Recent Heavy Flavor Results from the Tevatron

Outline:

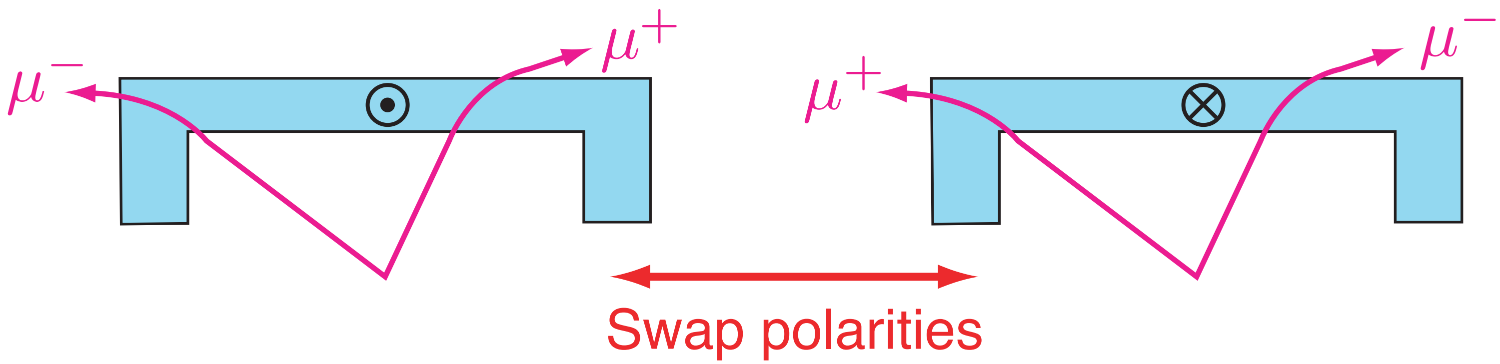
- Why is Tevatron still relevant?
- Production: D^+ cross section, asymmetries heavy & other baryons
- Spectroscopy: inclusive $X(4140)$, ***new*** exotic $X(5568)^{\pm}$ state
- Property: B_s^0 lifetime in CP eigenstate

Rick Van Kooten
Indiana University

28th Rencontres de Blois
Particle Physics and Cosmology
29 May – 3 June 2016

Relevancy of Tevatron (for Heavy Flavor)

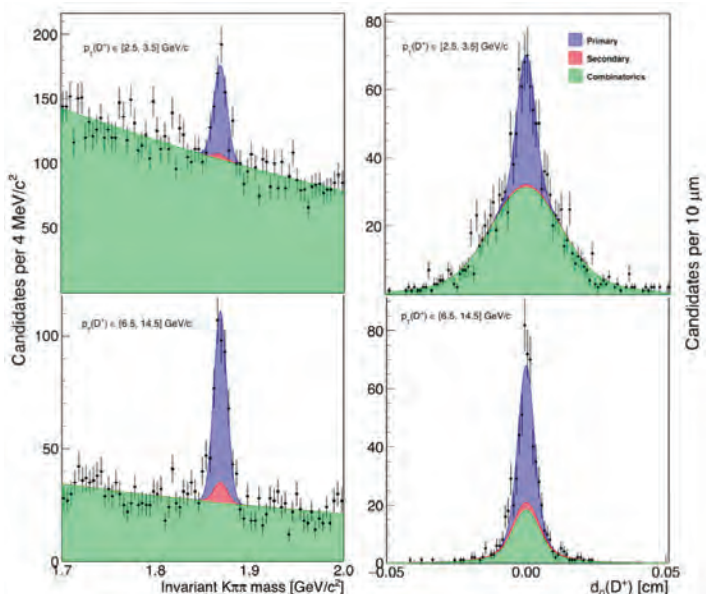
- Tevatron collided $p\bar{p}$ (c.f. LHC pp)
  - availability of different valence quarks in collision
  - CP invariant initial state
- DØ detector has both solenoidal and toroidal magnetic fields, swap polarities every two weeks $(++, --, +-, -+)$



- Difference in reconstruction efficiency between positive and negative particles minimized → helps cancel/reduce many detector charge asymmetries!
  (cancel to first order ~3% → ~0.1%)
- Legacy results, completeness

$D^{\pm}$ Cross Section

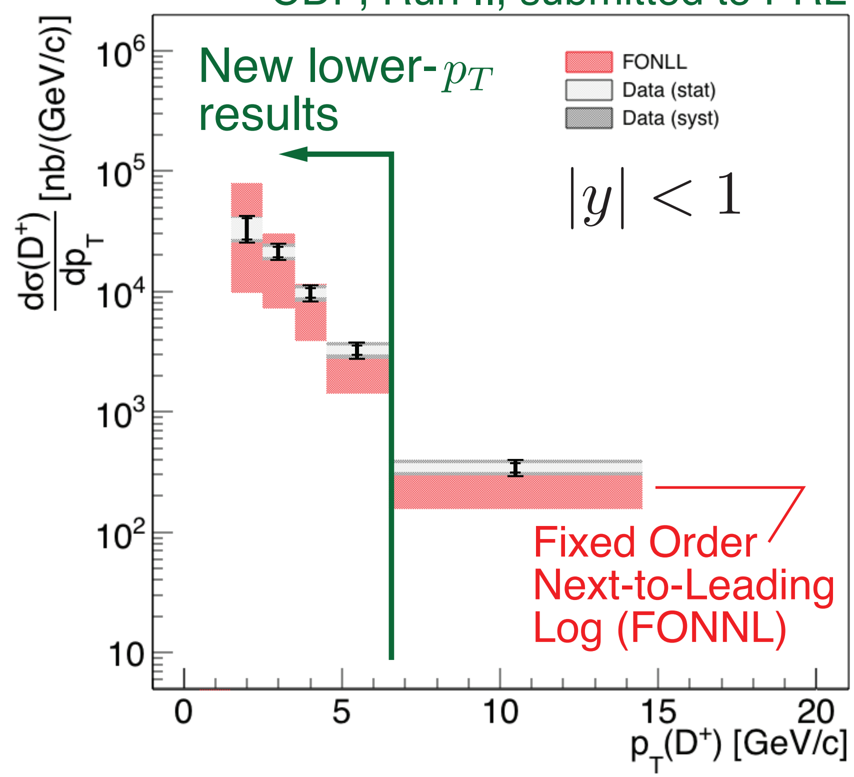
- Test and refine phenomenological models of strong interactions at small transferred four-momenta; regime in which perturbative expansions are challenging



$D^+ \rightarrow K^-\pi^+\pi^-$

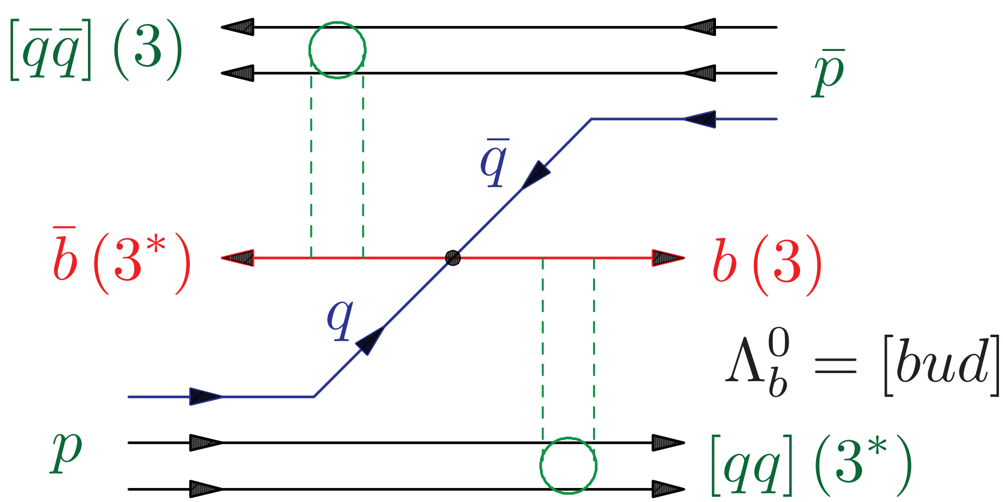
Separate prompt from non-prompt

CDF, Run II, submitted to PRL



- Bonus: in searches for astrophysical neutrinos, charm production cross-sections allow for improved estimations of background rates from neutrinos produced in decays of charm hadrons from cosmic-ray interactions with atmospheric nuclei

F-B Asymmetry in Λ_b^0 and $\overline{\Lambda}_b^0$ Production



Adapted from Rosner, Phys. Rev. D 90, 014023 (2014)

- or coalescence of intrinsic *b* quark at large momentum fraction x in Fock state of proton
  Brodsky
- etc.

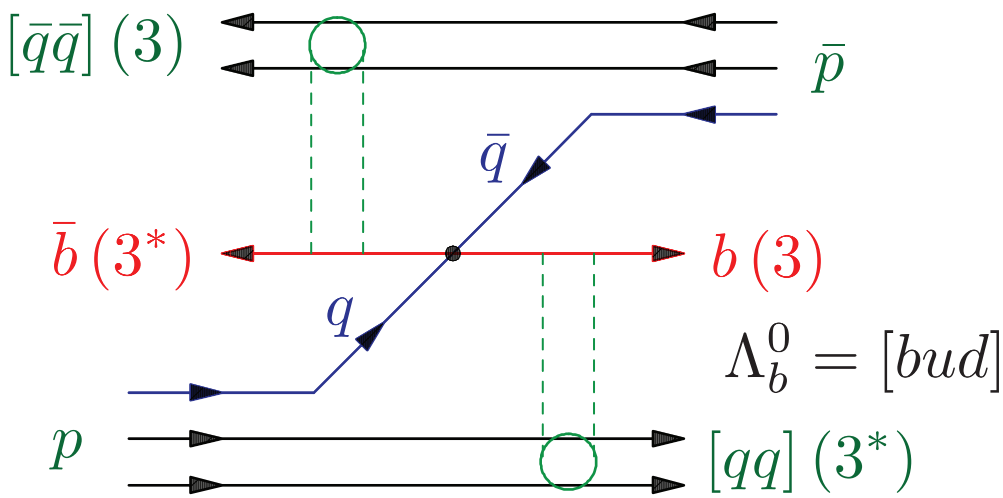
- "String" or "beam drag", Λ_b^0 tends to follow the proton
- String tension, estimated $\Delta p_z \approx 1.4\,\mathrm{GeV}$; $\Delta y \approx 1.4\,\mathrm{GeV}/E$
- "Forward" (*F*): particle (Λ_b^0 or $\overline{\Lambda}_b^0$) if shares valence quark flavors with same sign of rapidity; "Backward" (*B*), reverse association

$$A_{\mathrm{FB}} = \frac{\sigma(F) - \sigma(B)}{\sigma(F) + \sigma(B)}$$

$$R = \sigma(B)/\sigma(F)$$

for comparisons to other measurements

F-B Asymmetry in Λ_b^0 and $\overline{\Lambda}_b^0$ Production



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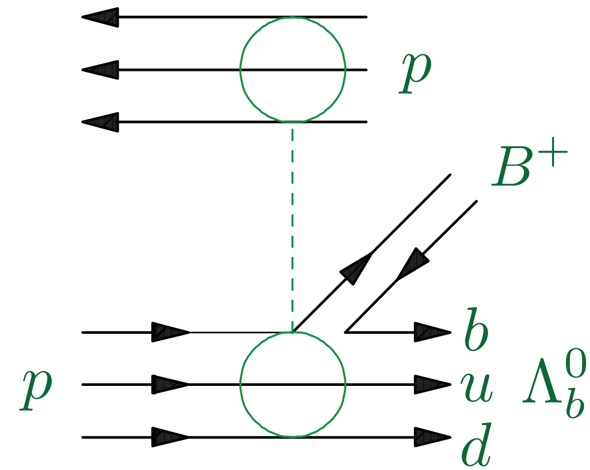

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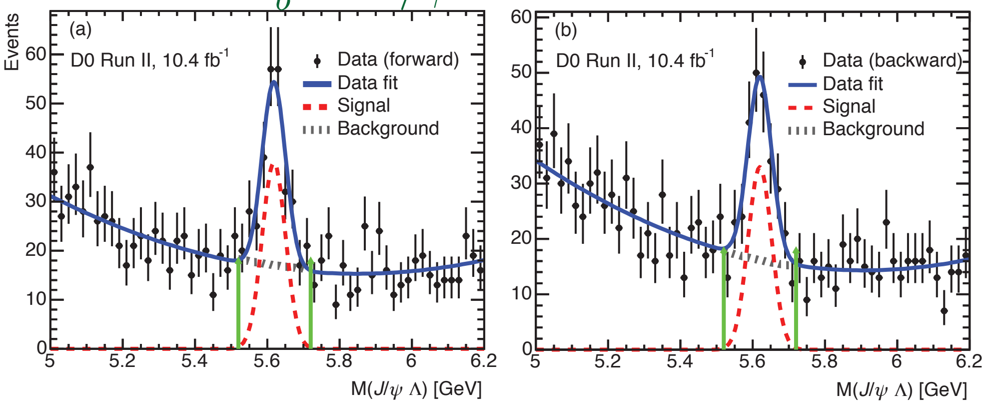
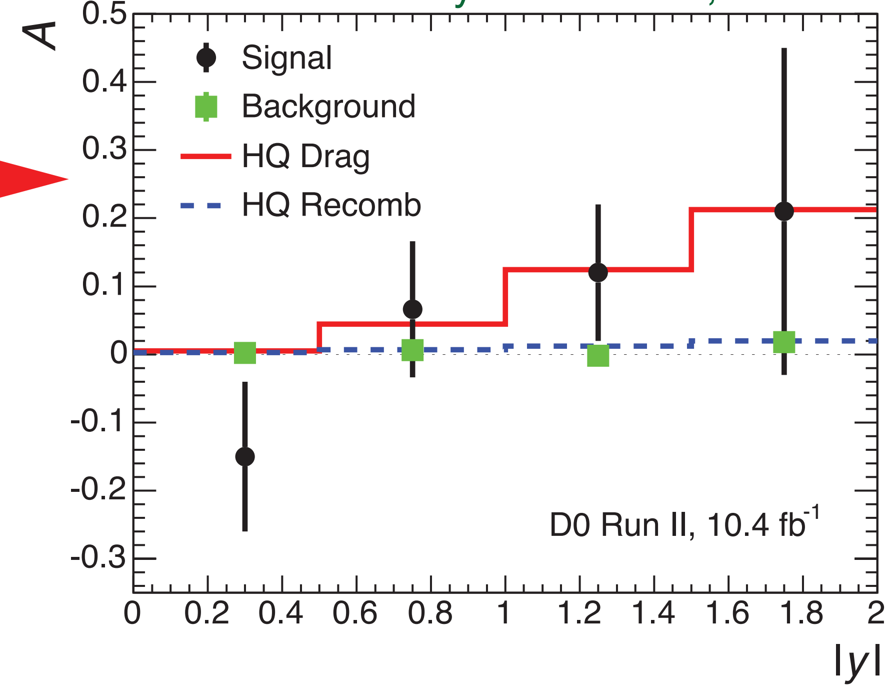
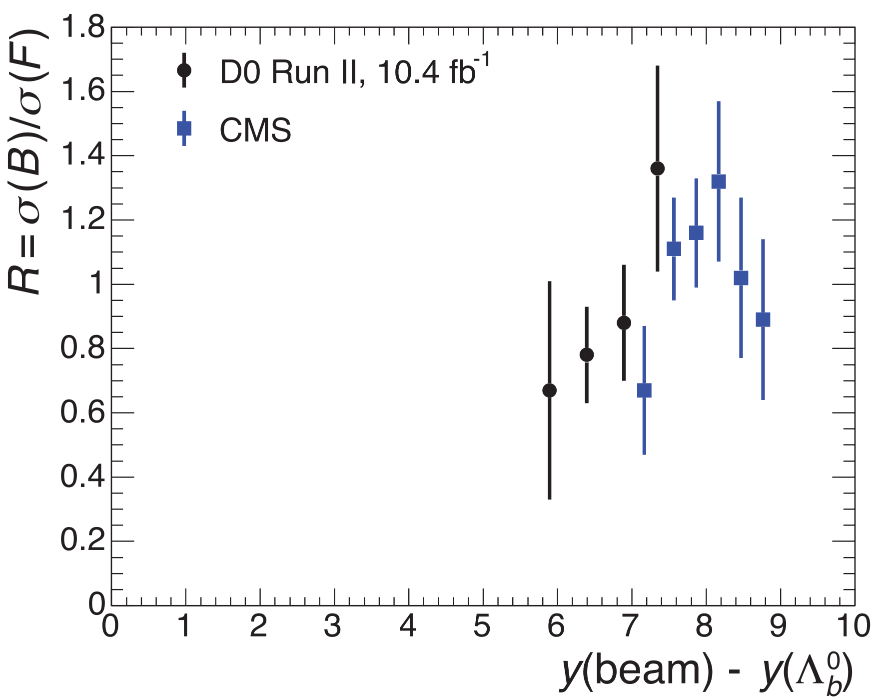
Forward $\Lambda_b^0 \to J/\psi\Lambda$ Backward



Phys. Rev. D **91**, 072008



- Weak trend, data more consistent with beam drag model
- Inconsistent with MC@NLO + Herwig



- pp, Λ_b^0 “Forward”,$\overline{\Lambda}_b^0$ “Backward”

F-B Asymmetry in Λ_b^0 and $\overline{\Lambda}_b^0$ Production

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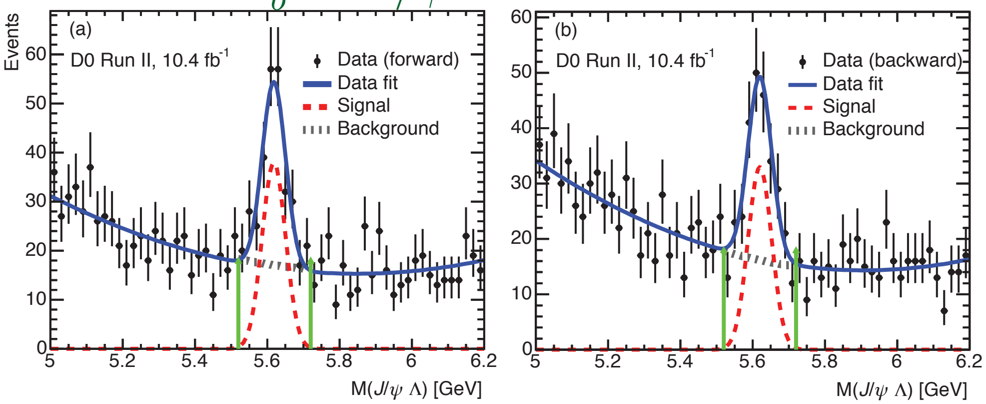

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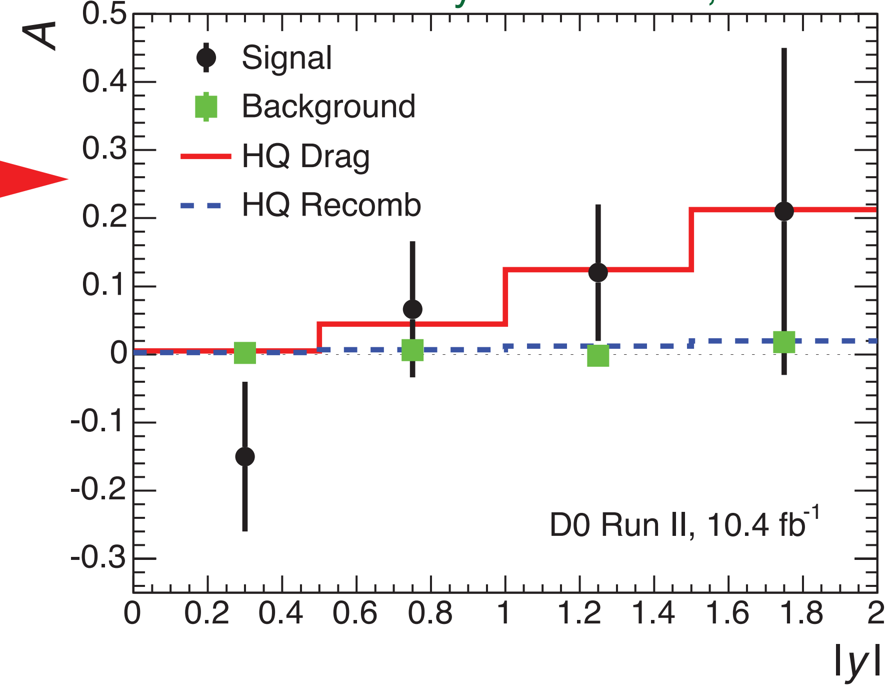

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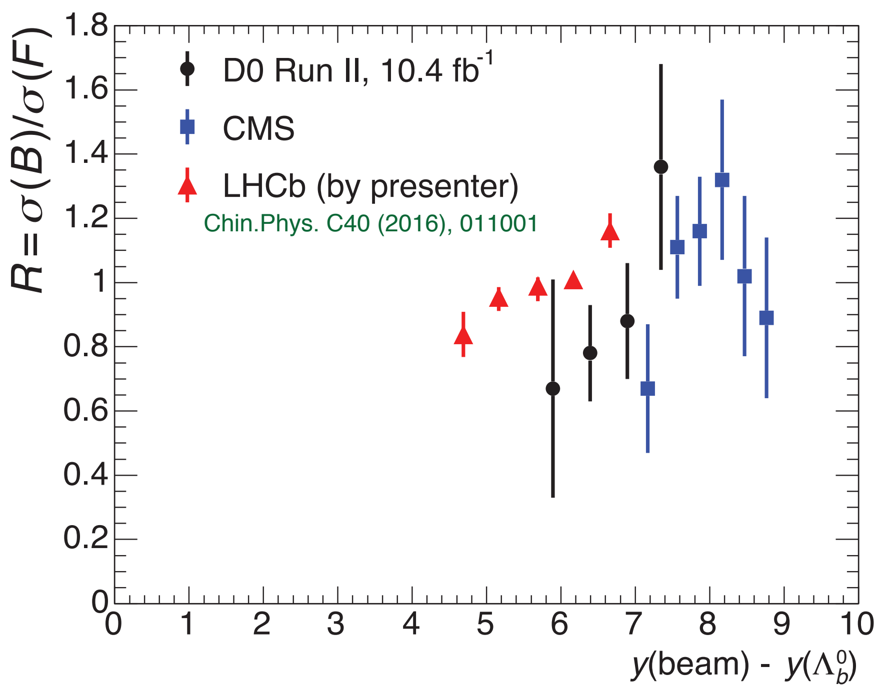
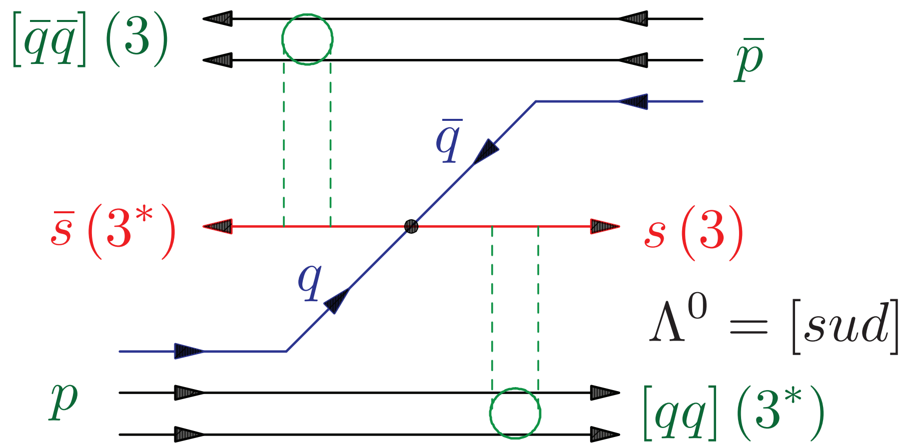


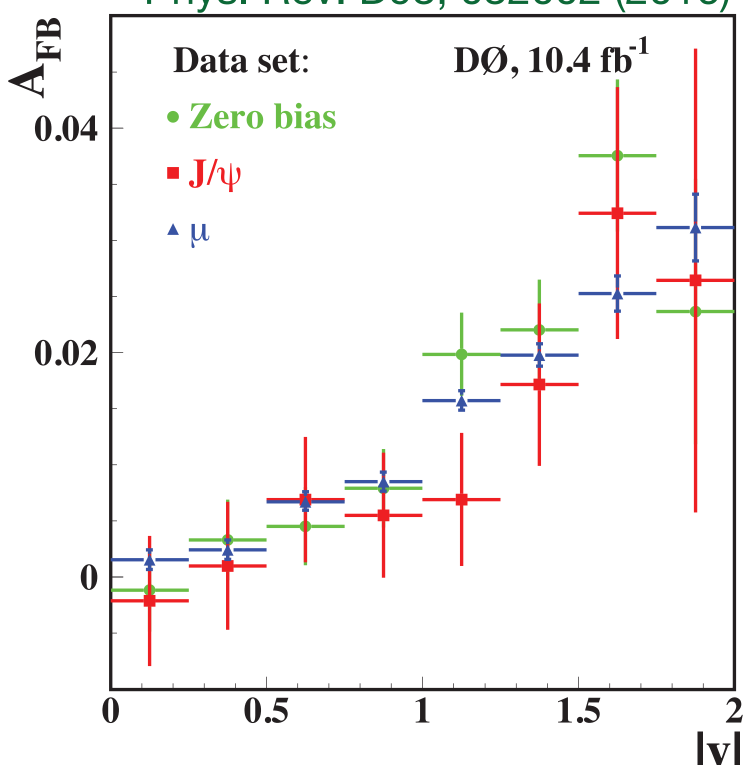
- pp, Λ_b^0 “Forward”,$\overline{\Lambda}_b^0$ “Backward”

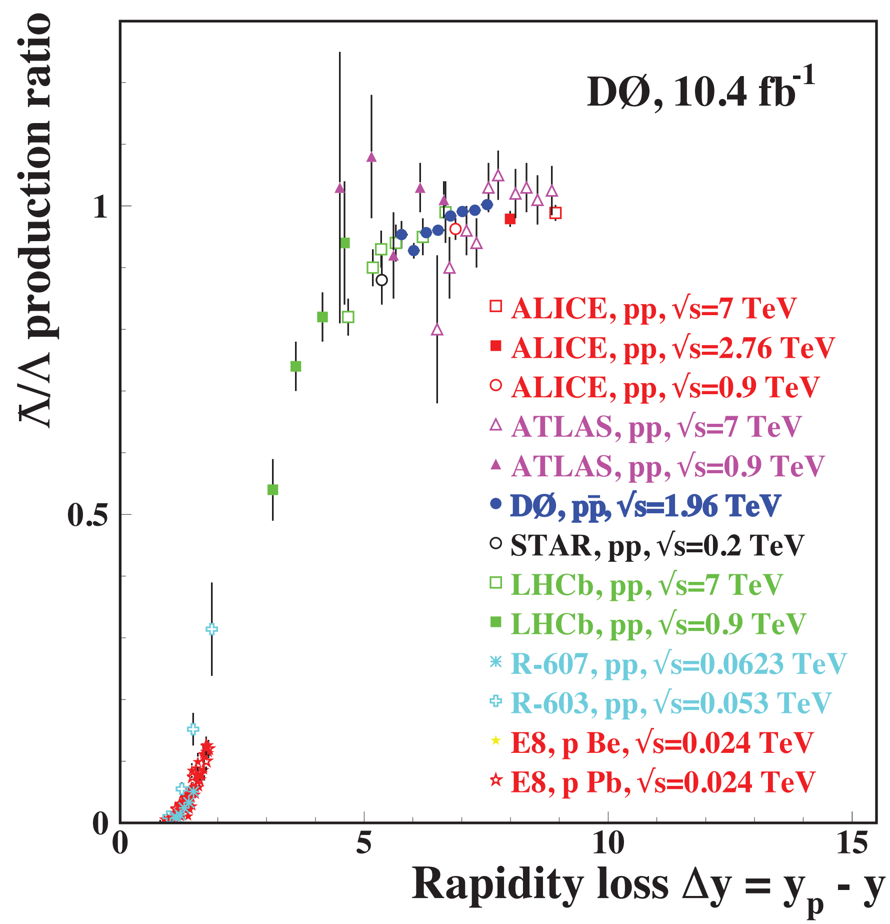
F-B Asymmetry in Λ^0 and $\overline{\Lambda}^0$ Production



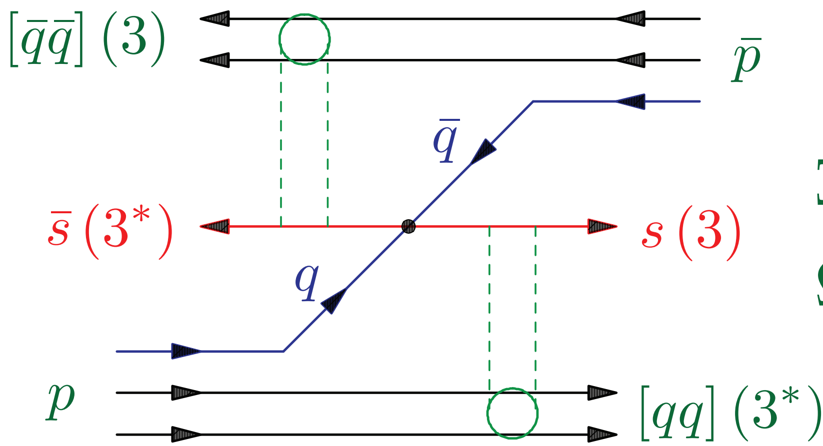
- plus other fragmentation, hadronization processes
- Λ^0 follows the proton

Phys. Rev. D93, 032002 (2016)





F-B Asymmetry in Ξ^- and Ω^- Production

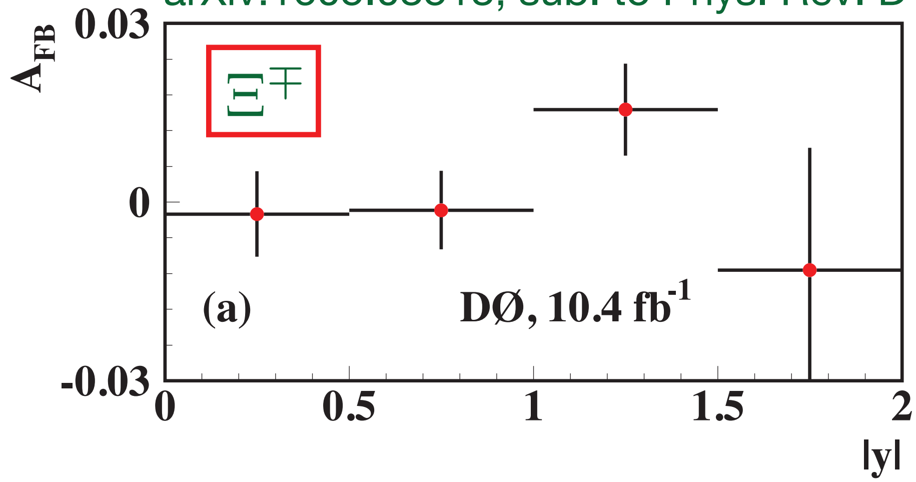


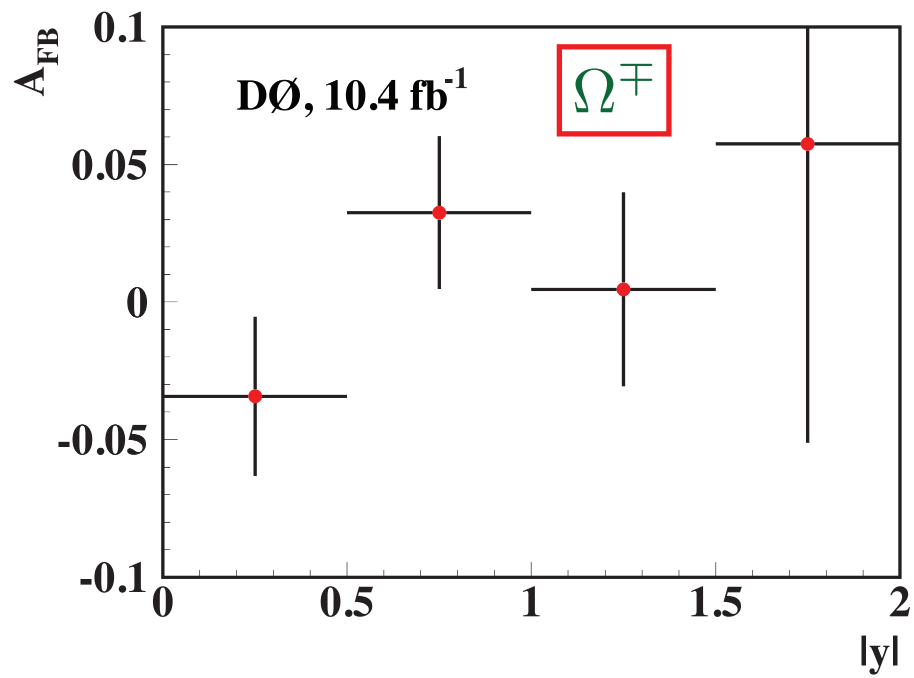
$\Xi^- = [dss]$

$\Omega^- = [sss]$

Expect $A_{\text{FB}} \approx 0$ since particles do not share a diquark with the proton

arXiv:1605.03513, sub. to Phys. Rev. D





- Both consistent with zero asymmetry, as expected

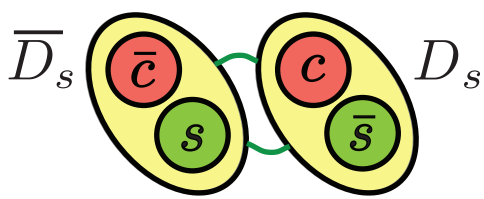
Prompt Production of $X(4140)$

$$Y(4140)$$

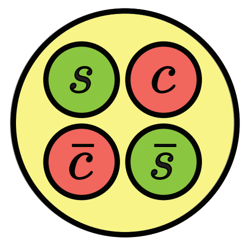
$$B^+ \to X(4140)\,K^+$$
$$\hookrightarrow J/\psi\phi$$

	Evidence?
CDF	✓
CMS	✓
DØ	✓
LHCb	X
BaBar	X
Belle	~

- What is it?



Hadronic Molecule?
(Doubtful since Belle non-observation in $\gamma\gamma \to J/\psi\phi$)



Tetraquark?

$c\bar{c}g$

Hybrid?

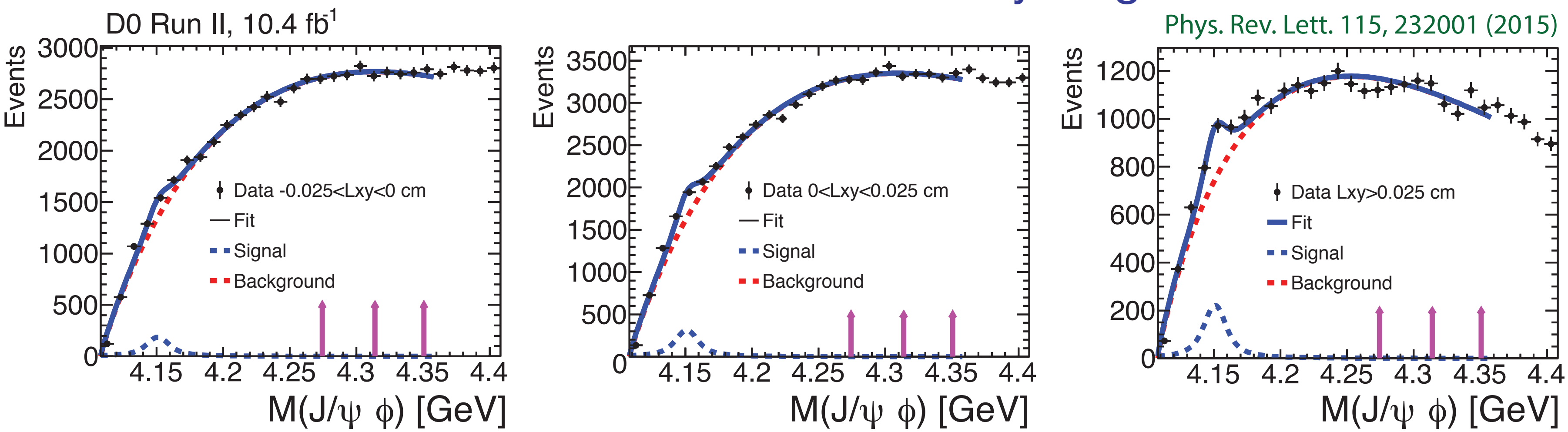
(see review in Int. J. Mod. Phys. A **28**, 133030 (2013))

- Differences in observability due to differences in production?

Prompt Production of $X(4140)$

- Production as function of transverse decay length

Phys. Rev. Lett. 115, 232001 (2015)



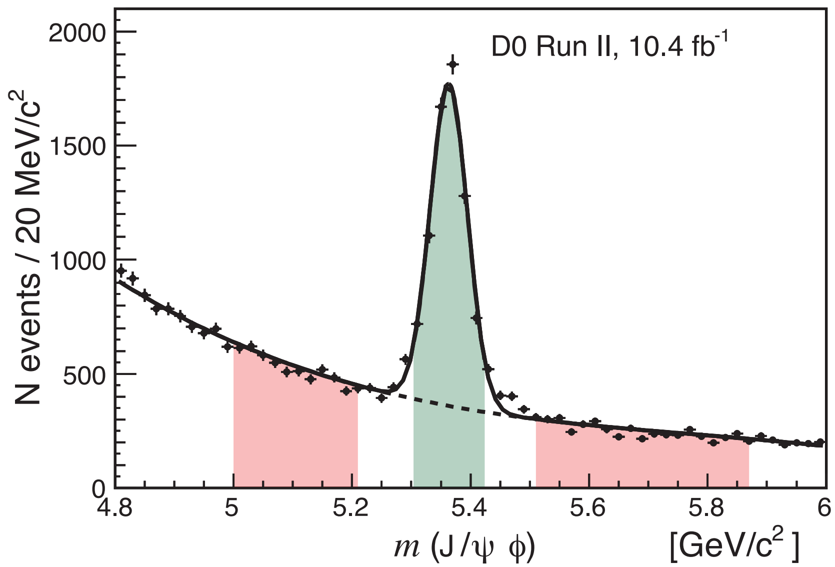
	$-0.025 < L_{xy} < 0\,\mathrm{cm}$	$0 < L_{xy} < 0.025\,\mathrm{cm}$	$L_{xy} > 0.025\,\mathrm{cm}$
Prompt:	474 ± 123	681 ± 149	~ 0
Non-prompt:	37 ± 26	156 ± 54	616 ± 170

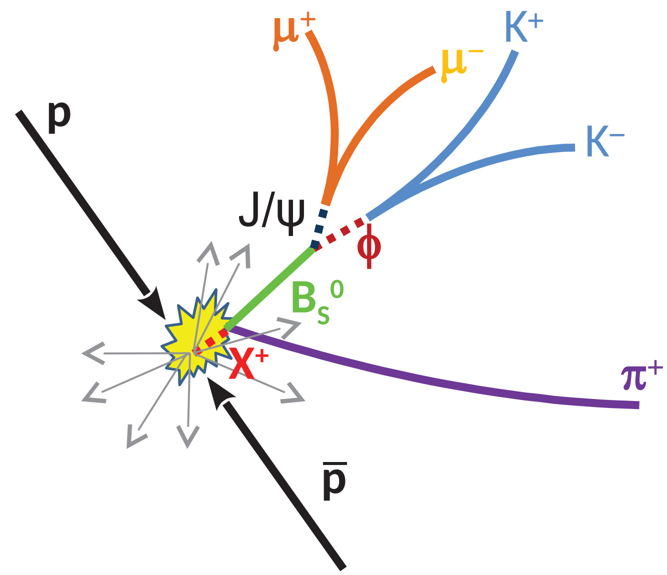
- First evidence (4.7σ) of prompt production of $X(4140)$
- Fraction of $X(4140)$ events originating from *b* hadrons is $f_b = 0.039 \pm 0.07 \pm 0.10$
- Evidence of non-prompt production via *b* hadrons other than B^+

New Exotic State $X(5568) \to B_s^0\pi^\pm$

- Reconstruct $B_s^0 \to J/\psi\phi$ ($\phi \to K^+K^-$, $J/\psi \to \mu^+\mu^-$)

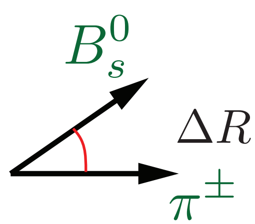
  $L_{xy}/\sigma(L_{xy}) > 3$



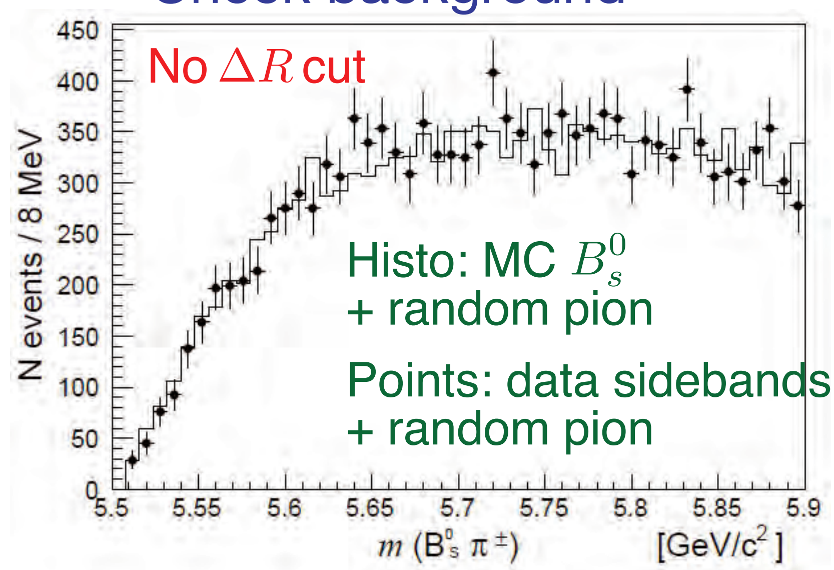


- Add a track, assumed to be a pion, consistent with coming from PV
- Consider signal with and w/o "cone cut"

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$$



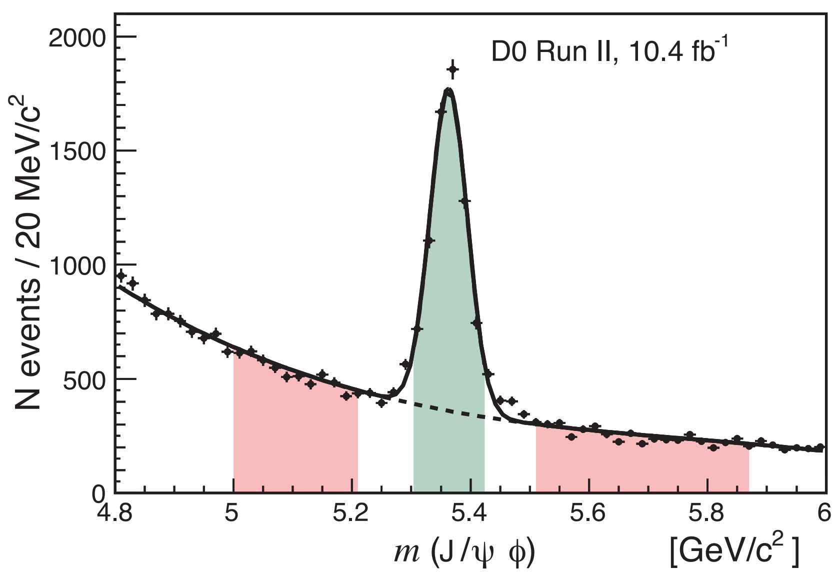
- Check background

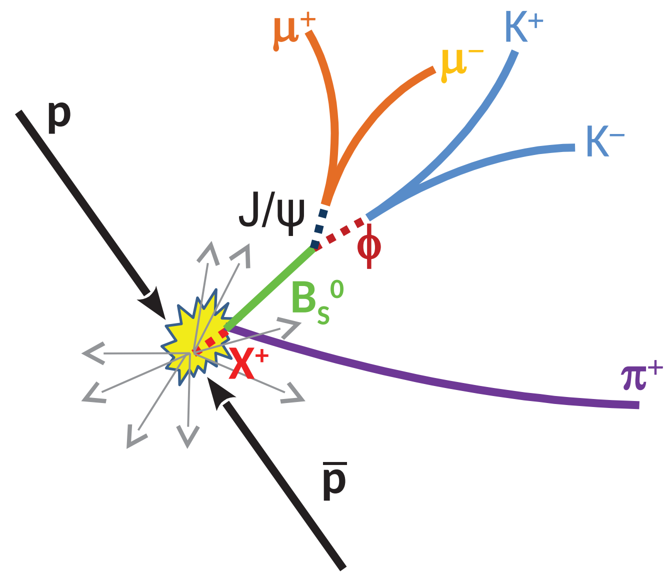


New Exotic State $X(5568) \to B_s^0 \pi^\pm$

- Reconstruct $B_s^0 \to J/\psi\,\phi$, with $\phi \to K^+K^-$ and $J/\psi \to \mu^+\mu^-$

  $L_{xy}/\sigma(L_{xy}) > 3$





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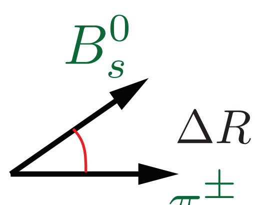
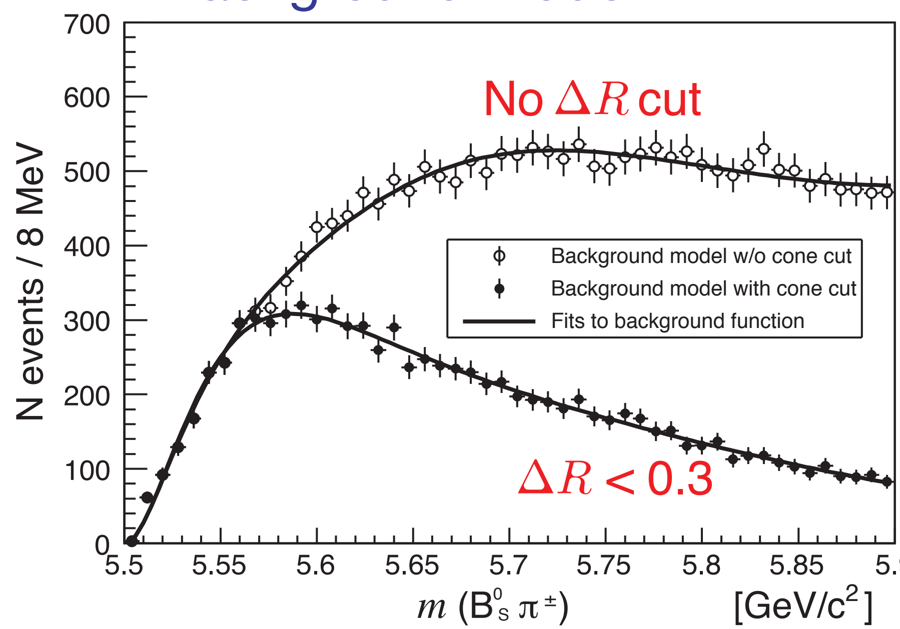
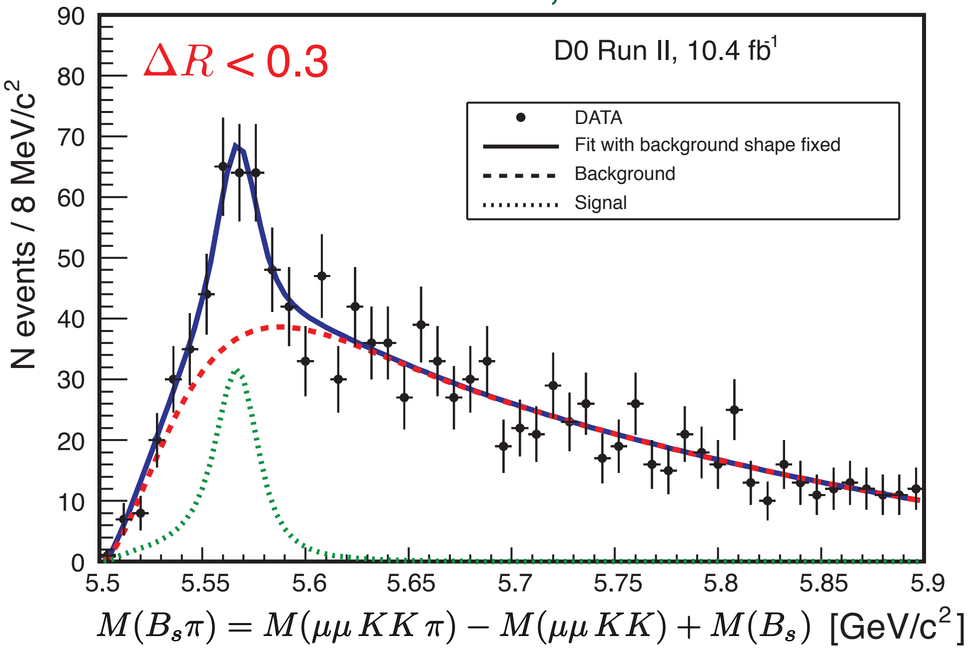


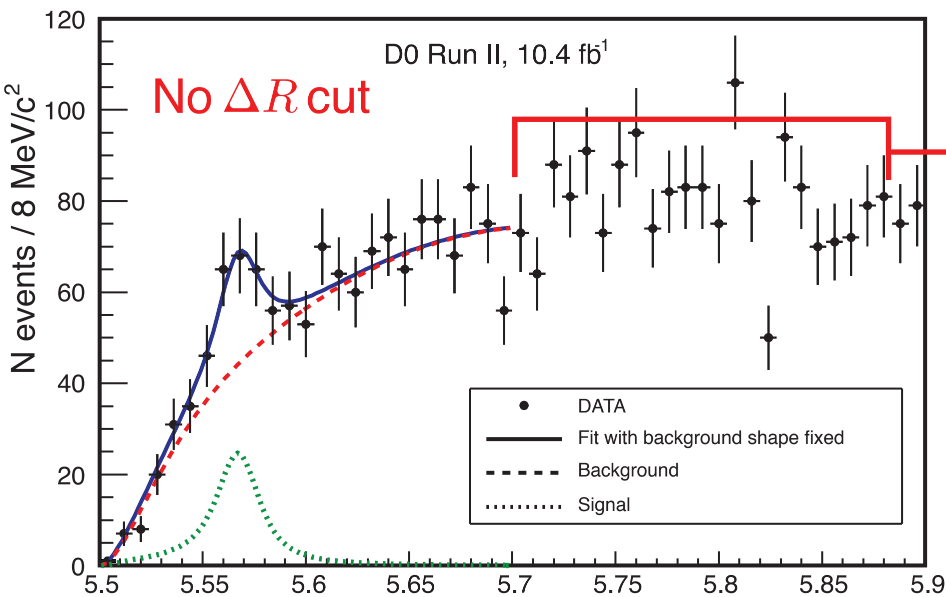
- Background model:



New Exotic State $X(5568) \to B_s^0 \pi^\pm$

arXiv:1602.07588, submitted to PRL





- Mass resolution: $\sigma = 3.9\,\mathrm{MeV}$

$$M_X = 5567.8 \pm 2.9\,^{+0.9}_{-1.9}\,\mathrm{MeV}$$

$$\Gamma_X = 21.9 \pm 6.4\,^{+5.0}_{-2.5}\,\mathrm{MeV}$$

Strong decay!

$$N_X = 133 \pm 31 \pm 15\,\mathrm{cand.}$$

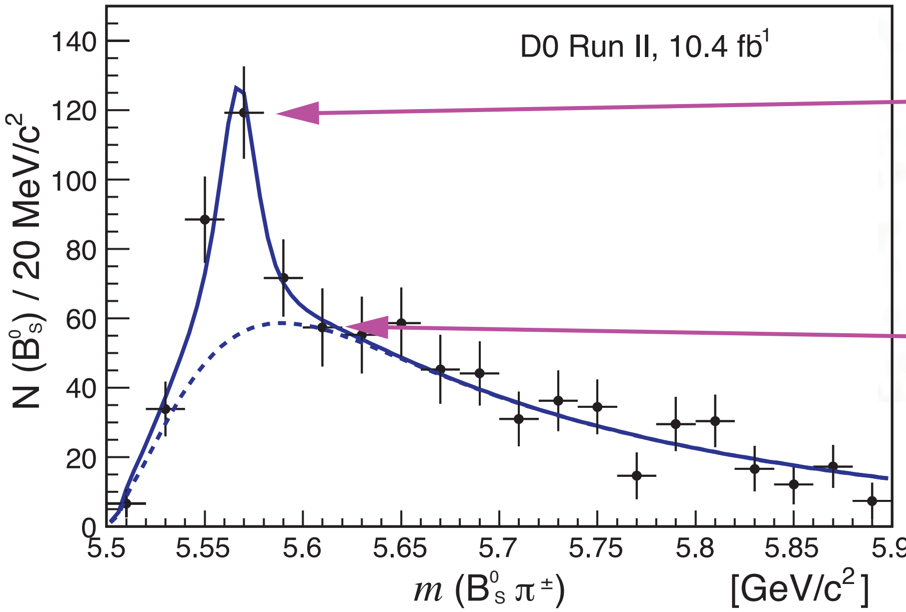
- Significance: local stat. only 6.6σ
  global, including look-elsewhere effect and systematics 5.1σ

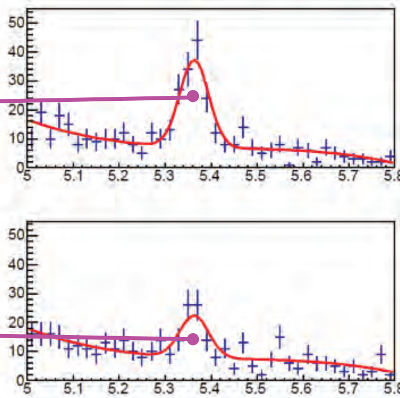
Possible higher-mass B_s^{**} states and/or $B_c \to B_s n\pi$, miss π^0

(..and yes, we see $B_c^+ \to B_s \pi^+$ at 6.27 GeV)

- Signal still there without ΔR cut
  Significance: 3.9σ

New Exotic State $X(5568) \to B_s^0\pi^\pm$





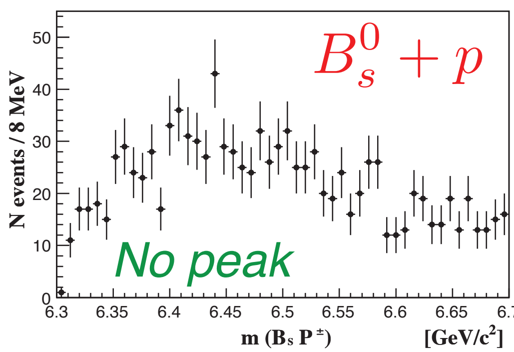
$5.56 < M(J/\psi\phi\pi) < 5.58$

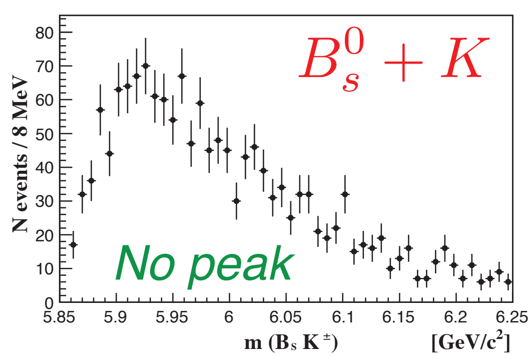
$5.60 < M(J/\psi\phi\pi) < 5.62$

- Alternative fit: fit for B_s^0 signal yield in bins of $M(J/\psi\phi\pi)$
  removes combinatorial background

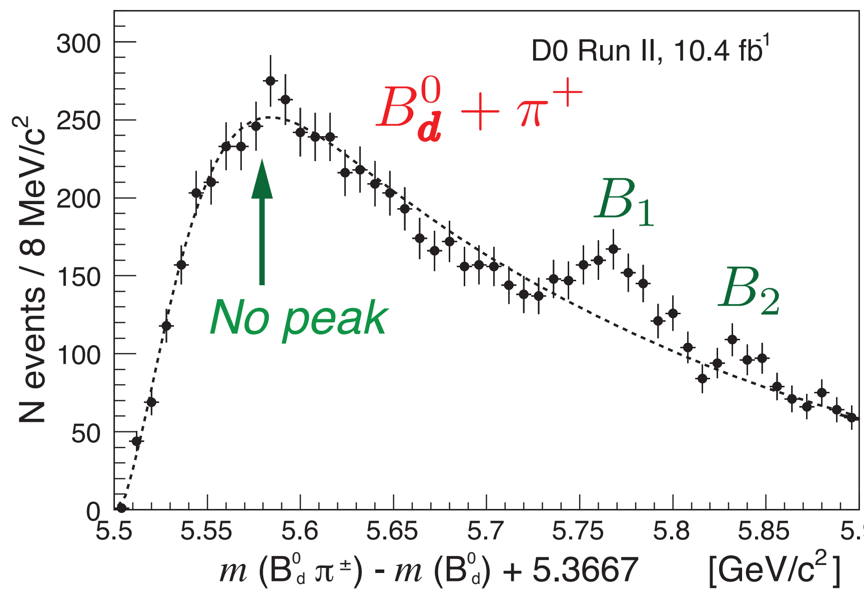
Null tests:

- Instead of pion, assign other masses...





- $B_d^0 \to J/\psi K^{*0}$ almost identical topology



New Exotic State $X(5568) \to B_s^0\pi^\pm$

- Production rate (for comparisons to others): normalize to B_s^0

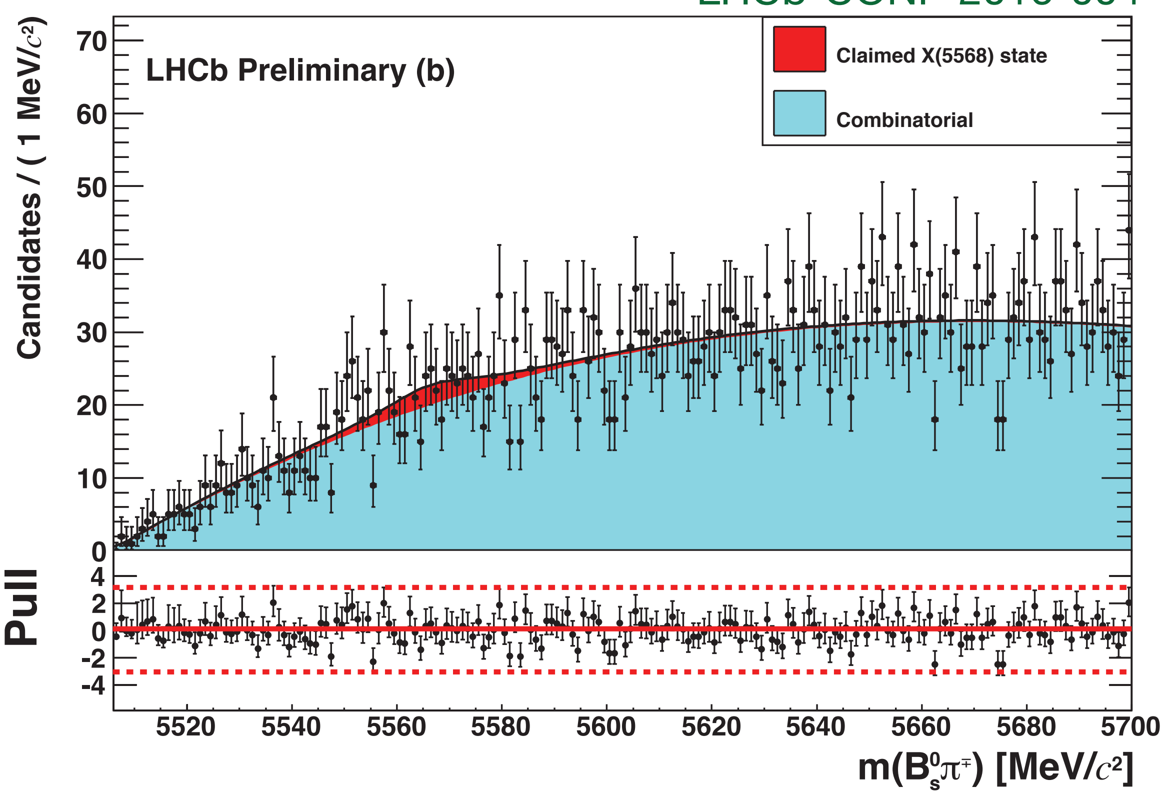
$$R_X = \frac{\sigma(X)\cdot\mathcal{B}(X(5568)\to B_s^0\pi^\pm)}{\sigma(B_s^0)} = (8.6\pm1.9\pm1.4)\%$$

$10 < p_T(B_s) < 30\,\mathrm{GeV}$

$|\eta| < 2$

Others checking:

LHCb-CONF-2016-004



- ~20 times more B_s^0
- No evidence:

$$R_X < 1.6\%\ (90\%\,CL)$$

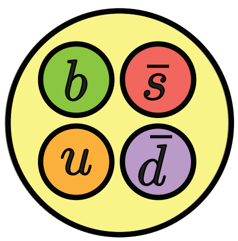
$$p_T(B_s) > 10\,\mathrm{GeV},\ 2 < \eta < 5$$

- Note: $X(4140) \to J/\psi\phi$ also not seen by LHCb, although evidence at CMS, CDF, DØ (two modes); *only* $X(3872) \to J/\psi\pi^+\pi^-$ seen by all

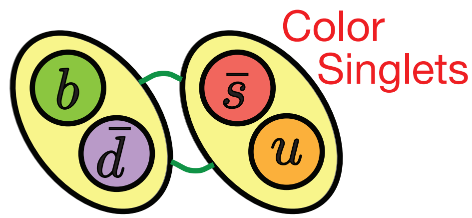
New Exotic State $X(5568) \to B_s^0 \pi^{\pm}$

So, what is it? *"A strange charged beauty"*

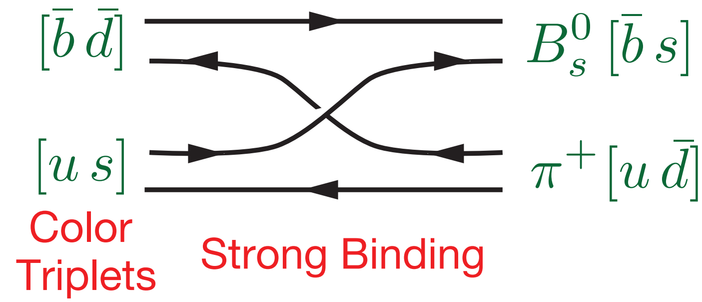
- Unique: only *XYZ* state of four different quarks, mass determination dominated by one heavy quark



Tetraquark?



Loosely Bound Hadronic Molecule?



"Diquark-Antidiquark-onium"

Maiani et al., PRL **93**, 212002 (2004)
PRD **89**, 114010 (2014)

- If $X(5568)^- \to B_s^0 \pi^-$
  then $J^P = 0^+$
  could be analog of
  $a_0(980)$: $[\bar{s}\bar{d}][us]$
  replace $s \Rightarrow b$: $[\bar{s}\bar{d}][ub]$

- If $X(5617)^- \to B_s^{0*} \pi^-$
  $\hookrightarrow B_s^0 \gamma$ miss!
  then $J^P = 1^+$
  could be analog of
  Z_b^+: $[\bar{b}\bar{d}][ub]$
  replace $\bar{b} \Rightarrow \bar{s}$: $[\bar{s}\bar{d}][ub]$

B_s^0 Lifetime in CP-Odd Decay Channel

$$B_s^0 \to J/\psi\, f_0(980)$$

$f_0(980) \hookrightarrow \pi^+\pi^-$

$J/\psi \hookrightarrow \mu^+\mu^-$

B_s^0 Lifetime in CP-Odd Decay Channel

$$B_s^0 \rightarrow J/\psi\, f_0(980) \quad J^{PC} = 0^{++}$$

$J = 0$

$f_0(980) \hookrightarrow \pi^+\pi^-$

$J/\psi \hookrightarrow \mu^+\mu^-$

$J^{PC} = 1^{--}$

From angular momentum conservation, CP-odd decay state

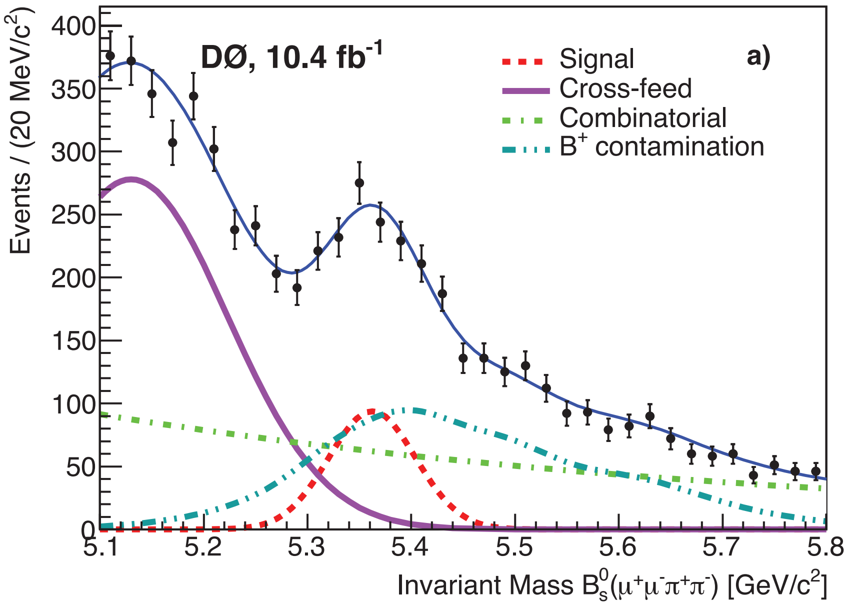
- B_s^0 decay a mixed system with light (*L*) and heavy (*H*) mass eigenstates
- $\Gamma_H \approx \Gamma_{\mathrm{CP\,odd}}$ for small CP violation in mixing ($\phi_s = -0.033 \pm 0.033$)

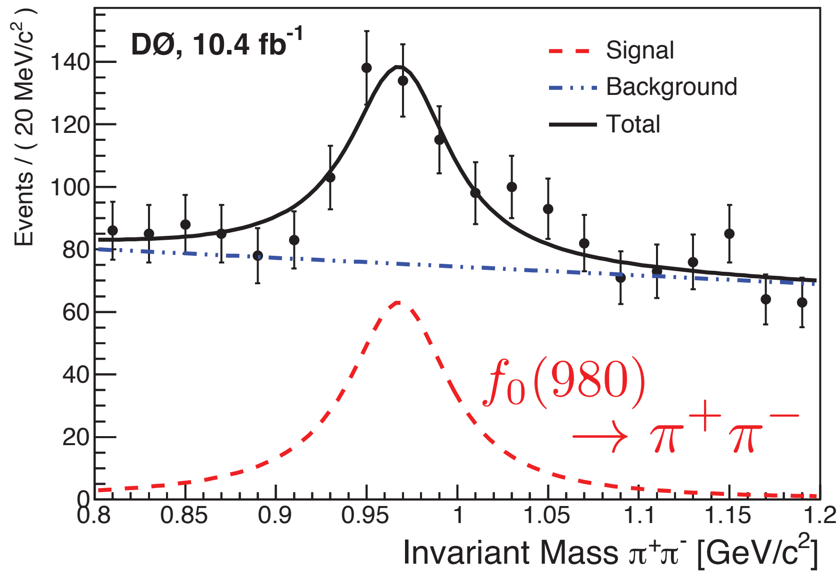
WA, HFAG Spring 2016

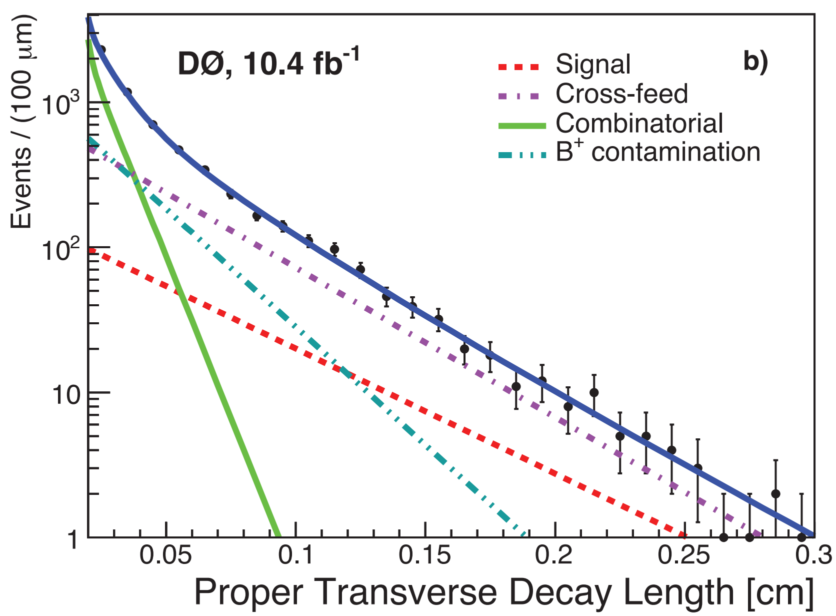
$$1/\Gamma_{\mathrm{CP\,odd}} = (1/\Gamma_H) \times [(1-\phi_s^2) \times \Delta\Gamma_s]$$

B_s^0 Lifetime in CP-Odd Decay Channel

$B_s^0 \to J/\psi f_0(980)$





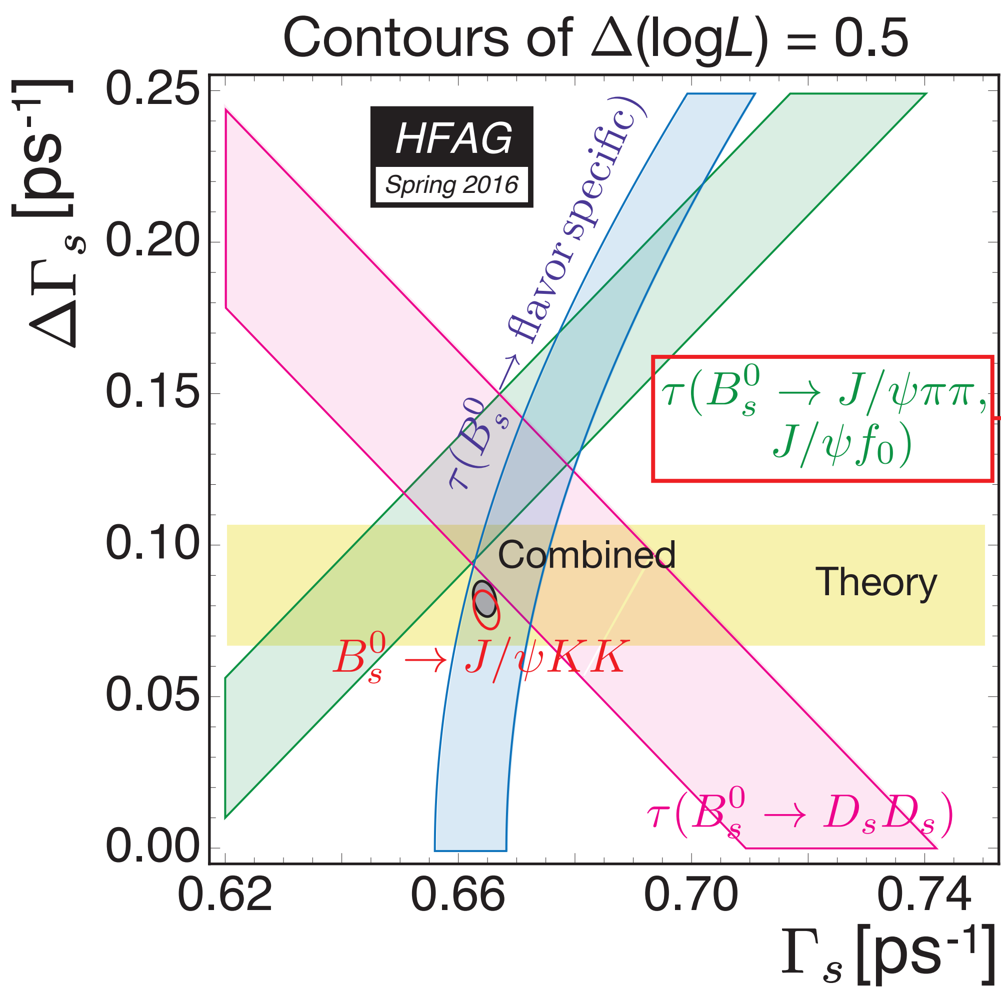


arXiv:1603.01302, submitted to Phys. Rev. D

$$\tau(B_s^0) = 1.70 \pm 0.14 \pm 0.05\,\mathrm{ps}$$

$$\Gamma_H = 0.59 \pm 0.05 \pm 0.02\,\mathrm{ps}^{-1}$$

B_s^0 Lifetime in CP-Odd Decay Channel



$$\Delta\Gamma_s = \Gamma_L - \Gamma_H\,,$$

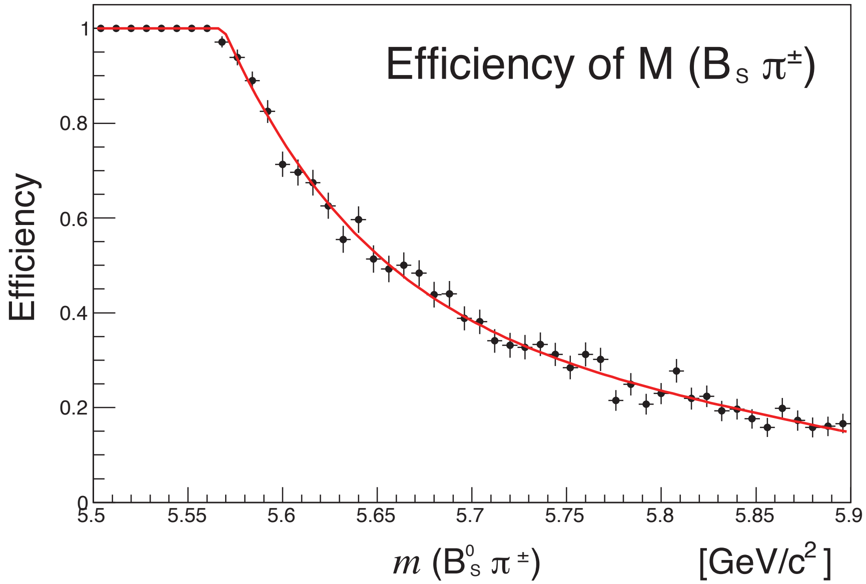
combine with measurements from CDF and LHCb

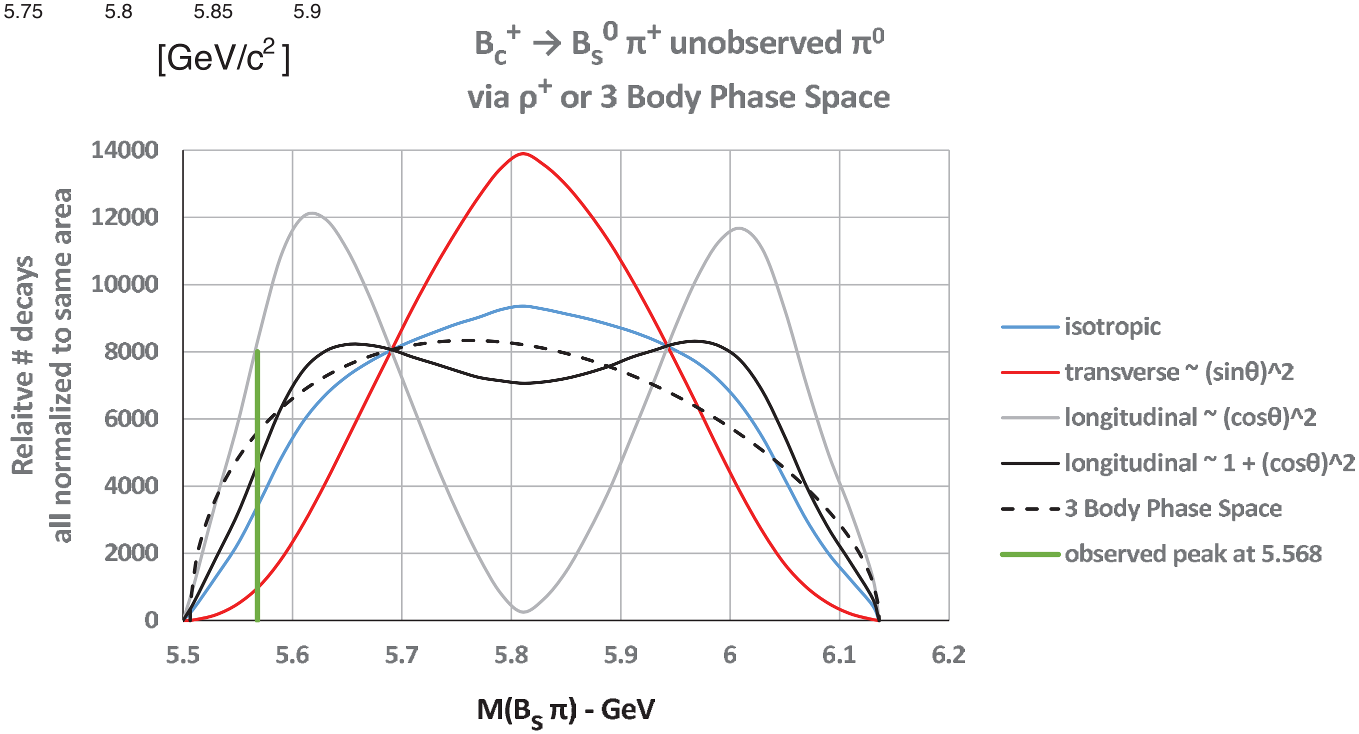
Thank you for your attention

Backups

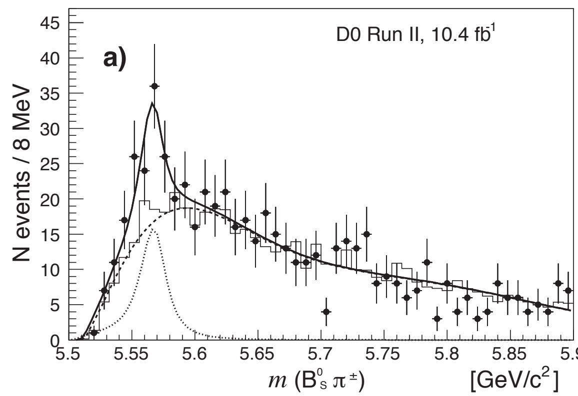
↓

New Exotic State $X(5568) \to B_s^0\pi^\pm$

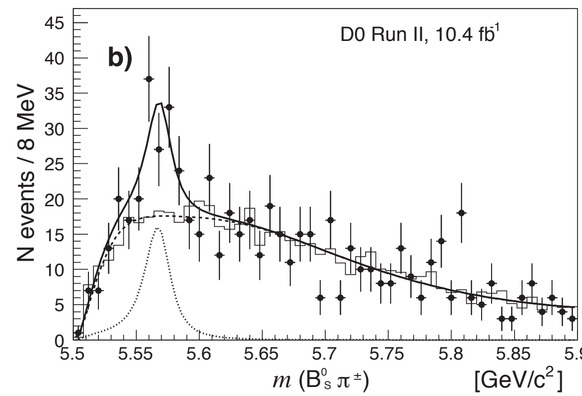




New Exotic State $X(5568) \to B_s^0\pi^\pm$



$10 < p_T(B_s^0) < 15$ GeV



$15 < p_T(B_s^0) < 30$ GeV

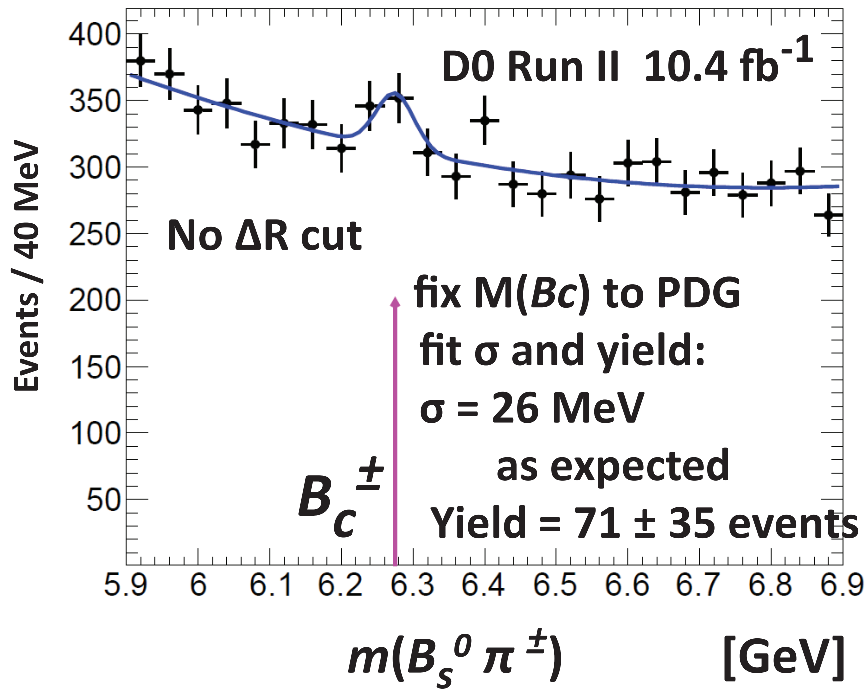
Parameter	$10 < p_T(B_s^0) < 15$ GeV/c^2	$15 < p_T(B_s^0) < 30$ GeV/c^2
N(X(5568))	58.6 ± 16.7	67.5 ± 21.8
M(X(5568))	5566.3 ± 3.3	5568.9 ± 4.4
$\Gamma(B_s^+(5568))$	18.4 ± 7.0	21.7 ± 8.4
$N(B_s^0)$	2463 ± 63	1961 ± 56
$\epsilon(\pi^\pm)$	$(26.1 \pm 3.2)\%$	$(42.1 \pm 6.5)\%$
$\rho(X(5568)/B_s^0)$	$(9.1 \pm 2.6 \pm 1.6)\%$	$(8.2 \pm 2.7 \pm 1.6)\%$

Averaging over $10 < p_T(B_s^0) < 30$ GeV $\quad \rho = (8.6 \pm 1.9 \pm 1.4)\%$.

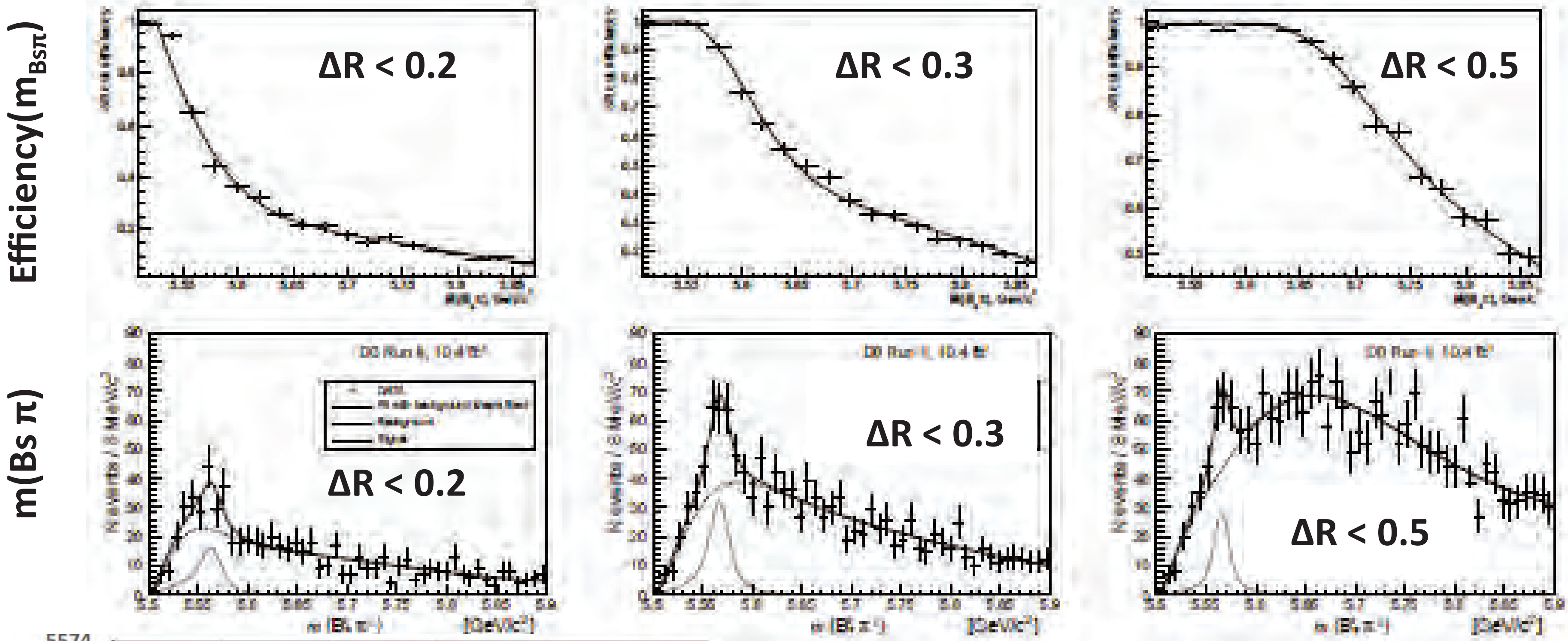
This study also makes a good cross-check.

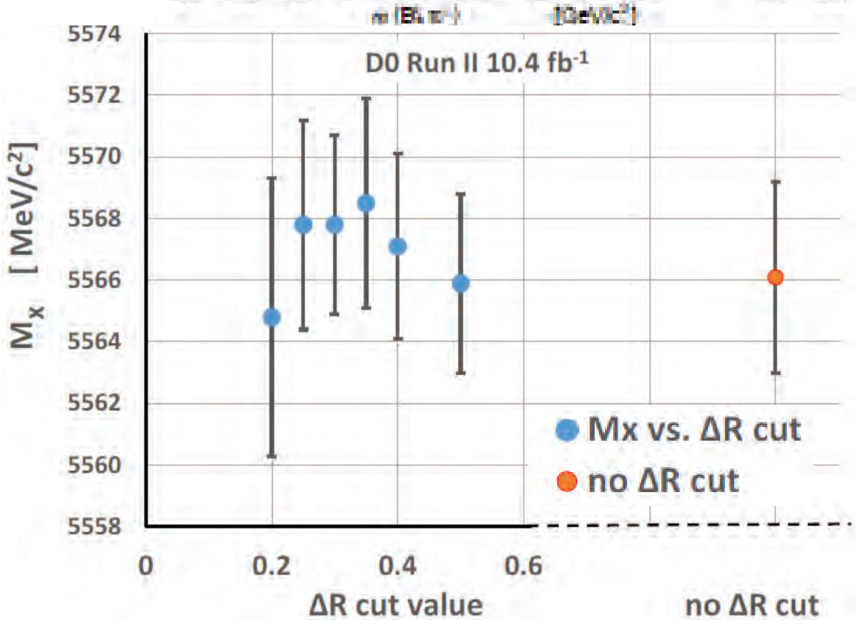
New Exotic State $X(5568) \to B_s^0\pi^\pm$

See $B_c^- \to B_s^0\pi^-$?



New Exotic State $X(5568) \to B_s^0\pi^\pm$



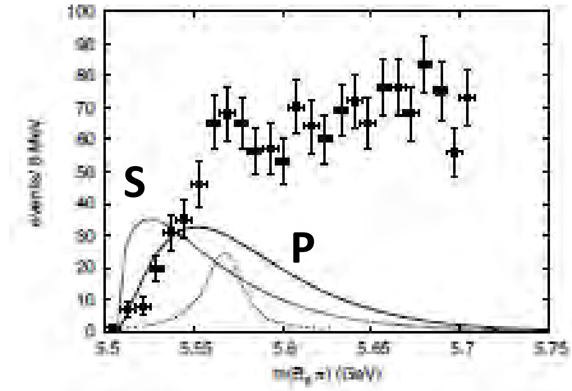


- Fitted mass does not depend on value of cone cut even though peak of background moving around; not creating peak

From Peter Garbincius

Short Survey of Interpretations of $B_s^0\pi^\pm$ state

through Friday 4/29, there are 28 theory articles on arXiv:



<u>Threshold Enhancement</u>

T.J. Burns & E.S. Swanson – arXiv:1603.04366

– S & P waves - *unlikely* – wrong shape!

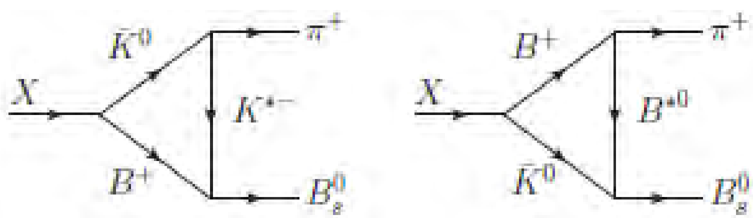
<u>CUSP Rescattering Effects</u> – singularities in loop diagrams

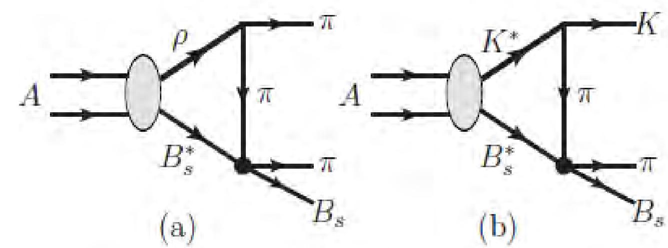
T.J. Burns & E.S. Swanson – arXiv:1603.04366

M. Albaladejo, *et al*. - arXiv: 1603.09340

X-H Liu & G. Li – arXiv:1603.00708

C-J Xiao & D-Y Chen – arXiv:1603.00228





shape (solid curve) fits - why not?

need $B_s^*\pi \rightarrow B_s^*\pi$ rescattering at 5555 MeV

not likely: P-wave scatter too weak,

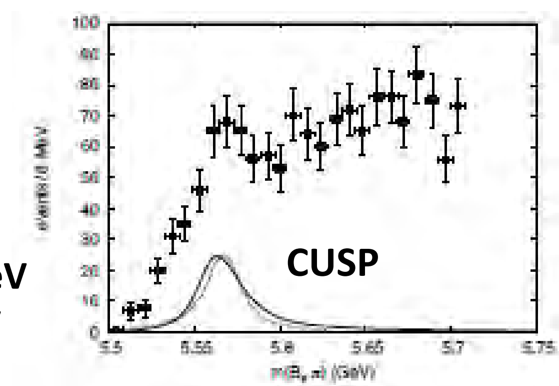
scale to produce Γ_X = 22 MeV is an

order of magnitude smaller than typical,

$B_s^*\pi \rightarrow B_s\pi\gamma$ is unusual since no flavor exchange.

a cusp in $BK \rightarrow B_s\pi$ scattering is more likely, but would be at 5570 MeV

→ expect an analog $B\pi$ state ~ 5465 MeV and B_sK state ~ 5909 MeV



Is $B_s^0 \pi^{\pm}$ state a CUSP?

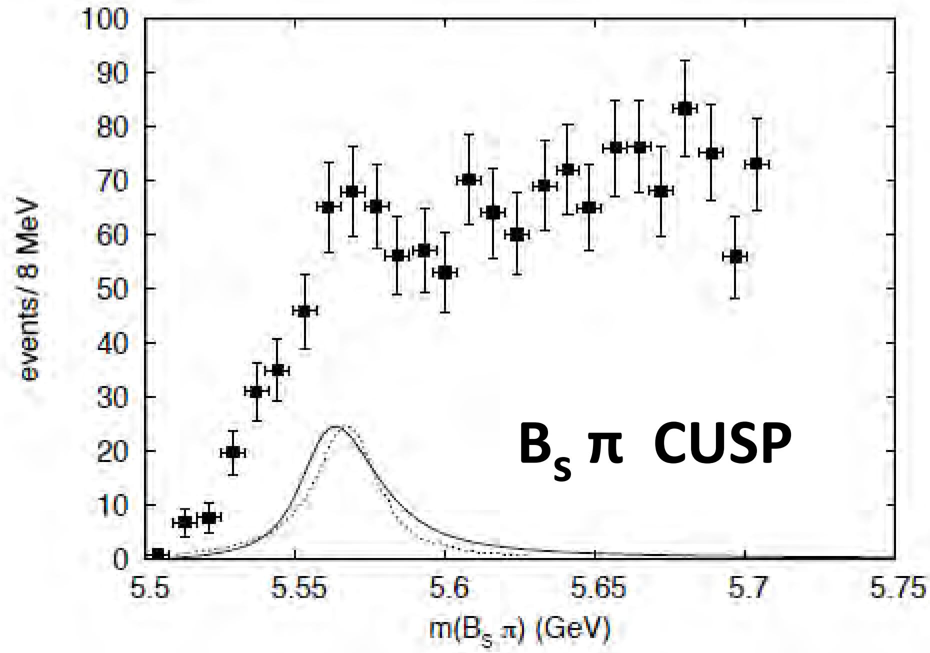
T.J. Burns & E.S. Swanson
- arXiv:1603.04366

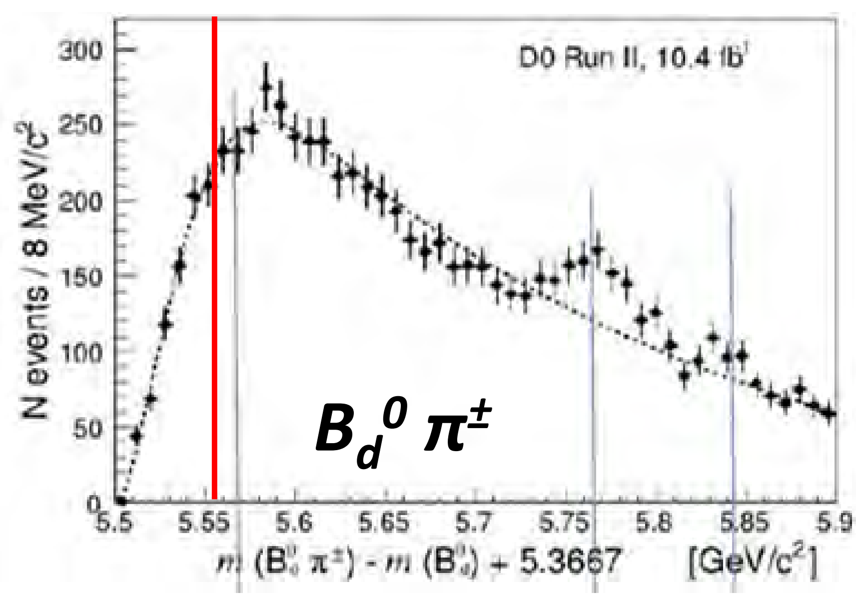
no **analogous CUSP observed**

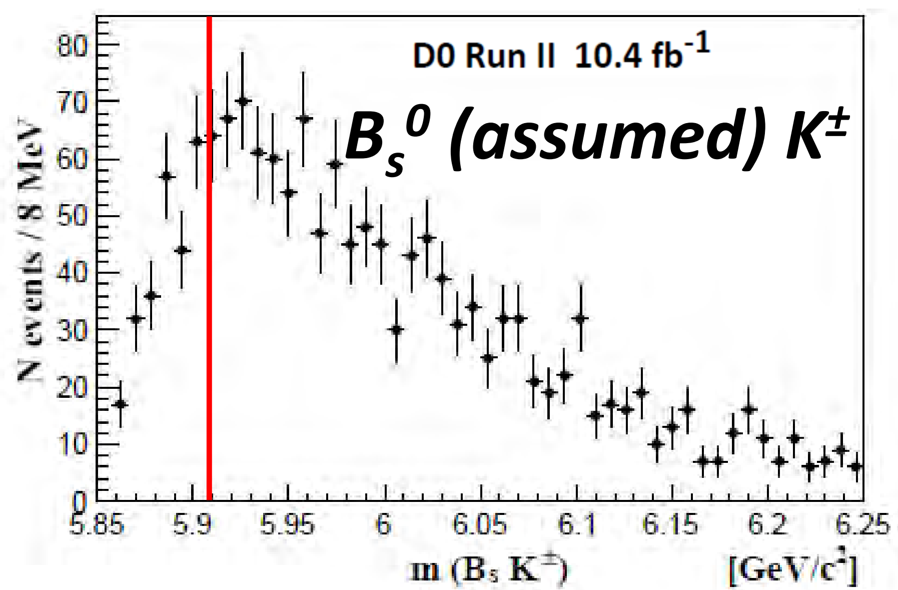
for *$B\pi$* state ~ 5465 *MeV/c²*

(5552 *MeV/c² on plot below left*)

or *$B_s K$* state ~ 5909 *MeV/c²*







note: {Q=5465-(5279.6+139.5)}+5506=5552

Short Survey of Interpretations of $B_s^0 \pi^{\pm}$ state

<u>Loosely-Bound Molecule</u>

T.J. Burns & E.S. Swanson – arXiv:1603.04366

– *unlikely* since Binding Energy of *B-K* > 200 MeV

S.S. Agaev *et al*. - arXiv: 1603.02708 – QCD two-point and light-cone sum rules

expect lowest mass X_b to be a *B-K* molecule with M_{Xb} = 5764 ± 142 MeV

<u>Tetraquark</u>

T.J. Burns & E.S. Swanson – arXiv:1603.04366

– *X*(5568) {*u d s b*} is *unexpectedly light*

Ξ_b & Ξ_b^* (*bsu*) 5794 & 5945 MeV add d-quark

¼ (3 *B** + *B* + 3 *K** + *K*) = 6107 MeV

¼ (3 B_s^* + B_s + 3 ρ + π) = 6019 MeV

|I, I_3> = |1, ±1> *X*(5568) should also have

2 neutral $B_s \pi^0$ partners |1,0> and |0,0>

narrow, since no open hadronic channels

Short Survey of Interpretations of $B_s^0 \pi^\pm$ state

<u>diquark – antidiquark</u> = {color triplet} X anti{color triplet)

→ leading to strong forces and strong binding

L. Maiani *et al.*, *New Look at Scaler Mesons*, PRL 93, 212001 (2004)

A. Ali *et al*. - arXiv: 1604.01731 – est lightest X_b0+ {*bdus*} at 5770 MeV, just below BK threshold

predict 0+ & 1+ {*cdus*} at 2365 & 2501 MeV ~ 50 MeV heavier than Ds0(2317) & Ds1(2460)

suggests search for $B_c^+ \rightarrow \pi^+ + X_b^0$ ($\rightarrow B_s^0 \pi^0$) or $B_c^+ \rightarrow \pi^0 + X_b^+$ ($\rightarrow B_s^0 \pi^+$)

Q-F Lu & Y-B Dong - arXiv: 1603.06417 – relativized quark model by Godfrey and Isgur

minimum M{*sqbq*} = 6196 MeV and minimum M{*sqcq*} = 2873 MeV

Z-G Wang – arXiv: 1603.20498 - use three point QCD sum rules

for M_X = 5568 MeV, predicts Γ_x = 20.5 ± 8.1 MeV, agreeing with D0 Γ_x ~ 22 MeV

C.M. Zanetti et al. – arXiv:1602.09041 – QCD sum rule – predicts MX = 6.39 ± 0.10 MeV

<u>hybridized tetraquarks</u>

A. Esposito *et al*. arXiv: 1603.07667 – neither purely compact tetraquarks or molecule

inspired by Feshbach metastable states, expect MX ~ 5771 MeV