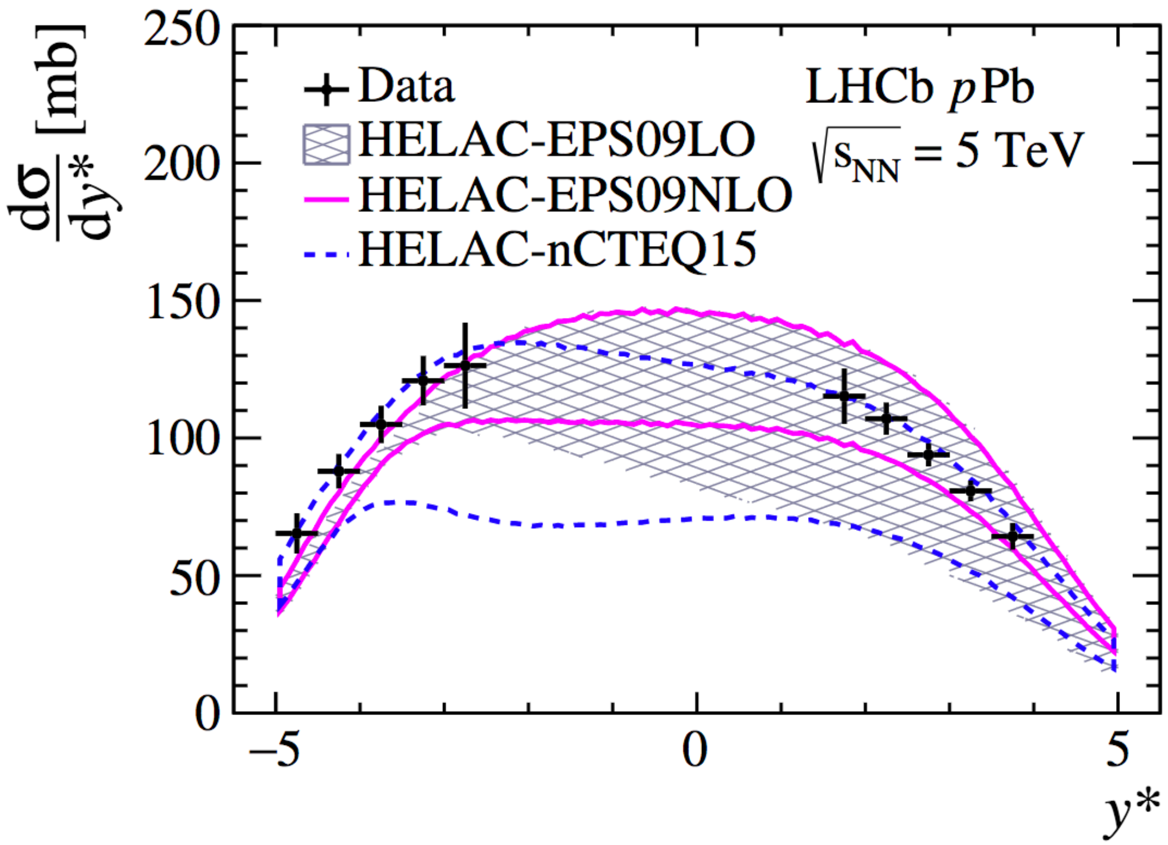

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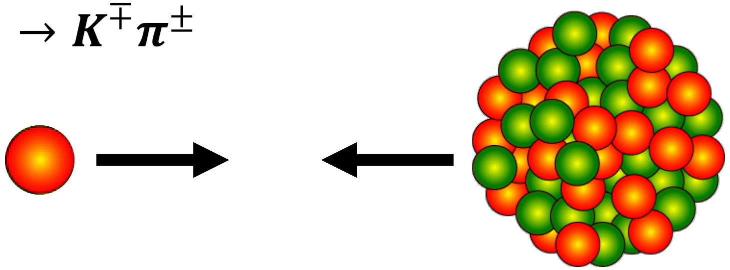
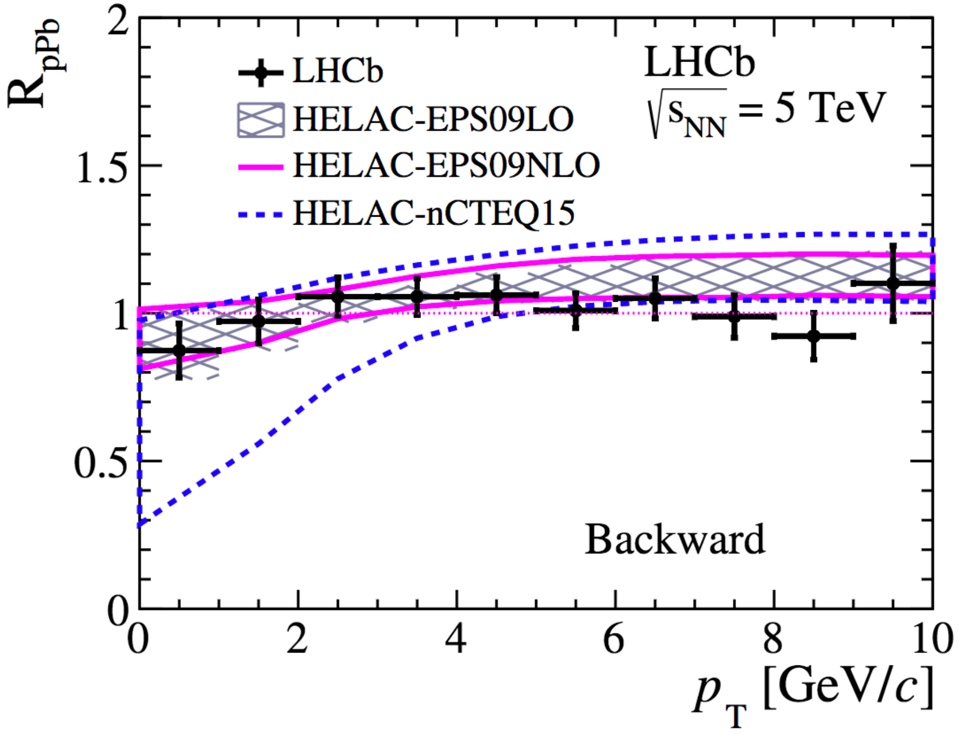
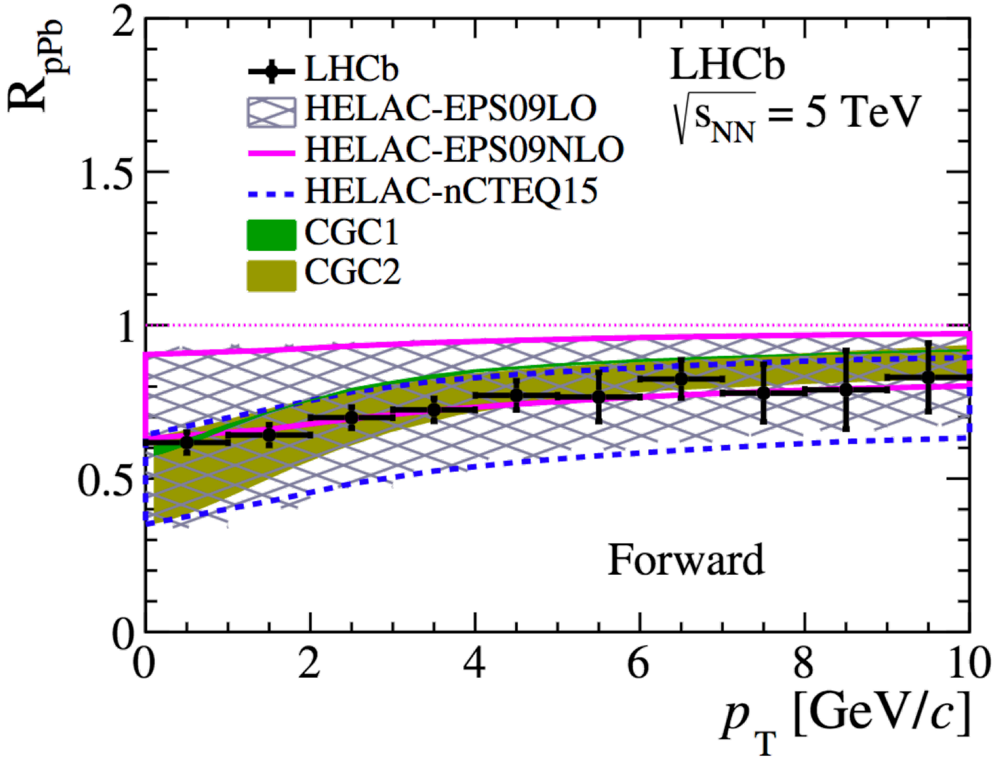
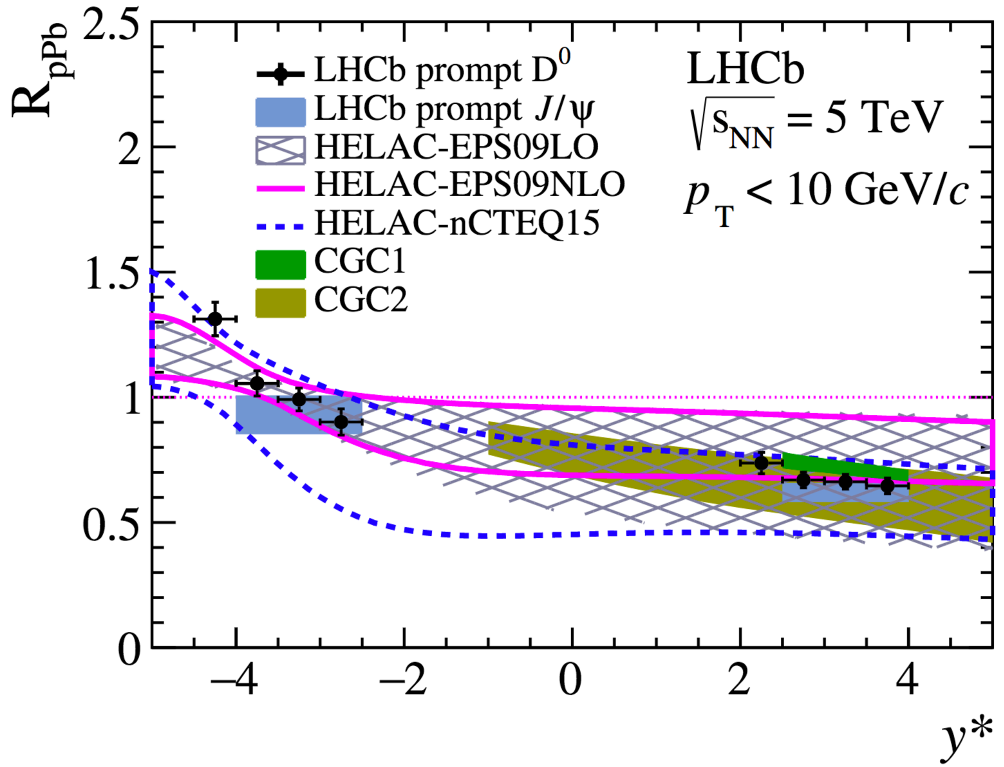






Error bars < calculation uncertainties

Open Charm Mesons in *p*Pb collisions: D^0



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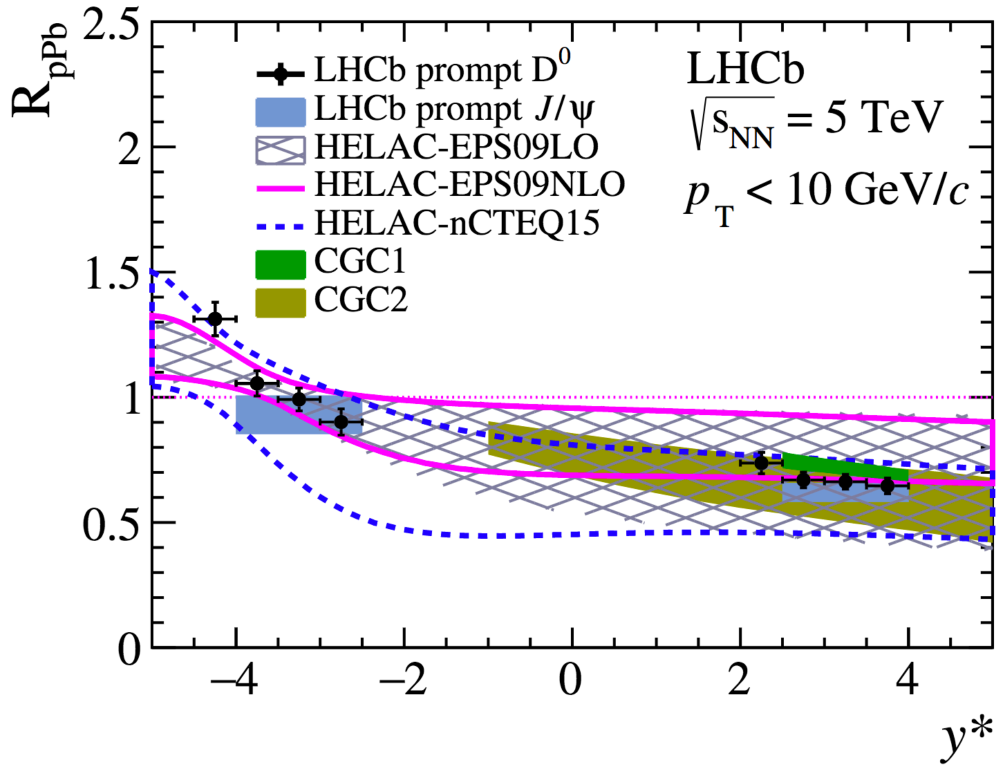
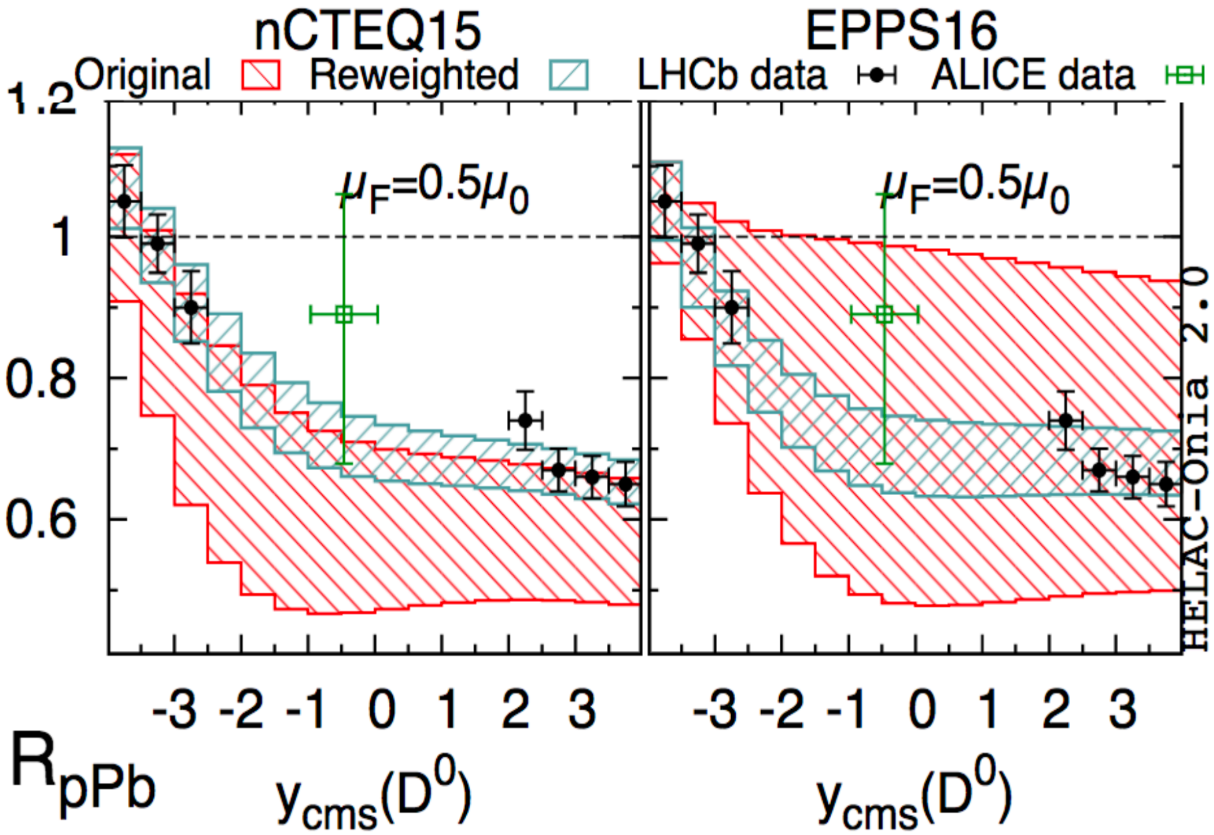


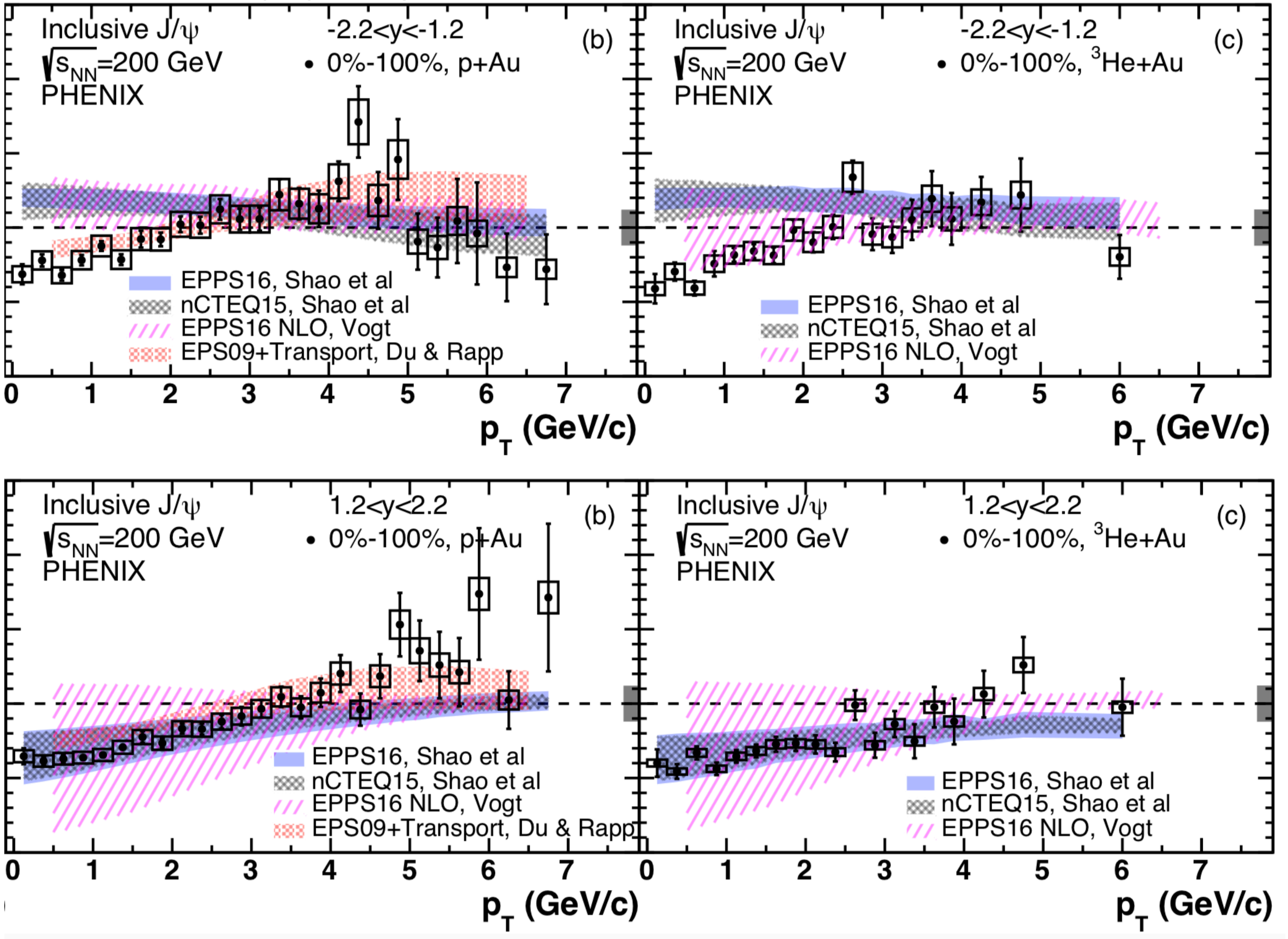


This data is already being used to constrain the gluon nPDF down to x~5x10^{-6}

Kusina, Lansberg, Schienbein, Shao,
Gluon shadowing and antishadowing in heavy-flavor production at the LHC
Phys. Rev. Lett. 121, 052004 (2018)

Comparisons with PHENIX p/He+A data

PHENIX: 1910.14487

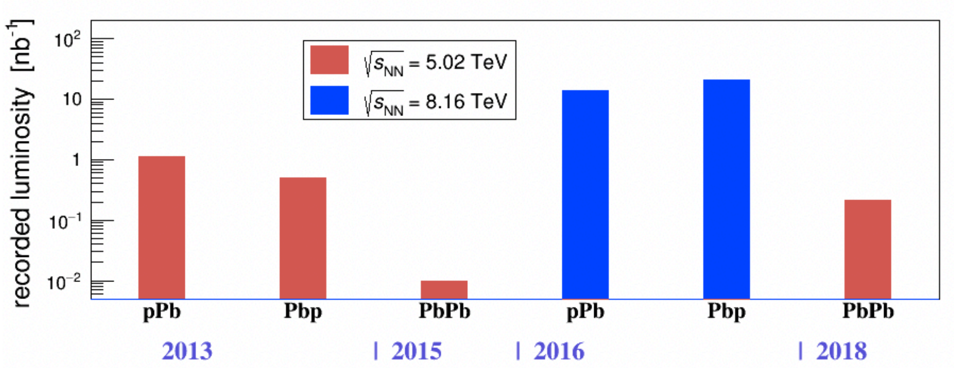


PHENIX recently released p/He+Au Jpsi data at fwd/bkwd rapidity

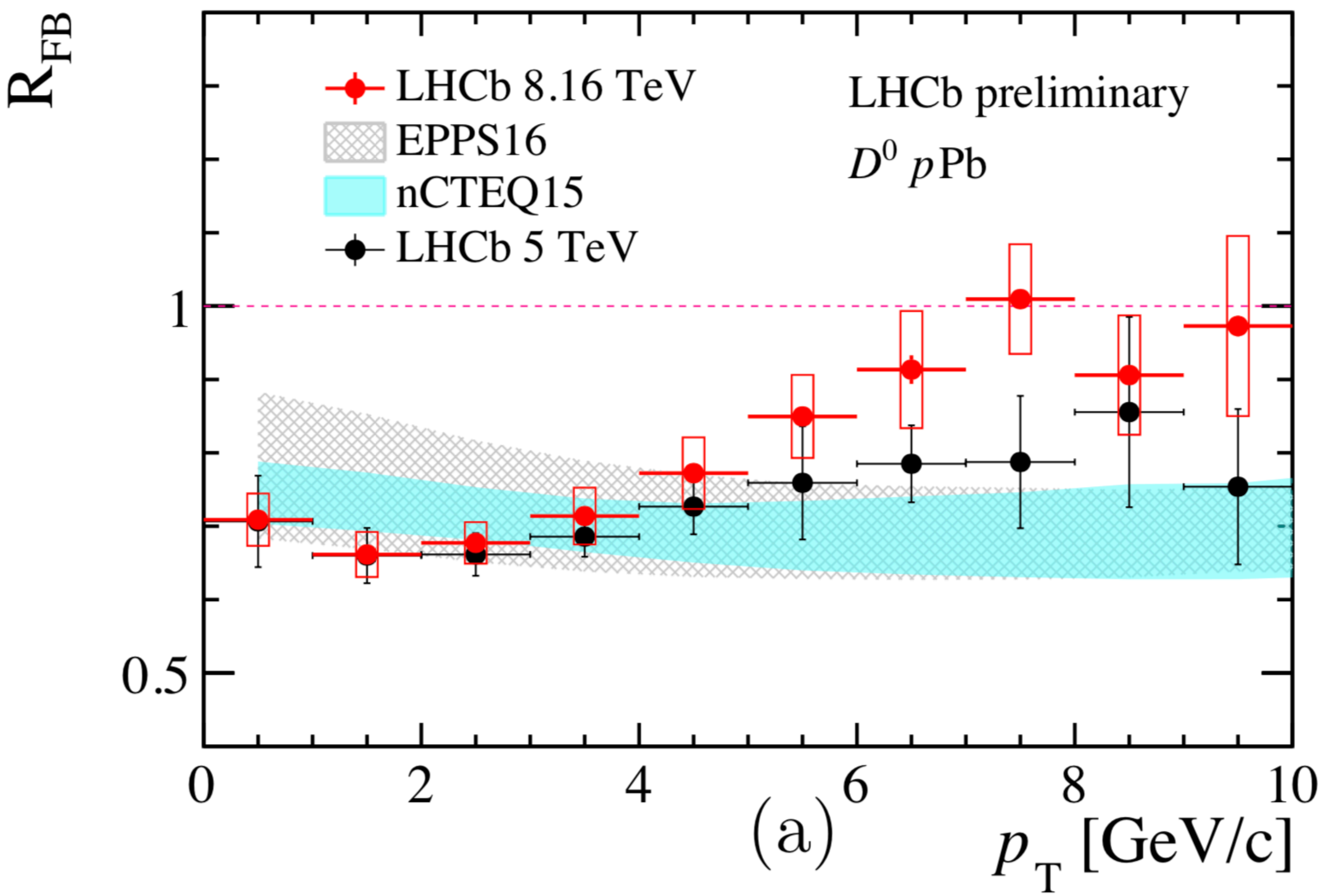
Comparison with reweighted nPDF calculation shows deviations at low pT in backwards rapidity

Described by transport calculation

New D results



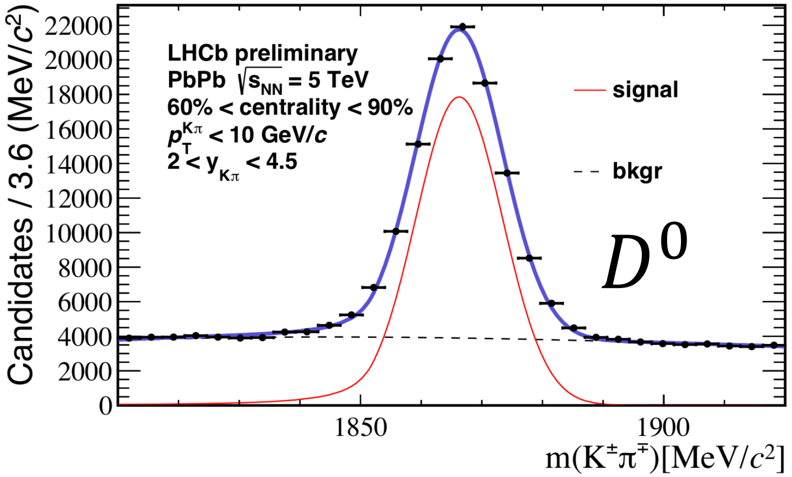
LHCb-CONF-2019-004

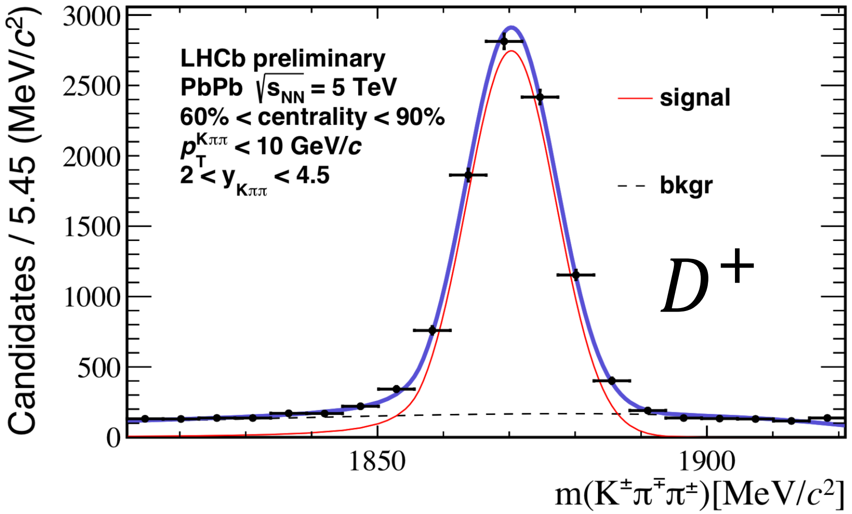


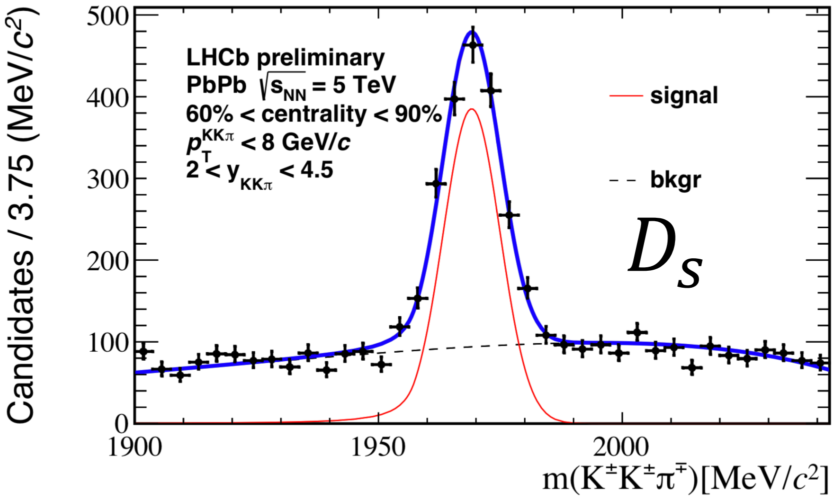
New preliminary results from 8 TeV pPb data set:

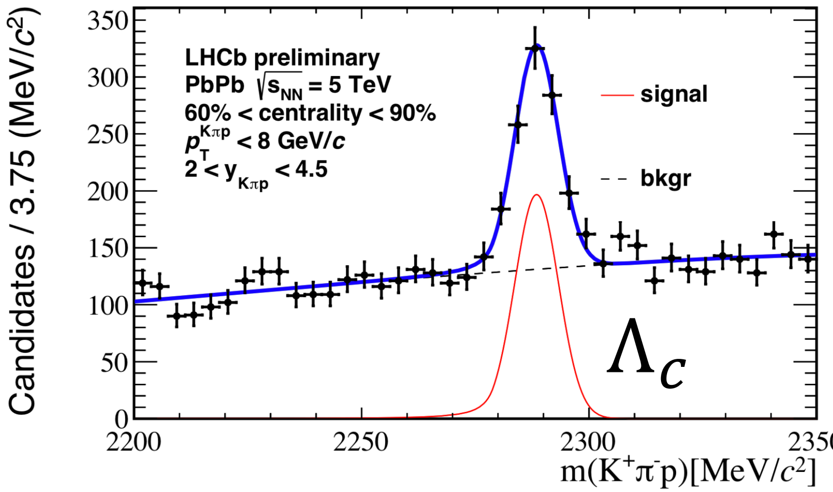
Significantly better statistical precision
Final evaluation of systematics underway
->More precise constraints on nPDFs

PbPb results to come







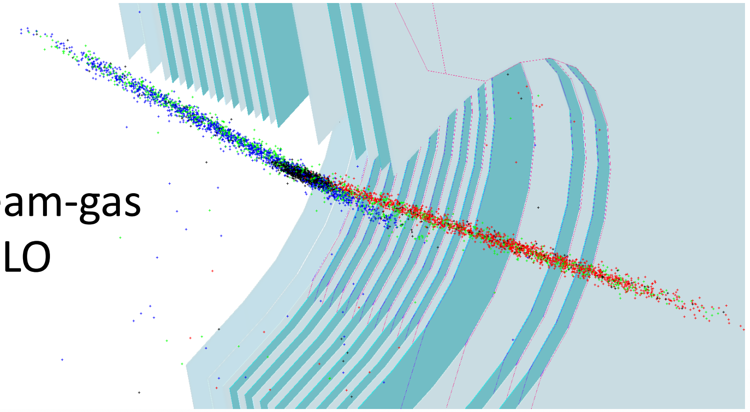


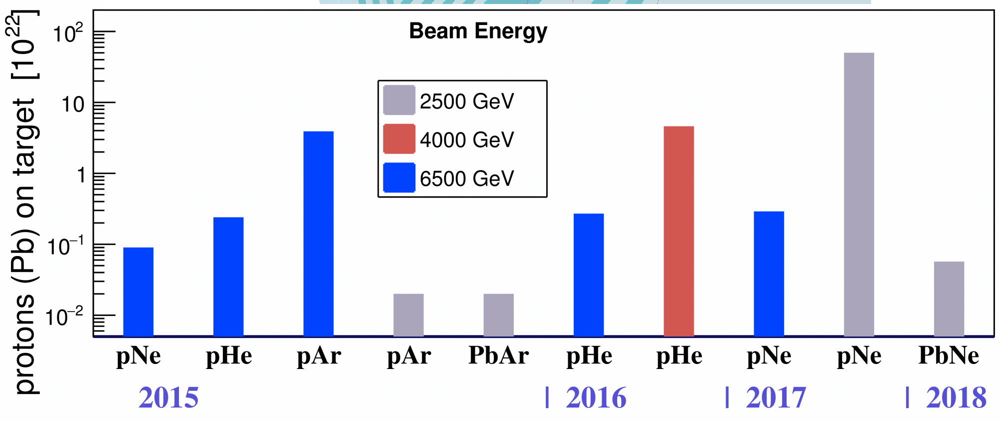
Unique results on charm hadrochemistry to come

Fixed target configuration - SMOG

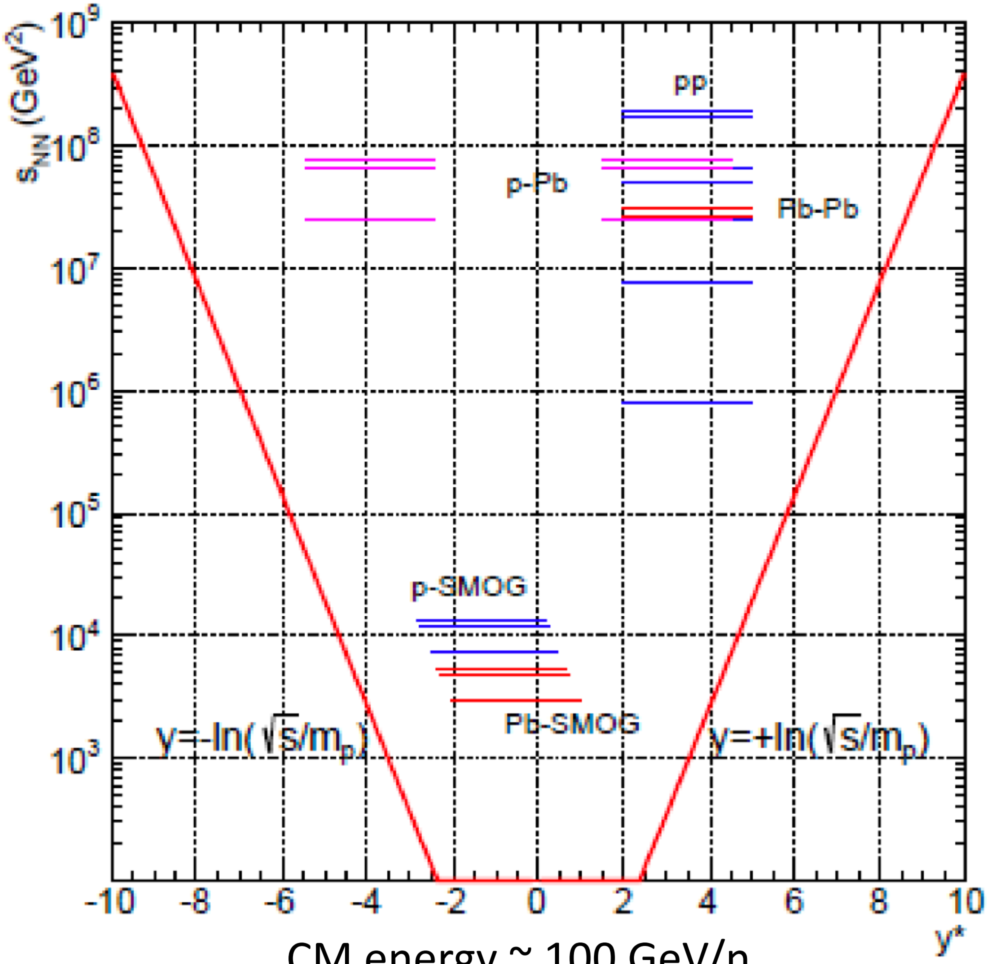
A unique capability at LHCb: inject noble gas into beampipe
Originally intended for precise luminosity measurements:
Precision on 2012 pp data is ±1.16%, best ever at bunched beam collider
JINST **9** P12005 (2014)

Reconstructed beam-gas vertices inside VELO





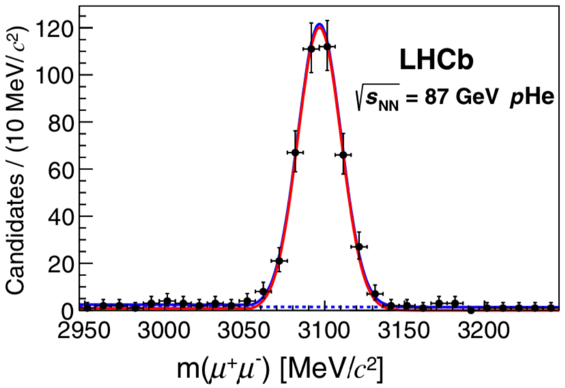
"System for Measurement of Overlap with Gas"

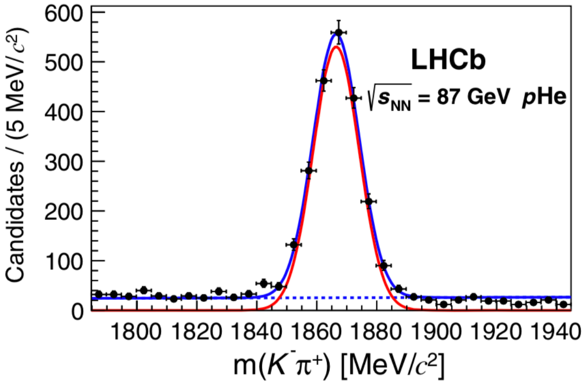


CM energy ~ 100 GeV/n
No limits on centrality

First SMOG Heavy Flavor Result

Phys. Rev. Lett. 122, 132002 (2019)

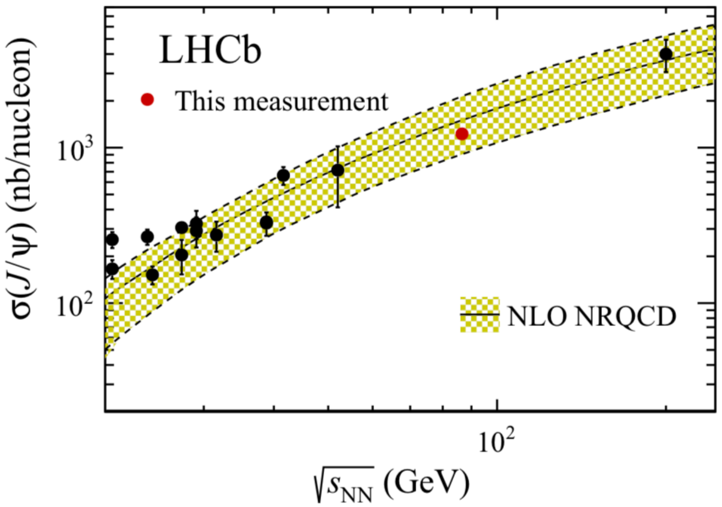


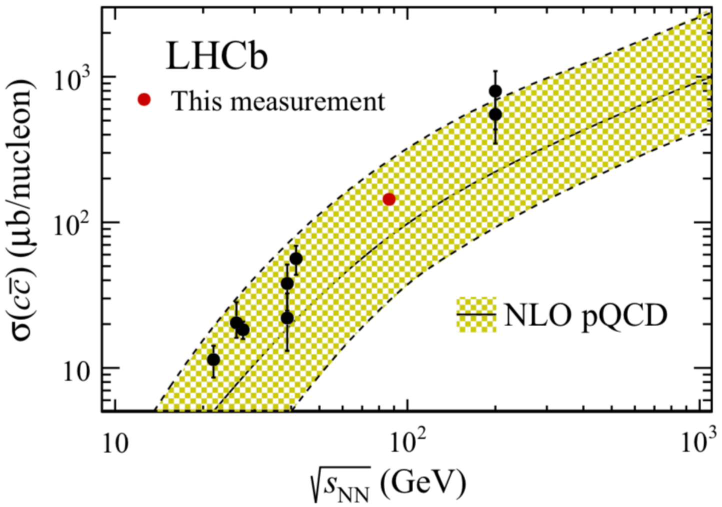


First charm result from SMOG: pHe and pAr data

Unique access to precision heavy flavor probes in energy range between SPS and RHIC

MAJOR upgrade to SMOG system ongoing





Outline

- LHCb Physics program
- Apparatus
- Heavy Ions at LHCb
  - Collider Mode
  - Fixed Target Mode (SMOG)
- Exotics at LHCb
- Upgrades

Quark Model of Hadrons

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}$A and AAA, that is, "deuces and treys".

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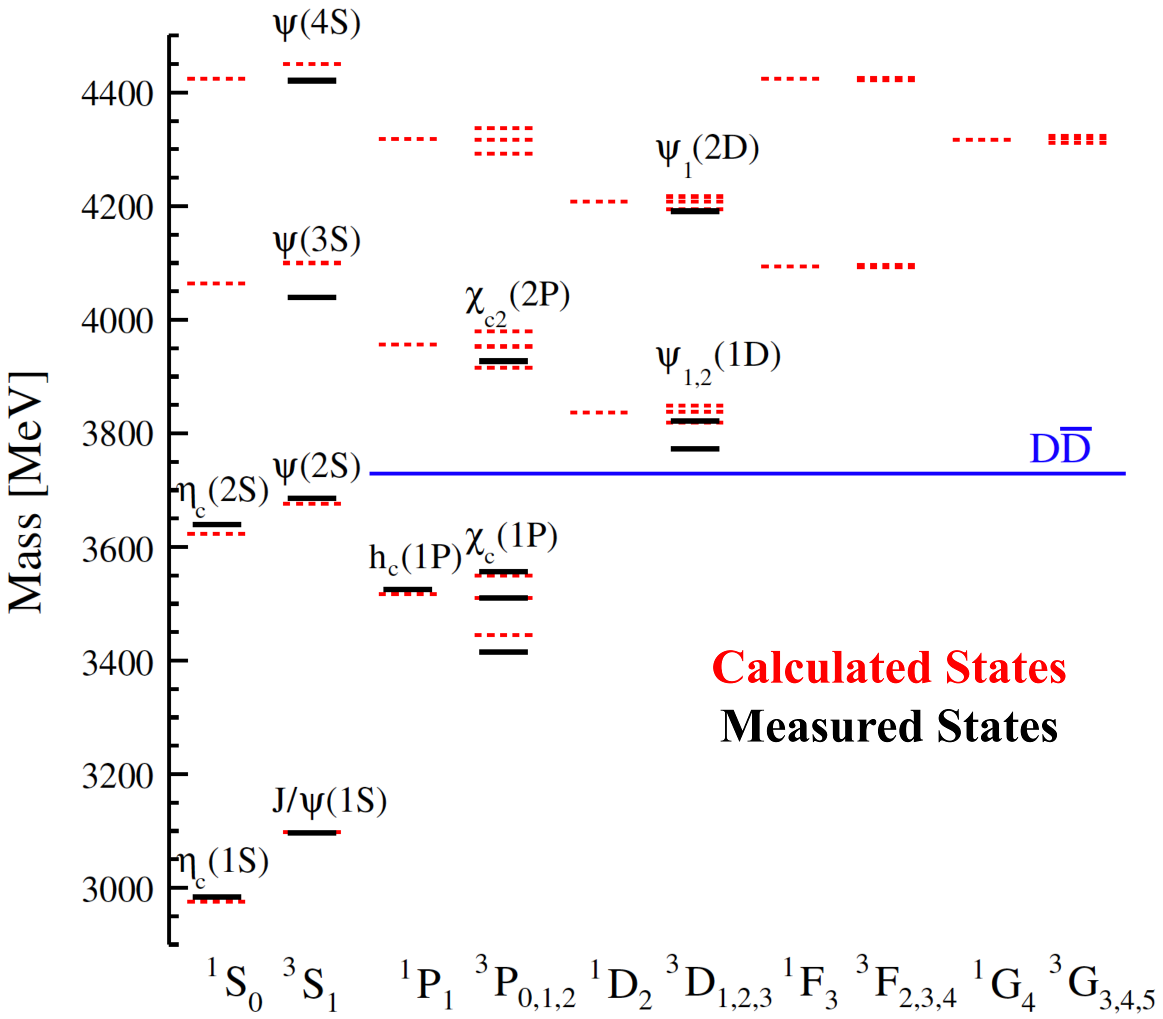
States with >3 quarks have been expected since the beginning of the quark model

Conventional $c\bar{c}$ States



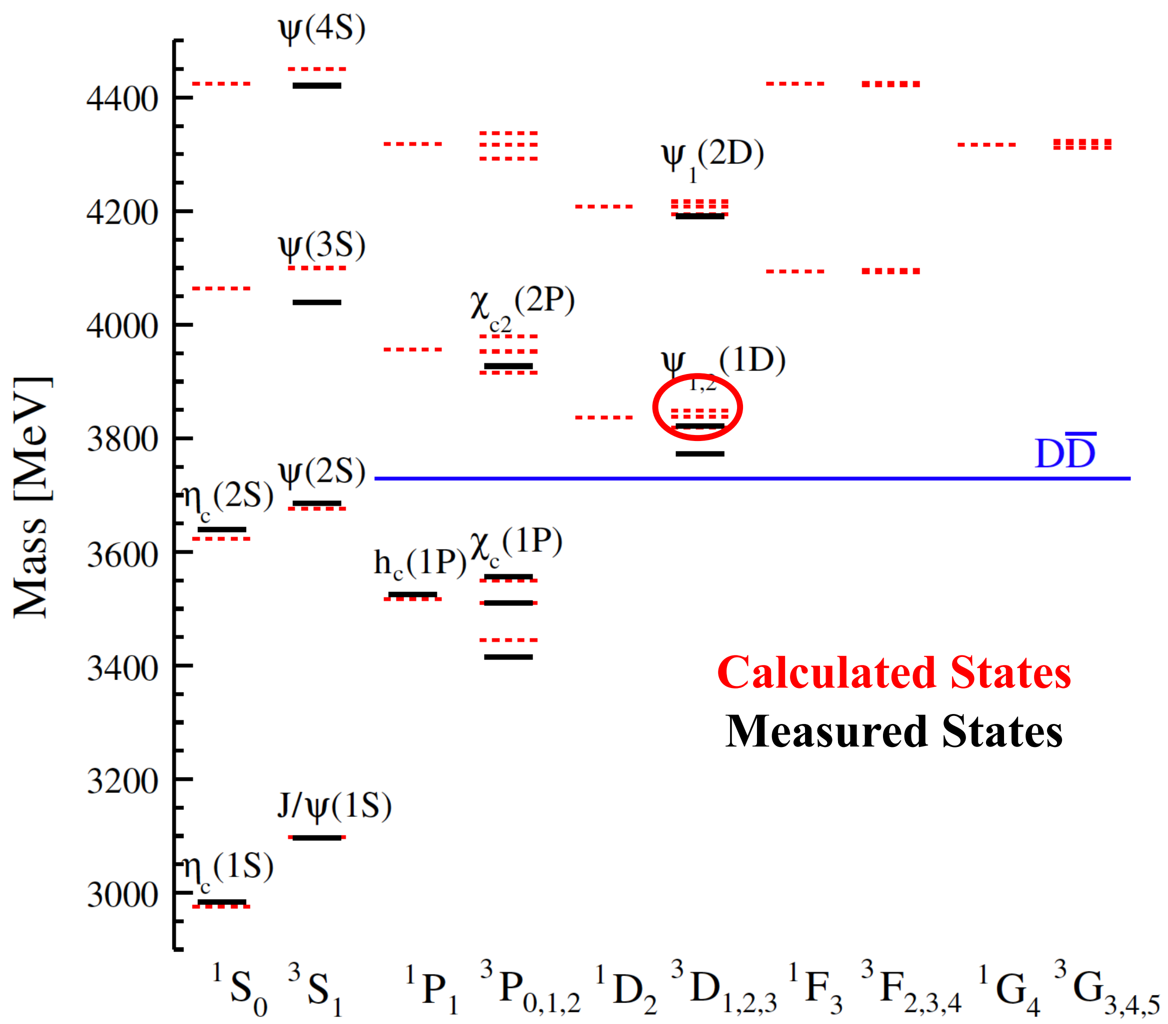
Rev. Mod. Phys. 90, 015003 (2018)

Nonrelativistic potential model: solve Schrodinger equation with the potential

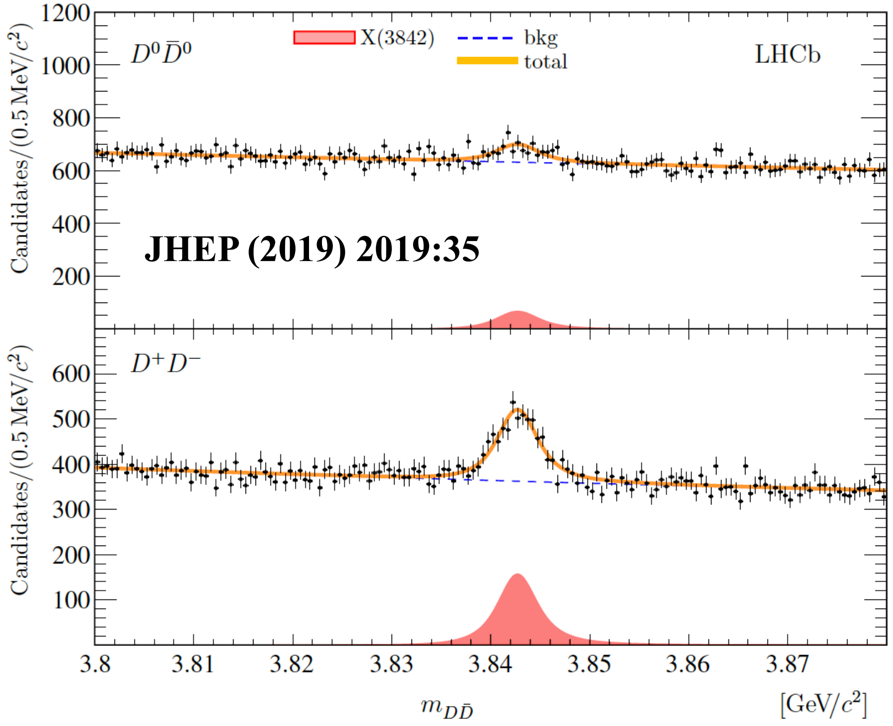
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

Barnes, Godfrey, Swanson,
Phys. Rev. D 72, 054026 (2005)

Conventional $c\bar{c}$ States



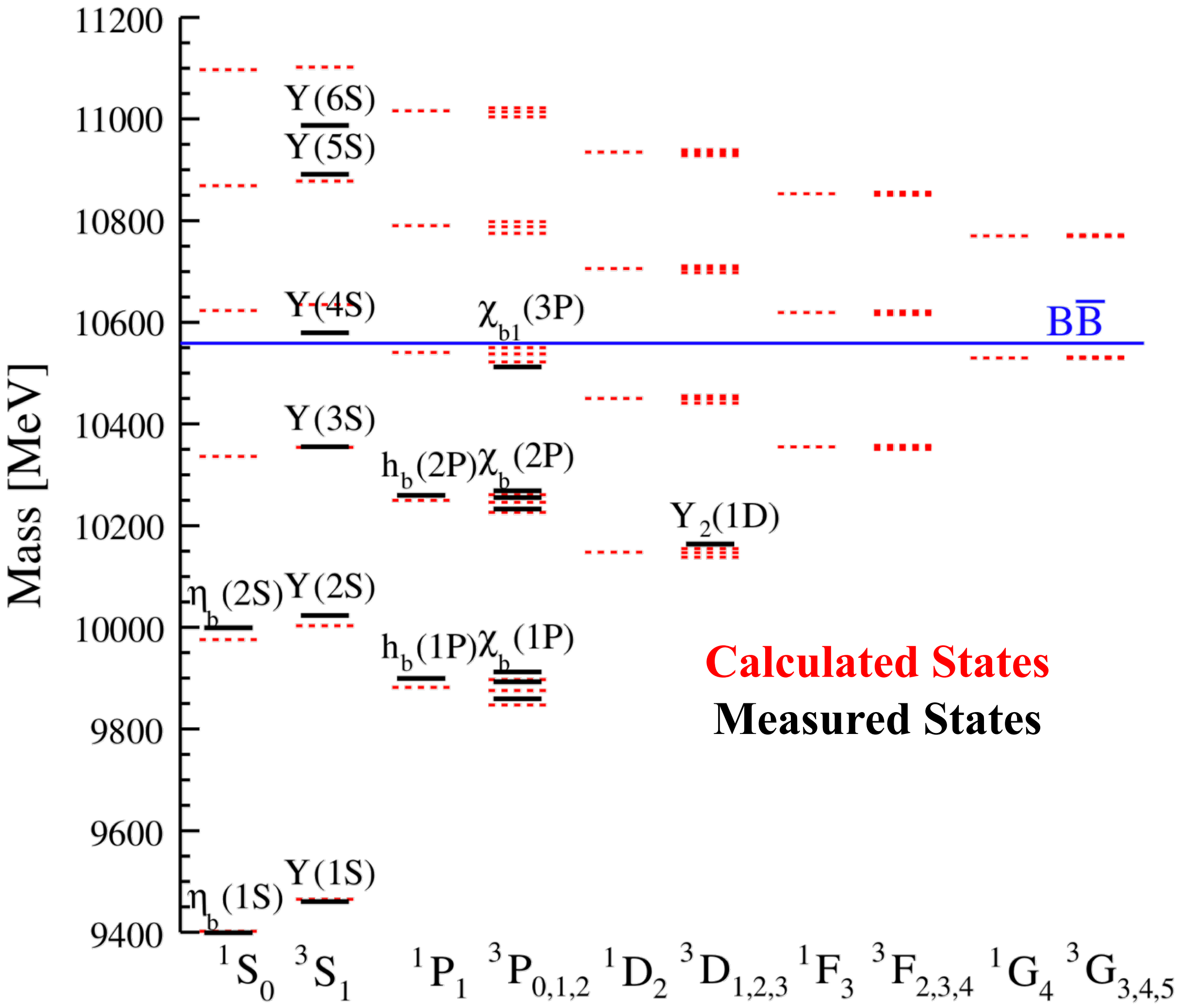
Rev. Mod. Phys. 90, 015003 (2018)



New charmonium states still being found: LHCb observed state consistent with $\psi_3(1^3D_3)$ found in $\boldsymbol{D\bar{D}}$ and $\boldsymbol{D^+D^-}$ mass spectra in 2019

Measured mass: 3842.71 ± 0.16 ± 0.12 MeV
Predicted mass: 3849 MeV

Conventional $b\bar{b}$ States

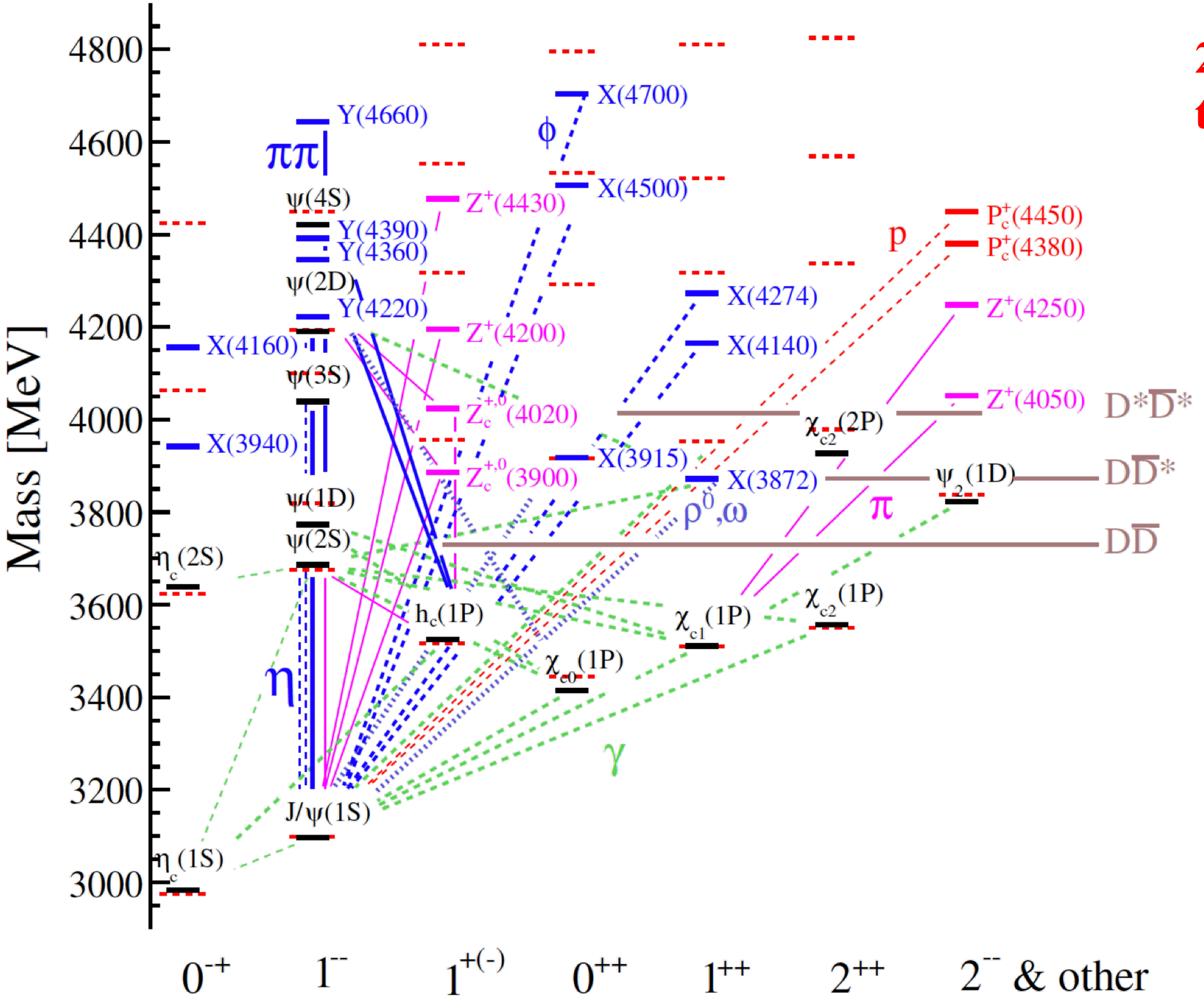


Rev. Mod. Phys. 90, 015003 (2018)

The allowed $c\bar{c}$ and $b\bar{b}$ bound states are well understood*

Crucial to account for conventional states when searching for exotics

Exotic $c\bar{c}$ States



Rev. Mod. Phys. 90, 015003 (2018)

20+ states containing $c\bar{c}$ have been discovered since 2003 that do not fit in the picture of typical charmonium:

Collectively known as "*XYZ*" particles

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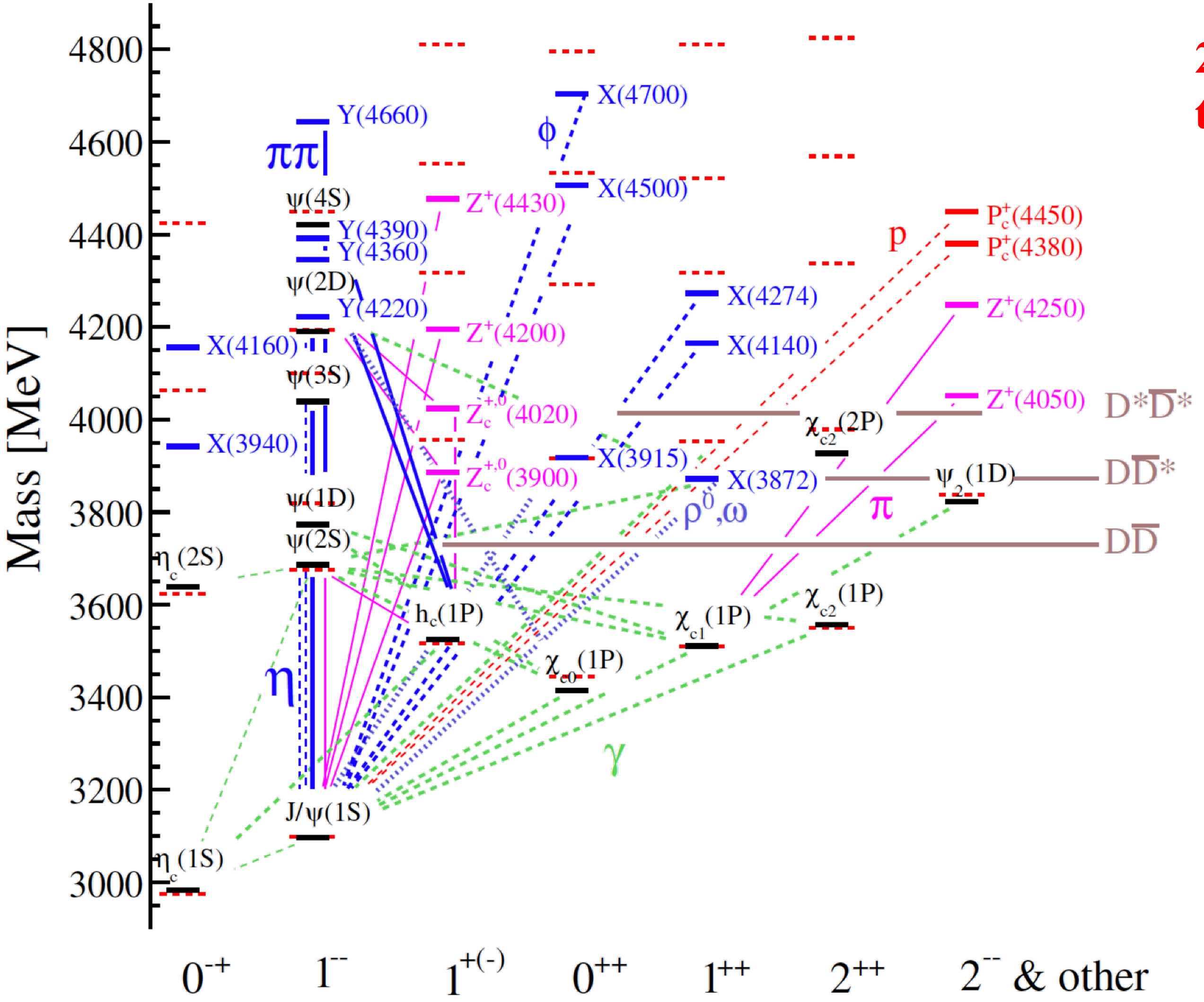

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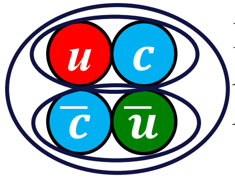
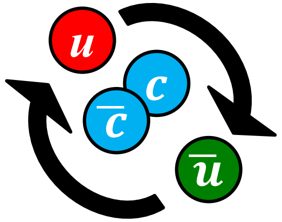
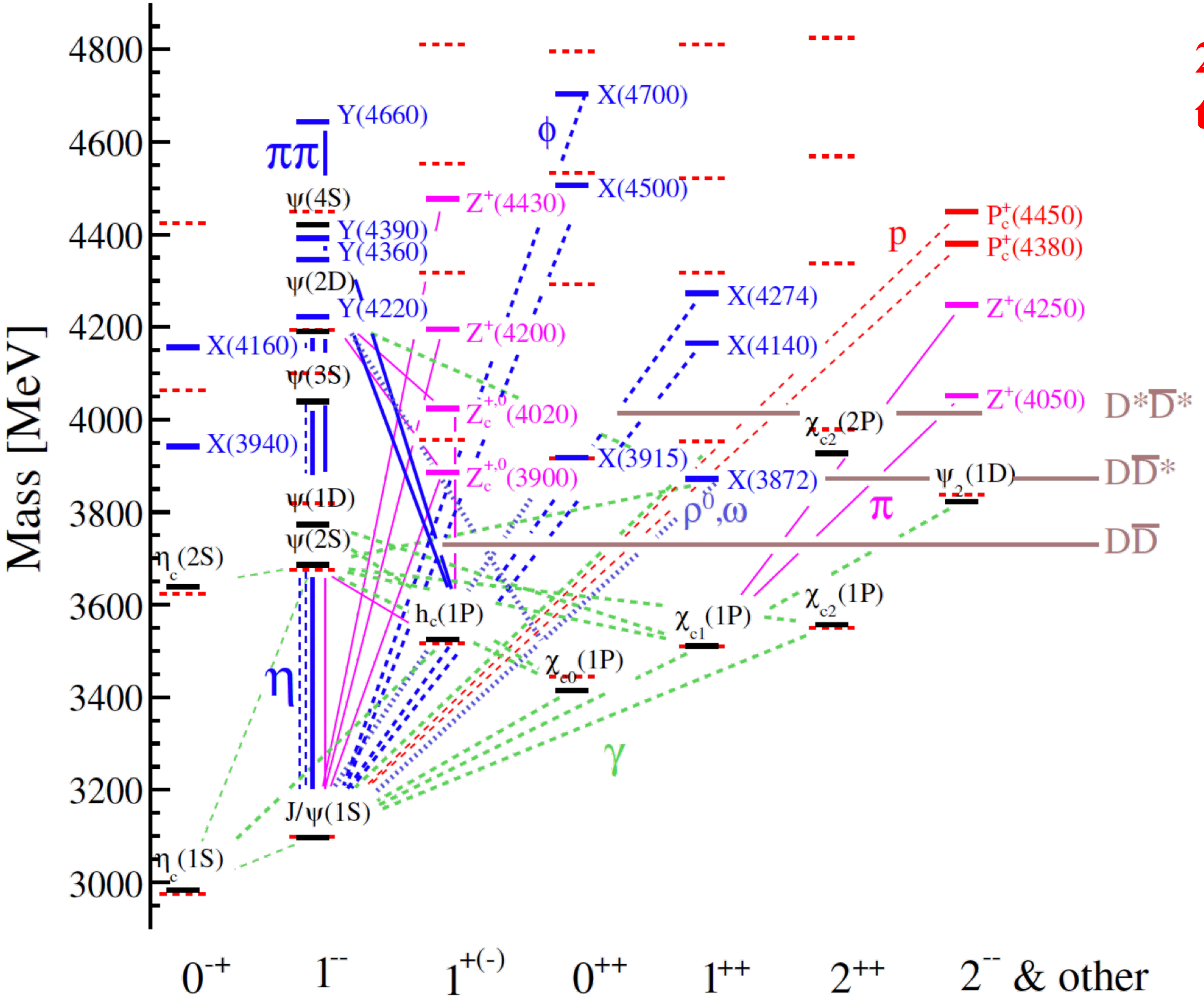


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



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

Exotic $c\bar{c}$ States



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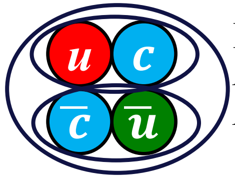

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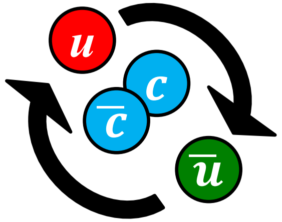

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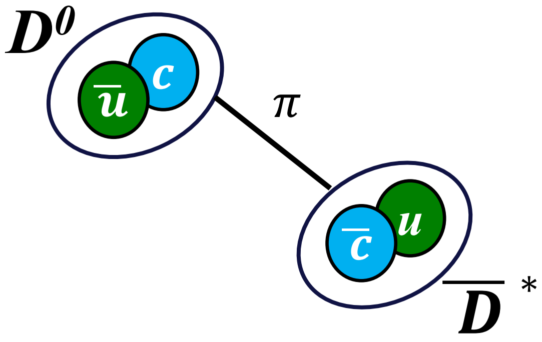
Hadronic Molecules
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



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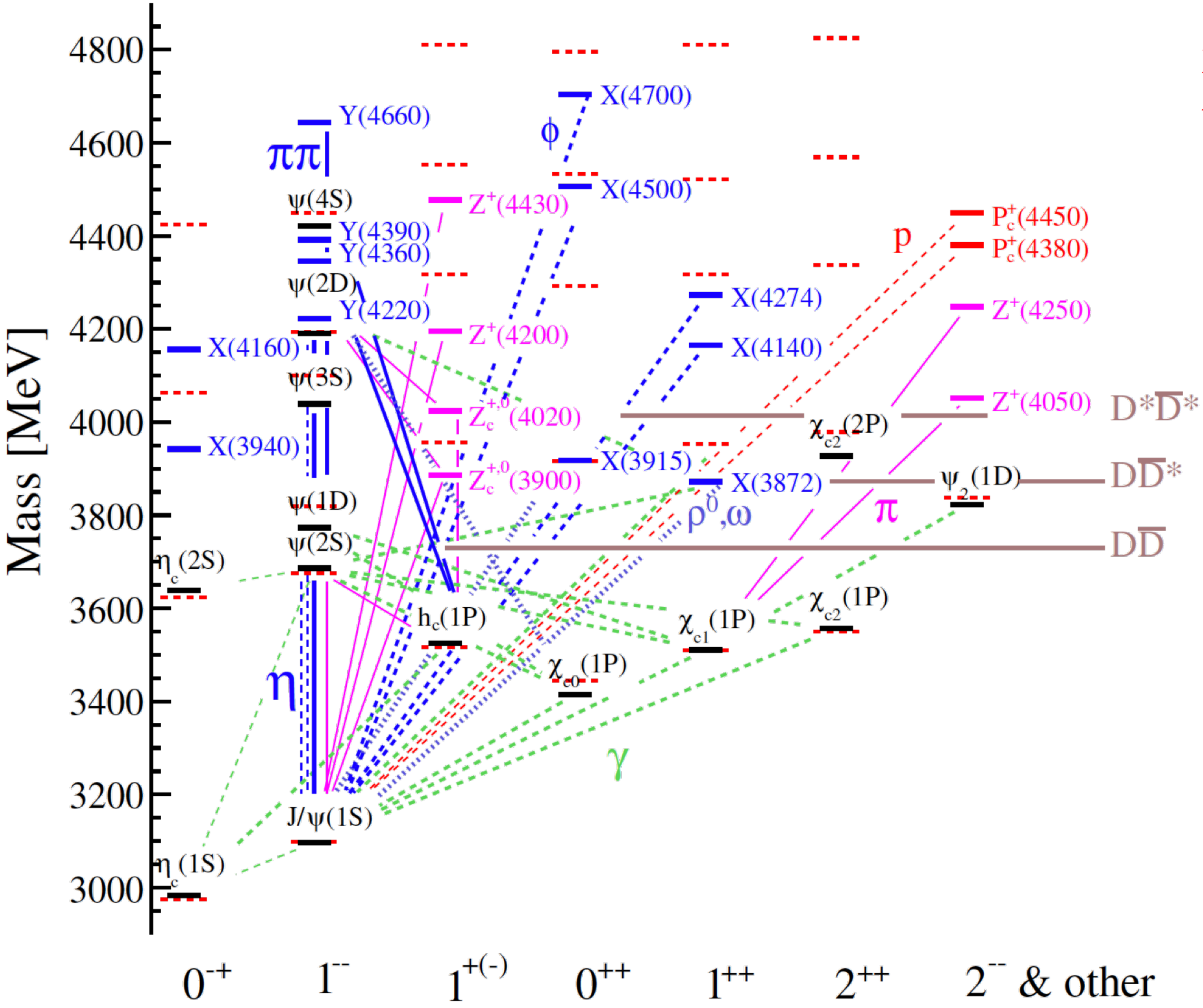

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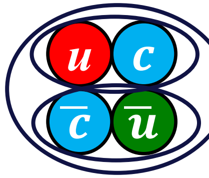

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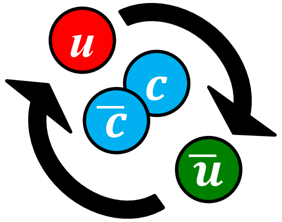

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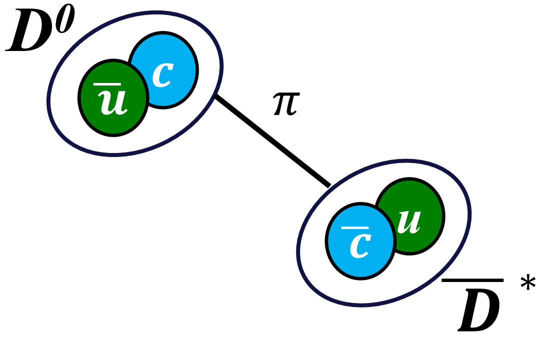


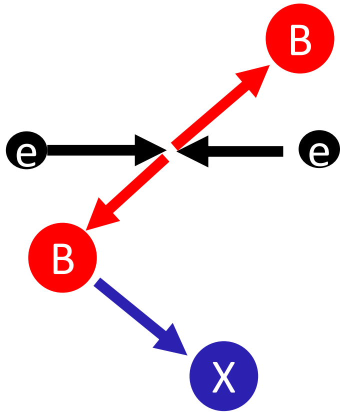
Mixtures of exotic + conventional states

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

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

Production of Exotic States

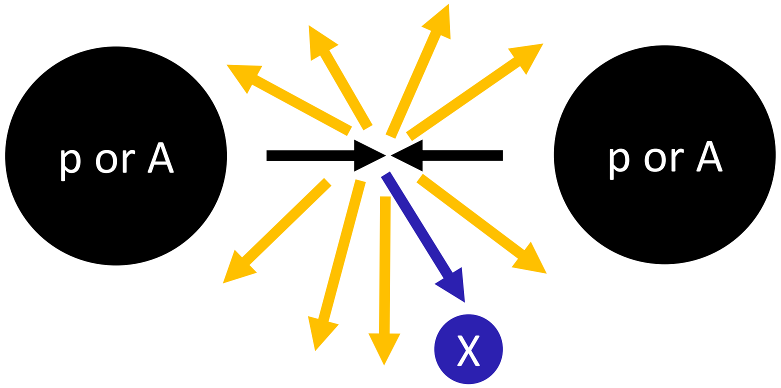
Discovery in B decays



B factories: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
Belle, BaBar
- Well constrained initial state
- Low backgrounds

Hadron Colliders eg LHC: $pp \rightarrow B\bar{B} + X$
LHCb, ATLAS, CMS, D0, CDF, etc
- High rate
- Large total cross section
- Access to wider range of states

Prompt production



AA, pA(?): high particle density
- Production via coalescence or recombination at freezeout

pp, pA: low particle density
- Breakup of weakly bound states in late stages

Recent LHCb Discovery – P_c States

Select daughters from the decay

$$\Lambda_b^0 \rightarrow J/\psi p K^-$$

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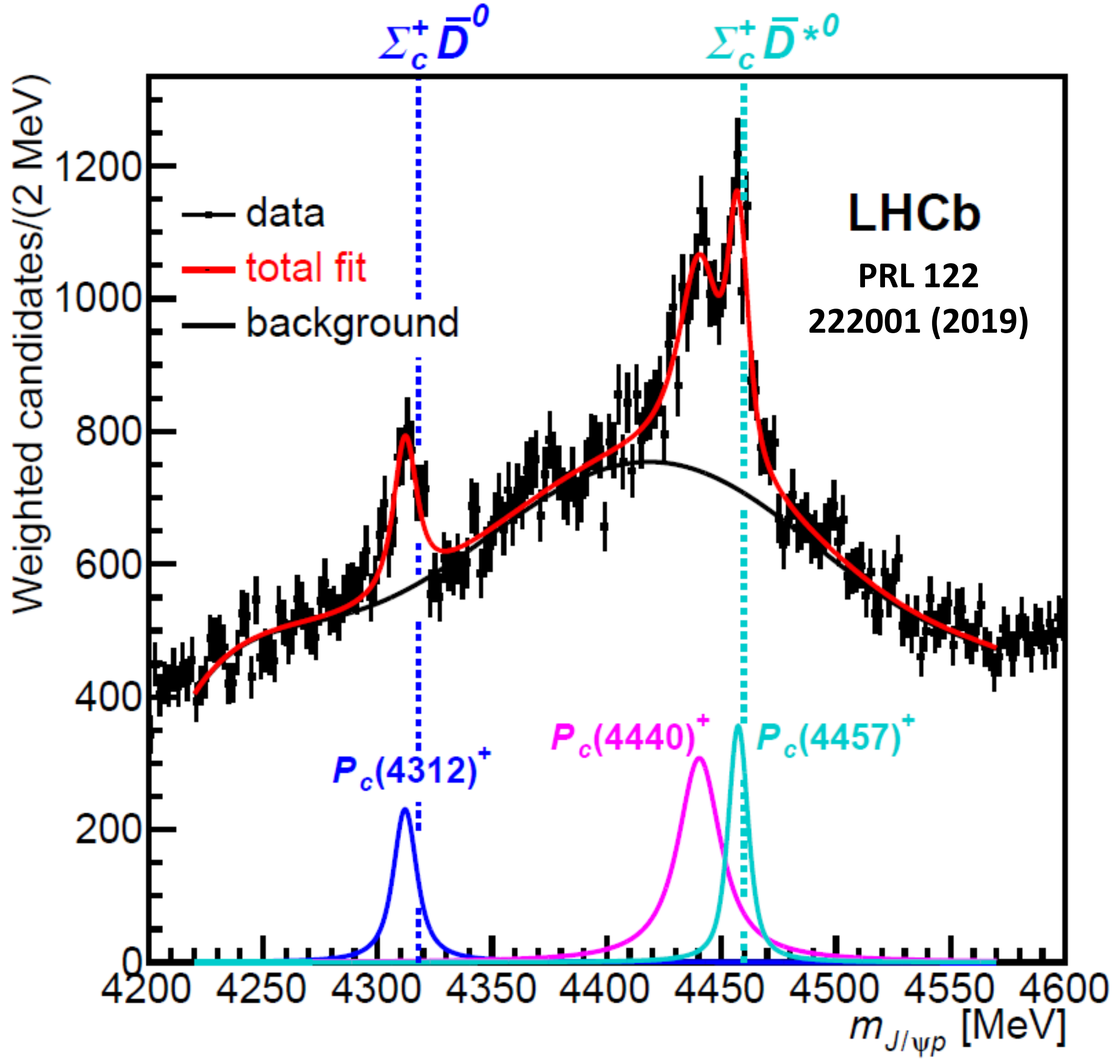

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Select daughters from the decay

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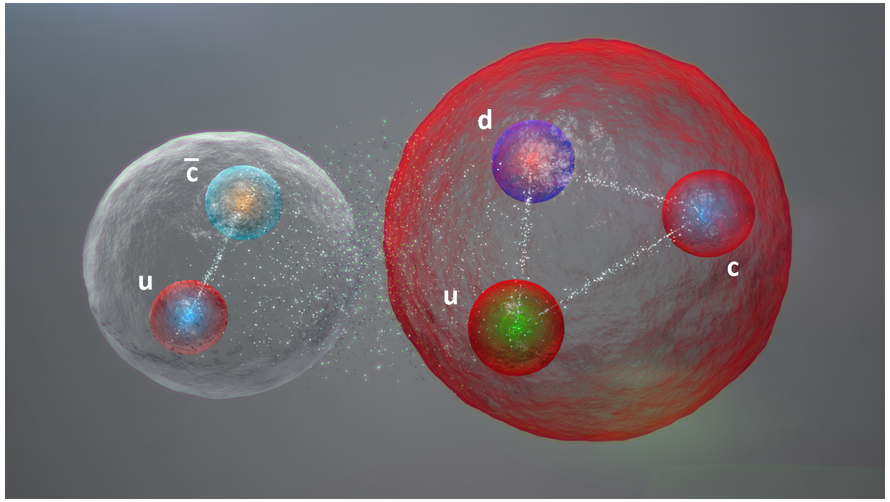
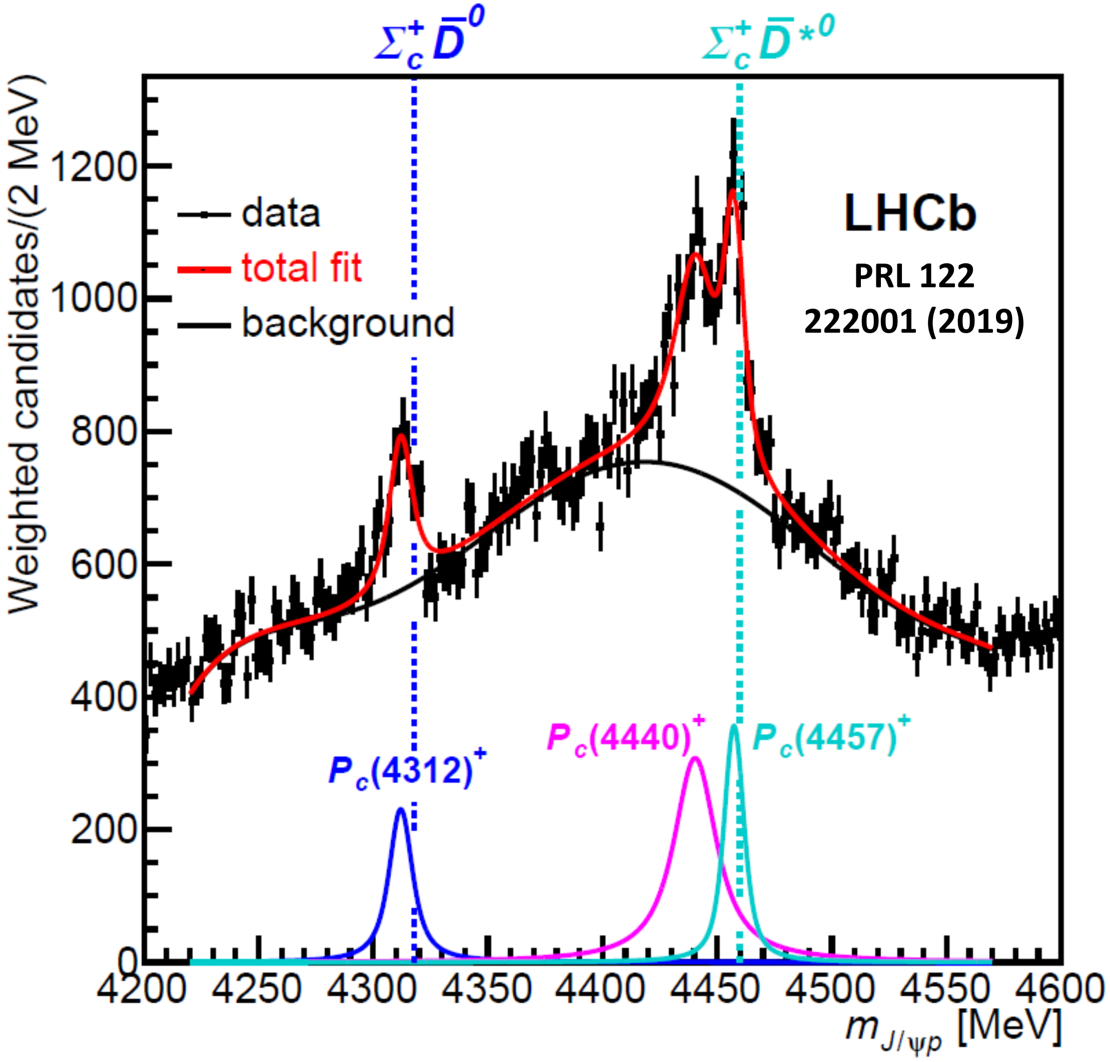
Masses are close to meson+baryon thresholds – candidate for hadronic molecule





Prompt production has not been studied

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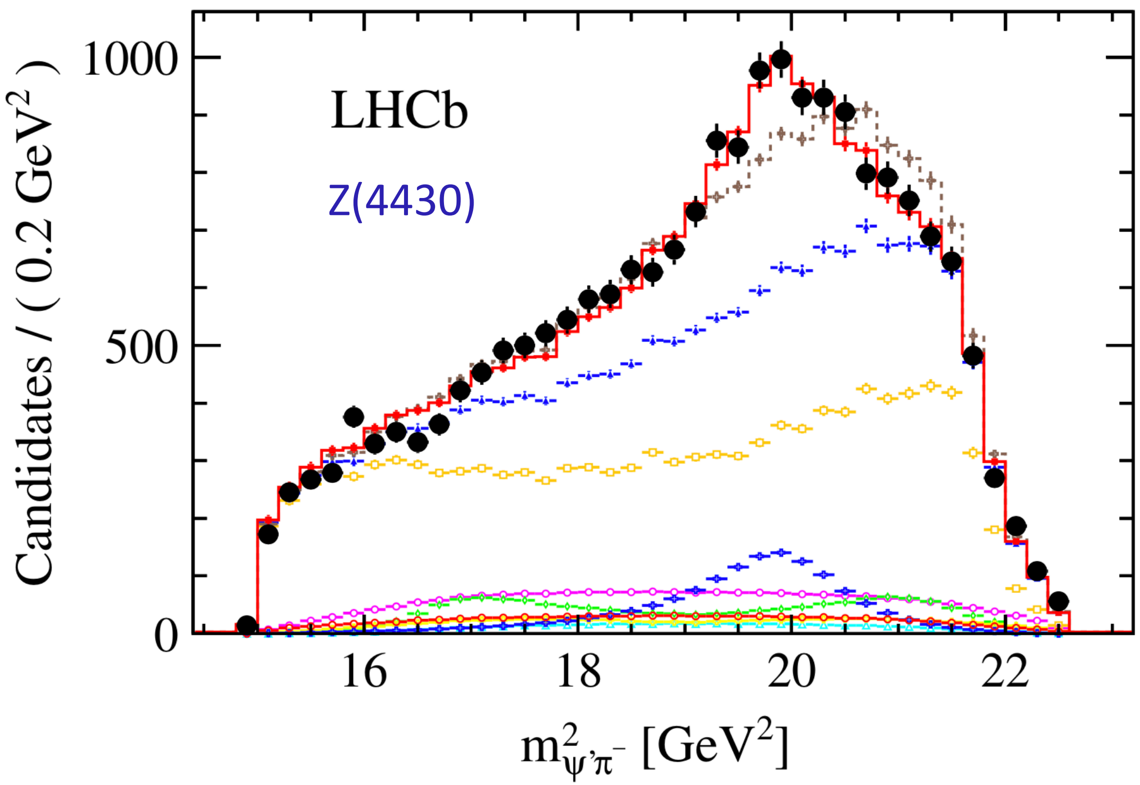
Phys Rev Lett 112 222002 (2014)



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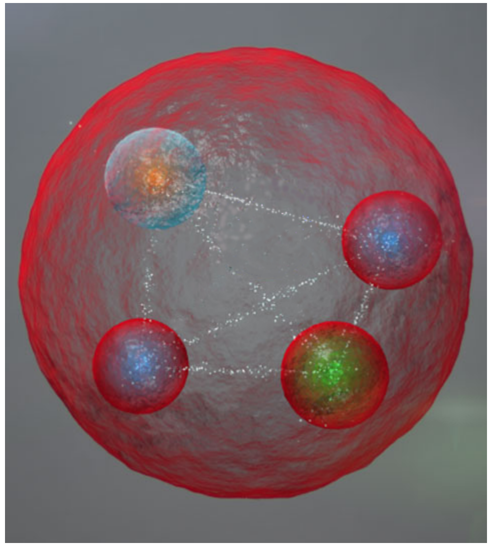
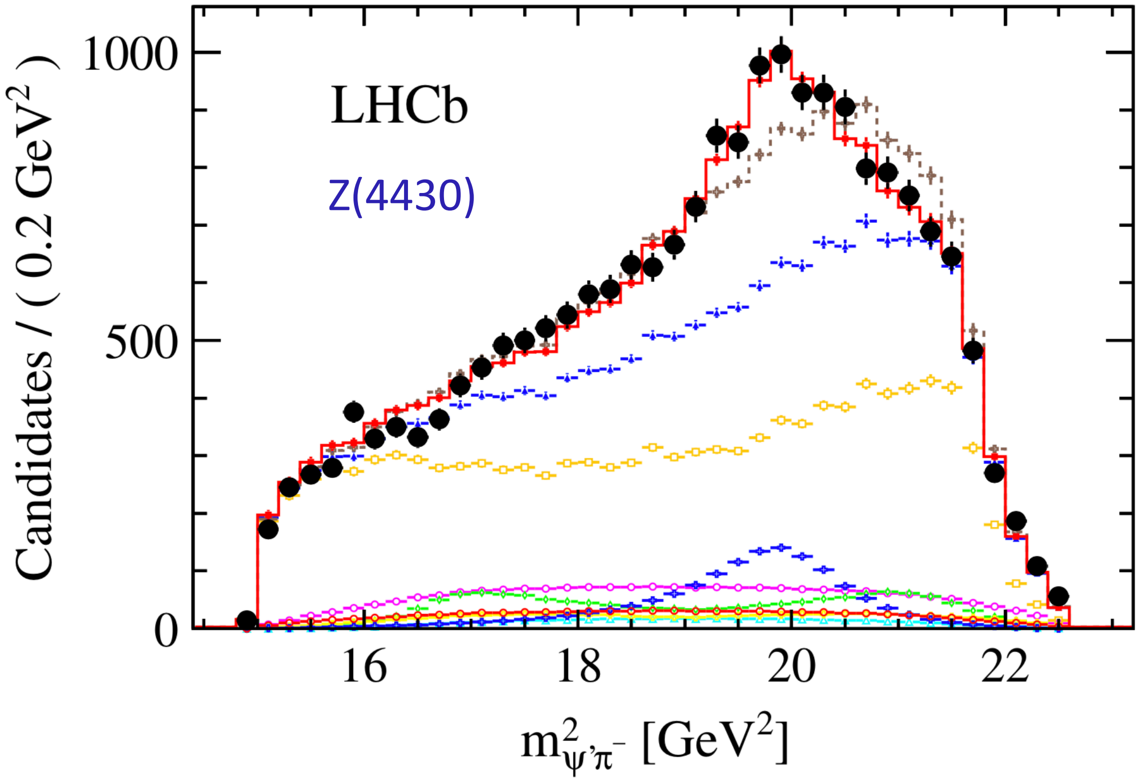


Minimal 4 quark content: $c\bar{c}q\bar{q}$

Masses are NOT close to any hadron+hadron threshold – candidate for compact tetraquark

Phys Rev Lett 112 222002 (2014)



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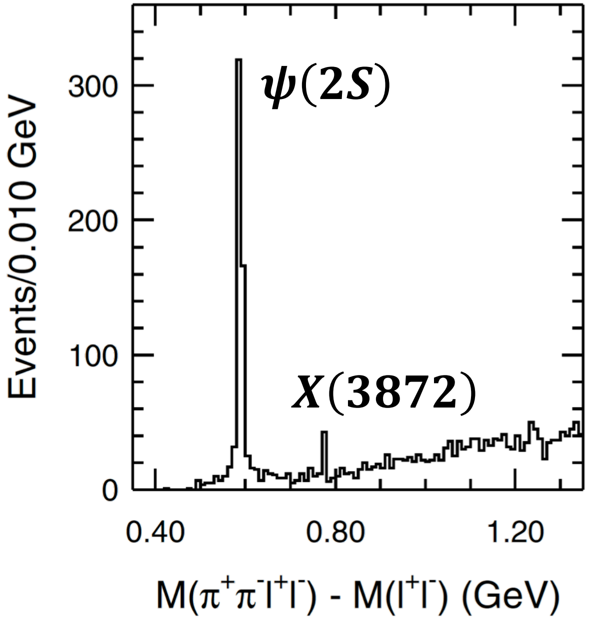
X(3872) - a puzzle

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

Belle Collaboration
PRL 91 262001 (2003)



The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003

LHCb measured quantum numbers (PRL 110 222001 2013)

- Incompatible with expected charmonium states

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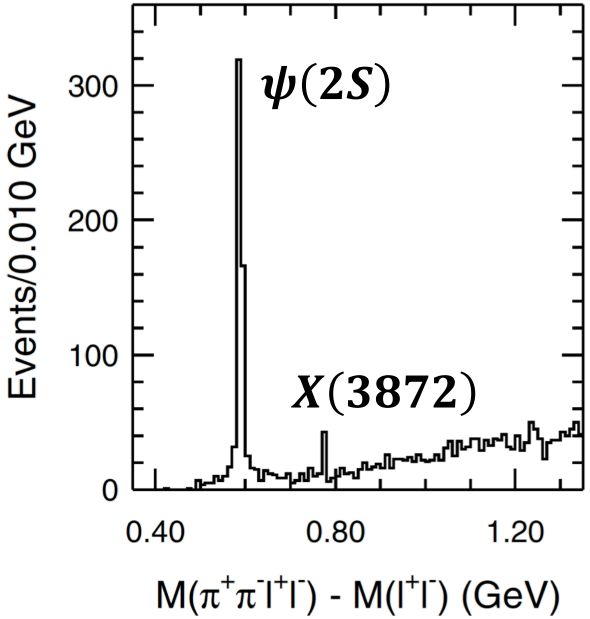

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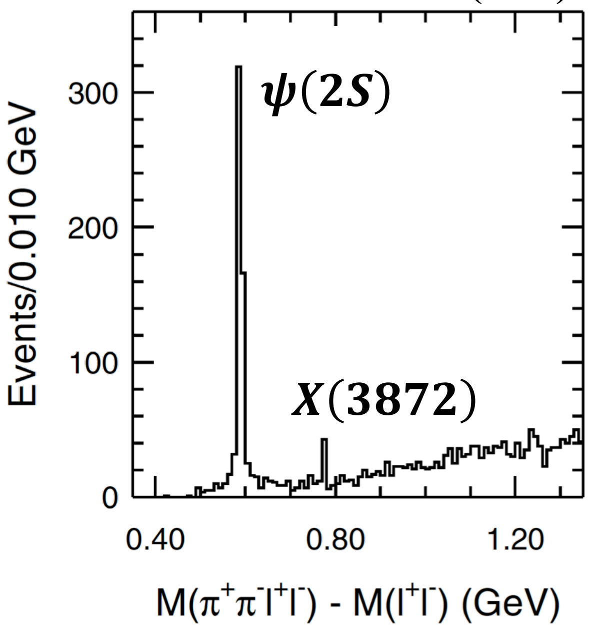

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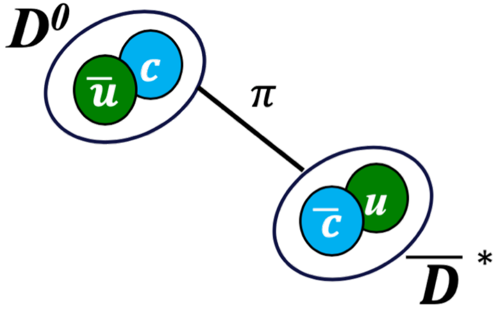
$D^0\overline{D}^*$ ***Molecule***



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

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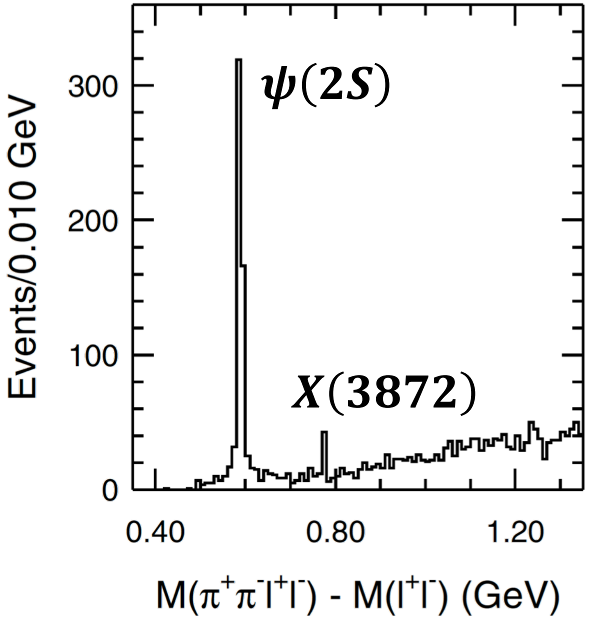

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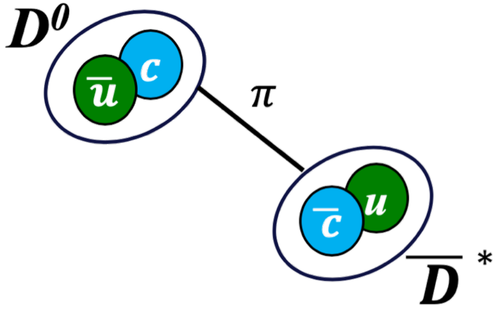
Large prompt production fraction (~80%) – inconsistent with D recombination in pp*

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



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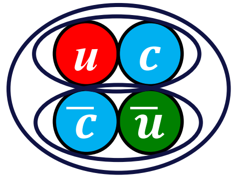
Compact tetraquark

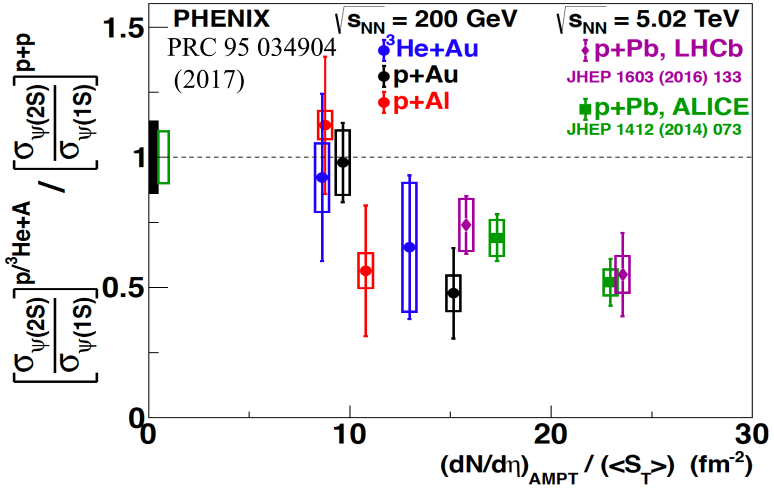


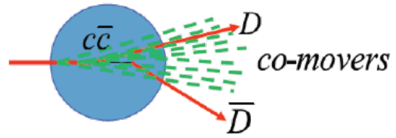
Tightly bound via color exchange between diquarks
Small **radius, ~1 fm**

*Tension in theoretical literature:
c.f. Bignamini, Grinstein et al
PRL 103 162001 (2009)
vs
Artoisenet, Braaten
PRD 81 114018 (2010)

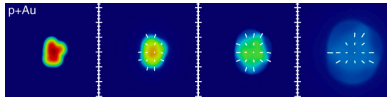
Effects of Binding Energy

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





cf. PLB 749 98 (2015)



PHENIX, Nature Physics 15 214 (2019)

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

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

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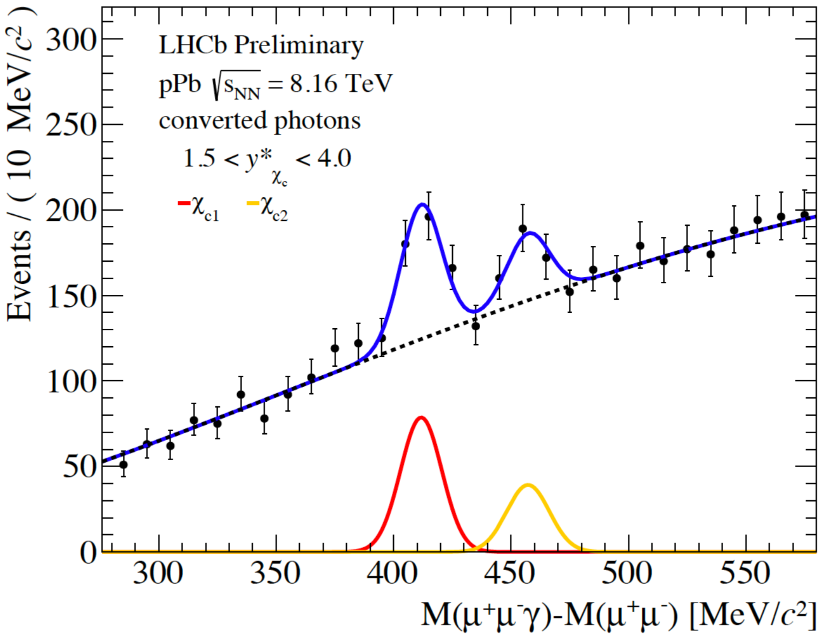

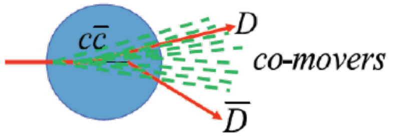

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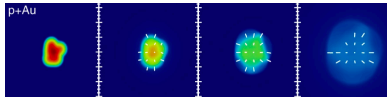

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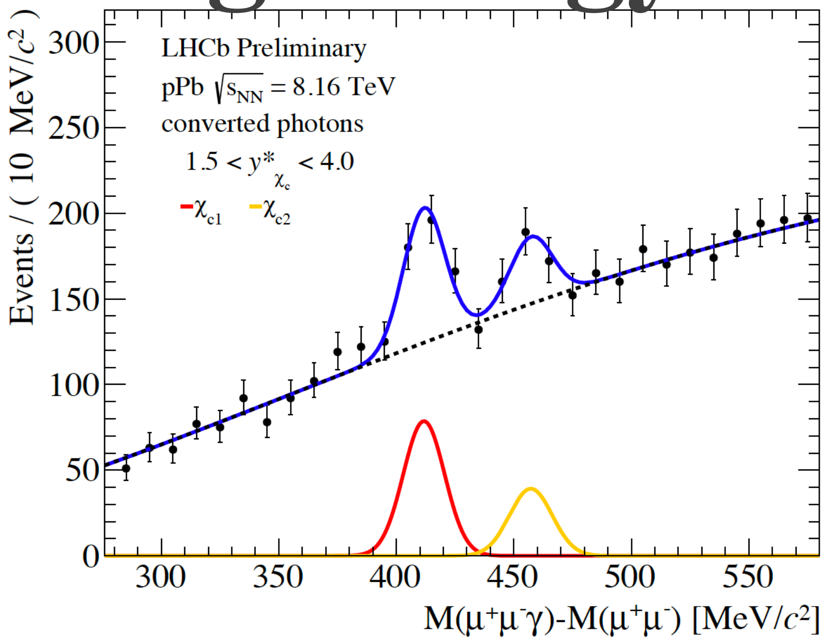
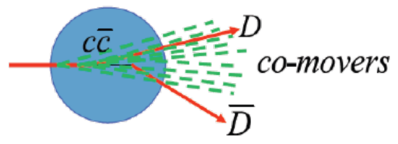
- In general, final state effects are required to explain difference in suppression between states
- Prevalent in regions with high particle multiplicity





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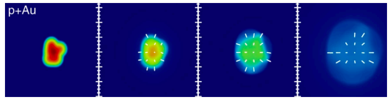
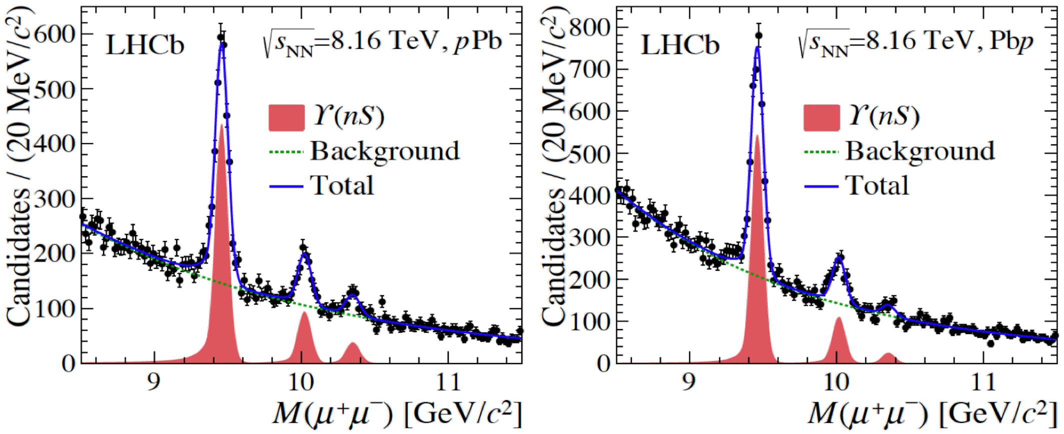


PHENIX, Nature Physics 15 214 (2019)

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

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

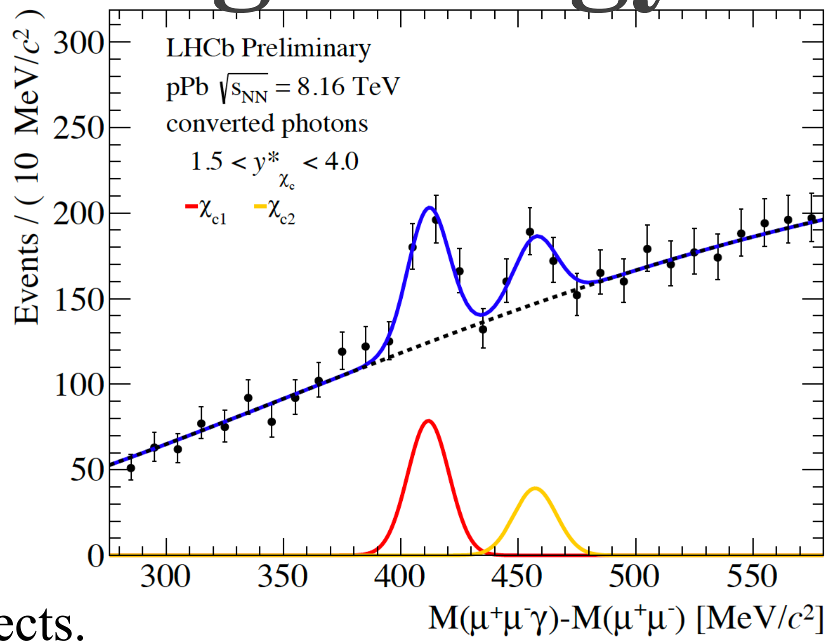


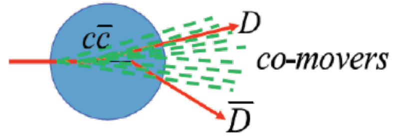
Effects of Binding Energy

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

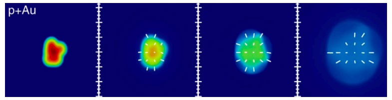
- In general, final state effects are required to explain difference in suppression between states
- Prevalent in regions with high particle multiplicity

- Weakly bound hadronic molecules may show similar effects.





cf. PLB 749 98 (2015)

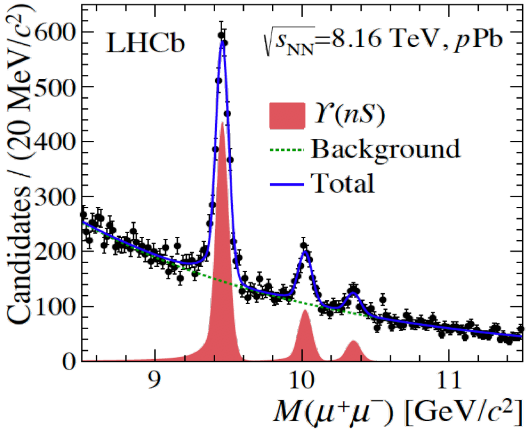


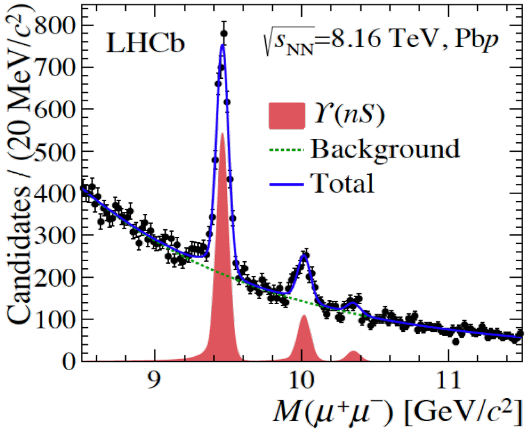
PHENIX, Nature Physics 15 214 (2019)

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



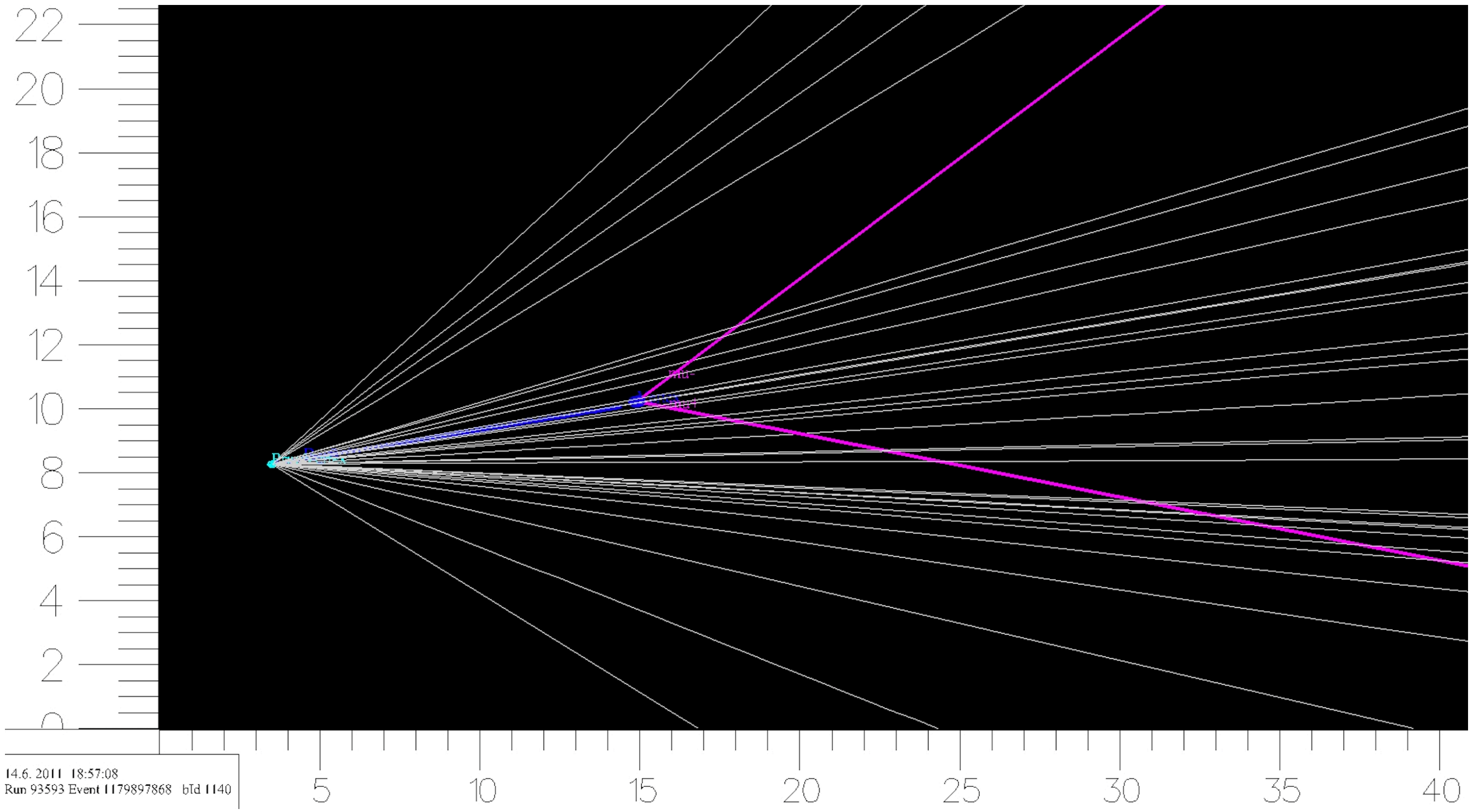


Probing X(3872) structure via interactions with the underlying event

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

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



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

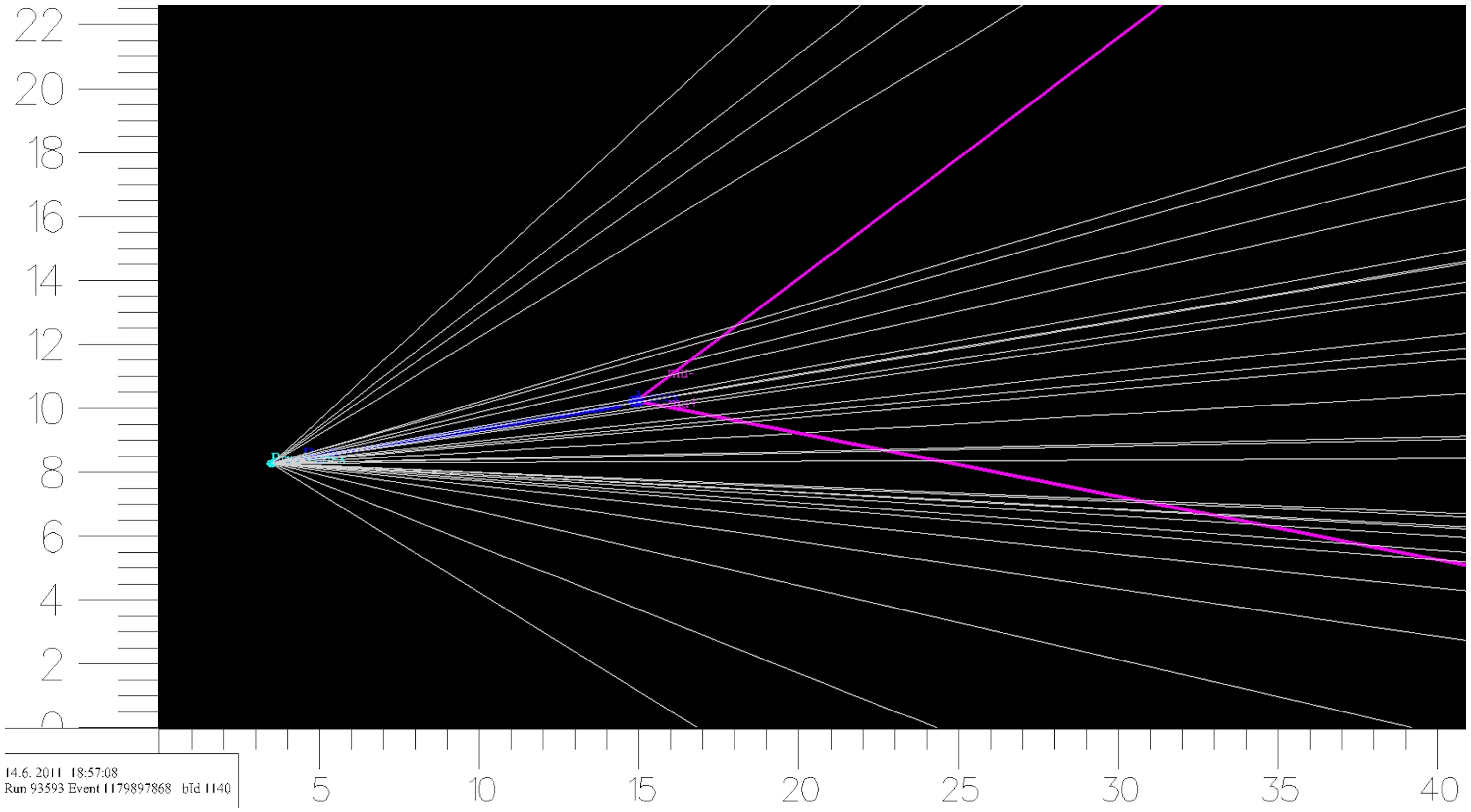
Prompt production:

- 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)



X(3872) selection

LHCb-CONF-2019-005

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

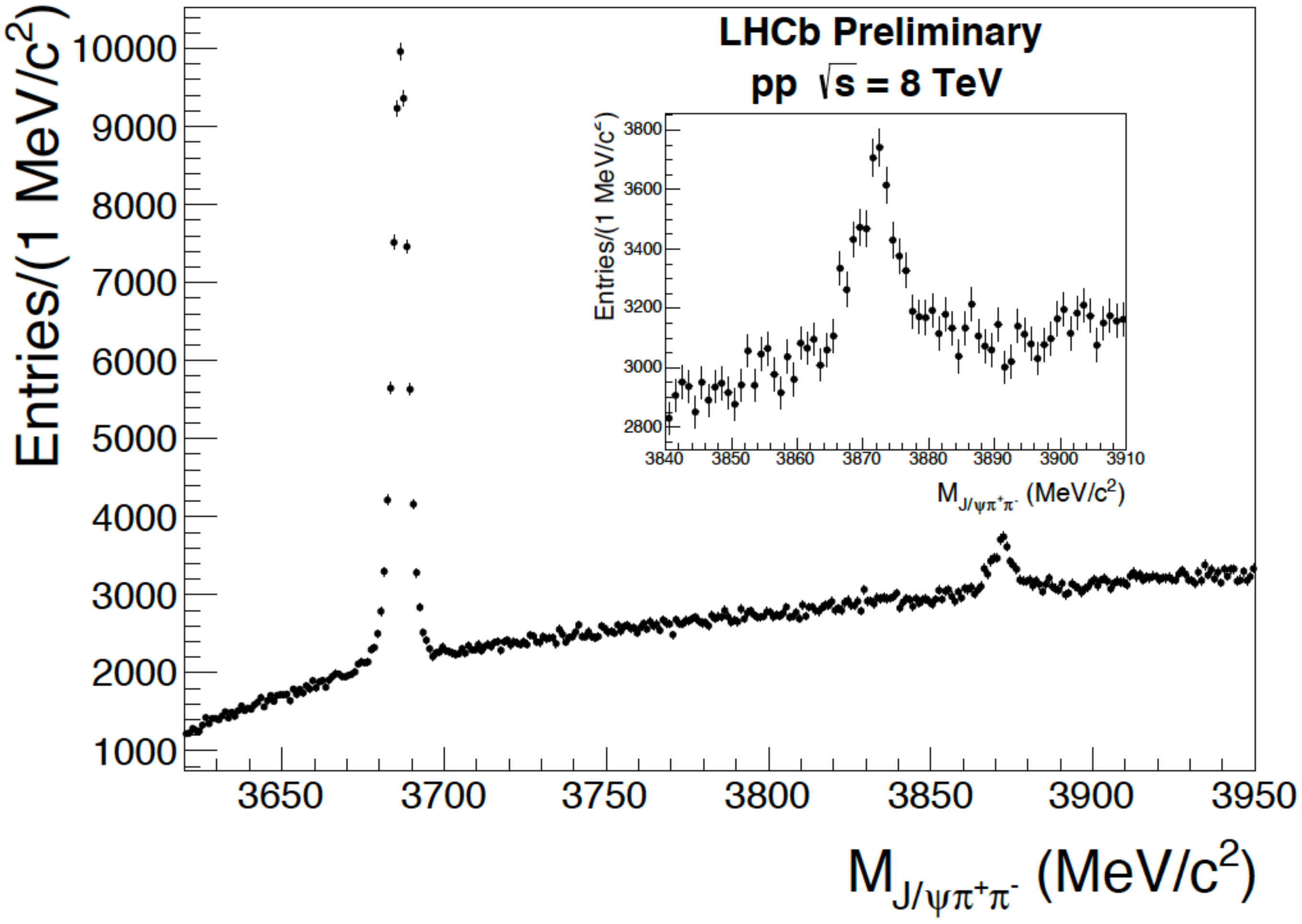
$$X(3872) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho(\rightarrow \pi^+\pi^-)$$

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

Select J/ψ from dimuons, combine with two identified pions. Perform kinematic refit, constraining J/ψ mass to known value and all four tracks to identical vertex.

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

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



Prompt / *b*-decay separation

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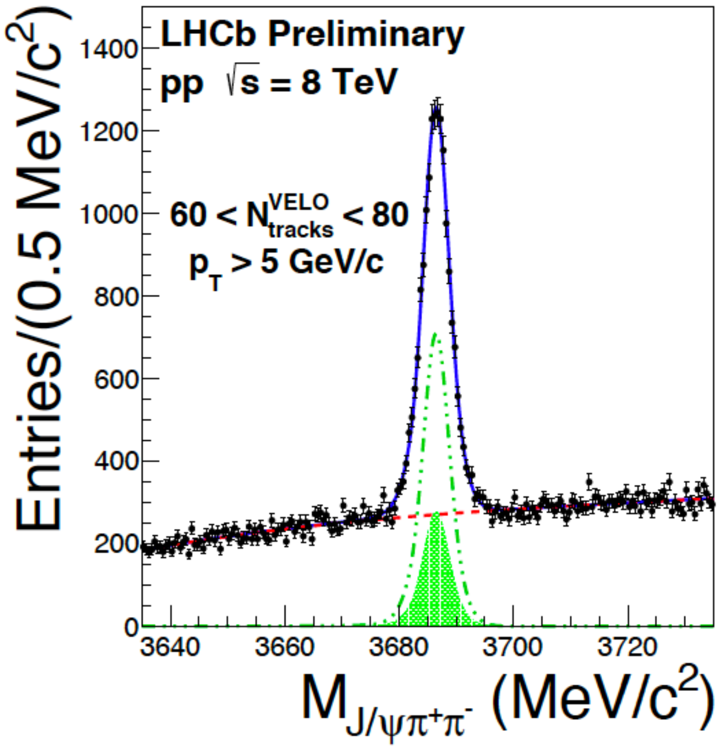
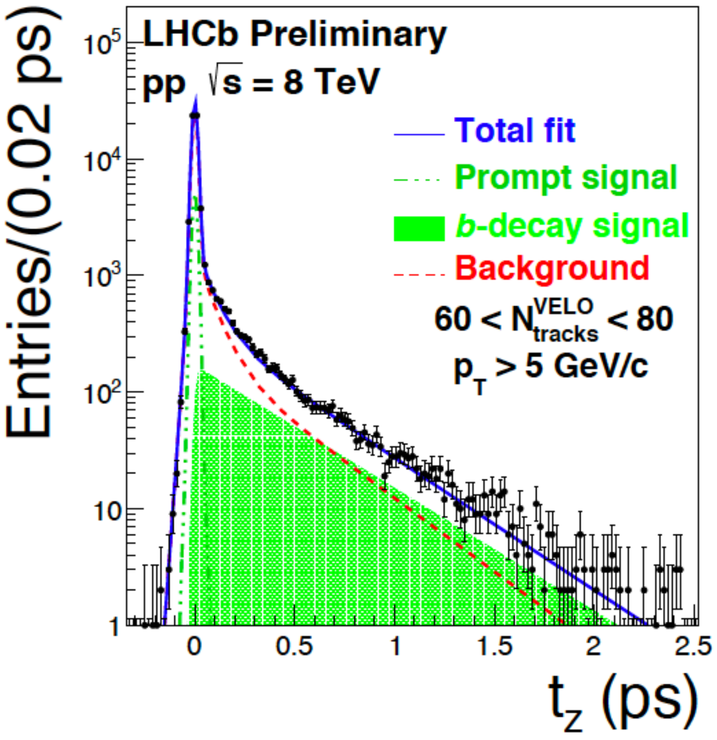
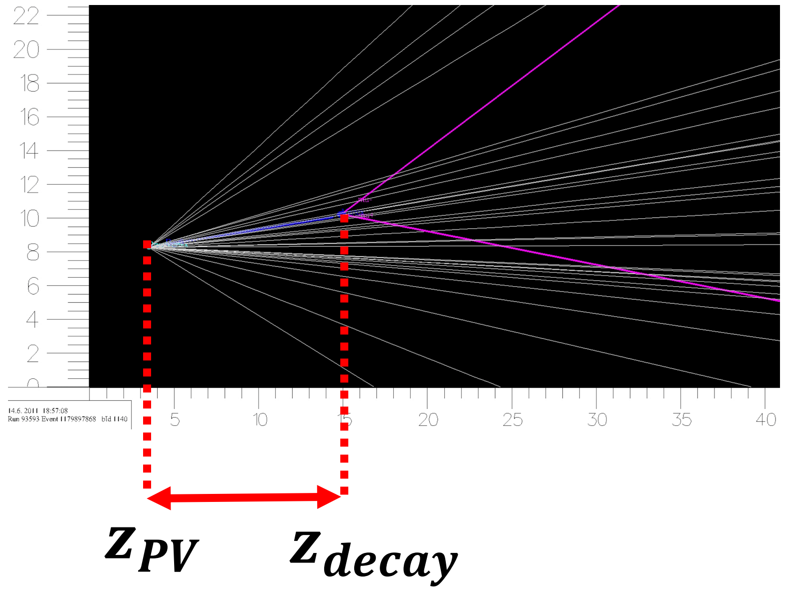




Simultaneous fit to invariant mass and pseudo proper time spectrum:

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



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

Prompt fraction

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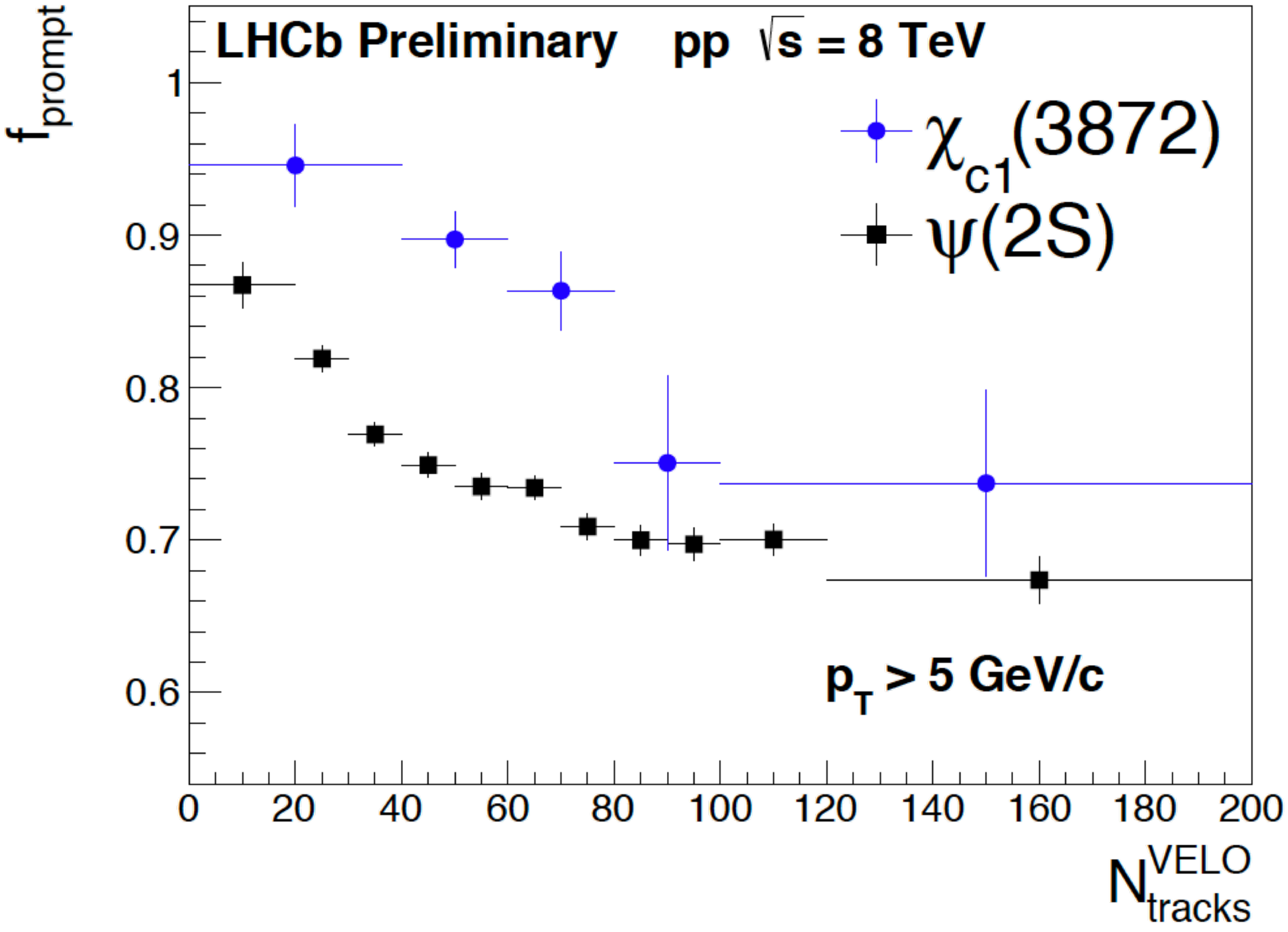

$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{b-decay}}$$

- Significant decrease in prompt fraction of both $X(3872)$ and $\psi(2S)$ as event activity increases:

Prompt fraction

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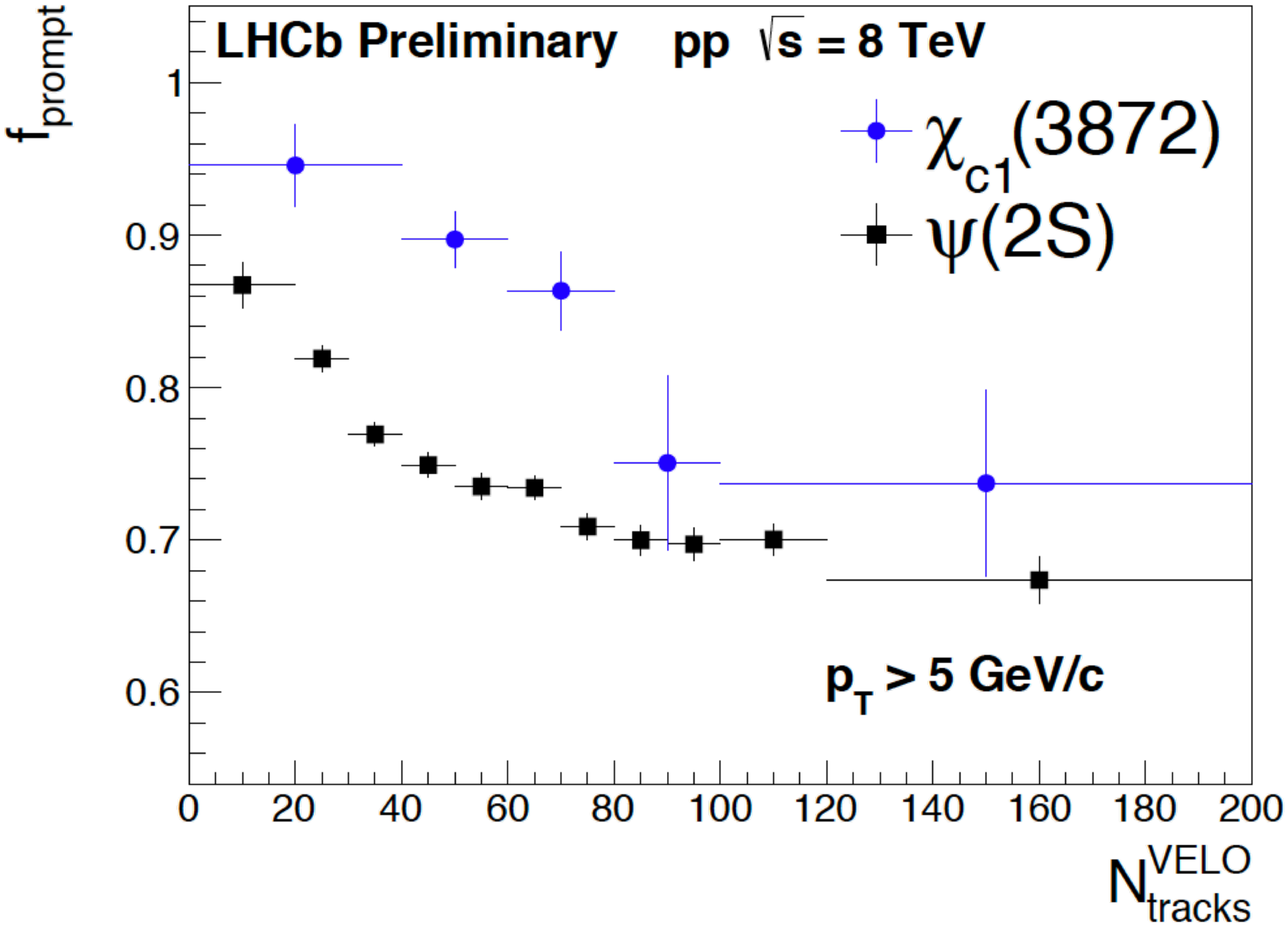

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- Significant decrease in prompt fraction of both $X(3872)$ and $\psi(2S)$ as event activity increases:
- Events with $b\bar{b}$ production naturally have higher multiplicity, due to fragmentation and decays
  - OPAL, PLB 550 33 (2002)

Prompt fraction

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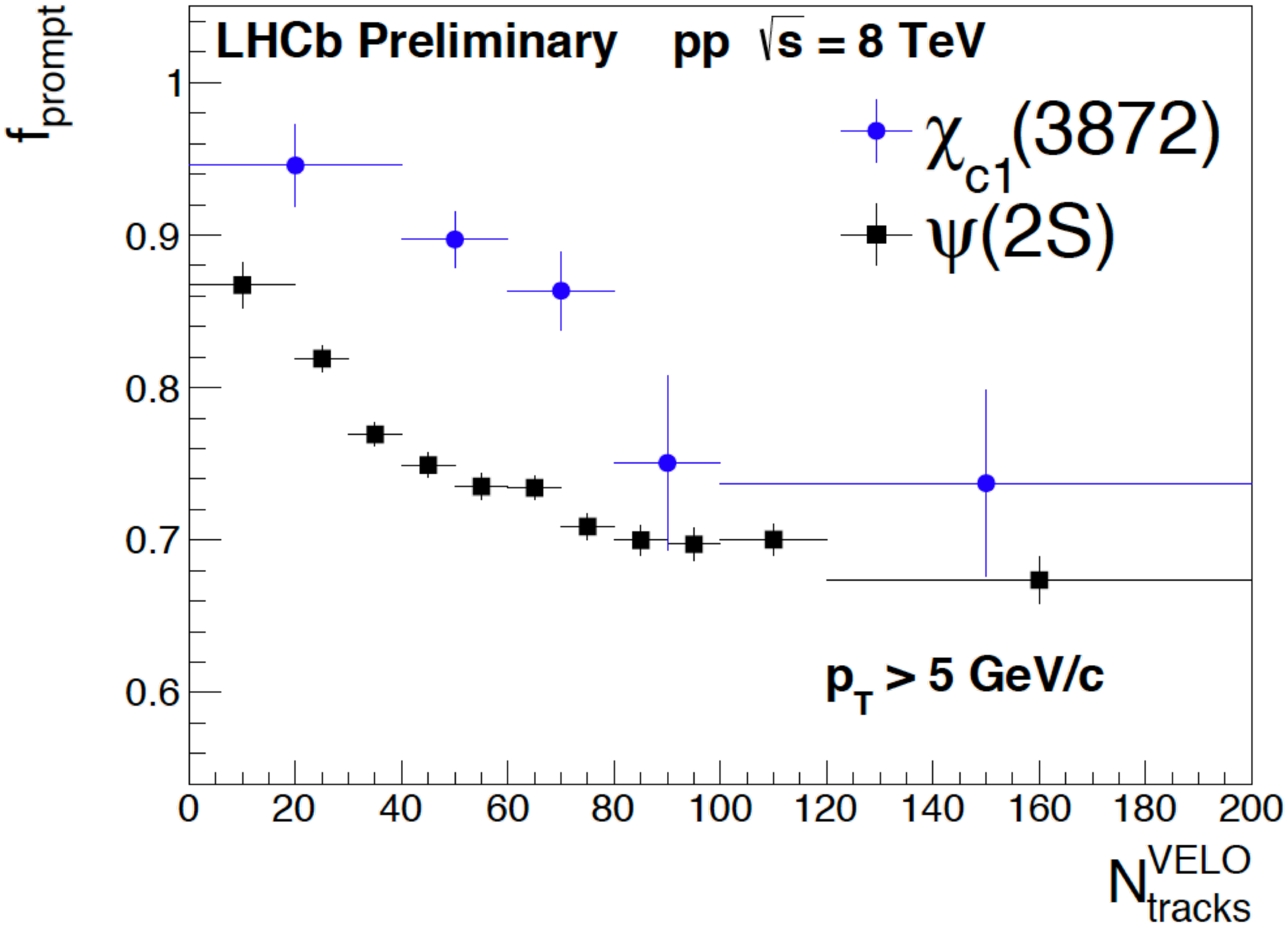

$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{b-decay}}$$

- Significant decrease in prompt fraction of both $X(3872)$ and $\psi(2S)$ as event activity increases:
- Events with $b\bar{b}$ production naturally have higher multiplicity, due to fragmentation and decays
  - OPAL, PLB 550 33 (2002)
- Formation of prompt $X(3872)$ and $\psi(2S)$ may be disrupted at the vertex, which cannot affect production via b decays in vaccum.

Ratio of cross sections

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\,\pi^+\pi^-]} = \frac{N_{\chi_{c1}(3872)}\, f_{\text{prompt}}^{\chi_{c1}(3872)}}{N_{\psi(2S)}\, f_{\text{prompt}}^{\psi(2S)}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$

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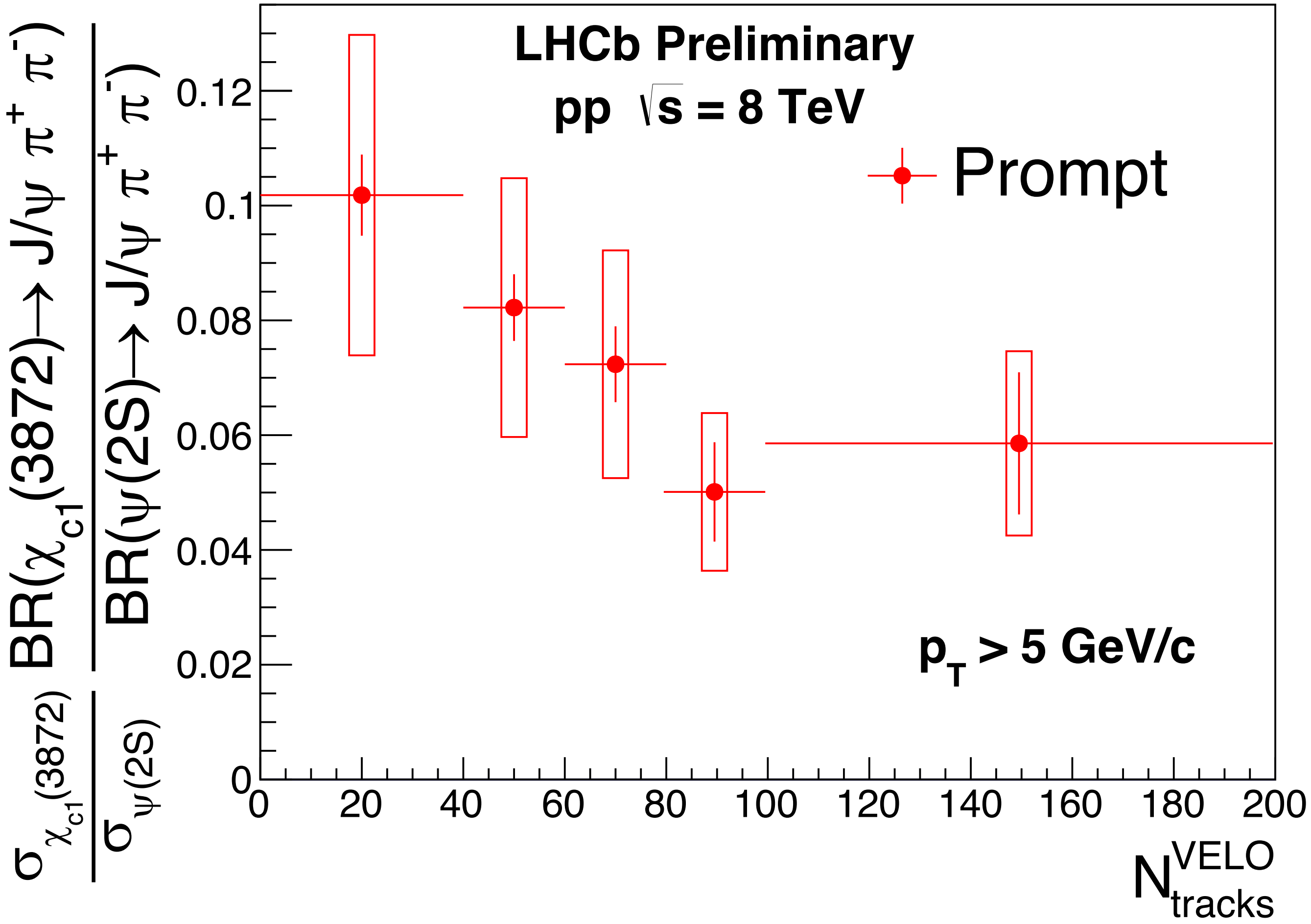

Prompt Component:
Increasing suppression of $X(3872)$ production relative to $\psi(2S)$ as event activity increases

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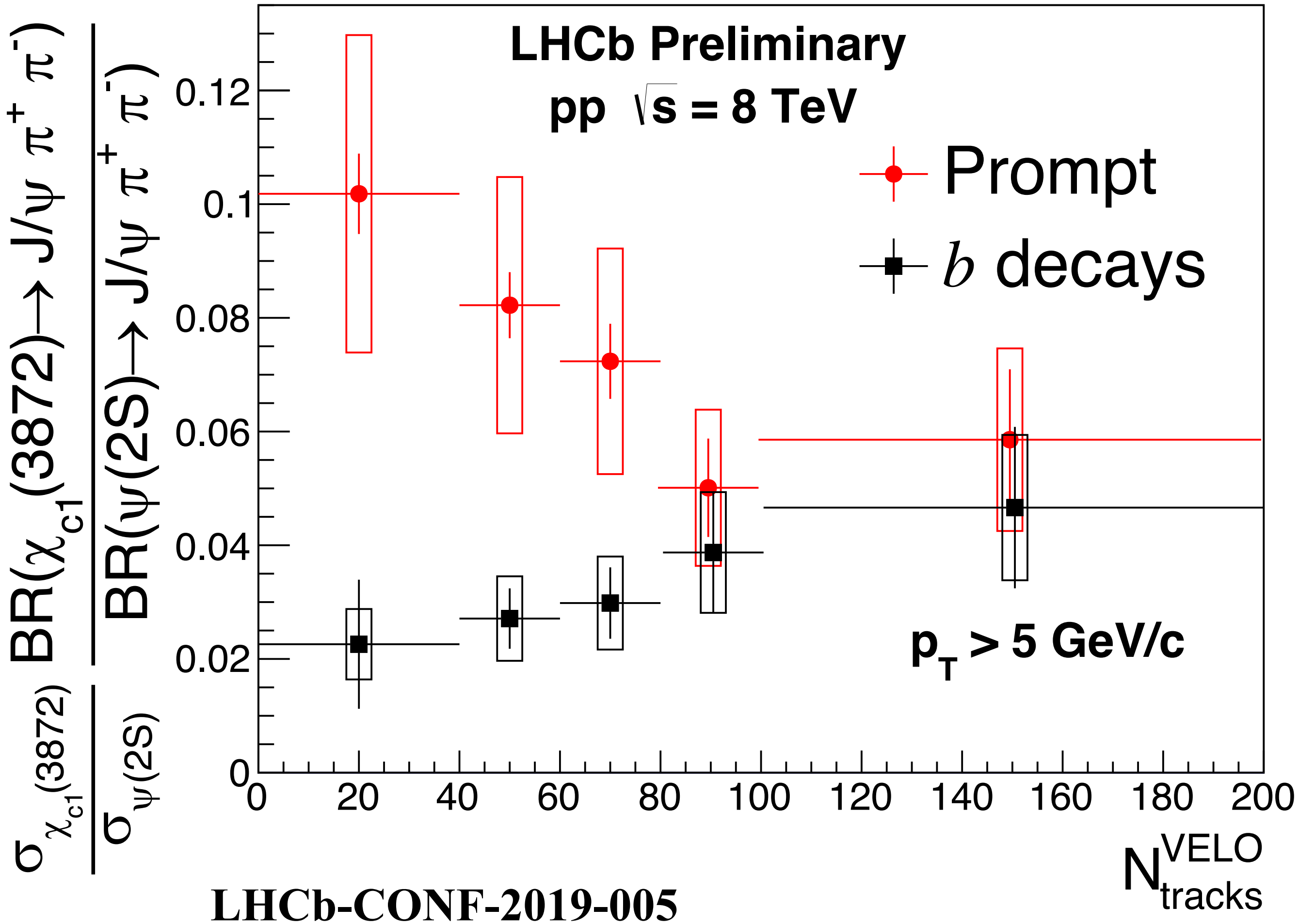
Ratio of cross sections

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = \frac{N_{\chi_{c1}(3872)}\, f_{\text{prompt}}^{\chi_{c1}(3872)}}{N_{\psi(2S)}\, f_{\text{prompt}}^{\psi(2S)}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$



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Prompt Component:
Increasing suppression of $X(3872)$ production relative to $\psi(2S)$ as event activity increases

b-decay component:
No significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching fractions.
Consistent with ATLAS measurement
R = 0.0395±0.0032±0.0008 (p_T>10GeV/c)
JHEP 2017:117 (2017)

Ratio of cross sections

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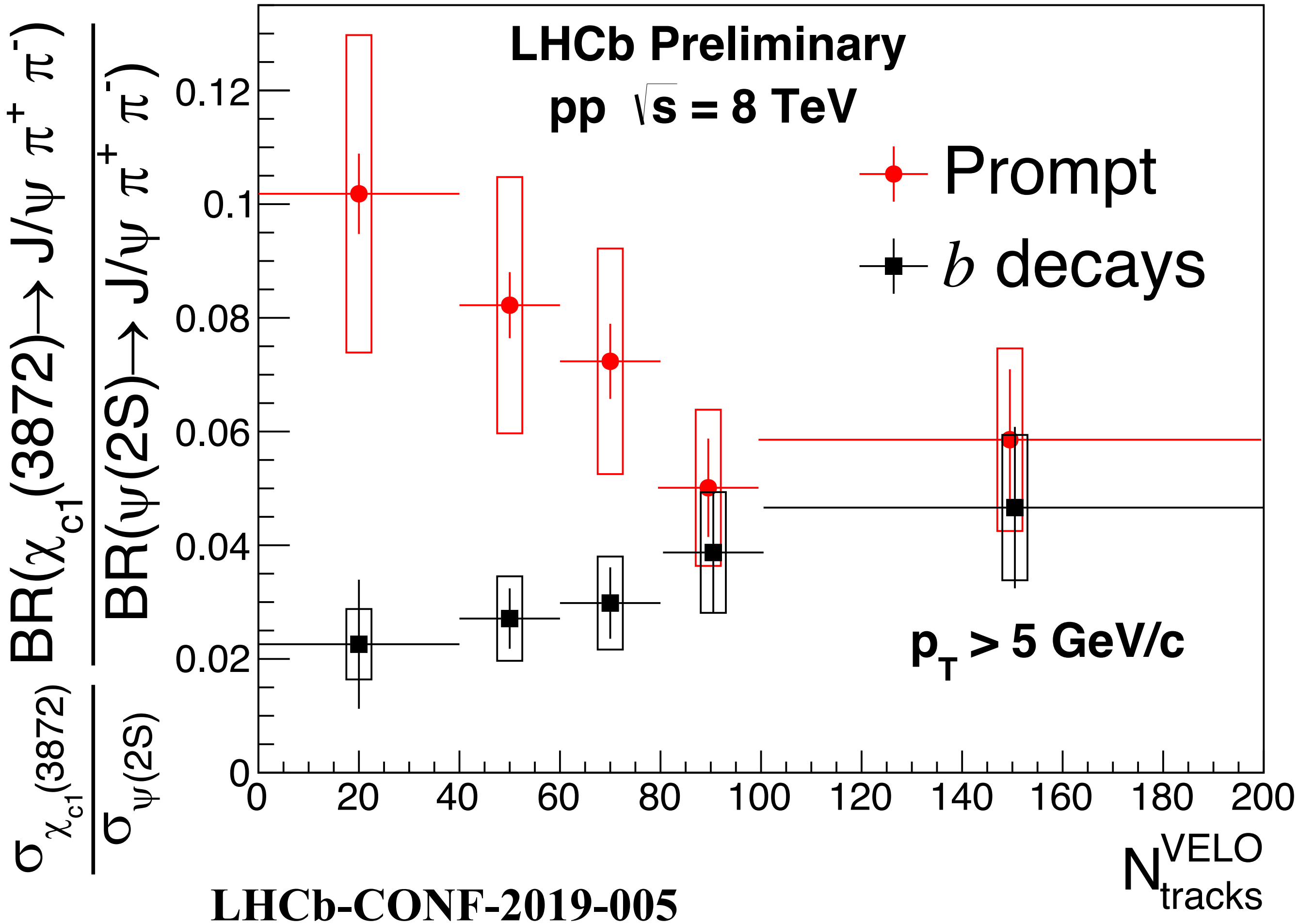

LHCb-CONF-2019-005

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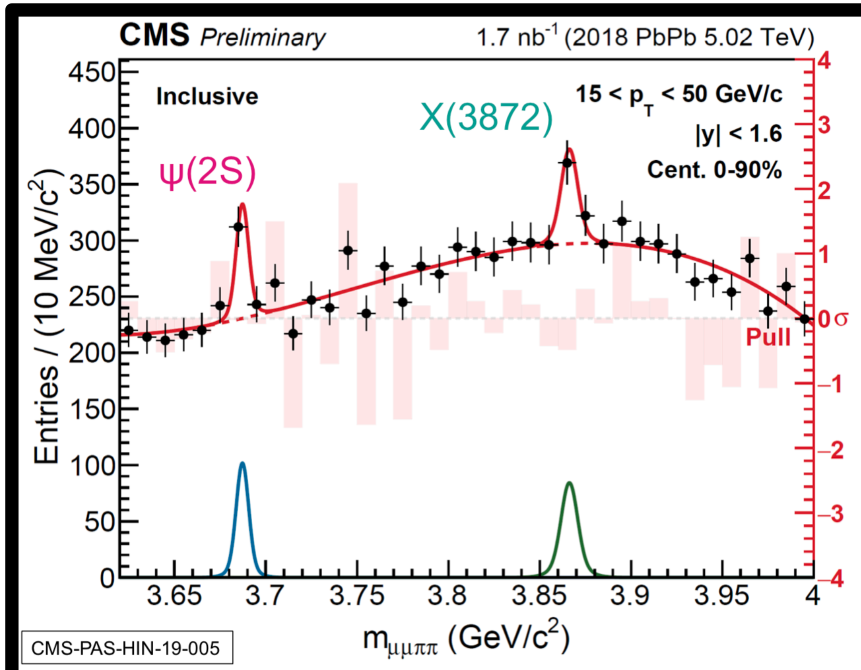
CMS Result – X(3872) in PbPb

See slides from YJ Lee, Quark Matter 2019



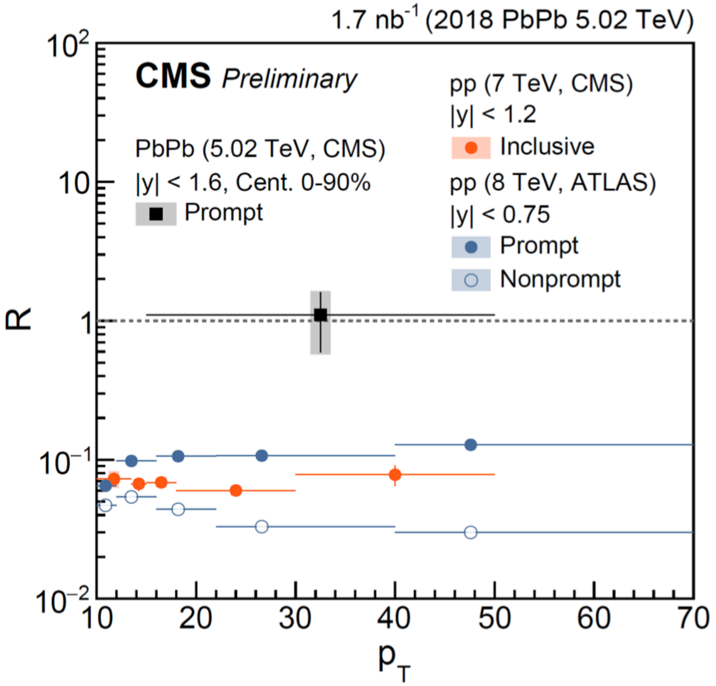
$$R = N^{(\mathrm{Corr})}_{X(3872)} / N^{(\mathrm{Corr})}_{\psi(2S)}$$

In PbPb collisions:

$$R = 1.10 \pm 0.51\ (\mathrm{stat.}) \pm 0.53\ (\mathrm{syst.})$$

Indication of R enhancement in PbPb collisions with respect to pp at 7 and 8 TeV

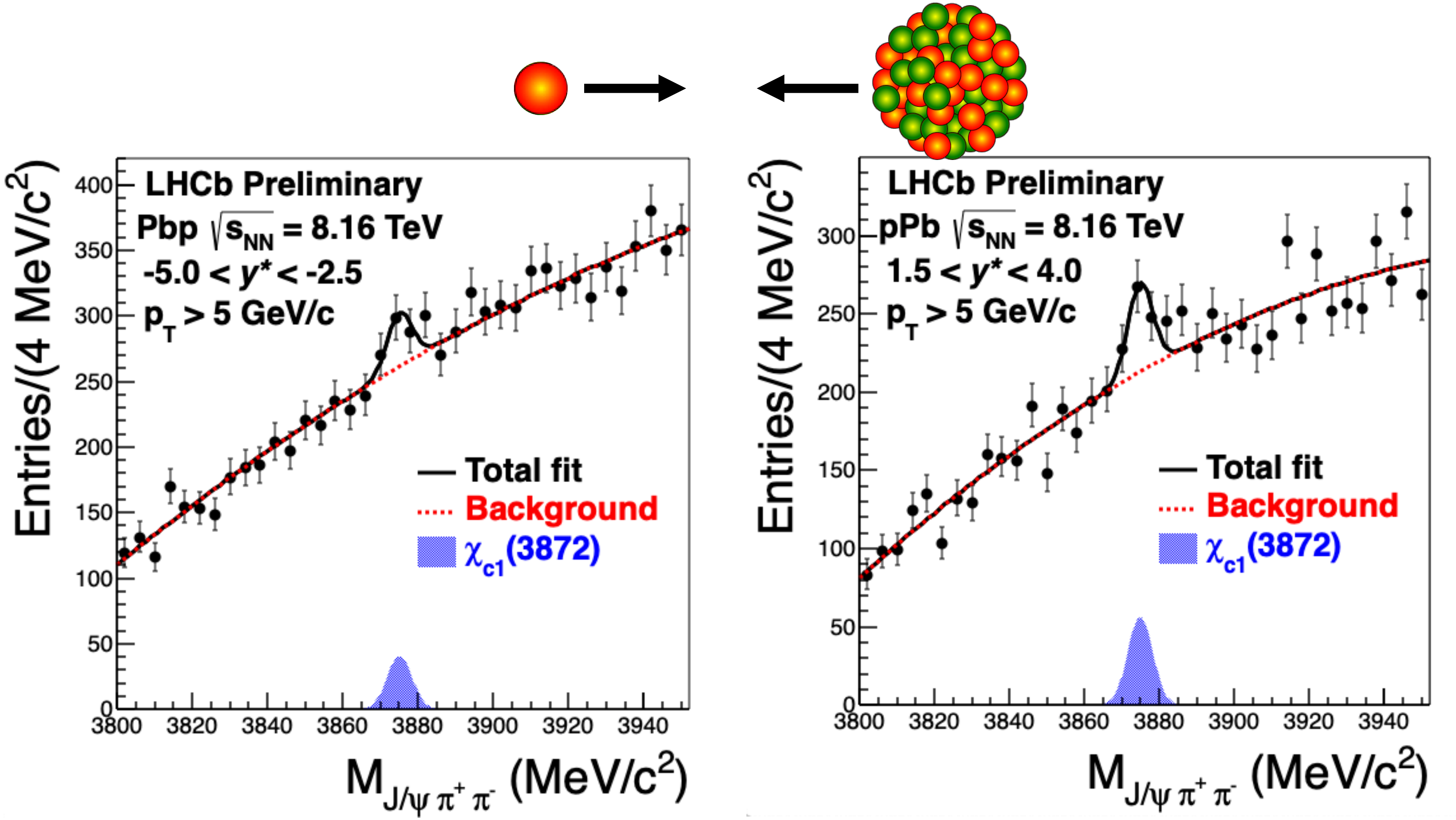
CMS-PAS-HIN-19-005



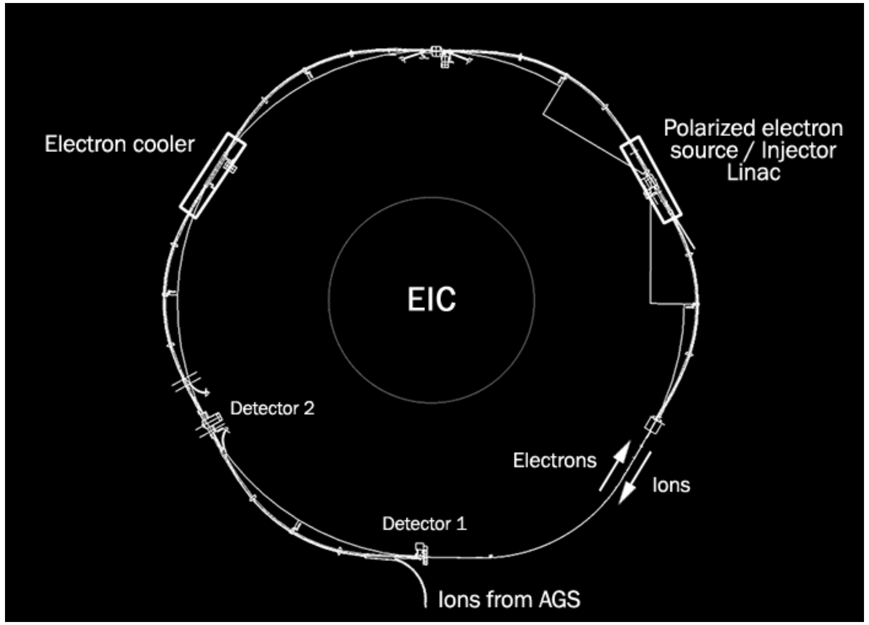
Hint of recombination in PbPb (pT > 15 GeV) ??

Large error bars preclude firm conclusions

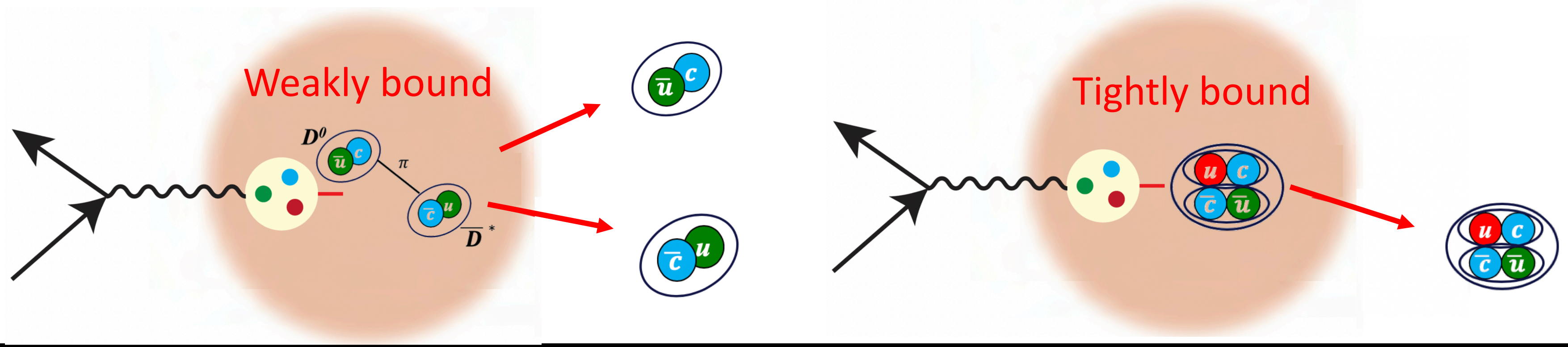
X(3872) in pPb collisions



Studies at a future EIC



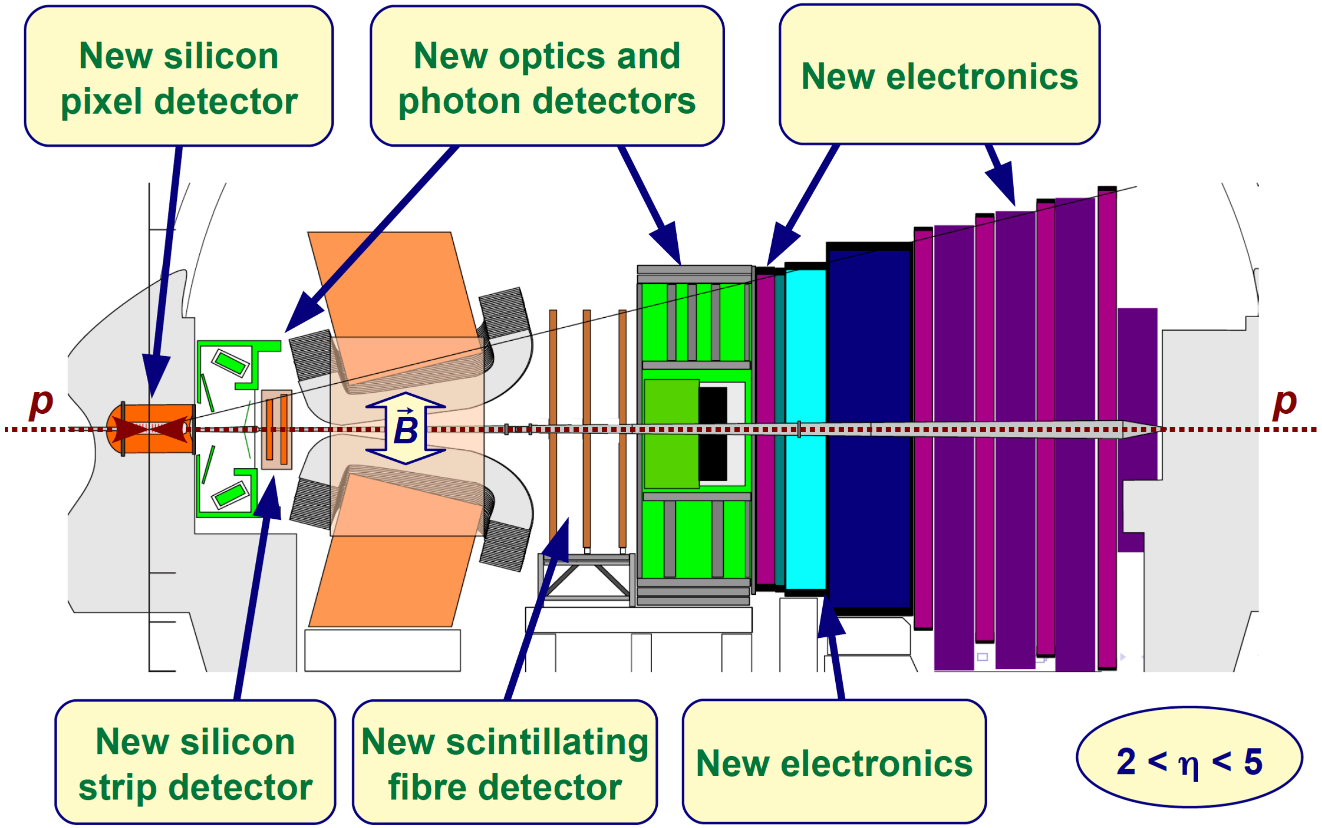
- Electron ion collisions – clean environment for complicated reconstruction
- High luminosity, high rate -> high statistics for rare probes
- Production inside the nucleus exposes exotics to a dense QCD environment – potentially disrupting formation
  - Discrimination between molecular and compact tetraquark pictures
- Requires tracking and reconstruction in forward (nucleus-going) direction – research at LANL is ongoing w/LDRD funds



Outline

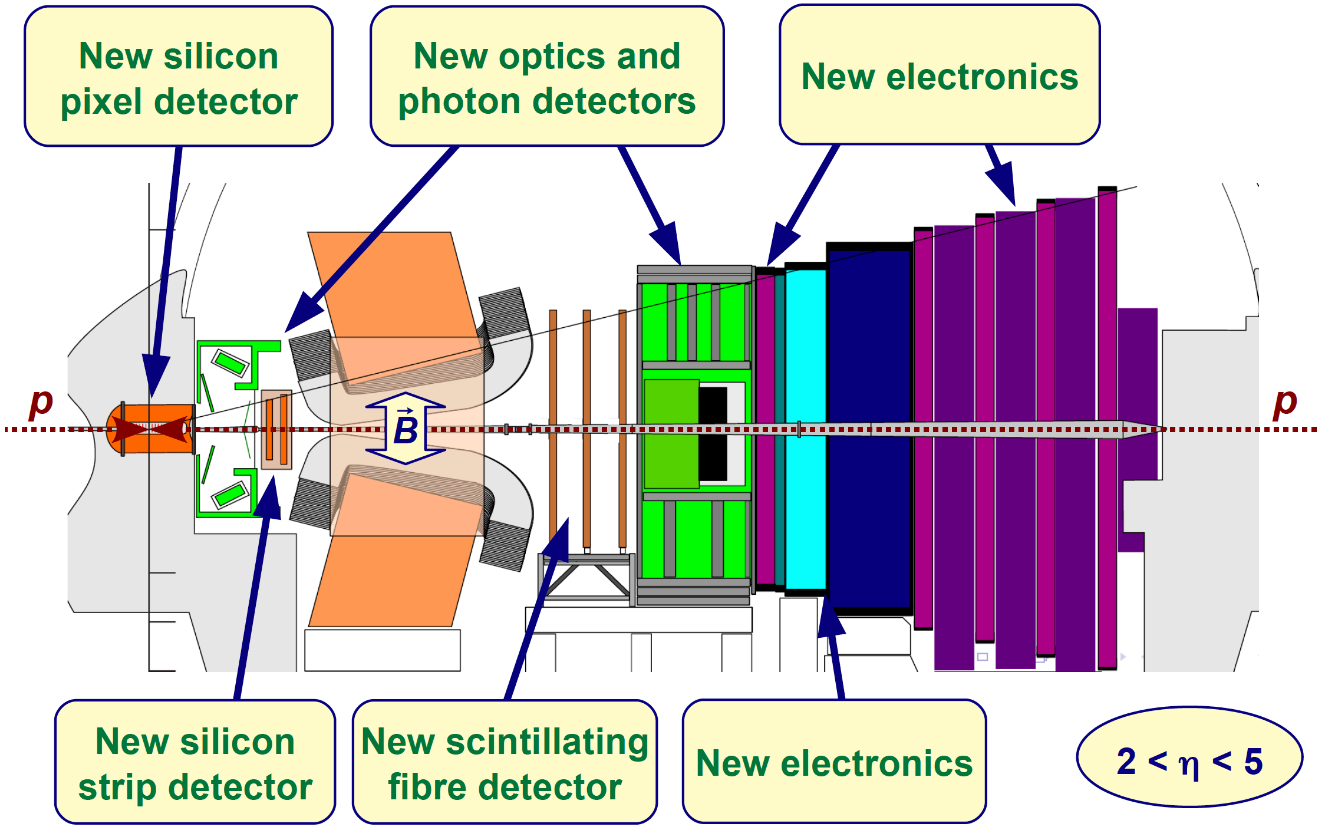
- LHCb Physics program
- Apparatus
- Heavy Ions at LHCb
  - Collider Mode
  - Fixed Target Mode (SMOG)
- Exotics at LHCb
- Upgrades

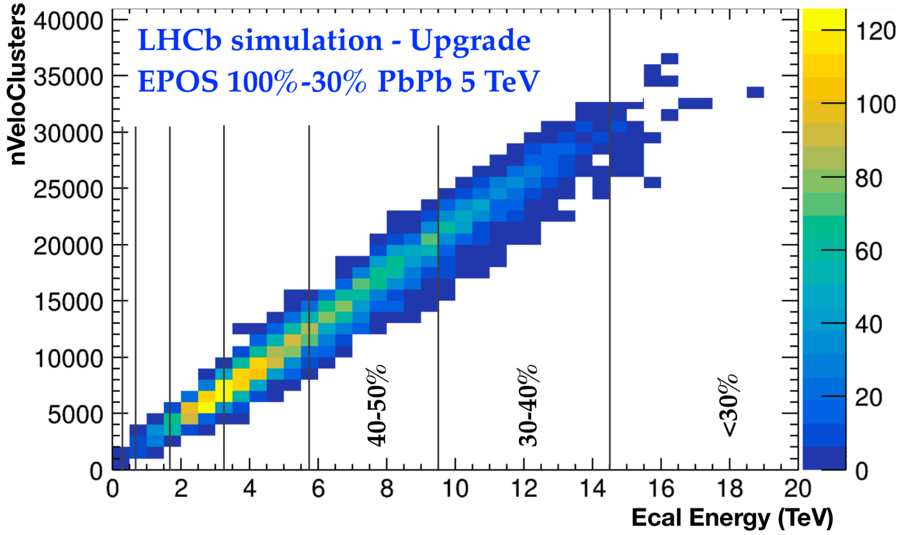
Massive Upgrades Underway

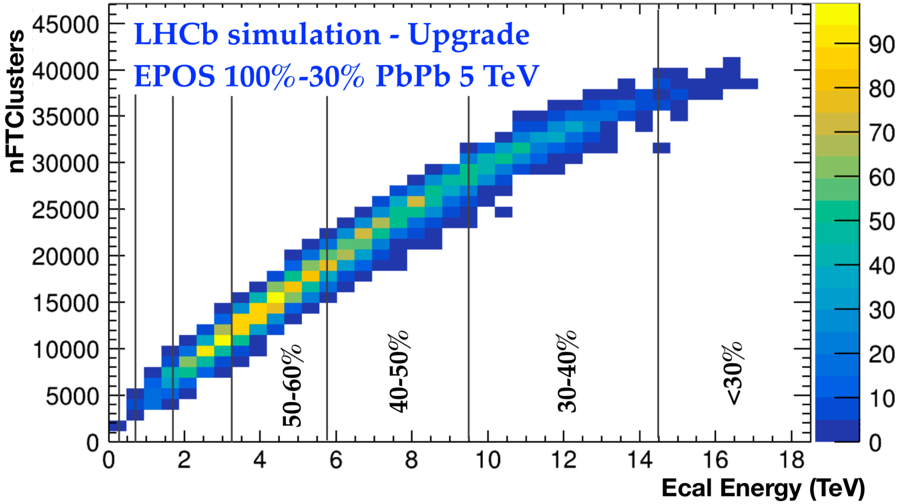


Trigger-less readout of full 40MHz LHC collision rate

Massive Upgrades Underway



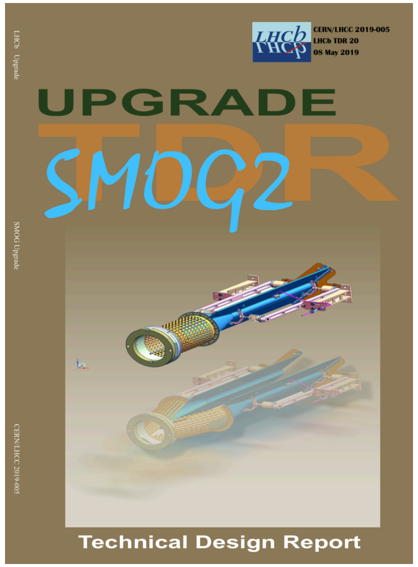


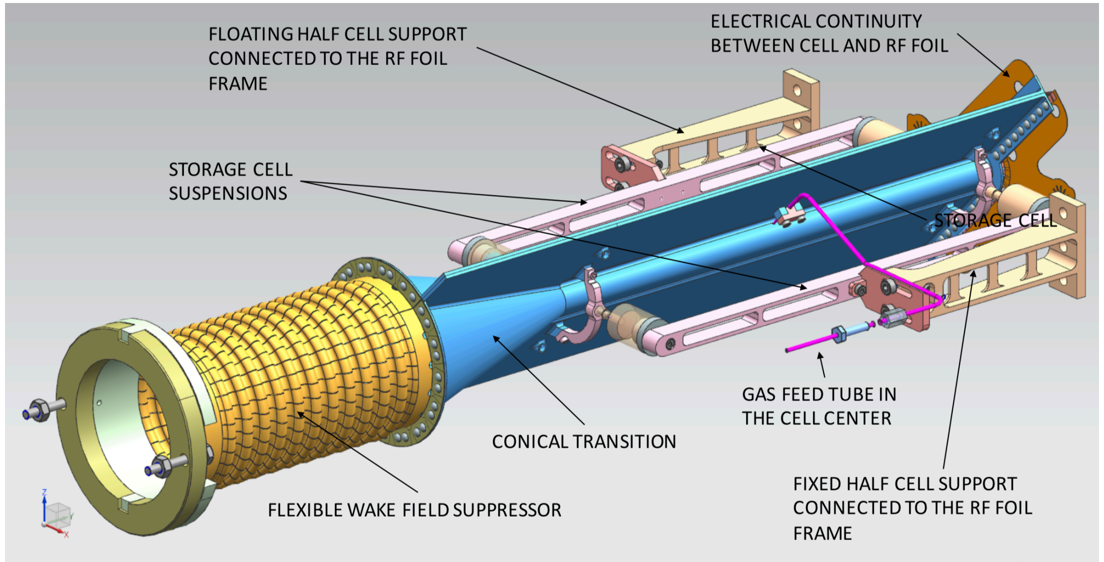


Trigger-less readout of full 40MHz LHC collision rate

Tracking up to at least 30% in PbPb collisions

SMOG II





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

1 yr of pAr data at 115 GeV:

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

+ flow in various small systems?
Net proton fluctuations?

SMOG II can potentially run simultaneously with pp physics
Factor of ~100 increase in rates over current SMOG
Installation is happening NOW

Summary

- LHCb has an active, growing program in heavy ion physics, in fixed target and collider modes.

- The LHCb detector has unique capabilities for the study of exotics:
  - Full particle ID
  - Access to low pT
  - Prompt production of exotics is new, largely unexplored territory

- Significant upgrades are well underway that will significantly expand LHCb reach in heavy ions
  - Full software reconstruction and triggering
  - Increased reach in centrality
  - SMOG II

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