Observation of the Baryonic FCNC Decay $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ and the Angular Analysis in $B \rightarrow K^{(*)} \mu^+ \mu^-$ Decays at CDF

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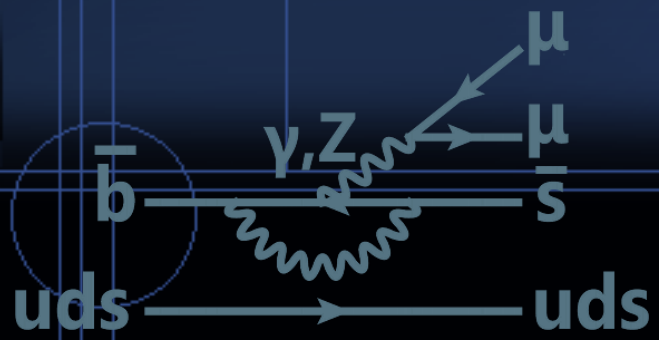
on behalf of the CDF collaboration
University of Tsukuba

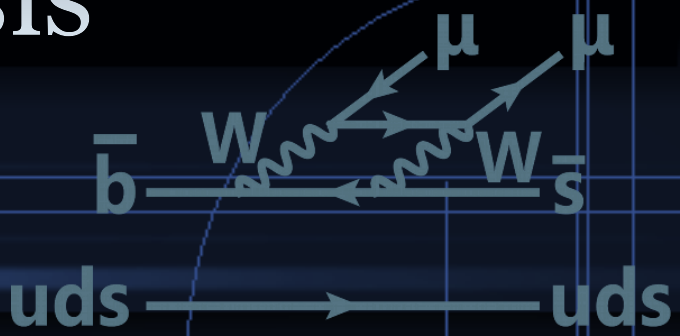
Fermilab Wine & Cheese Seminar

August 19th, 2011



Outline

- b→sμμ rare decays
- Event selection
- BR measurements
- Angular analysis

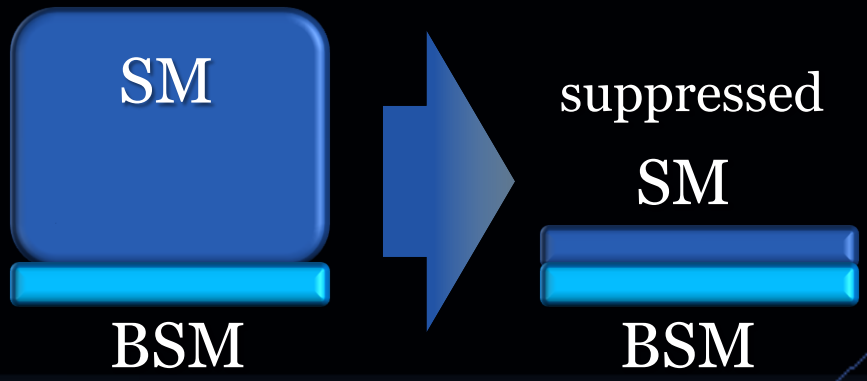


Why rare decays?

The success of the Standard Model

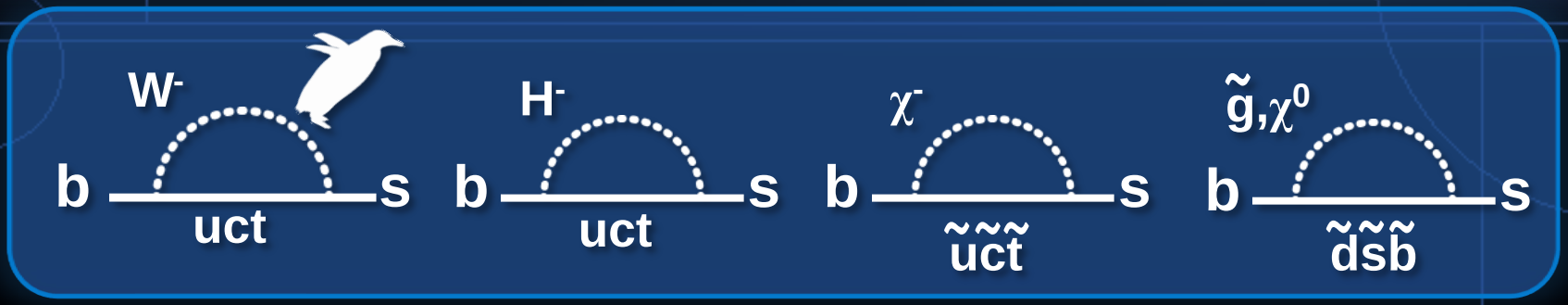
means no direct evidence for new physics at the known energy scale.

How can we pursue NP?



Look for hidden signature of BSM in rare phenomena

Key tool: FCNC



- **Flavor-Changing Neutral Current**

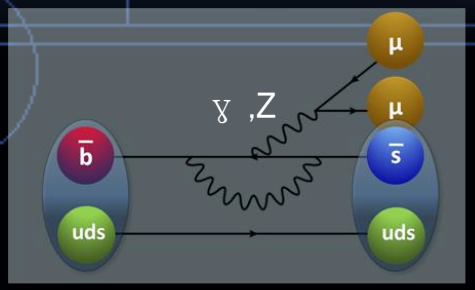
SM
- Tree amplitudes forbidden
- Occur via higher order loop amplitudes

BSM
- Heavy BSM particle could contribute to the loop
  - ✓ Modifies the decay amplitude

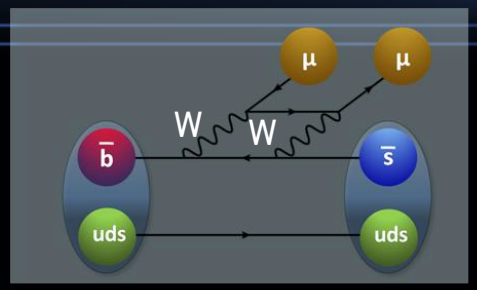
How to distinguish BSM penguins?

SUSY
Technicolor
Extra dimension
Fourth generation

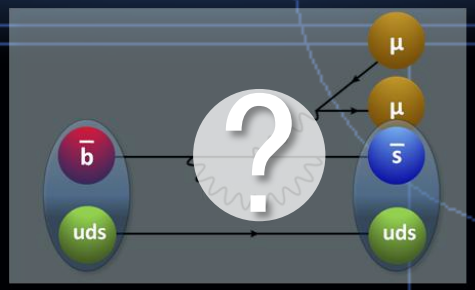
Rare and rich: b→sμμ



EW penguin



W-box diagram



Rare
- suppressed by α_{EM} in SM
  - ✓ Br(b→sμμ)=$O(10^{-6})$
  - ✓ Accessible due to abundant b quark production

Powerful Tevatron
Excellent CDF detector

Rich
- Rich signals
  - ✓ Various b species B^0, B^+, B_s, Λ_b…
- Rich phenomenology
  - ✓ Complex kinematics (three-body decay)

→total BR, differential BR, angular analysis

Provides discrimination of BSM models

Goal of this talk

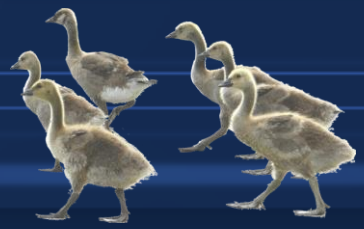
- Multidimensional approach toward BSM with rich $b \to s\mu\mu$ samples

✓ Various Observables

- Total BR
  - Requires little data
  - Limited sensitivity to NP

- Differential BR
  - Requires more data
  - Sensitive to NP

- Angular analysis
  - Requires lots of data
  - Most sensitive to NP



✓ Various Channels

- $B^0 \to K^{*0}\mu\mu$
- $B^+ \to K^+\mu\mu$
- $B^+ \to K^{*+}\mu\mu$
- $B^0 \to K_S\mu\mu$
- $B_s \to \phi\mu\mu$
- $\Lambda_b \to \Lambda\mu\mu$

CDF analysis history

Search for the Flavor-Changing Neutral Current Decays $B^+ \rightarrow \mu^+\mu^-K^+$ and $B^0 \rightarrow \mu^+\mu^-K^{*0}$
- Phys. Rev. Lett. 83, 3378 (1999).

CDF RunI 88 pb^{-1}

Search for the Decay $B_s \rightarrow \mu^+\mu^- \varphi$ in $p\bar{p}$ Collisions at $\sqrt{s}$=1.8 TeV
- Phys. Rev. D65, 111101 (2002).

CDF RunI 91 pb^{-1}

Search for the Rare B Decays $B^+ \rightarrow \mu^+\mu^-K^+$, $B^0 \rightarrow \mu^+\mu^-K^*(892)^0$, and $B_s^0 \rightarrow \mu^+\mu^- \varphi$ at CDF
- Phys. Rev. D79, 011104(R) (2009).

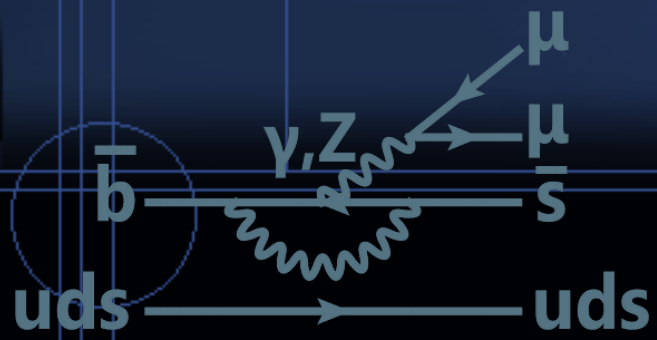
CDF RunII 924 pb^{-1}

Measurement of the Forward-Backward Asymmetry in the $B \rightarrow K^{(*)} \mu^+\mu^-$ Decay and First Observation of the $B_s^0 \rightarrow \varphi\mu^+\mu^-$ Decay
- Phys. Rev. Lett. 106, 161801 (2011).

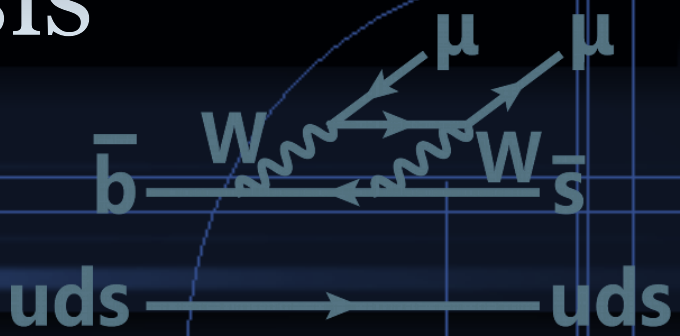
CDF RunII 4.4 fb^{-1}

This talk:
Update using 6.8 fb^{-1}

Outline

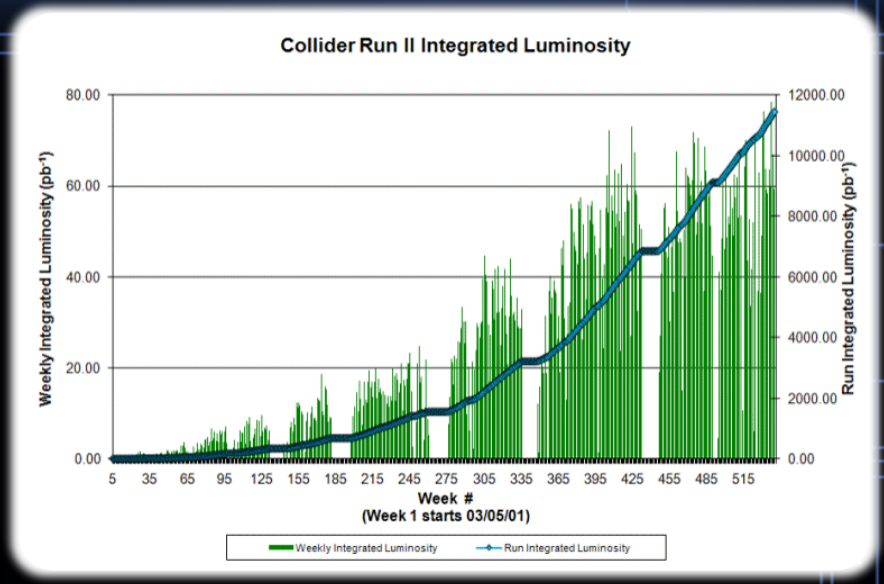


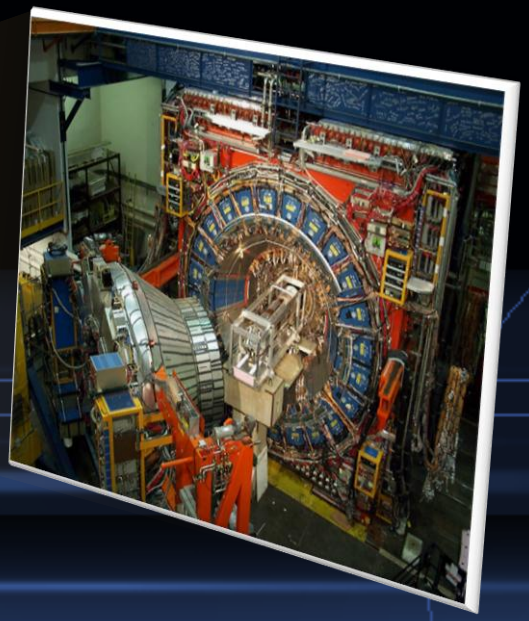
- b→sμμ rare decays
- Event selection
- BR measurements
- Angular analysis



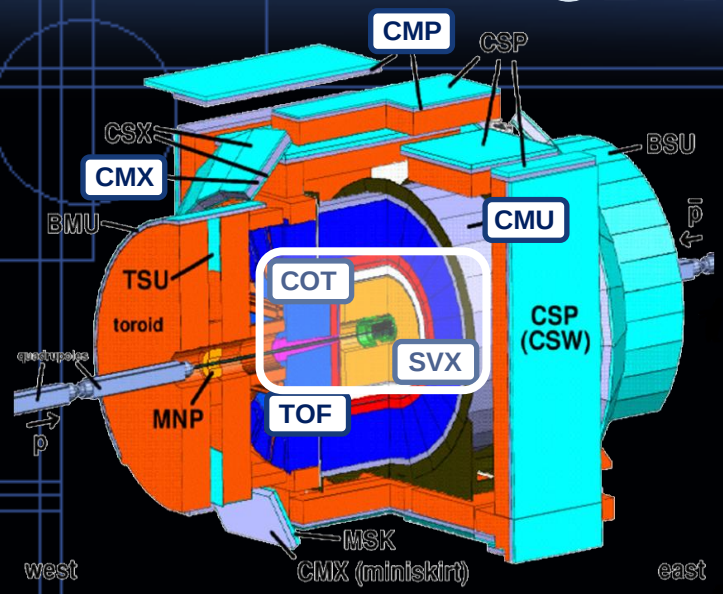
Tevatron

- Tevatron
  - ✓ $p\bar{p}$ collisions at $\sqrt{s}$=1.96TeV
- >9.7fb^{-1} data on tape
  (6.8 fb^{-1} used for the analysis)





CDF II detector



- A general purpose detector
  - ✓ Suitable for b→sμμ analysis

Tracking system

- Silicon tracker (SVX)
- Drift Chamber (COT)

Excellent tracking

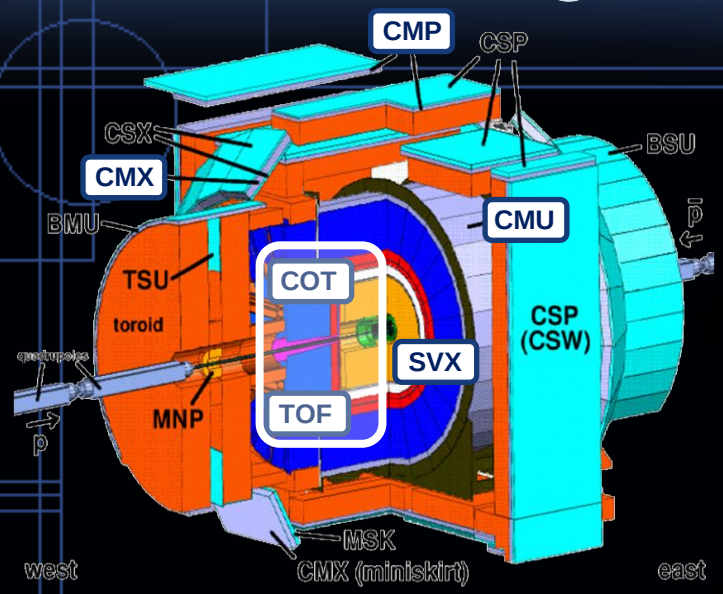
PID

- COT (dE/dx)
- TOF

-precise momentum
-$\sigma(p_T)/p_T^2 \sim 0.07\%$ (GeV/c)$^{-1}$
- precise vertex
- $\sigma(d_o) \sim 35$ μm for $p_T > 2$ GeV/c

- Muon chambers
  - CMU/CMP ($|\eta|<0.6$)
  - CMX ($0.6<|\eta|<1.0$)

CDF II detector



- A general purpose detector
  - ✓ Suitable for b→sμμ analysis

Tracking system

- Silicon tracker (SVX)
- Drift Chamber (COT)

PID

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- TOF

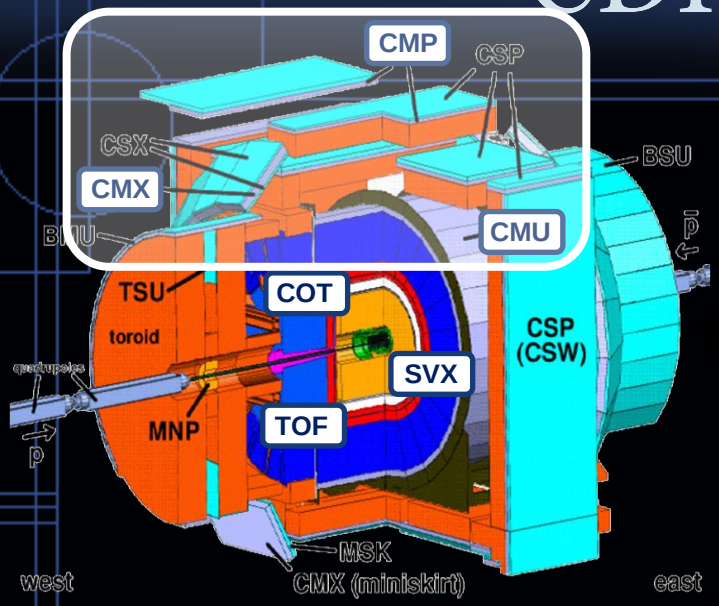
Good K-π separation

- 1.4σ K-π separation for p>2 GeV/c track

Muon chambers

- CMU/CMP (|η|<0.6)
- CMX (0.6<| η |<1.0)

CDF II detector



- A general purpose detector
  - ✓ Suitable for b→sμμ analysis

Tracking system

- Silicon tracker (SVX)
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PID

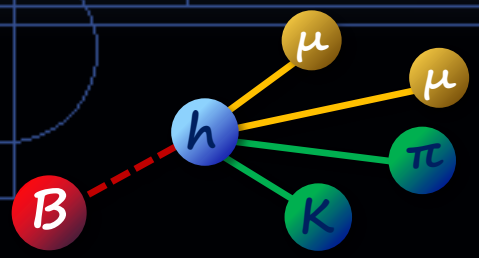
- COT (dE/dx)
- TOF

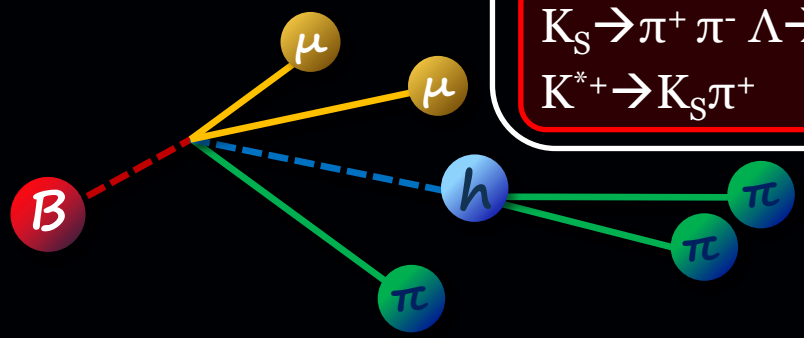
Muon chambers

- CMU/CMP (|η|<0.6)
- CMX (0.6<| η |<1.0)

Provide dimuon trigger

Event selection: overview





h hadrons

$\varphi \rightarrow K^+ K^-$

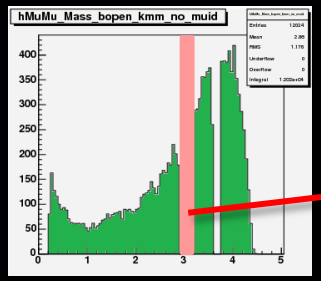
$K^{*o} \rightarrow K^+ \pi^-$

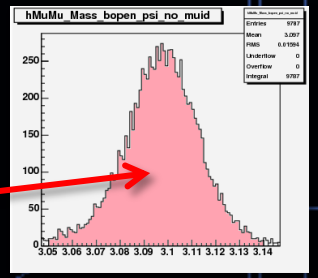
$K_S \rightarrow \pi^+ \pi^-$ $\Lambda \rightarrow p\pi^-$

$K^{*+} \rightarrow K_S \pi^+$

V^o decay

Signal mode	Control sample
$B^o \rightarrow K^{*o}\mu\mu$	$B^o \rightarrow J/\psi K^{*o}$
$B^+ \rightarrow K^+\mu\mu$	$B^+ \rightarrow J/\psi K^+$
$B_s \rightarrow \varphi\mu\mu$	$B_s \rightarrow J/\psi\varphi$
$B^+ \rightarrow K^{*+}\mu\mu$	$B^+ \rightarrow J/\psi K^{*+}$
$B^o \rightarrow K_S\mu\mu$	$B^o \rightarrow J/\psi K_S$
$\Lambda_b \rightarrow \Lambda\mu\mu$	$\Lambda_b \rightarrow J/\psi\Lambda$





Dimuon mass

- Start from dimuon trigger
  - ✓ Reconstruct $H_b \rightarrow h\mu\mu$
  - ✓ Optimize event selection by NN

12 channel analysis!

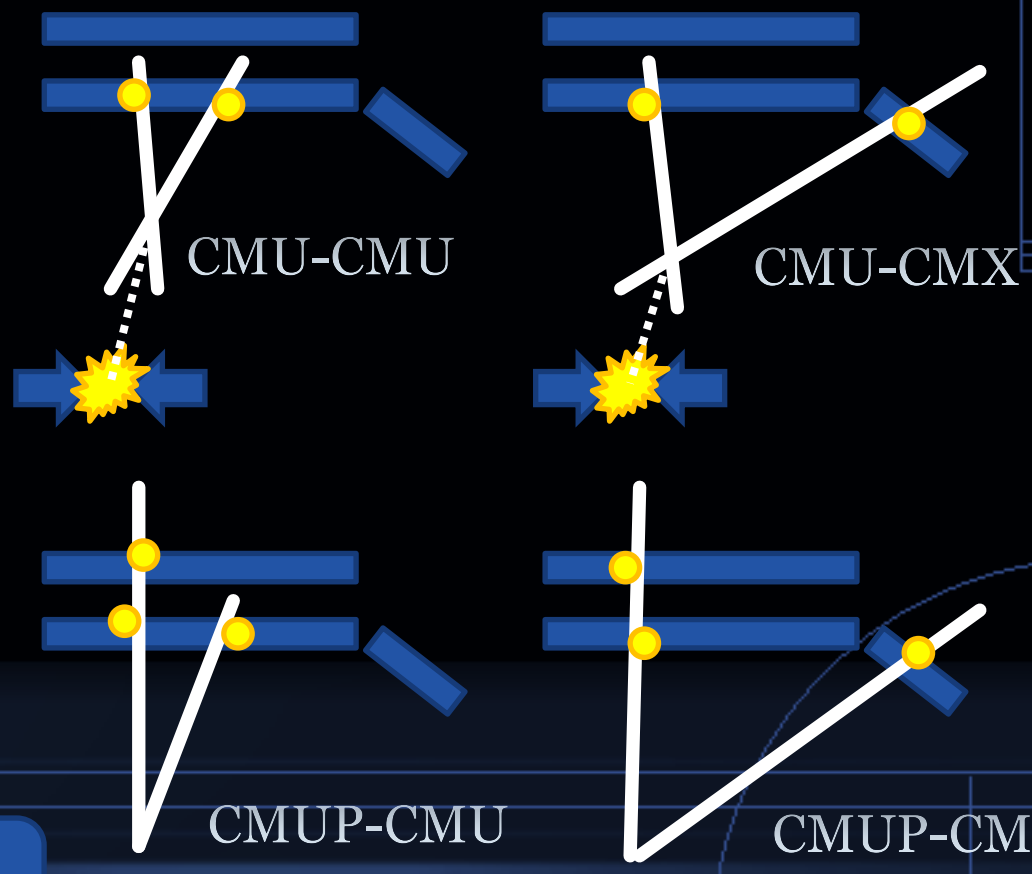
Trigger path

- Four dimuon triggers

- LXY
  - $p_T(\mu)$>1.5 or 2.0 GeV/c
  - L_{xy}>100um

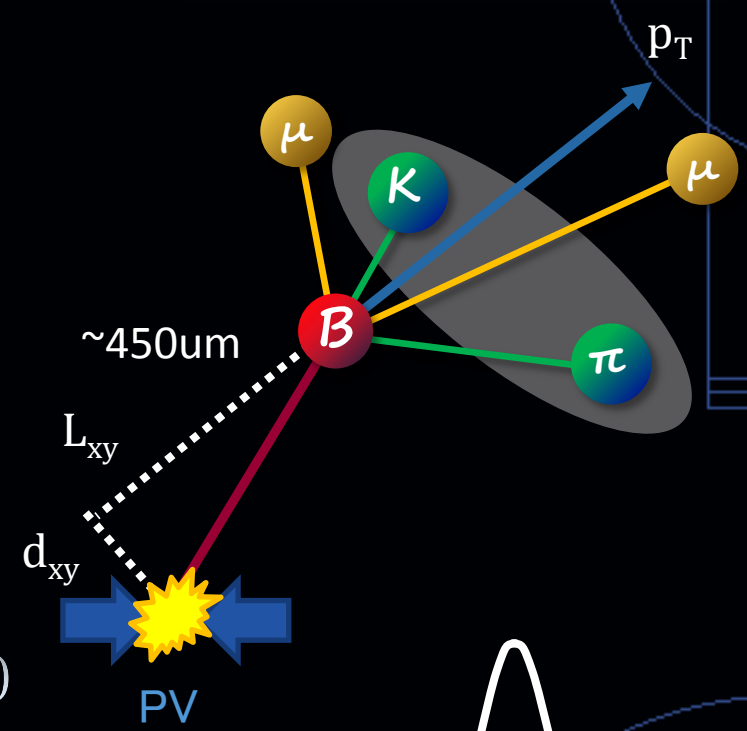
- CMUP
  - $p_T(\mu)$>1.5 or 2.0 GeV/c
  - One muon has CMP hit and $p_T(\mu)$>3.0GeV/c

- All categories are exclusive
  - Require CMUP when LXY is not fired

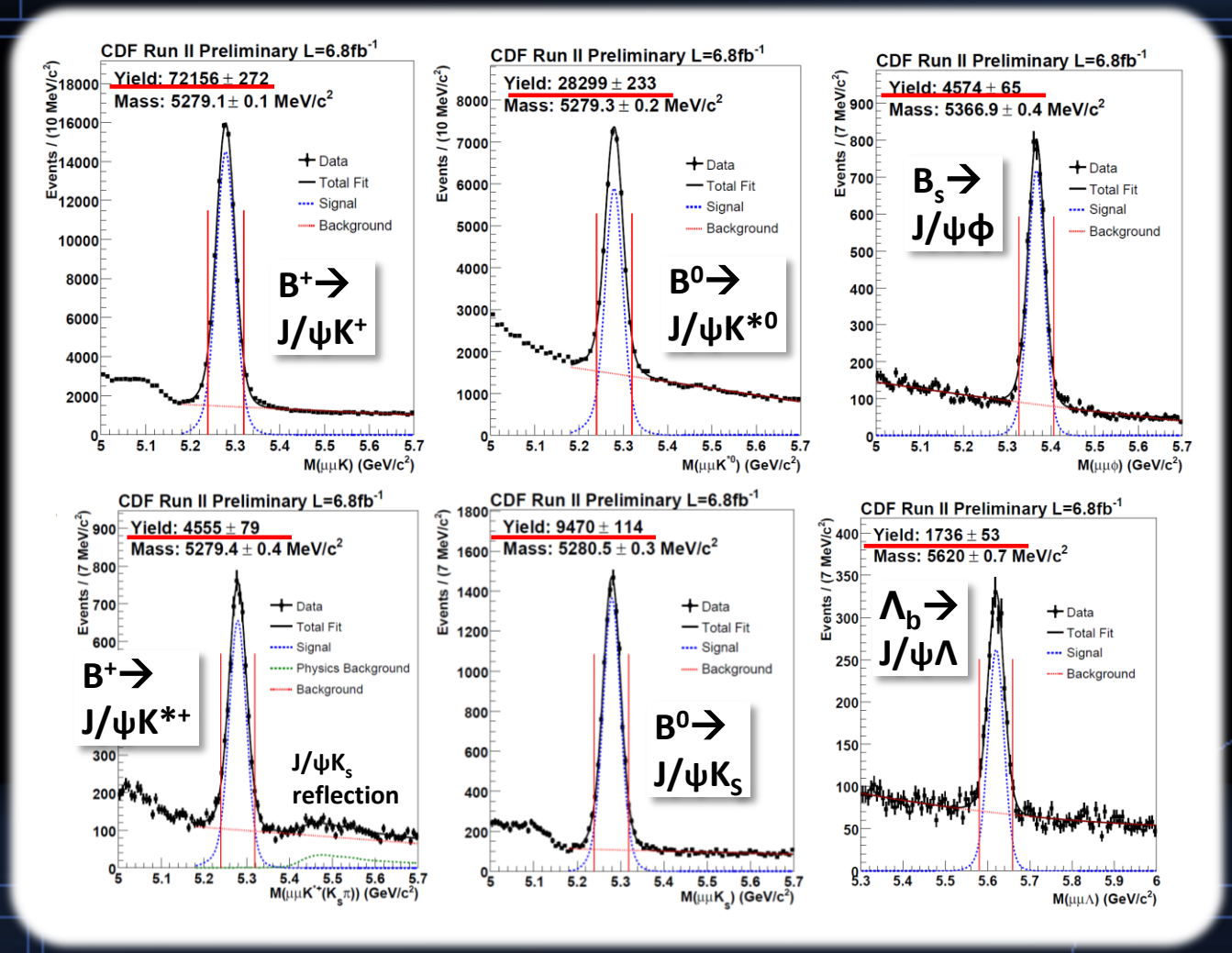


Loose event selection

- Track quality
  - ✓ Number of hits
- Vertex quality
  - ✓ Vertex probability
- Kinematics
  - ✓ p_T
  - ✓ L_{xy}, d_{xy}
- Particle ID
  - ✓ Kaon ID (dE/dx+TOF)
  - ✓ Muon ID
- Hadron mass
  - ✓ K^{*0}, φ, K_s, K^{*+}, Λ (around world's average mass, 10~20 or 50~100MeV/c^2)
  - ✓ J/ψ for control sample



Control sample yields

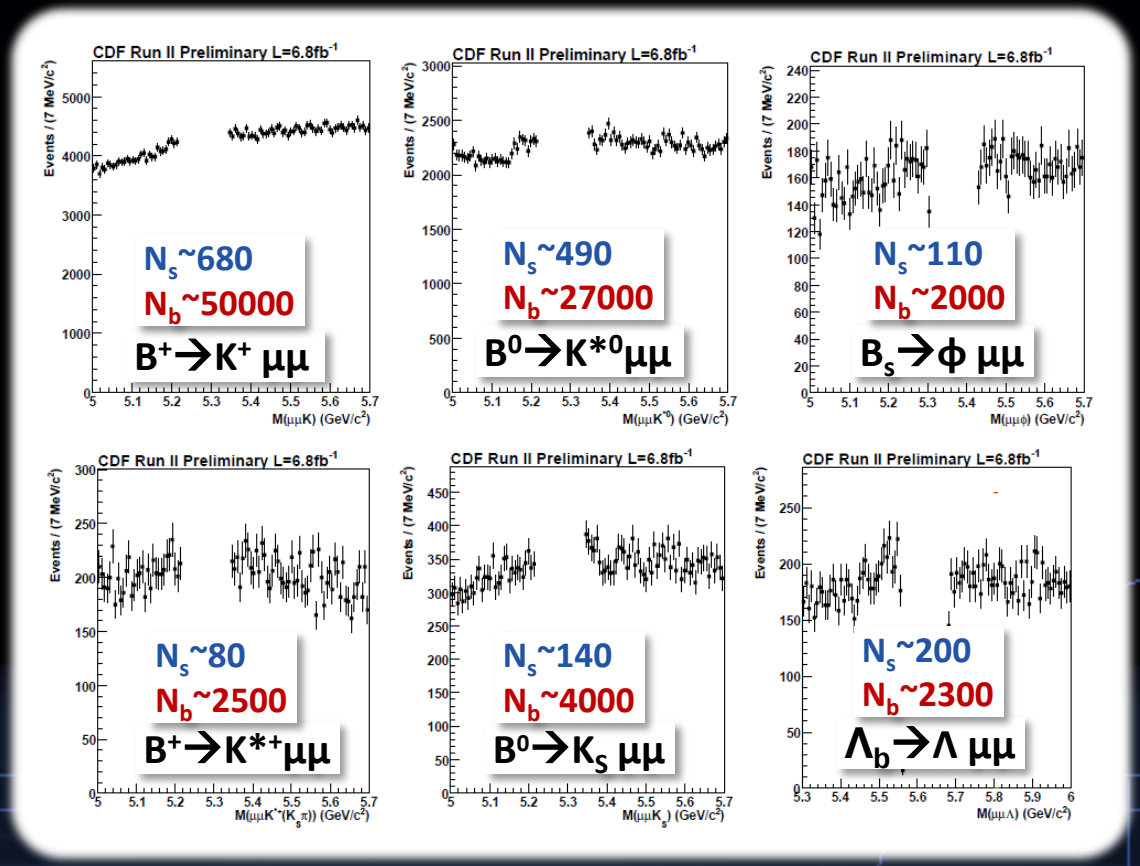


- Clean signals for all channels

Rare decay candidates

- Expected rare decay yields are 100 times smaller than the control sample's while suffering from larger backgrounds due to wide dimuon mass range

N_s: expected signal
N_b: # of candidates



- Large backgrounds…challenging analysis!

More background reduction

- Dominant BG: accidental combination of hadron+muons

Optimized by neural network

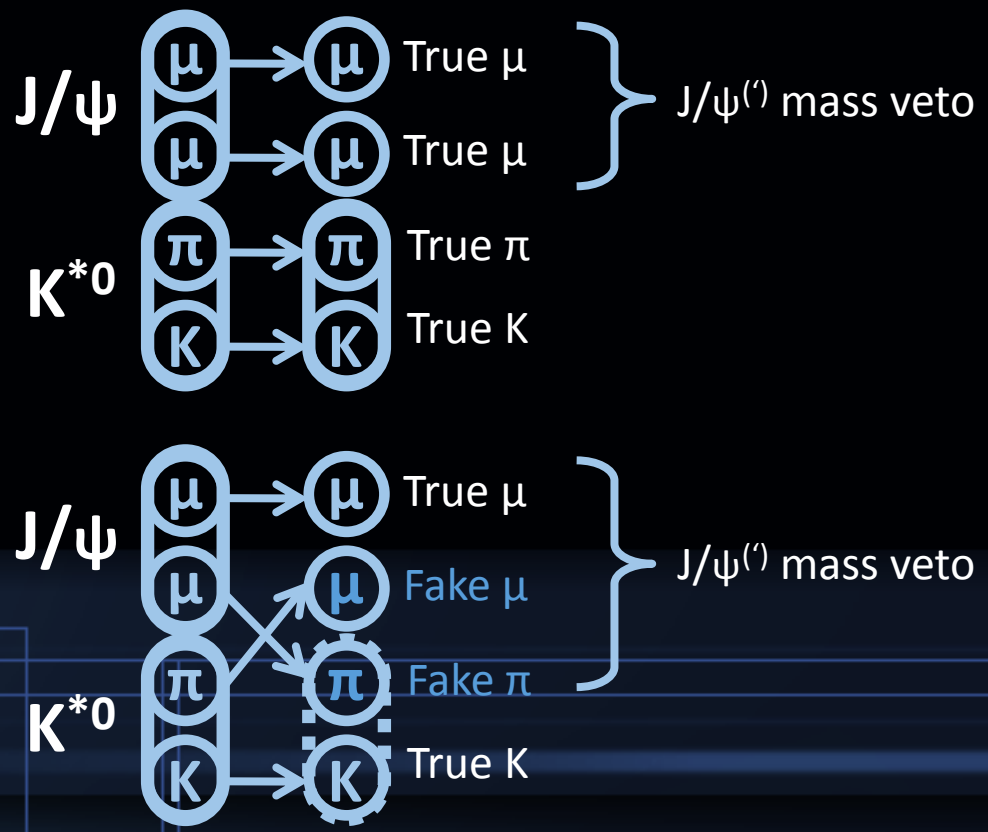
- Possible physics BG:
  - Charmonium decays ($H_b \rightarrow J/\psi h$)
  - Charm decays ($H_b \rightarrow D(\rightarrow h'h'')h$)
  - Charmless decays ($H_b \rightarrow hh'h''$)
  - Cross-feed among $b \rightarrow s\mu\mu$ decays

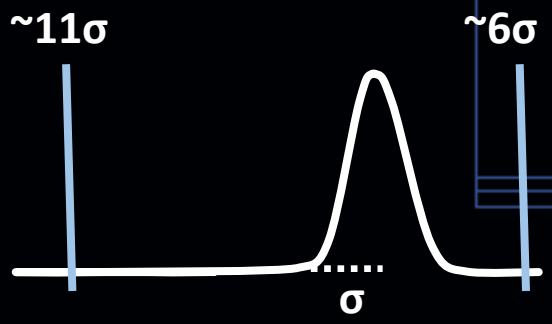
Reduced by vertexing, mass cut, kaon and muon ID

Also apply some vetoes:
Charmonium mass
Charm hadron mass

Physics BG: Charmonium decays

- $H_b \rightarrow J/\psi(\rightarrow \mu\mu)h$
  - ✓ ~100 times large BR



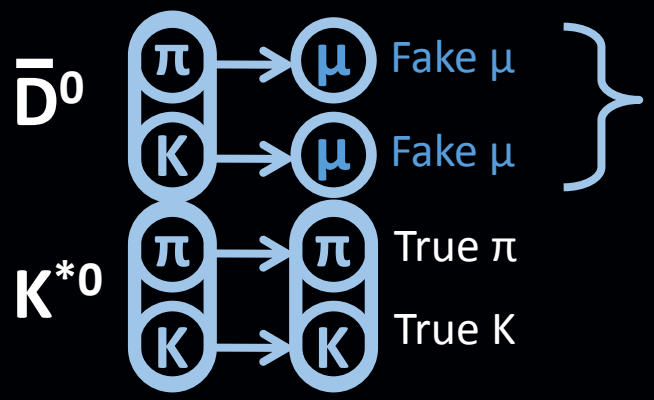


Wide mass veto
to remove radiative tail

Physics BG: Charm decays

- $H_b \rightarrow D(\rightarrow h'h'')h)$
  - ✓ 1~100 times large BR

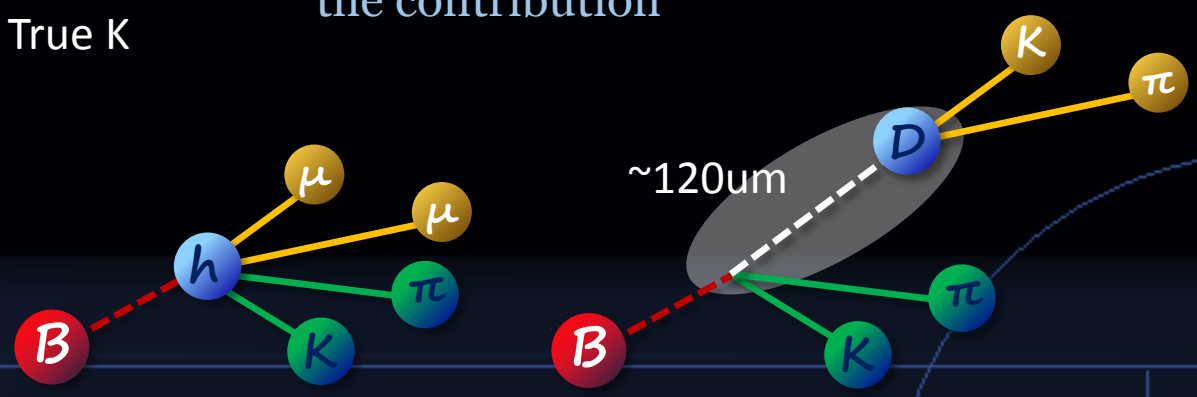
$D^0, D^+, D_s, \Lambda_c \ldots$



D mass veto

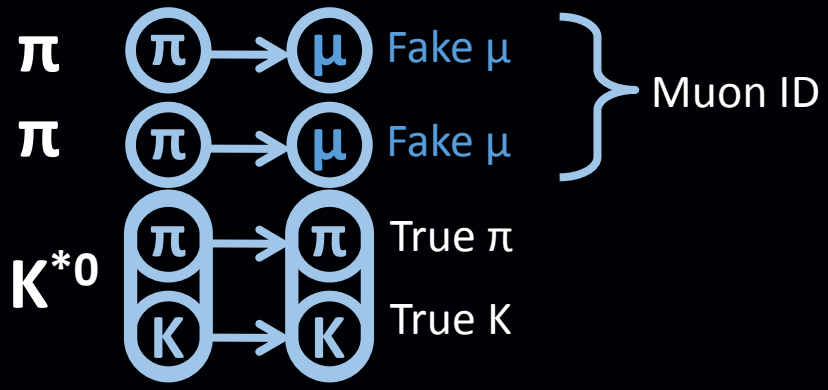
Muon ID

Long-lived D vertex also reduces the contribution



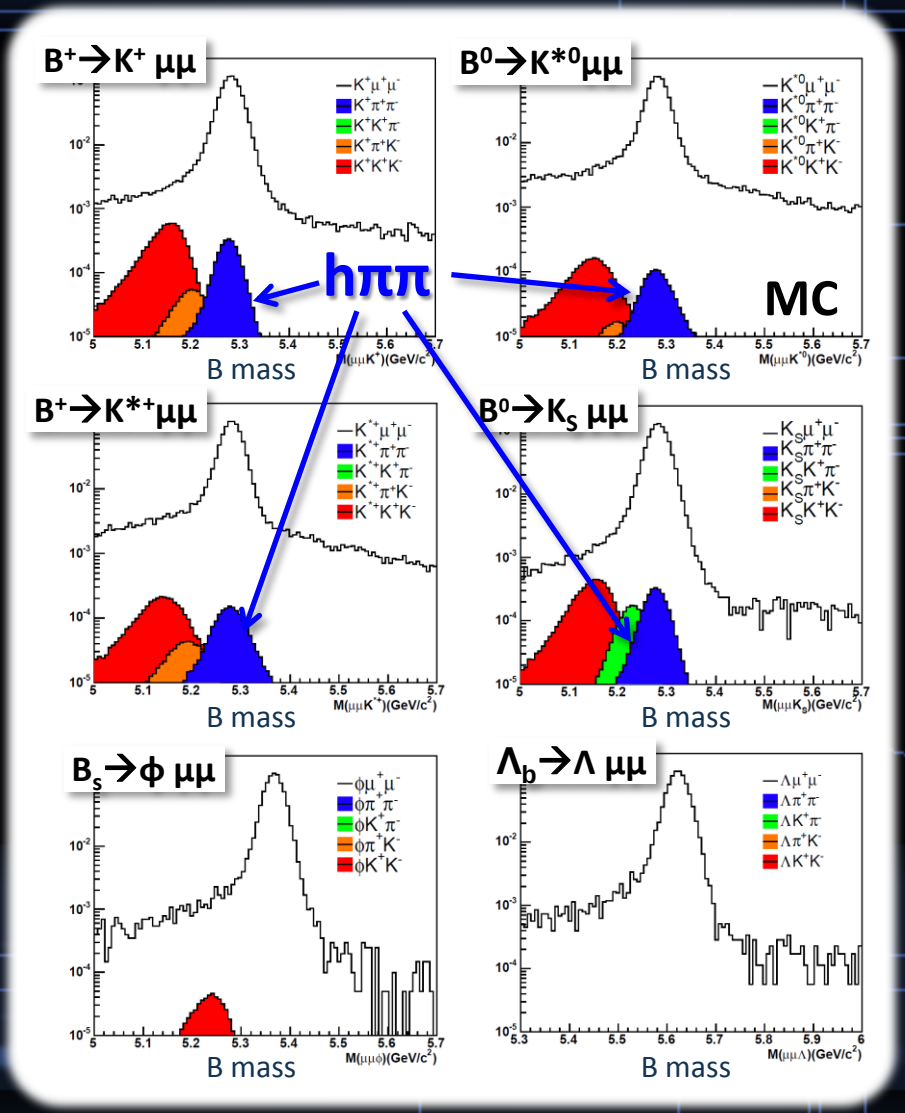
Physics BG: Charmless decays

- $H_b \rightarrow hh'h''$
  - ✓ 1~10 times large BR



Cannot be vetoed by the intermediate mass

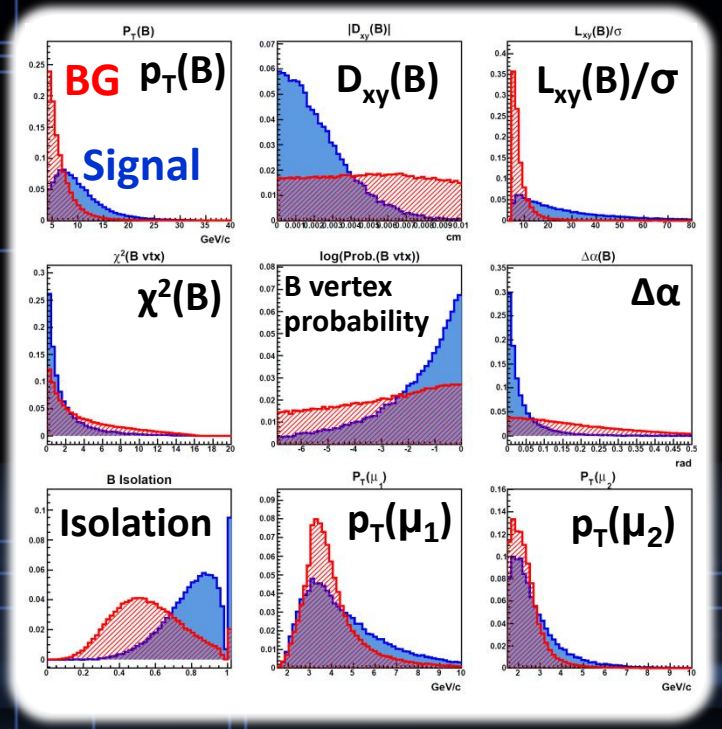
Negligibly small due to good muon ID

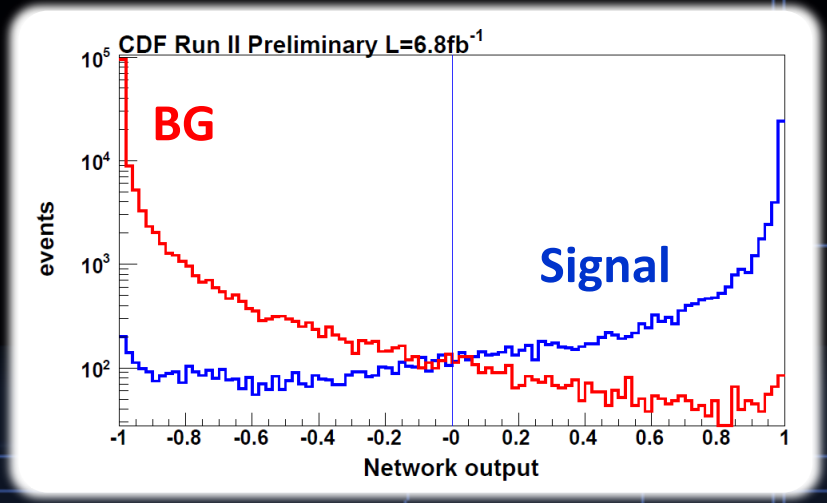


Neural Network: training

- Employ Neurobayes™
- Signal is taken from MC
- BG is taken from sideband

- Use 15-18 kinematical variables
- Most effective variables
  - ✓ H_b kinematics (e.g. L_{xy}, D_{xy})



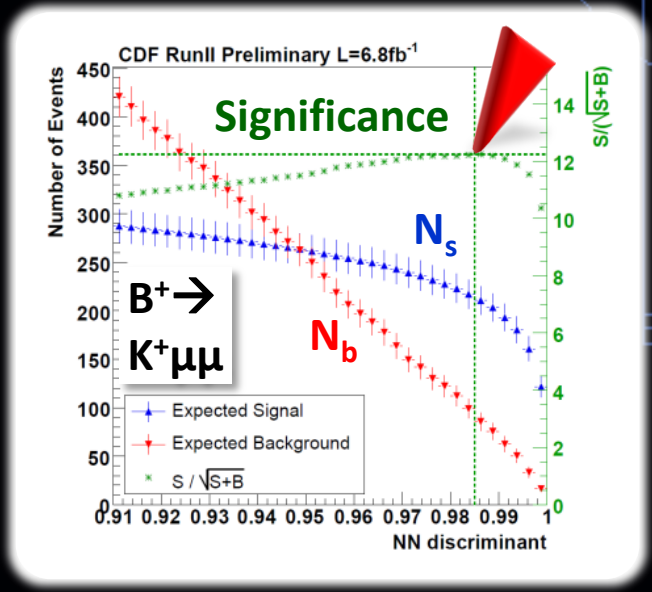


Neural Network: optimal cut

- Find optimal NN cut to maximize the significance

$$N_s/\sqrt{N_s + N_b}$$

N_s: expected # of signal
N_b: expected # of BG



- $\Lambda_b \rightarrow \Lambda\mu\mu$ is optimized by

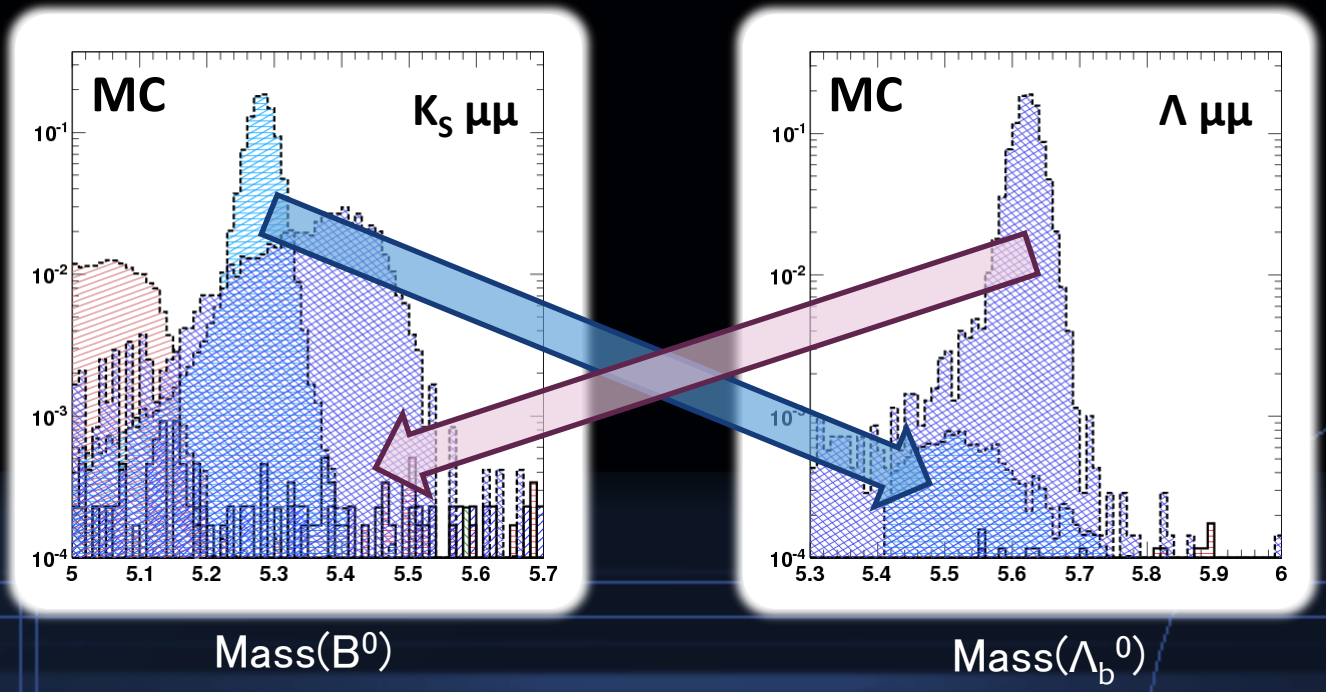
$$N_s/(5/2 + \sqrt{N_b})$$

G. Punzi, arXiv:physics/0308063 (2003)

since this is a search aiming at first observation

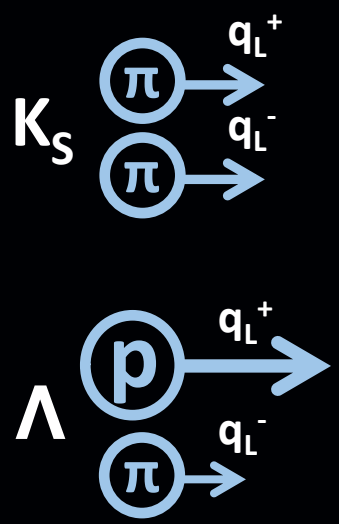
b→sμμ cross-feed (1)

- Dominant physics background after all event selection
  - ✓ Generally small in the signal region
- Possible larger cross-feed between $B^0 \rightarrow K_s\mu\mu$ and $\Lambda_b \rightarrow \Lambda\mu\mu$



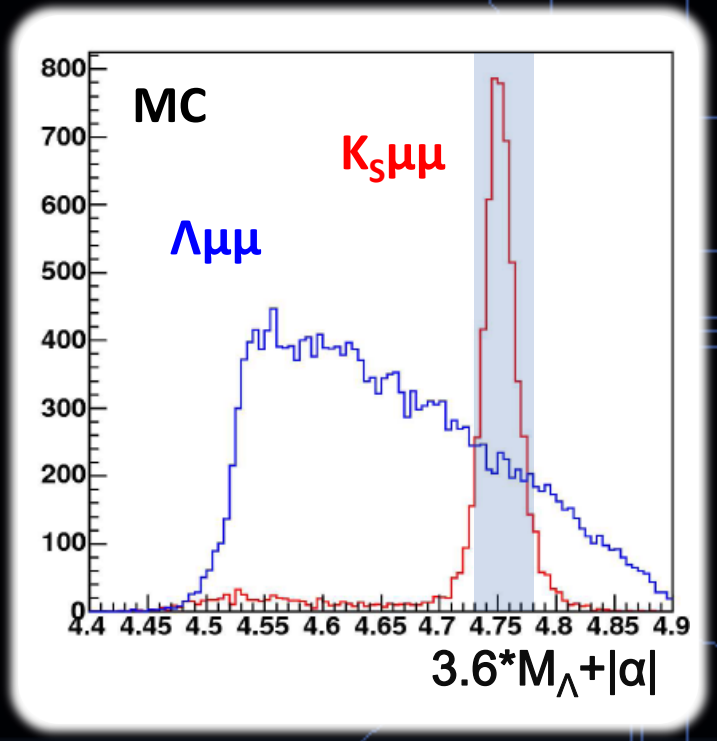
b→sμμ cross-feed (2)

- To reduce cross-feed event, evaluate momentum imbalance of daughter particles



$$\alpha \equiv \frac{q_L^+ - q_L^-}{q_L^+ + q_L^-}$$

indicates "cross-feed region"

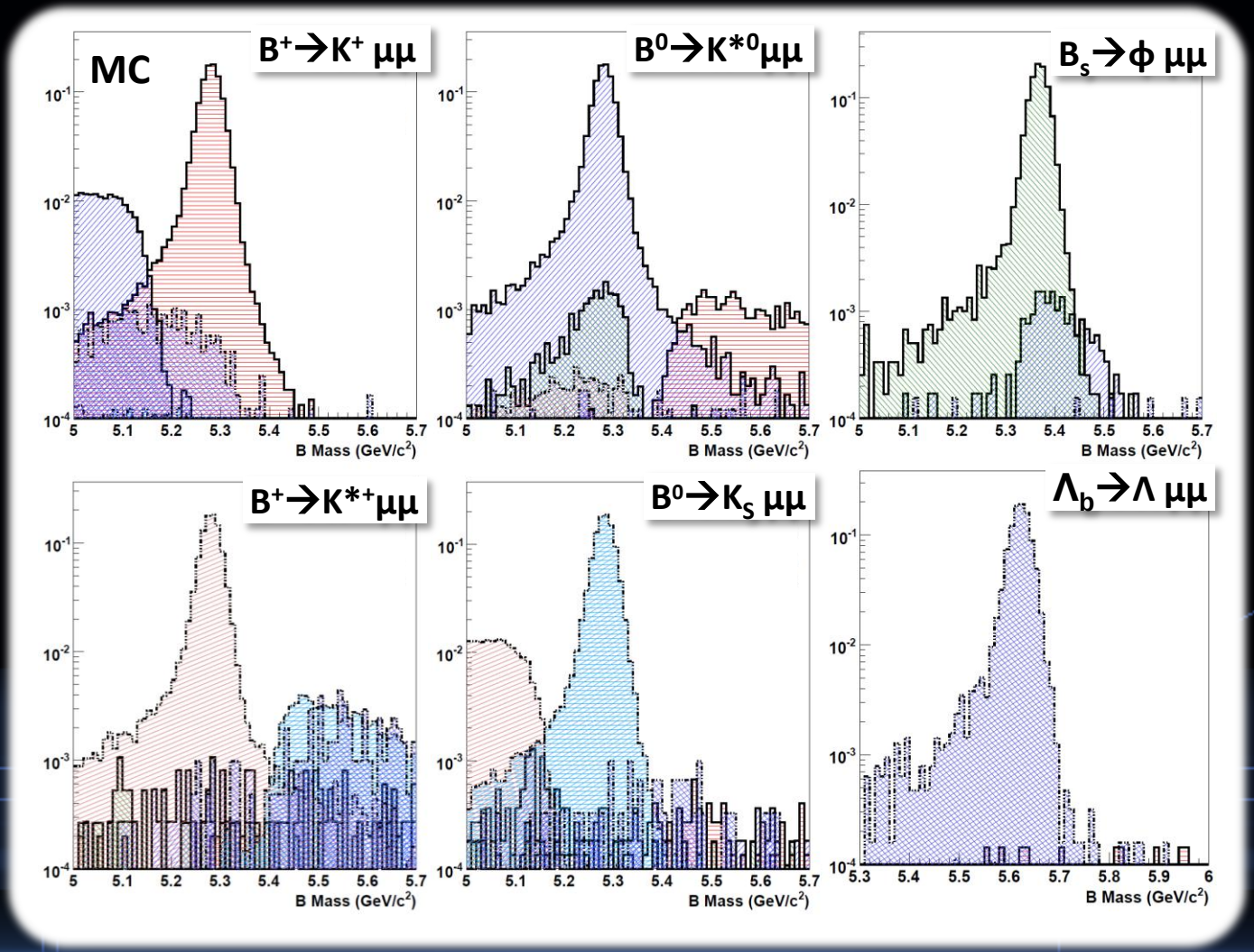


q_L: projected momentum to Λ/K_s direction

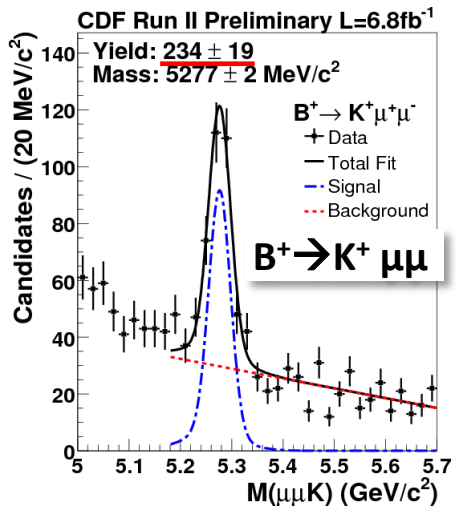
$K_S\mu\mu$
→removes 90% of Λ (signal loses 7%)
$\Lambda\mu\mu$
→removes 76% of K_S (signal loses 11%)

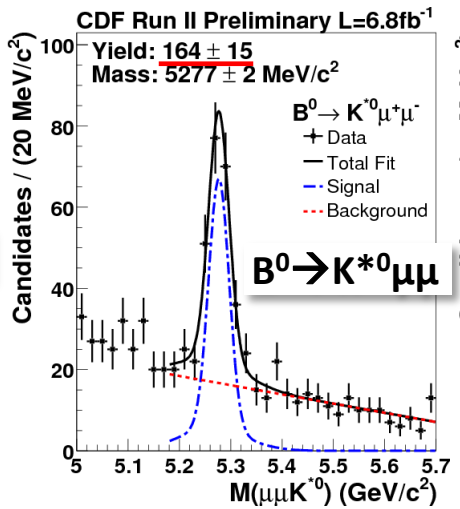
b→sμμ cross-feed (3)

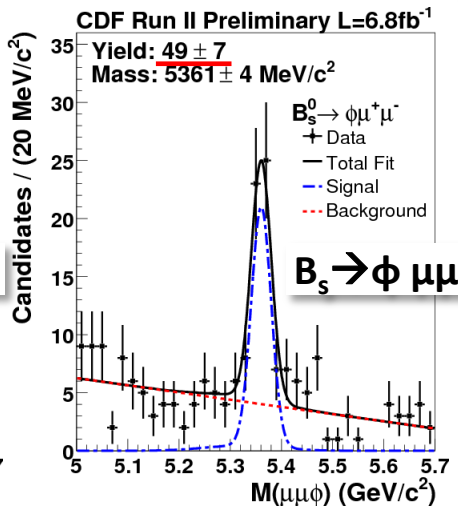
- No significant cross-feed (Largest: $K^{*0} \leftarrow\rightarrow \varphi$ (~1%))

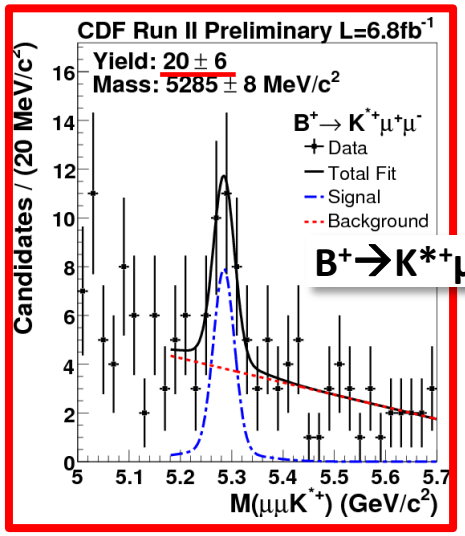


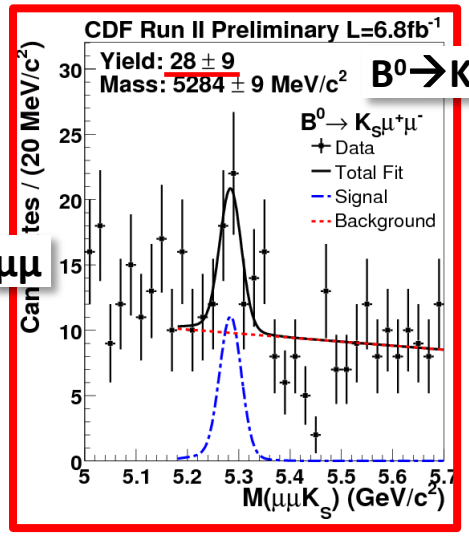
Rare decay yields









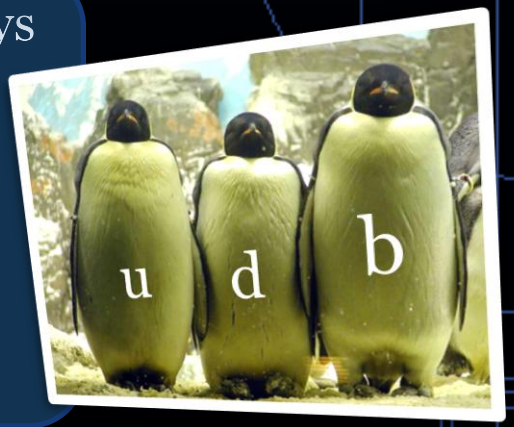


Remove 99.1~99.8% of BG while keeping 20~50% of signal

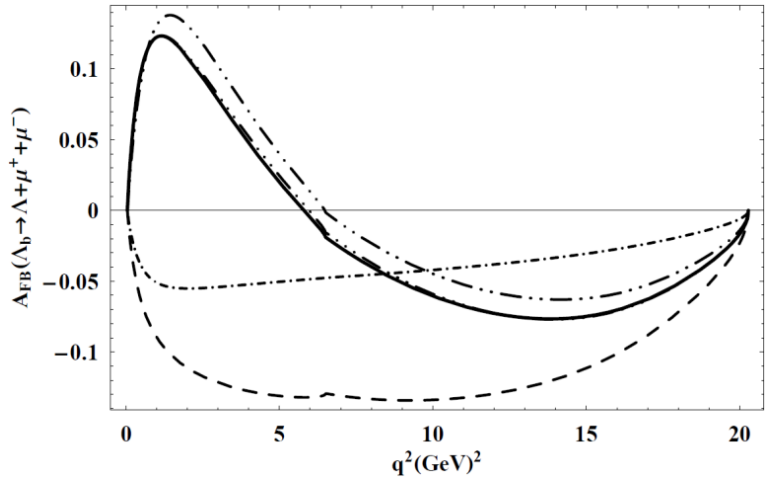
(*) First reconstruction in hadron collisions

Baryonic rare decay: $\Lambda_b \to \Lambda\mu\mu$

- Simple extension of $b \to s\mu\mu$ transition to b-baryon decays
  - ✓ **Different sensitivity from $K^*\mu\mu$**
- Small but accessible BR ~$O(10^{-6})$
- No experimental search result (although >25 theory papers)
- Can measure A_{FB} (difficult in $\varphi\mu\mu$)

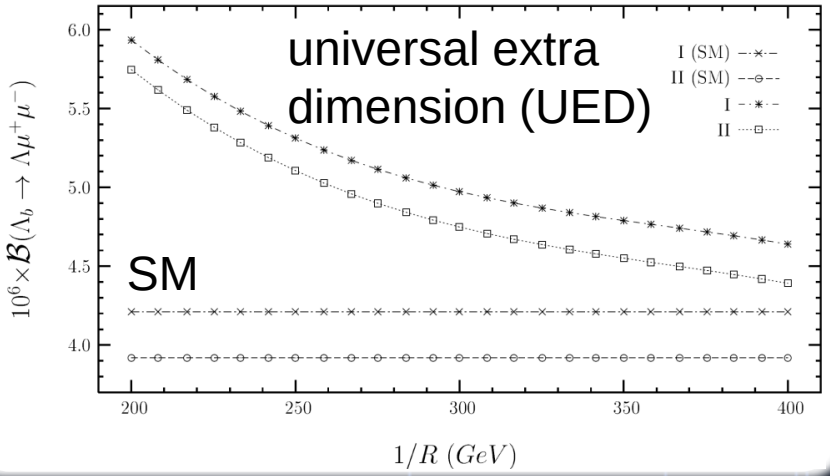


$A_{FB}(\Lambda_b \to \Lambda\mu\mu)$



M.J.Aslam, Y.M.Wang, C.D. Lu PRD78:114032 (2008)

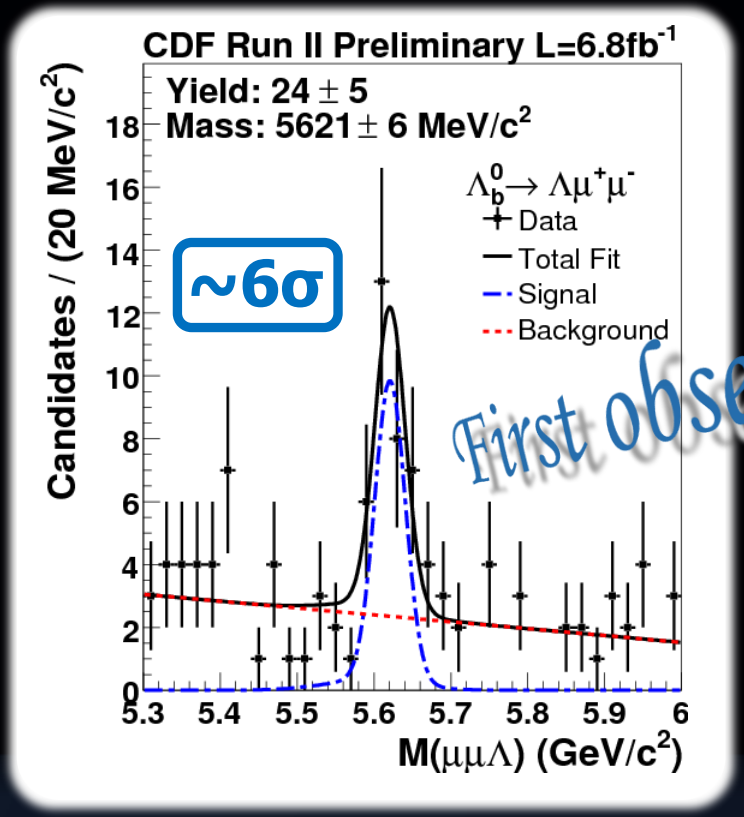
$BR(\Lambda_b \to \Lambda\mu\mu)$ vs UED parameter



T.M.Aliev, M.Savci, EPJC50:91-99 (2007)

$\Lambda_b \rightarrow \Lambda\mu\mu$ observation

First experimental search for baryonic $b \rightarrow s\mu\mu$ decay



First observation!

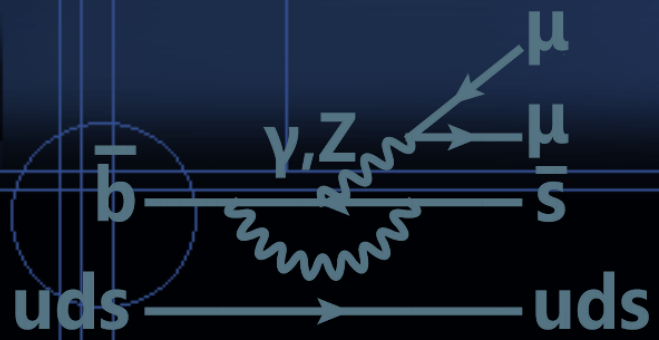
Expectations

- ✓ $(4.0 \pm 1.2) * 10^{-6}$ Phys.Rev.D81,056006 (2010)
- ✓ $4.4 * 10^{-6}$ Phys.Rev.D78,114032 (2008)
- ✓ $2.08 * 10^{-6}$ Phys.Rev.D64,074001 (2001)

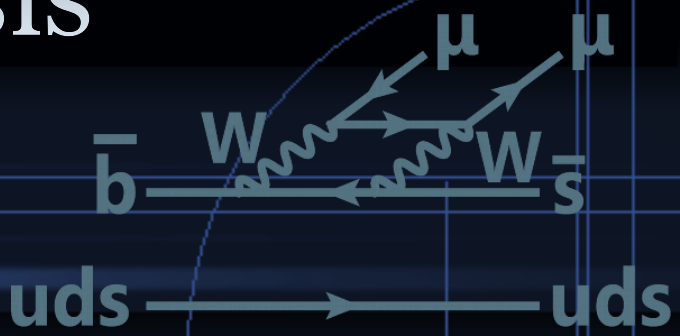
$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\mu^+ = [1.73 \pm 0.42(\text{stat}) \pm 0.55(\text{syst})] \times 10^{-6}$$

The rarest Λ_b decay to date

Outline



- b→sμμ rare decays
- Event selection
- BR measurements
- Angular analysis



BR measurement: overview

- Relative BR

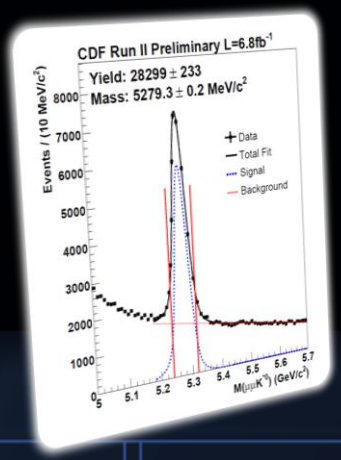
$$\frac{\mathcal{B}(H_b \to h\mu^+\mu^-)}{\mathcal{B}(H_b \to J/\psi h)} = \frac{N_{h\mu^+\mu^-}}{N_{J/\psi h}} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\varepsilon_{\rm rel}}$$

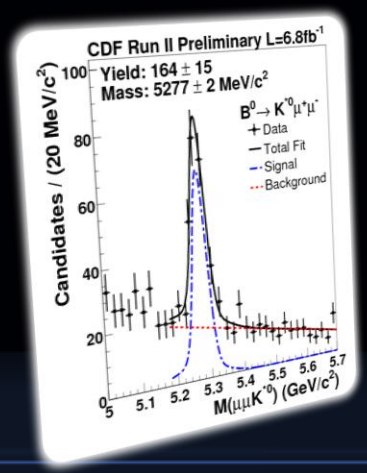
h=K, K*, φ, Λ

Control channel yield

Rare channel yield

Relative reconstruction efficiency





$$\varepsilon_{\rm rel} \equiv \frac{\varepsilon_{h\mu^+\mu^-}}{\varepsilon_{J/\psi h}}$$

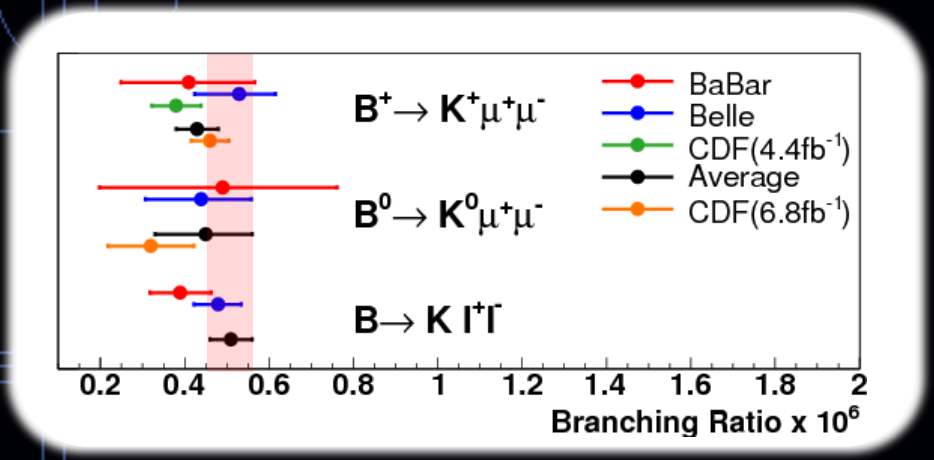
- Determined from signal MC

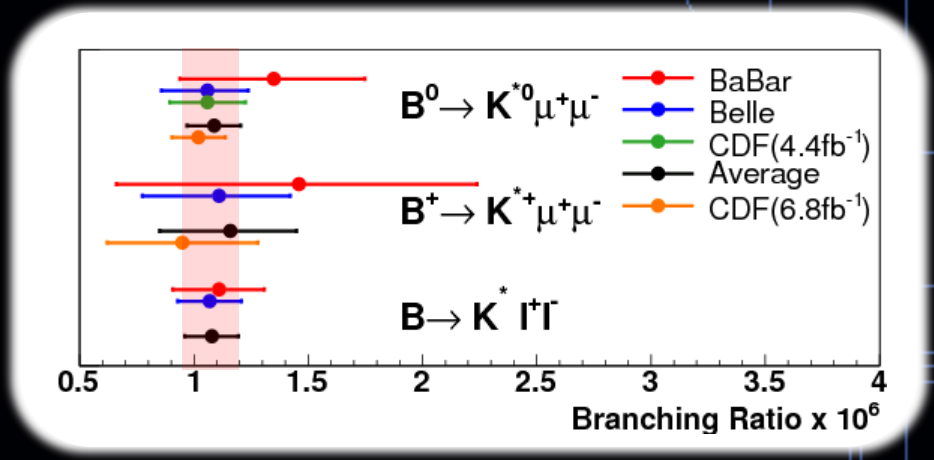
- Many common systematics are canceled
- Obtain absolute BR by world's average BR

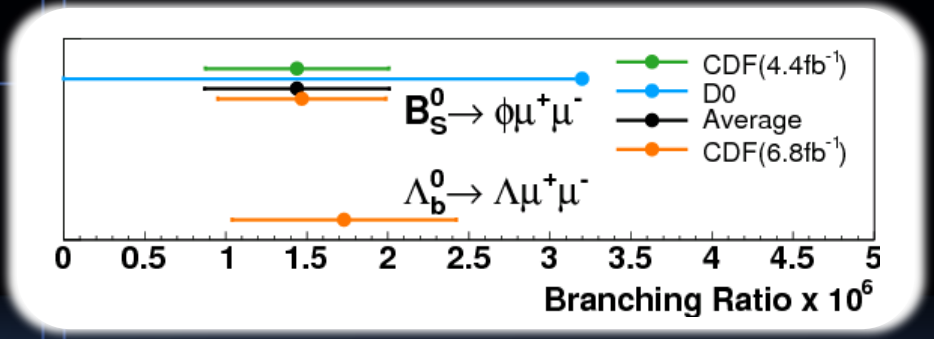
BR: systematics

- Dominant sources:
  - ✓ MC reweight (0.5-4.0%)
  - ✓ Trigger turn-on (0.8-7.2%)
    - Study muon efficiency near threshold ($p_T(\mu)$~1.5/2.0/3.0GeV/c)
    - Repeat analysis with different $p_T(\mu)$ threshold for each trigger
- Total systematics (3.7~11.9%)
- Absolute BR
  - ✓ additional uncertainty from BR($H_b \rightarrow J/\psi h$) (3.4~30.8%)

Total BR: summary



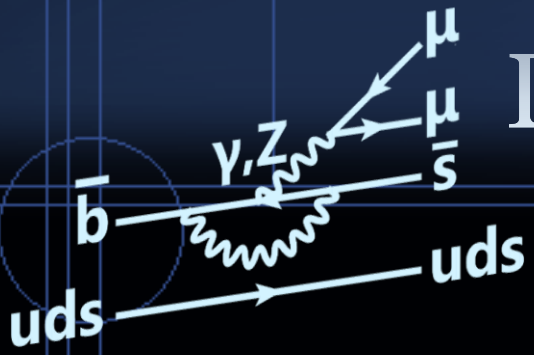




(*) All BRs except CDF@6.8fb^{-1} are taken from HFAG 2010 August

- World's most precise b→sμμ BR measurements!

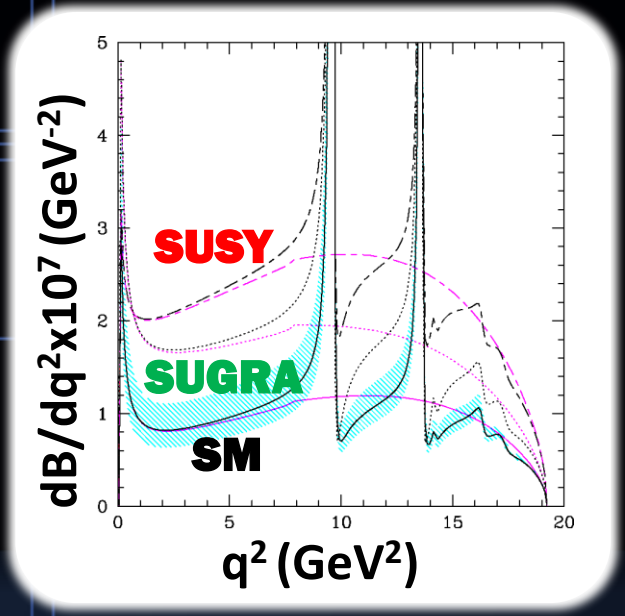
Differential BR (1)



- Breakdown complex b→sμμ dynamics
  - ✓ Use dimuon mass squared ($q^2=M_{\mu\mu}^2$)

γ-penguin | Low q^2 → High q^2 | Z-penguin, W-box diagram

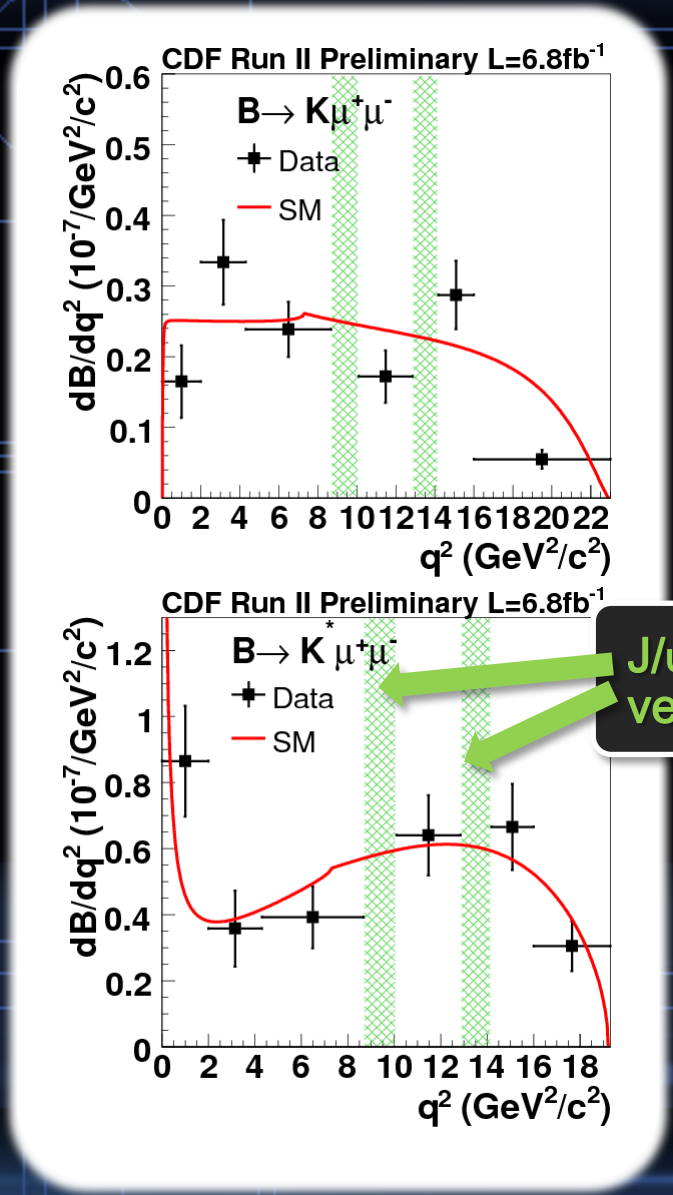
  - ✓ Test exclusive b→sμμ decay model
  - ✓ Enable precise comparison with theory in "clean" region ($1<q^2<6$)
    - Provide discrimination of BSM models



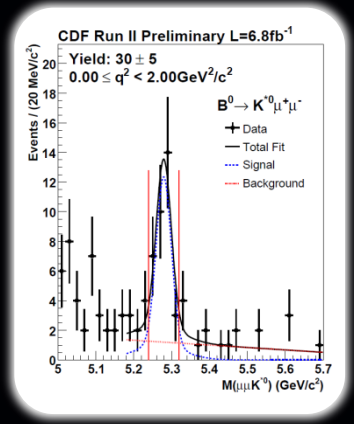
A. Ali *et al.*, PRD61:074024 (2000)

- Dominant uncertainty
  - ✓ Theory: hadronic form factor
  - ✓ Experiment: statistics

Differential BR (2)



- Divide data by six q^2 region
  - Common binning among Belle, CDF, and LHCb
  - Measure yield in each q^2 bin and calculate dB



$B^+ \to K^+\mu\mu$ $B^0 \to K^{*0}\mu\mu$

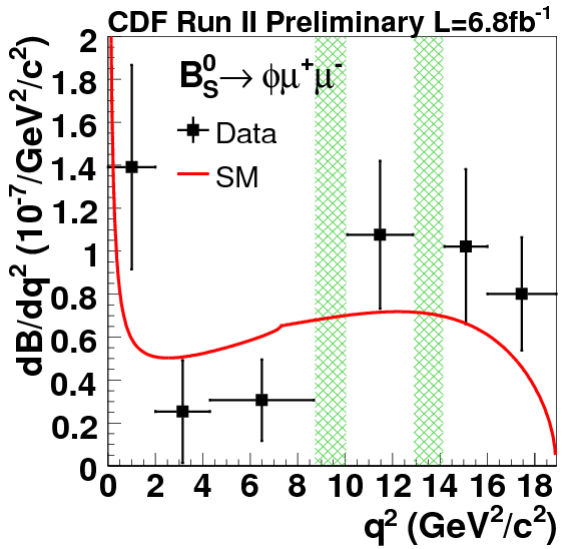
$B^0 \to K^0\mu\mu$ $B^+ \to K^{*+}\mu\mu$

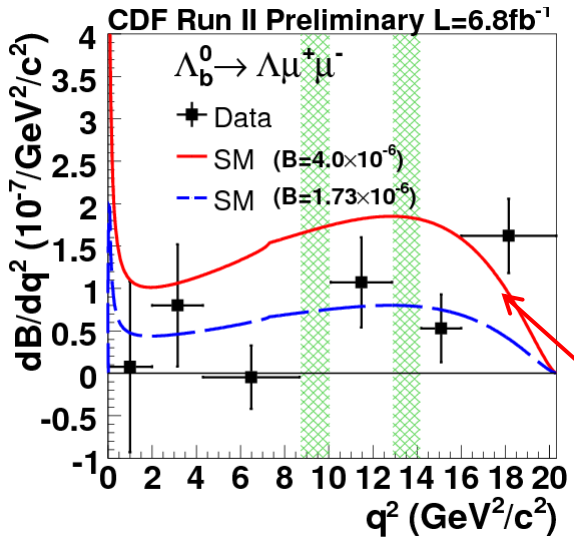
(*) First measurements in hadron collisions

$B \to K\,\mu\mu$ $B \to K^*\,\mu\mu$

- Combined BR is calculated assuming isospin symmetry

Differential BR (3)

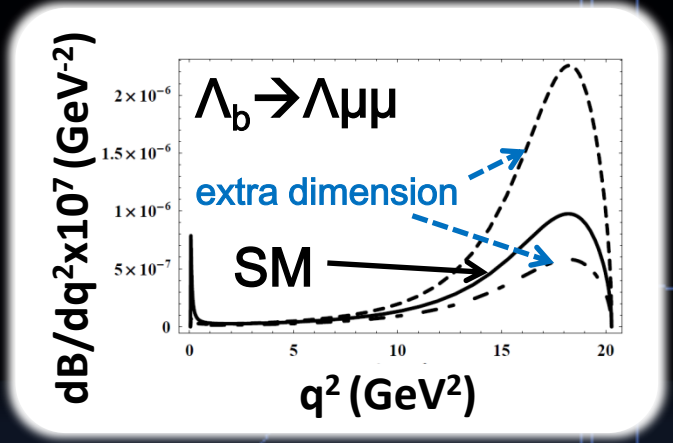




SM prediction

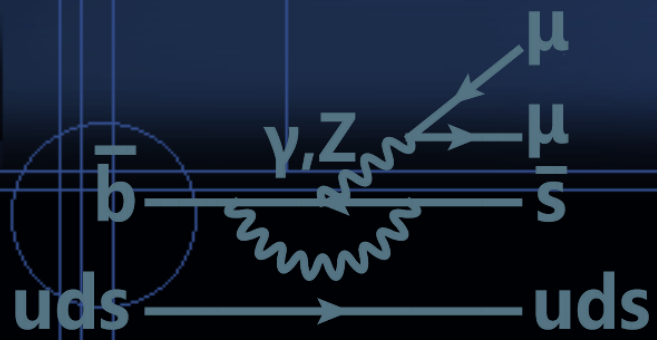
T. M. Aliev, K. Azizi, and M. Savci, PRD81, 056006 (2010)

- Most theory calculation are on $B \to K^{(*)}\mu\mu$
  - ✓ Precise dB measurements other than $B \to K^{(*)}\mu\mu$ could improve the theoretical prediction
  - ✓ Could give unique constraint on BSM in future
- First results from an experiment

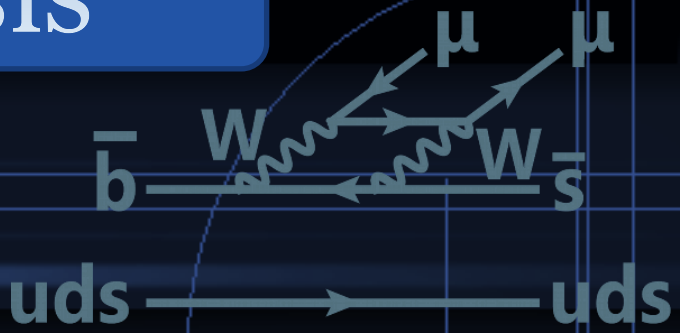


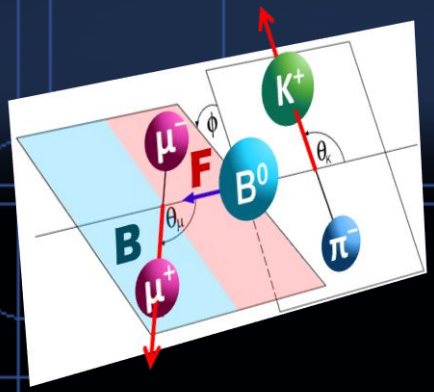
Y.-M. Wang, M.J. Aslam, C.-D. Lu, arXiv:0810.0609 (2008)

Outline

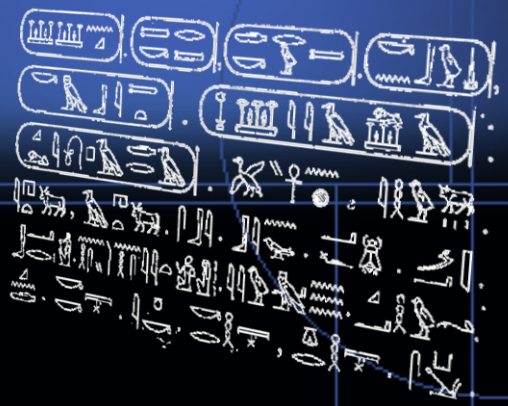


- b→sμμ rare decays
- Event selection
- BR measurements
- Angular analysis





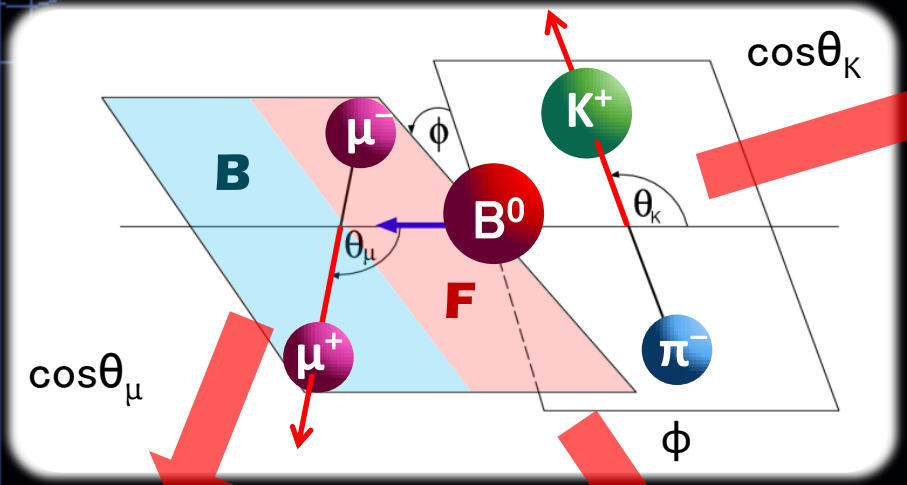
Angular analysis

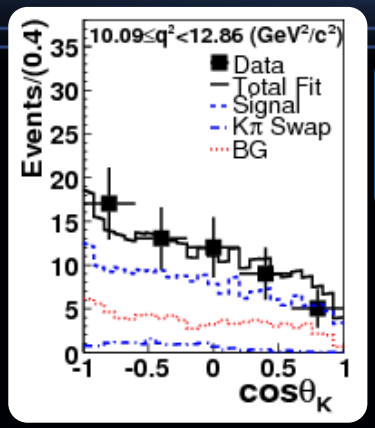


- Decipher b→sμμ decay amplitude by the kinematics (q^2 + angular distribution)
  - ✓ Access more detailed structure than differential BR
- Require more statistics
- Theory uncertainty canceled in the Asymmetry
  - ✓ Provides powerful probes sensitive to new physics!

Angular distribution

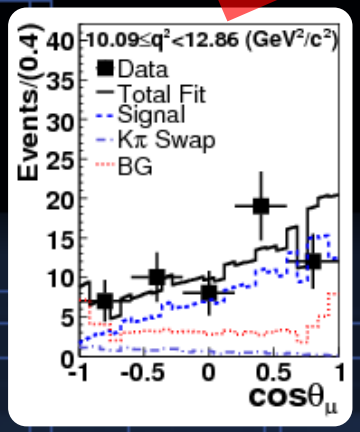
- One can extract various information from the decay angular distribution





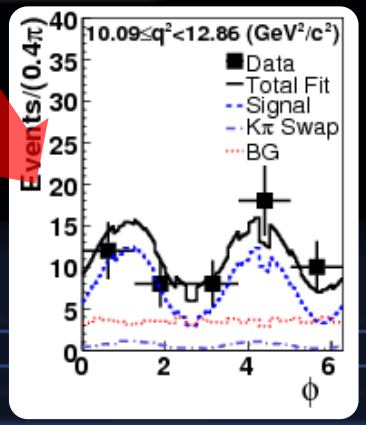
K* polarization

F_L



FB asymmetry

A_{FB}



NEW

$A_T^{(2)}$ Transverse polarization asymmetry

A_{im} T-odd CP asymmetry

Fit procedure

Perform angular analysis with maximum likelihood fit

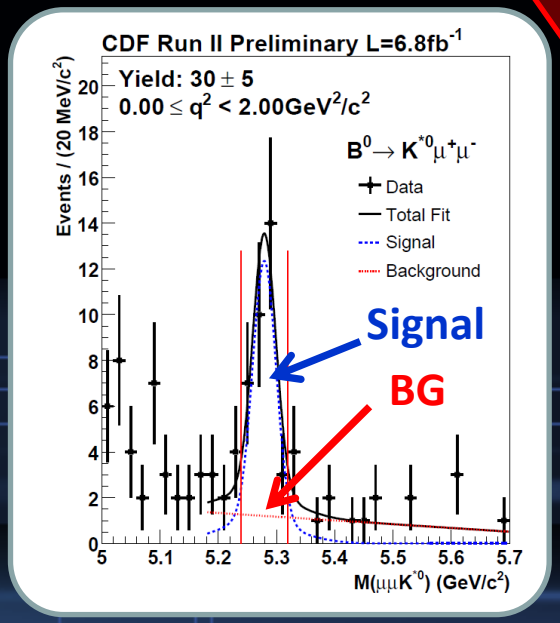
$$\mathcal{L} = \prod\left(f_{\rm sig}\mathcal{P}_{\rm sig}(M_B)\mathcal{F}_{\rm sig}(\cos\theta) + (1-f_{\rm sig})\mathcal{P}_{\rm bg}(M_B)\mathcal{F}_{\rm bg}(\cos\theta)\right)$$

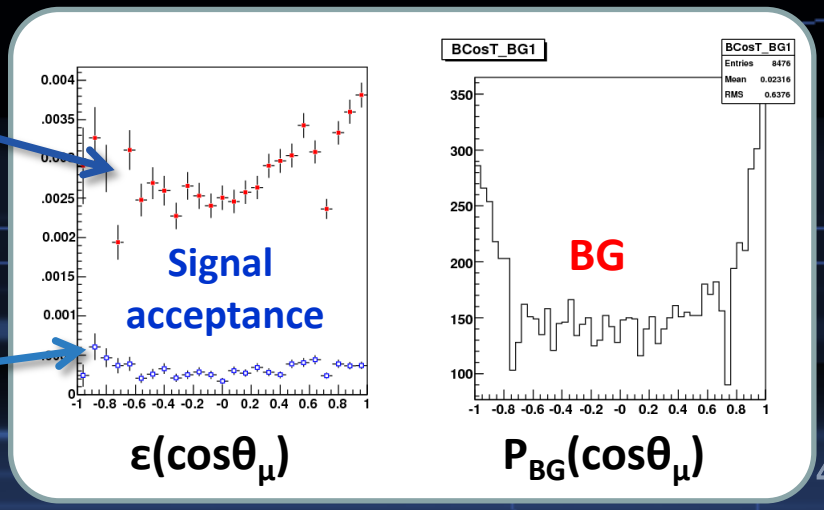
Signal fraction

B mass shape

Angular distribution

$$\left[\frac{3}{4}F_L(1-\cos^2\theta_\mu)+\frac{3}{8}(1-F_L)(1+\cos^2\theta_\mu)+A_{FB}\cos\theta_\mu\right]\times\varepsilon(\cos\theta_\mu)$$

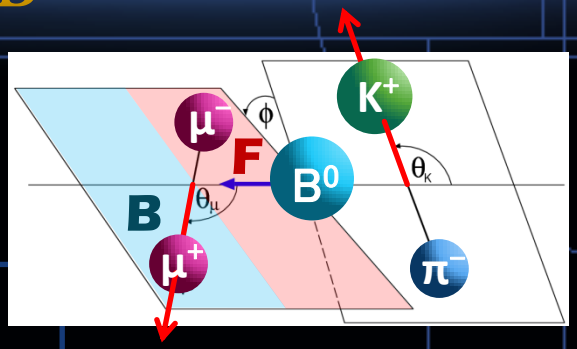




Golden probe: A_{FB}

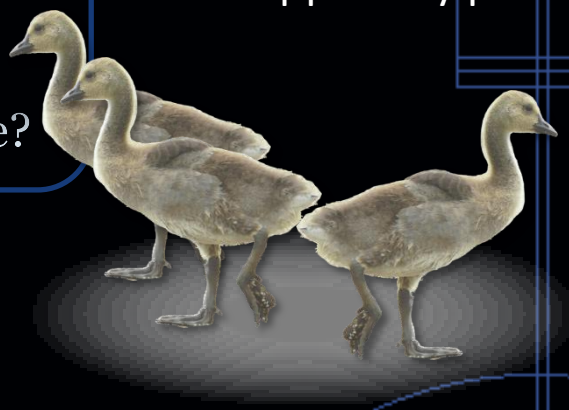
- Forward-Backward asymmetry:

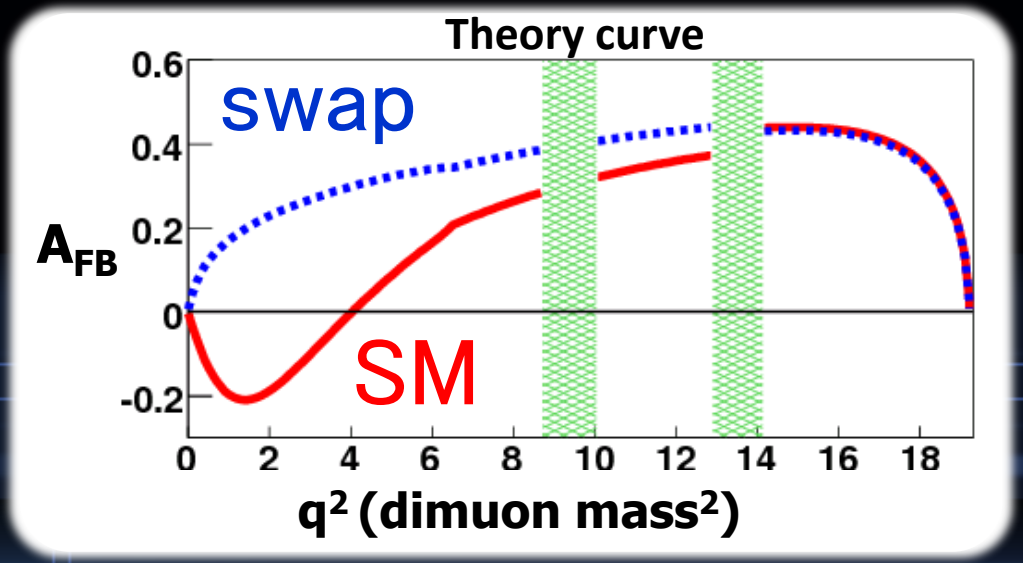
$$A_{FB}(q^2) \equiv \frac{\Gamma(q^2, \cos\theta_\mu > 0) - \Gamma(q^2, \cos\theta_\mu < 0)}{\Gamma(q^2, \cos\theta_\mu > 0) + \Gamma(q^2, \cos\theta_\mu < 0)}$$



$B^0 \rightarrow K^{*0}\mu\mu$ decay plane

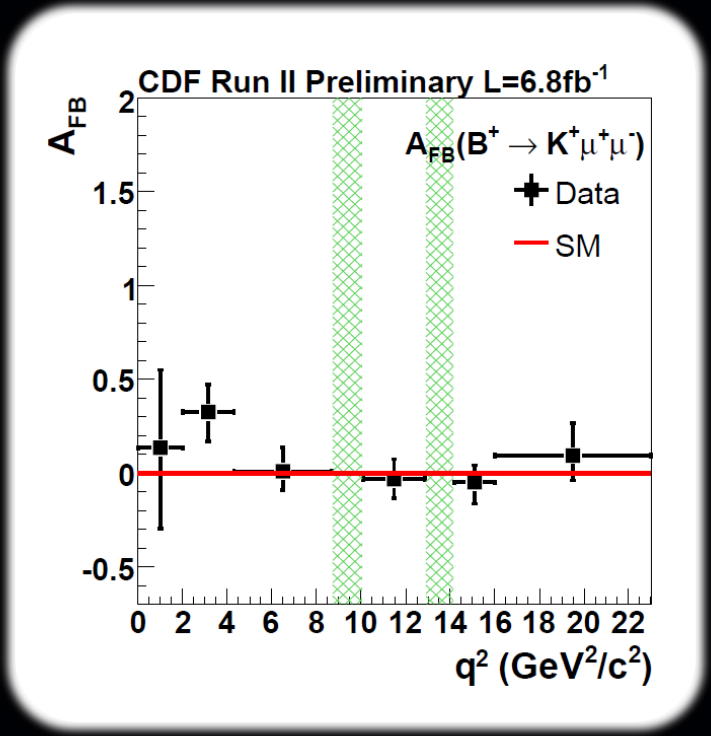
- Most interesting observable of $b \rightarrow s\mu\mu$
  - ✓ NP could swap the sign of A_{FB} at low q^2
  - ✓ Belle reports **2.7σ** deviation from SM
  - ✓ $BR(B \rightarrow X_s ll)$ disfavors the swap solution…puzzle?





Results: $A_{FB}(B^+ \rightarrow K^+\mu\mu)$

A_{FB}

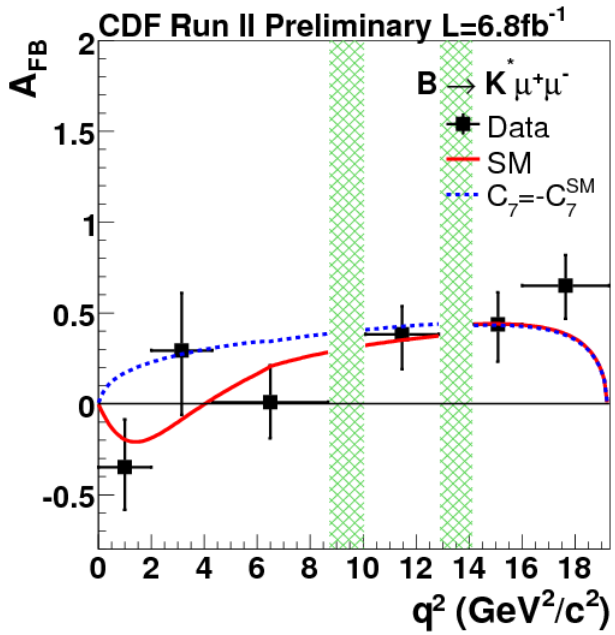


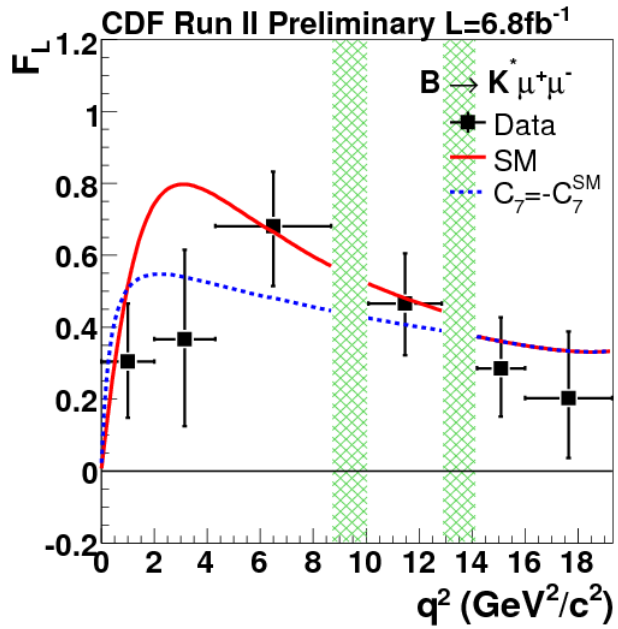
- SM and many BSM models expect quite small A_{FB}
- Some BSM models allow A_{FB}~0.4 at high q^2
- Most precise $A_{FB}(B \rightarrow Kll)$ measurement

Results: A_{FB} and $F_L(B \rightarrow K^* \mu\mu)$

Simultaneous fit with K^{*0} and K^{*+}

A_{FB}

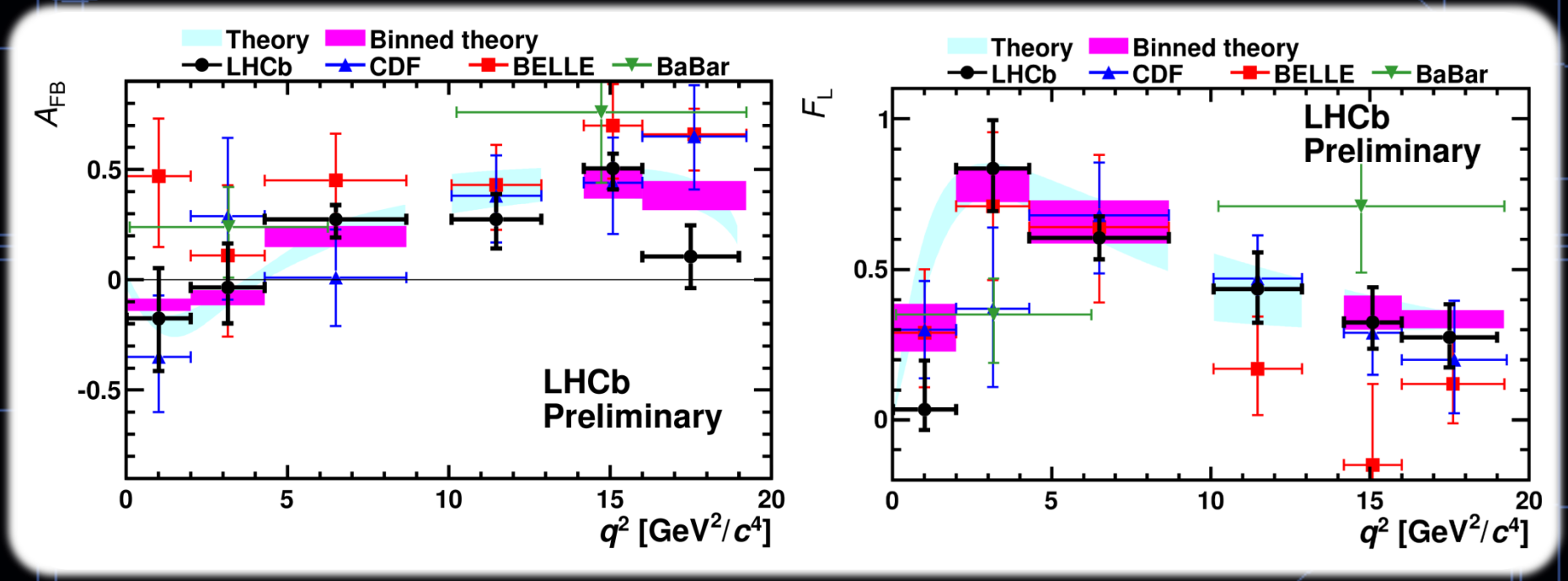




F_L

- Among the most precise A_{FB}/F_L measurements
- Consistent with SM and "swap" BSM model

A_{FB} / F_L comparison



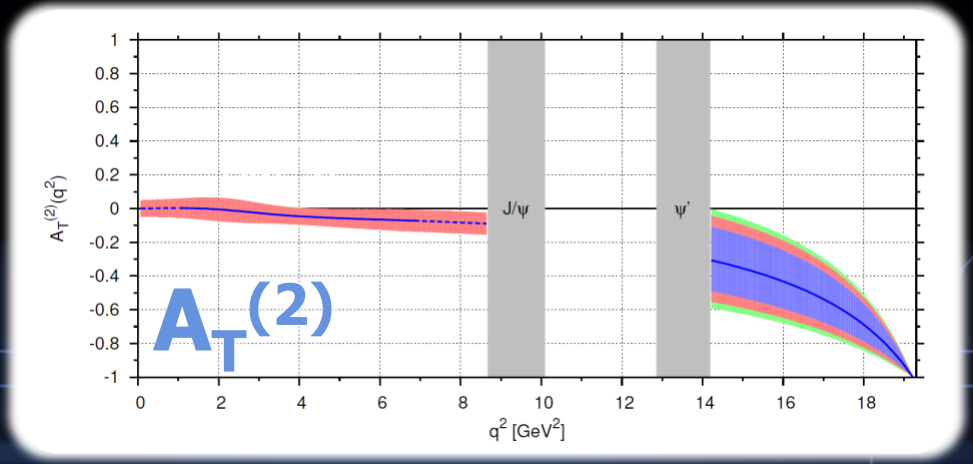
Ulrik Egede, PANIC 2011

http://web.mit.edu/panic11/talks/monday/PARALLEL-2I/3-1640/egede/151-0-Egede.pdf

New probes: $A_T^{(2)}$ and A_{im}

- Observables sensitive to right-handed currents
  - ✓ Small in SM
  - ✓ RH currents can drive asymmetries up to large values ~1
- Provide unique discrimination of NP models
  - ✓ $A_T^{(2)}$: CP conserving RH currents
  - ✓ A_{im} : CP violating RH currents
- No experimental result so far

BSM:~±1

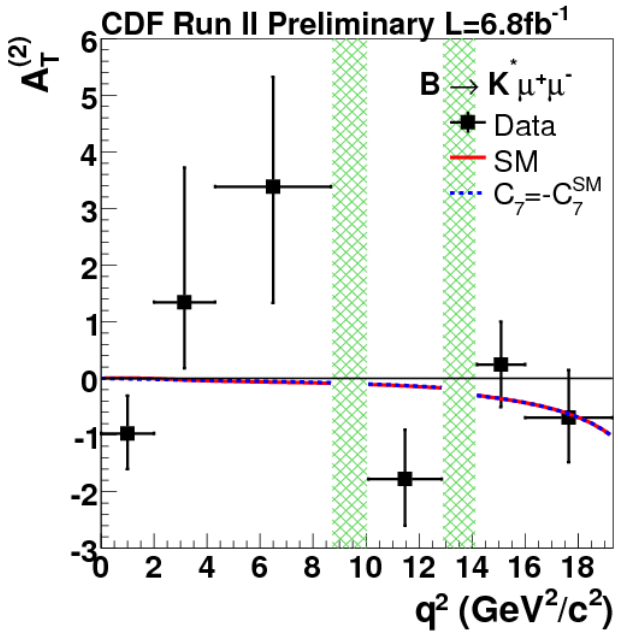


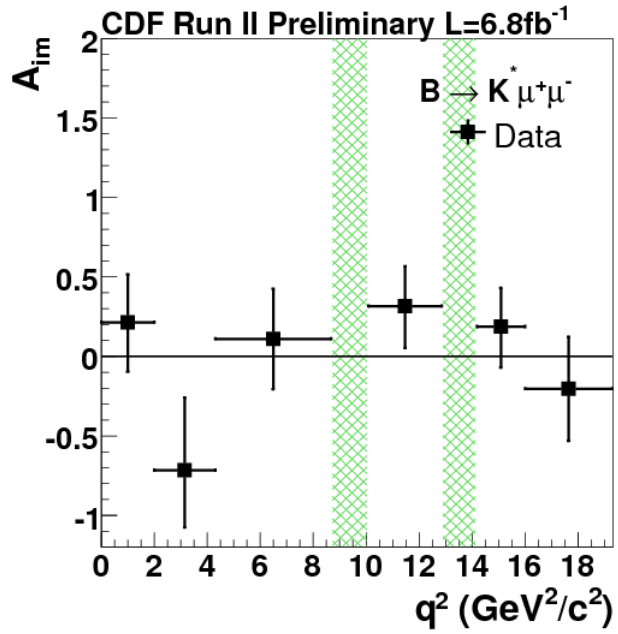
arXiv:1006.5013
C. Bobeth, G. Hiller, D. van Dyk

Results: $A_T^{(2)}$ and $A_{im}(B \rightarrow K^* \mu\mu)$

Simultaneous fit with K^{*0} and K^{*+}

$A_T^{(2)}$





A_{im}

- First measurement of RH currents sensitive $A_T^{(2)}$ and A_{im}
- No significant deviation from SM with current accuracy

Systematic uncertainties

- Dominant source is the uncertainties on the signal fraction in the signal window (e.g. 0.06-0.09 for A_{FB})
- Total uncertainties are in the ranges 0.09-0.16 for A_{FB}, 0.02-0.10 for F_L, 0.2-3.6 for $A_T^{(2)}$, 0.04-0.21 for A_{im}
- Smaller than the statistical uncertainties

Summary

- CDF updated the $b \rightarrow s\mu\mu$ analysis with $6.8 fb^{-1}$
  - ✓ Not only more data, analysis greatly improved
- Results:
  - ✓ First observation of $\Lambda_b \rightarrow \Lambda\mu\mu$
  - ✓ First measurement of dB in $B_s \rightarrow \varphi\mu\mu$ and $\Lambda_b \rightarrow \Lambda\mu\mu$
  - ✓ First measurement of $A_T^{(2)}$ and A_{im}
  - ✓ World's best or comparable precision
    - Total and differential BR in exclusive $b \rightarrow s\mu\mu$ decays
    - A_{FB} and F_L measurement
  - ✓ No discrepancy with SM found yet
- CDF leads exploration of $b \rightarrow s\mu\mu$ physics
- Submitted two letters to Phys.Rev.

arXiv:1107.3753
arXiv:1108.0695

Special Thanks

We are deeply grateful to Wolfgang Altmannshofer, Christoph Bobeth, Danny van Dyk, and Joaquim Matias, who helped us by close communication and many valuable suggestions about the analysis.

Thank you so much!

Backup

References

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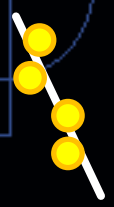
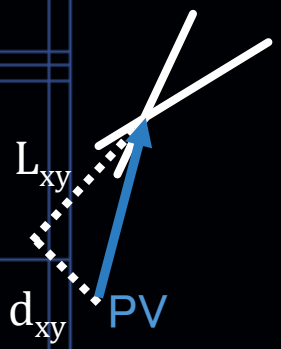
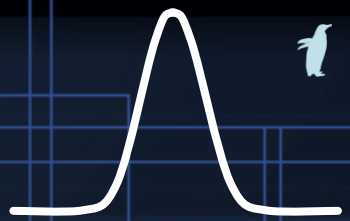
- We draw theoretical curves of the angular observables by EOS. However we stress that these curves are plotted at the other kinematical region than the original authors expected to use.

Loose event selection



- Track quality
  - ✓ Number of hits
- Vertex quality
  - ✓ Vertex probability
- Kinematics
  - ✓ p_T
  - ✓ L_{xy}, d_{xy}
- Particle ID
  - ✓ Kaon ID (dE/dx+TOF)
  - ✓ Muon ID
- Hadron mass
  - ✓ K^{*0}, φ, K_s, K^{*+}, Λ (around PDG mass, 10~20 or 50~100MeV/c²)
  - ✓ J/ψ for control sample

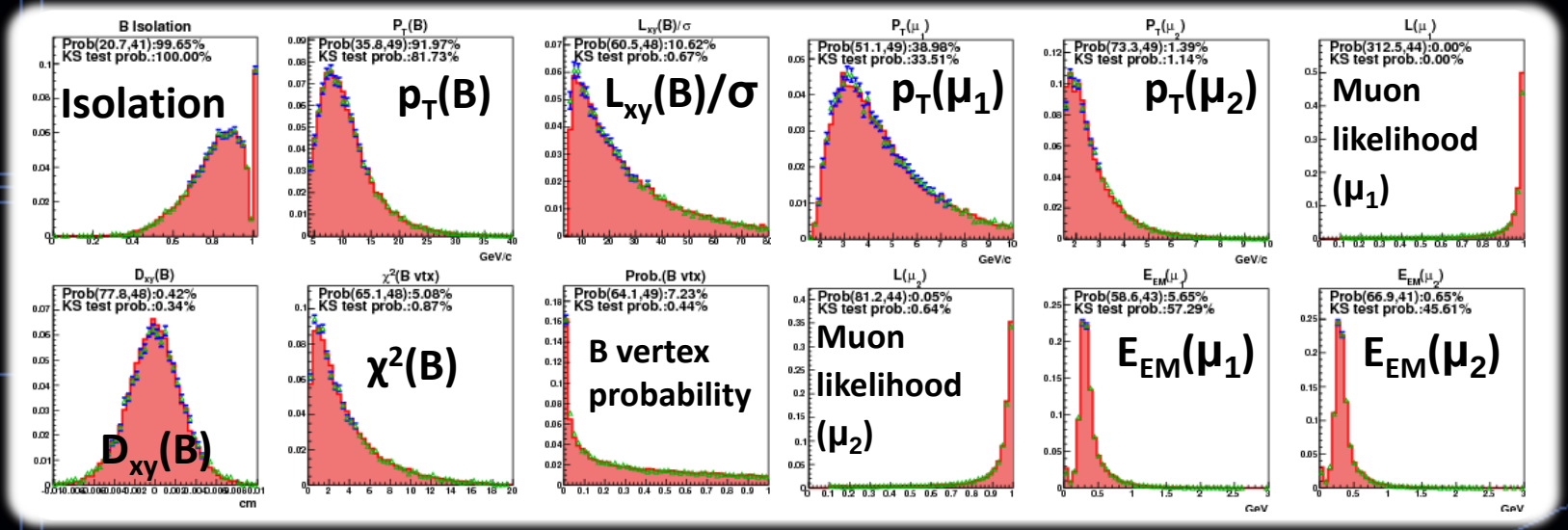


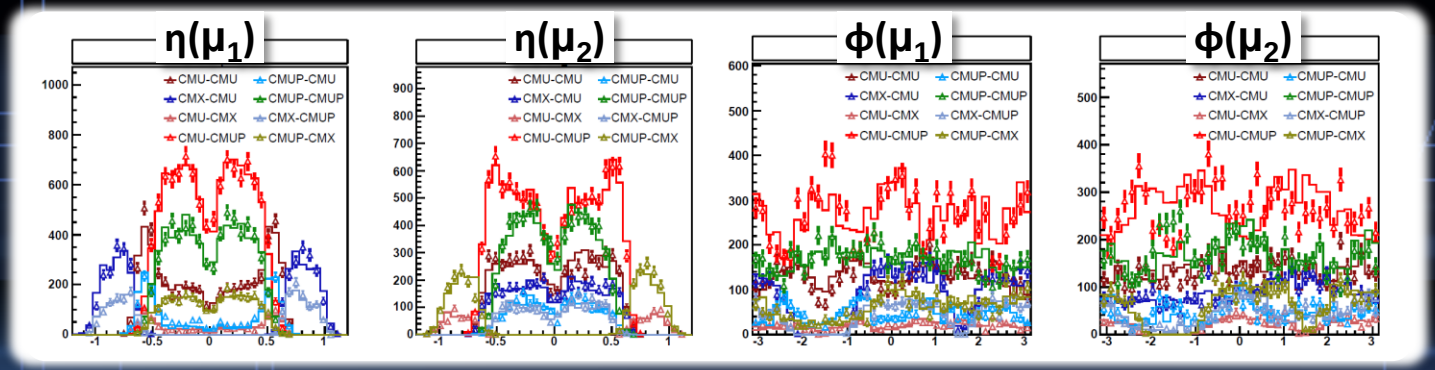


Variable	Cut Value
Si hits (no V^0 daughter)	≥ 3 SVX axial layers hit
COT hits	≥ 5 hits in 2(2) stereo(axial) layers
$p_T(h)$	$\geq 1\,\mathrm{GeV}/c$
$p_T(\mathrm{trk})$	$\geq 0.4\,\mathrm{GeV}/c$
$p_T(\pi$ from $K_S^0)$	$\geq 0.3\,\mathrm{GeV}/c$
$p_T(\pi$ from $K^{*+})$	$\geq 0.3\,\mathrm{GeV}/c$
Vertex prob χ^2	$\geq 1 \times 10^{-3}$
$L_{xy}(B)/\sigma L_{xy}(B)$	≥ 5
$L_{xy}(K_S^0, \Lambda^0)$	≥ 0.5cm
$L_{xy}(K_S^0, \Lambda^0)/\sigma(K_S^0, \Lambda^0)$	≥ 3
$p_T(B)$	$\geq 4\,\mathrm{GeV}/c$
$\lvert d_0(B)\rvert$	$\leq 120\mu$m
$p_T(\mu)$	confirms trigger
$L(\mu)$	≥ 0.1
$CLL(K)$	≥ -4 for K^{*0},ϕ

MC tuning

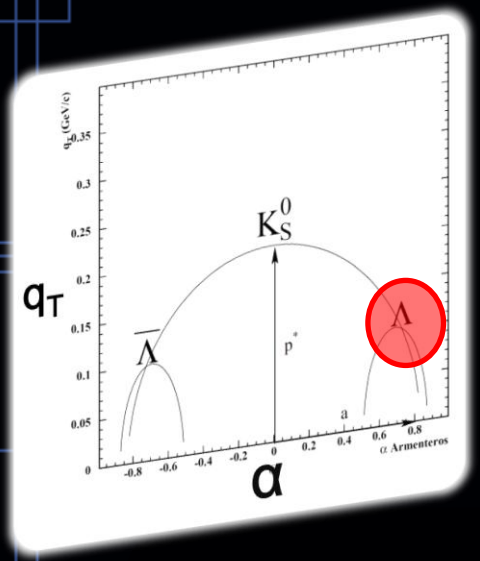
- Reweigh MC to match data
  - $p_T(H_b)$, isolation, E_{EM}, E_{HAD}… ←Use each control sample
  - Muon composition (trigger groups)





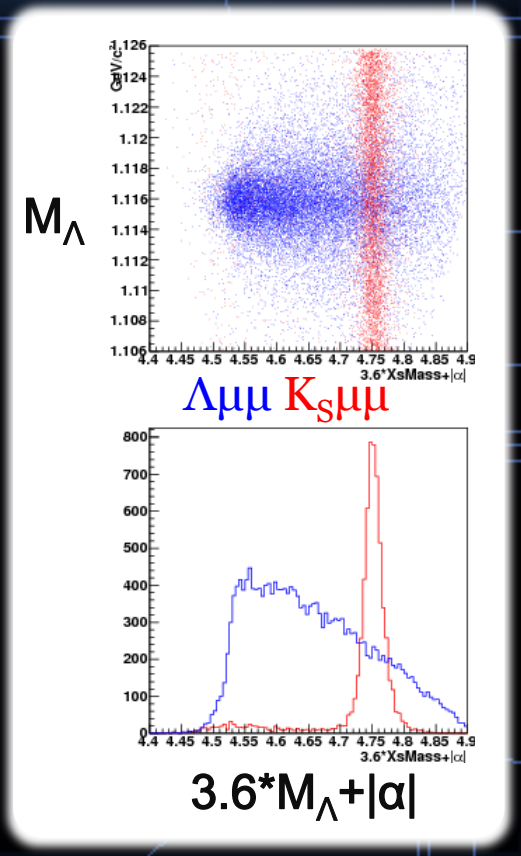
b→sμμ cross-feed (2)

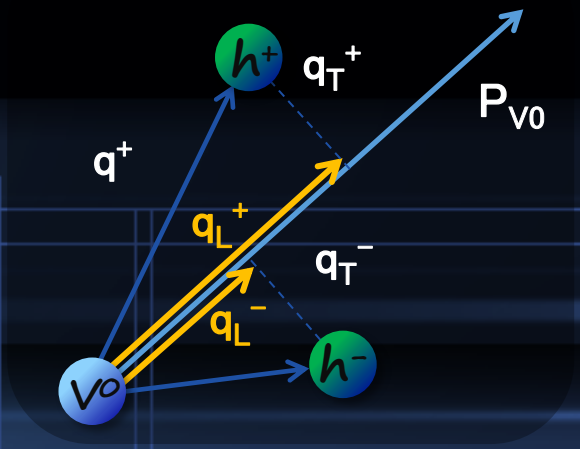
- To eliminate the contaminations, we adopt Armenteros-Podolanski parameterization:



$$\alpha \equiv \frac{q_L^+ - q_L^-}{q_L^+ + q_L^-}$$

represents momentum imbalance of daughter particles





K_Sμμ
→removes 90% of Λ (signal loses 7%)
Λμμ
→removes 76% of K_S (signal loses 11%)

Neural Network: optimal cut

- Find optimal NN cut to maximize the significance

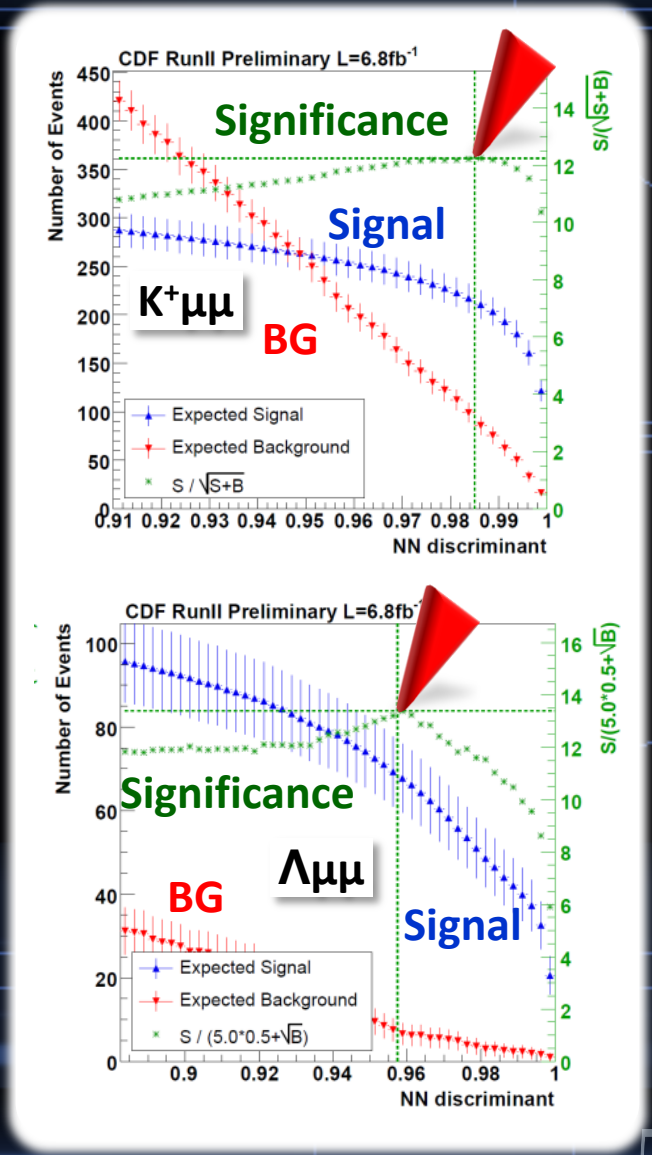
$$N_s/\sqrt{N_s + N_b}$$

- $\Lambda_b \rightarrow \Lambda\mu\mu$ is optimized by

$$N_s/(5/2 + \sqrt{N_b})$$

G. Punzi, arXiv:physics/0308063 (2003)

since this is the first observation channel



BR: systematics

- Dominant sources:
  - ✓ MC reweight (0.5-4.0%)
  - ✓ Trigger turn-on (0.8-7.2%)

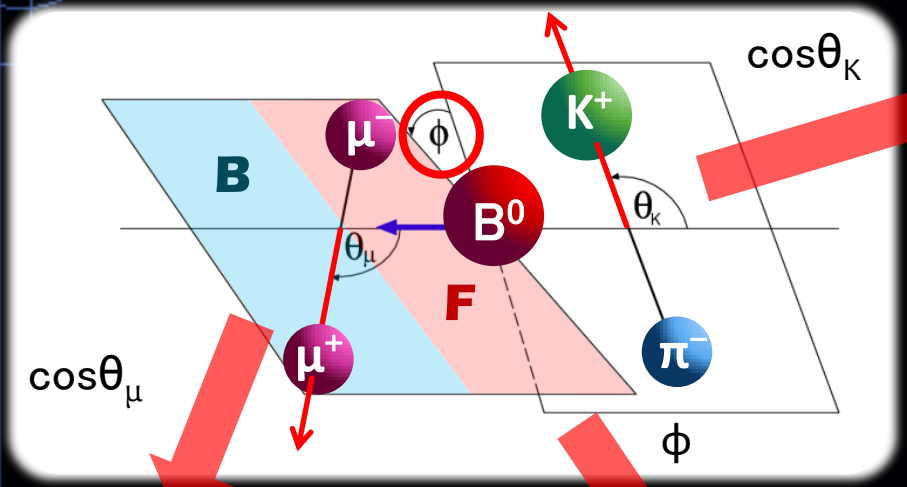
Source	$K^+\mu^+\mu^-$	$K^{*0}\mu^+\mu^-$	$\phi\mu^+\mu^-$	$K^0_S\mu^+\mu^-$	$K^{*+}\mu^+\mu^-$	$\Lambda\mu^+\mu^-$
Theory model	0.9	0.7	1.7	0.5	0.7	3.4
MC reweight	2.8	1.5	1.8	3.5	0.5	4.0
Trigger turn-on	0.8	2.3	4.4	2.9	4.5	7.2
Particle ID	-	0.4	2.0	-	-	-
Low p_T hadrons	0.2	0.2	0.2	0.2	0.2	0.2
B_s lifetime	-	-	0.2	-	-	-
Polarization	-	0.5	0.1	-	0.5	6.6
Control mode stat.	0.5	0.9	1.7	1.2	2.0	3.3
MC stat.	0.2	0.4	0.3	0.1	0.5	0.3
NN cut	0.1	0.2	0.3	0.4	0.4	1.8
Efficiency total	3.1	3.1	5.8	4.7	5.1	11.7

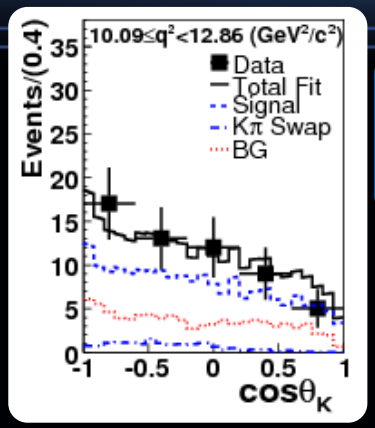
Source	$K^+\mu^+\mu^-$	$K^{*0}\mu^+\mu^-$	$\phi\mu^+\mu^-$	$K^0_S\mu^+\mu^-$	$K^{*+}\mu^+\mu^-$	$\Lambda\mu^+\mu^-$
Efficiency	3.1	3.1	5.8	4.7	5.1	11.7
BR($J/\psi \to \mu^+\mu^-$)	1.0	1.0	1.0	1.0	1.0	1.0
Signal PDF	0.2	0.3	0.2	0.4	0.3	0.4
Background PDF	2.3	0.9	2.6	1.3	2.2	1.0
Peaking BG	0.9	1.6	1.1	0.6	0.9	0.1
BR($H_b \to J/\psi h$)	3.4	4.5	30.8	3.7	5.6	29.7
Total	5.3	5.8	31.5	6.2	8.0	32.0

- Absolute BR: large uncertainty from the control channel

Angular distribution

- One can extract various information from the decay angular distribution





K* polarization

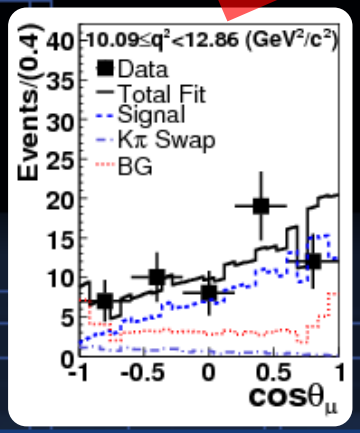
F_L

$$\frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

NEW

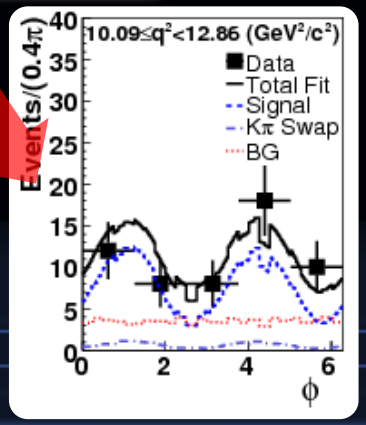
$A_T^{(2)}$ Transverse polarization asymmetry

A_{im} T-odd CP asymmetry



FB asymmetry

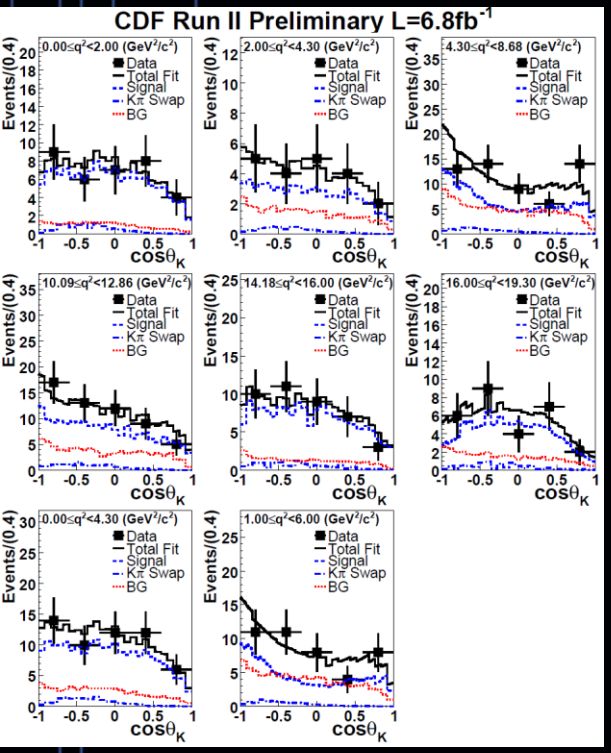
A_{FB}

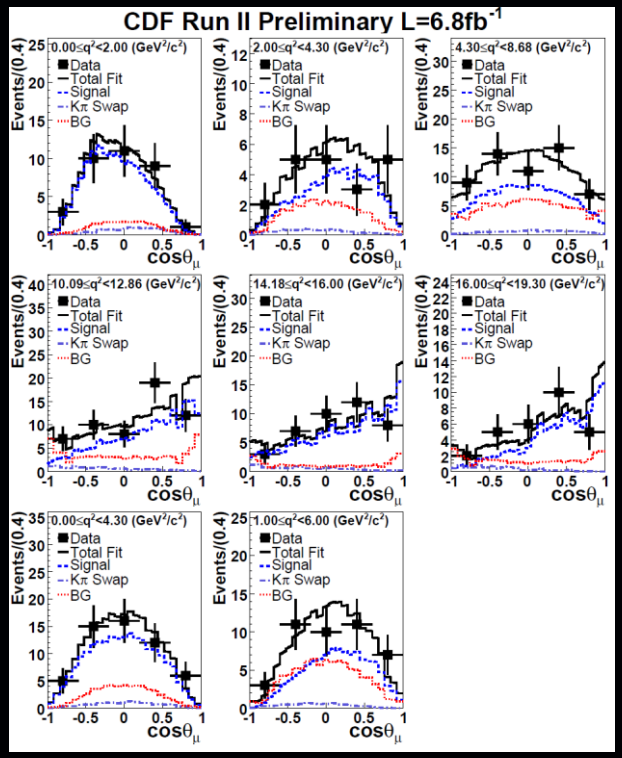


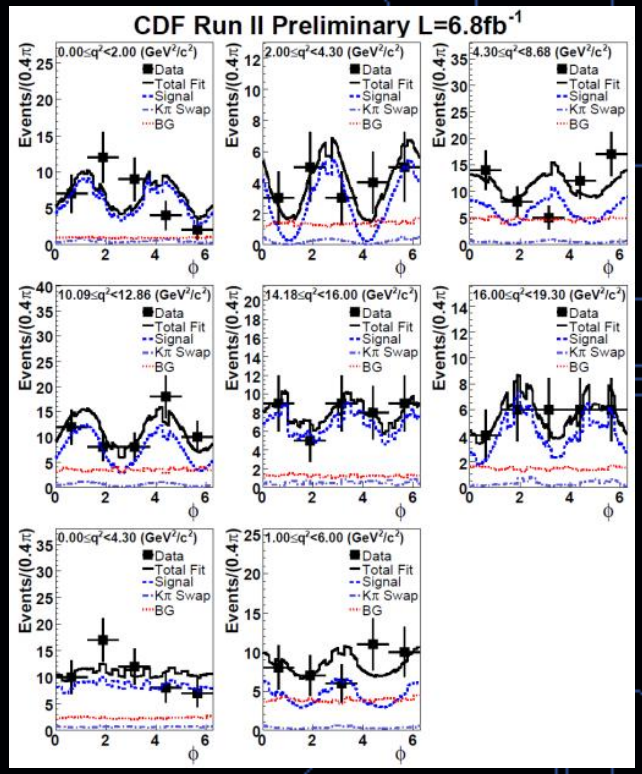
$$\frac{3}{4}F_L(1-\cos^2\theta_\mu) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\mu) + A_{FB}\cos\theta_\mu$$

$$\frac{1}{2\pi}\left[1+\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{im}\sin 2\phi\right]$$

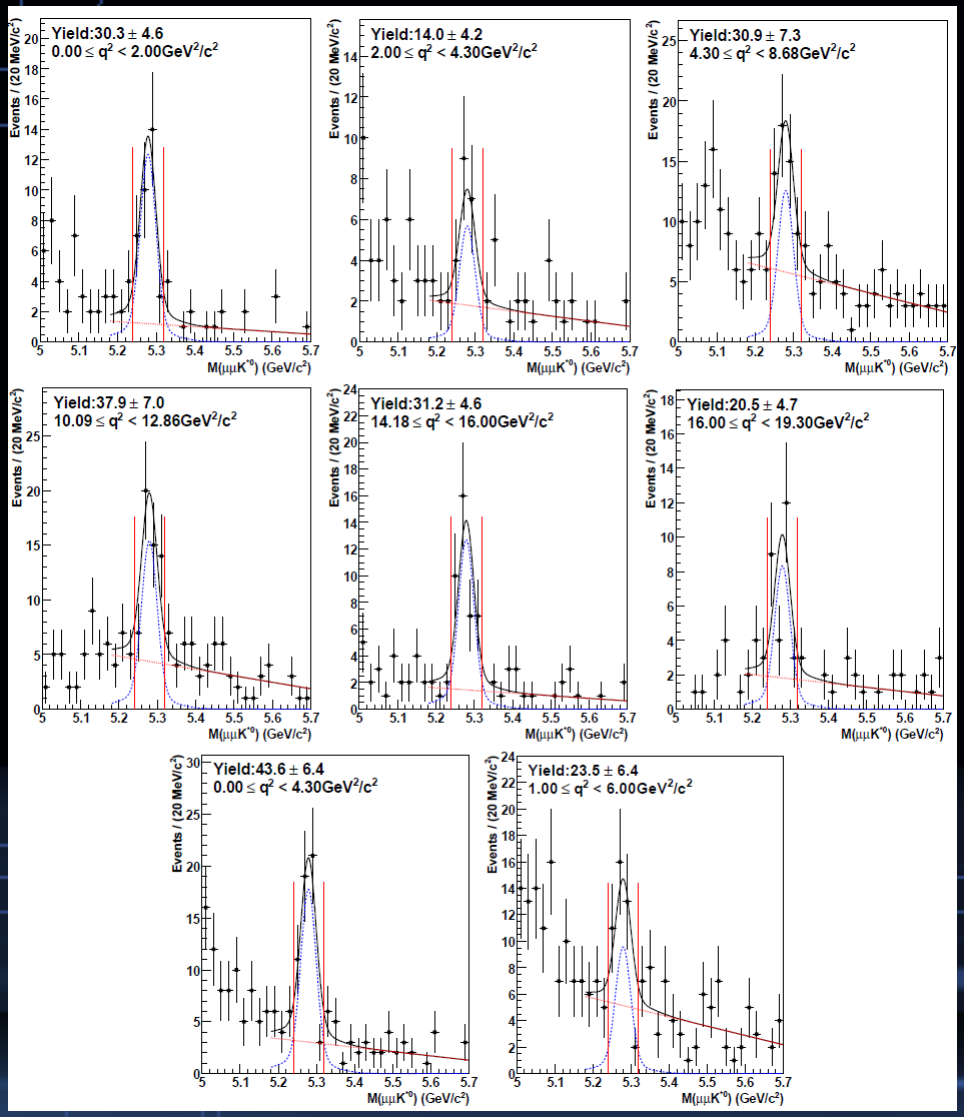
Angular fit results







$K^{*0}\mu\mu$ q^2 bin yield



q^2 (GeV$^2/c^2$)	$N_{\rm sig}$	$N_{\rm pkg}$	$N_{\rm BG}$
0.00-2.00	30.34 ± 4.59	0.39	4.81
2.00-4.30	13.97 ± 4.19	0.18	7.22
4.30-8.68	30.89 ± 7.25	0.39	23.20
10.09-12.86	37.89 ± 6.97	0.48	17.45
14.18-16.00	31.23 ± 4.65	0.40	5.79
16.00-19.30	20.47 ± 4.73	0.26	7.29
0.00-4.30	43.63 ± 6.38	0.56	12.18
1.00-6.00	23.52 ± 6.42	0.30	20.57

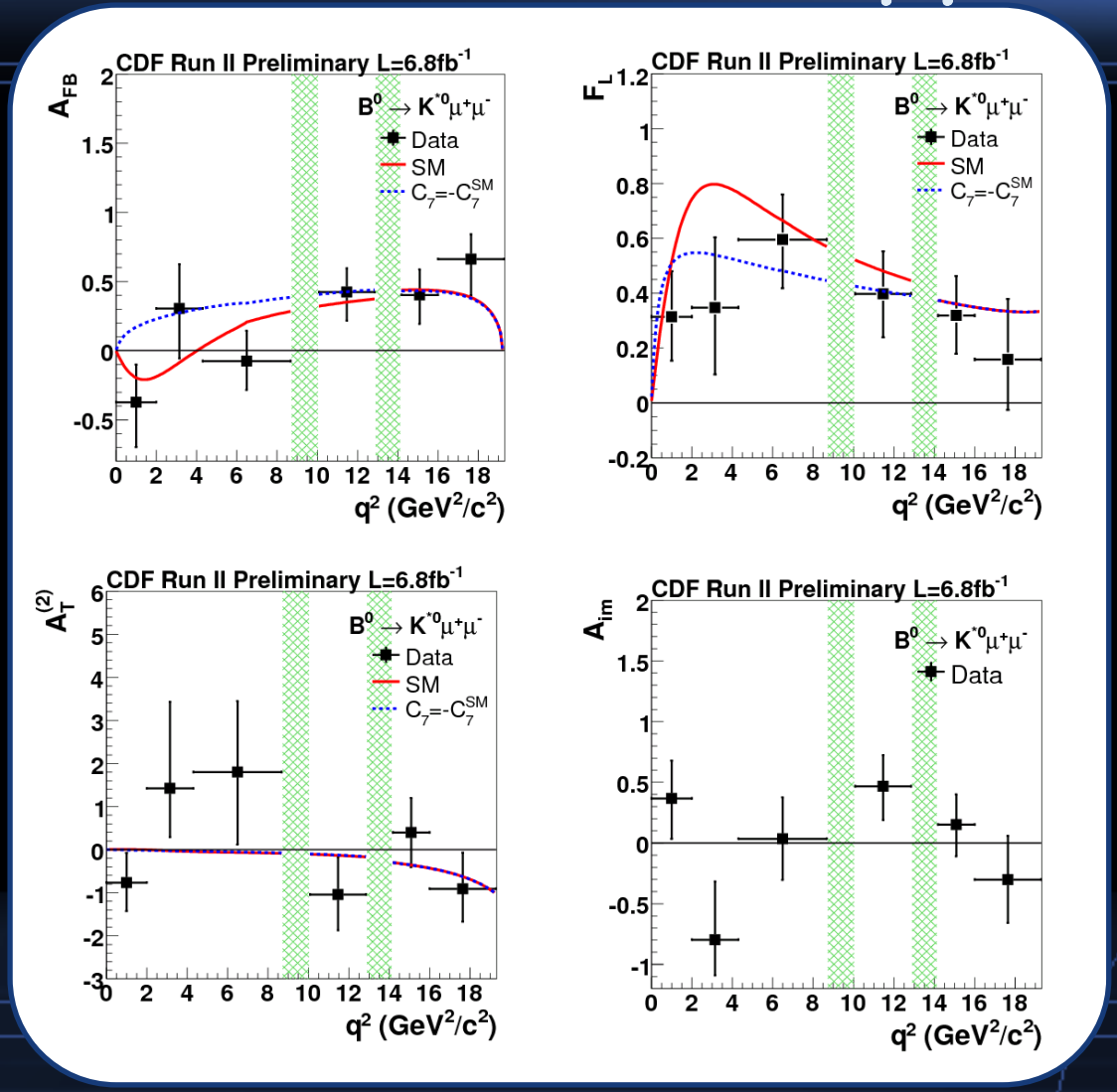
Results: $B^0 \rightarrow K^{*0}\mu\mu$

A_{FB}

F_L

$A_T^{(2)}$

A_{im}



- Same final state as 4.4fb^{-1} analysis
- Consistent with combined fit