Belle II

t

Summer 2019 $\mathscr{L} = 6.5/\text{fb}$

Spring 2020 $\mathscr{L} = \mathscr{O}(10/\text{fb})$

Summer 2020 $\mathscr{L} = \mathscr{O}(100/\text{fb})$

A beautiful Summer:

Belle II Status and Outlook

florian.bernlochner@uni-bonn.de

Florian Bernlochner

UNIVERSITÄT BONN

Belle II at the Summer conferences

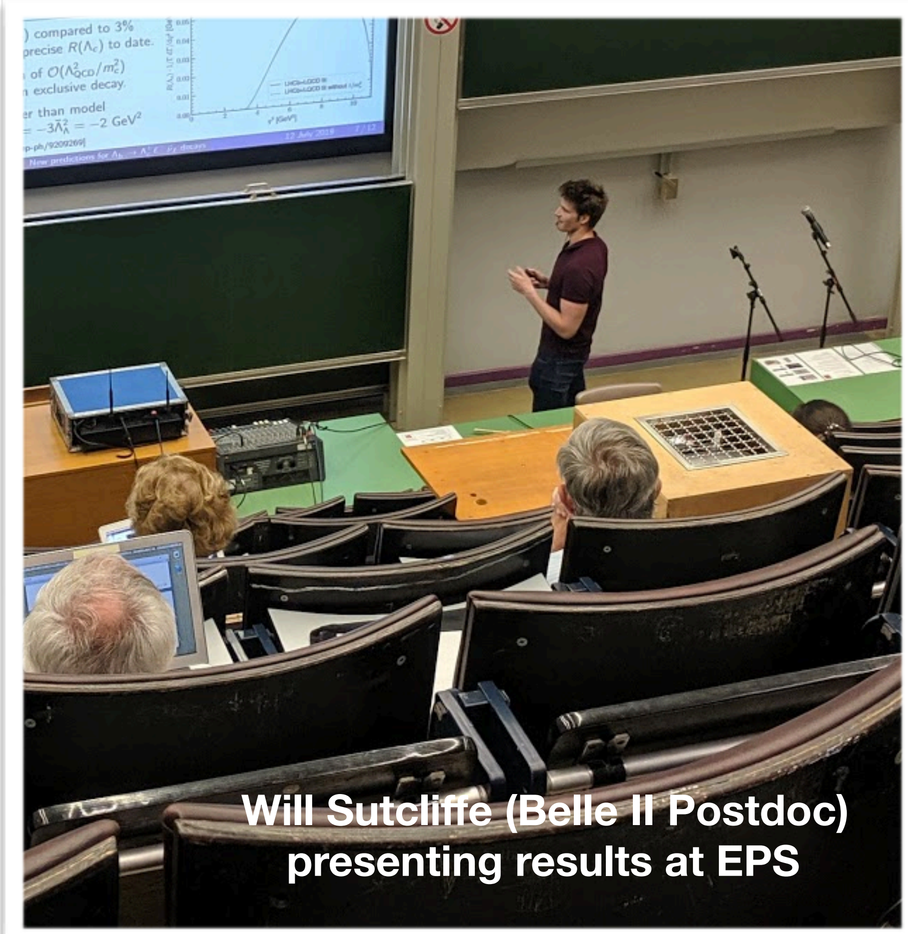
EUROPEAN PHYSICAL SOCIETY HEP2019

11 Contributions

LP2019

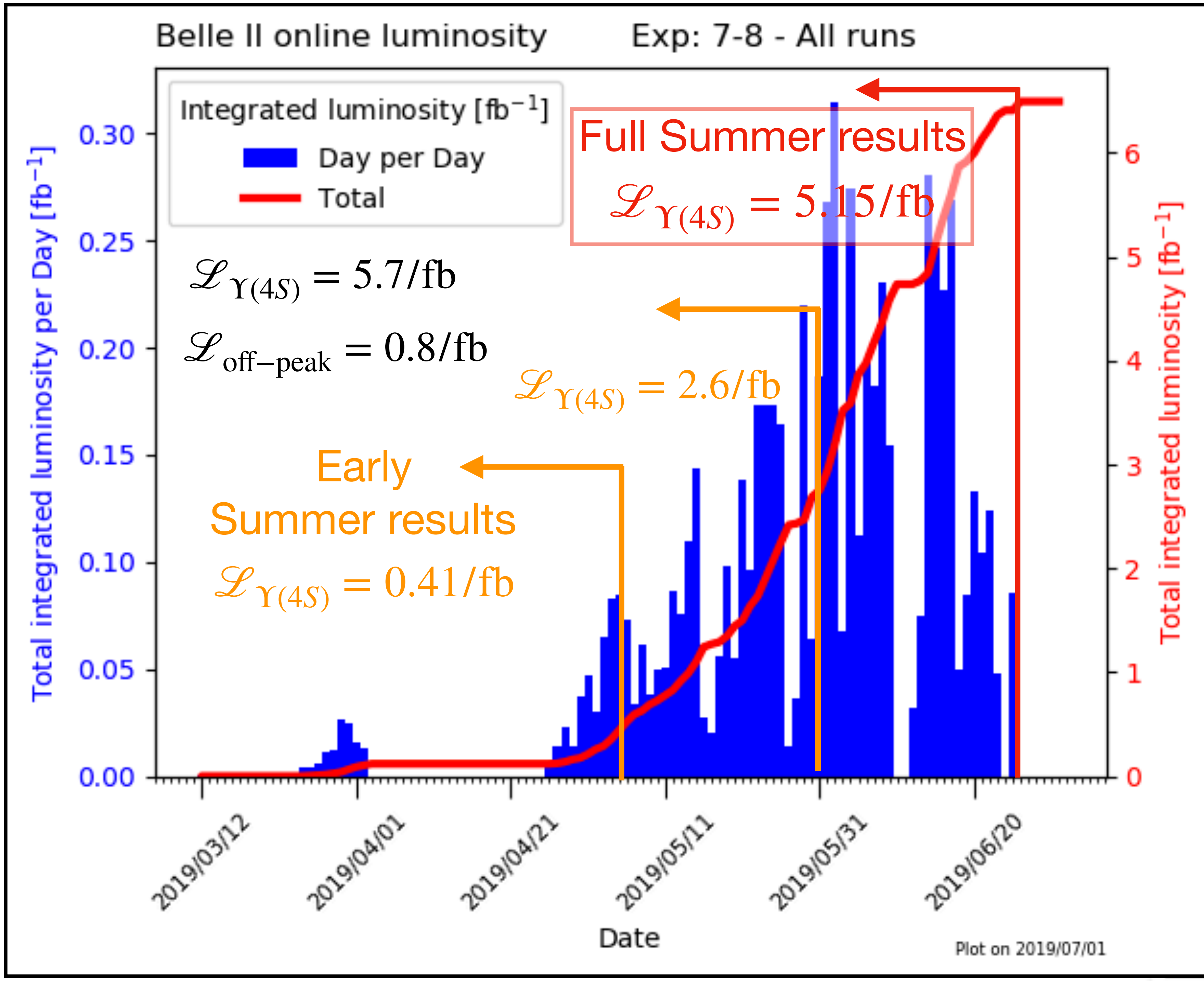
7 Contributions

+ several smaller workshops and other conferences

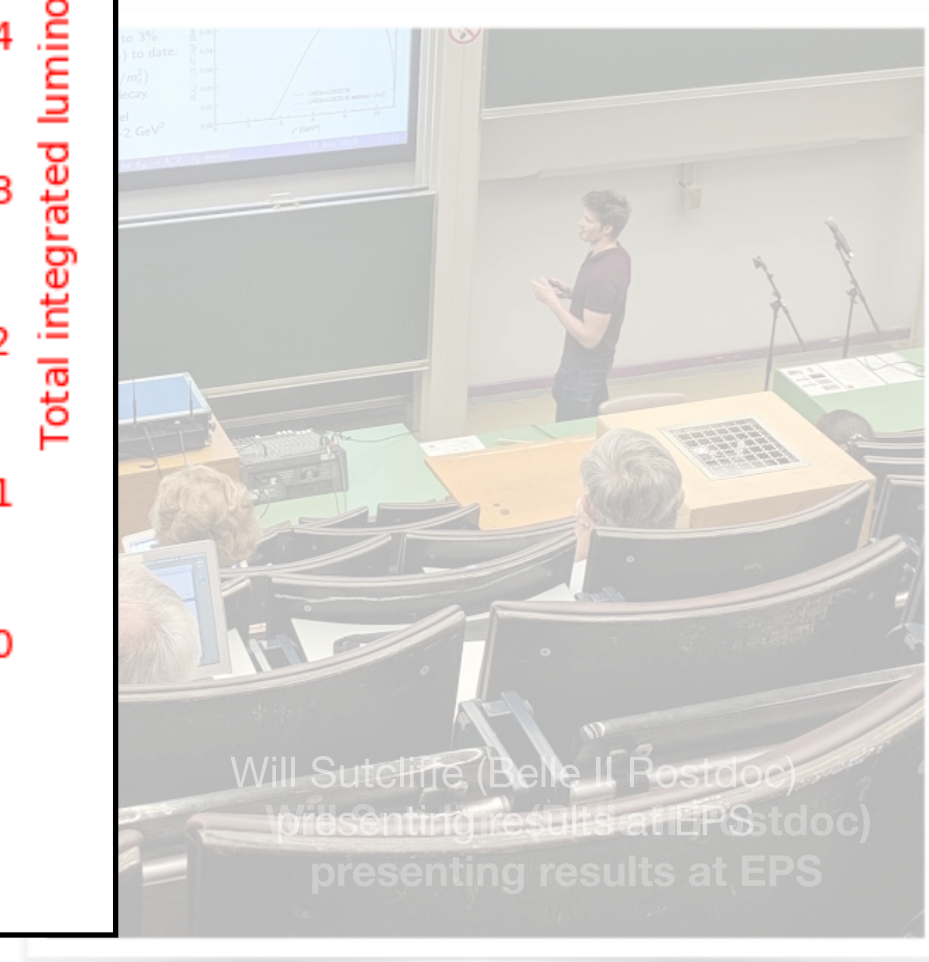


Will Sutcliffe (Belle II Postdoc) presenting results at EPS

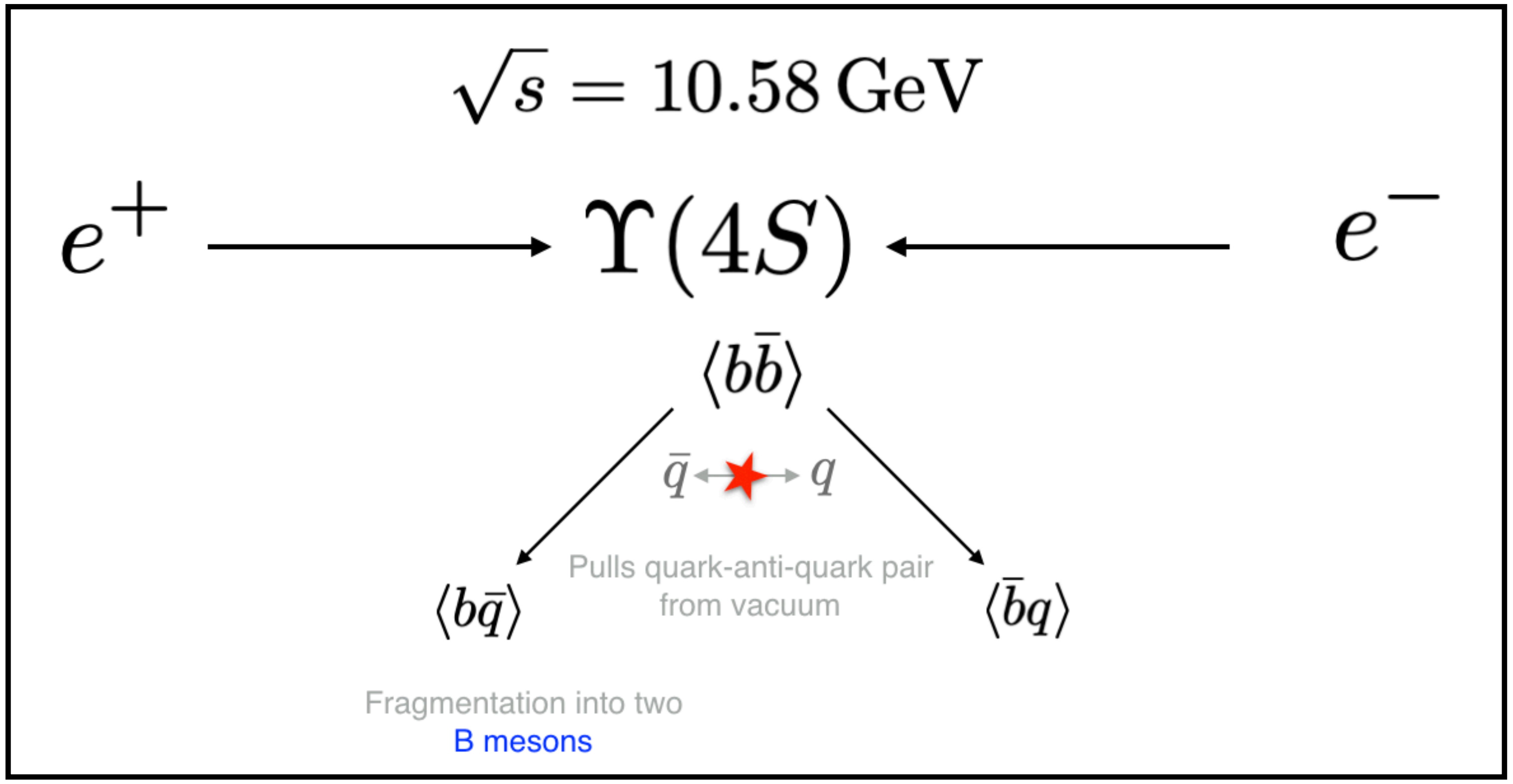
Belle II at the Summer conferences



ntributions



B Mesons in a nutshell

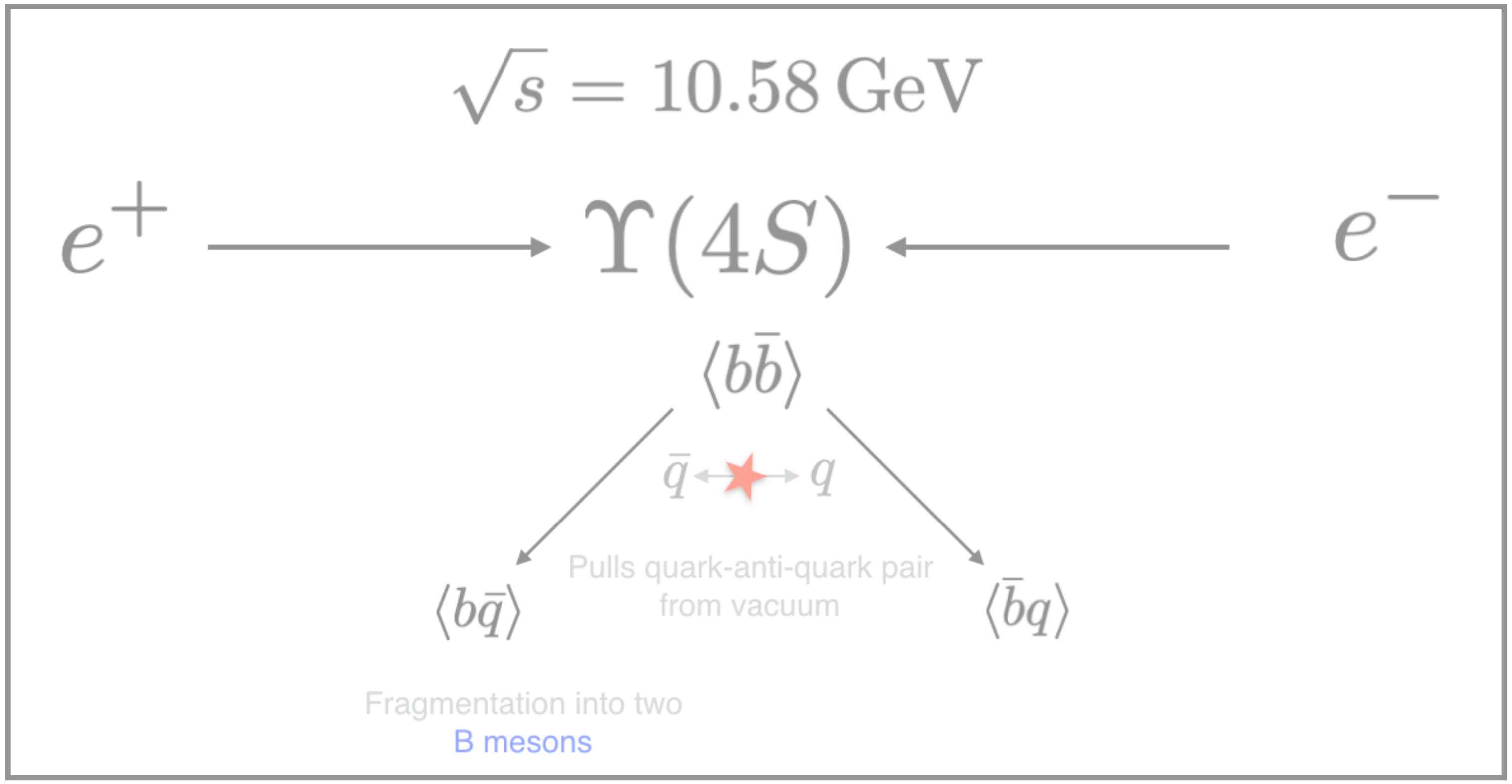


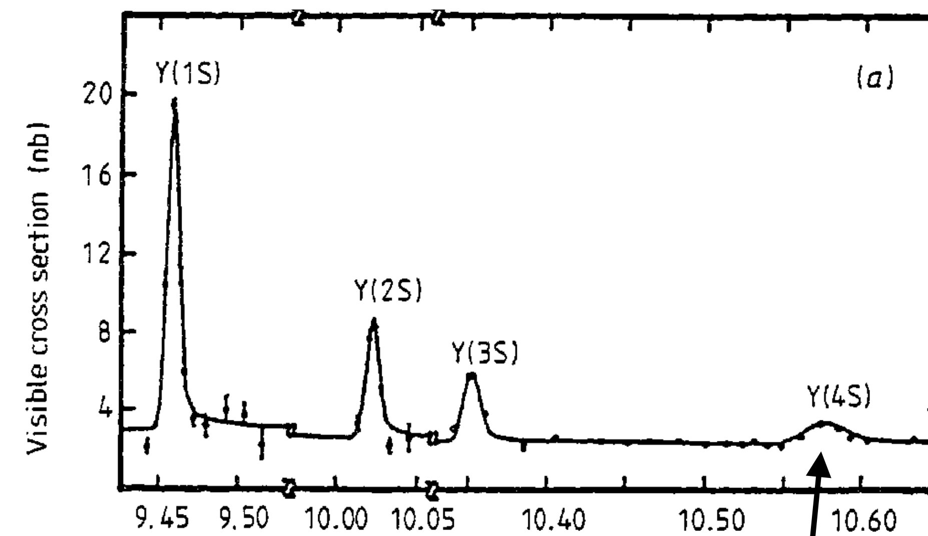
$$\left(m_{\Upsilon(4S)}, \vec{0}\right) = \left(\sqrt{m_B^2 + |\vec{p}_B|^2}, \vec{p}_B\right) + \left(\sqrt{m_B^2 + |\vec{p}_B|^2}, -\vec{p}_B\right)$$

$$\downarrow$$

$$m_{\Upsilon(4S)} = 2\sqrt{m_B^2 + |\vec{p}_B|^2} \longrightarrow |\vec{p}_B| = \sqrt{m_{\Upsilon(4S)}^2/4 - m_B^2} \approx 340\,\mathrm{MeV}$$

B Mesons in a nutshell



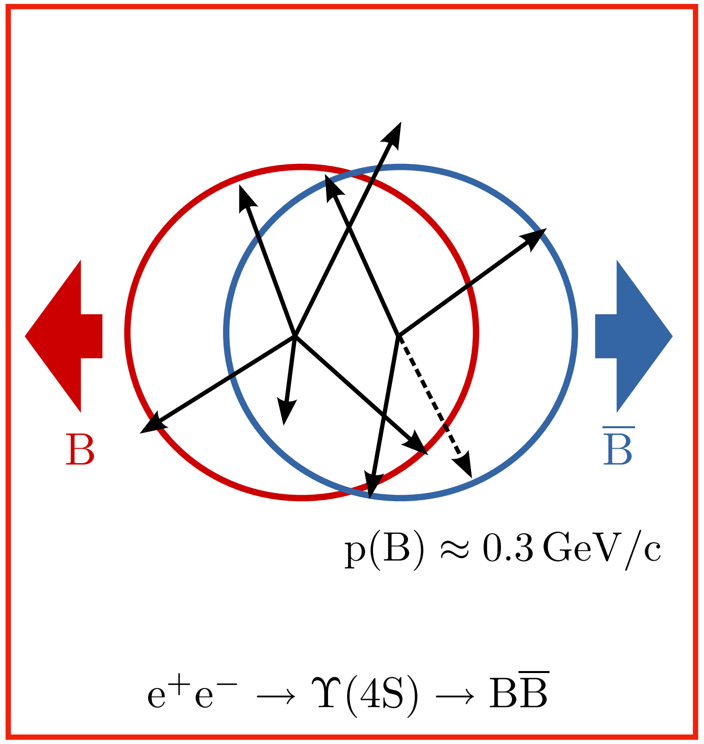


$$\left(m_{\Upsilon(4S)}, \vec{0}\right) = \left(\sqrt{m_B^2 + |\vec{p}_B|^2}, \vec{p}_B\right) + \left(\sqrt{m_B^2 + |\vec{p}_B|^2}, -\vec{p}_B\right)$$

$$m_{\Upsilon(4S)} = 2\sqrt{m_B^2 + |\vec{p}_B|^2} \longrightarrow |\vec{p}_B| = \sqrt{m_{\Upsilon(4S)}^2/4 - m_B^2} \approx 340\,\mathrm{MeV}$$

Repeat a similar calculation for a charm quark $m_c \approx 1.4\,\mathrm{GeV}$ and you will get about **5 GeV**

B-Meson counting



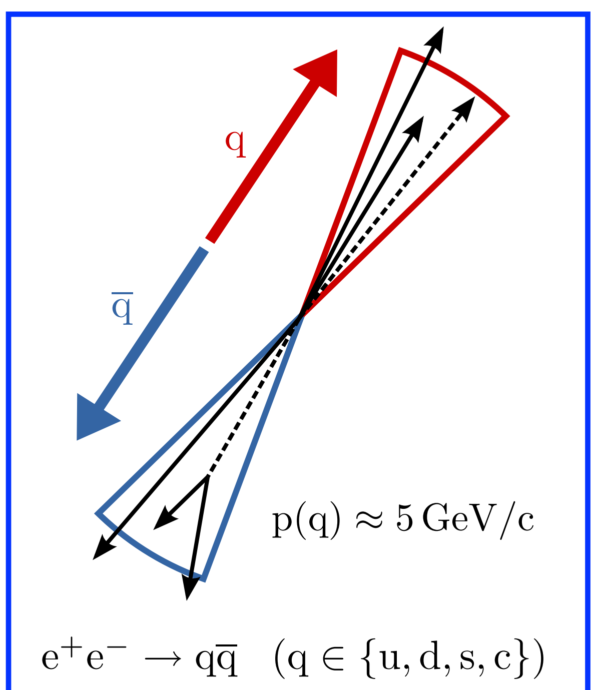
Fox-Wolfram Moment:

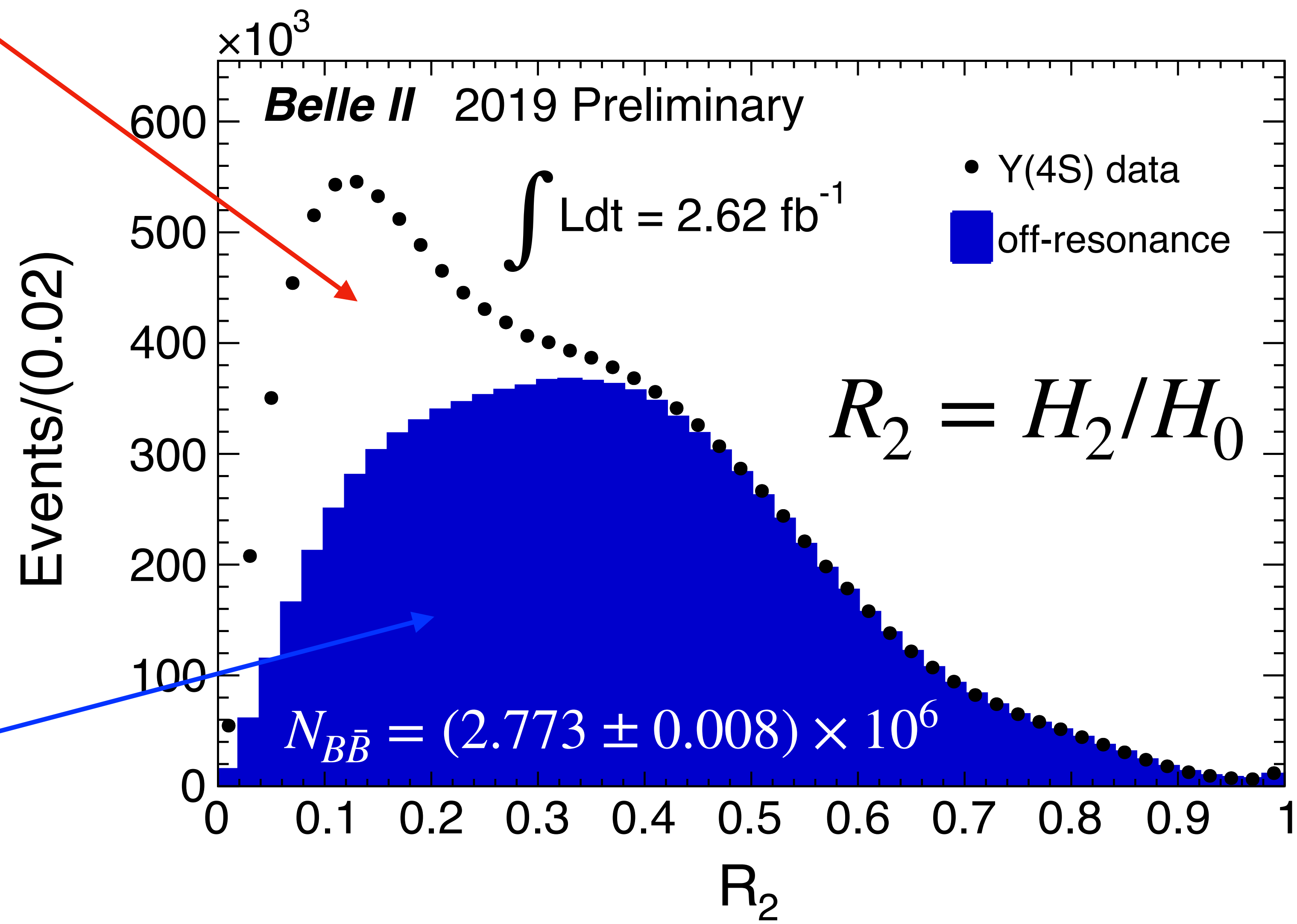
Legende Polynomial

$$H_l = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{\left(\sum_i |\vec{p}_i|\right)^2} P_l(\cos\theta_{ij})$$

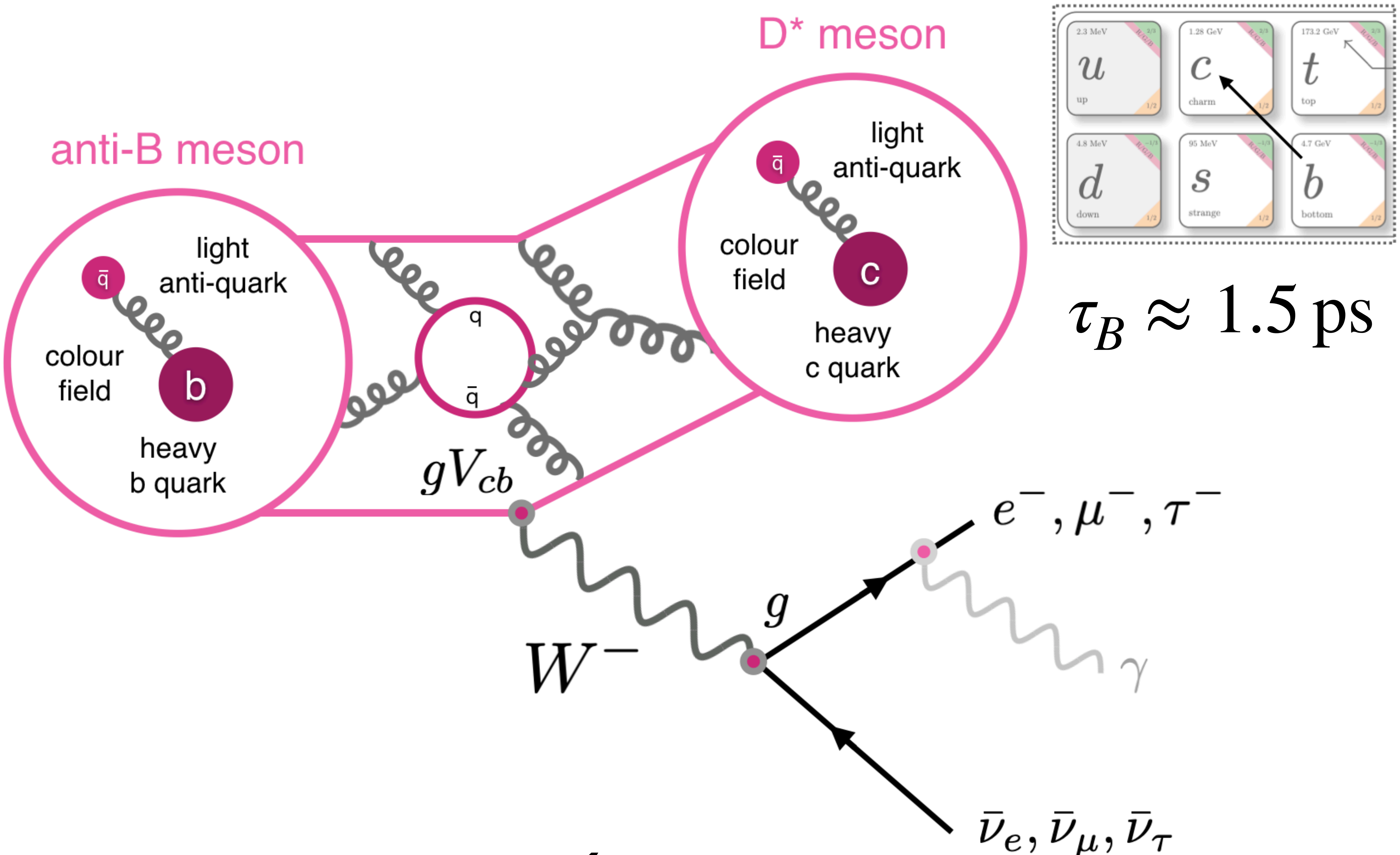
$|\vec{p}_i|$: 3-Momentum of charged tracks or neutral clusters

θ_{ij} : Opening angle between *ith* and *jth* particle





Rediscovery of $B^0 \to D^{*-}\ell^+\nu_\ell$



$\tau_B \approx 1.5\,\mathrm{ps}$

$$\mathscr{B} \approx 11\,\%$$

Properties of $B^0 \to D^{*-}\ell^+\nu_\ell$

Four-momentum conservation:

$$p_B = p_{D^*\ell} + p_\nu$$

As the mass of the neutrino is ~ zero GeV^2 :

$$0\,\mathrm{GeV}^2 = p_\nu^2 = \left(p_B - p_{D^*\ell}\right)^2 = m_B^2 + m_{D^*\ell}^2 - 2p_B \cdot p_{D^*\ell} = \boxed{m_{\mathrm{miss}}^2}$$

Properties of $B^0 \to D^{*-}\ell^+\nu_\ell$

Four-momentum conservation:

$$p_B = p_{D^*\ell} + p_\nu$$

As the mass of the neutrino is equal to zero:

$$0\,\mathrm{GeV}^2 = p_\nu^2 = \left(p_B - p_{D^*\ell}\right)^2 = m_B^2 + m_{D^*\ell}^2 - 2 p_B \cdot p_{D^*\ell} = m_{\mathrm{miss}}^2$$

Here:

$$p_B \cdot p_{D^*\ell} = E_B E_{D^*\ell} - \vec{p}_B \cdot \vec{p}_{D^*\ell} = E_B E_{D^*\ell} - |\vec{p}_B||\vec{p}_{D^*\ell}|\cos\theta_{B,D^*\ell}$$

Properties of $B^0 \to D^{*-}\ell^+\nu_\ell$

Four-momentum conservation:

$$p_B = p_{D^*\ell} + p_\nu$$

As the mass of the neutrino is equal to zero:

$$0\,\mathrm{GeV}^2 = p_\nu^2 = \left(p_B - p_{D^*\ell}\right)^2 = m_B^2 + m_{D^*\ell}^2 - 2p_B \cdot p_{D^*\ell} = m_{\mathrm{miss}}^2$$

Here:

$$p_B \cdot p_{D^*\ell} = E_B E_{D^*\ell} - \vec{p}_B \cdot \vec{p}_{D^*\ell} = E_B E_{D^*\ell} - |\vec{p}_B||\vec{p}_{D^*\ell}|\cos\theta_{B,D^*\ell}$$

Putting this together and solve for the angle:

$$0 = m_B^2 + m_{D^*\ell}^2 - 2\left(E_B E_{D^*\ell} - |\vec{p}_B||\vec{p}_{D^*\ell}|\cos\theta_{B,D^*\ell}\right)$$

$$\Rightarrow \boxed{\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}}$$

Properties of $B^0 \to D^{*-}\ell^+\nu_\ell$

Four-momentum conservation:

$$p_B = p_{D^*\ell} + p_\nu$$

$$m^2_{\text{miss}} = \left((\frac{1}{2}E_{\text{beam}},0,0,0) - p_{D^*\ell} \right)^2 \approx p_\nu^2 = 0\,\text{GeV}^2$$

As the mass of the neutrino is equal to zero:

$$0\,\text{GeV}^2 = p_\nu^2 = \left(p_B - p_{D^*\ell}\right)^2 = m_B^2 + m_{D^*\ell}^2 - 2p_B \cdot p_{D^*\ell} = m^2_{\text{miss}}$$

Here: $$0\,\text{GeV}^2 = p_\nu^2 = \left(p_B - p_{D^*\ell}\right)^2 = m_B^2 + m_{D^*\ell}^2 - 2p_B \cdot p_{D^*\ell} = m^2_{\text{miss}}$$

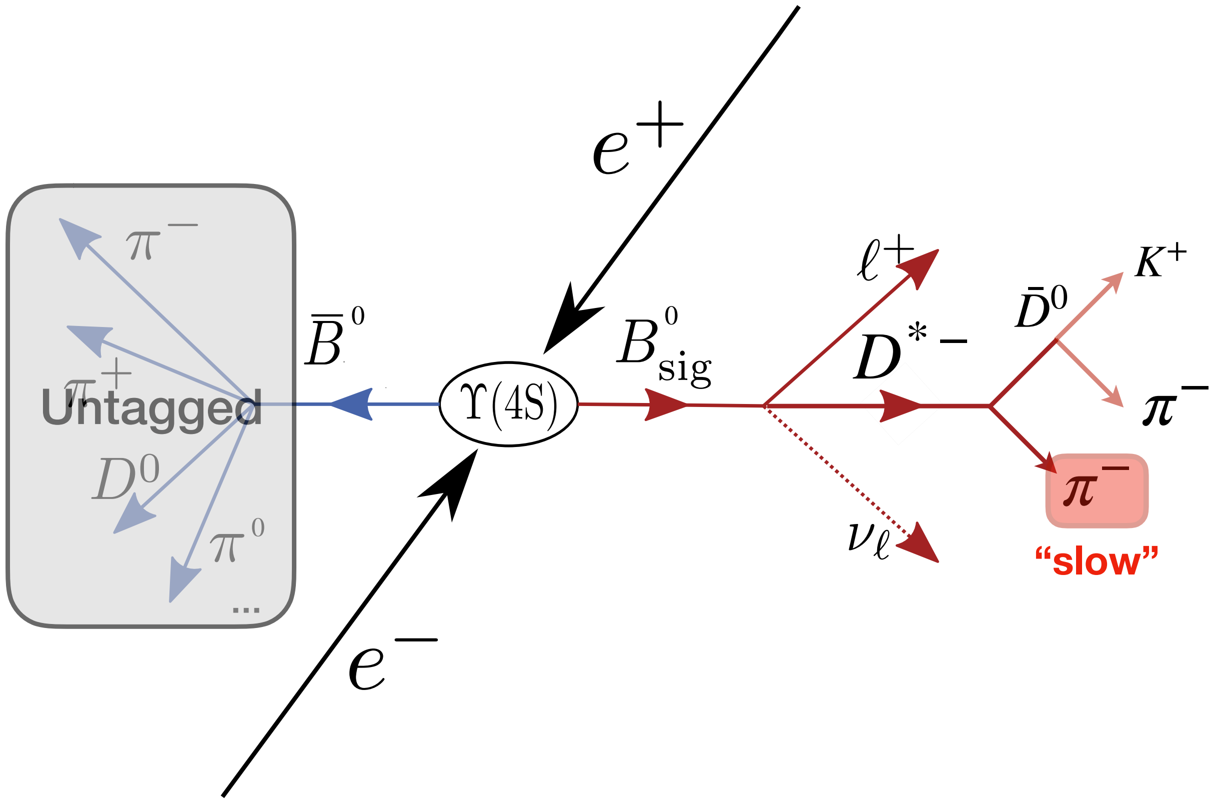
$$p_B \cdot p_{D^*\ell} = E_B E_{D^*\ell} - \vec{p}_B \cdot \vec{p}_{D^*\ell} = E_B E_{D^*\ell} - |\vec{p}_B||\vec{p}_{D^*\ell}|\cos\theta_{B,D^*\ell}$$

Putting this together and solve for the angle:

$$0 = m_B^2 + m_{D^*\ell}^2 - 2\left(E_B E_{D^*\ell} - |\vec{p}_B||\vec{p}_{D^*\ell}|\cos\theta_{B,D^*\ell}\right)$$

$$\Rightarrow \cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$$

Rediscovery of $B^0 \to D^{*-}\ell^+\nu_\ell$



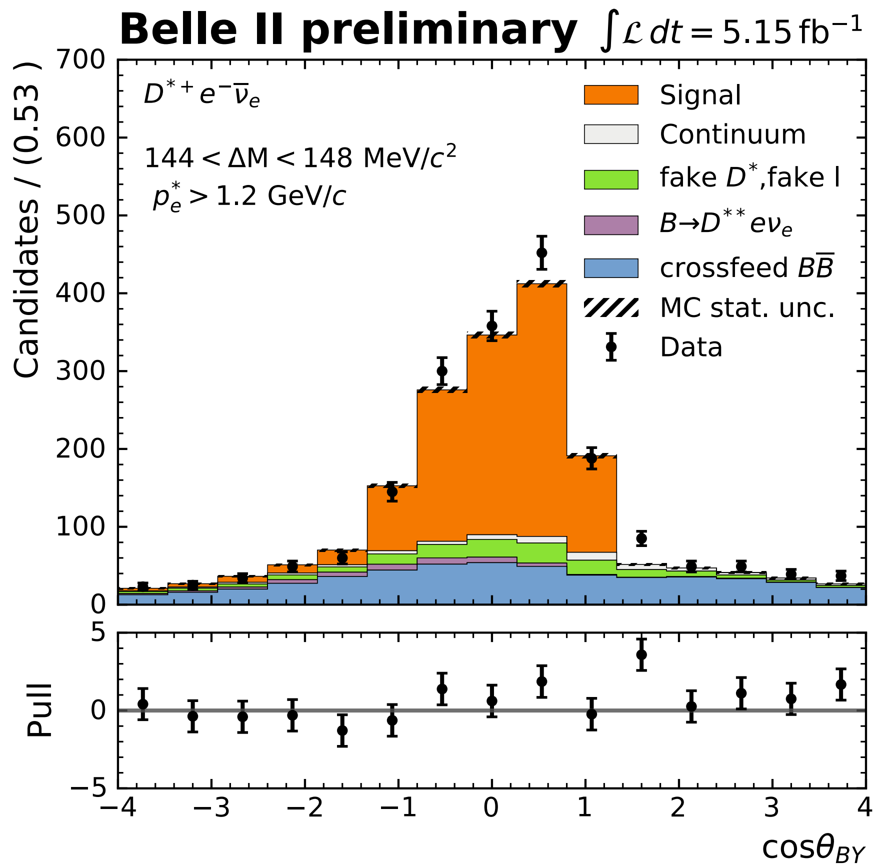
Particle	Selection
Tracks	IP in $z < 2$ cm
Tracks	IP in r-ϕ plane < 0.5 cm
ℓ	$1.2 < p_\ell^* < 2.4$ GeV$/c$
e	Electron likelihood > 0.85
μ	Muon likelihood > 0.9
slow π	$p_\pi^* < 0.5$ GeV$/c$
D^0	$1.85 < M_D < 1.88$ GeV$/c^2$
D^*	$0.144 < M_{D^*} - M_D < 0.148$ GeV$/c^2$
D^*	$p_{D^*} < 2.5$ GeV$/c$

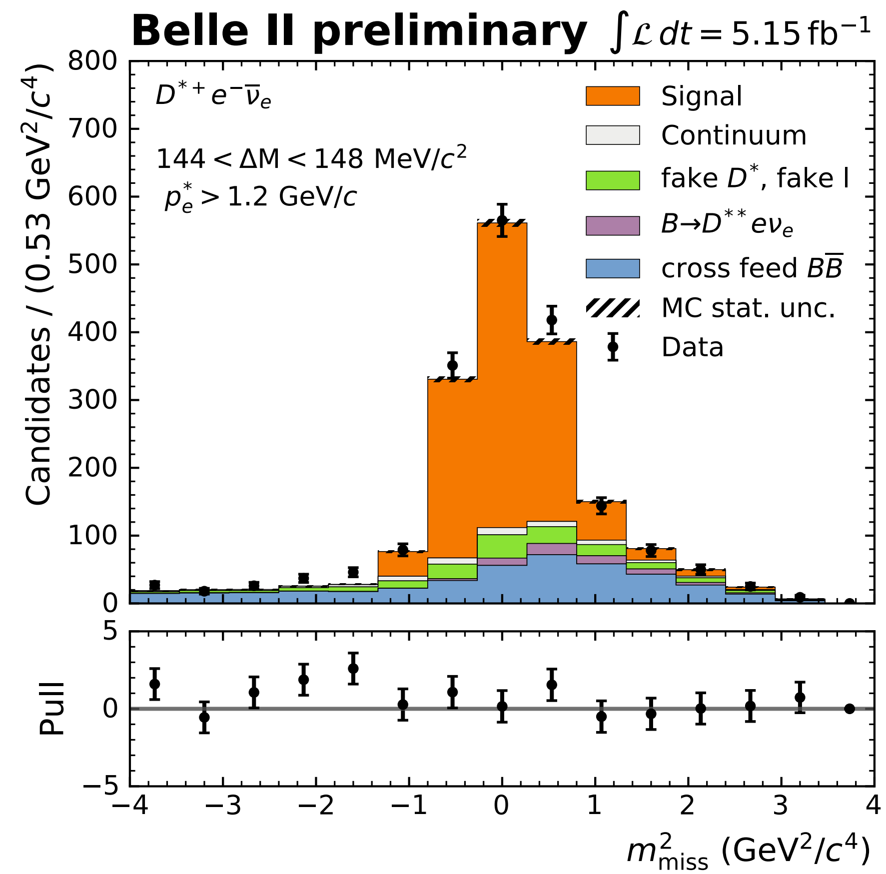
$$\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|} \in [-1,1)$$

$$m_{\rm miss}^2 = \left((\frac{1}{2}E_{\rm beam},0,0,0) - p^*_{D^*\ell} \right)^2 \approx p_\nu^2 = 0\,\mathrm{GeV}^2$$

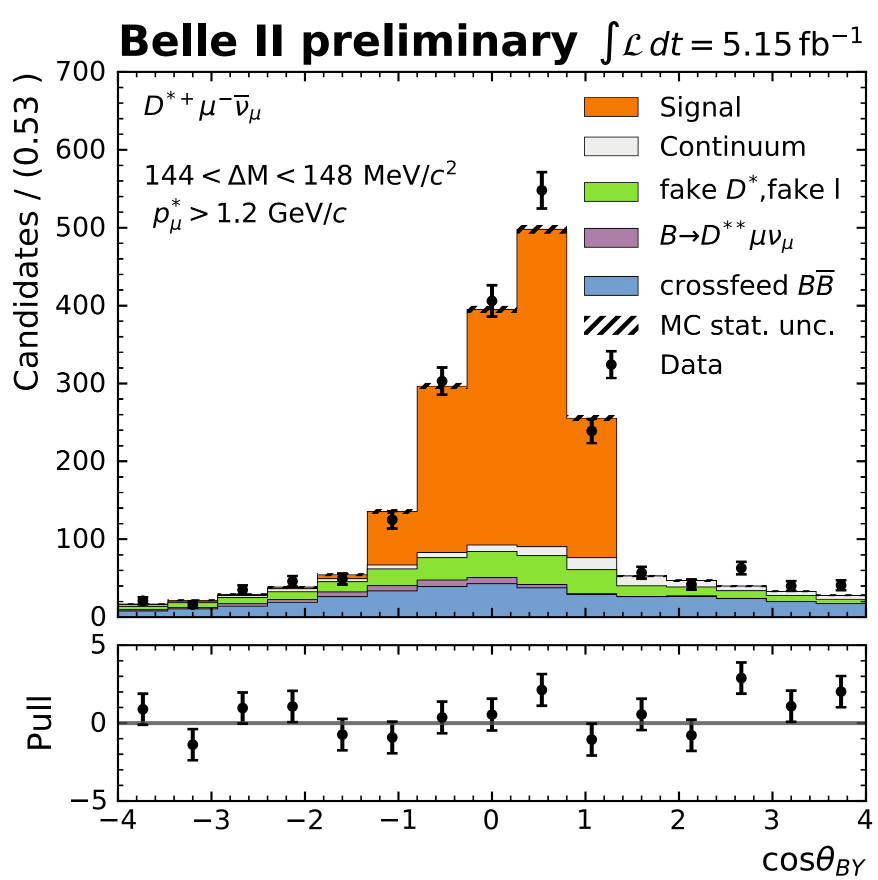
$\cos\theta_{B,D^*\ell}$ m^2_{miss}

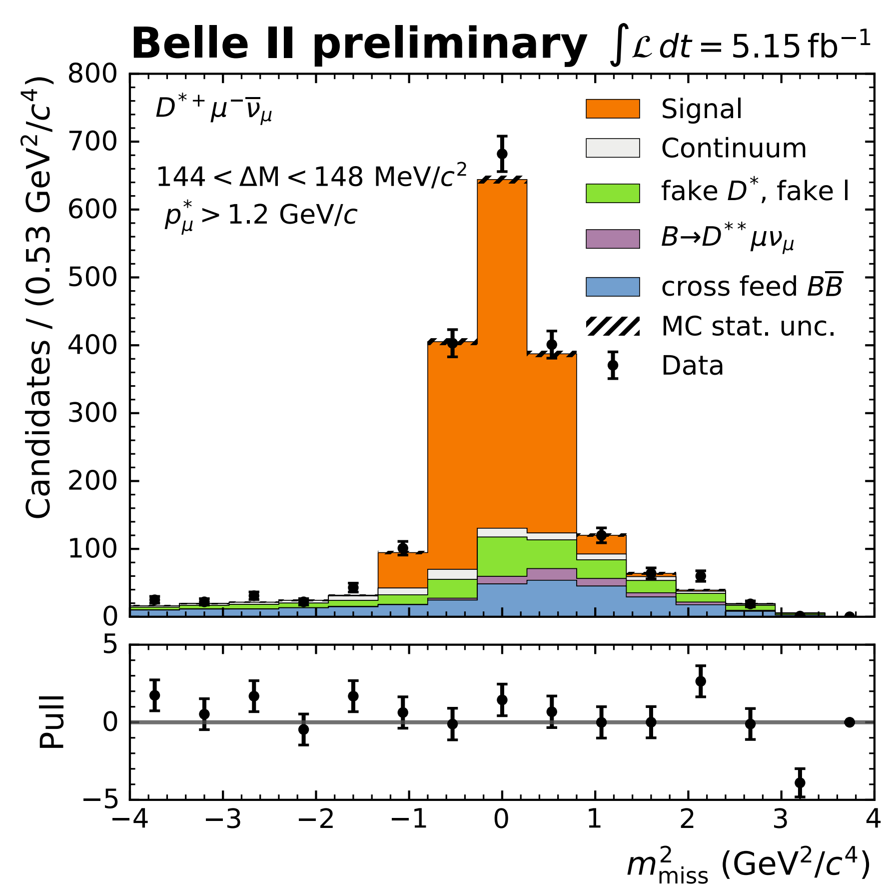
$\ell = e$





$\ell = \mu$



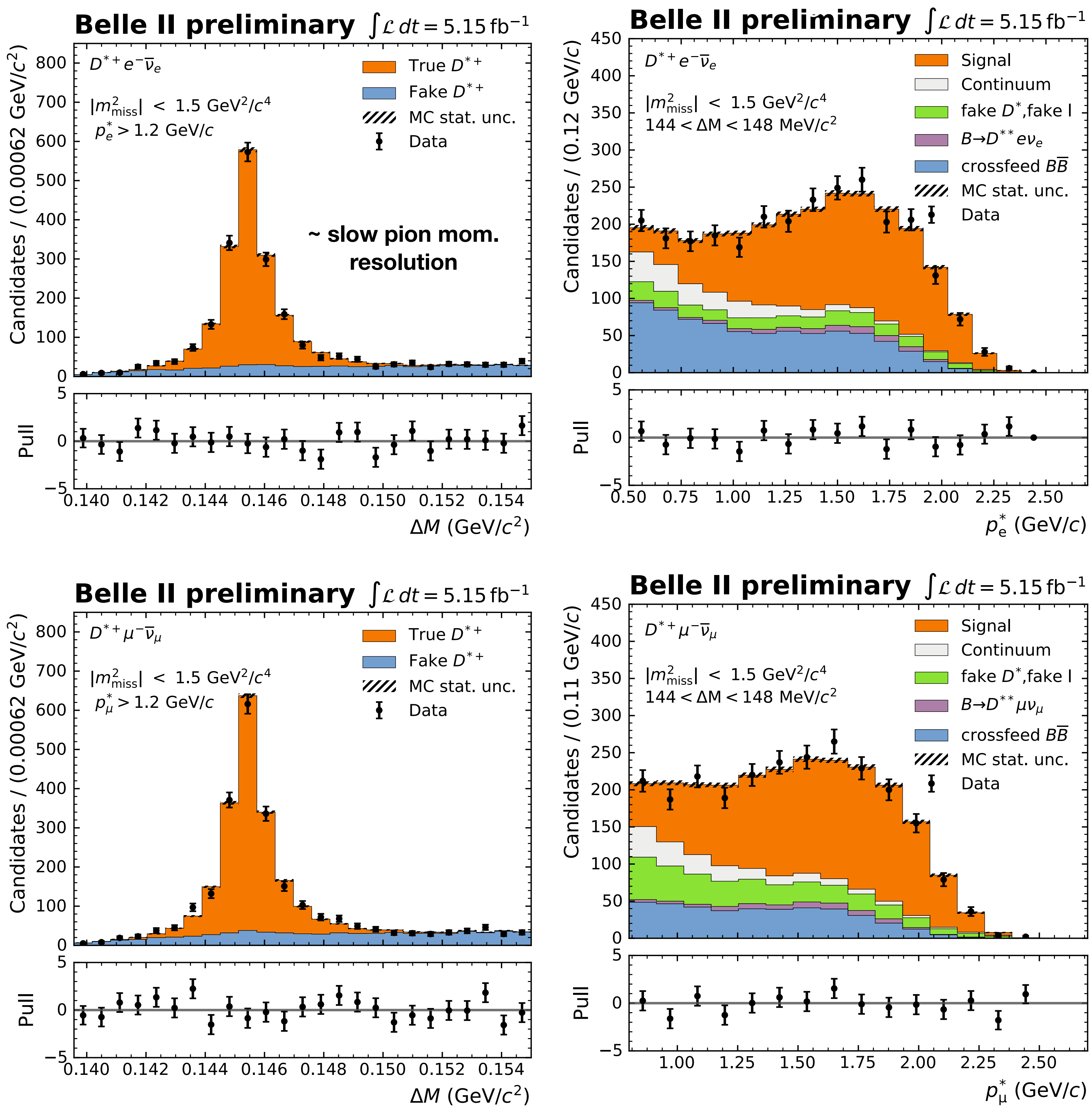


$$\Delta M = m_{D^*} - m_D$$

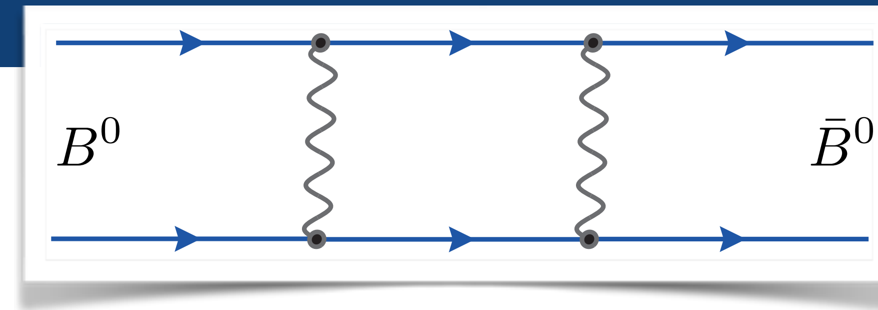
p_ℓ^* ← CM

$\ell = e$

$\ell = \mu$



Rediscovering of B-Mixing with $B^0 \to D^{*-}\ell^+\nu_\ell$

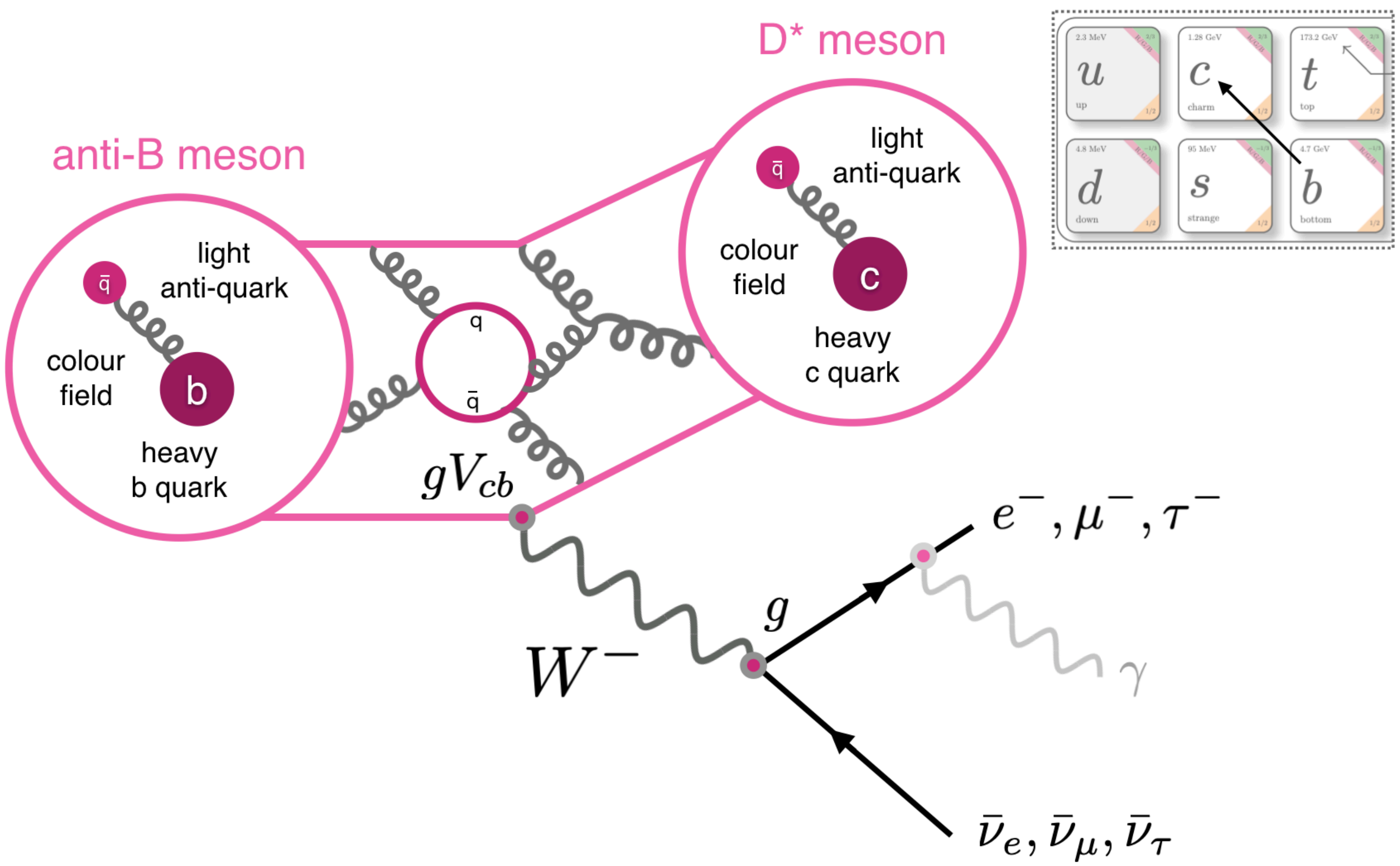


Charge of lepton encodes B-Meson type:

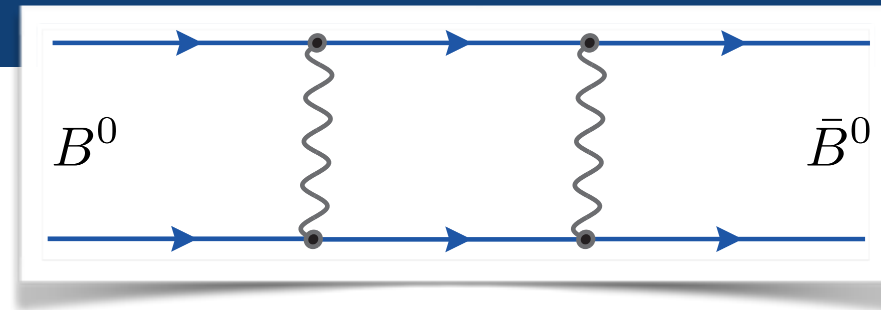
$$\ell^- \leftrightarrow \bar{B}^0$$

$$\ell^+ \leftrightarrow B^0$$

$$B \to X\ell\bar{\nu}_\ell$$



Rediscovering of B-Mixing with $B^0 \to D^{*-}\ell^+\nu_\ell$

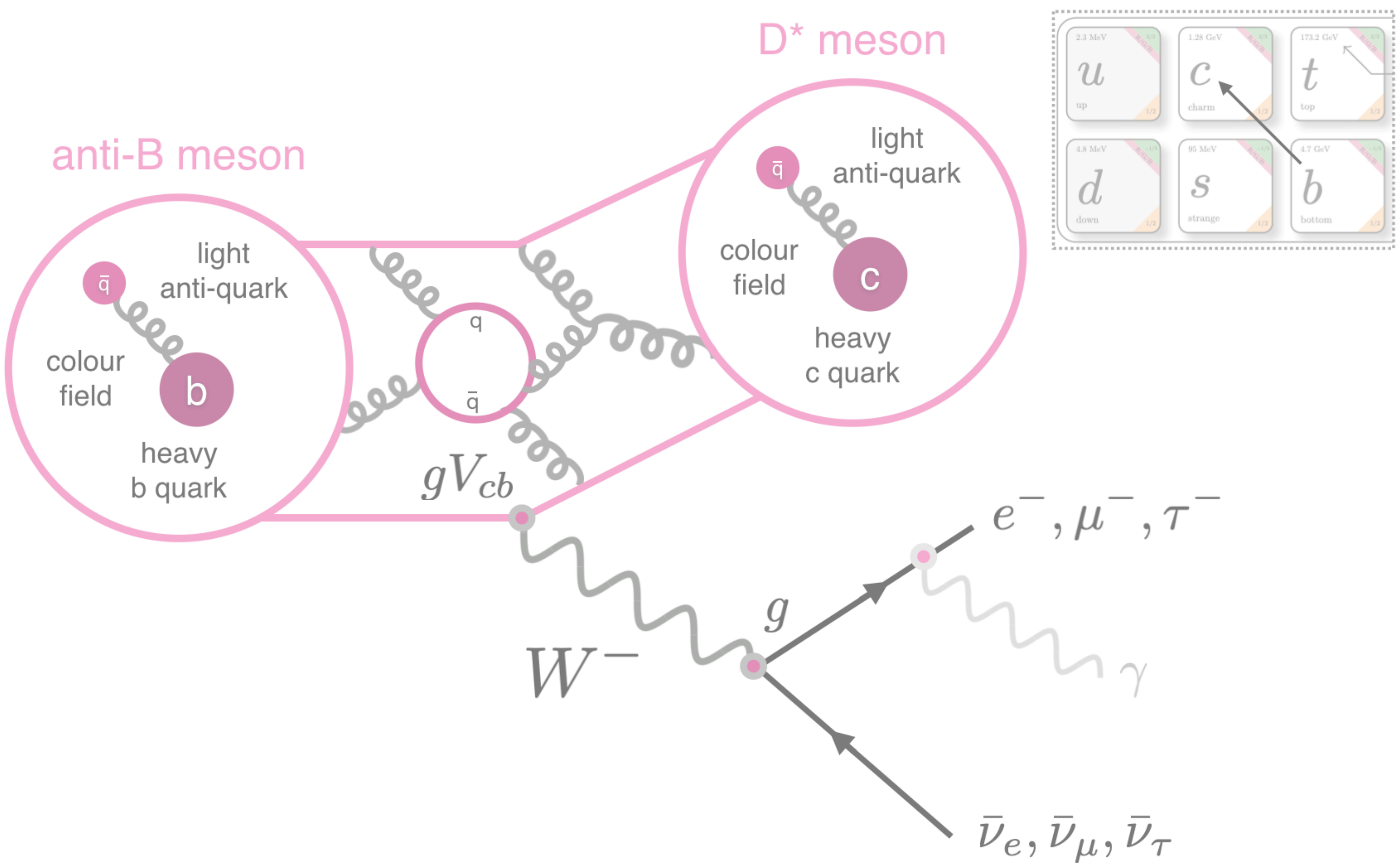


Charge of lepton encodes B-Meson type:

$$\ell^- \leftrightarrow \bar{B}^0$$

$$\ell^+ \leftrightarrow B^0$$

Establish existing of Mixing: **double-tag** SL decays, information encoded in $N_{\ell^+\ell^-}, N_{\ell^+\ell^+}$



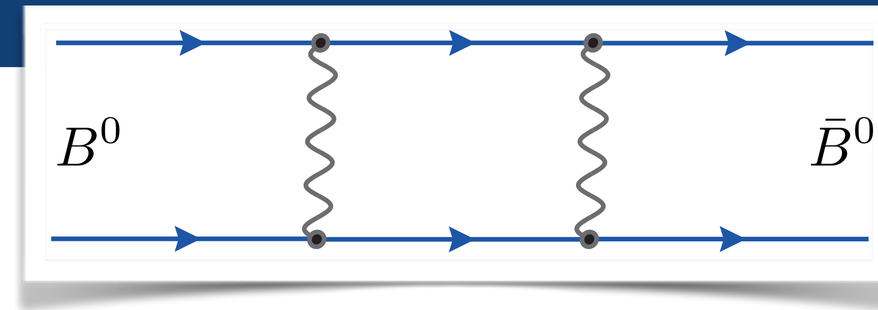
time-integrated mixing probability:

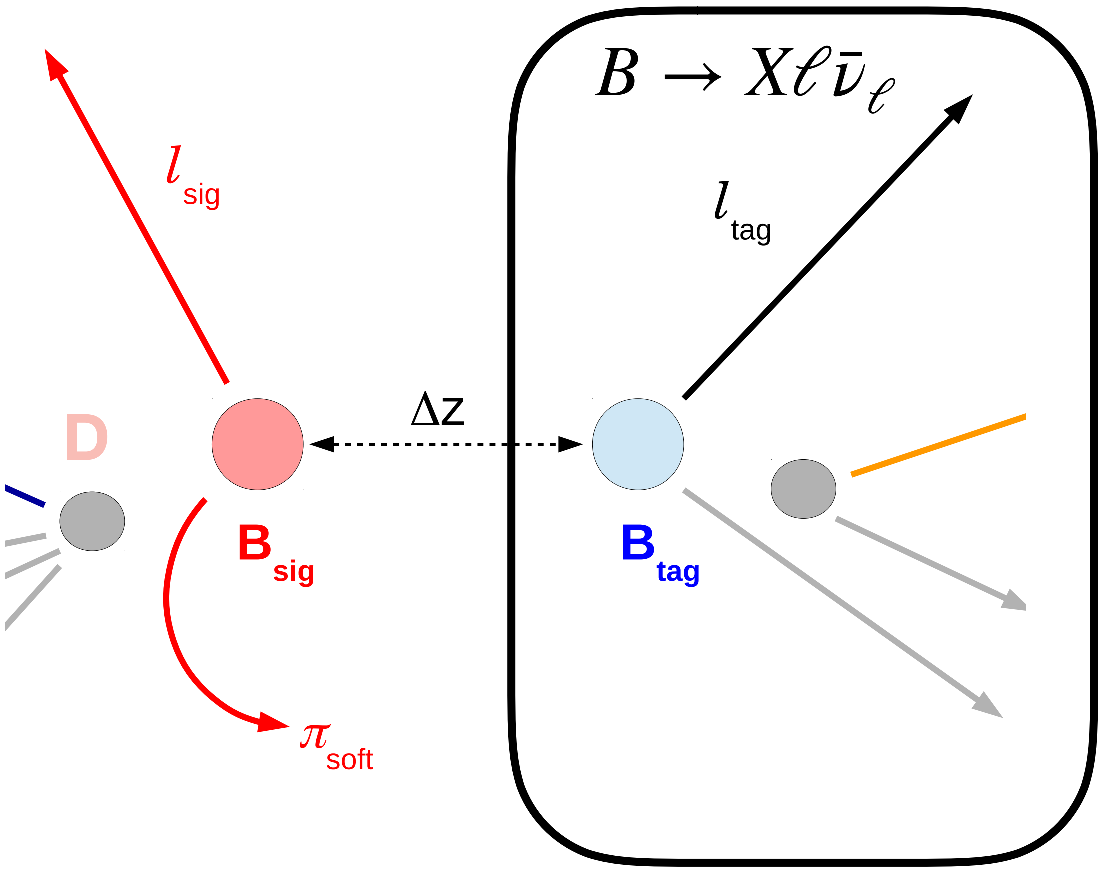
ratio of efficiencies

$$\chi_d = \frac{N_{\ell^+\ell^-} \times \epsilon}{N_{\ell^+\ell^+} + N_{\ell^+\ell^-} \times \epsilon}$$

$$\chi_d = 0.174 \pm 0.009$$

Rediscovering of B-Mixing with $B^0 \to D^{*-}\ell^+\nu_\ell$





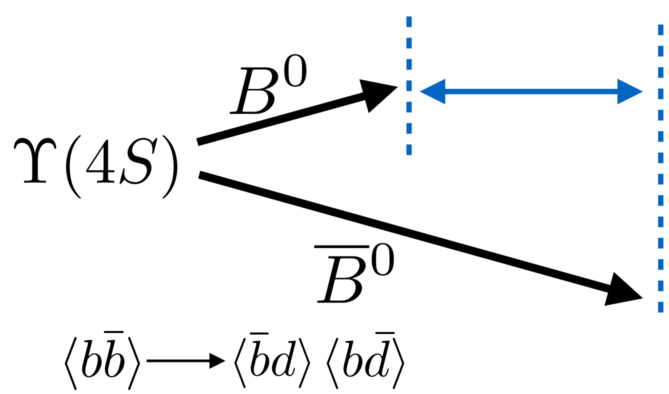
Tag-Side

time-integrated mixing probability:

ratio of efficiencies

$$\chi_d = \frac{N_{\ell^+\ell^-} \times \epsilon}{N_{\ell^+\ell^+} + N_{\ell^+\ell^-} \times \epsilon}$$

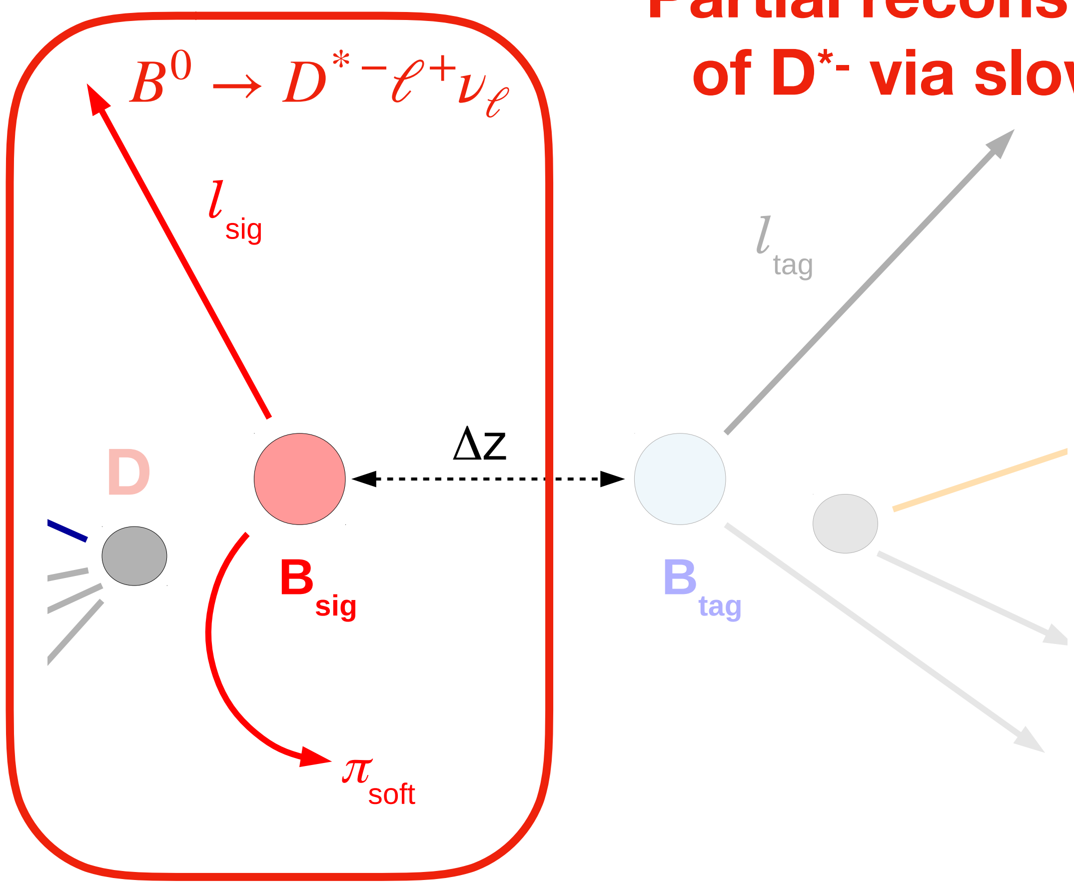
$$\chi_d = 0.174 \pm 0.009$$



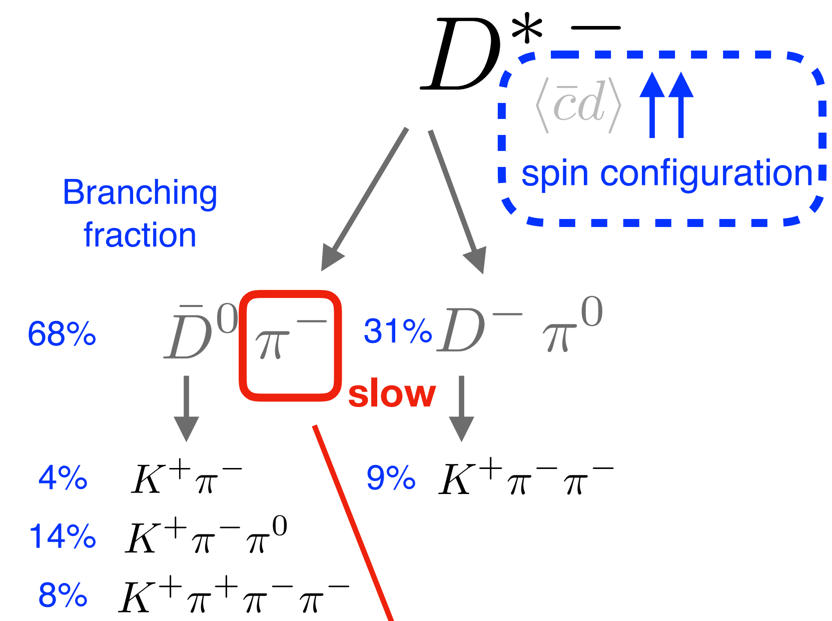
$$\Delta z = c\,\beta\,\gamma\,\Delta t \approx 130\,\mu\text{m}$$

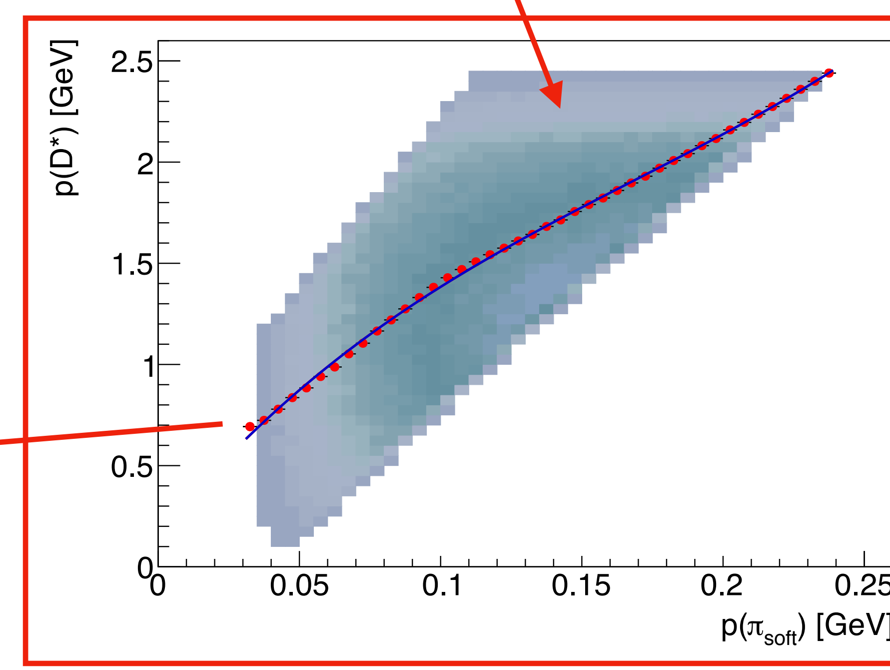
Rediscovering of B-Mixing with $B^0 \to D^{*-}\ell^+\nu_\ell$

Partial reconstruction of D*- via slow pion



Signal-side

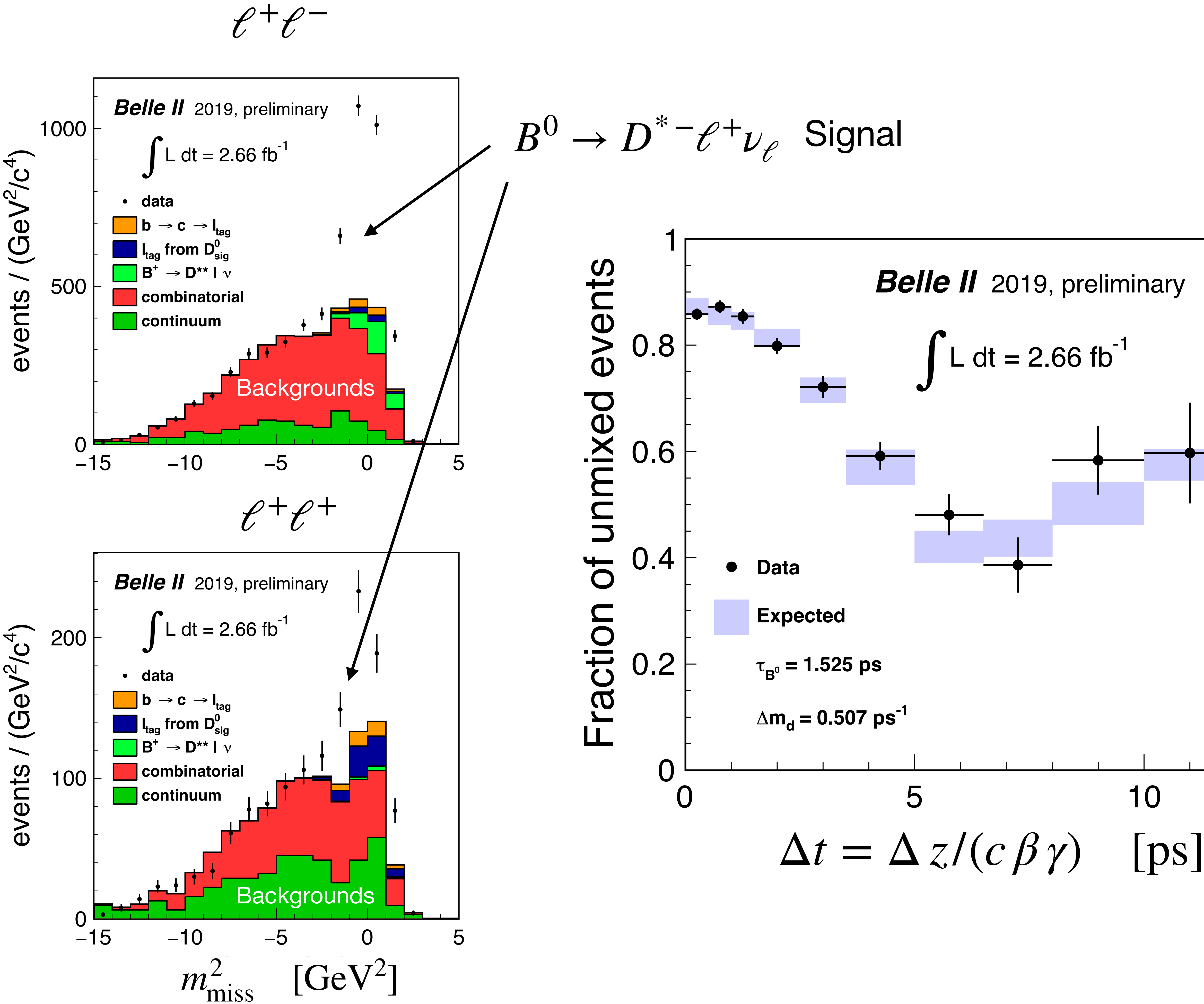




Calibration function from fit to MC:

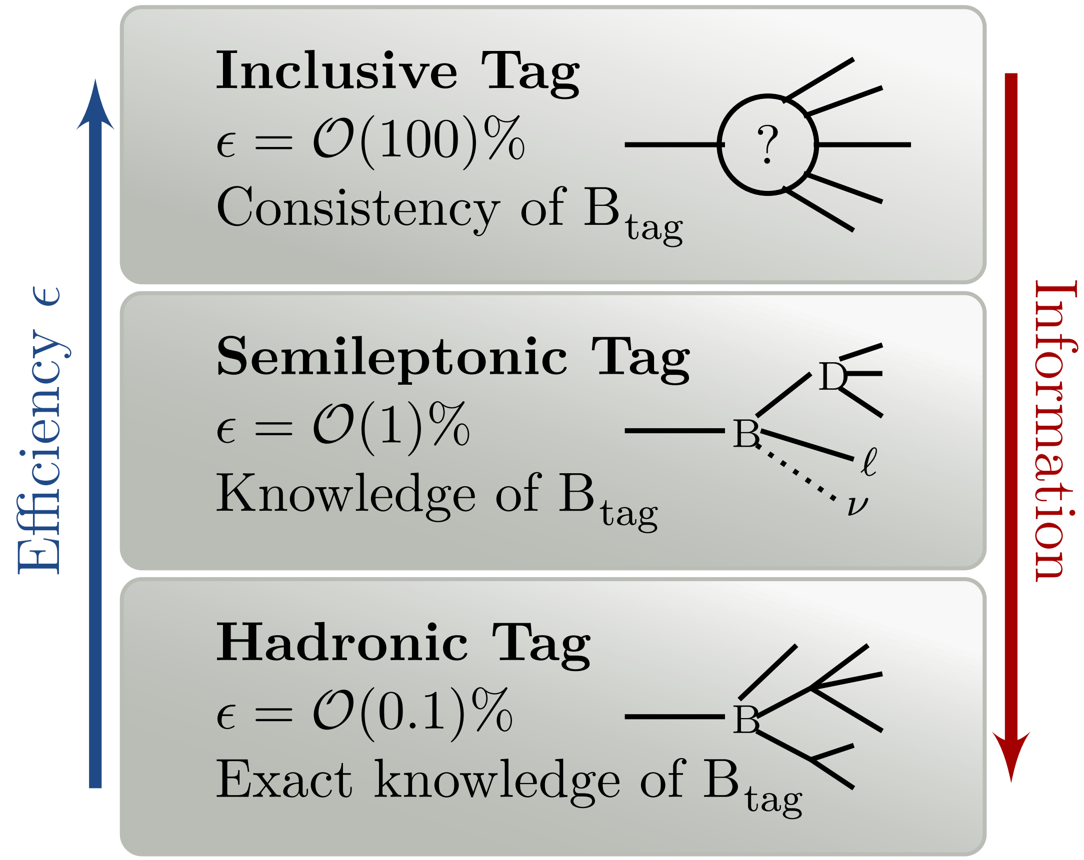
$$p(D^{*-}) = 0.195 + 15.95\, p(\pi_s^-) - 51.50\, p^2(\pi_s^-) + 101.5\, p^3(\pi_s^-)\ .$$

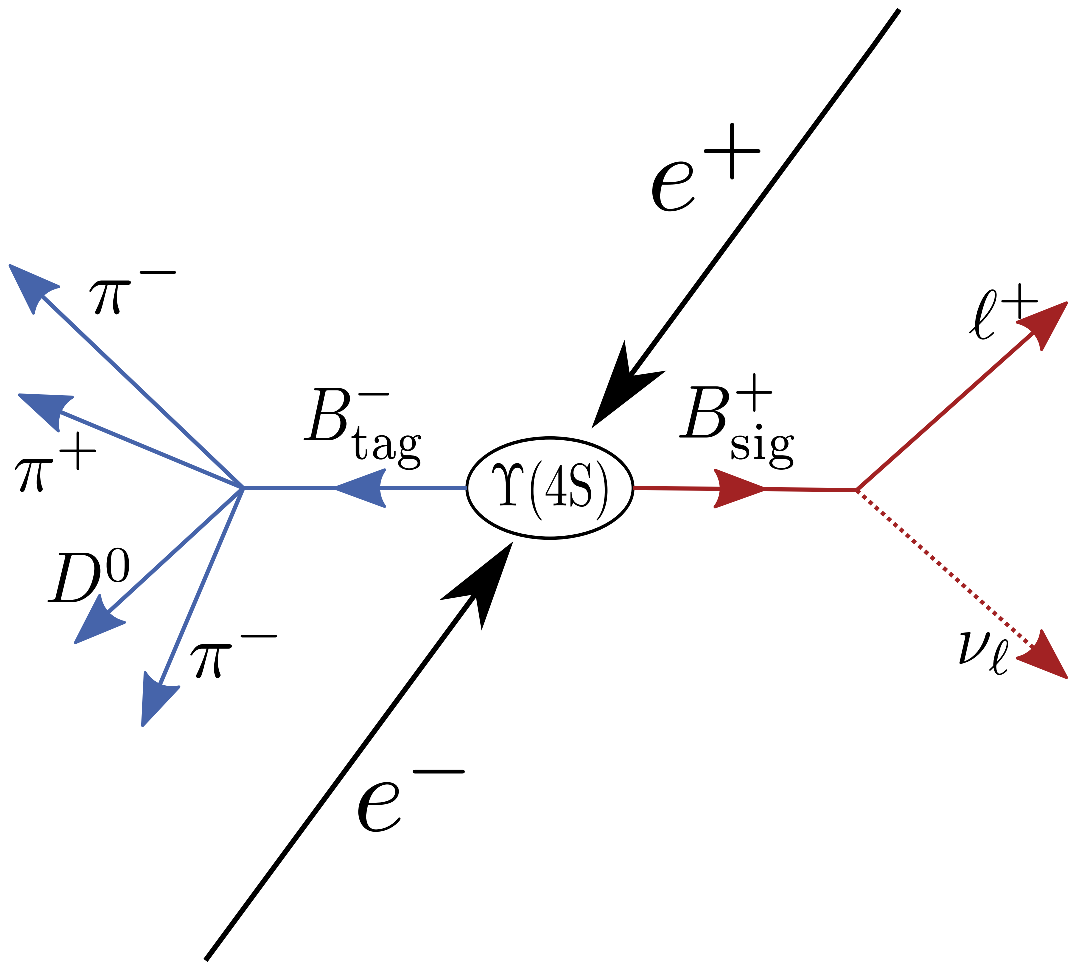
$$m^2_{\text{miss}} = \left((\frac{1}{2}E_{\text{beam}},0,0,0) - p^*_{D^*\ell} \right)^2 \approx p_\nu^2 = 0\,\text{GeV}^2$$



$\ell^+\ell^-$
$\ell^+\ell^+$
$B^0 \to D^{*-}\ell^+\nu_\ell$ Signal
Belle II 2019, preliminary
$\int$ L dt = 2.66 fb^{-1}
data
b → c → l$_{tag}$
l$_{tag}$ from D$^0_{sig}$
B$^+$ → D** l ν
combinatorial
continuum
Backgrounds
events / (GeV^2/c^4)
$m^2_{\rm miss}$ [GeV^2]
Fraction of unmixed events
Data
Expected
τ_{B^0} = 1.525 ps
Δm_d = 0.507 ps^{-1}
$\Delta t = \Delta z/(c\,\beta\,\gamma)$ [ps]

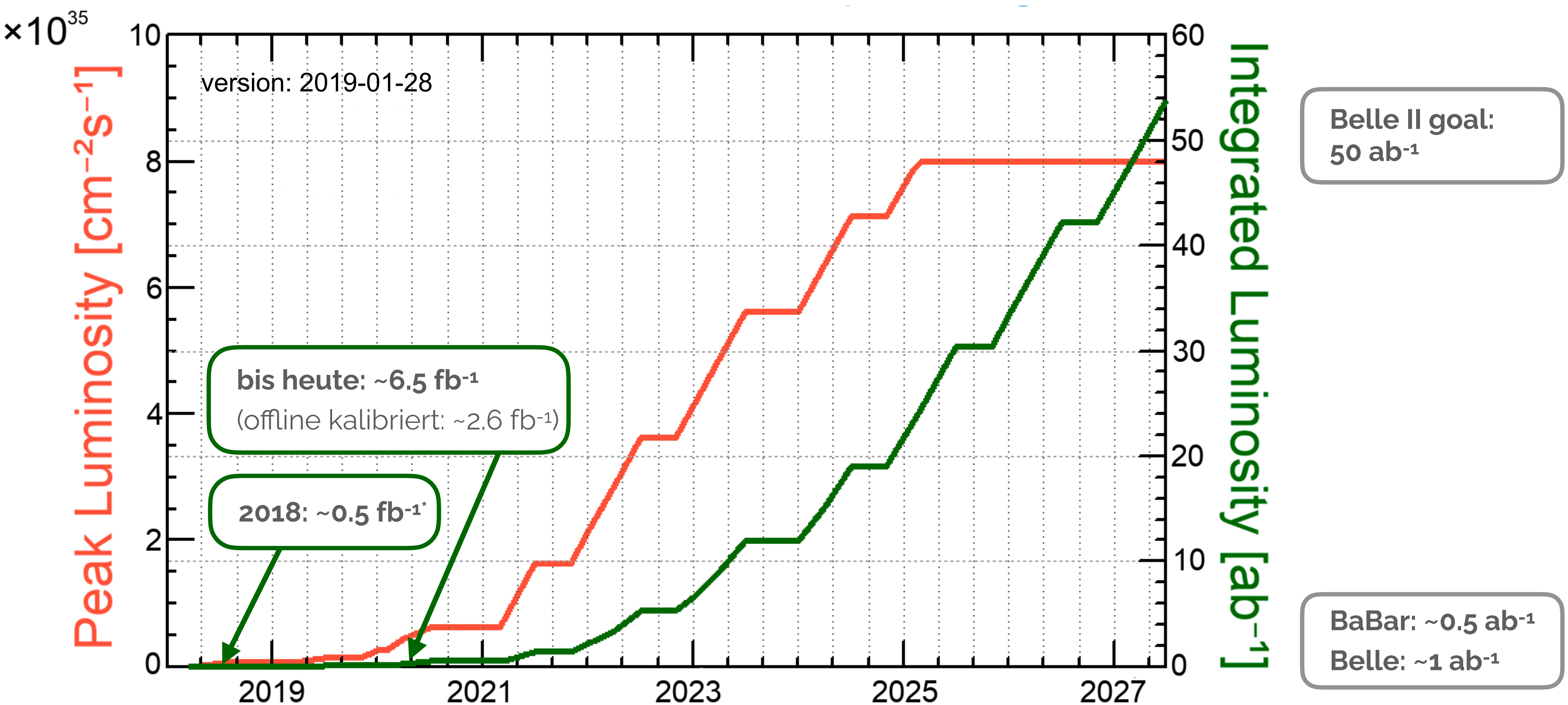
Hadronic Tagging with the Full Event Interpretation





$$p_\nu = \left(p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_\ell \right)$$

We saw plenty of this in Will's talk



Next milestones: Winter 2020 (15 - 25/fb) and Summer 2020 (50-200/fb)

BPAC's assessment:

38 The goal of the Belle II collaboration to collect 200 fb^{-1} of data by the time of the
39 summer conferences in 2020 appears to be extremely ambitious. However, the committee
40 fully encourages the collaboration to make every effort for this goal, since this would allow
41 the collaboration to start providing physics results comparable to the Belle experiment
42 in the core physics programme.

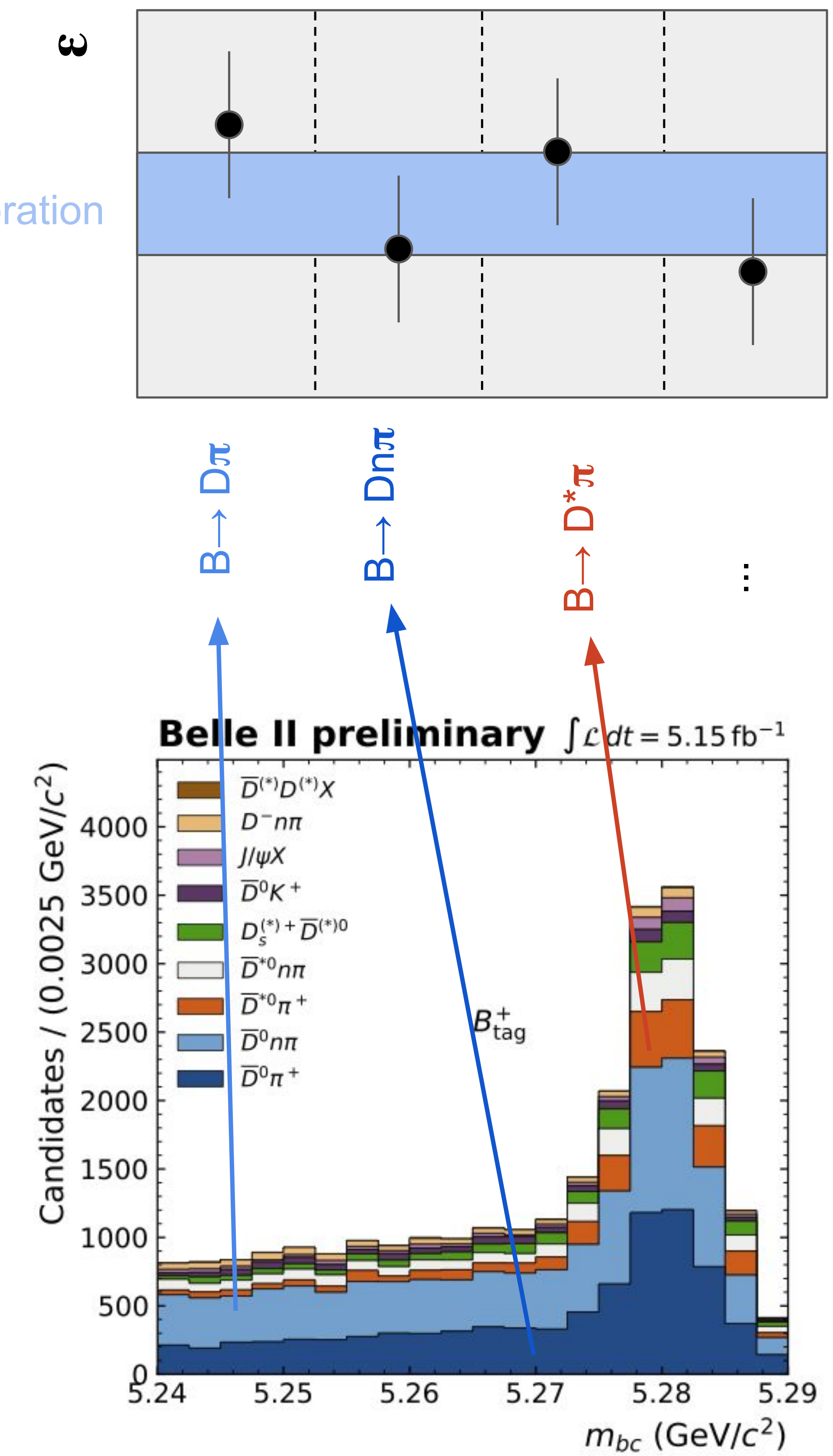
25/fb Program (Moriond 2020)

- **Hadronic FEI Performance** Studies with first **Calibration** using incl. SL $B \to X l \nu$ decays
- **Semilep. FEI Performance** Studies with detailed analysis of tag-side (cosBY, Prob., Eff.) and signal-side properties
- First **untagged** $\boldsymbol{B \to D^* l \nu}$ **BF** measurement
- Establish $\mathbf{|V_{ub}| \neq 0}$ with endpoint of incl. $B \to X l \nu$ SL decays
- **Hadronic FEI,** $\boldsymbol{B \to D/D^* l \nu}$ rediscovery

Hadronic FEI

Next Goals:

- **Full Calibration** using $B \to Xl\nu$ as a standard candle
  - Procedure: Reconstruct $B \to Xl\nu$ *using tagged events*
    - *single Lepton with high momentum, clean up ROE for X reconstruction*
    - *Determine BF after applying all signal-side corrections (e.g. PID)*
      - $\varepsilon = N_{reco} / N_{expected}$
  - First global, once we have enough int. lumi, differential in **Modes** and **Signal Probability**
- **Rediscover SL D* and D decays**

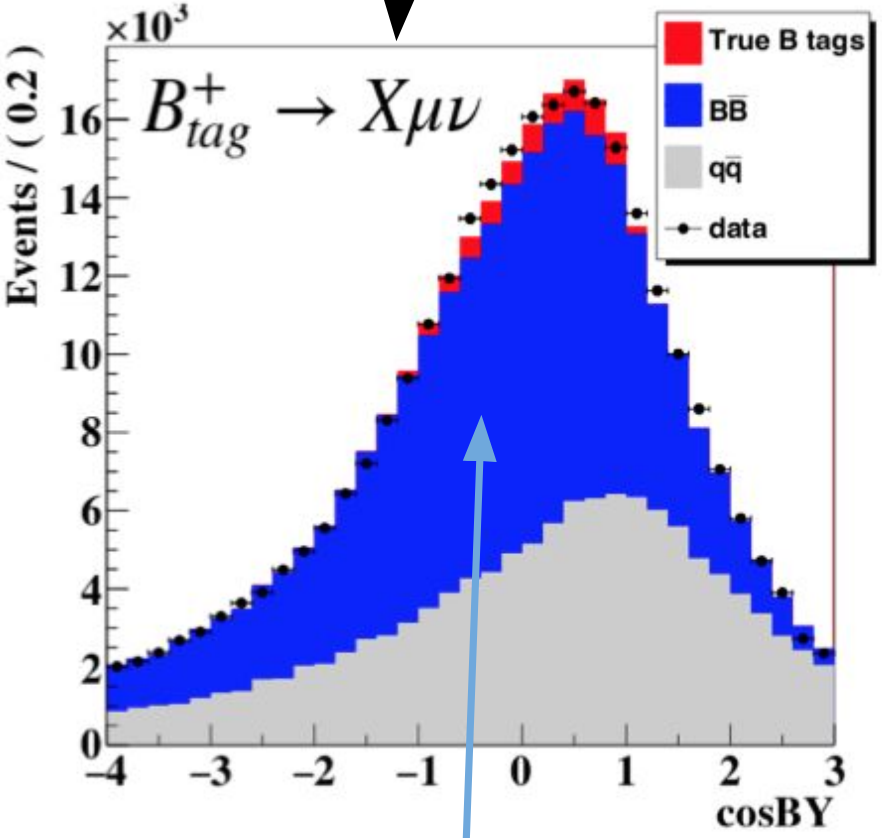


SL FEI

Next Goals:

- Understand tag-side Properties
  - Focus in D and D* (no D** → D(*)**π**)
  - For truth matching a tag, how strict should we be?
    - Very strict: only fully correctly reconstructed tags
    - Less strict: Allow for a number of wrongly assigned particles in D, D*
      - How many charged and neutrals?
    - Very loose: Correct if Lepton is reconstructed correctly?
- **Moriond goal:** Sig-Prob and cosBY plot for public consumption
- After this: **Calibration studies**

X = D/D* or all FEI modes?



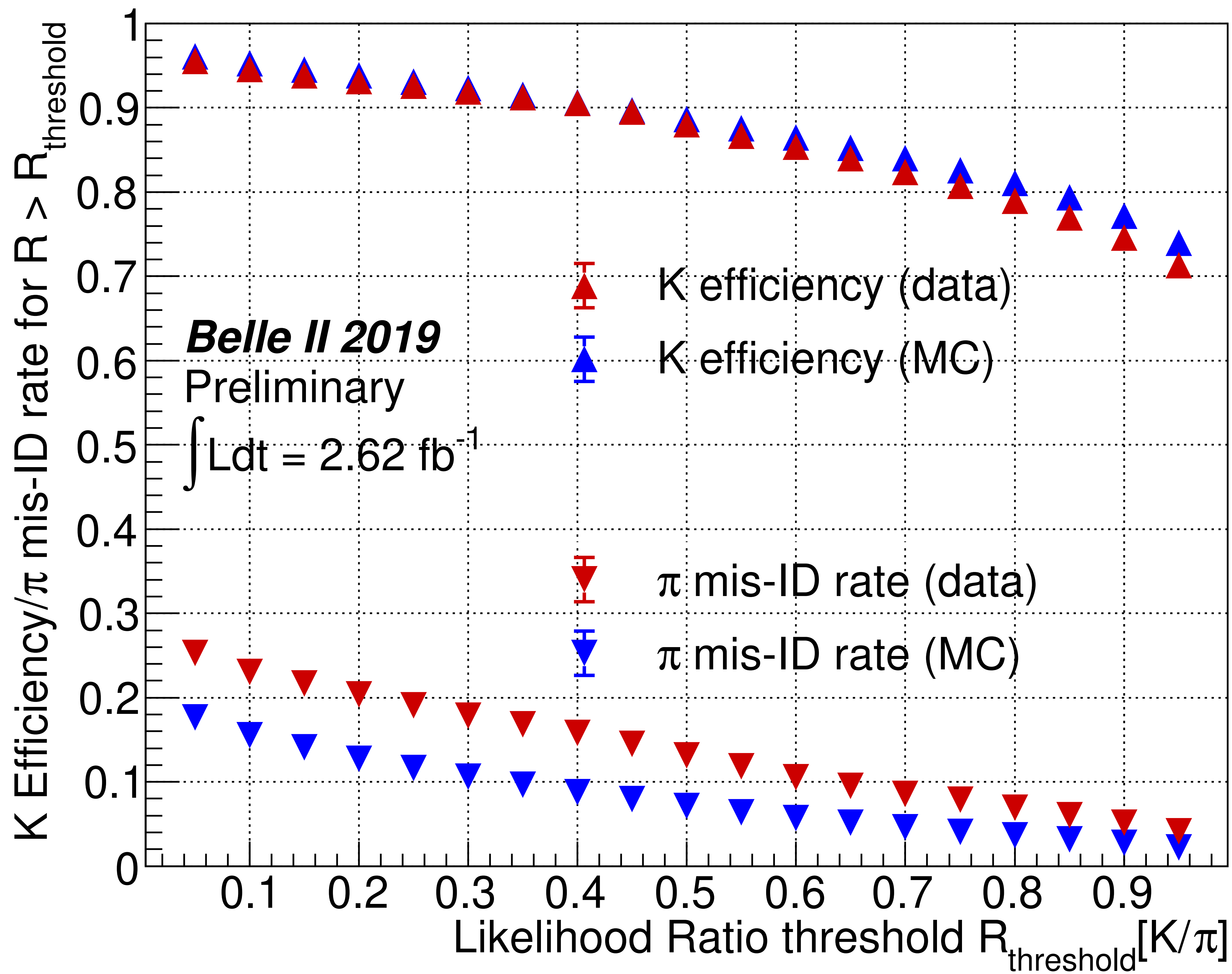
What are these?

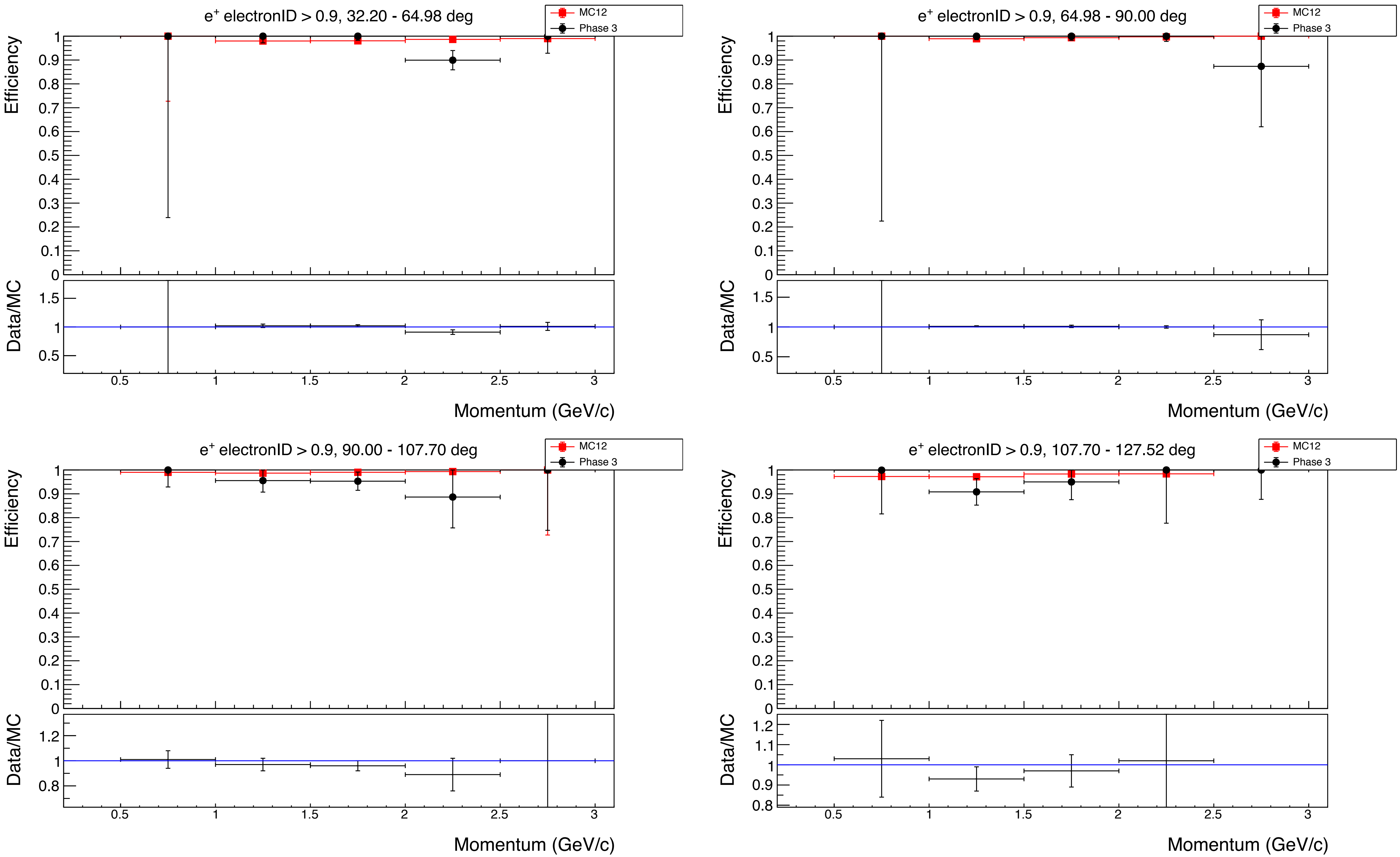
200/fb Program (Summer 2020)

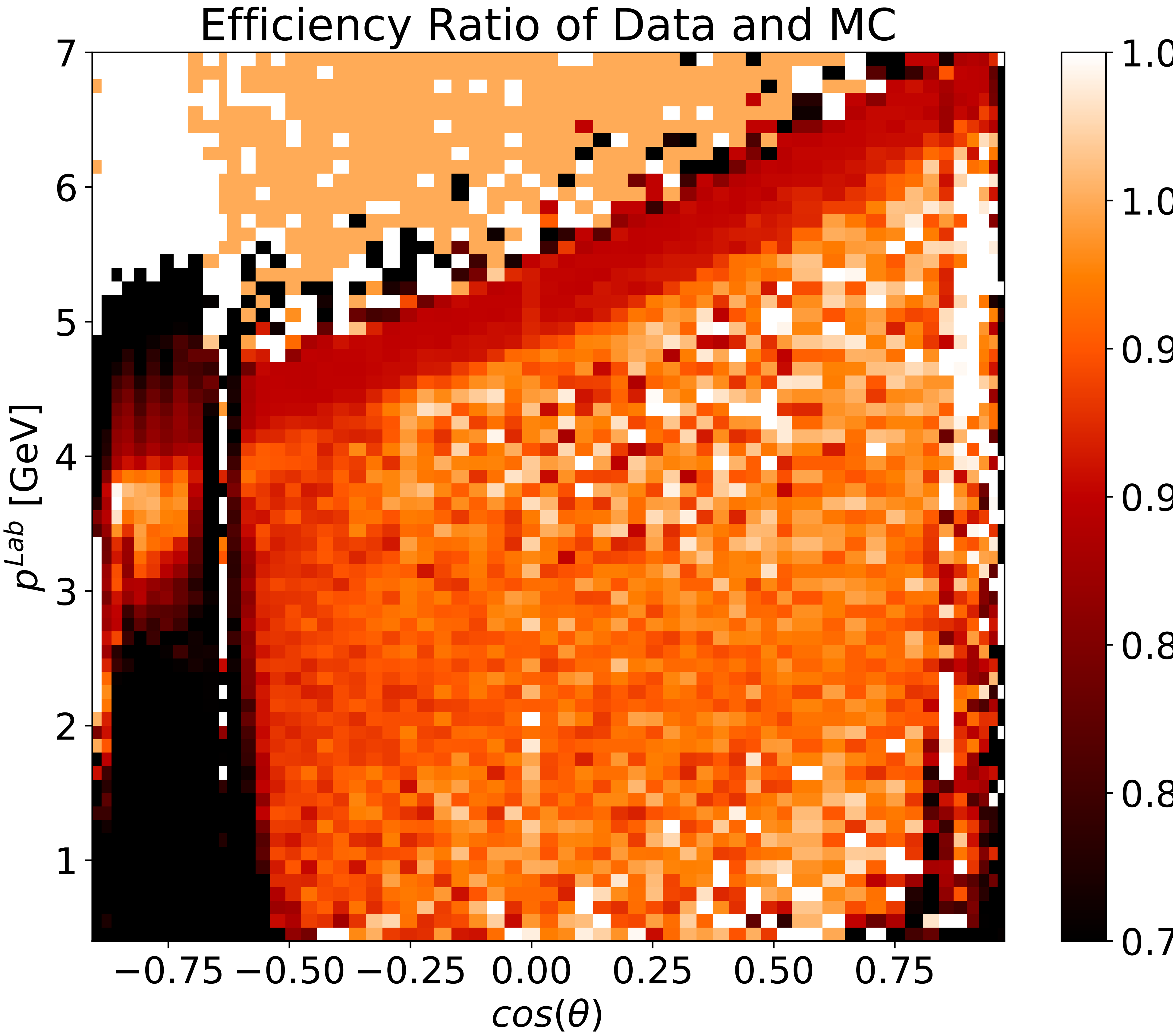
- **Hadronic FEI Performance, full calibration** as a function of modes and Signal Prob. → **Paper**
- **SL FEI Performance, full calibration** → **Paper**
- **Untagged / Tagged $B \to \pi\, l\, \nu$**
- **Untagged $B \to D^*\, l\, \nu$:** BF + Form Factors + $|V_{cb}|$
- **Had. FEI: $B \to D/D^*\, l\, \nu$:** Validation of E_{ECL} shape, BF + Form Factors + $|V_{cb}|$
- **Hadronic FEI: Towards $B \to D/D^*\, \tau\, \nu$ rediscovery**
- **Hadronic FEI: Incl. $|V_{ub}|$ & $|V_{cb}|$**
- **Hadronic FEI: B → $\tau\, \nu$:** first limit

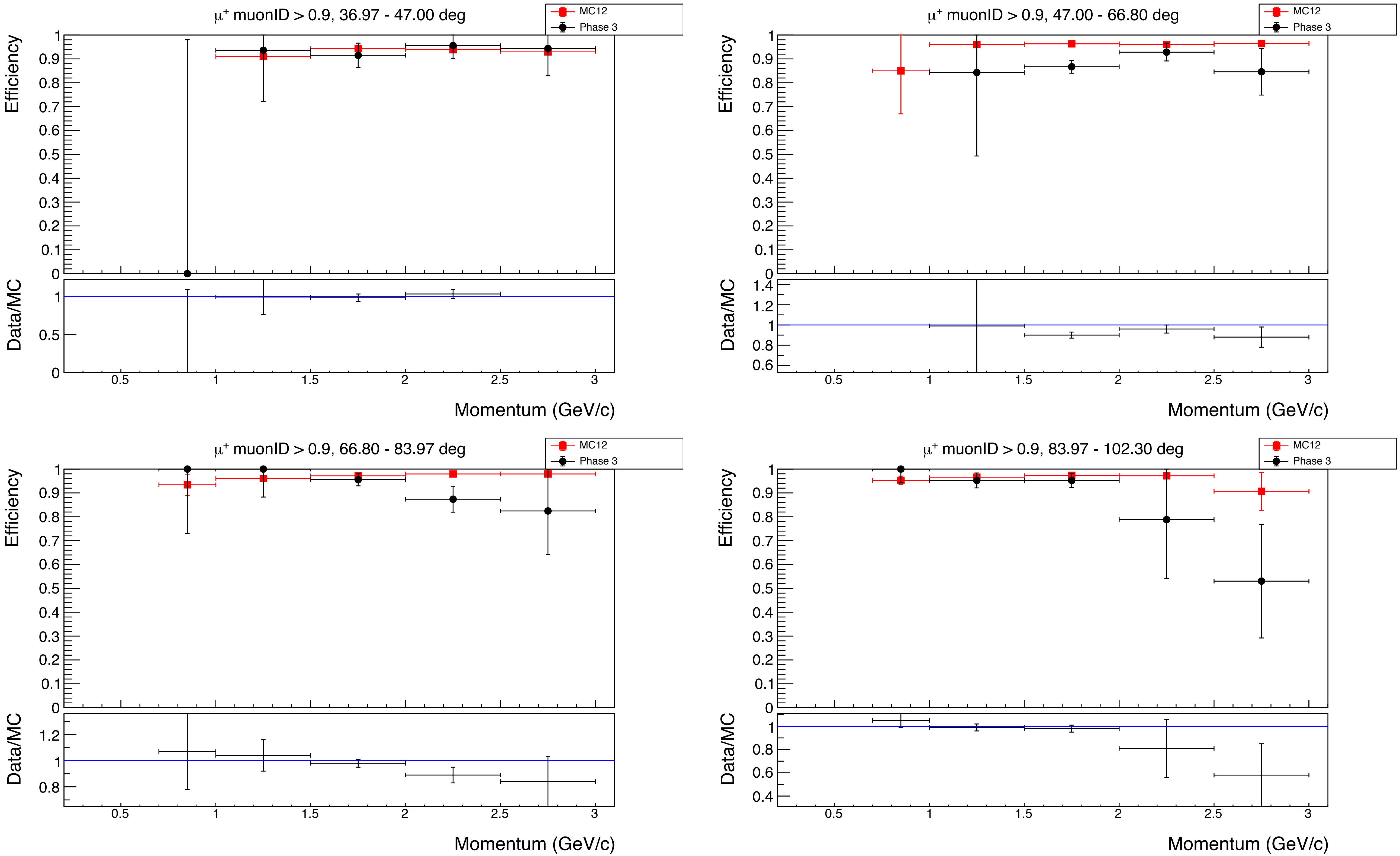
Backup

Kaon/pion Separation ($D^* \to D^0[K^-\pi^+]\pi^+$)




e+ electronID > 0.9, 32.20 - 64.98 deg
e+ electronID > 0.9, 64.98 - 90.00 deg
e+ electronID > 0.9, 90.00 - 107.70 deg
e+ electronID > 0.9, 107.70 - 127.52 deg
MC12
Phase 3
Efficiency
Data/MC
Momentum (GeV/c)


Efficiency Ratio of Data and MC
p^{Lab} [GeV]
7
6
5
4
3
2
1
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
$cos(\theta)$
1.0
1.0
0.9
0.9
0.8
0.8
0.7


μ⁺ muonID > 0.9, 36.97 - 47.00 deg
MC12
Phase 3
Efficiency
Data/MC
Momentum (GeV/c)
μ⁺ muonID > 0.9, 47.00 - 66.80 deg
MC12
Phase 3
Efficiency
Data/MC
Momentum (GeV/c)
μ⁺ muonID > 0.9, 66.80 - 83.97 deg
MC12
Phase 3
Efficiency
Data/MC
Momentum (GeV/c)
μ⁺ muonID > 0.9, 83.97 - 102.30 deg
MC12
Phase 3
Efficiency
Data/MC
Momentum (GeV/c)