Belle II

Recent Results and Prospects

Planck 2021
30.06.2021

Bundesministerium
für Bildung
und Forschung

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ORIGINS
Excellence Cluster

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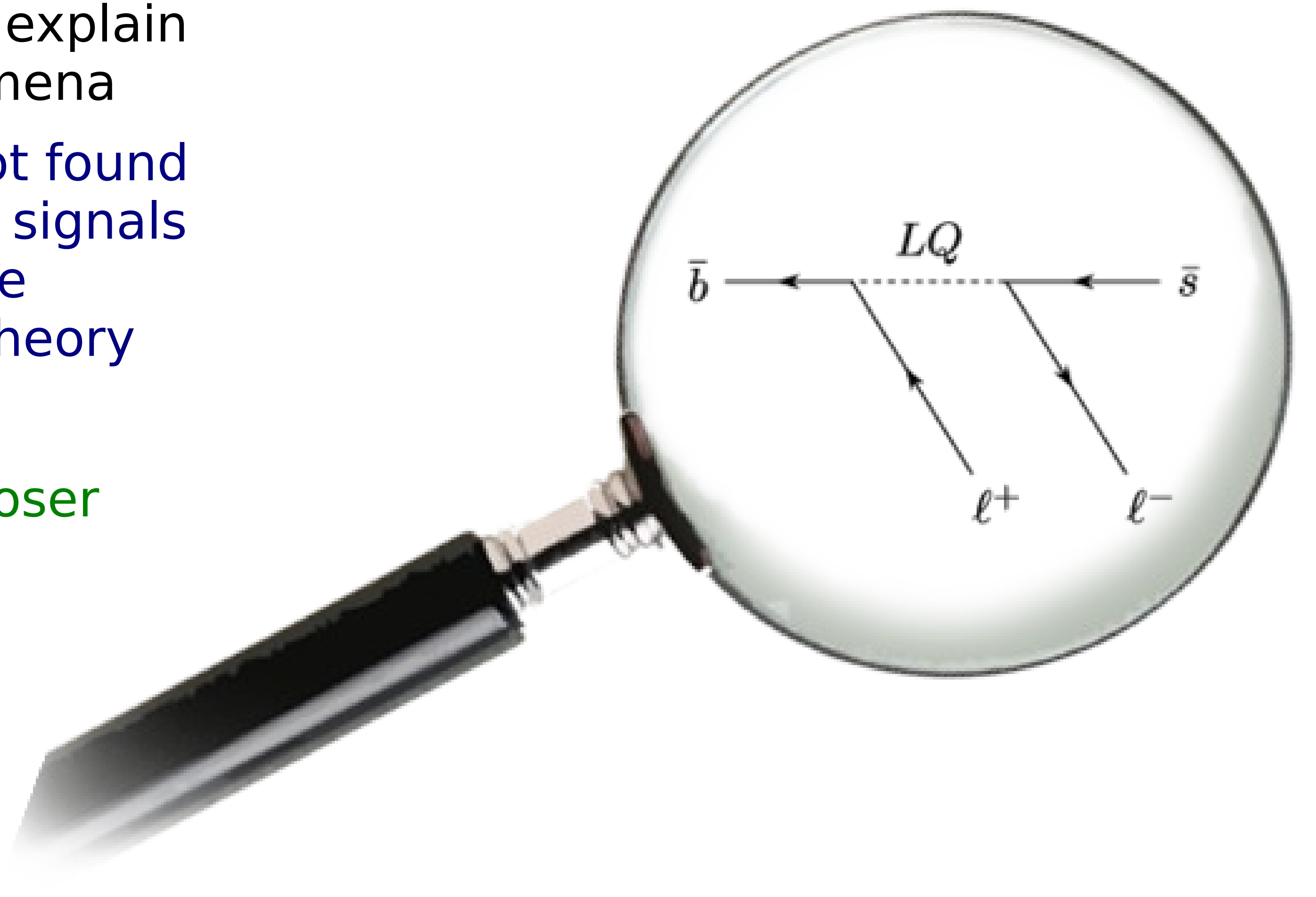
† June 28, 2021

Search for Tiny Effects

- The standard model of particle physics fails to explain several phenomena
- ✗ But we have not found any convincing signals that point to the more general theory

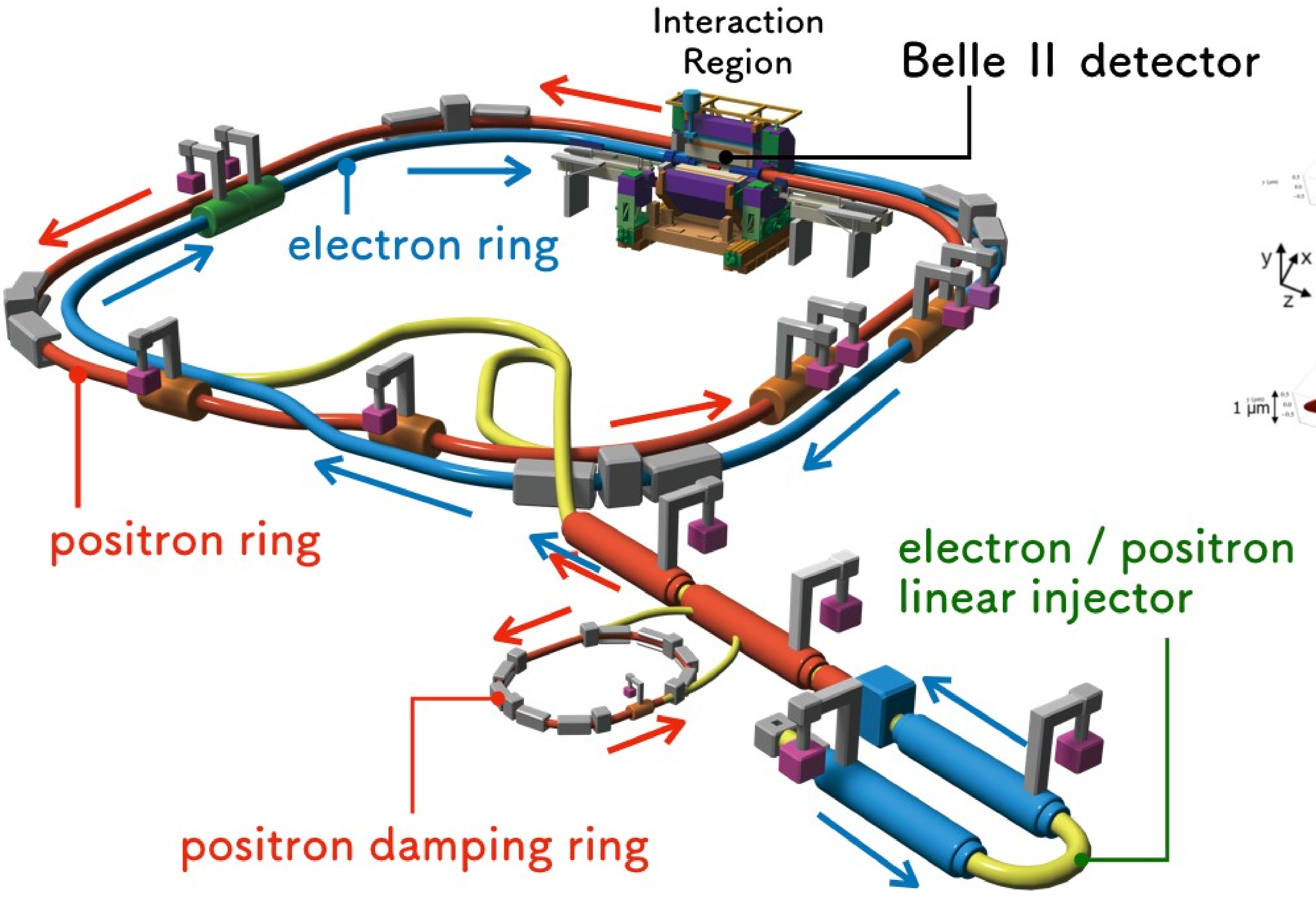
- ➔ Have to look closer
- ➔ Be smarter
- ➔ Or both



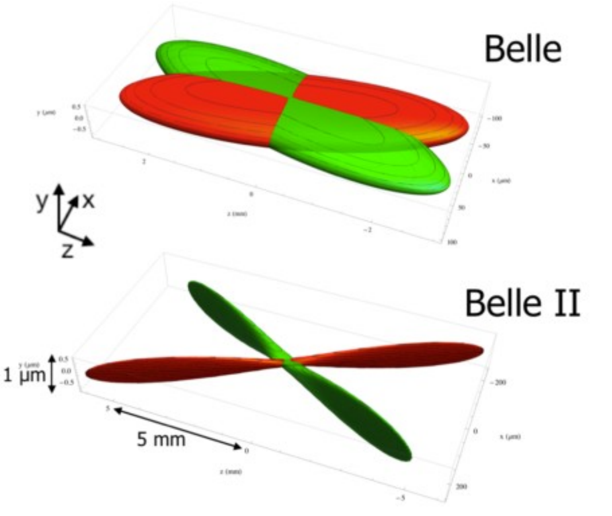
Outline

- Experimental conditions
- Recent results
  - Semileptonic decays
  - $b \rightarrow sll$ transitions
  - Dark matter searches
  - Matter antimatter asymmetries
- Outlook and conclusions

SuperKEKB: e^+e^- @ $\sqrt{s} \approx 10.6$ GeV



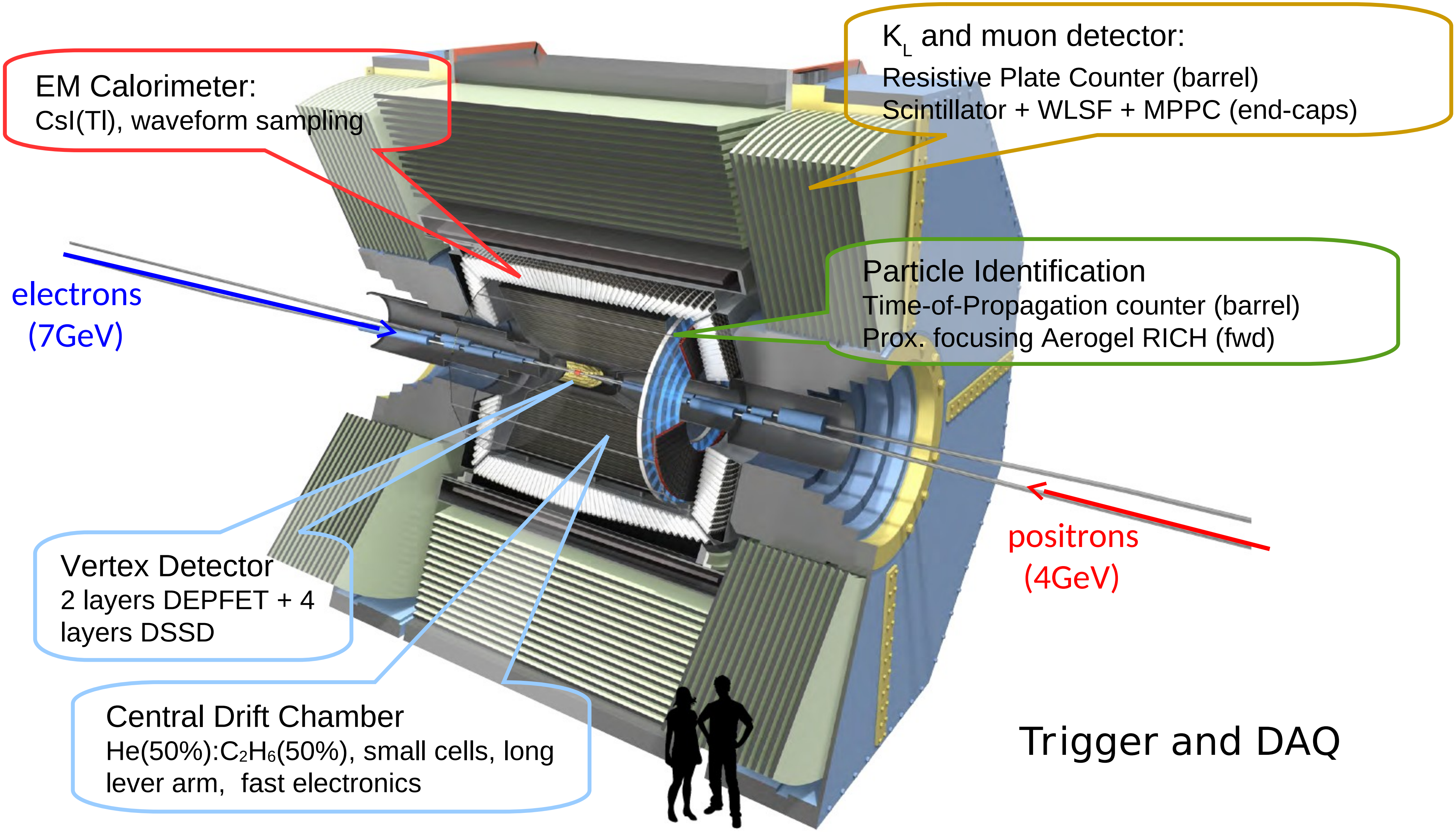
Nano beams:



- Goal: 50 ab^{-1} (50x Belle)
- Challenge: machine induced backgrounds

Belle II Detector

TDR: arXiv:1011.0352



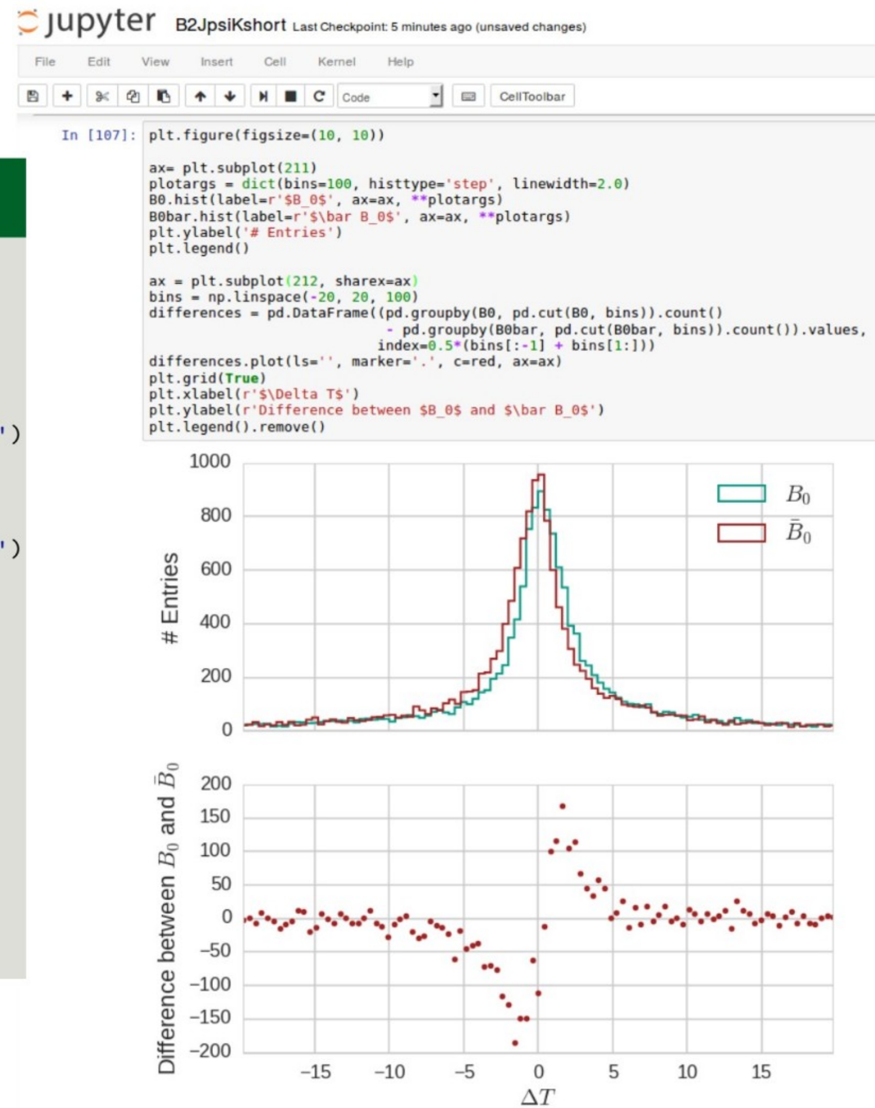
Trigger and DAQ

Software and Computing

- >1M lines of offline software

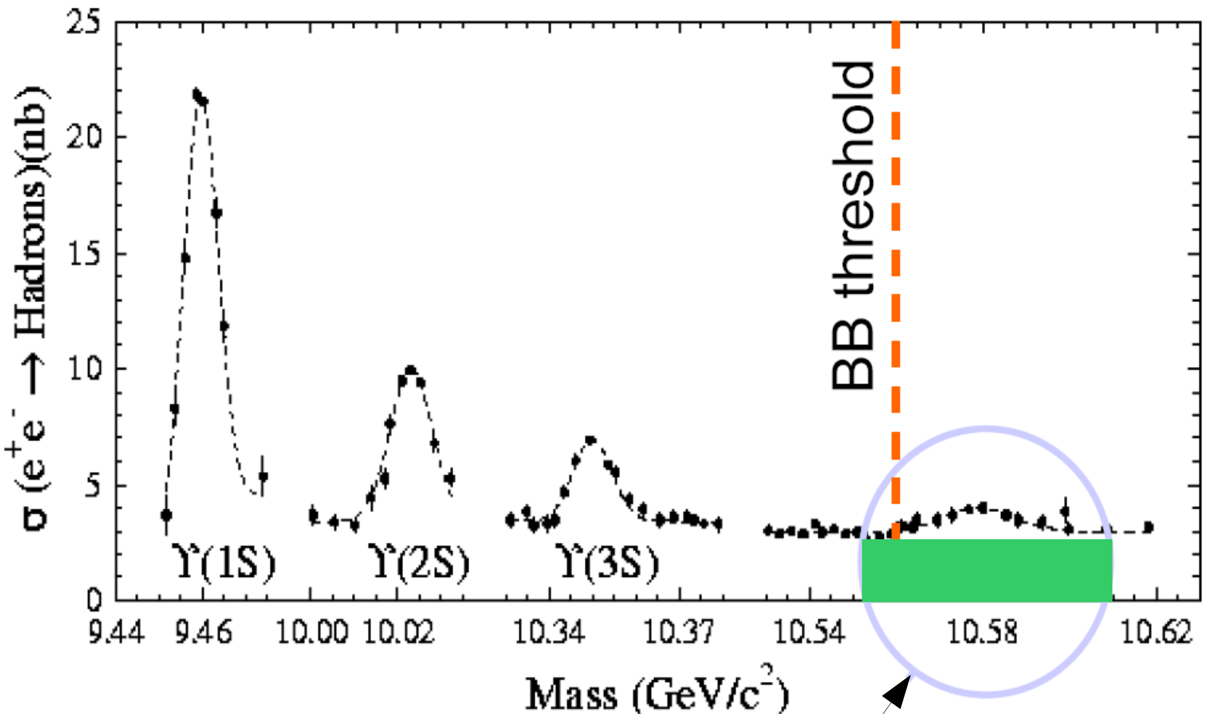
Example: reconstruct $B^0 \to J/\psi(\to\mu^+\mu^-)\ K^0_S(\to\pi^+\pi^-)$

```
# create Ks -> pi+ pi- list from V0
# keep only candidates with 0.4 < M(pipi) < 0.6 GeV
fillParticleList('K_S0:pipi', '0.4 < M < 0.6')

# reconstruct J/psi -> mu+ mu- decay
# keep only candidates with 3.0 < M(mumu) < 3.2 GeV
reconstructDecay('J/psi:mumu -> mu+:loose mu-:loose', '3.0 < M < 3.2')

# reconstruct B0 -> J/psi Ks decay
# keep only candidates with 5.2 < M(J/PsiKs) < 5.4 GeV
reconstructDecay('B0:jspiks -> J/psi:mumu K_S0:pipi', '5.2 < M < 5.4')

# perform B0 kinematic vertex fit using only the mu+ mu-
# keep candidates only passing C.L. value of the fit > 0.0 (no cut)
vertexRave('B0:jspiks', 0.0, 'B0 -> [J/psi -> ^mu+ ^mu-] K_S0')

# build the rest of the event associated to the B0
buildRestOfEvent('B0:jspiks')

# perform MC matching (MC truth asociation). Always before TagV
matchMCTruth('B0:jspiks')

# calculate the Tag Vertex and Delta t (in ps)
# breco: type of MC association.
TagV('B0:jspiks', 'breco')
```



➔ Soon to be released as open source

Event Types

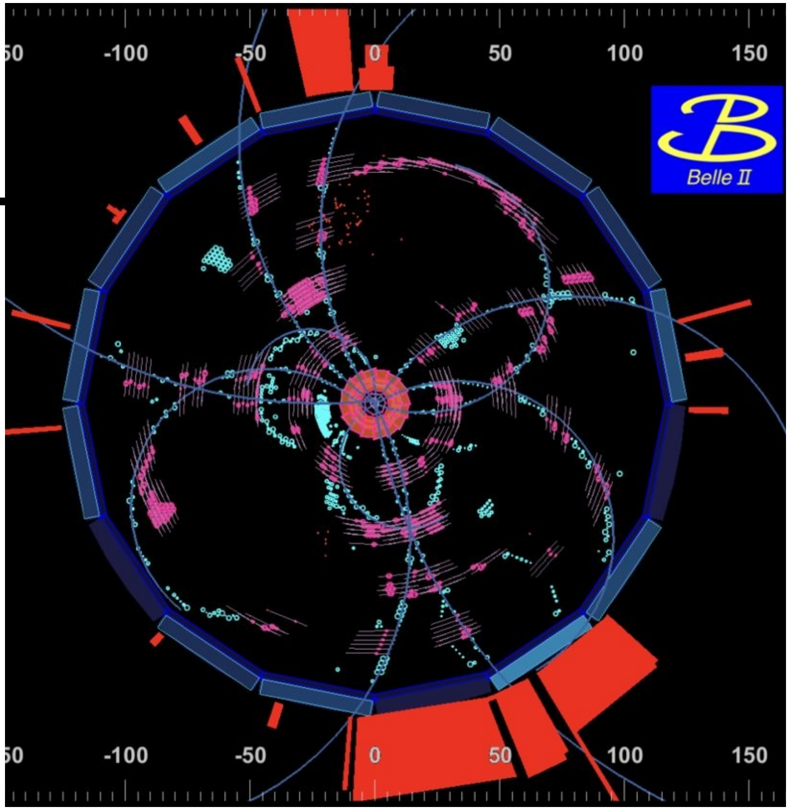


$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$

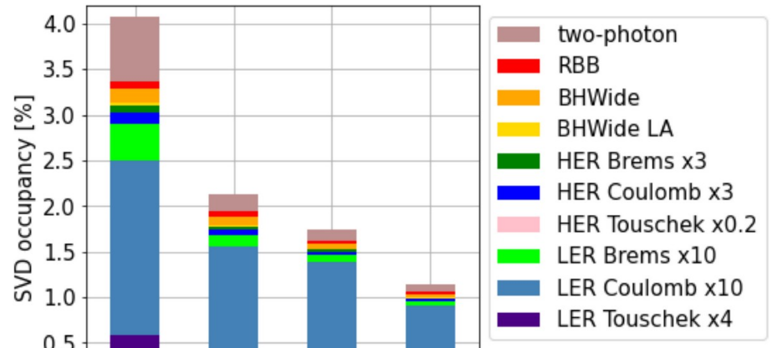
$\rightarrow q\overline{q}$ (continuum bkg.)

$\rightarrow \tau^+\tau^-$

$\rightarrow \mu^+\mu^-(\gamma)$, $e^+e^-(\gamma)$, ...



Machine induced backgrounds in SVD

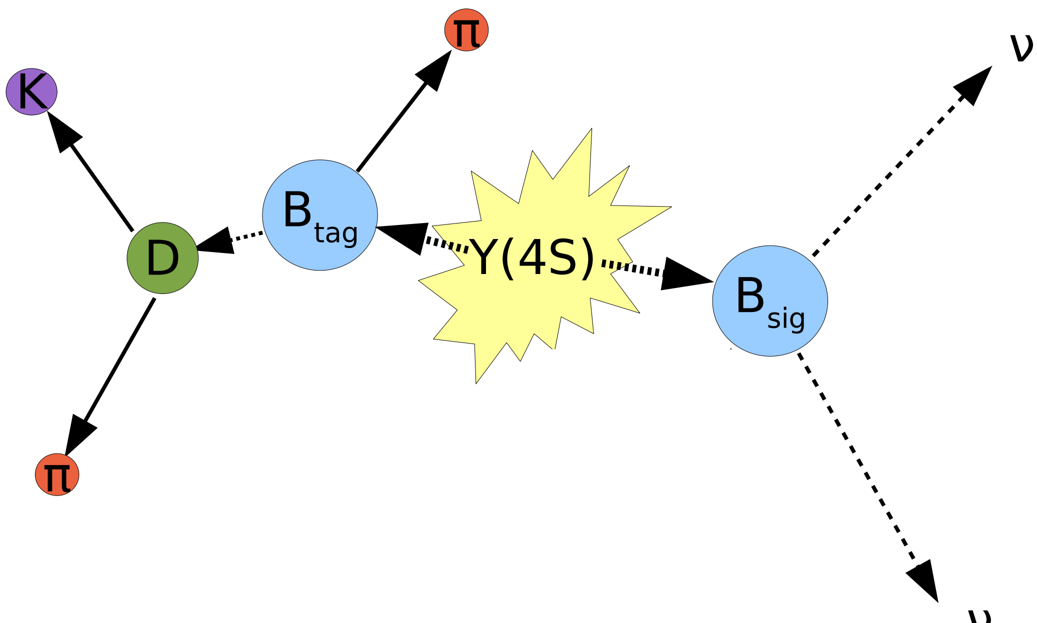


Extrapolation to design lumi

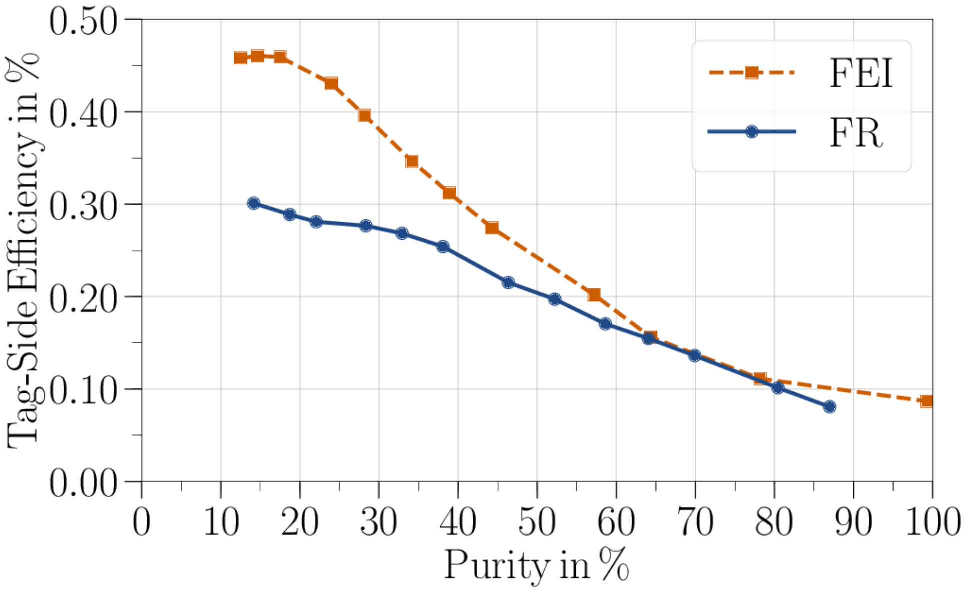
Complementarity with LHCb

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1}) goal	~50 (phase I)	~50,000
Background level	High	Low
Typical efficiency	Low	High
π^0, K_S efficiency	Low	High
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	30%

Reconstruction of Undetected Particles



Comput. Softw. Big Sci. 3 (2019) 1, 6



- Full reconstruction of B_{tag} decay in O(10.000) different decay chains with a sequence of BDTs → Full Event Interpretation (FEI)

➔ All remaining particles in the event belong to B_{sig} (→ hermeticity)

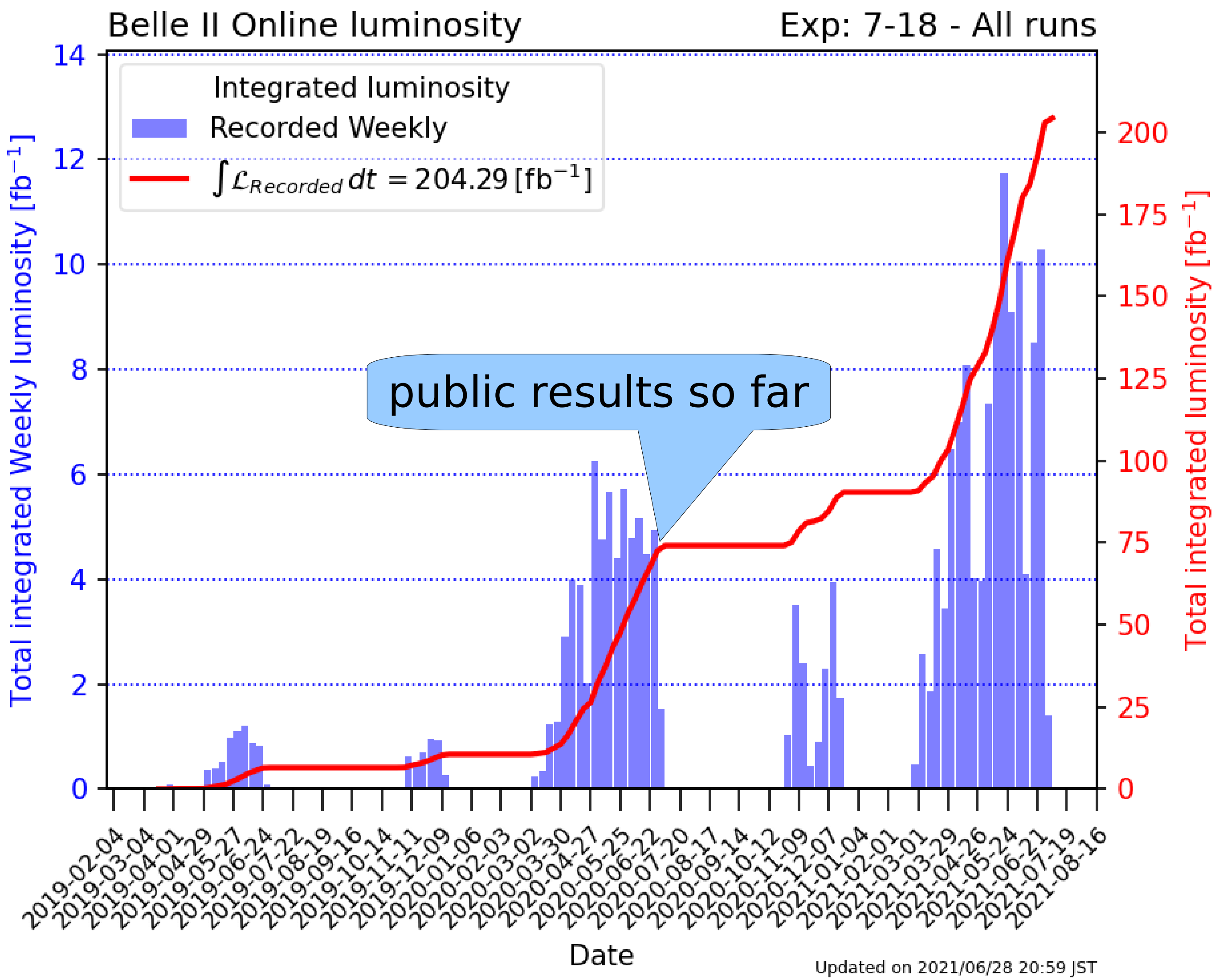
➔ 4-momentum of B_{sig} → 4-momentum of undetected particles

Data Taking Status

- Commissioning run in 2018
- Physics run started 2019
  - Collected 0.2 ab^{-1} so far

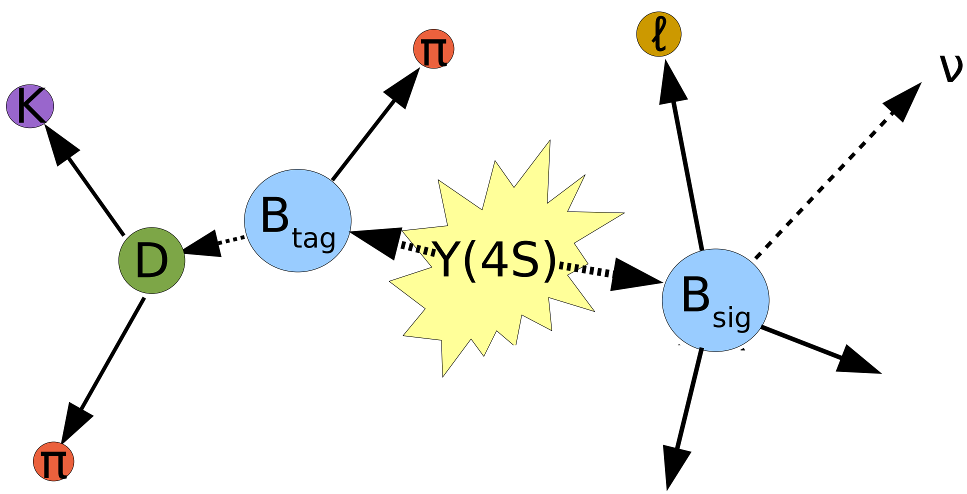
Records:

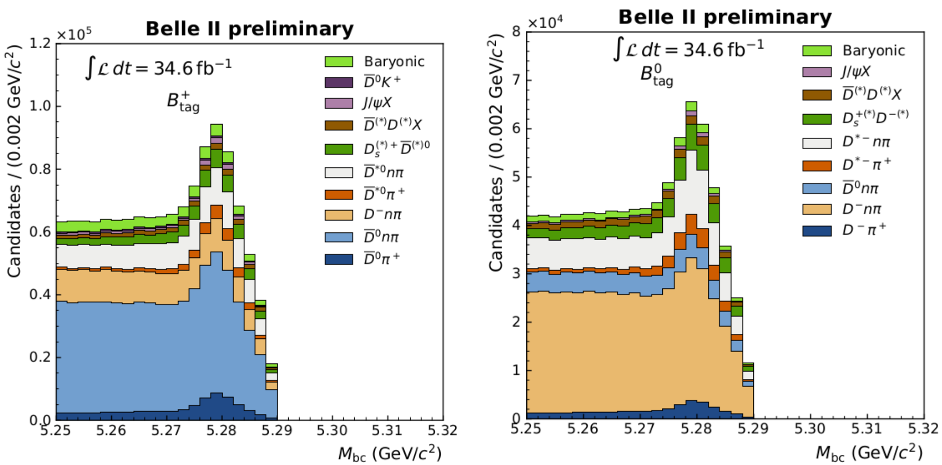
- $L = 3.1 \times 10^{34}\ cm^{-2}s^{-1}$ @ June 22, 2021
- $\int L = 12\ fb^{-1}$ / week (Belle: 8, BaBar: 5)

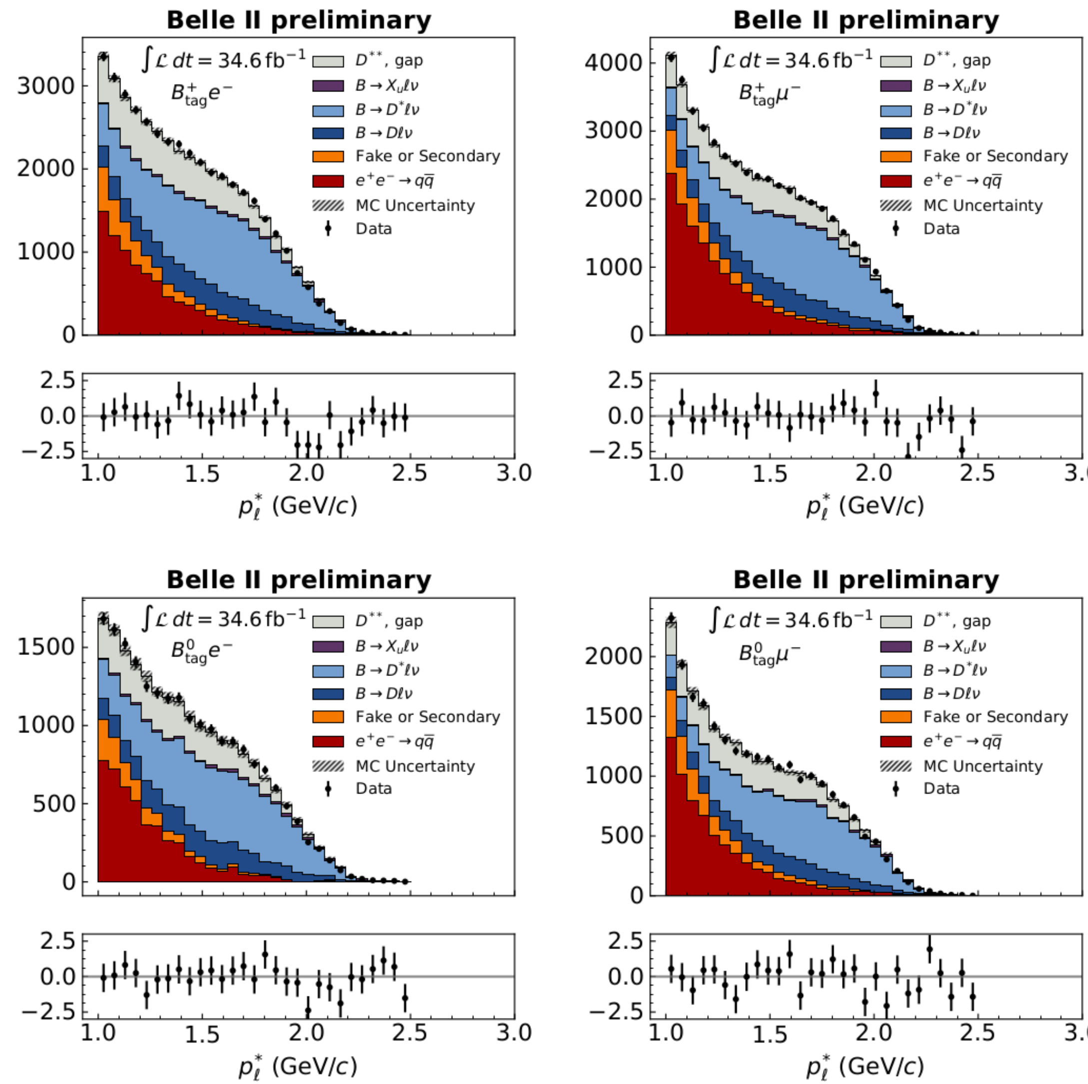


FEI Calibration

arXiv:2008.06096
BELLE2-CONF-PH-2020-005

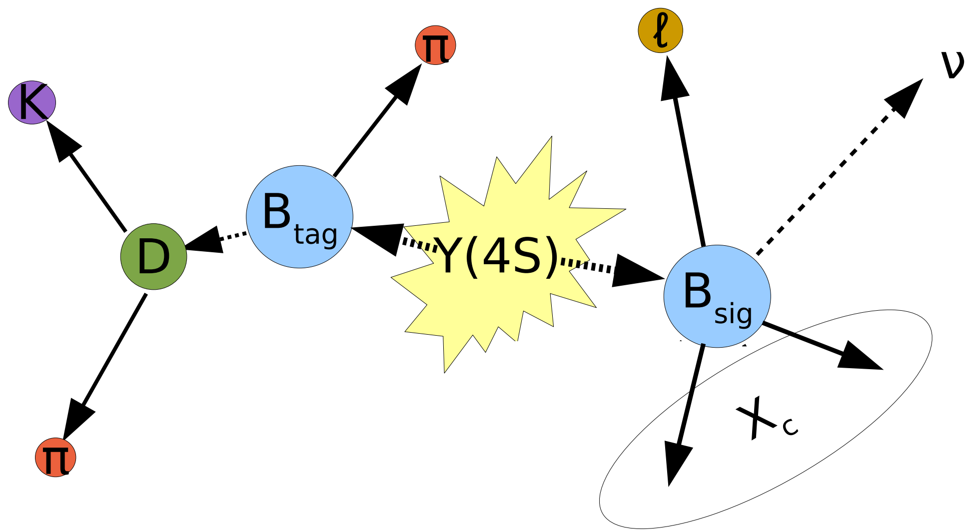


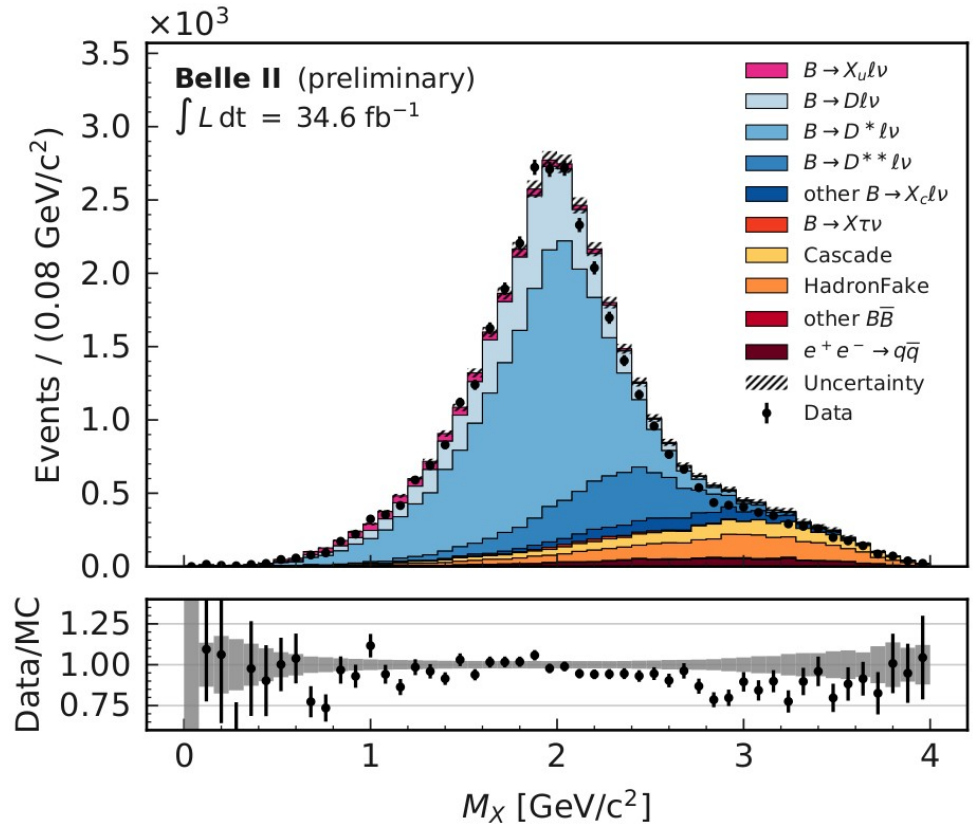


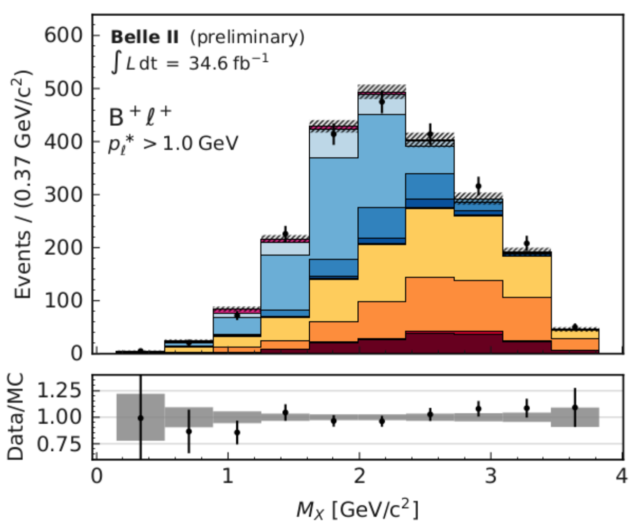


Hadronic Moments in $B \to X_c \ell \nu$

arXiv:2009.04493
BELLE2-CONF-PH-2020-011



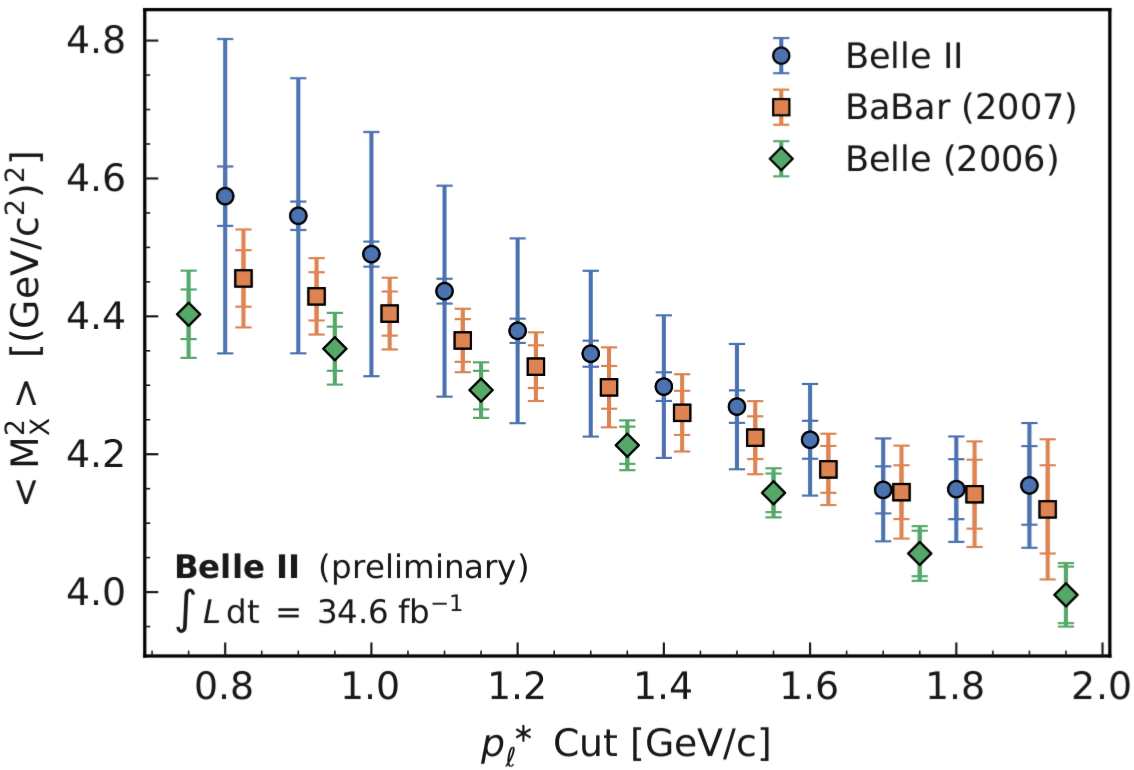




- Background constrained with same charge combinations
- Calibration factors from MC

Hadronic Moments in $B \to X_c \ell \nu$

arXiv:2009.04493
BELLE2-CONF-PH-2020-011



p_ℓ^* Cut in GeV/c	0.8	0.9	1.0	1.1	1.2	1.3
$\langle M_X^2 \rangle$ in (GeV/c1)^2	4.5743	4.5459	4.4902	4.4365	4.3790	4.3458
Stat. error (data)	0.0146	0.0151	0.0157	0.0165	0.0175	0.0189
Stat. error (signal prob.)	0.0405	0.0140	0.0092	0.0071	0.0017	0.0003
Stat. error (total)	0.0431	0.0206	0.0182	0.0180	0.0176	0.0189
Calib. function error	0.0473	0.0447	0.0427	0.0410	0.0393	0.0380
FEI eff..	0.0340	0.0201	0.0118	0.0060	0.0014	0.0005
PID eff.	0.0476	0.0210	0.0164	0.0109	0.0060	0.0046
$B \to X_u \ell \nu_\ell$ BF	0.0168	0.0157	0.0151	0.0150	0.0153	0.0160
Bias corr. (stat)	0.0115	0.0112	0.0110	0.0110	0.0112	0.0116
Bias corr. (model)	0.2099	0.1902	0.1687	0.1446	0.1254	0.1106
Sys. error (total)	0.2239	0.1985	0.1762	0.1519	0.1329	0.1187
Total error	0.2280	0.1996	0.1771	0.1530	0.1340	0.1202

p_ℓ^* Cut in GeV/c	1.4	1.5	1.6	1.7	1.8	1.9
$\langle M_X^2 \rangle$ in (GeV/c1)^2	4.2980	4.2691	4.2209	4.1483	4.1493	4.1547
Stat. error (data)	0.0208	0.0235	0.0274	0.0337	0.0426	0.0553
Stat. error (signal prob.)	0.0011	0.0017	0.0026	0.0054	0.0088	0.0137
Stat. error (total)	0.0208	0.0236	0.0275	0.0341	0.0435	0.0570
Calib. function error	0.0366	0.0355	0.0339	0.0296	0.0310	0.0303
FEI eff..	0.0020	0.0038	0.0050	0.0065	0.0092	0.0134
PID eff.	0.0037	0.0032	0.0035	0.0041	0.0051	0.0070
$B \to X_u \ell \nu_\ell$ BF	0.0171	0.0200	0.0228	0.0283	0.0358	0.0503
Bias corr. (stat)	0.0123	0.0135	0.0154	0.0184	0.0230	0.0303
Bias corr. (model)	0.0920	0.0764	0.0621	0.0483	0.0328	0.0185
Sys. error (total)	0.1013	0.0878	0.0761	0.0664	0.0629	0.0703
Total error	0.1034	0.0909	0.0810	0.0746	0.0765	0.0905

- Results for $<M_x^n>$ for n=1-6

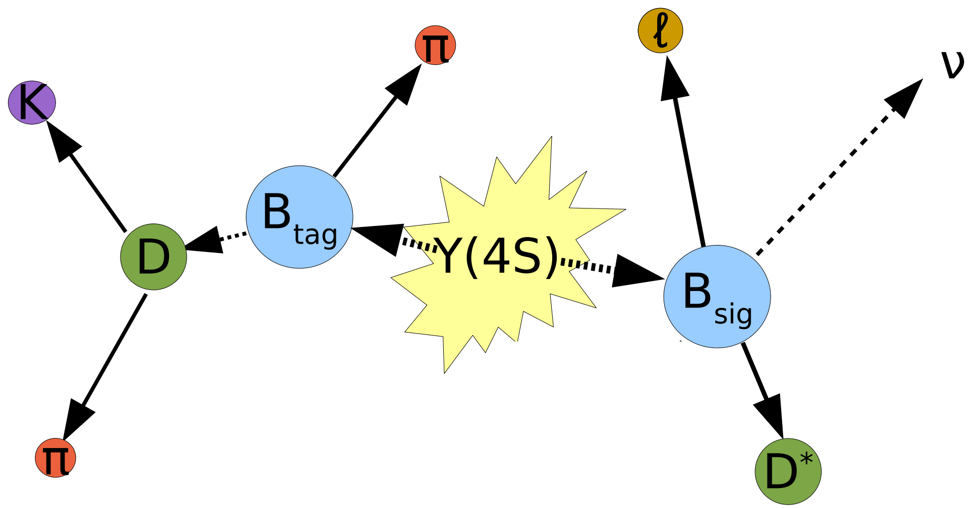
inclusive measurement

→ Step towards a $|V_{cb}|$ measurement

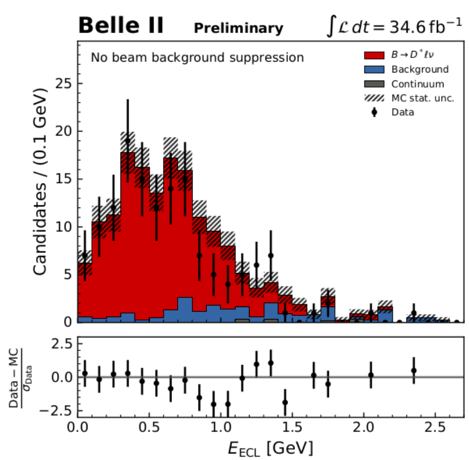
Eur.Phys.J.C 80 (2020) 10, 966

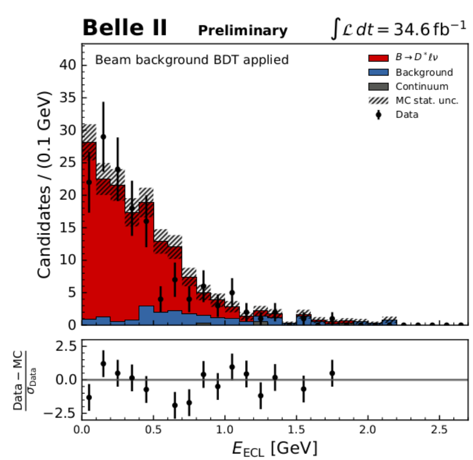
$B \to D^*\ell\nu$ Branching Fraction

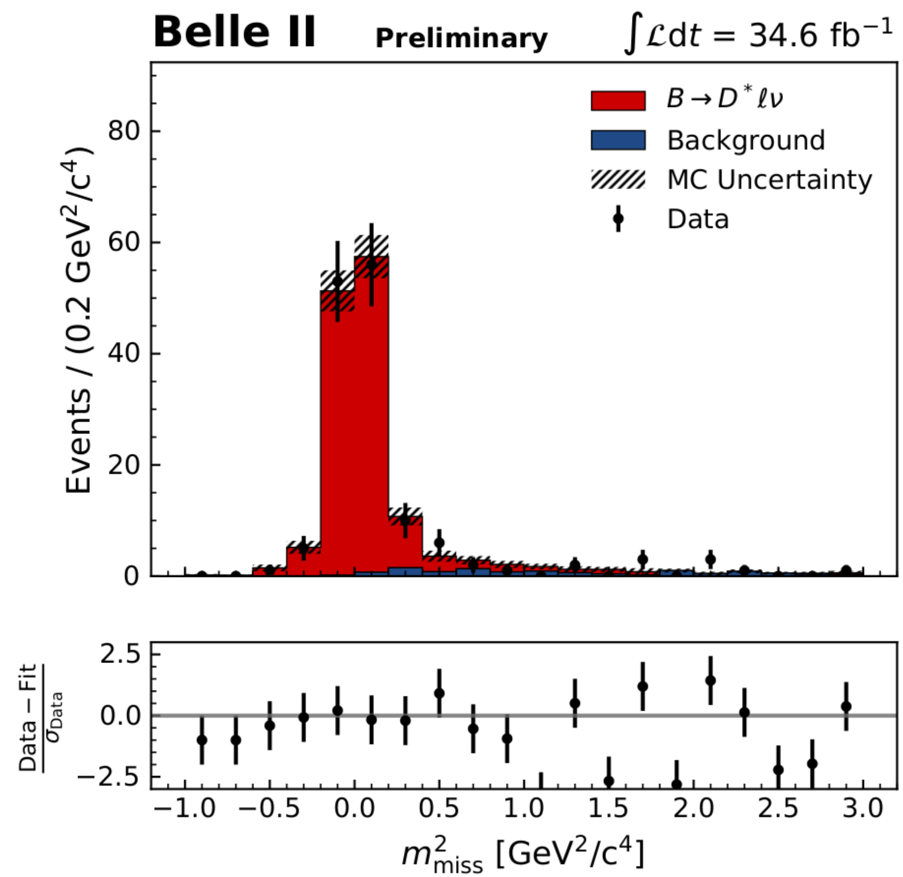
arXiv:2008.10299
BELLE2-CONF-PH-2020-009



$$m_{\mathrm{miss}}^2 = \left(p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_\ell\right)^2$$







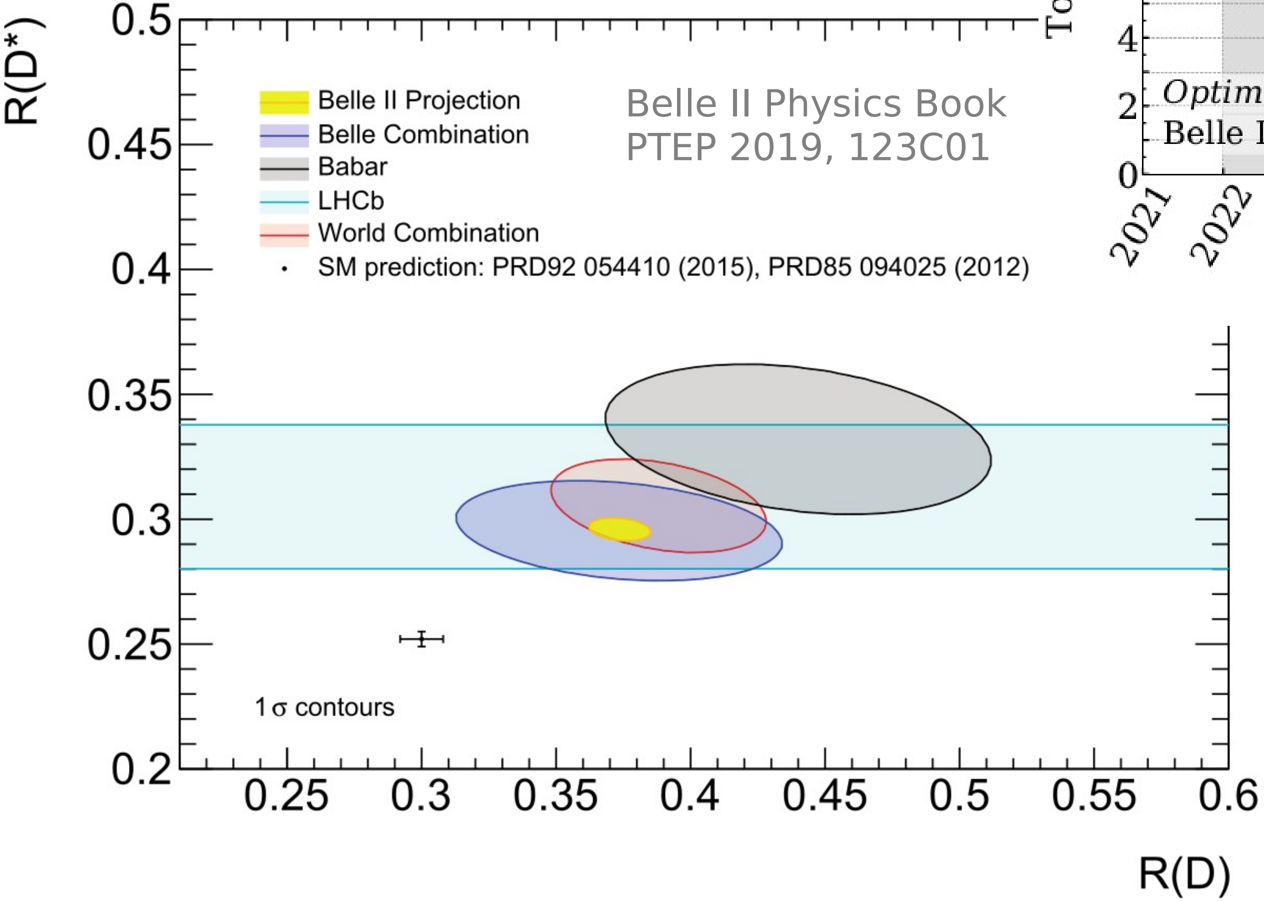
$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = \left(4.51 \pm 0.41_{\mathrm{stat}} \pm 0.27_{\mathrm{syst}} \pm 0.45_{\pi_s}\right)\%$$

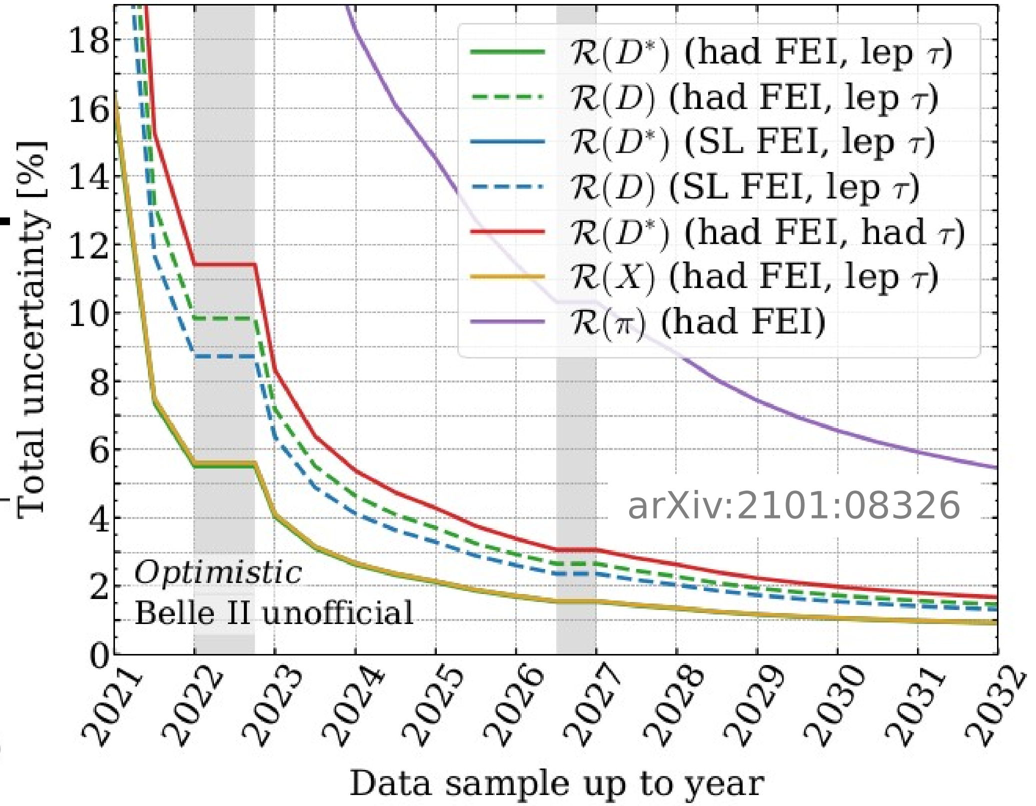
PDG: (5.06 ± 0.12) %

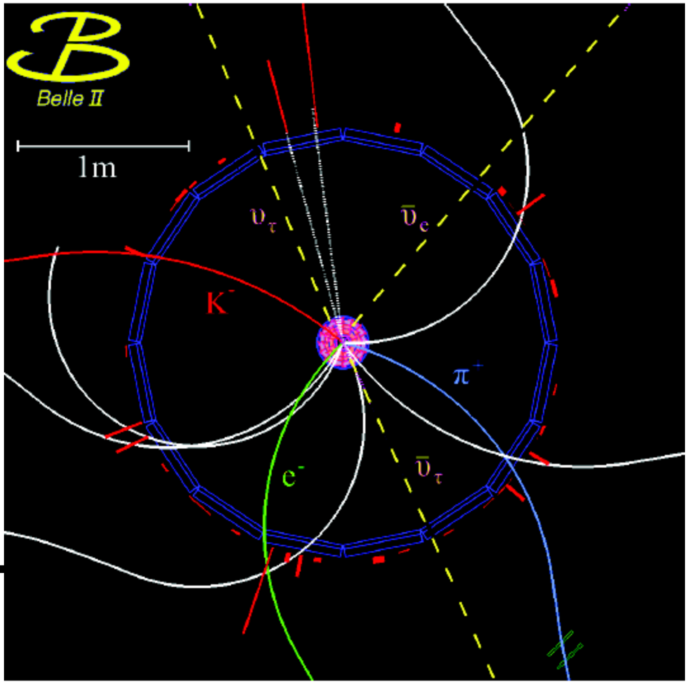
absolute branching fraction

Prospects for $R(D^{(*)})$

$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu_\tau)}{Br(B \to D^{(*)}\ell\nu_\ell)}$$

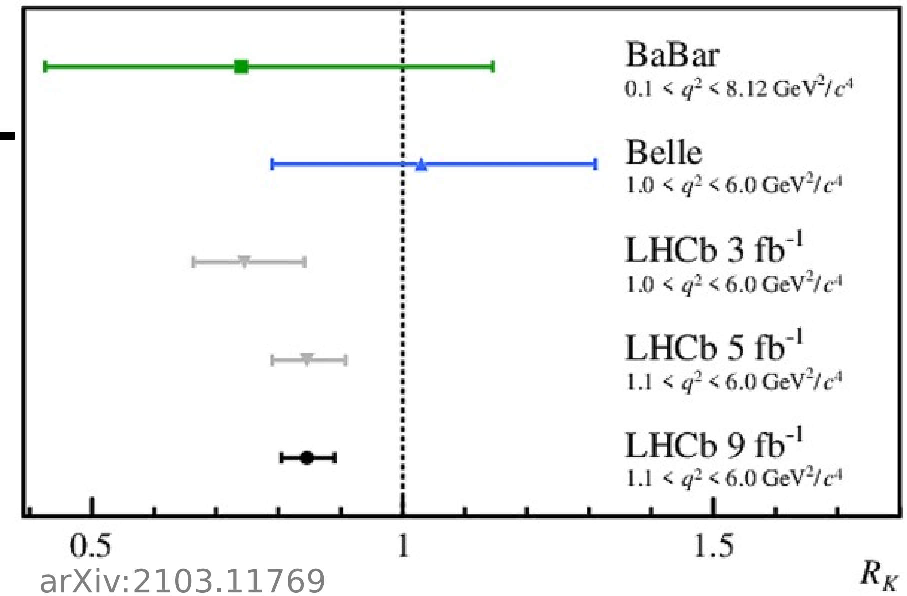






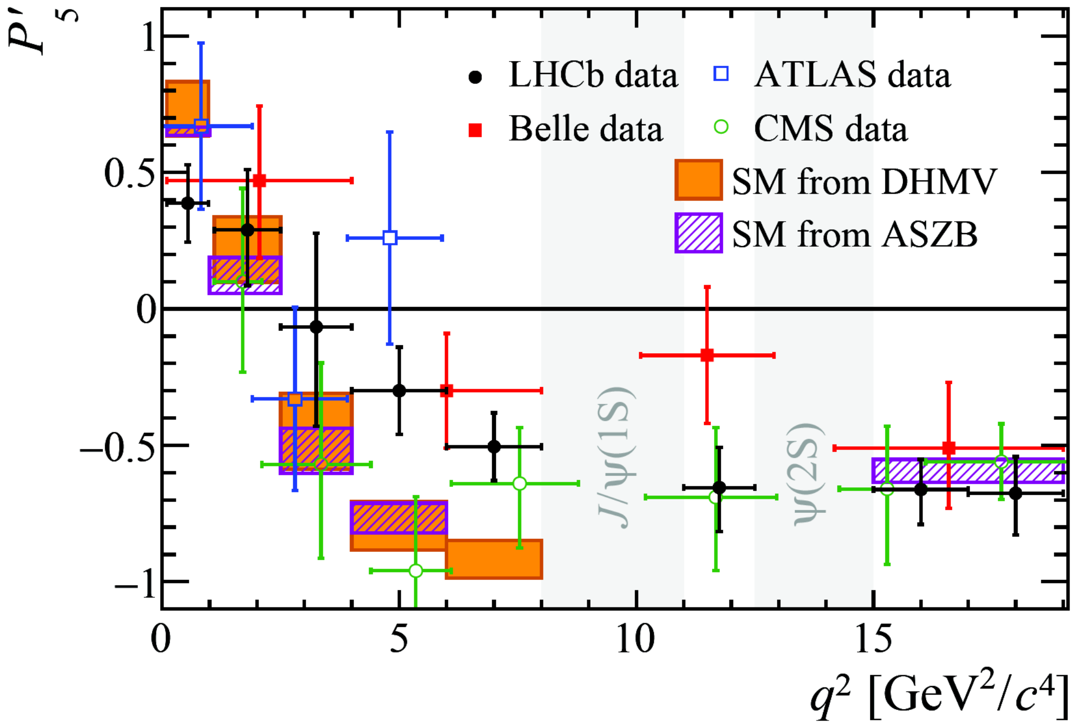
$b \to s\ell\ell$

$BR(B \to K\mu^+\mu^-) / BR(B \to Ke^+e^-)$

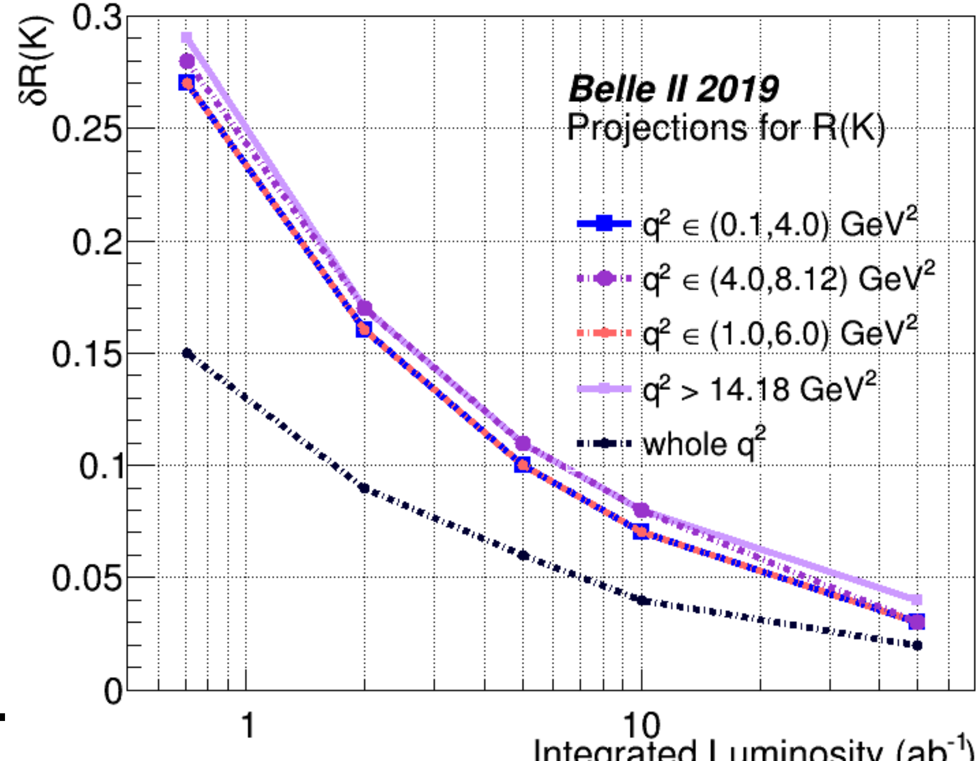


arXiv:2103.11769

$B \to K^*\mu^+\mu^-$

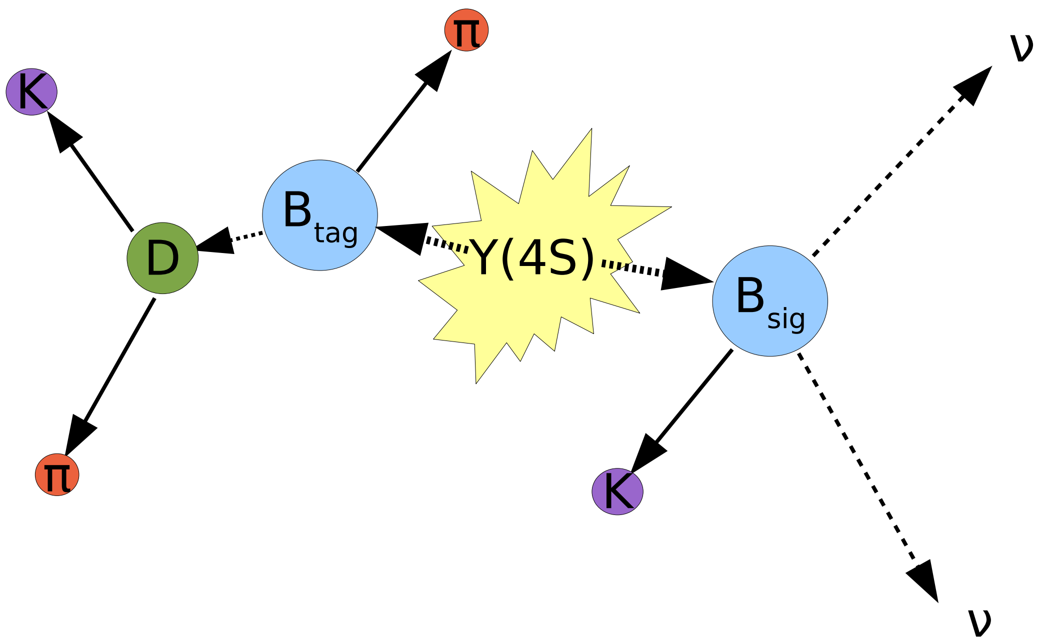


Observables uncertainty	Belle $0.71\ \text{ab}^{-1}$	Belle II $5\ \text{ab}^{-1}$	Belle II $50\ \text{ab}^{-1}$
P'_5 ([1.0, 2.5] GeV^2)	0.47	0.17	0.054
P'_5 ([2.5, 4.0] GeV^2)	0.42	0.15	0.049
P'_5 ([4.0, 6.0] GeV^2)	0.34	0.12	0.040
P'_5 (>14.2 GeV^2)	0.23	0.088	0.027

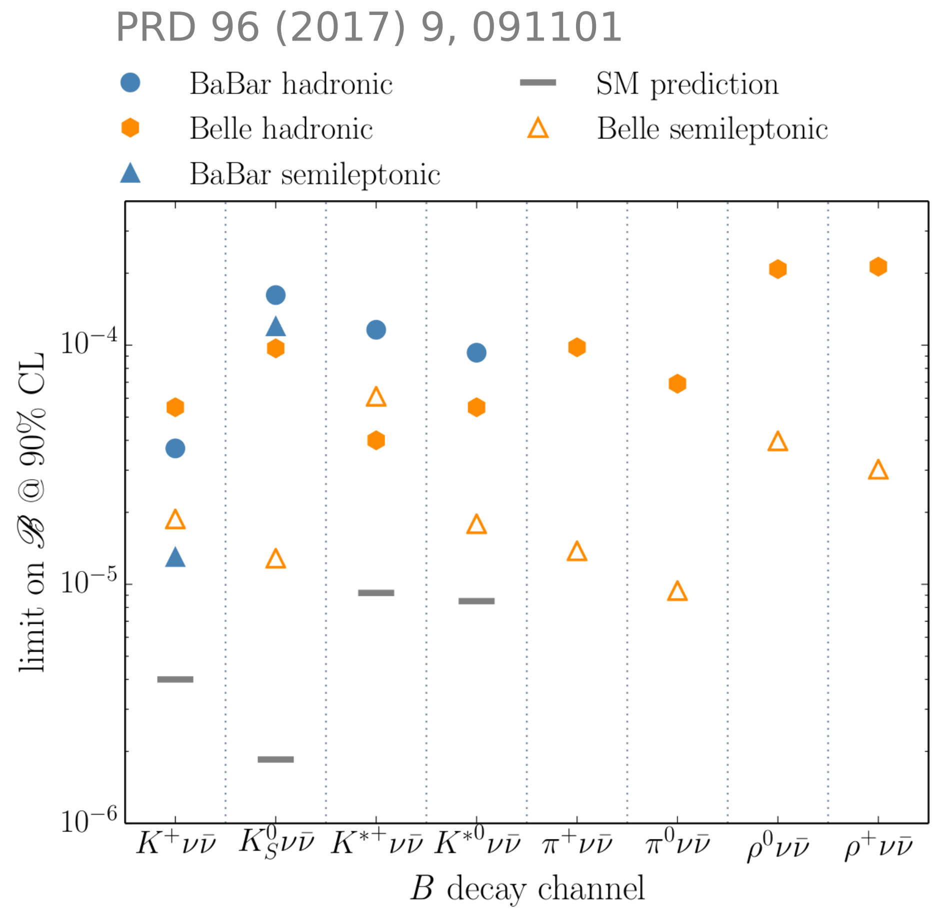


Similar sensitivity for $R(K^*)$ and $R(X_s)$

$B \to K\nu\bar{\nu}$

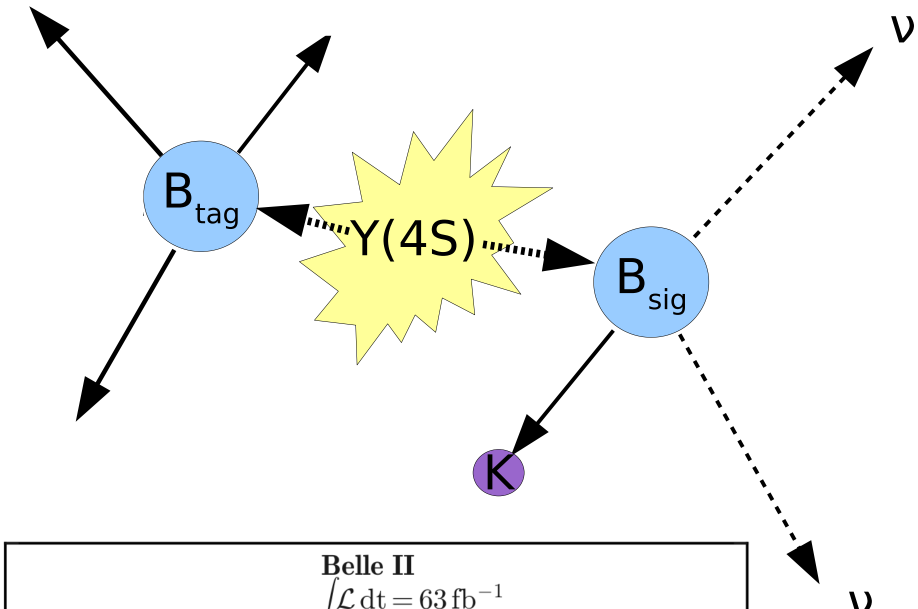


Observables uncertainty	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	—	—	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	—	—	0.077

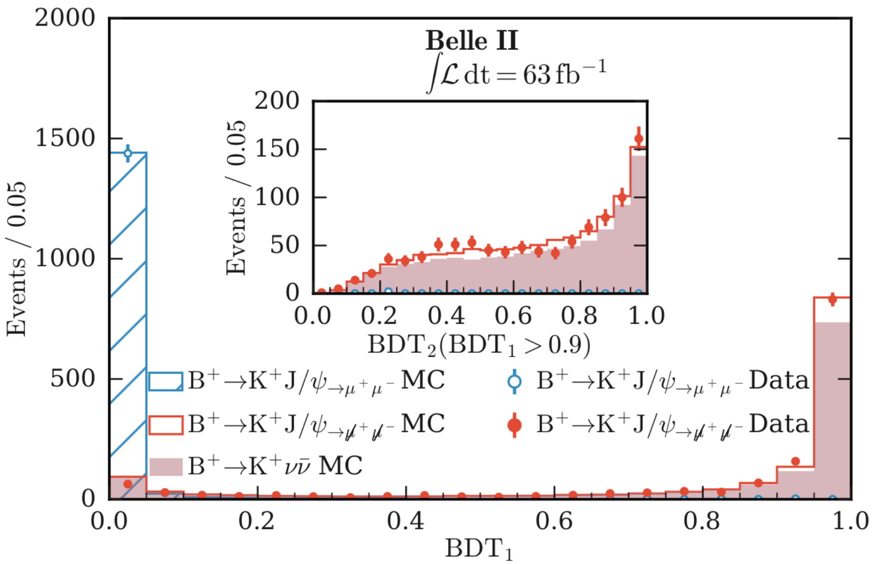


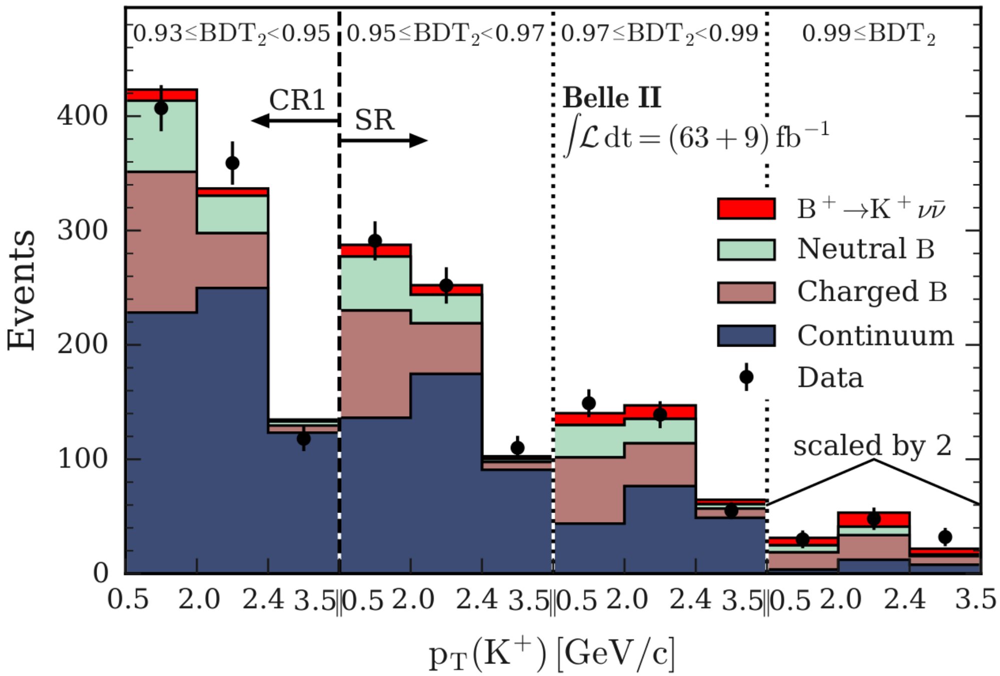
$B \to K\nu\bar{\nu}$

arXiv:2104.12624
submitted to PRL



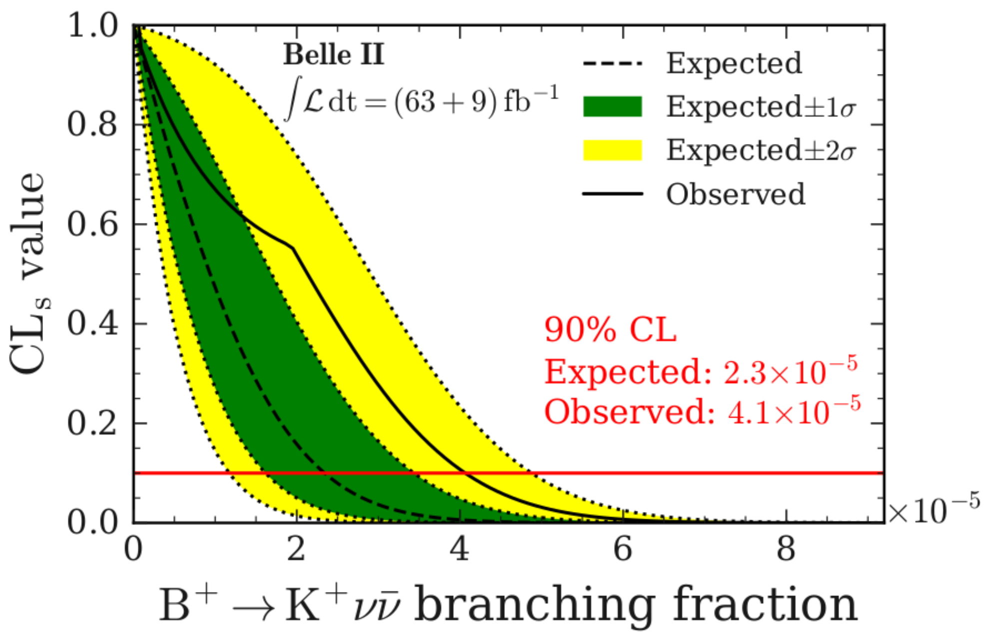
- Kaon candidate selection
- Inclusive tag → rest of event
- BDTs inputs: kaon mom., rest of event, event shape, D veto
- $B^+ \to K^+ J/\psi(\to\mu\mu)$ control sample

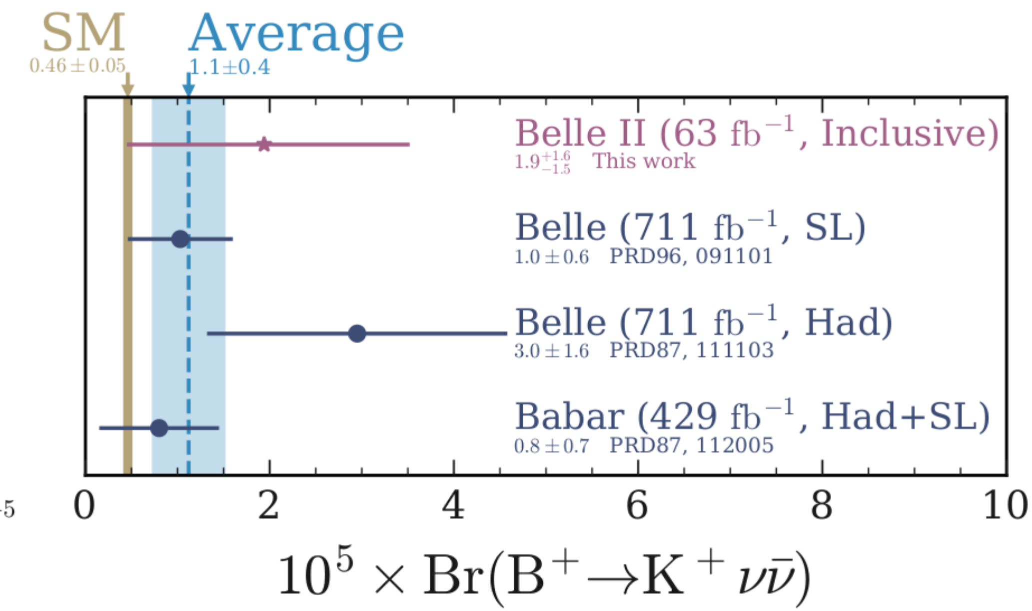




B → $K\nu\bar{\nu}$

arXiv:2104.12624

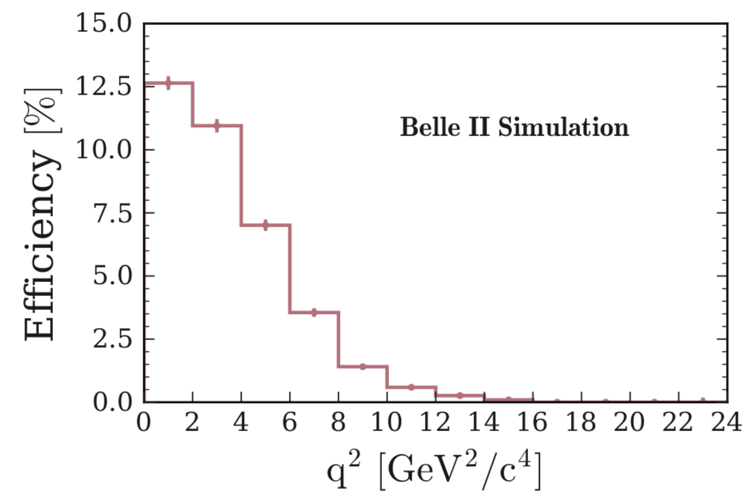




- Same sensitivity as Belle hadronic tag analysis with 10 times more data

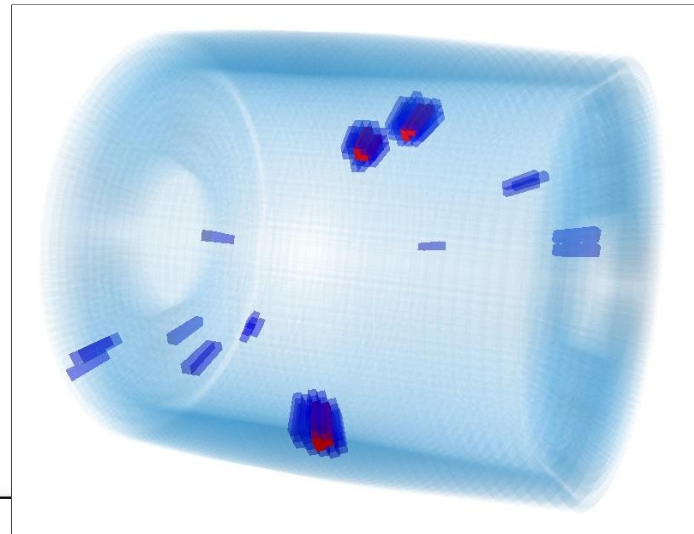
undetected particles

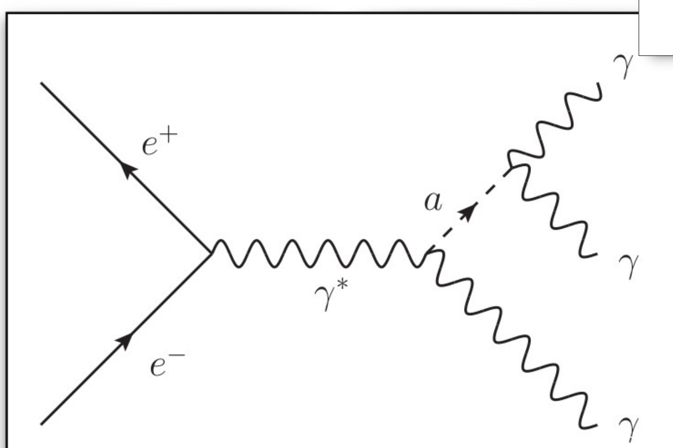
- Also sensitive to B → KX_{dark}



Search for Axion Like Particles

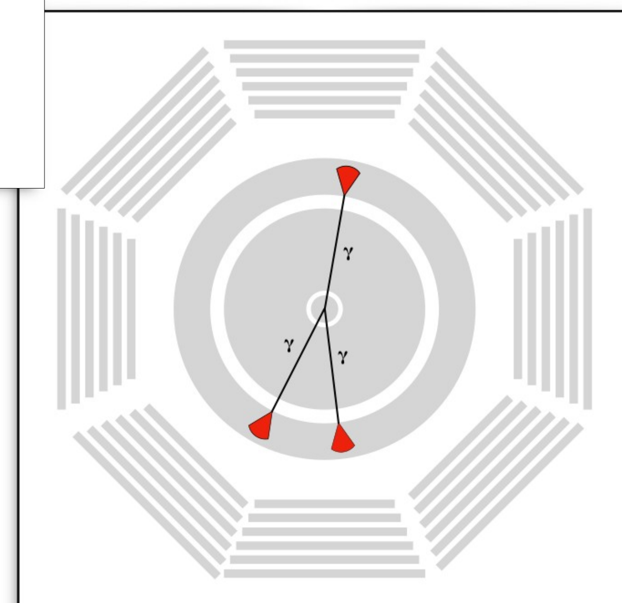
PRL 125 (2020) 16, 161806





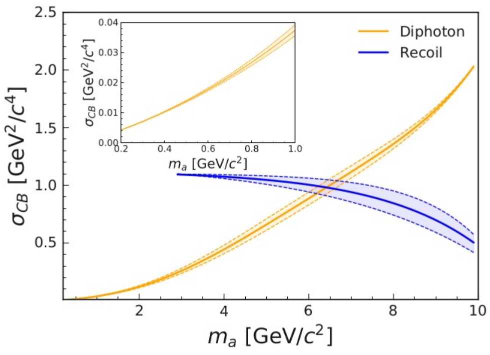
Signature:

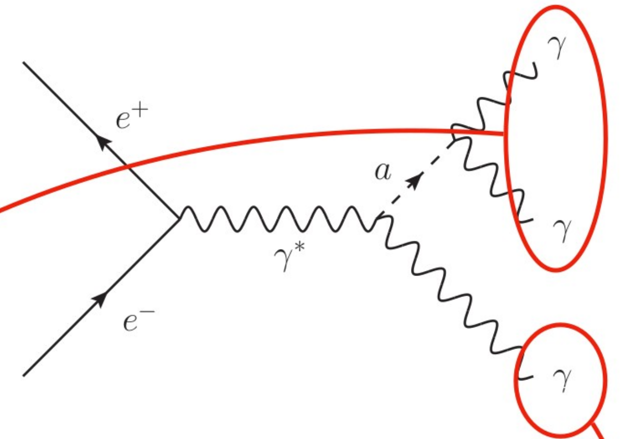
- Photon pair recoiling against third photon
- Peak in diphoton invariant mass



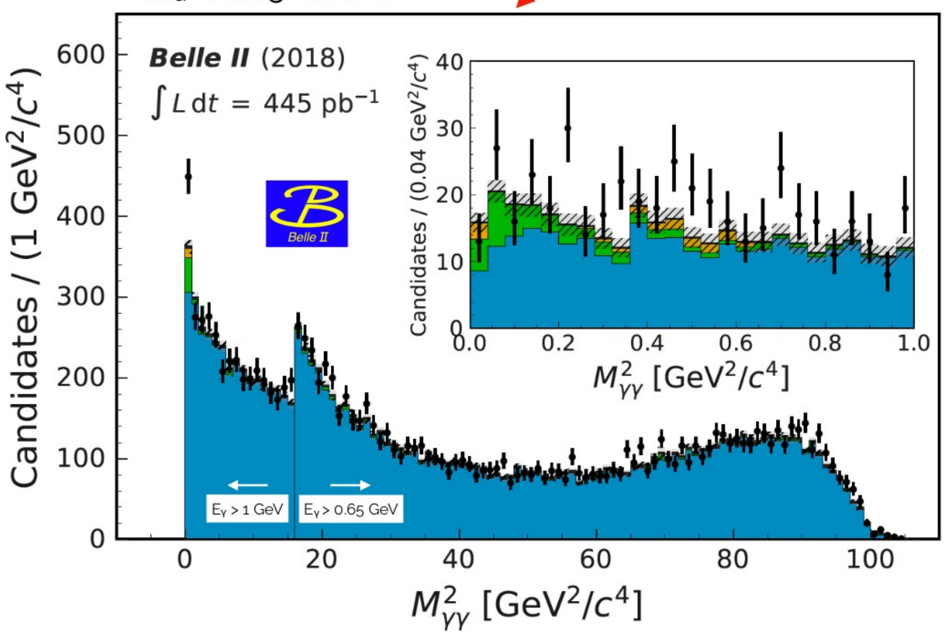
Search for Axion Like Particles

PRL 125 (2020) 16, 161806

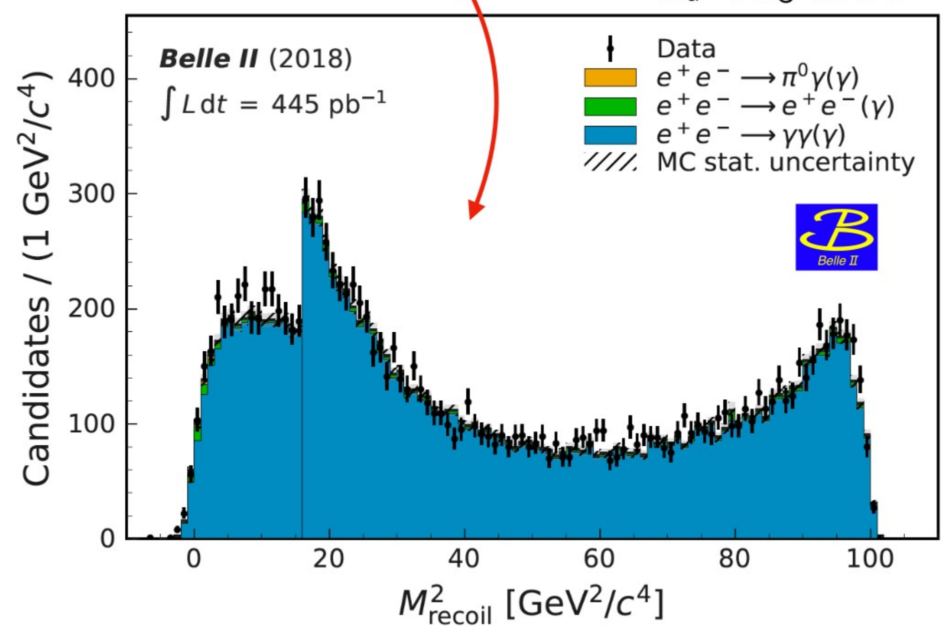




$m_a < 6.85$ GeV/c²

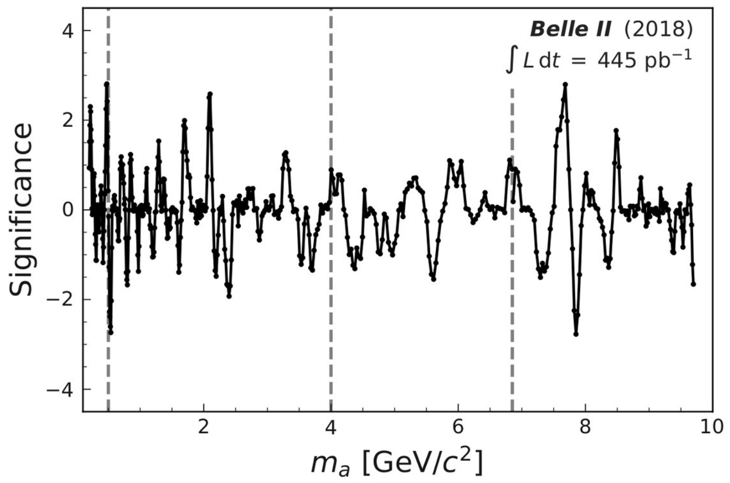


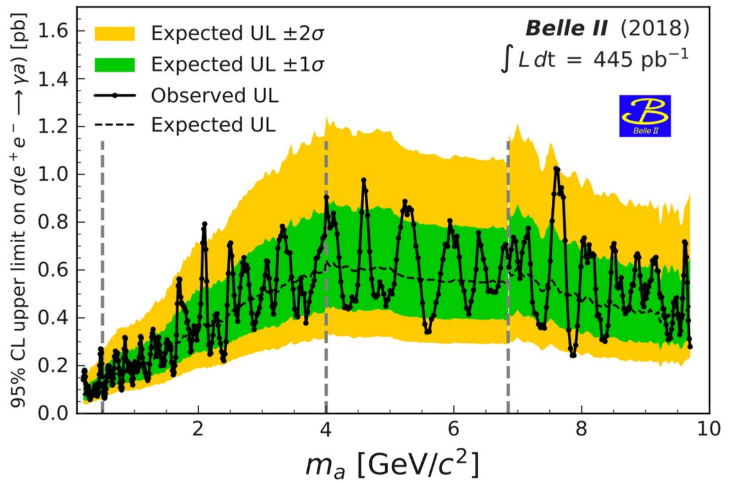
$m_a \geq 6.85$ GeV/c²

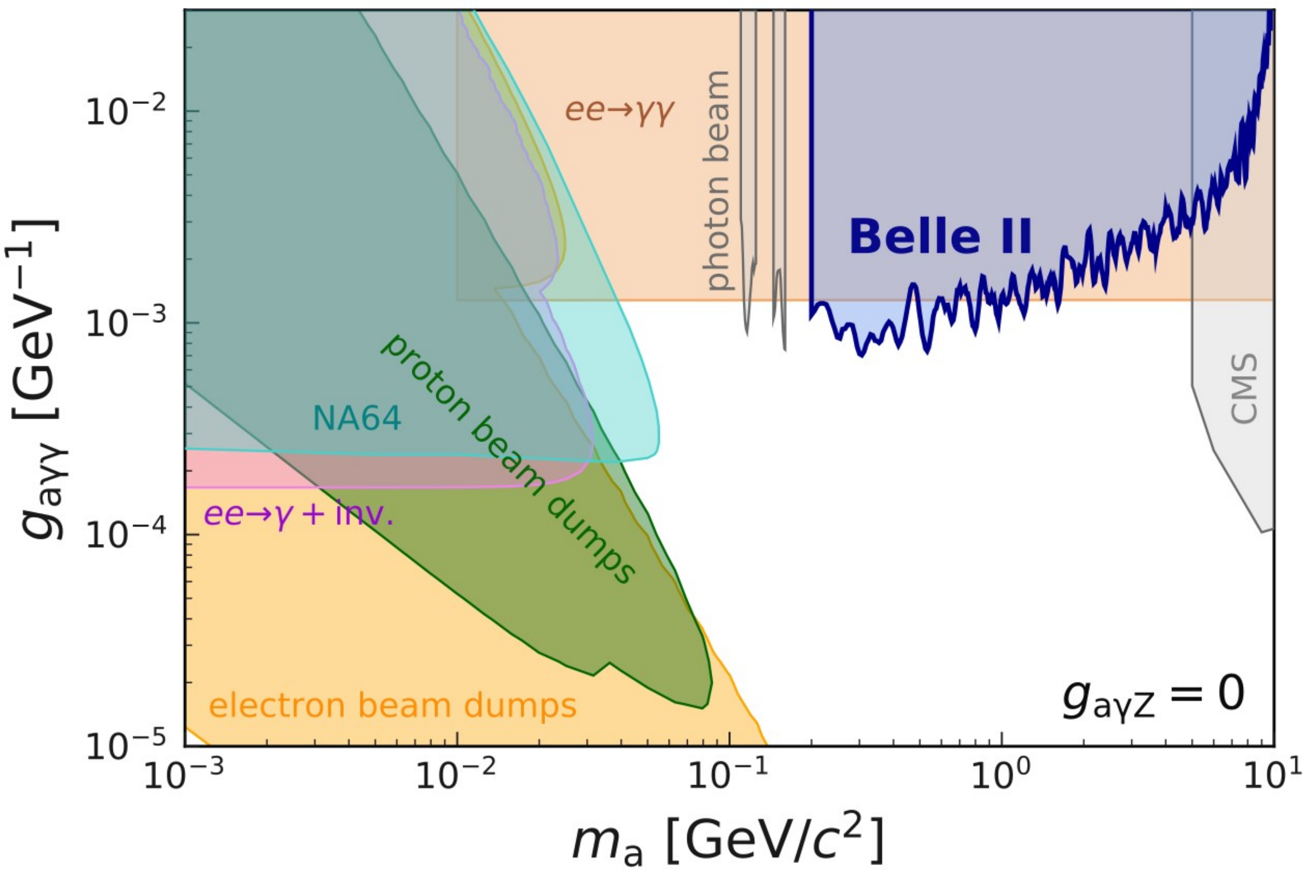


Search for Axion Like Particles

PRL 125 (2020) 16, 161806



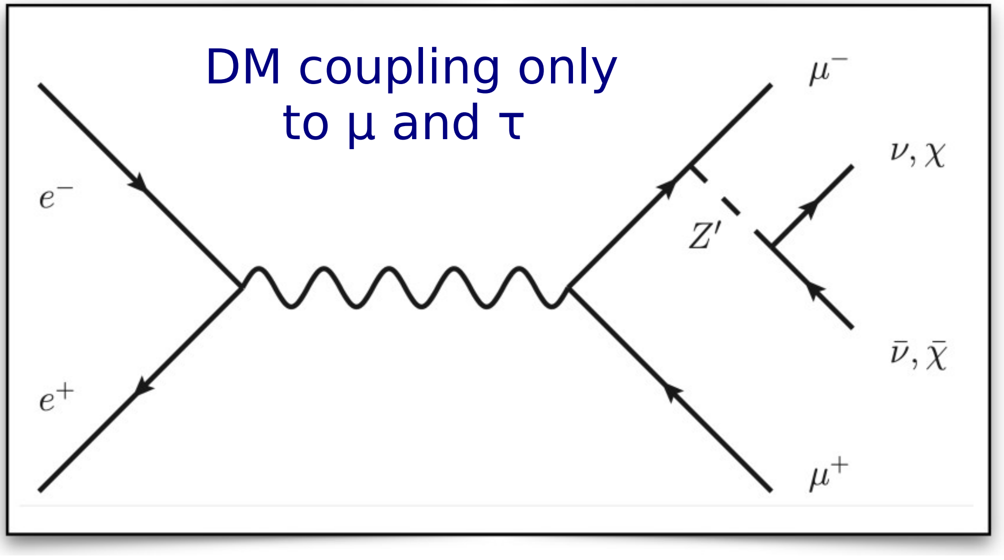


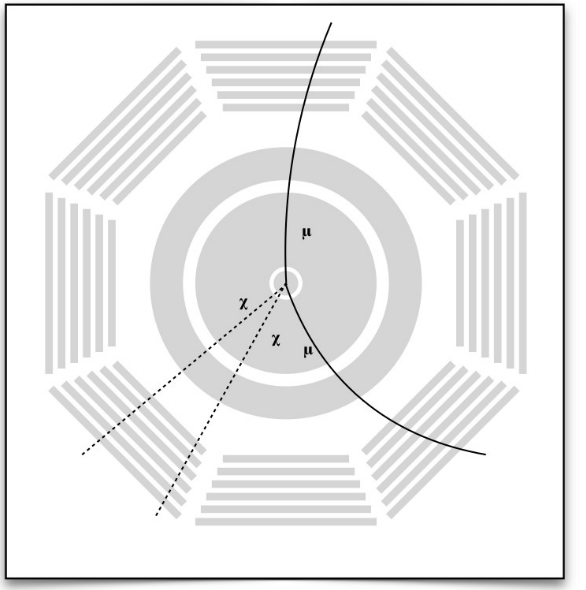


- No significant signal → limit on cross section
- Exclusion in mass/coupling parameter space
- Competitive result with only 0.0004 ab⁻¹

Search for Invisible Z'

PRL 124 (2020) 14, 141801



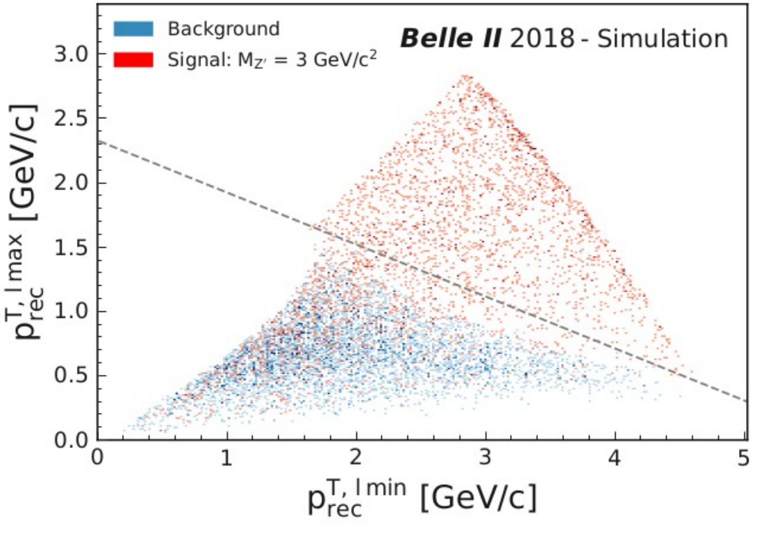


Signature:

- Two muons and missing momentum
- Peak in recoil mass

Main background:

- tau pair events
  → cut on transverse recoil momentum



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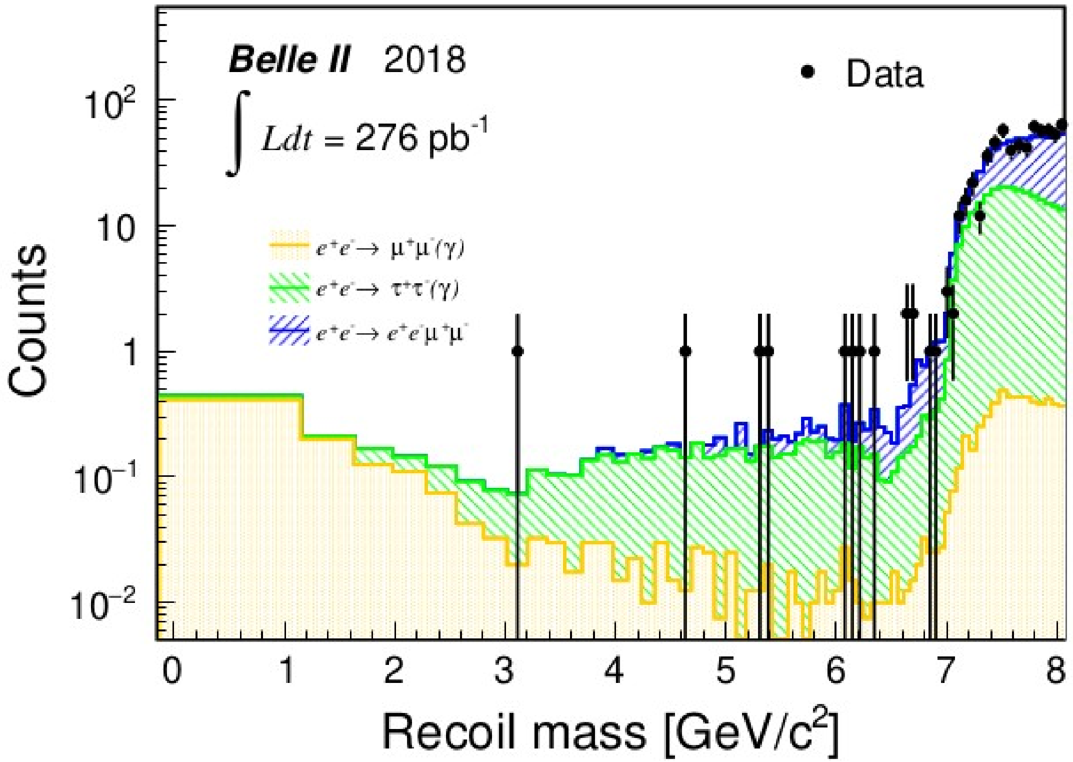
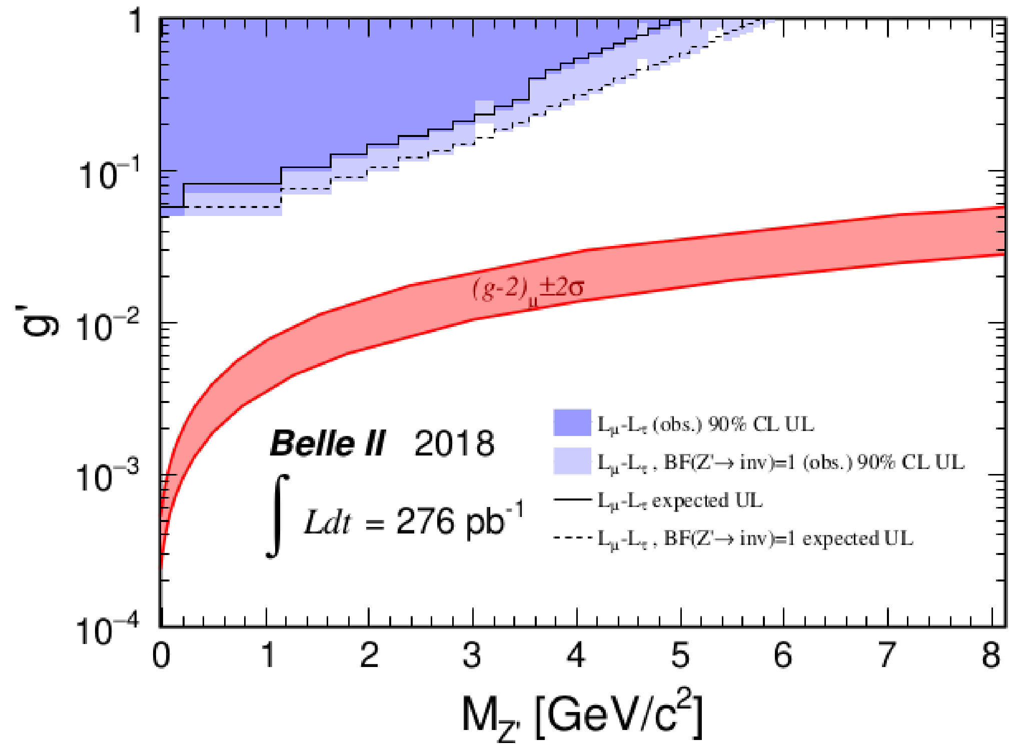
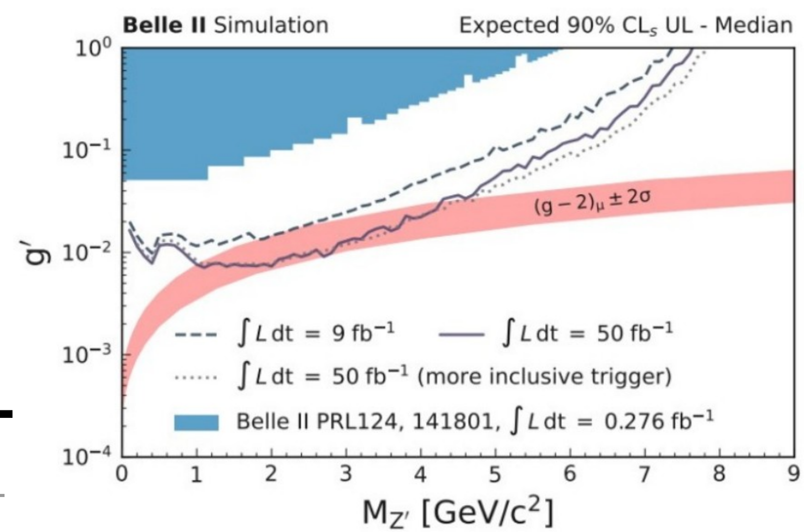


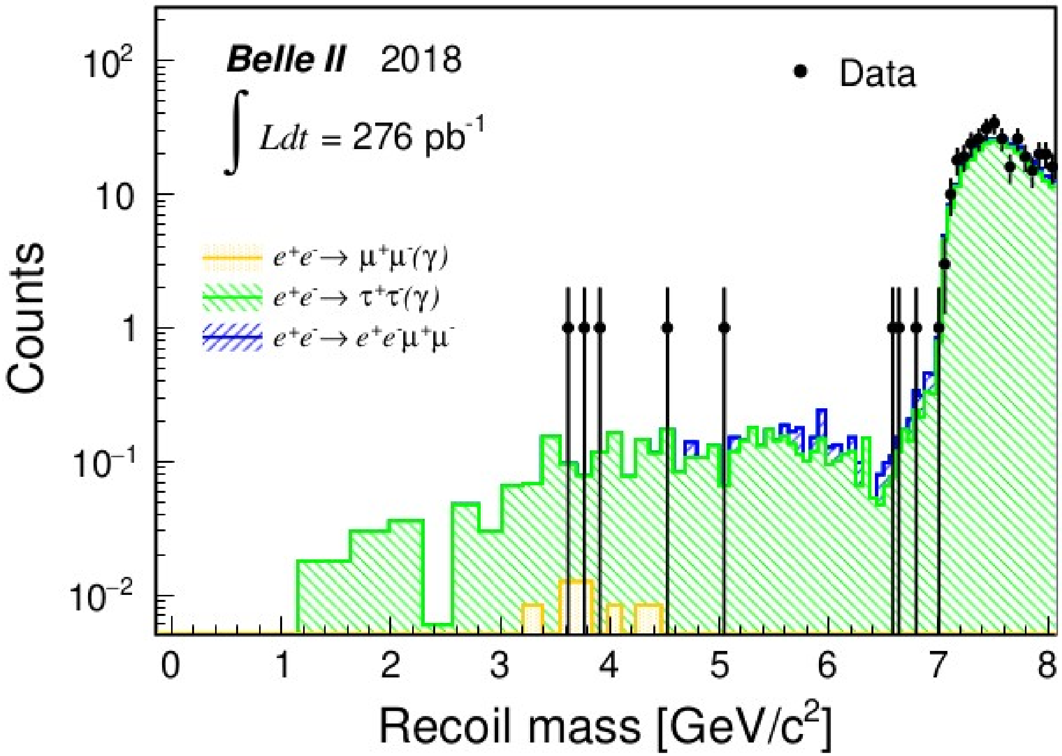


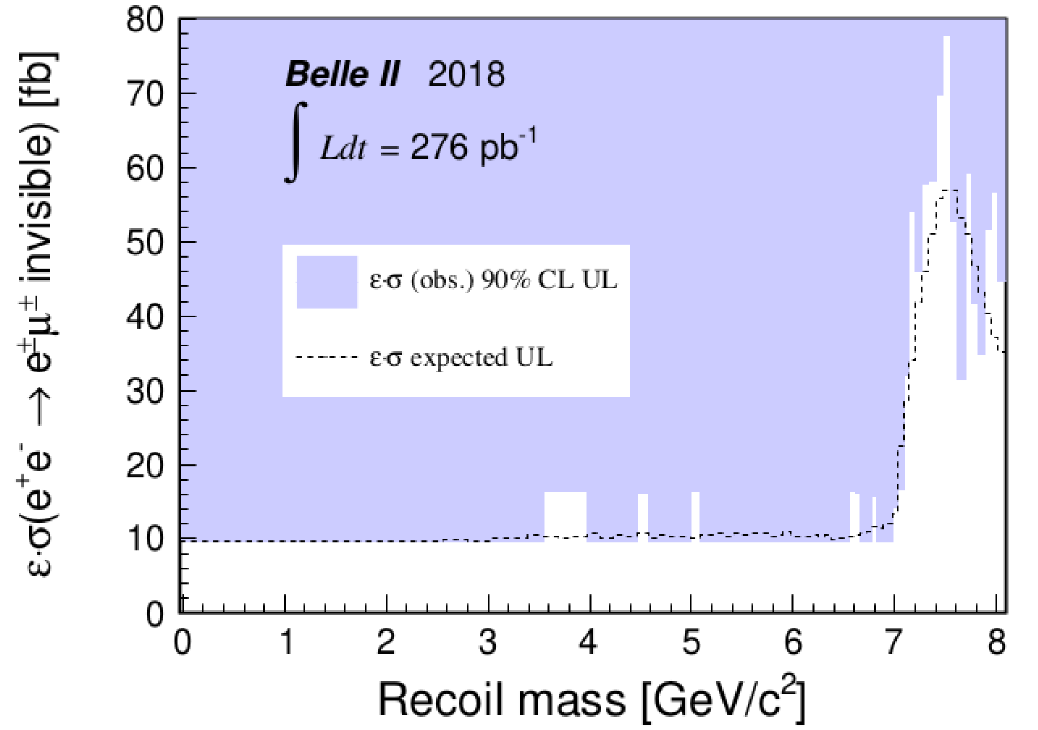
- No significant signal in μμ recoil mass
- → limit on Z’ mass and coupling constant
- → Probing region favored by g-2 with 50 fb^{-1}



Search for Invisible LFV Z’

PRL 124 (2020) 14, 141801

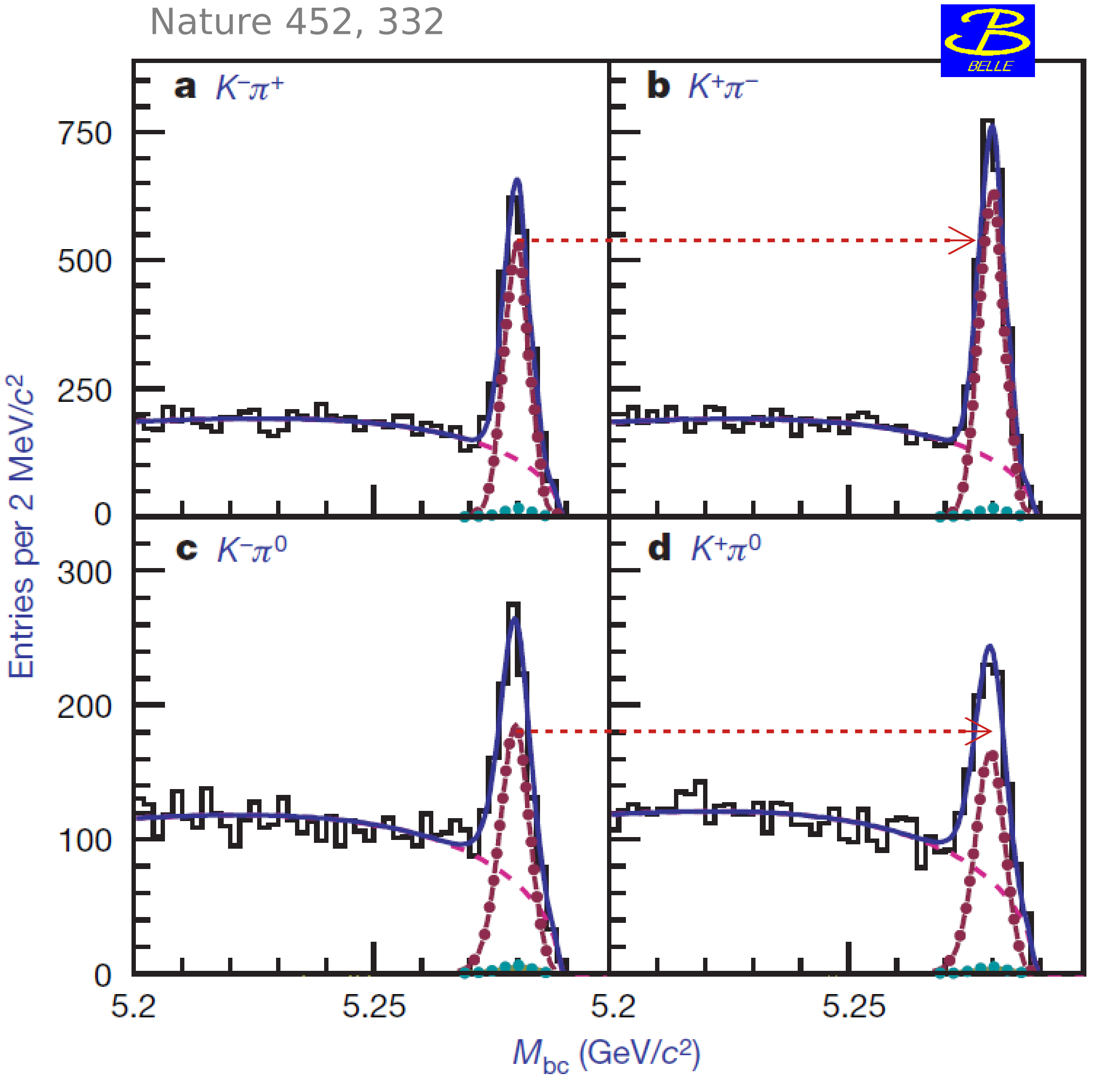




- Signature: muon, electron, missing momentum
- No significant signal in μe recoil mass
- → limit on efficiency times cross section

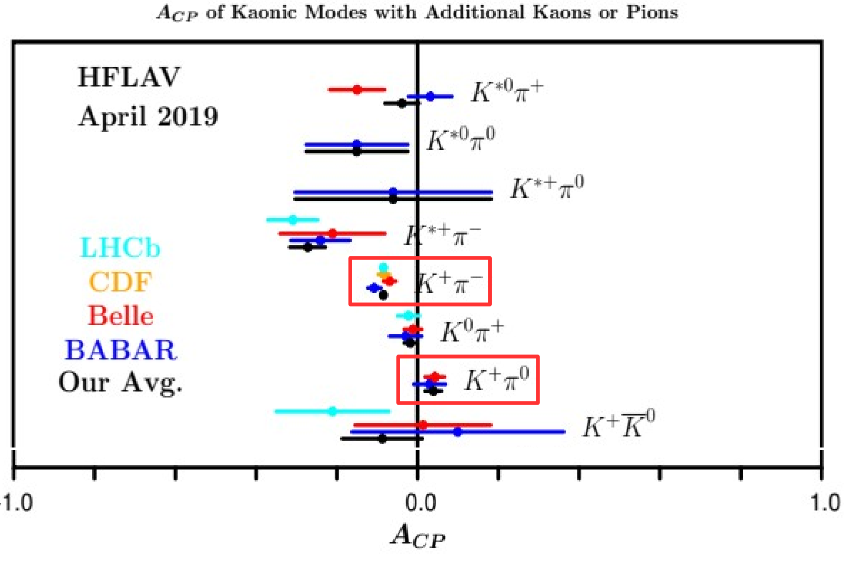
CP Asymmetries

Nature 452, 332



$A_{CP}(B^0 \to K^+\pi^-) \neq A_{CP}(B^+ \to K^+\pi^0)$

- Kπ puzzle



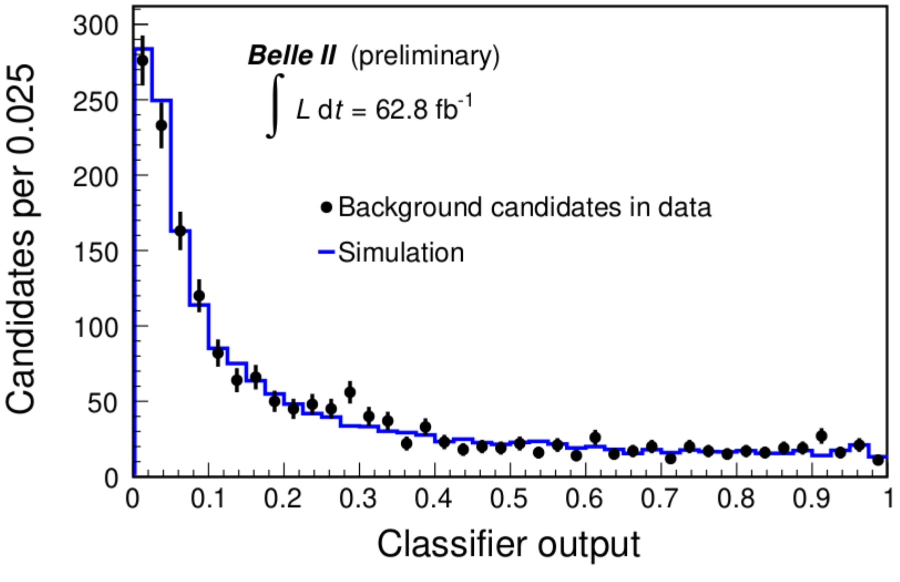
→ Reduced theoretical uncertainties in isospin sum rule including $A_{CP}(B^+ \to K^0\pi^+)$ and $A_{CP}(B^0 \to K^0\pi^0)$

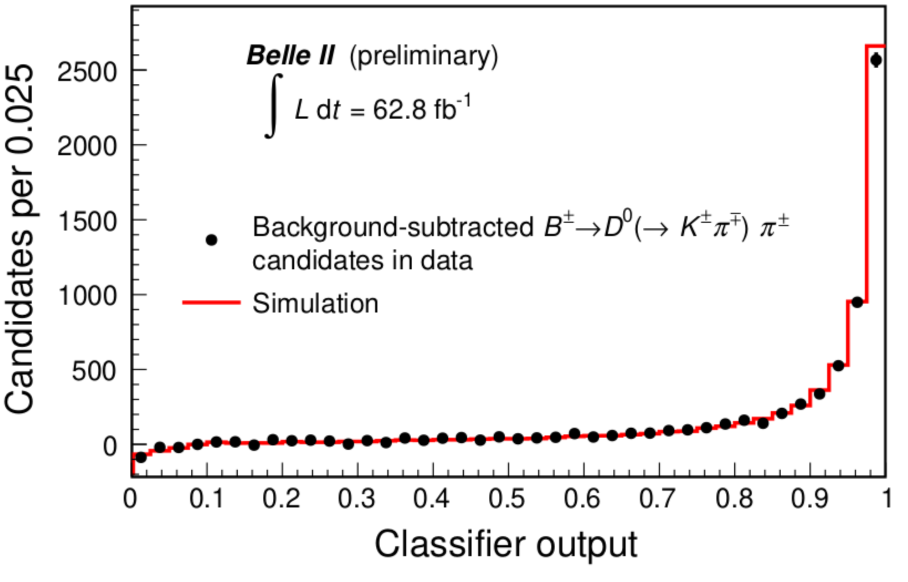
$A_{CP}(K^0\pi^0)$

arXiv:2104.14871
BELLE2-CONF-PH-2021-001

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- Time integrated measurement: $\mathcal{P}_{sig}(q) = \frac{1}{2}(1 + q\cdot(1-2w_r)\cdot(1-2\chi_d)\mathcal{A}_{K^0\pi^0})$
- Continuum background suppressed with BDT, validated with $B^0 \to D^0(\to K^-\pi^+)\pi^0$
- Flavor tagging

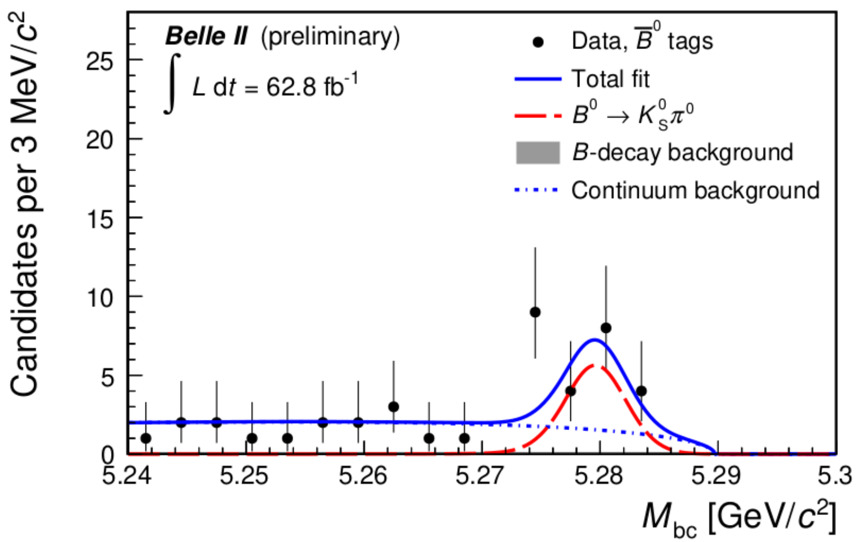


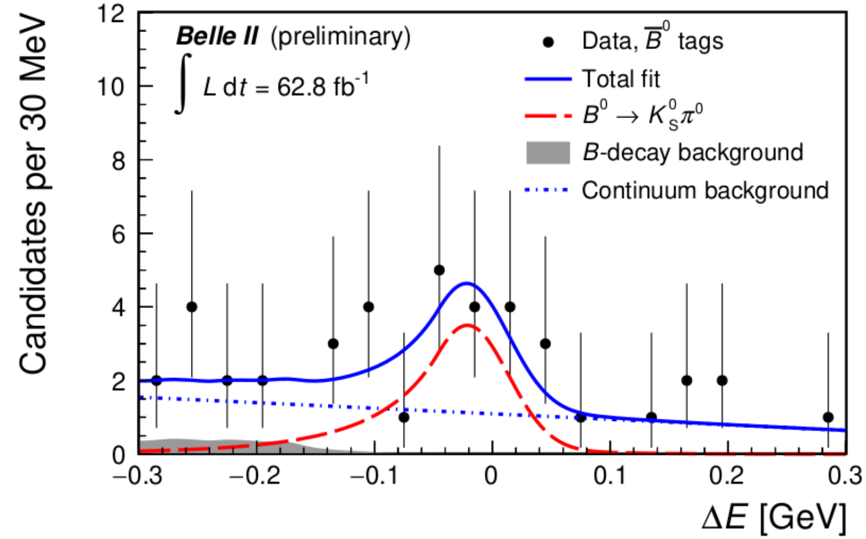


$A_{CP}(K^0\pi^0)$

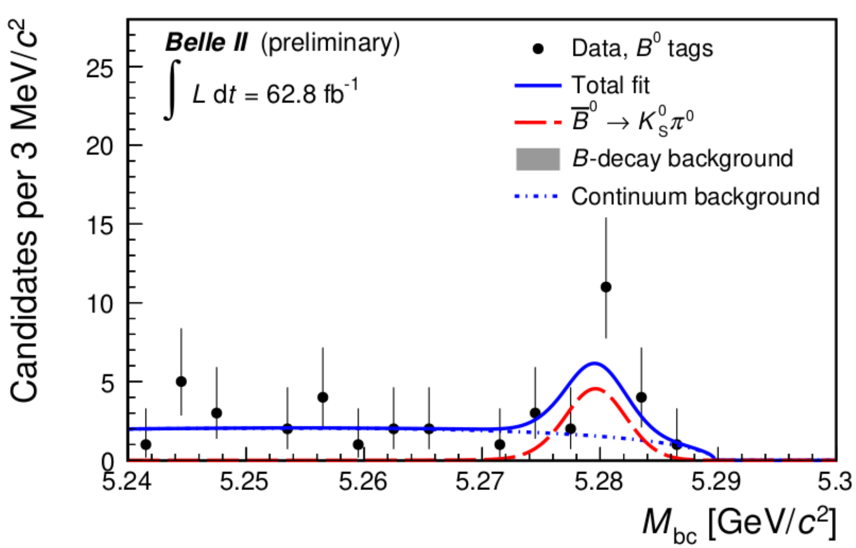
arXiv:2104.14871
BELLE2-CONF-PH-2021-001

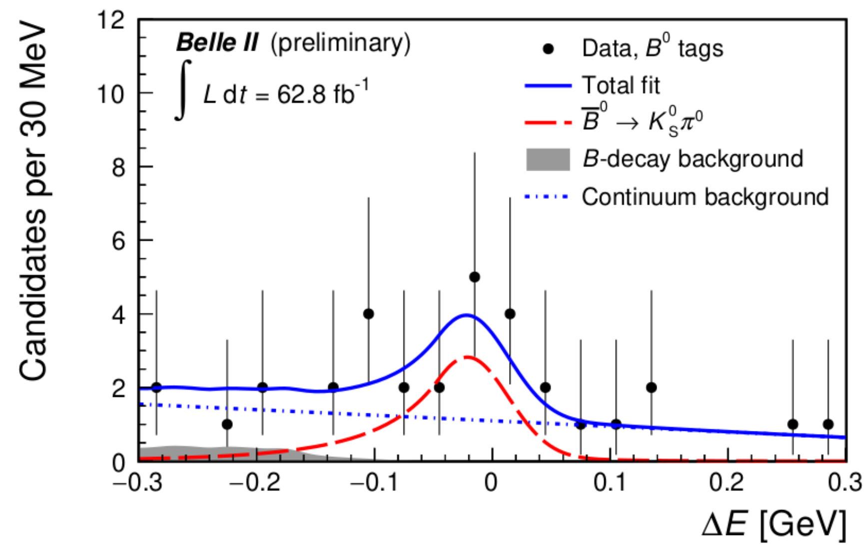
$\overline{B}^0$





B^0





$A_{CP}(K^0\pi^0)$

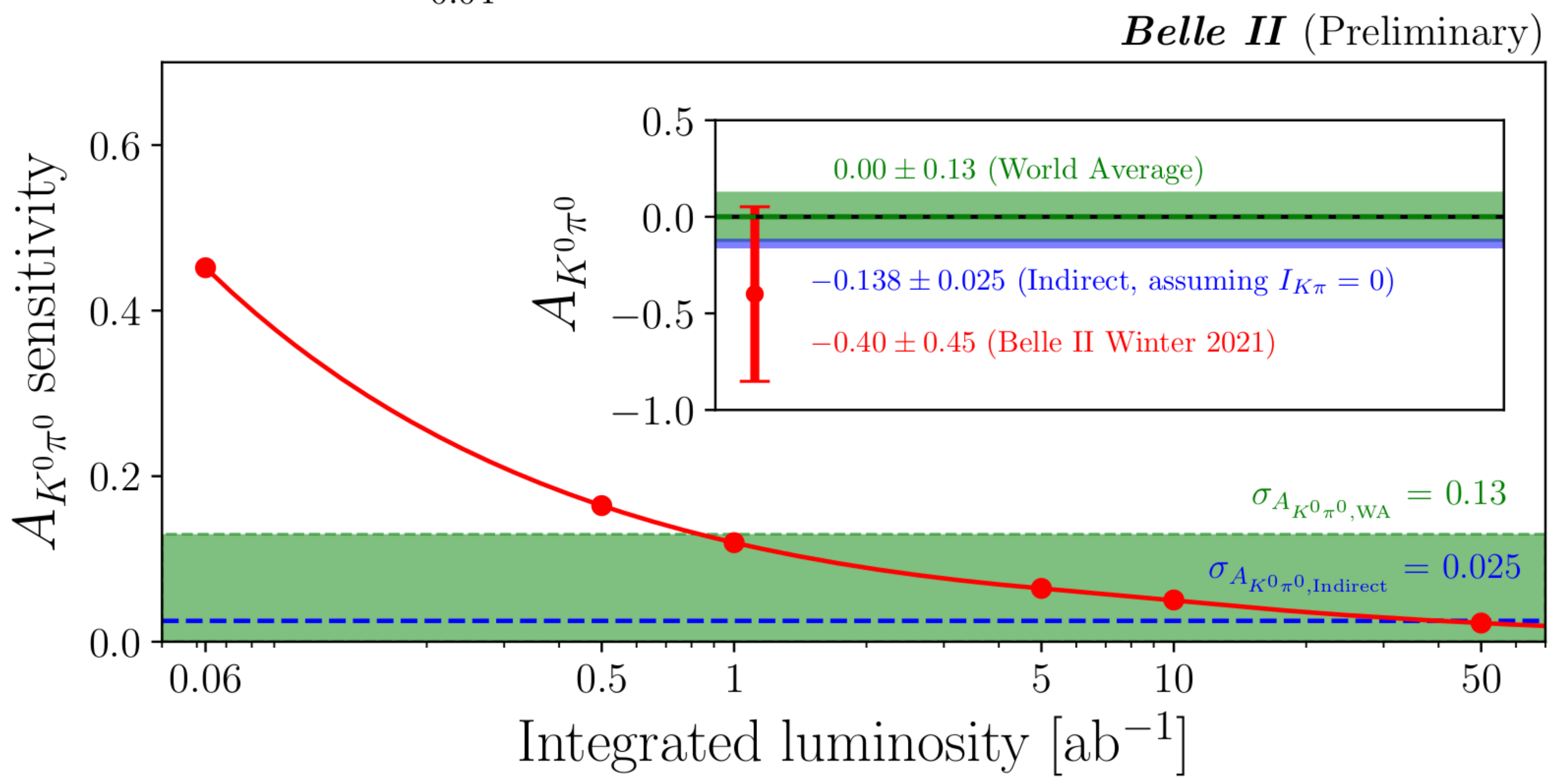
arXiv:2104.14871
BELLE2-CONF-PH-2021-001

Source	$\delta\mathcal{A}_{K^0\pi^0}$
Flavor tagging modelling	0.03
B^0 mixing parameter χ_d	<0.01
B-decay background asymmetry	0.03
Continuum background asymmetry	0.01
Total	0.04

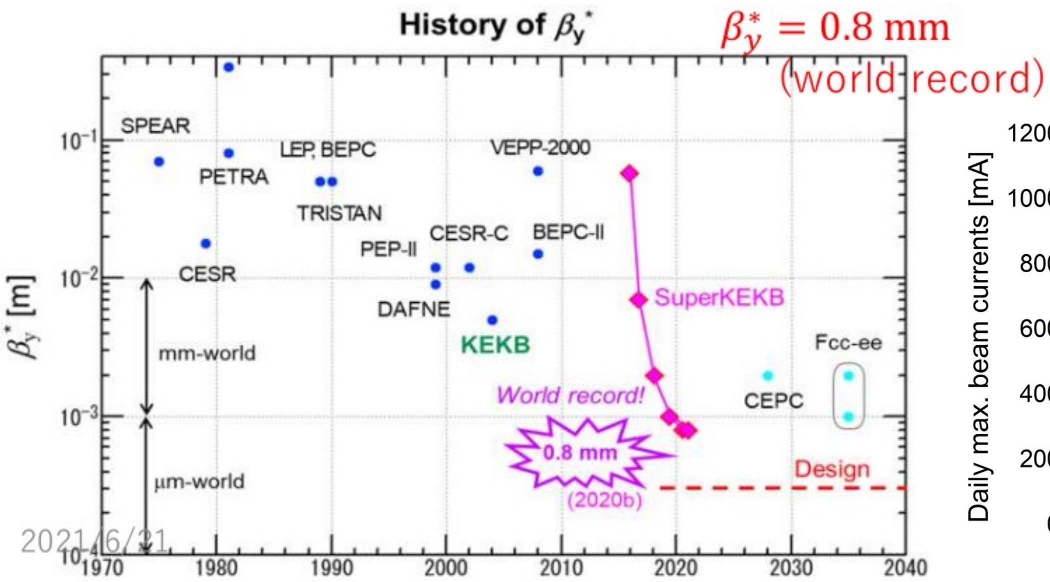
$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$$

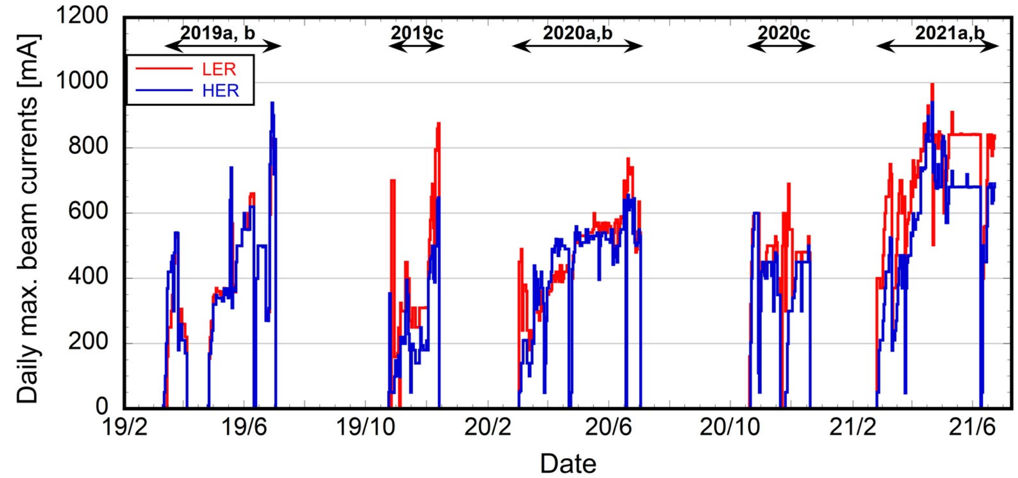
$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$$

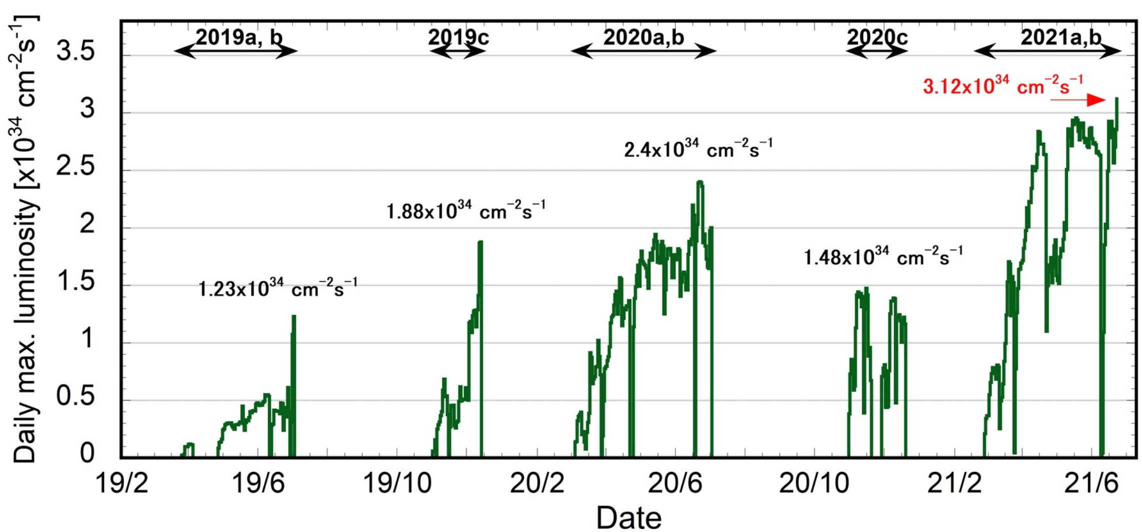
decay with neutrals



Accelerator Performance Evolution



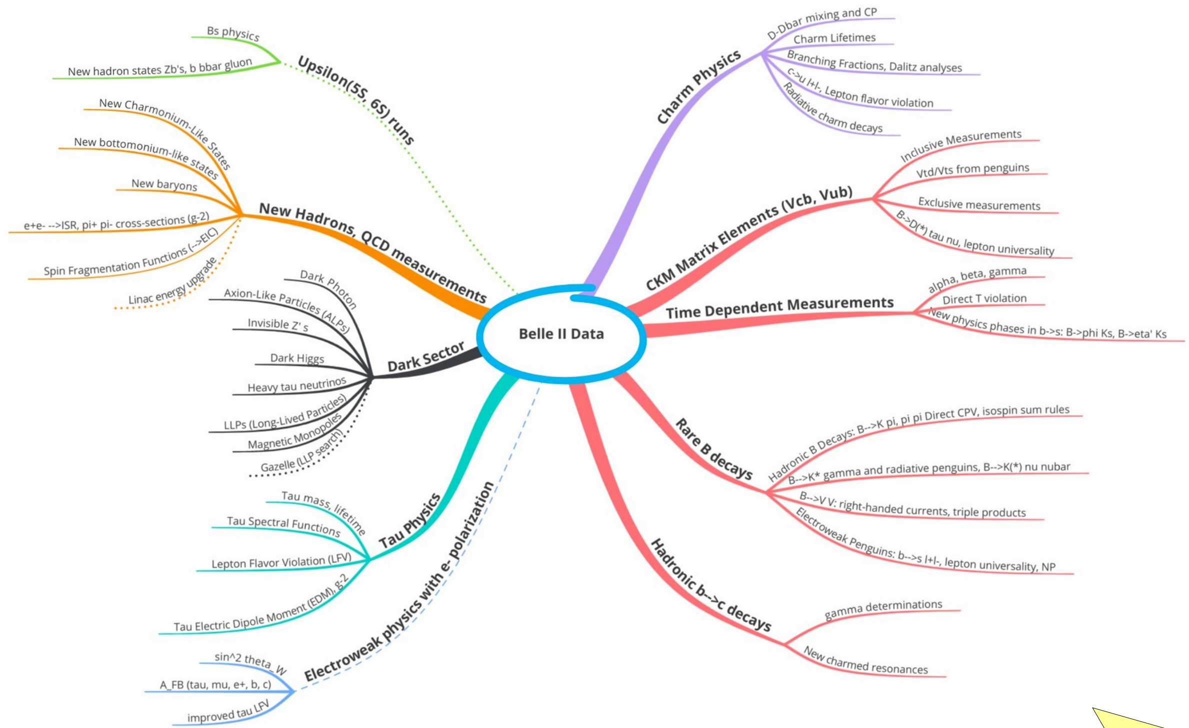


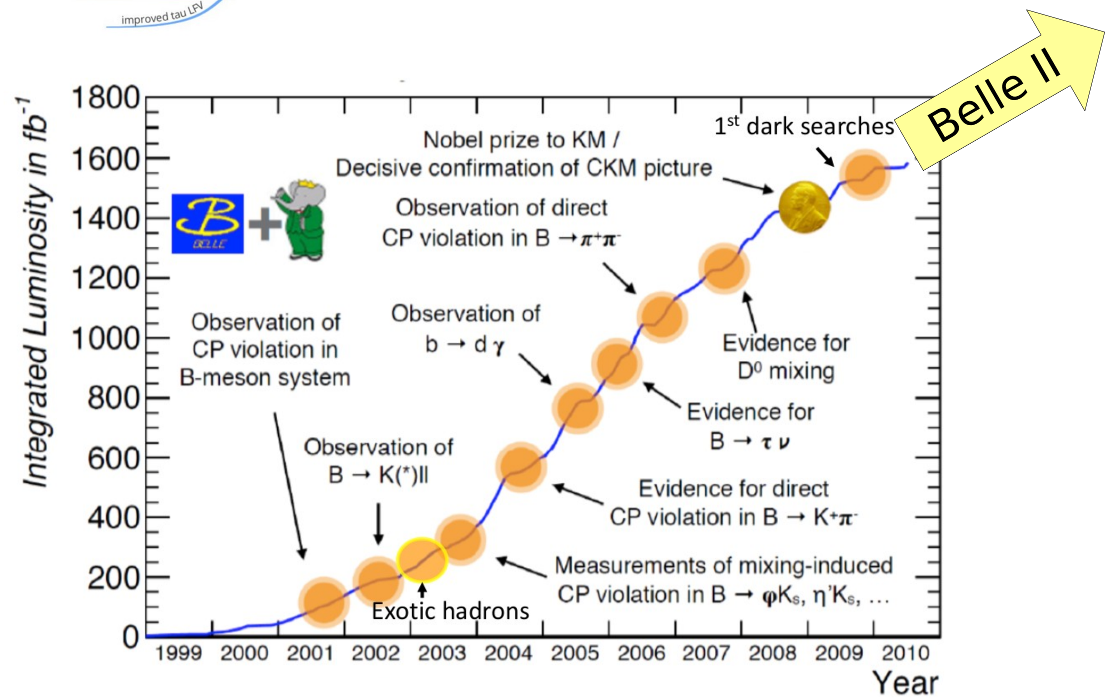


- ➔ $L = 3.12 \times 10^{34}\ cm^{-2}s^{-1}$ (world record)
- ➢ Update of projections in progress

Conclusions

- ✔ Belle II produced interesting and competitive results with little data already
- ✔ The Belle II physics program is very broad
- ✔ New ideas are extending the physics reach
- ➔ If new physics is found in the next ten years I think the chances are high that Belle II will have to say something about it



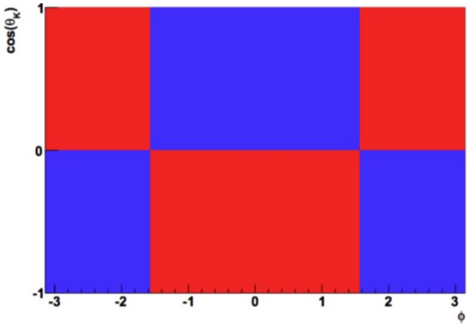


Backup

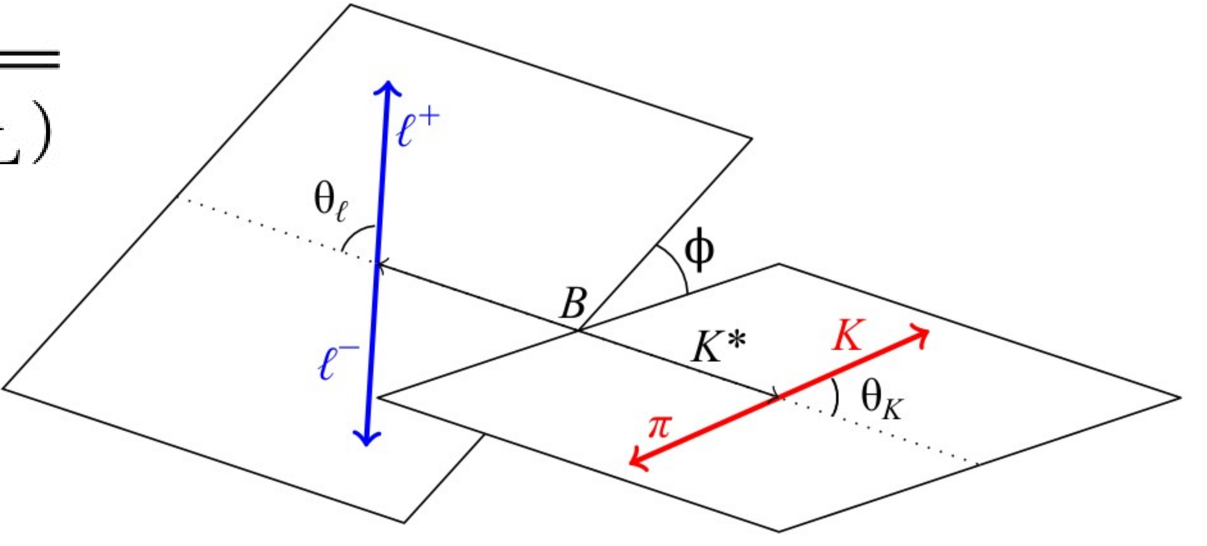
P5'

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

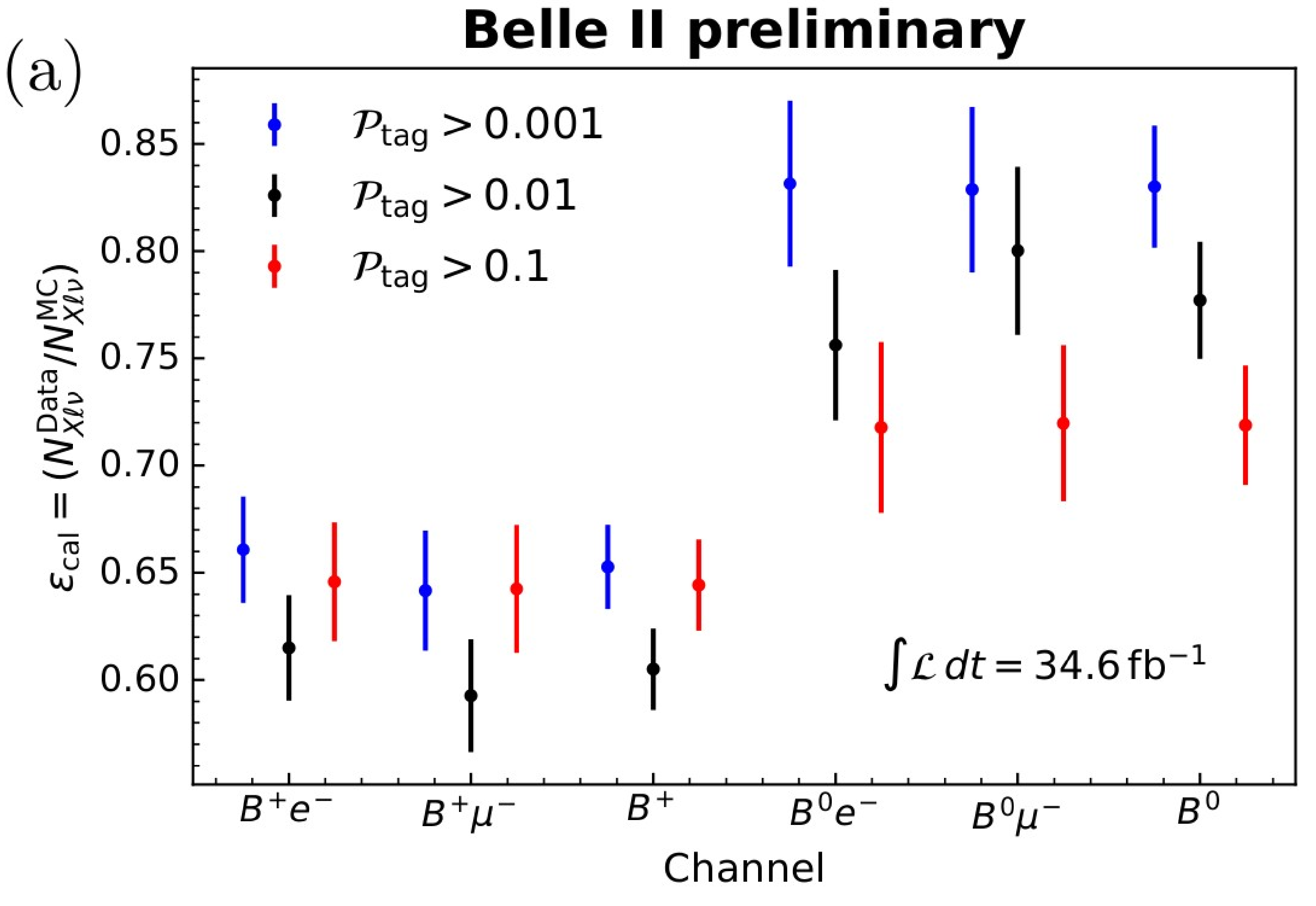


Counting S_5: blue minus red



FEI Calibration

arXiv:2008.06096
BELLE2-CONF-PH-2020-005



Hadronic Moments in $B \to X_c \ell \nu$

arXiv:2009.04493
BELLE2-CONF-PH-2020-011

Calibration:

$$\langle M_X^n \rangle = \frac{\sum_i w_i(M_X) M_{X,\mathrm{calib}\,i}^{\;n}}{\sum_i w_i(M_X)} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{true}}$$

- Difference of rec. and true M_X in bins of E_{miss}–p_{miss}, X_{mult}, p_ℓ^* → $M_{X,calib}$
- Difference of rec. and true moment → $\mathcal{C}_{calib}$
- Difference of true moment with and without event selection → $\mathcal{C}_{true}$