Test of lepton flavour universality with $B_s^0 \to \phi \ell^+ \ell^-$ decays at LHCb

Sebastian Schmitt
on behalf of the LHCb collaboration

08.10.2024

[LHCb-PAPER-2024-032]
(In preparation)

Bundesministerium
für Bildung
und Forschung

FSP LHCb
Erforschung von
Universum und Materie

RWTH AACHEN UNIVERSITY

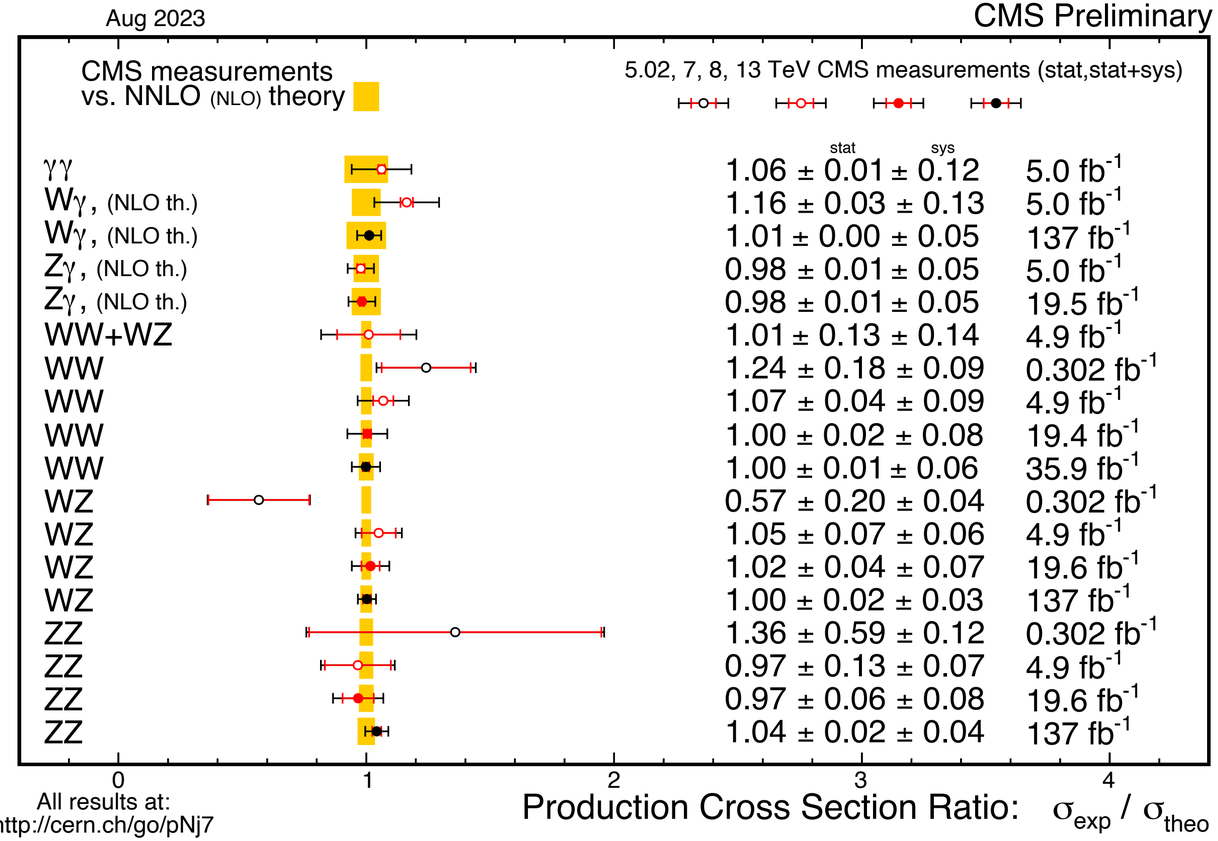
LHCb

Photo: Sebastian Schmitt

MOTIVATION

- Standard Model (SM) is a **great success!**

Excellent agreement with SM in direct searches



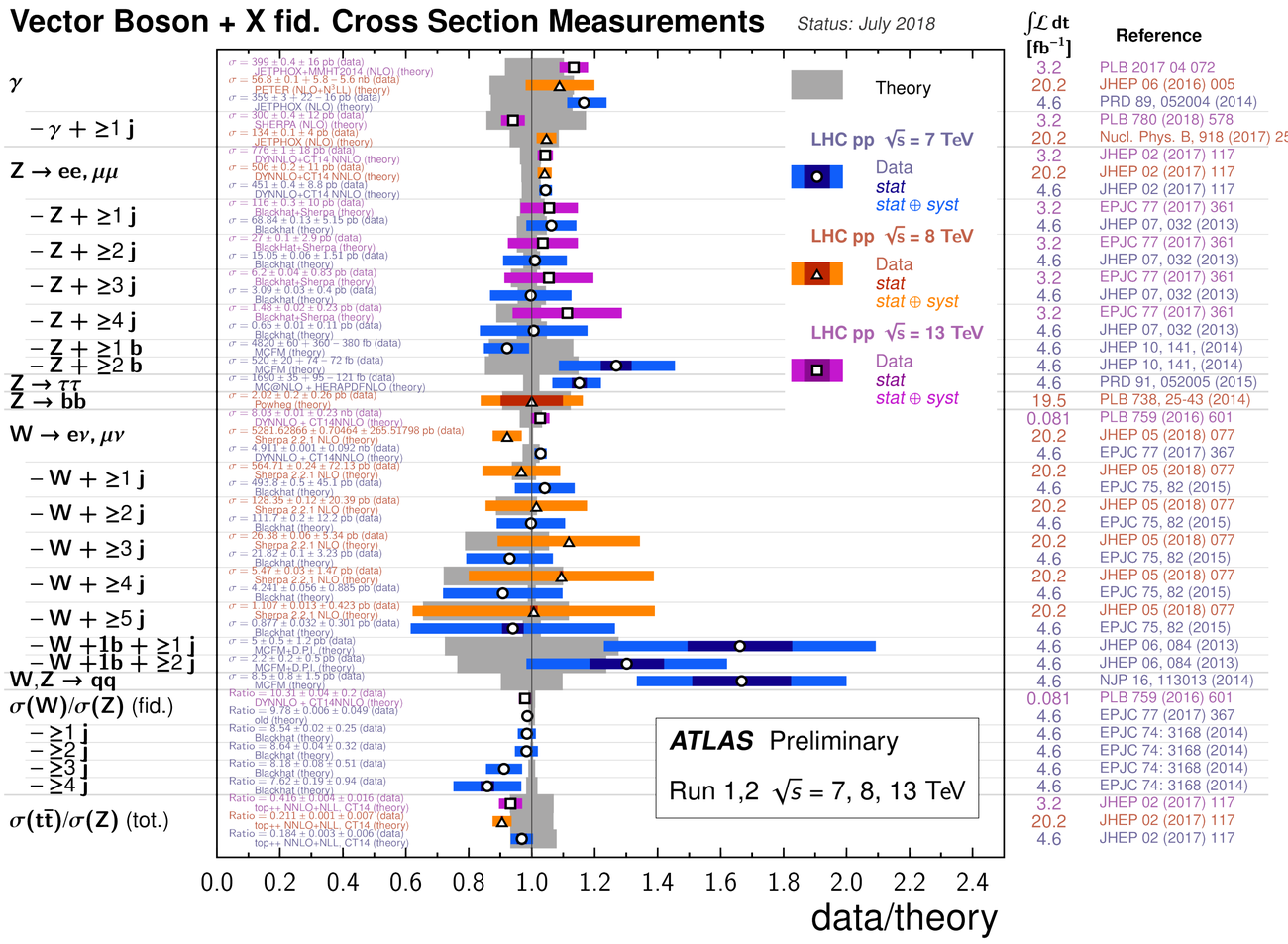
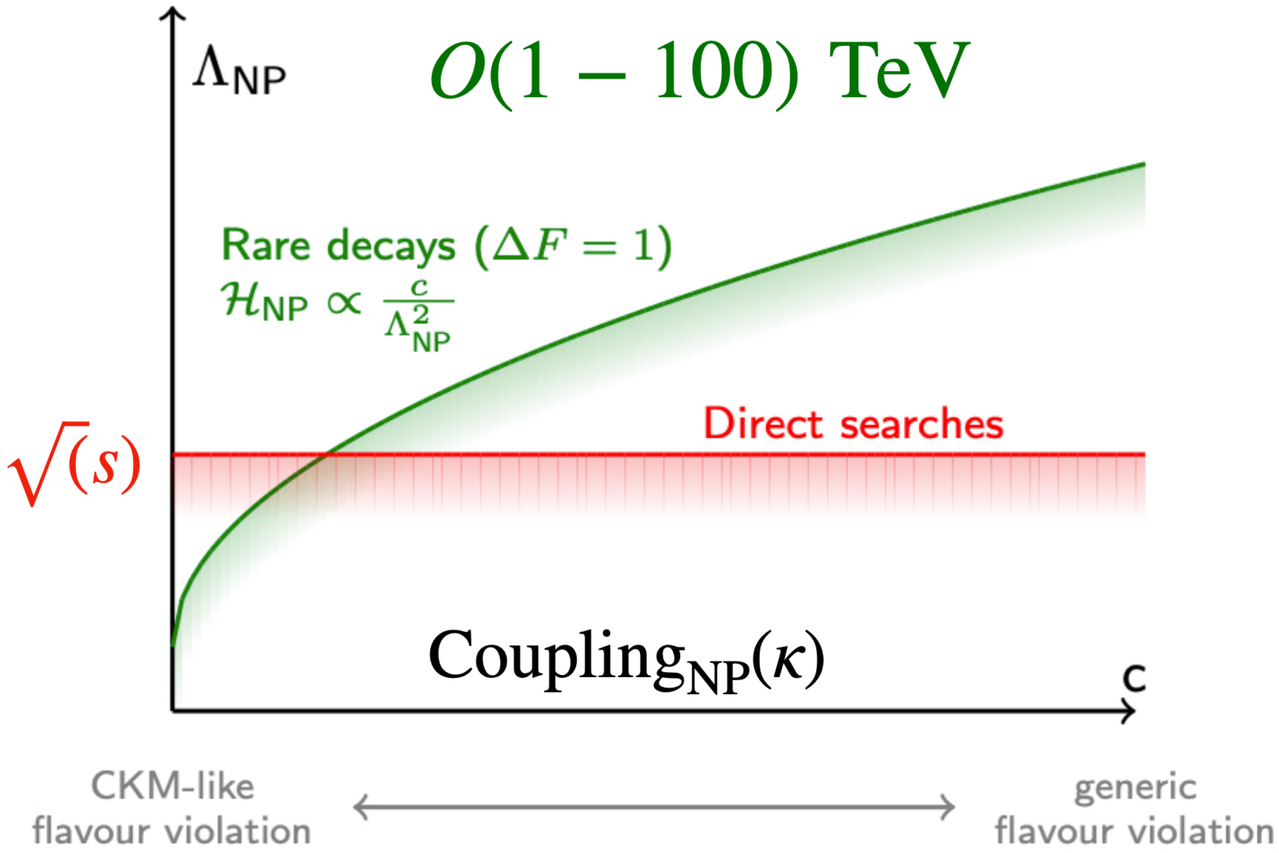


Photo: S. Schmitt

MOTIVATION

- **No direct evidence** for beyond SM particles yet
- Indirect searches can explore New Physics (NP) up to $\mathcal{O}(100\,\mathrm{TeV})$
- $b \to s\ell^+\ell^-$ transitions **sensitive probes** for NP
  - **Strongly suppressed** in the SM $\mathcal{B} \approx \mathcal{O}(10^{-6})$
  - Potential NP may **alter decay rates** or their distributions



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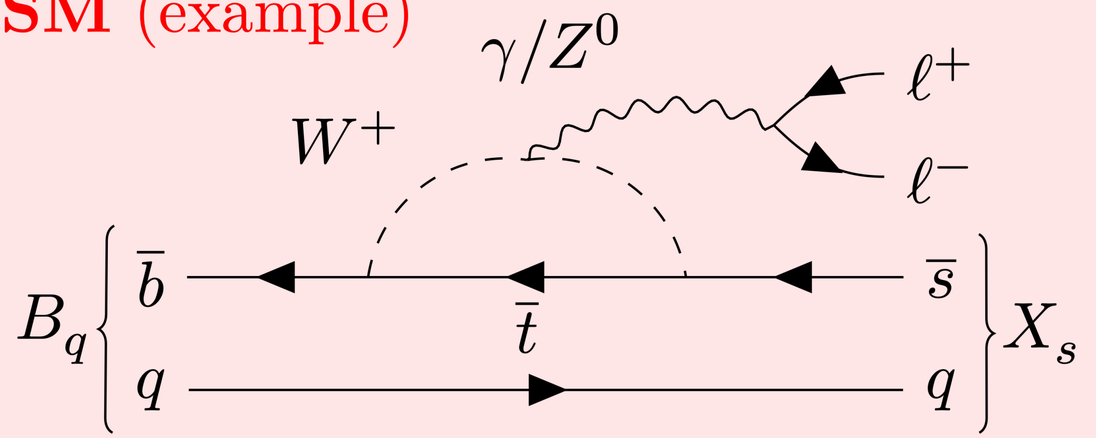


NP (example)

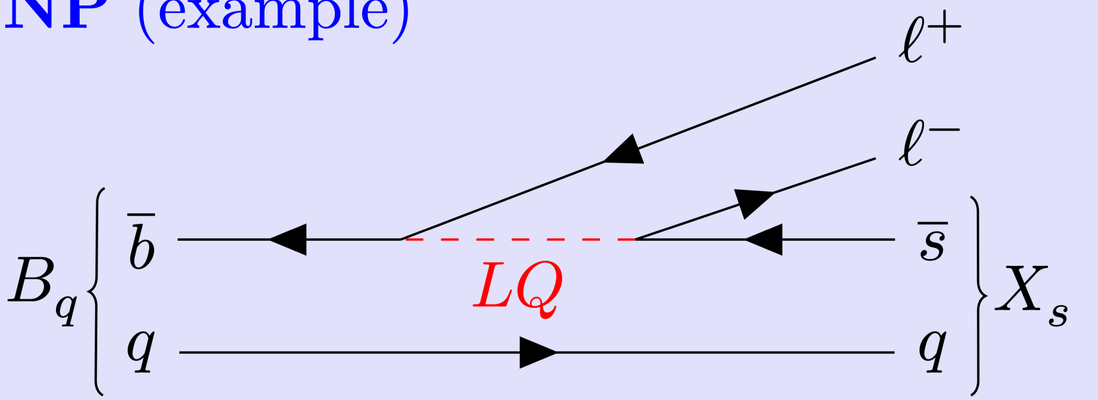


Photo: S. Schmitt

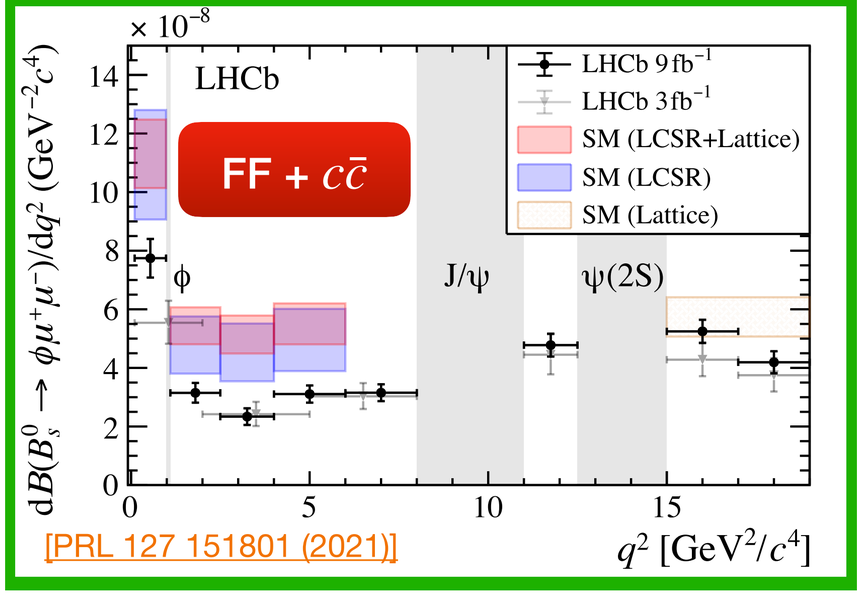
OBSERVABLES IN $b \to s\ell^+\ell^-$ DECAYS

- **Varying cleanliness** of the observables in $b \to s\ell^+\ell^-$ decays
- Hadronic **form factors** and **charm loops ($c\bar{c}$)** affect predictions

$$q^2 = m(\ell^+\ell^-)^2$$

Increasing precision of SM prediction

Branching Fractions



[PRL 127 151801 (2021)]

Angular Analyses

Universality Tests

Photo: S. Schmitt

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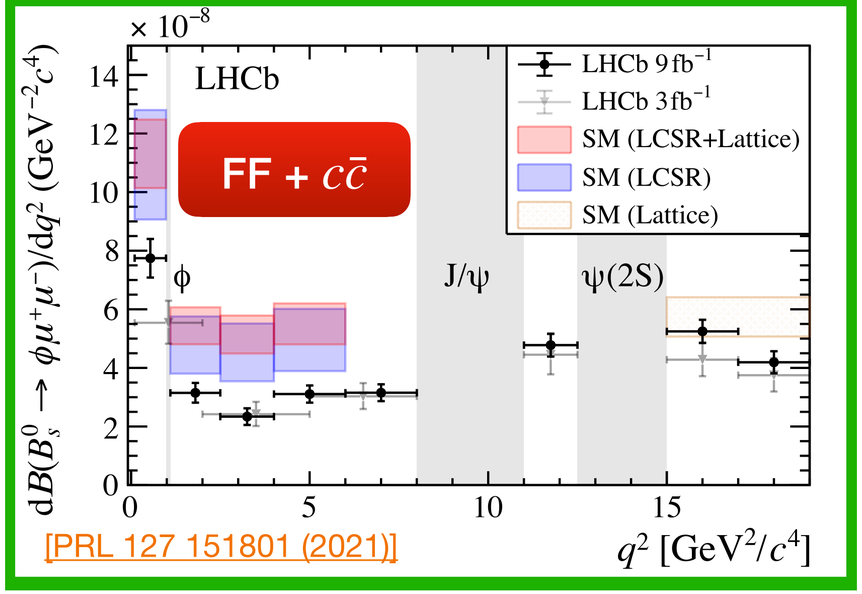

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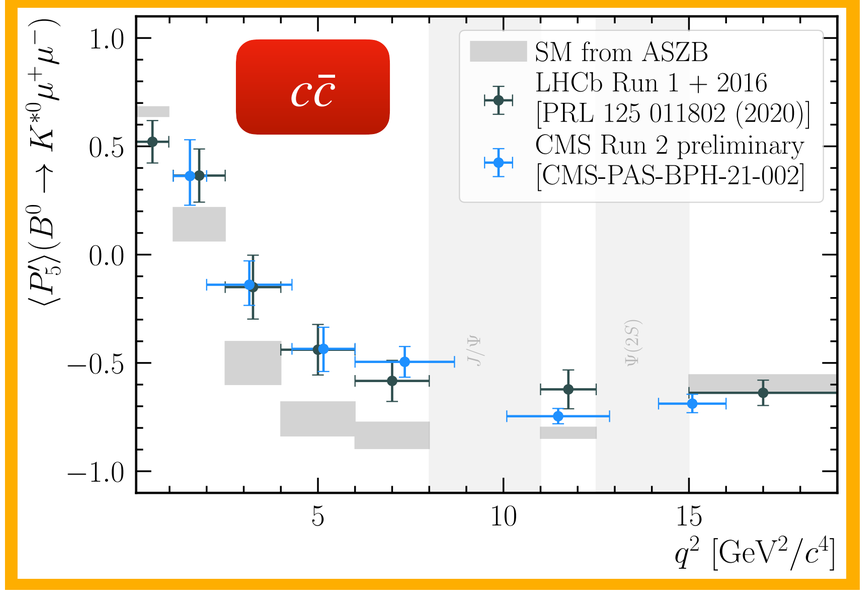

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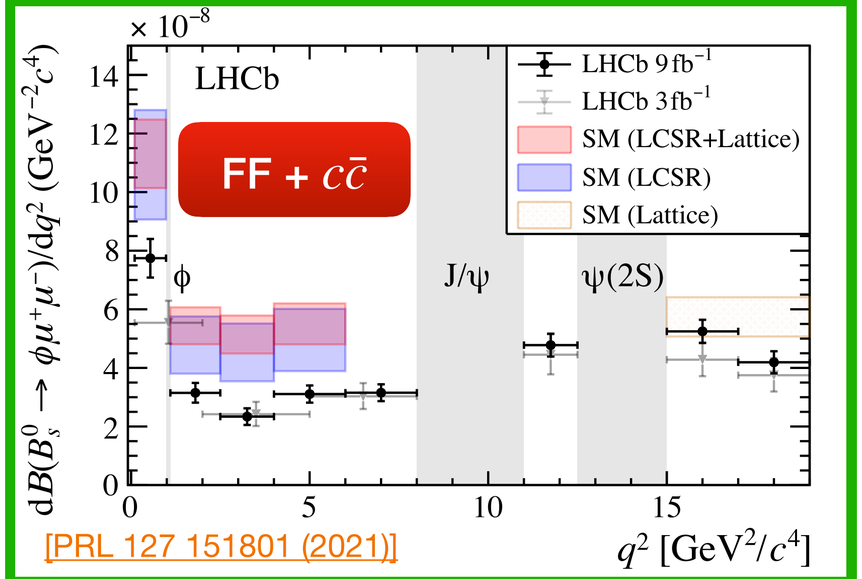

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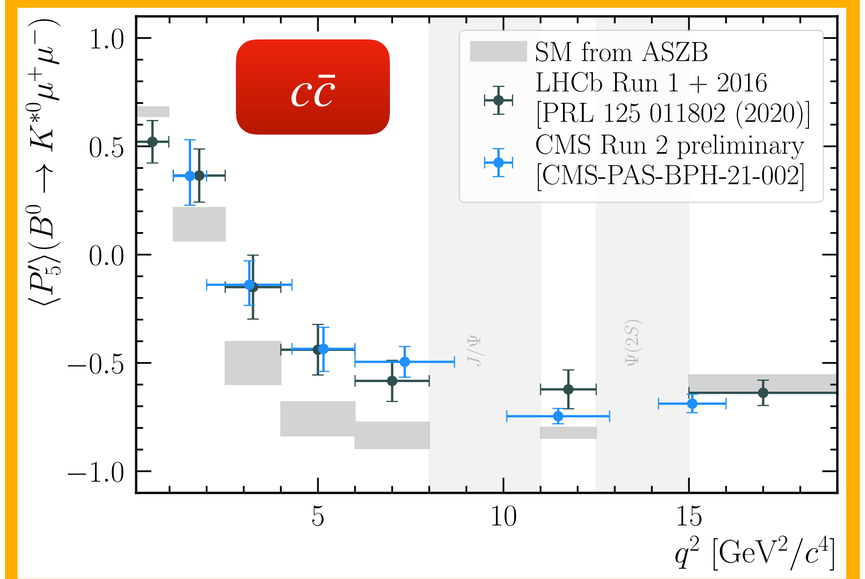

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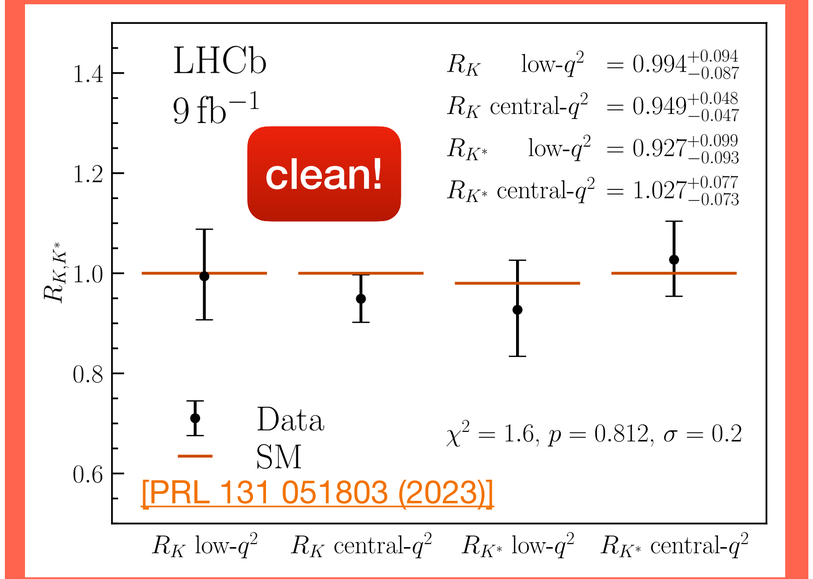


[PRL 131 051803 (2023)]

Photo: S. Schmitt

Interpreting Potential Deviations

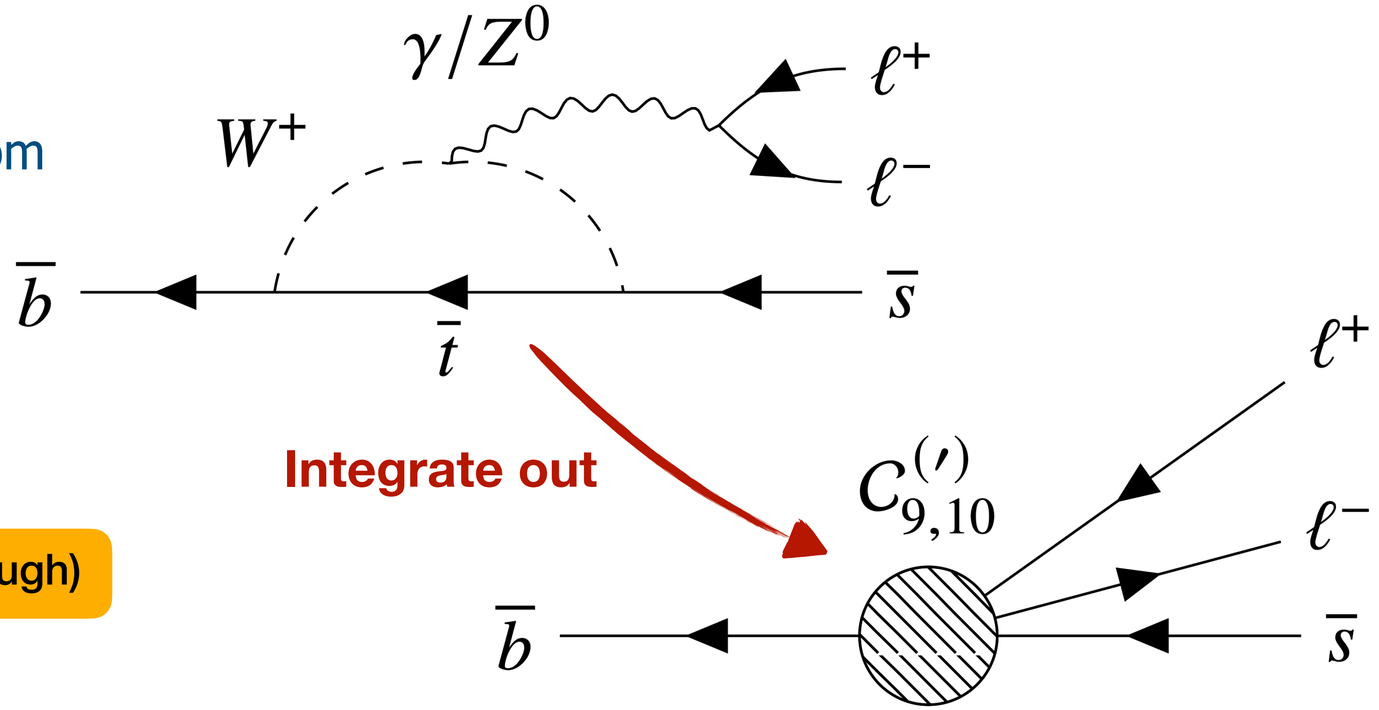
- Description of $b \to s\ell^+\ell^-$ with **effective field theory**
  - "Integrate out" heavy degrees of freedom
- Set of **effective couplings** C_i which can be computed in the SM
- Flavour universality tests use

$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathcal{B}(B \to Xe^+e^-)}{dq^2} dq^2} \overset{\text{SM}}{=} 1 \pm 0.01$$

(If q^2 large enough)

[Eur.Phys.J.C 76 (2016) 8]

- Different q^2-regions allow to **differentiate** between different NP scenarios



$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i^{\text{SM}} + C_i^{\text{NP}}) \mathcal{O}_i$$

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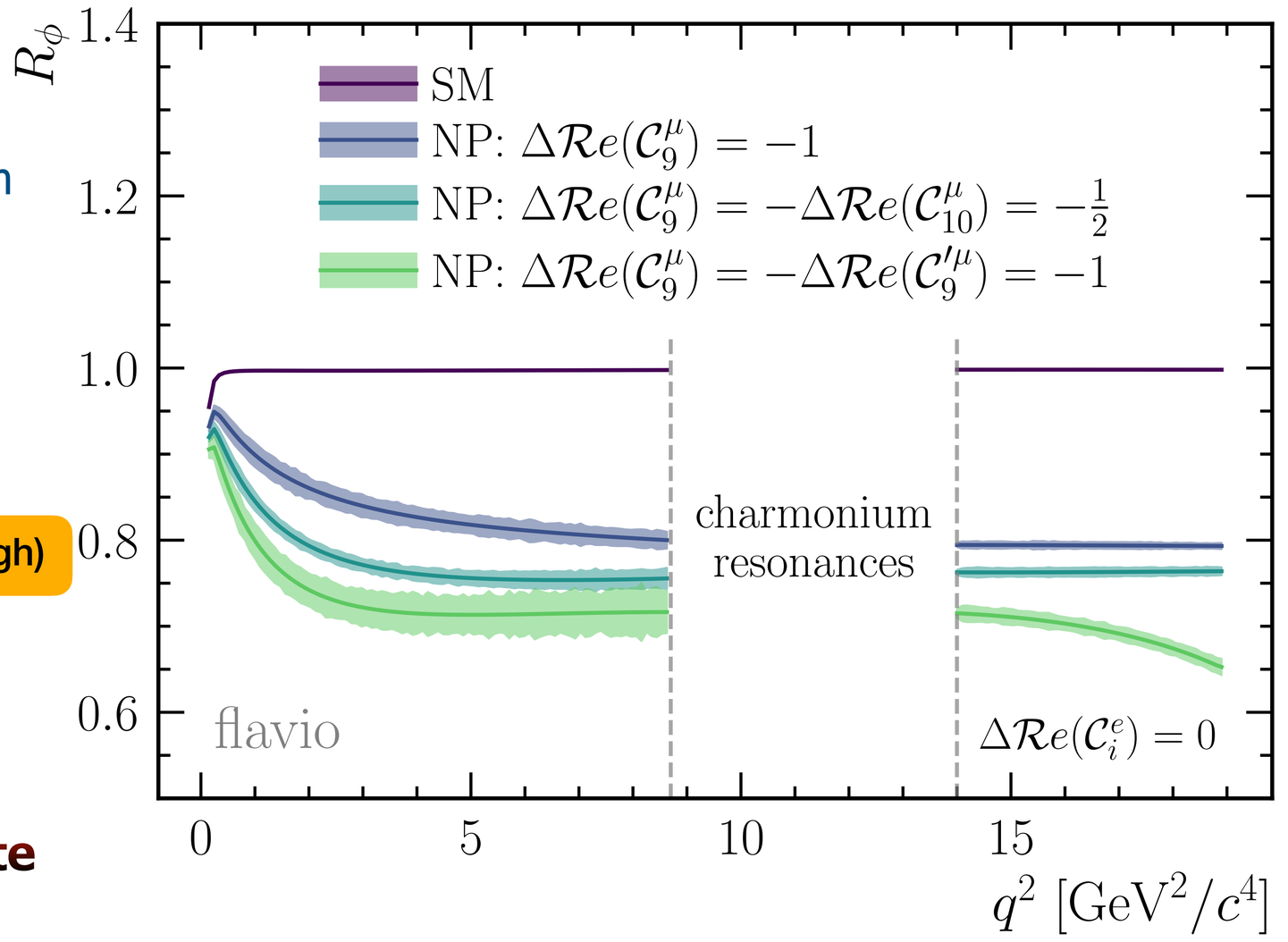

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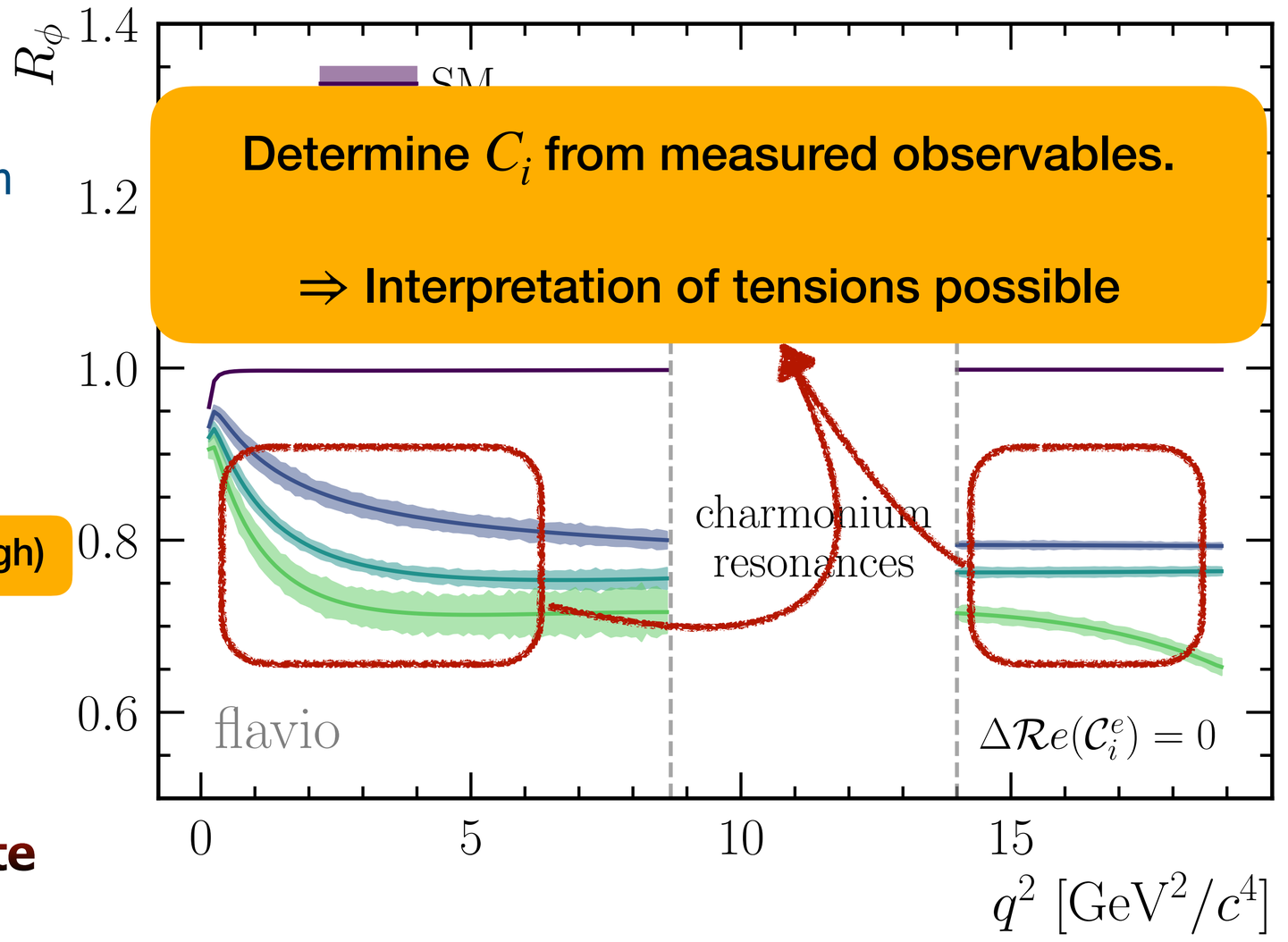
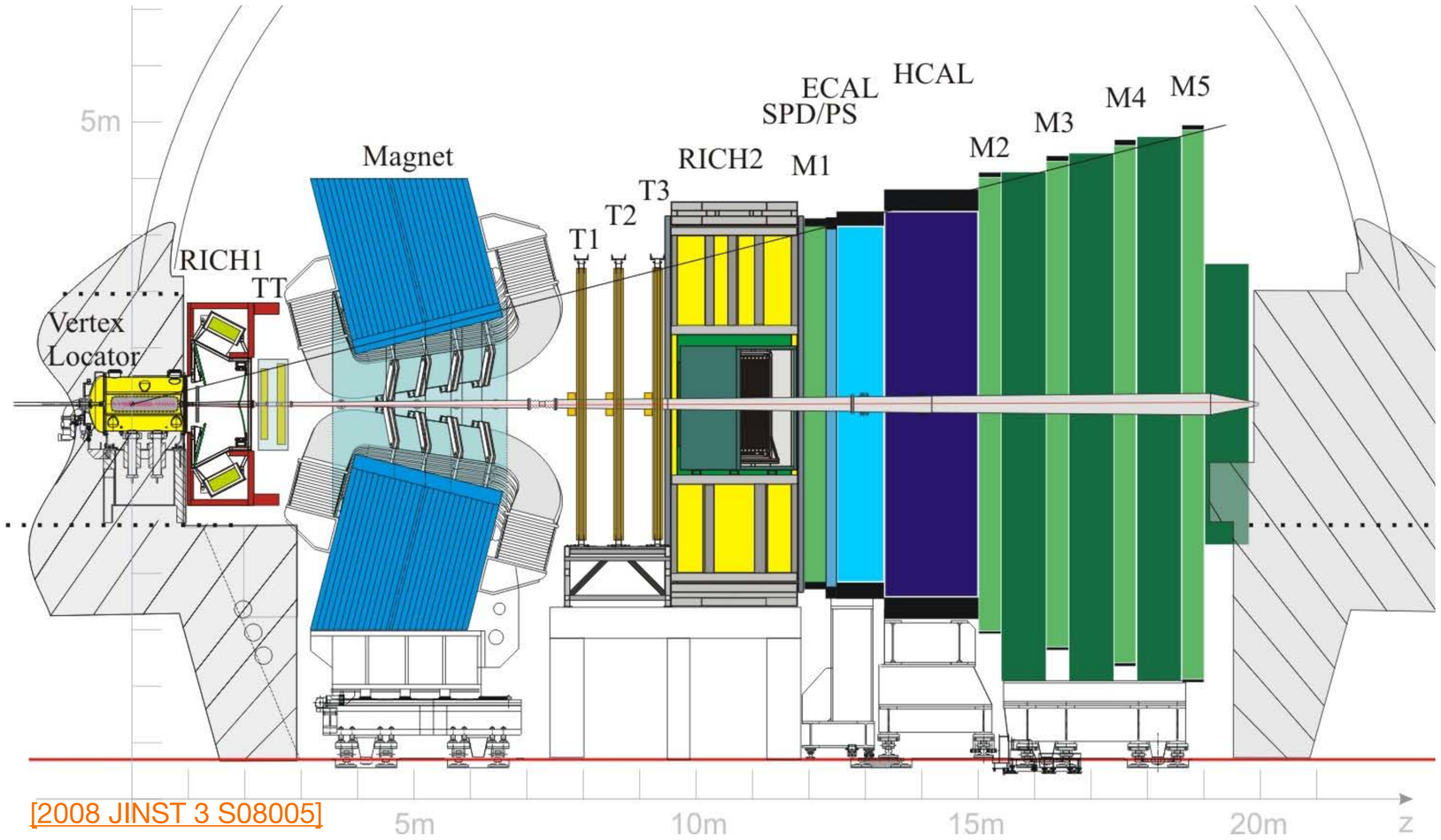
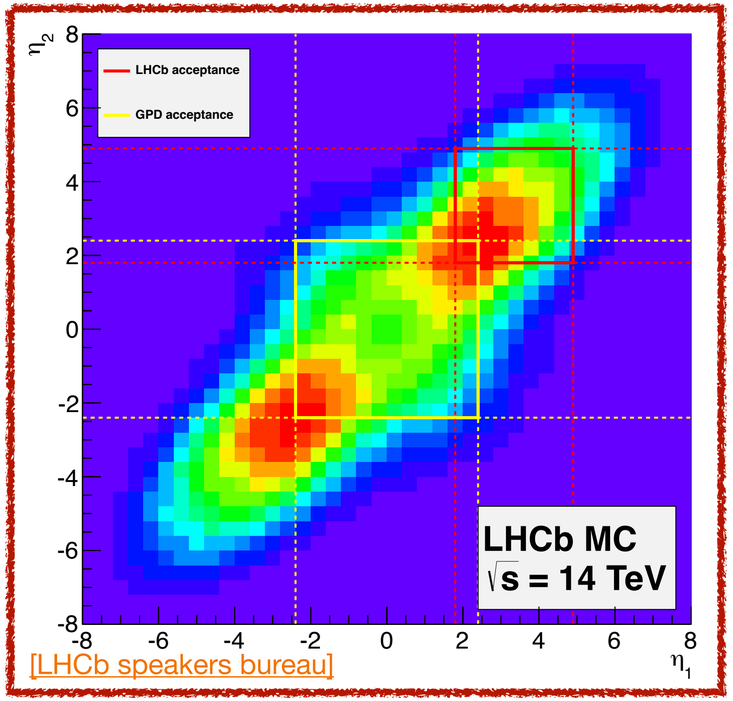


Photo: S. Schmitt

LHCb Detector in Run 1 and 2



[2008 JINST 3 S08005]



[LHCb speakers bureau]

- Single arm **forward spectrometer**
- Optimised for heavy **flavour physics**
- Coverage: $2 < \eta < 5$

Photo: S. Schmitt

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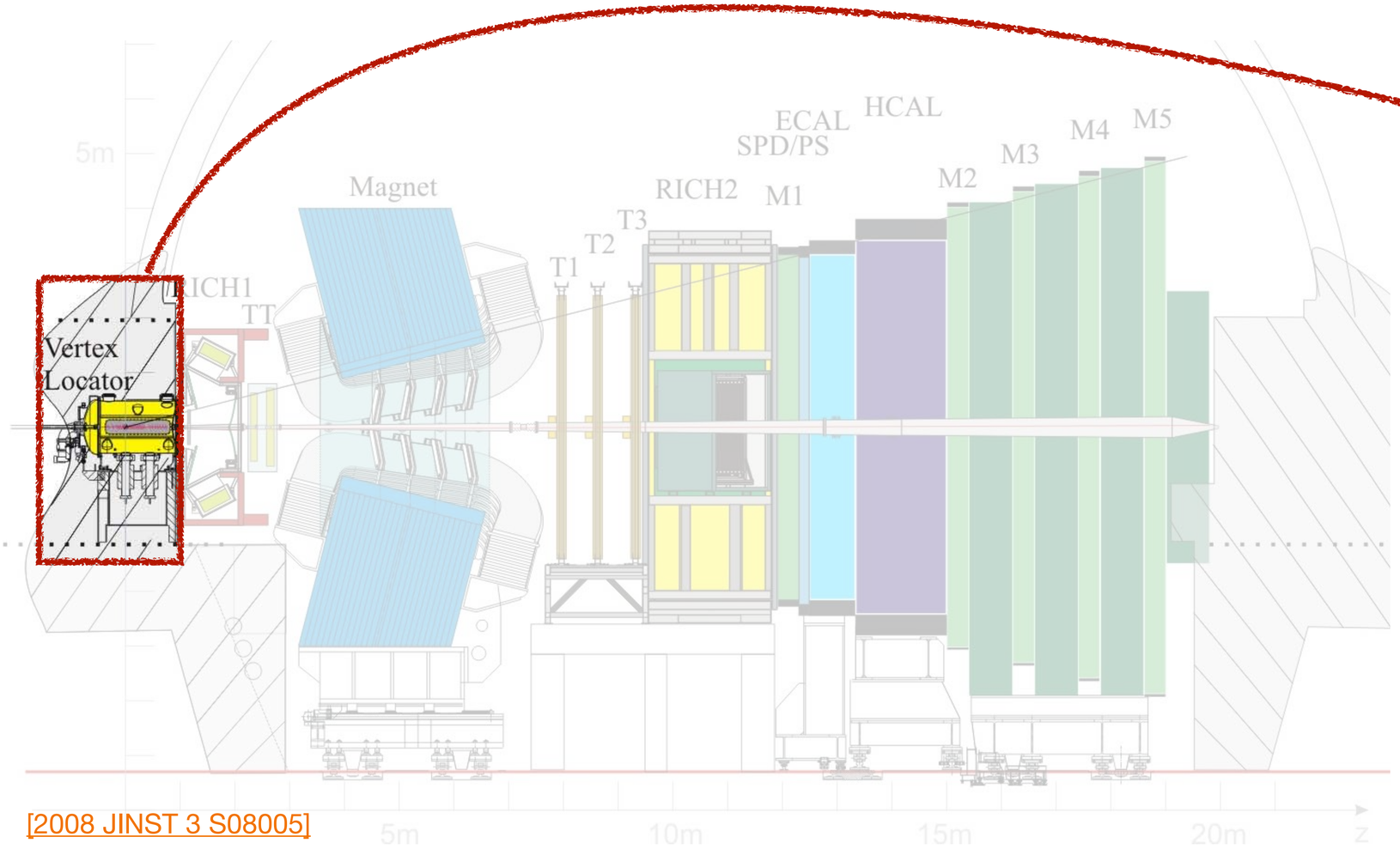

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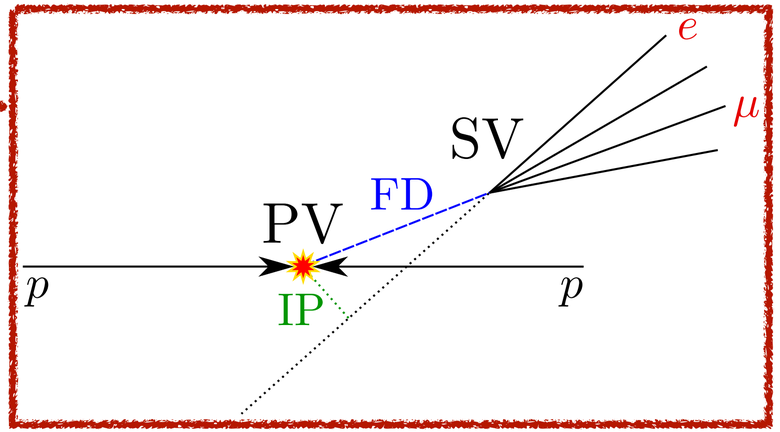

- Impact parameter (**IP**) resolution: $(15 + 29/p_{\mathrm{T}}\,[\mathrm{GeV}])\,\mu\mathrm{m}$
- Resolve secondary vertices of **long lived** B mesons ($\tau \approx \mathcal{O}(\mathrm{ps})$)

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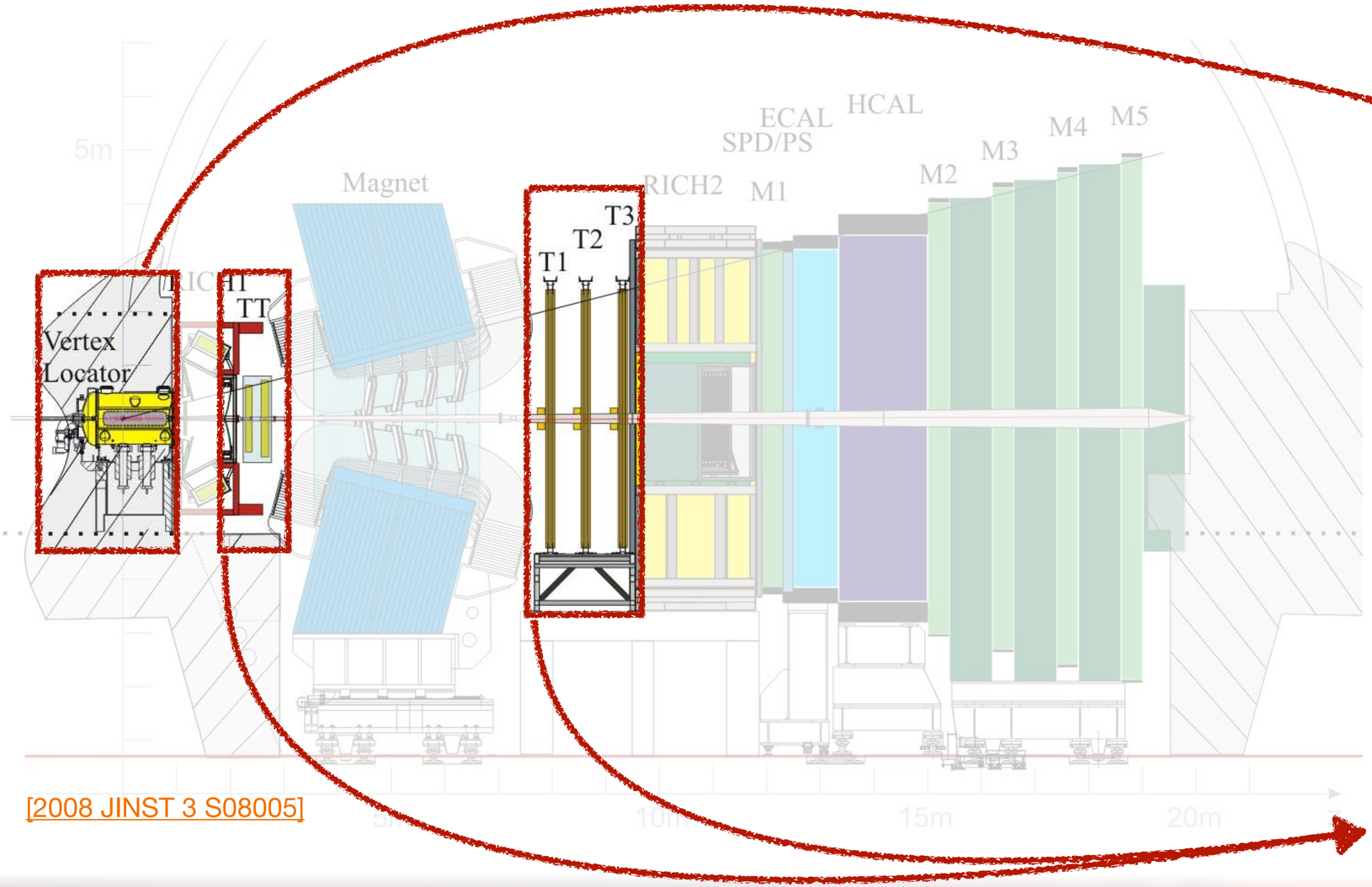

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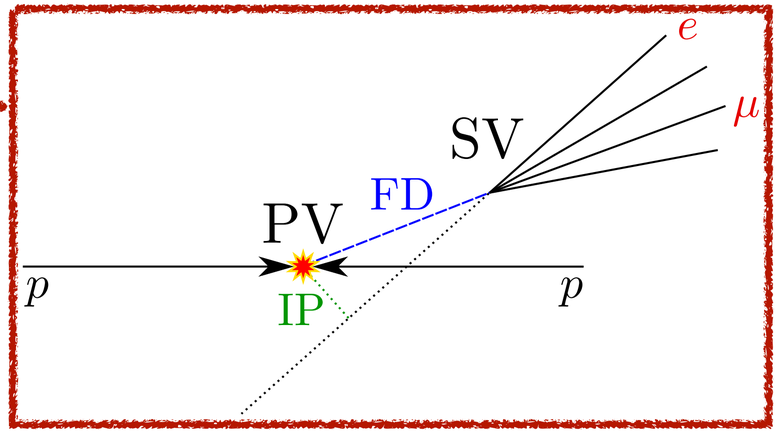

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- Momentum resolution: $\Delta p/p \approx 0.5 - 1\,\%$

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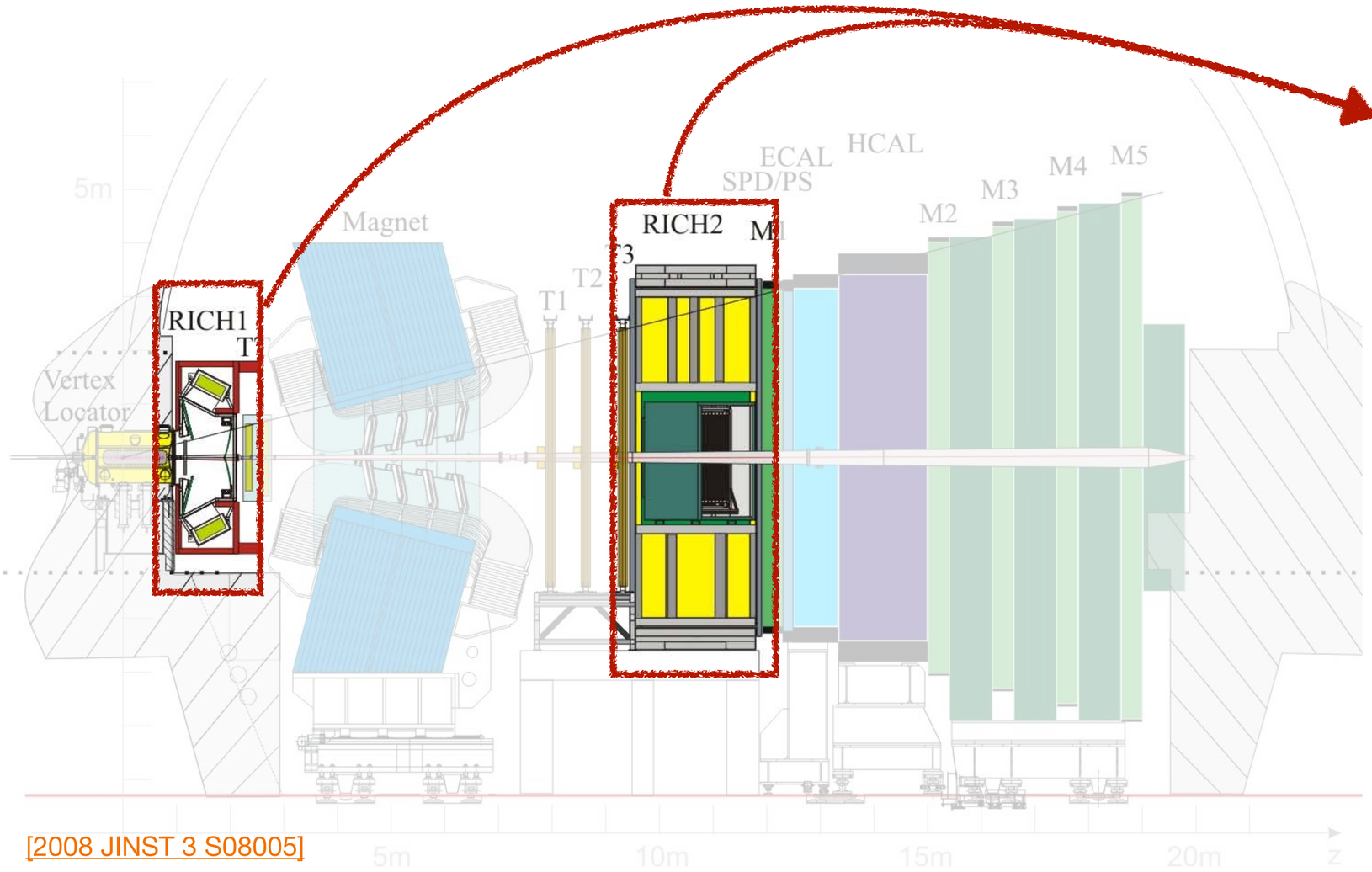

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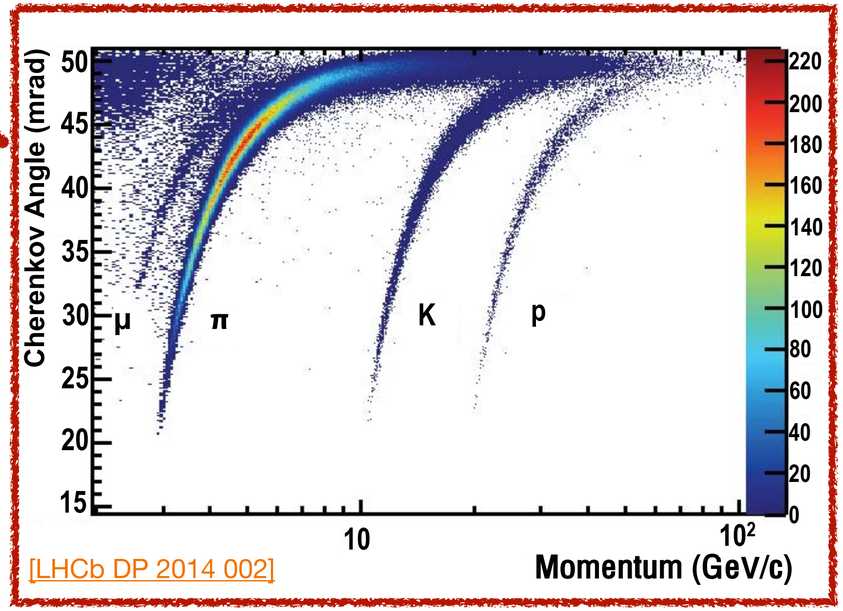

[LHCb DP 2014 002]

- **Excellent particle identification**:
  - $\mu : 97\,\% \, (\pi \rightarrow \mu : 1-3\,\%)$
  - $K : 95\,\% \, (\pi \rightarrow K : 5\%)$
  - $e : 90\,\% \, (h \rightarrow e : 5\,\%)$
- Combines info from **all** detectors, e.g. muon chambers

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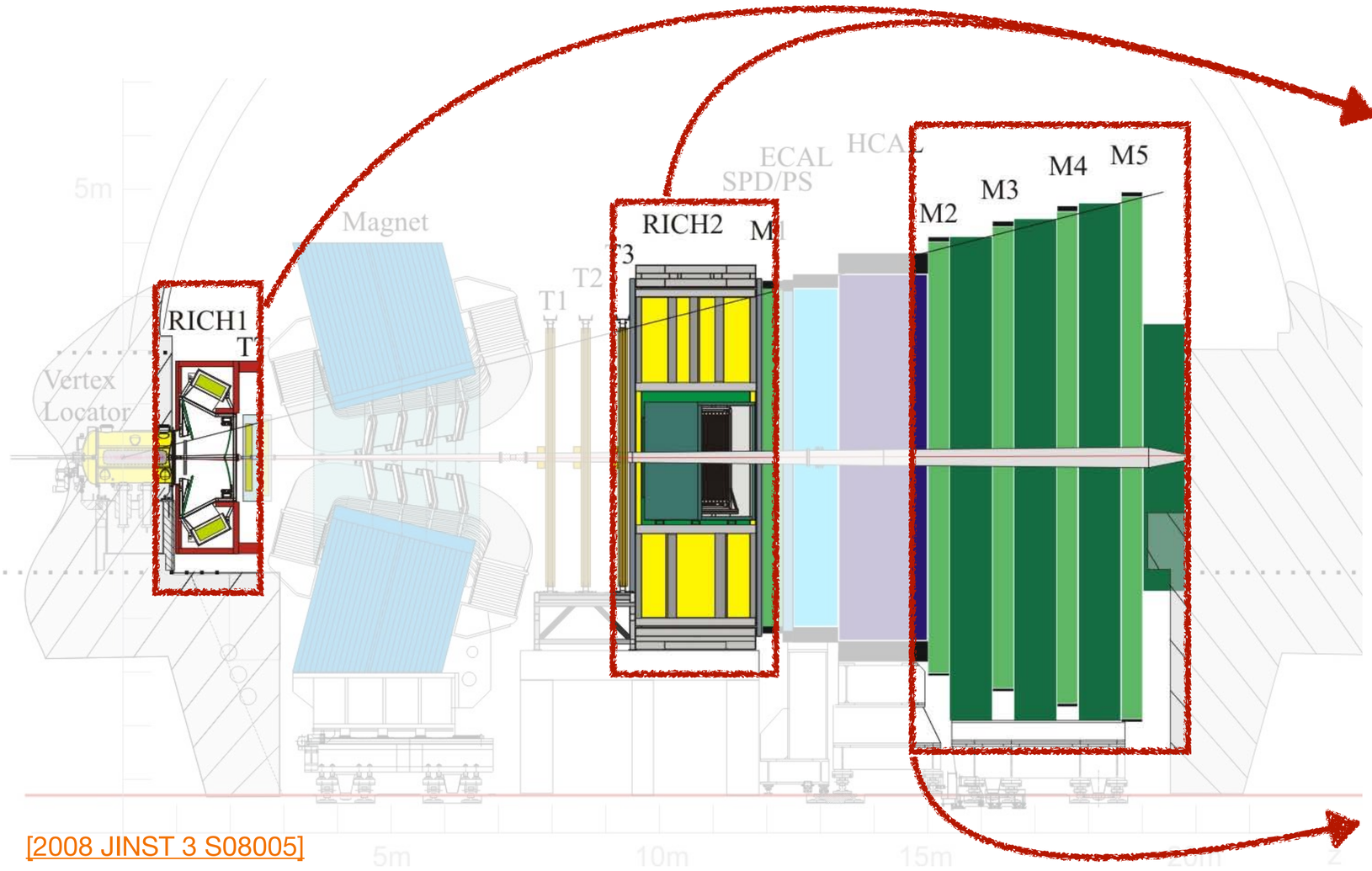

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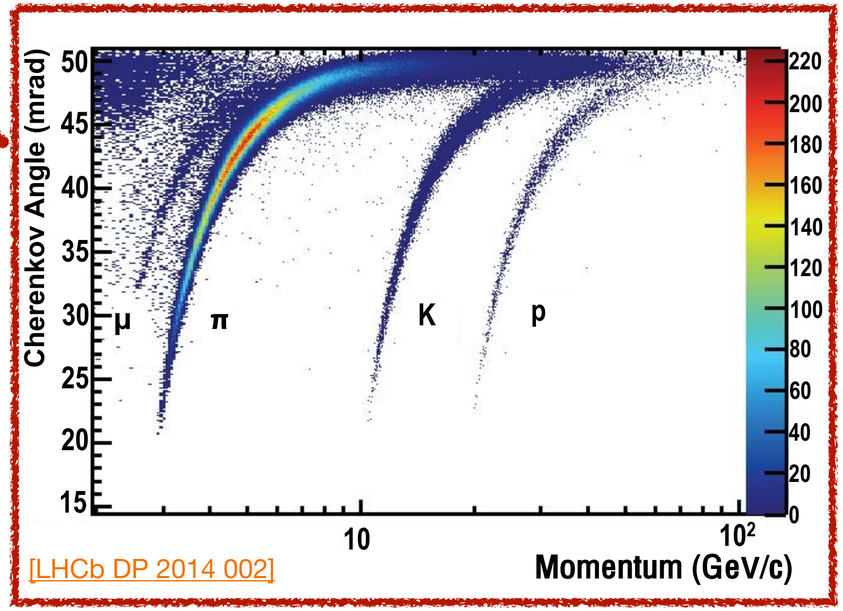

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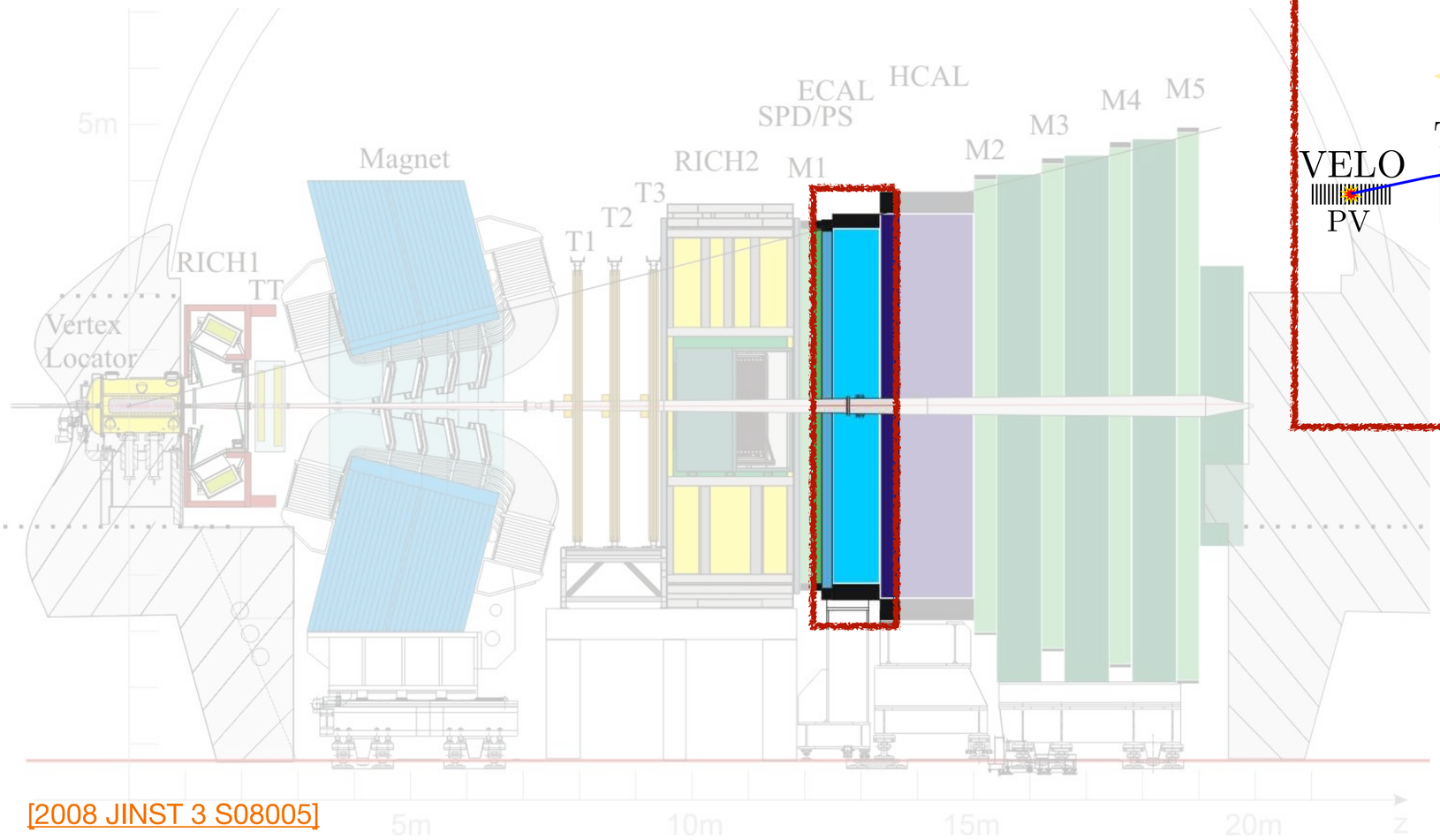

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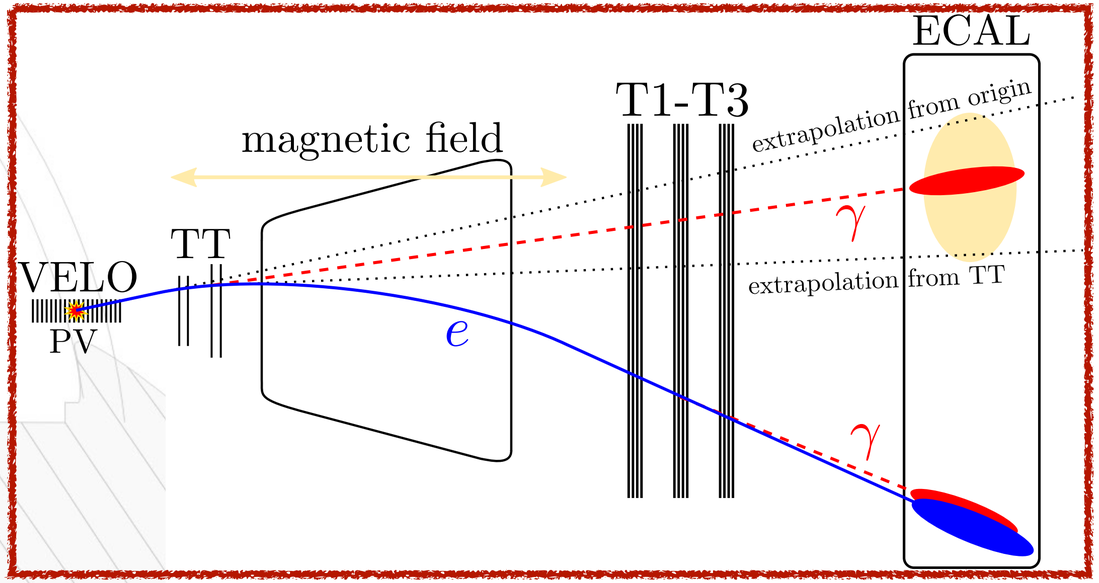
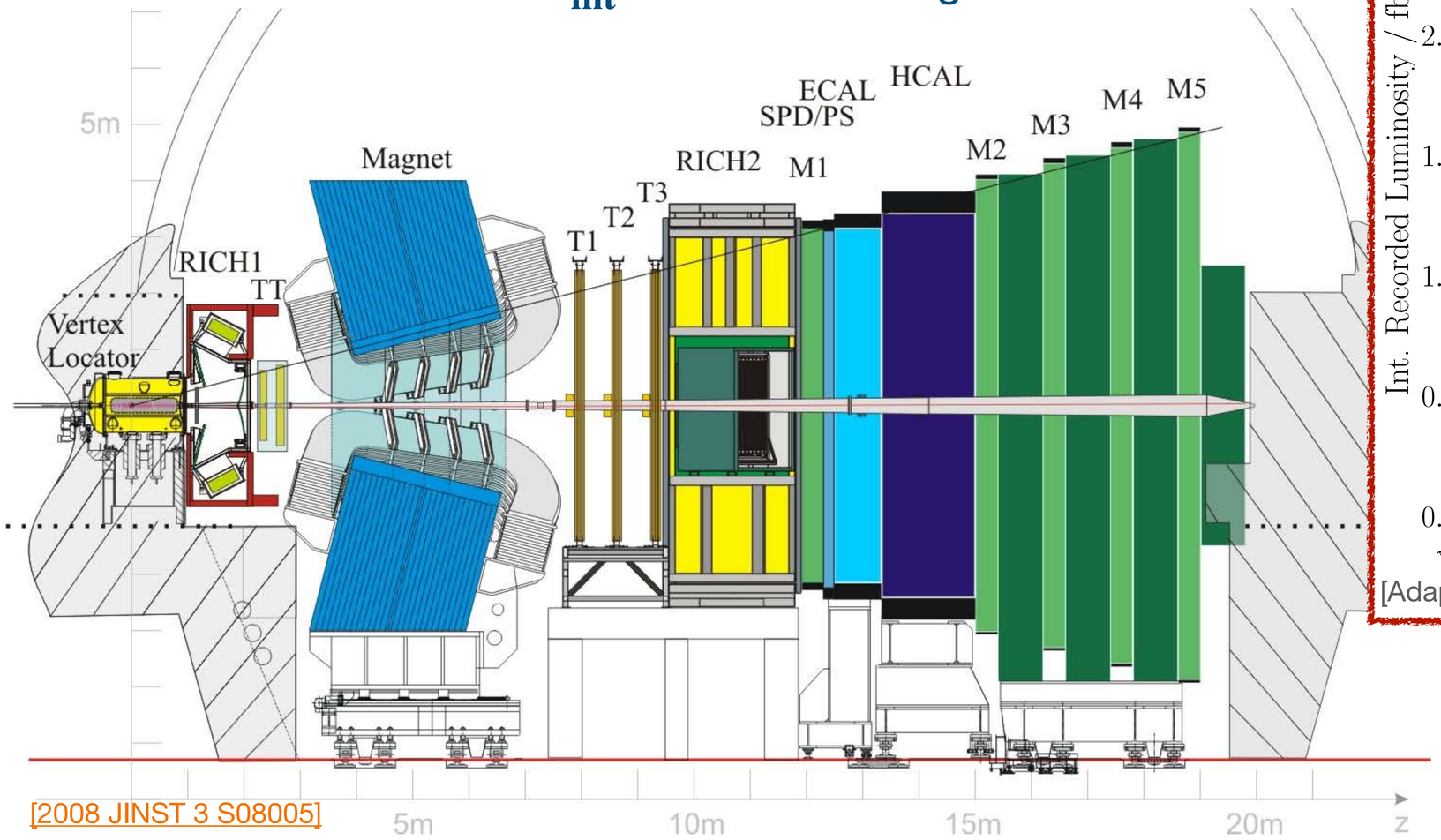


- Energy resolution:
  $\Delta E/E = 1\,\% + 10\,\%/\sqrt{\mathrm{E\,[GeV]}}$
- **Bremsstrahlung recovery** for electrons

Photo: S. Schmitt

LHCb Detector in Run 1 and 2

- Collected a total of $\mathscr{L}_{\text{int}} = 9\,\text{fb}^{-1}$ during Run 1 and 2



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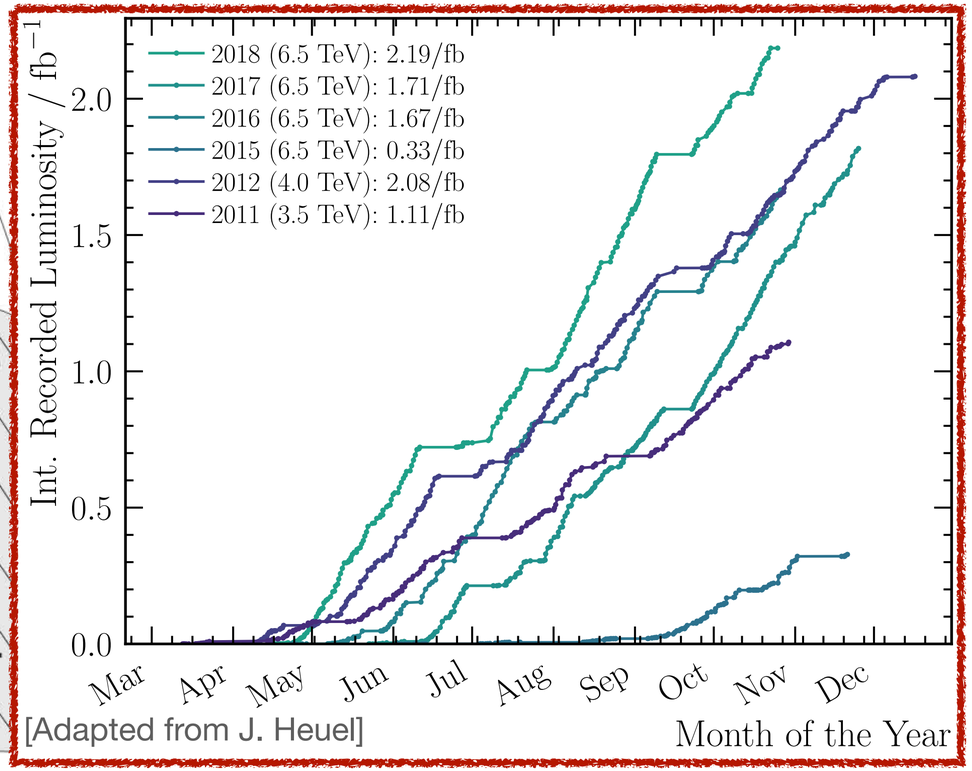


[Adapted from J. Heuel]

- Only possible due to the great work of the people operating LHC and LHCb!

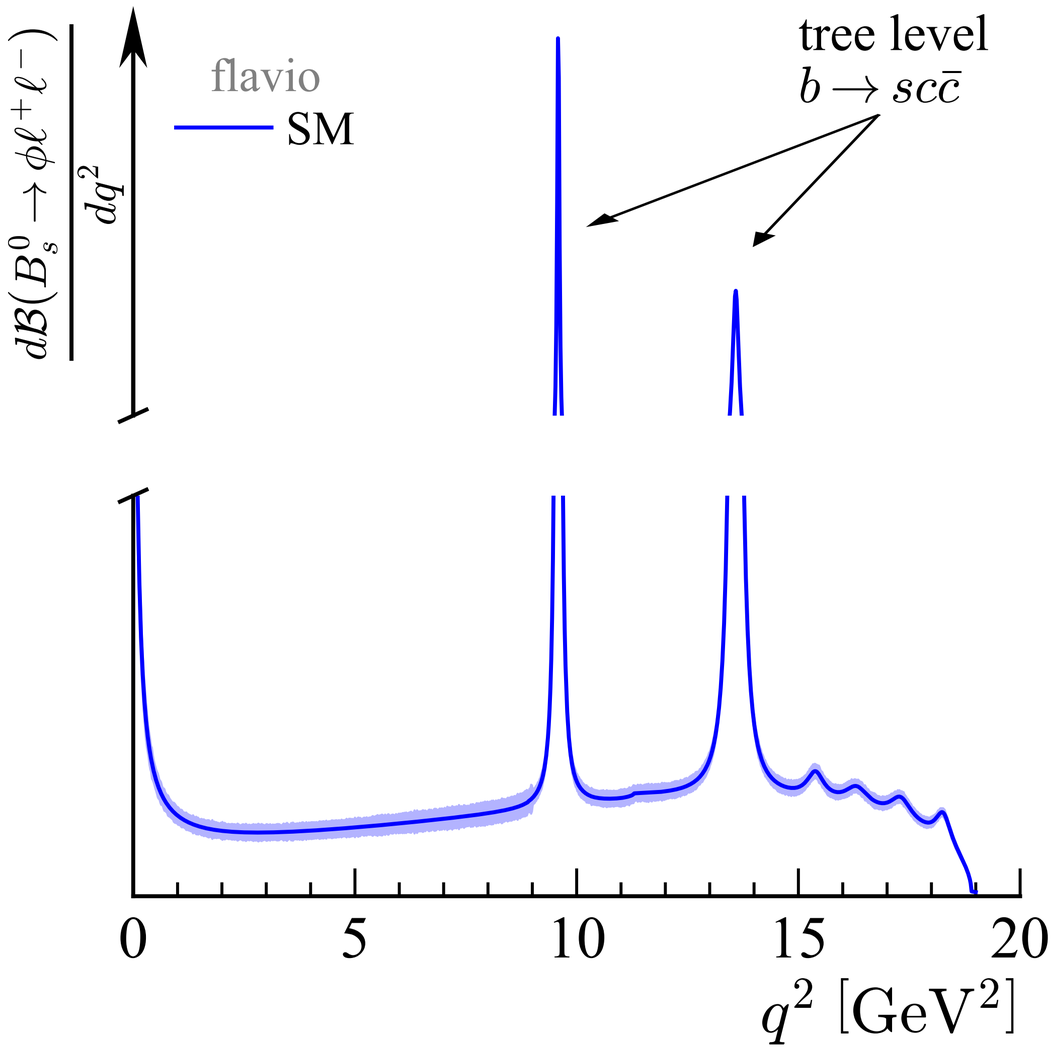
Photo: S. Schmitt

Analysis Strategy

- Measure R_ϕ depending on $q^2 = m(\ell^+\ell^-)^2$
  - low-q^2: $0.1 < q^2 < 1.1\,\mathrm{GeV}^2/c^4$
  - central-q^2: $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$
  - high-q^2: $15 < q^2 < 19\,\mathrm{GeV}^2/c^4$ ⇐ **First time!**
- Measure R_ϕ^{-1} as **blind double ratio:**

$$R_\phi^{-1} = \frac{\mathcal{B}\left(B_s^0 \to \phi e^+e^-\right)}{\mathcal{B}\left(B_s^0 \to \phi \mu^+\mu^-\right)} \Bigg/ \frac{\mathcal{B}\left(B_s^0 \to \phi J/\psi\left(e^+e^-\right)\right)}{\mathcal{B}\left(B_s^0 \to \phi J/\psi\left(\mu^+\mu^-\right)\right)}$$

- Most efficiency-related **systematic** uncertainties **cancel in double ratio**



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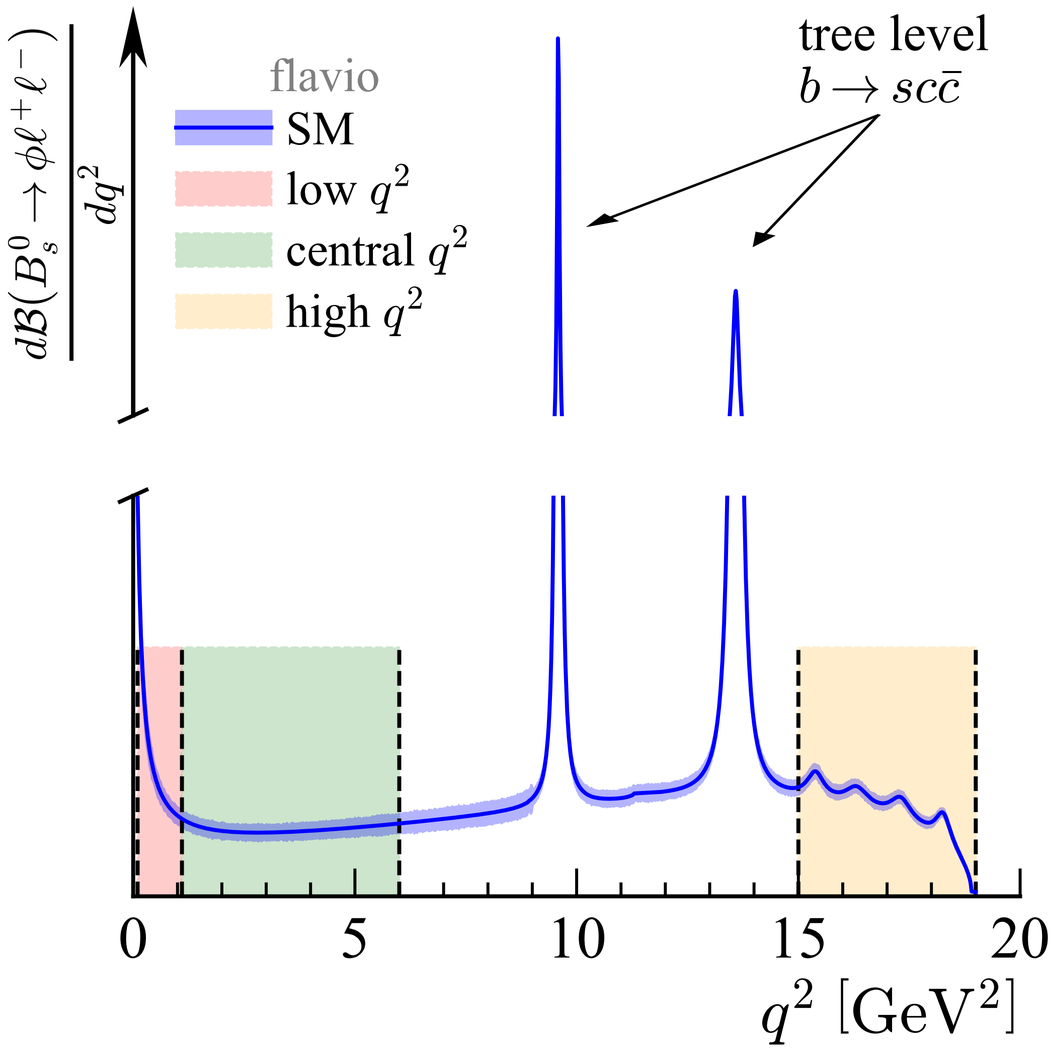

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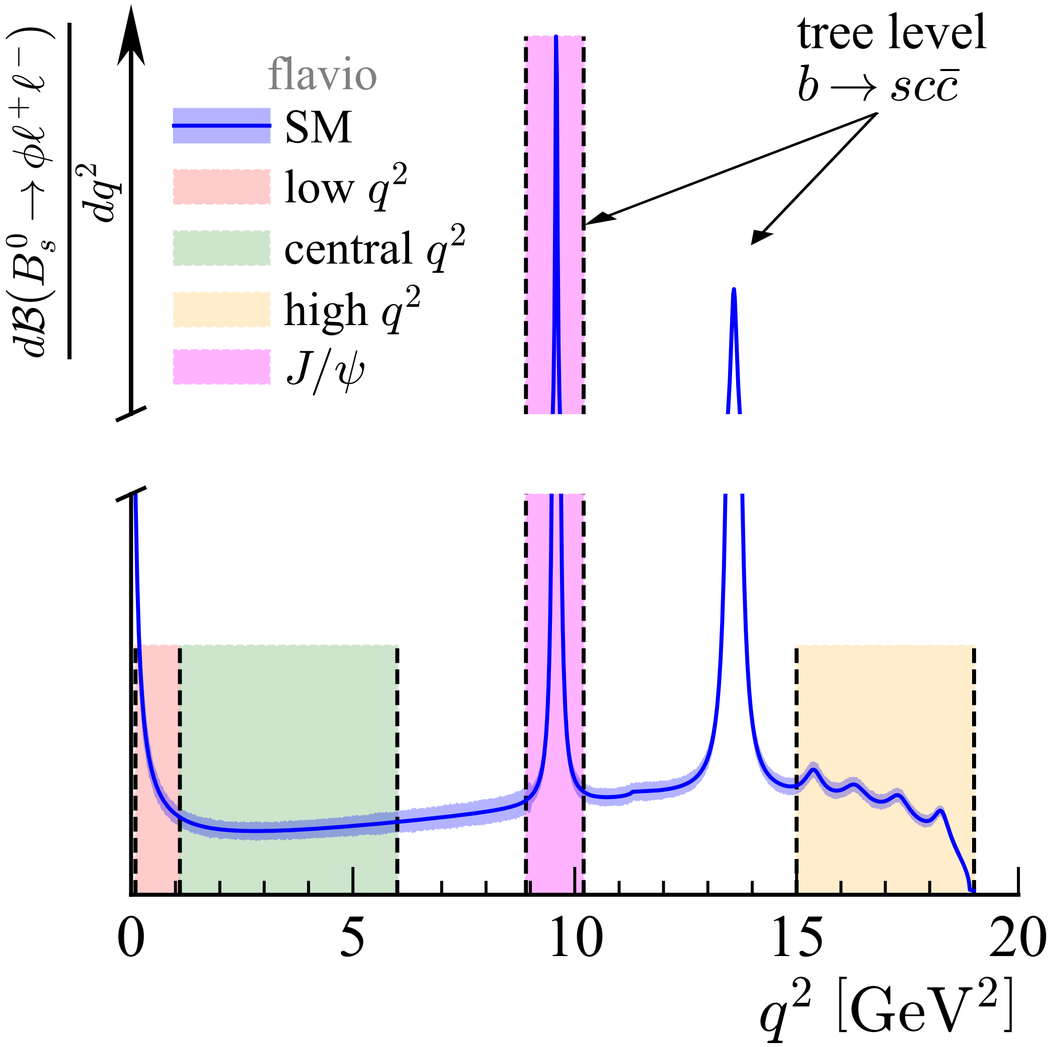

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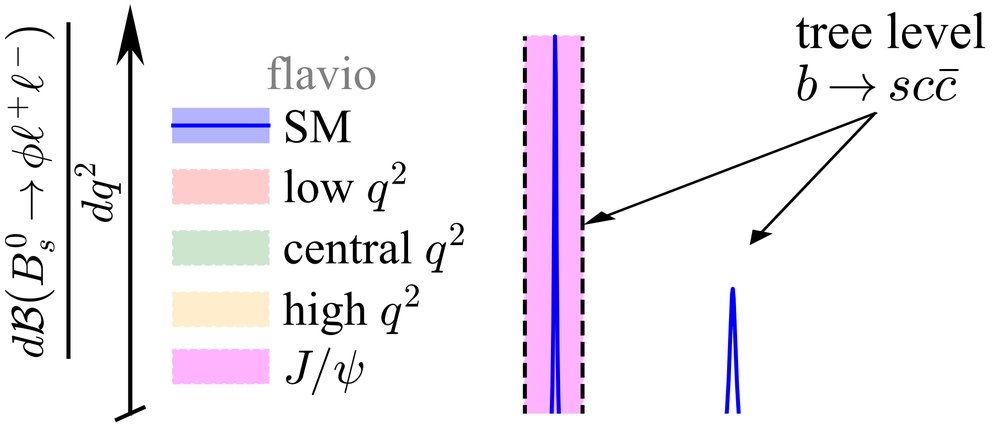

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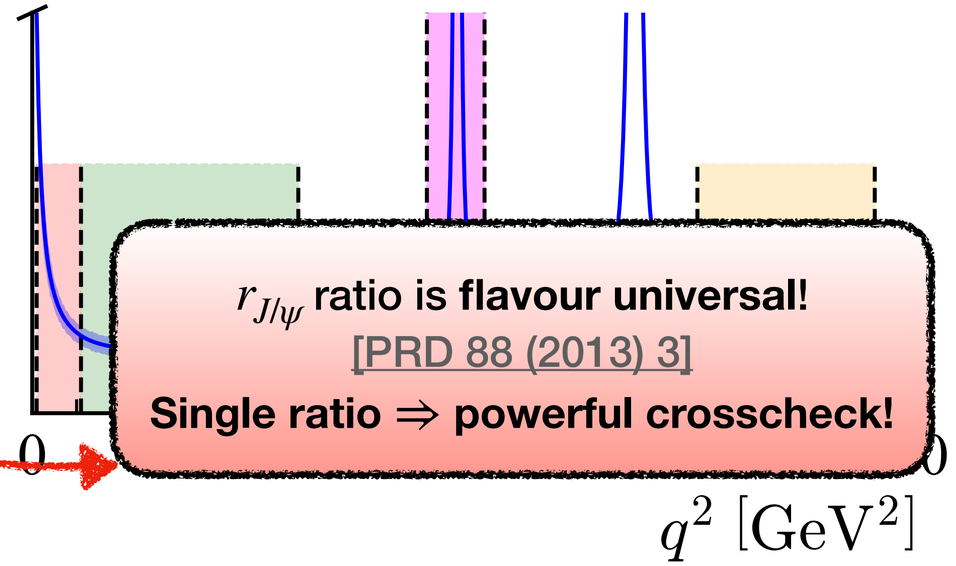

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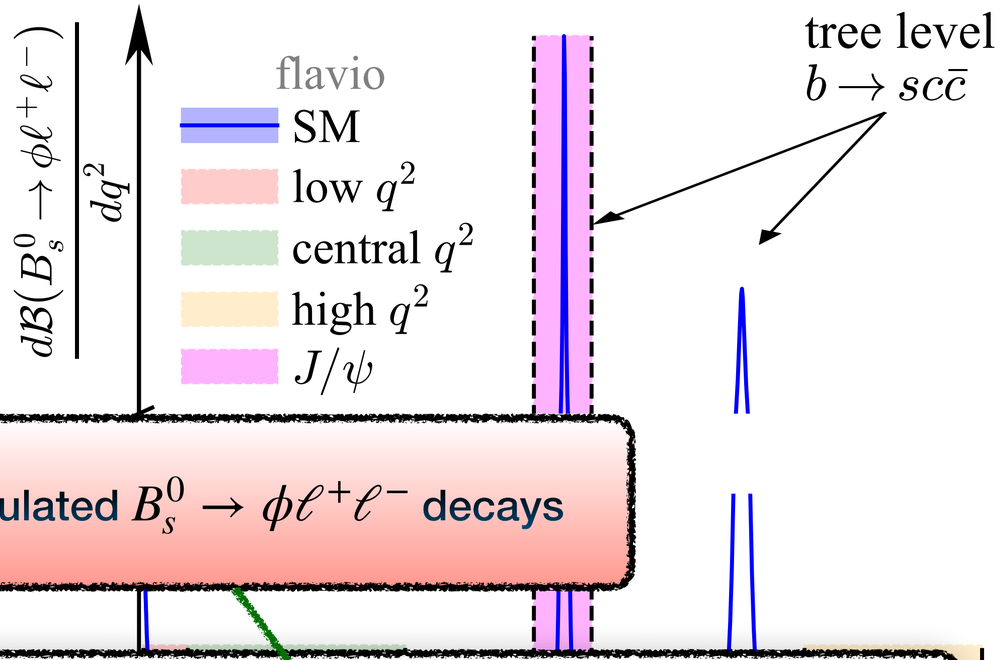


Extended maximum likelihood fits (blind!)

Simulated $B_s^0 \to \phi\ell^+\ell^-$ decays

Experimentally:

$$R_\phi^{-1} = \frac{\mathrm{N}\left(\phi e^+e^-\right)}{\mathrm{N}\left(\phi J/\psi\left(e^+e^-\right)\right)} \cdot \frac{\mathrm{N}\left(\phi J/\psi\left(\mu^+\mu^-\right)\right)}{\mathrm{N}\left(\phi\mu^+\mu^-\right)} \cdot \frac{\varepsilon\left(\phi J/\psi\left(e^+e^-\right)\right)}{\varepsilon\left(\phi e^+e^-\right)} \cdot \frac{\varepsilon\left(\phi\mu^+\mu^-\right)}{\varepsilon\left(\phi J/\psi\left(\mu^+\mu^-\right)\right)}$$

20

$y^2]$

Photo: S. Schmitt

Experimental Challenges with Electrons

- Electron PID more challenging
  - Background control crucial
- Smaller hardware **trigger efficiency**
  - Higher thresholds compared to muons
- Electrons emit more **bremsstrahlung**
  - Main source of energy loss for e^+e^-

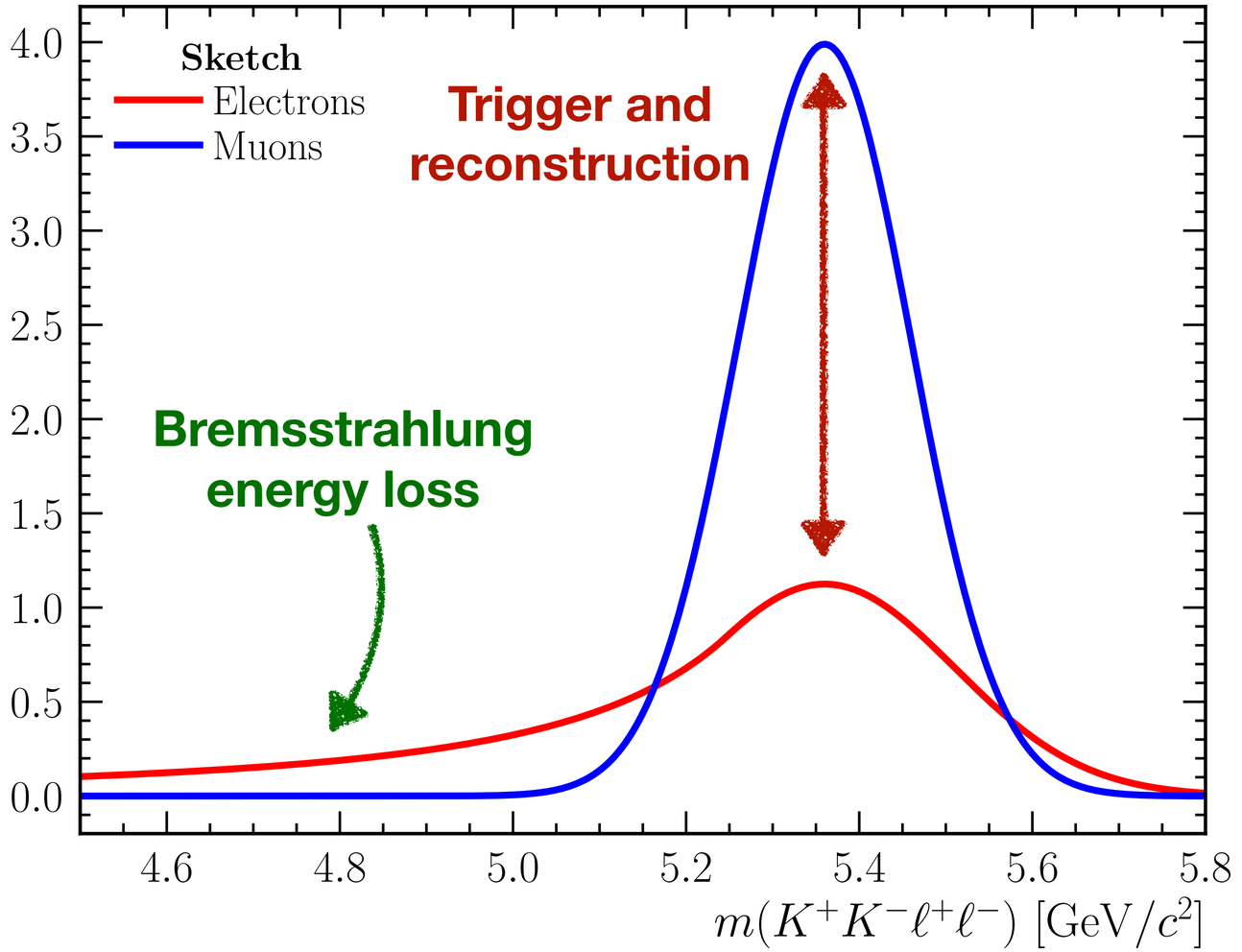
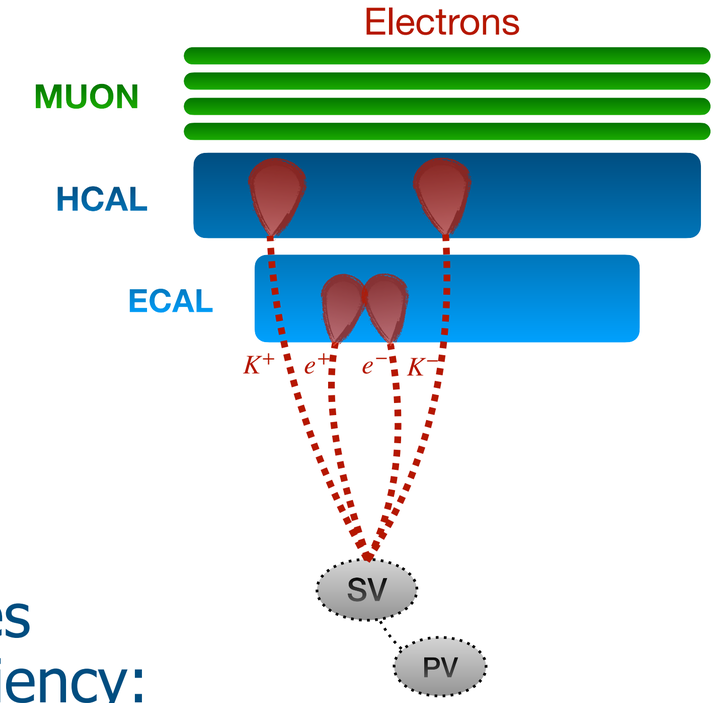


Photo: S. Schmitt

Triggering on Electrons

- Thresholds **lower for muons** compared to electrons
  - Muons: $p_{\mathrm{T}} > 1.5 - 1.8\,\mathrm{GeV}/c$
  - Electrons: $E_{\mathrm{T}} > 2.5 - 3.0\,\mathrm{GeV}$



- Combine different trigger categories to **maximise** electron trigger efficiency:
  1. Trigger independent of signal (“TIS”)
  2. Trigger on signal lepton from B_s^0 (“TOS”)

Photo: S. Schmitt

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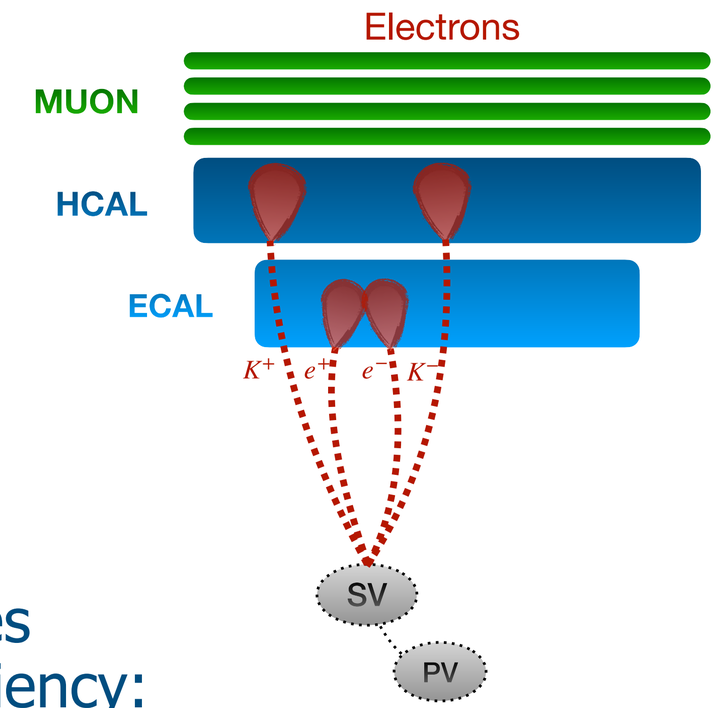

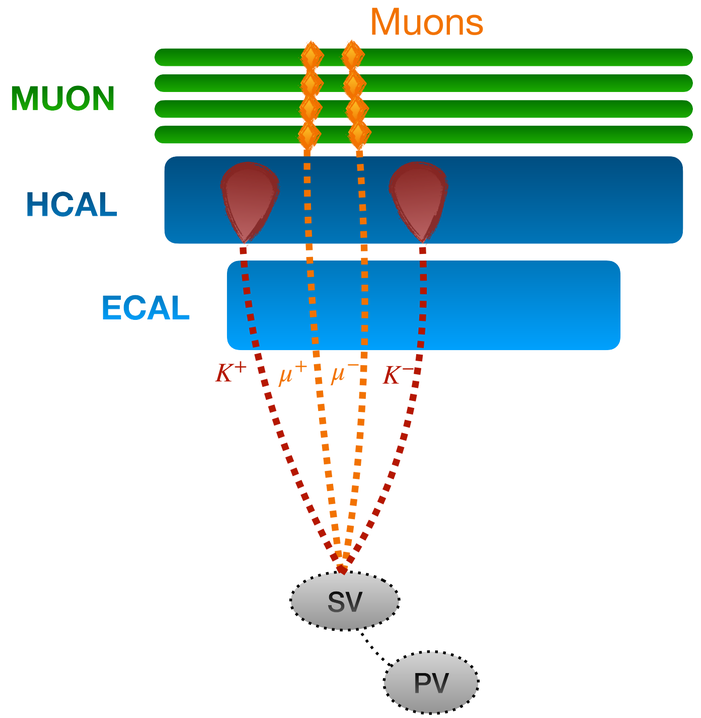

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Photo: S. Schmitt

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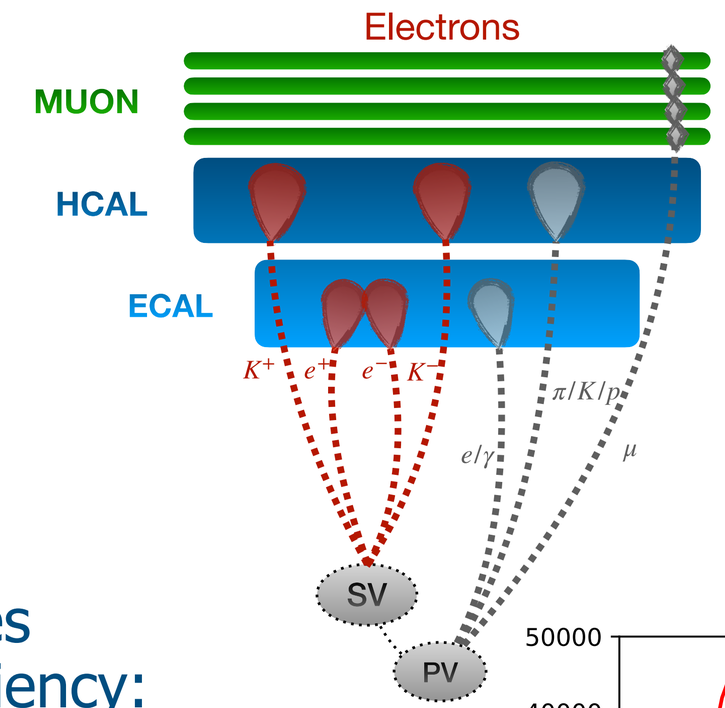
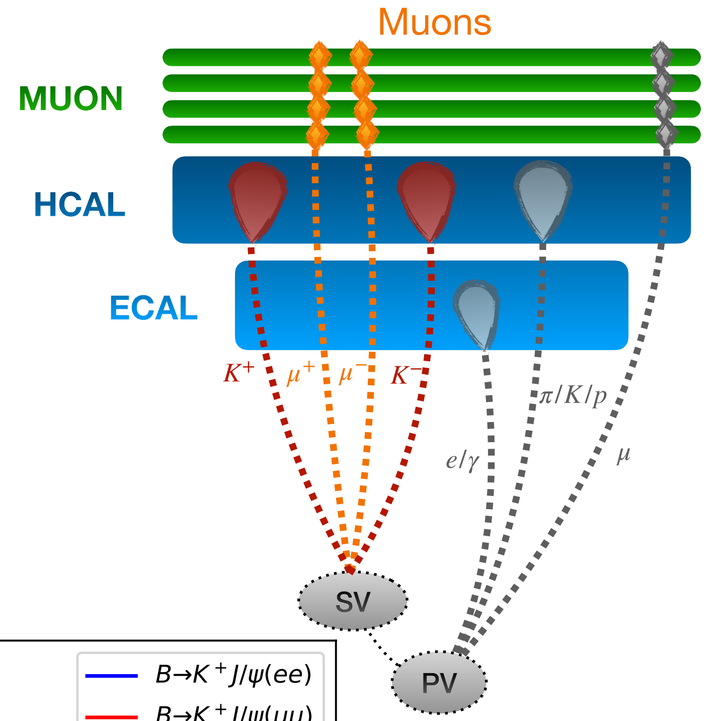




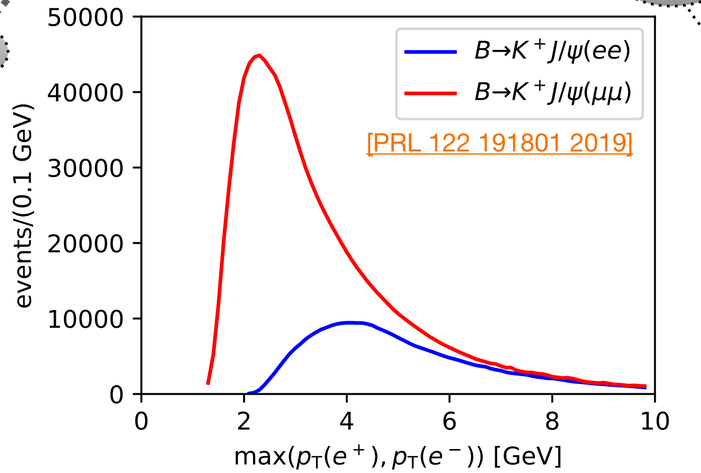


Photo: S. Schmitt

BREMSSTRAHLUNG

- Expect **on average one bremsstrahlung** photon emitted upstream of the magnet
- Corrected using **bremsstrahlung recovery**
  - $\mathcal{O}(50\,\%)$ efficient and **well modelled** in simulation
- Momentum resolution deteriorated
  - Wider fit range required
  - Higher background pollution

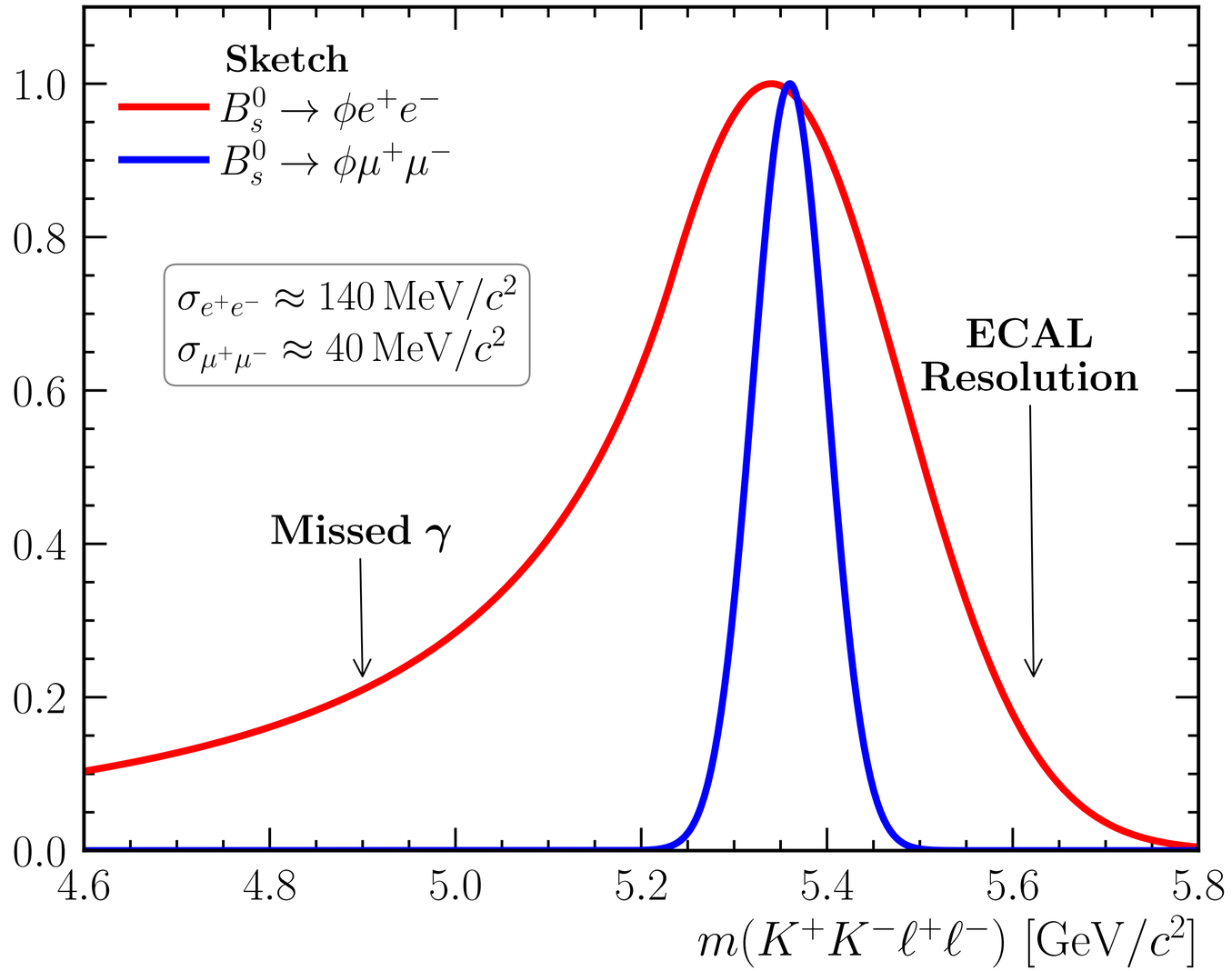
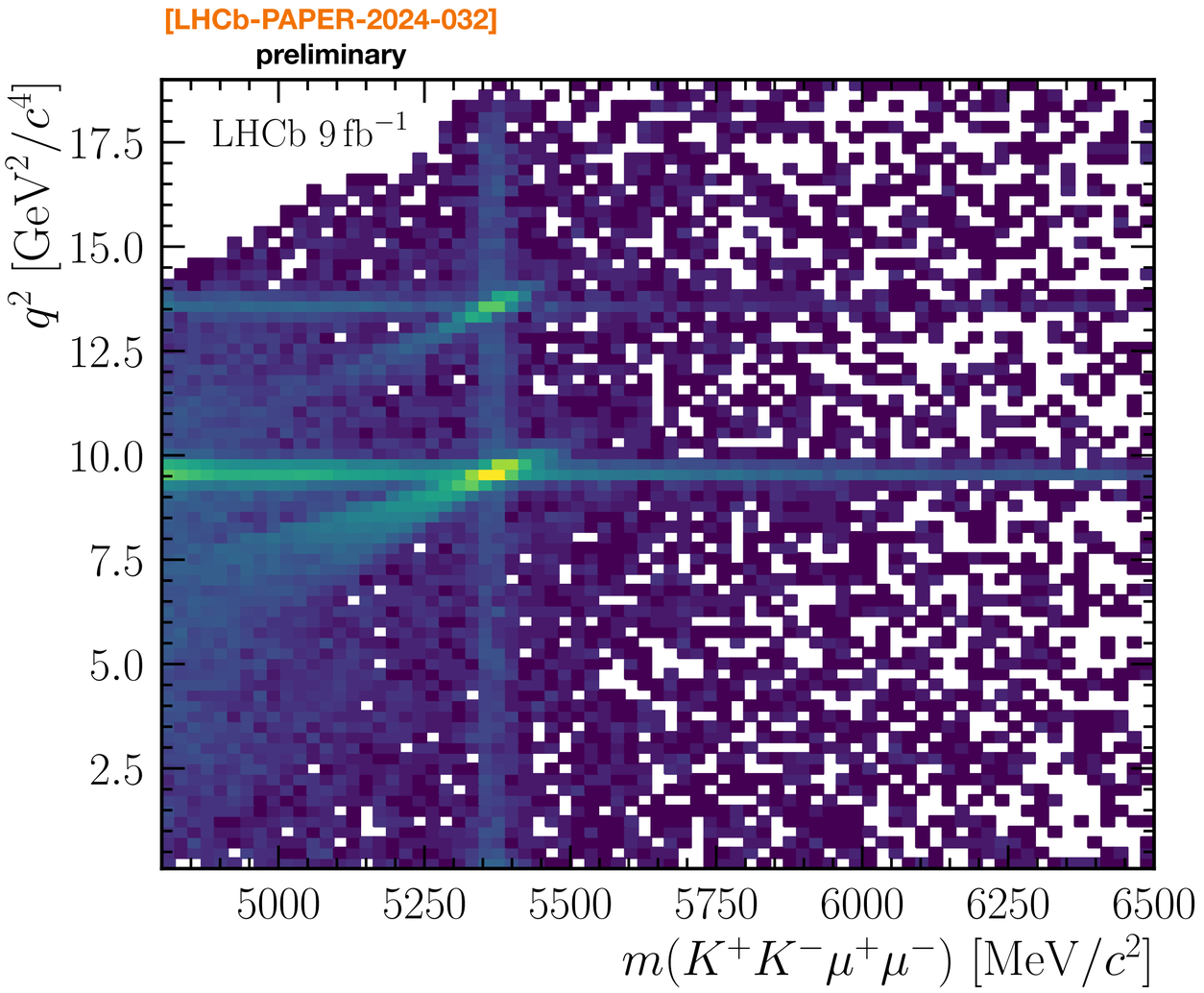


Photo: S. Schmitt

Effects of Bremsstrahlung



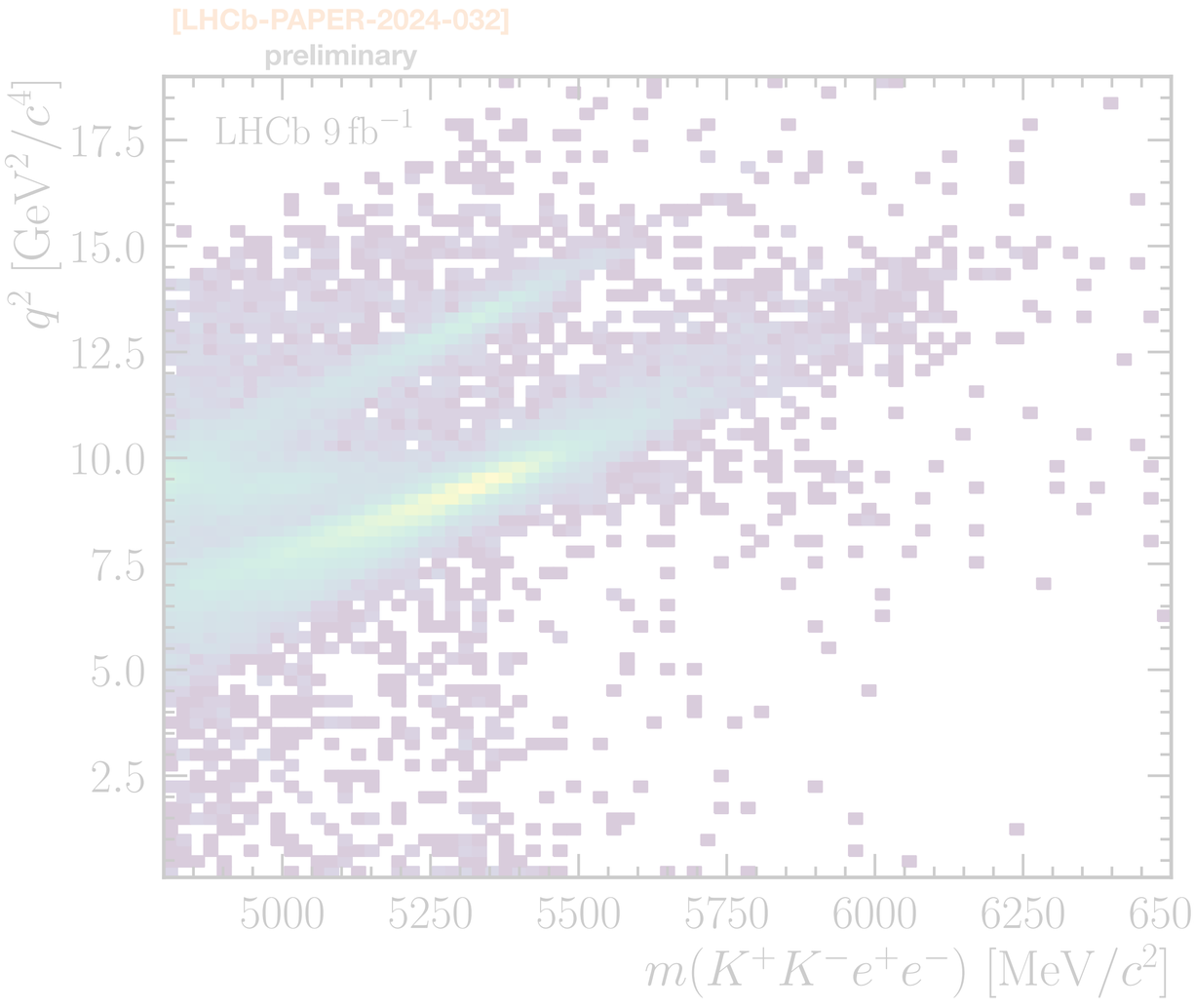


Photo: S. Schmitt

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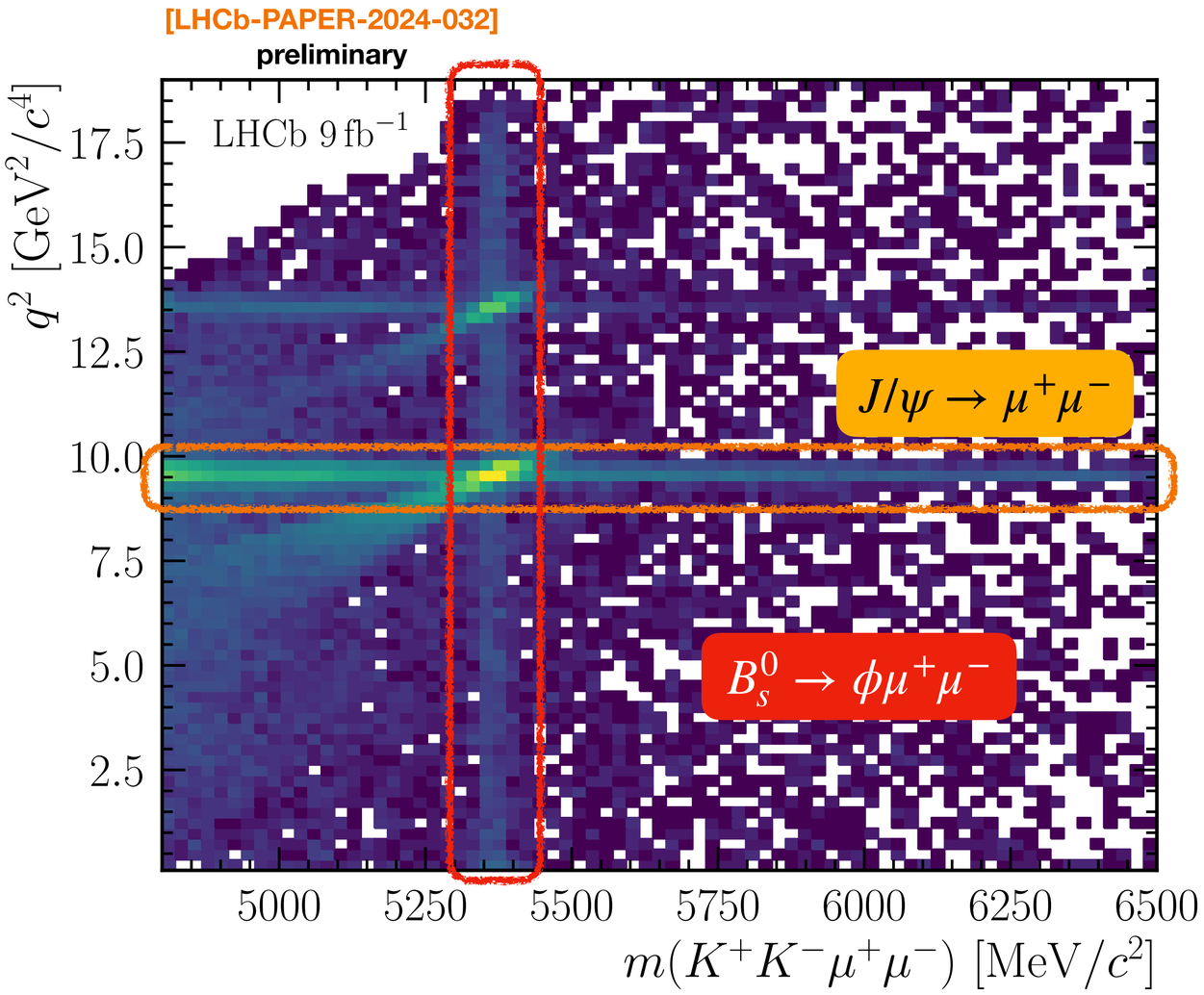

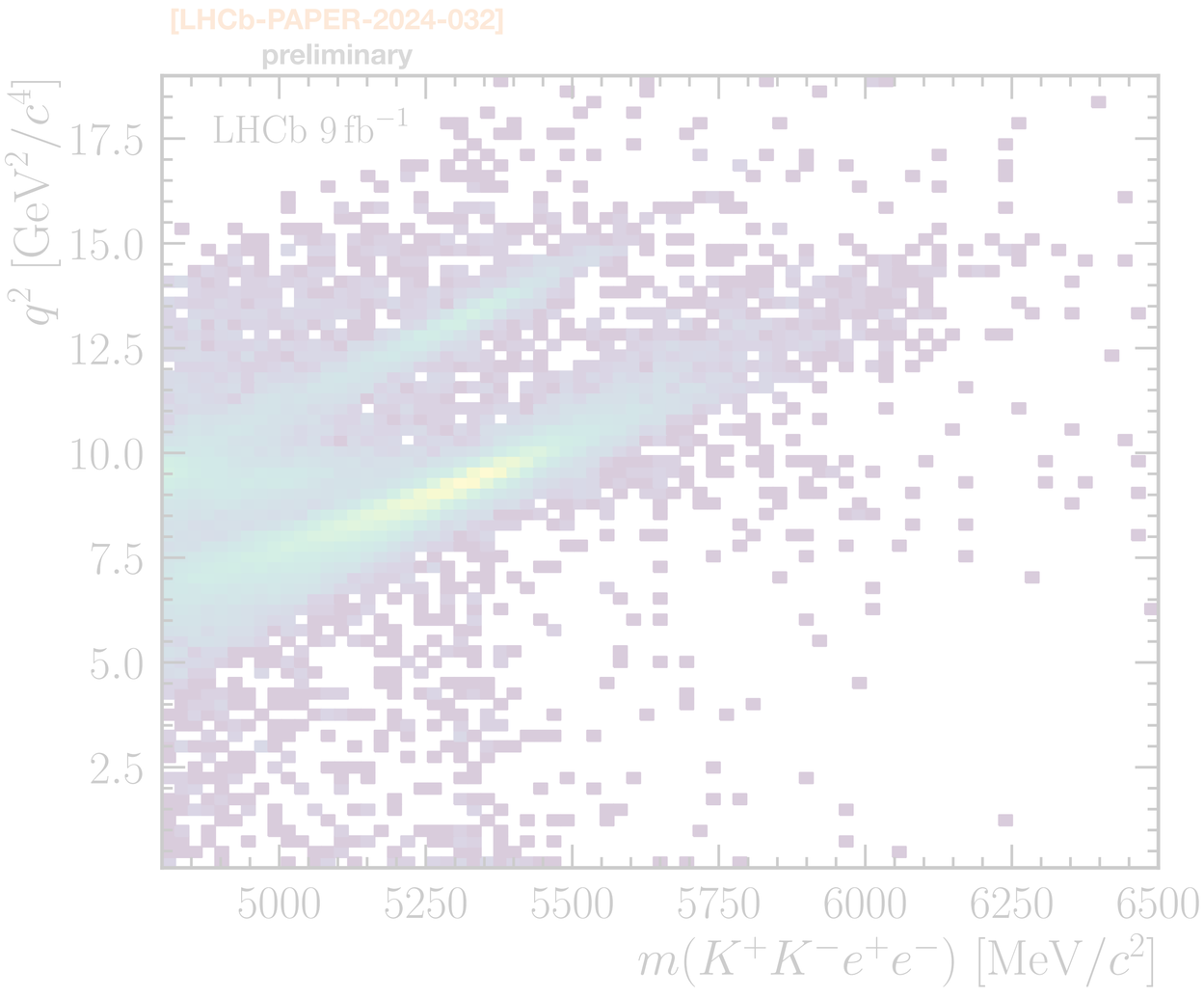

Photo: S. Schmitt

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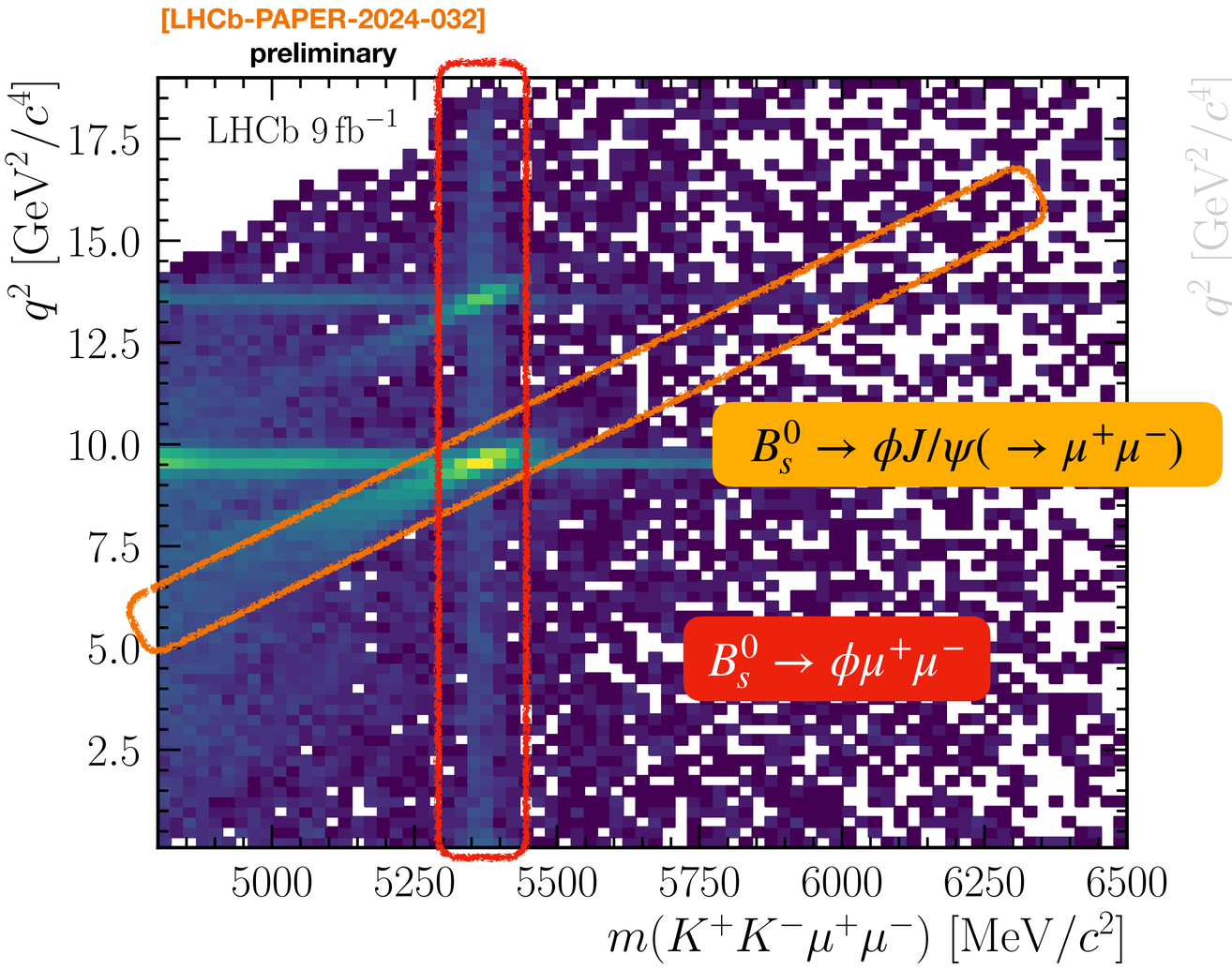

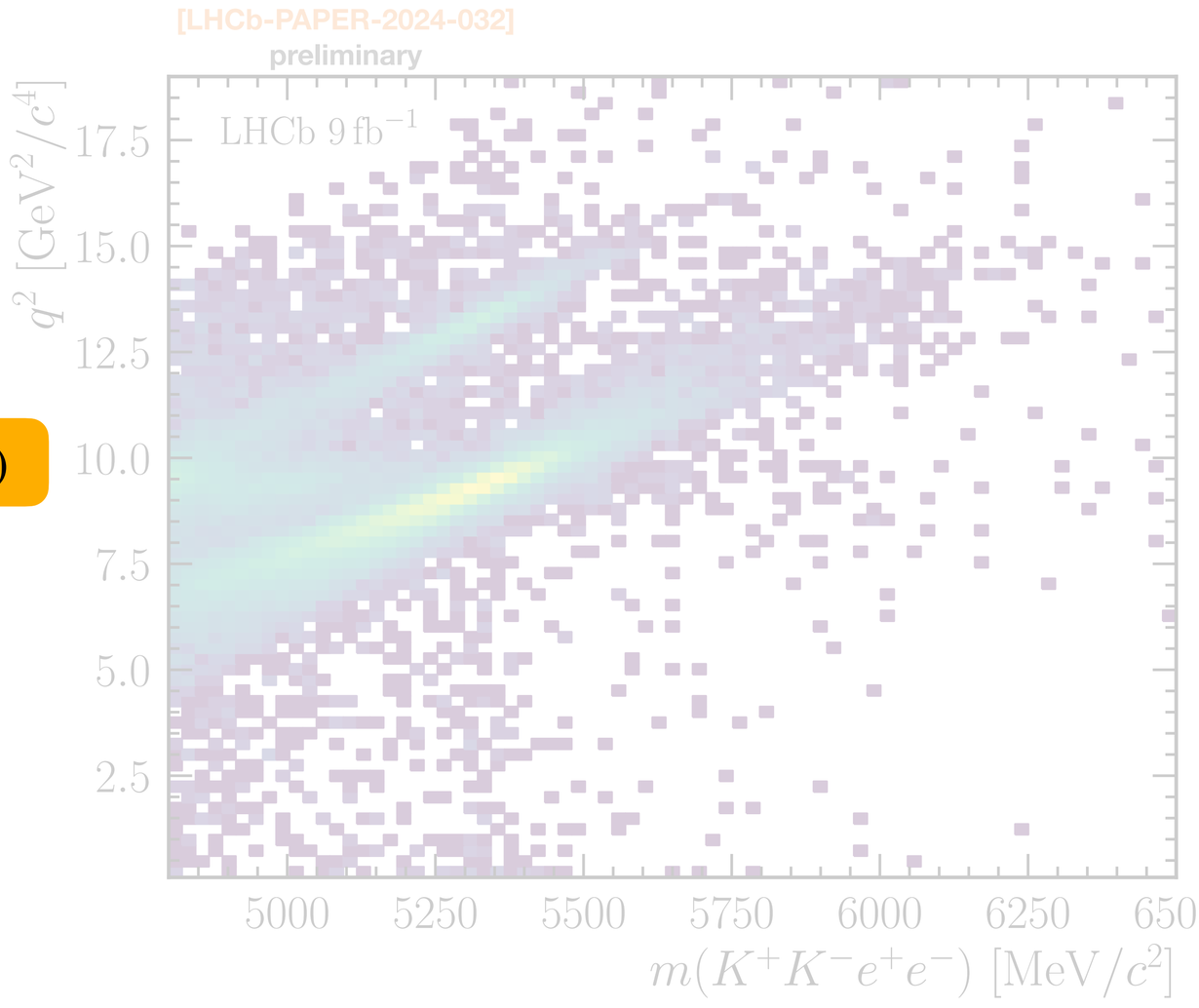

Photo: S. Schmitt

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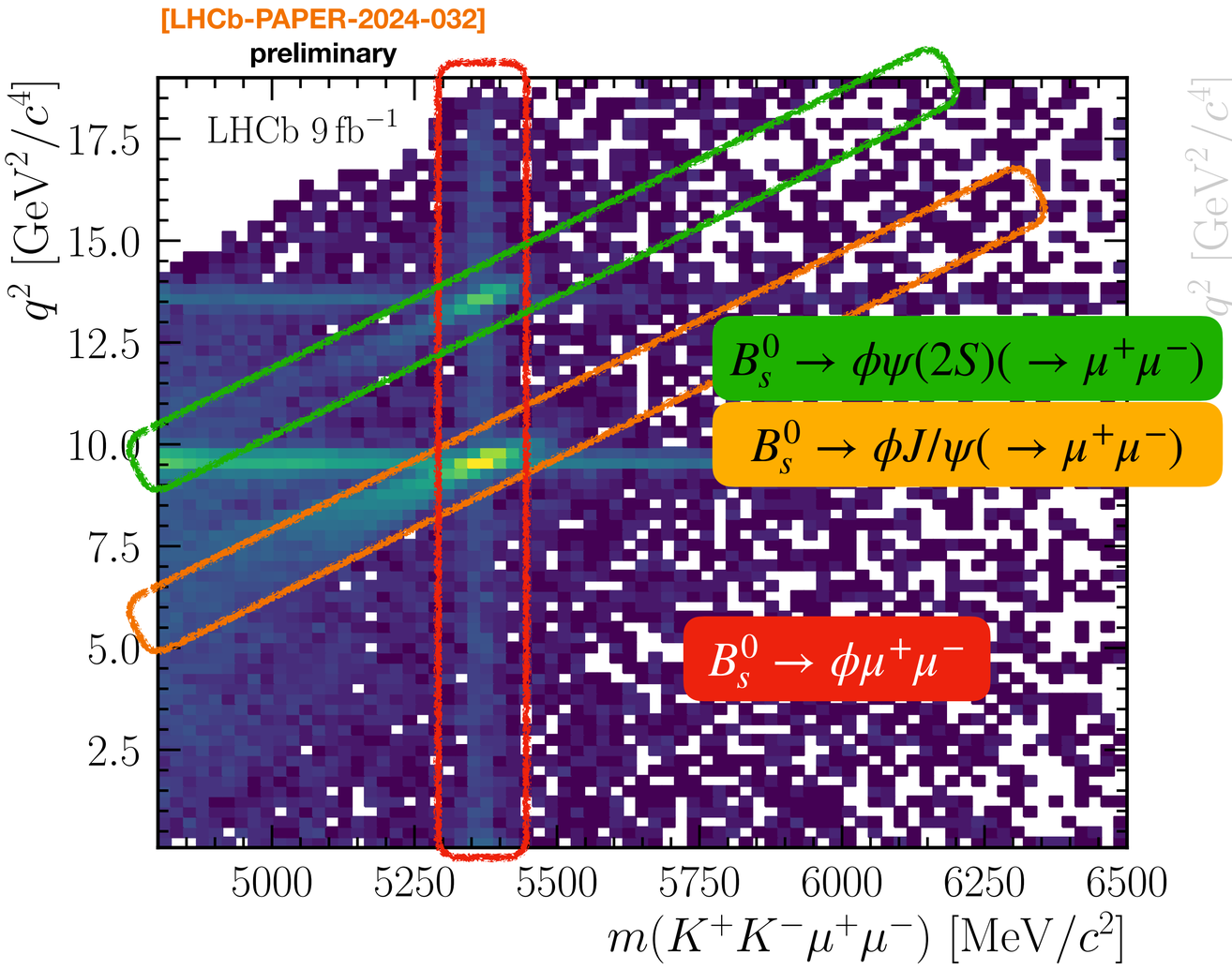

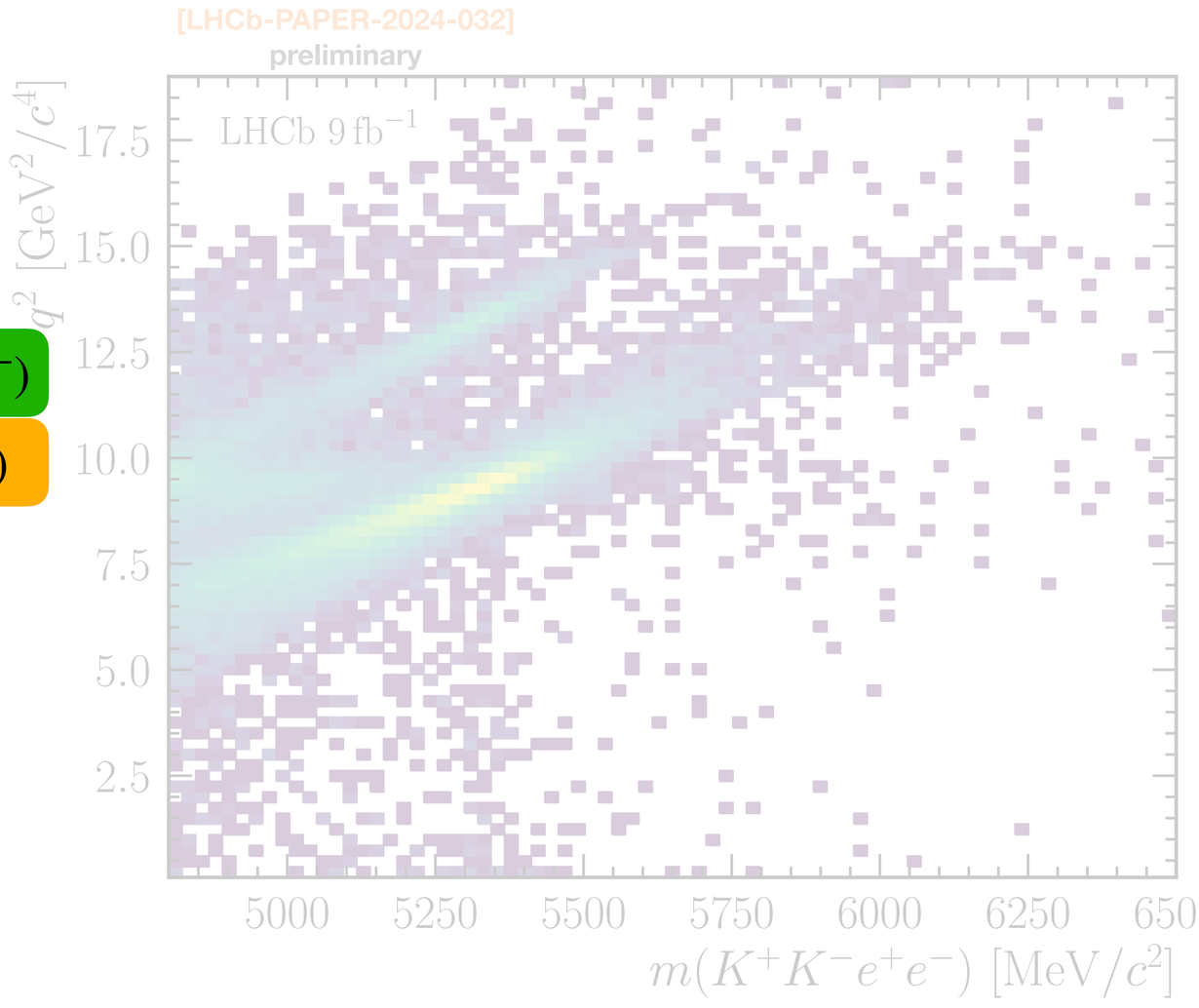

Photo: S. Schmitt

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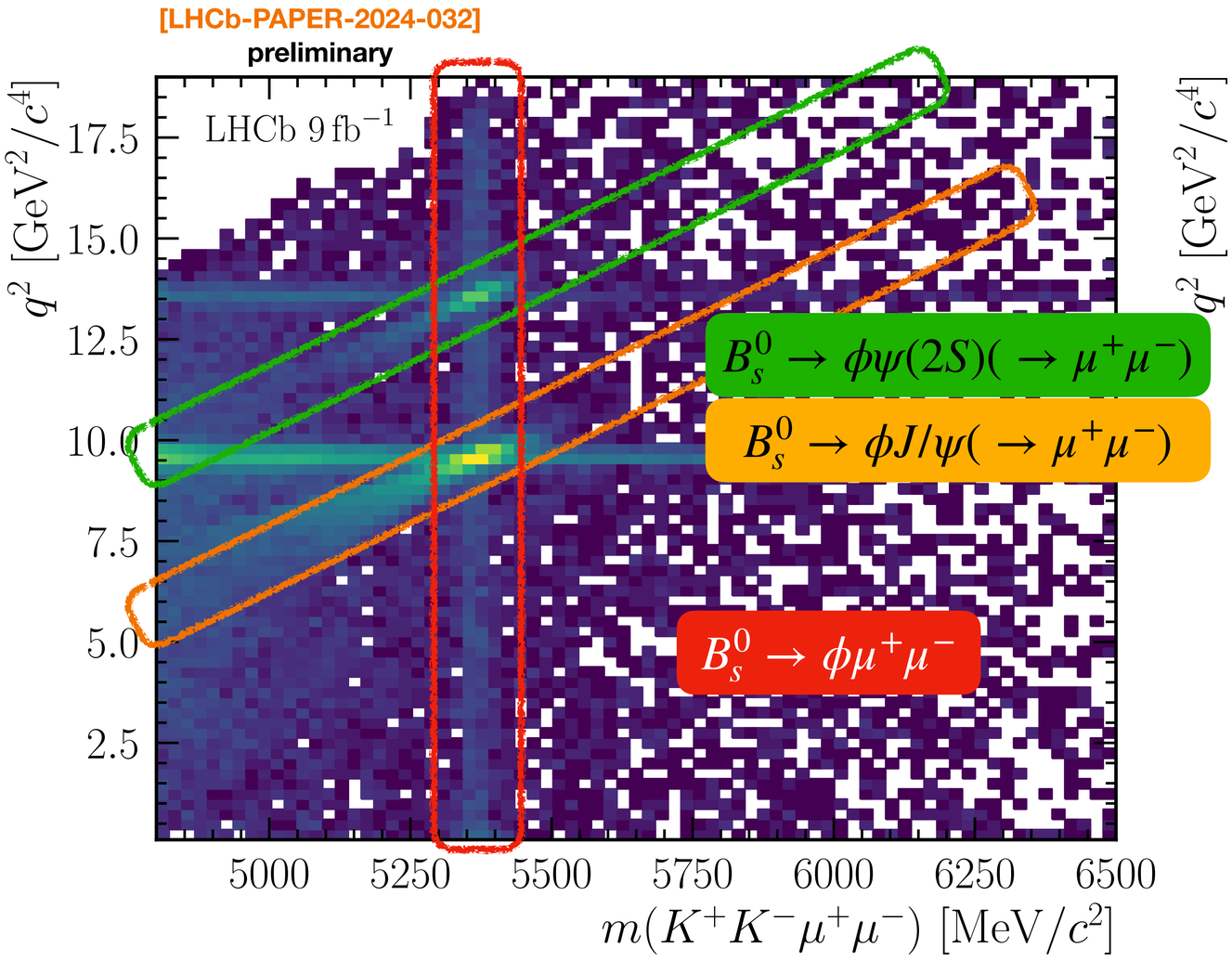

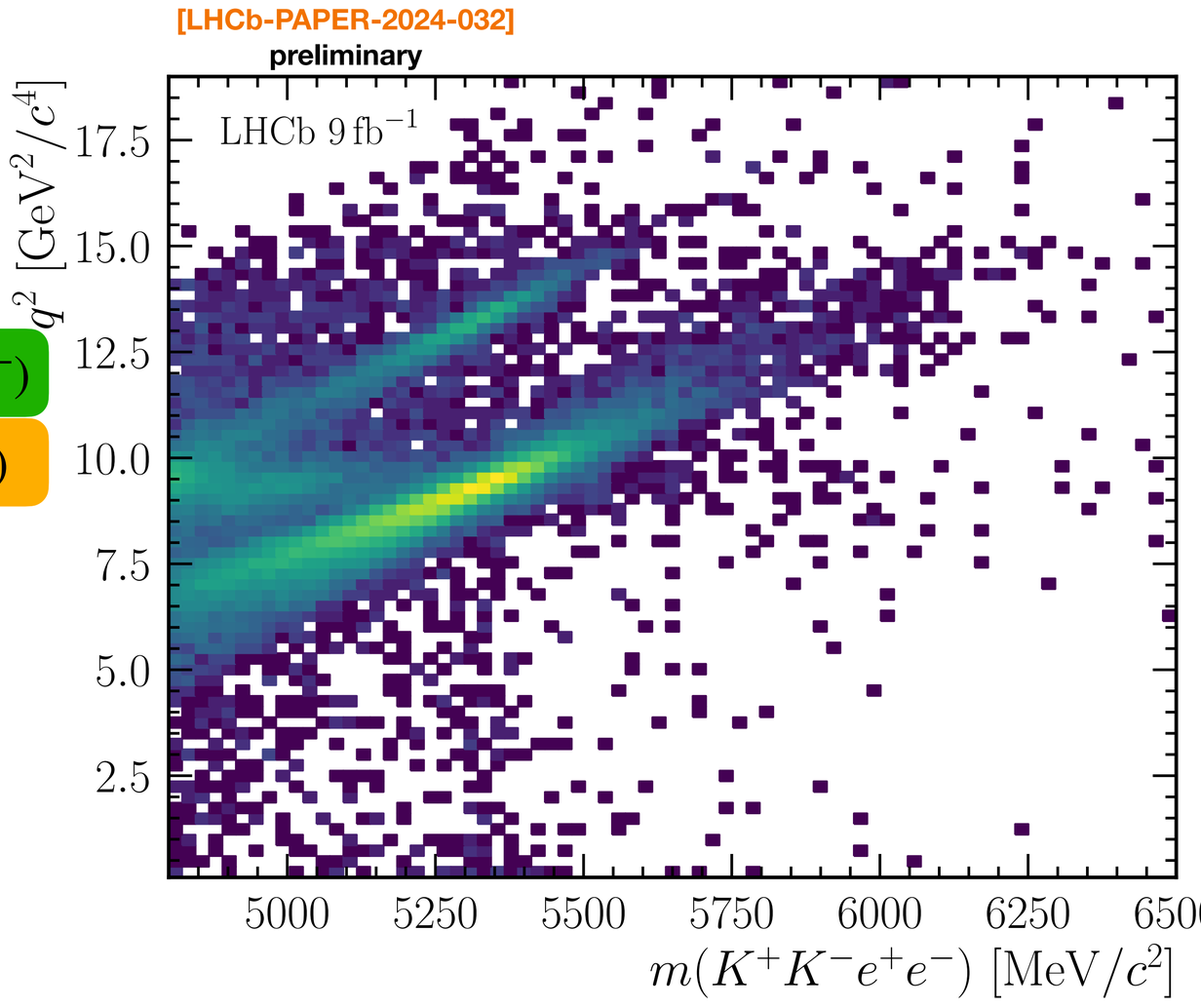

Photo: S. Schmitt

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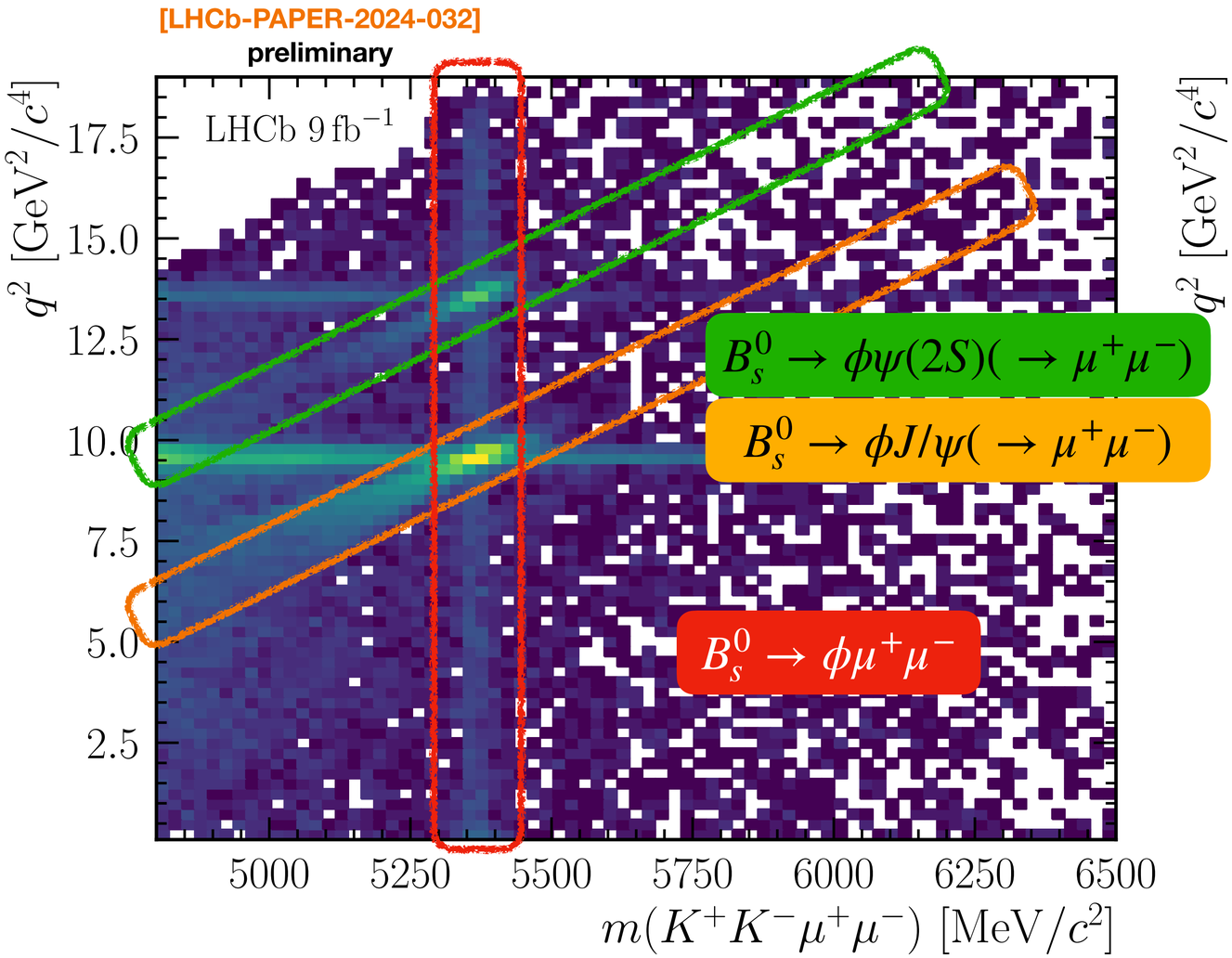

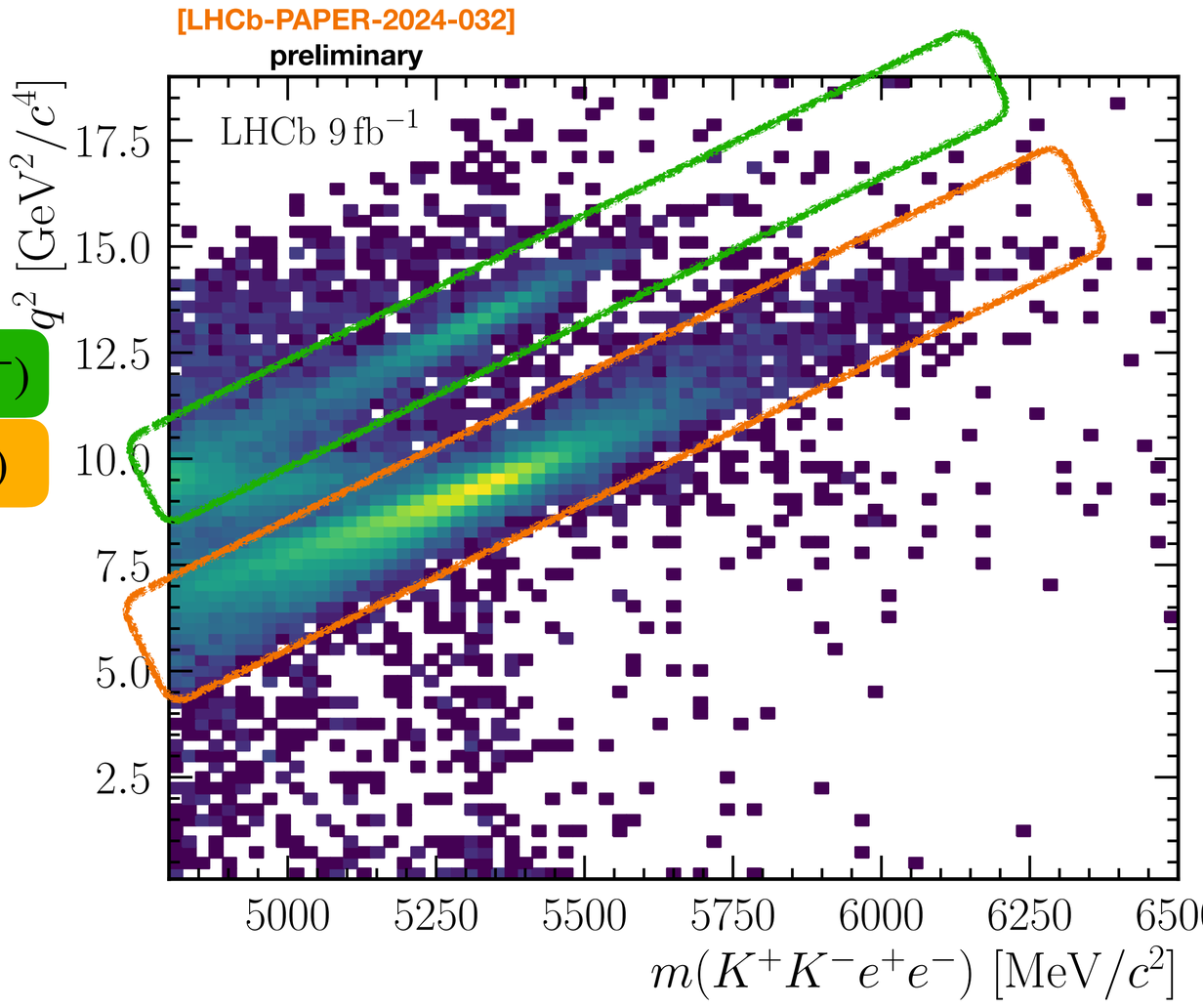

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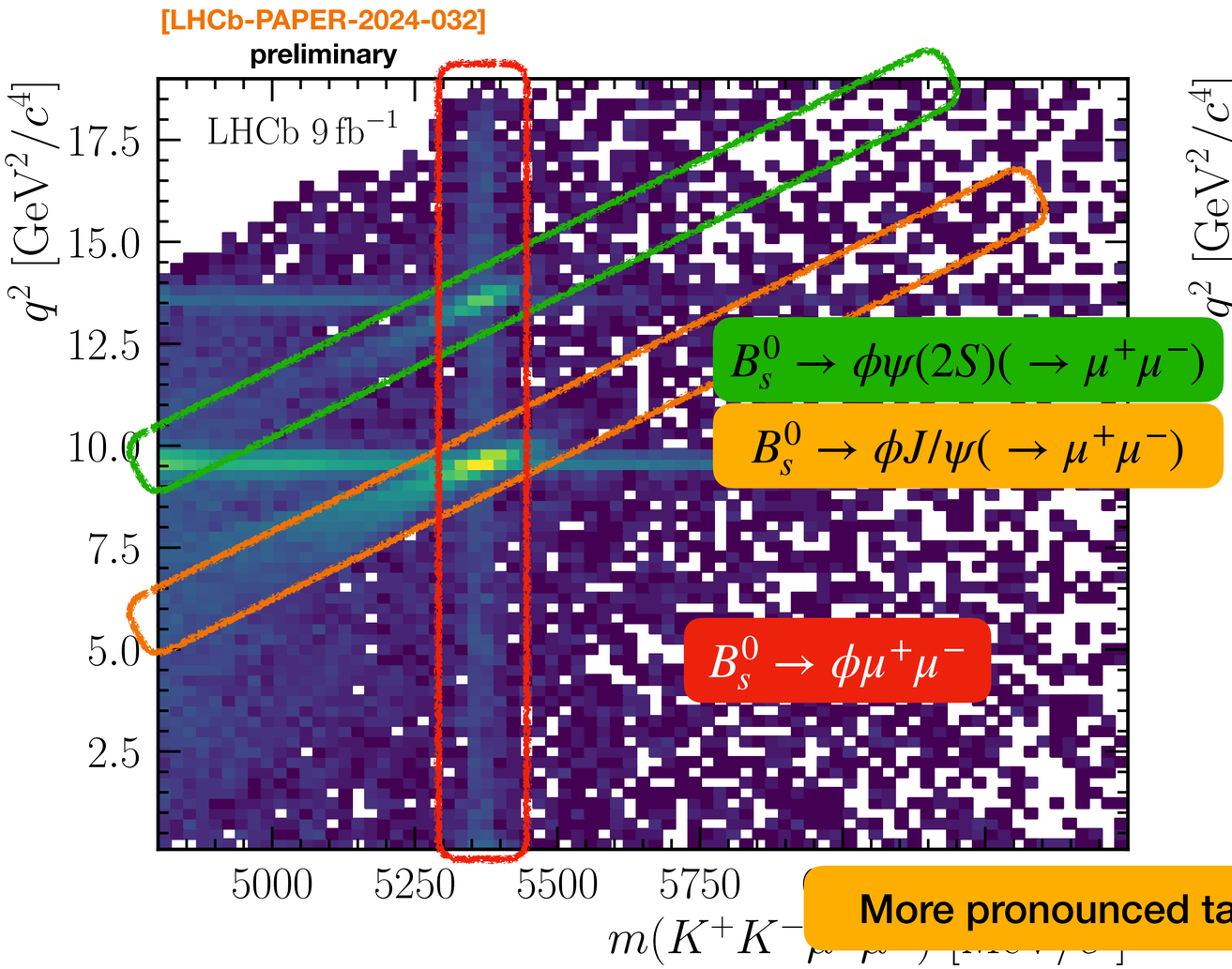
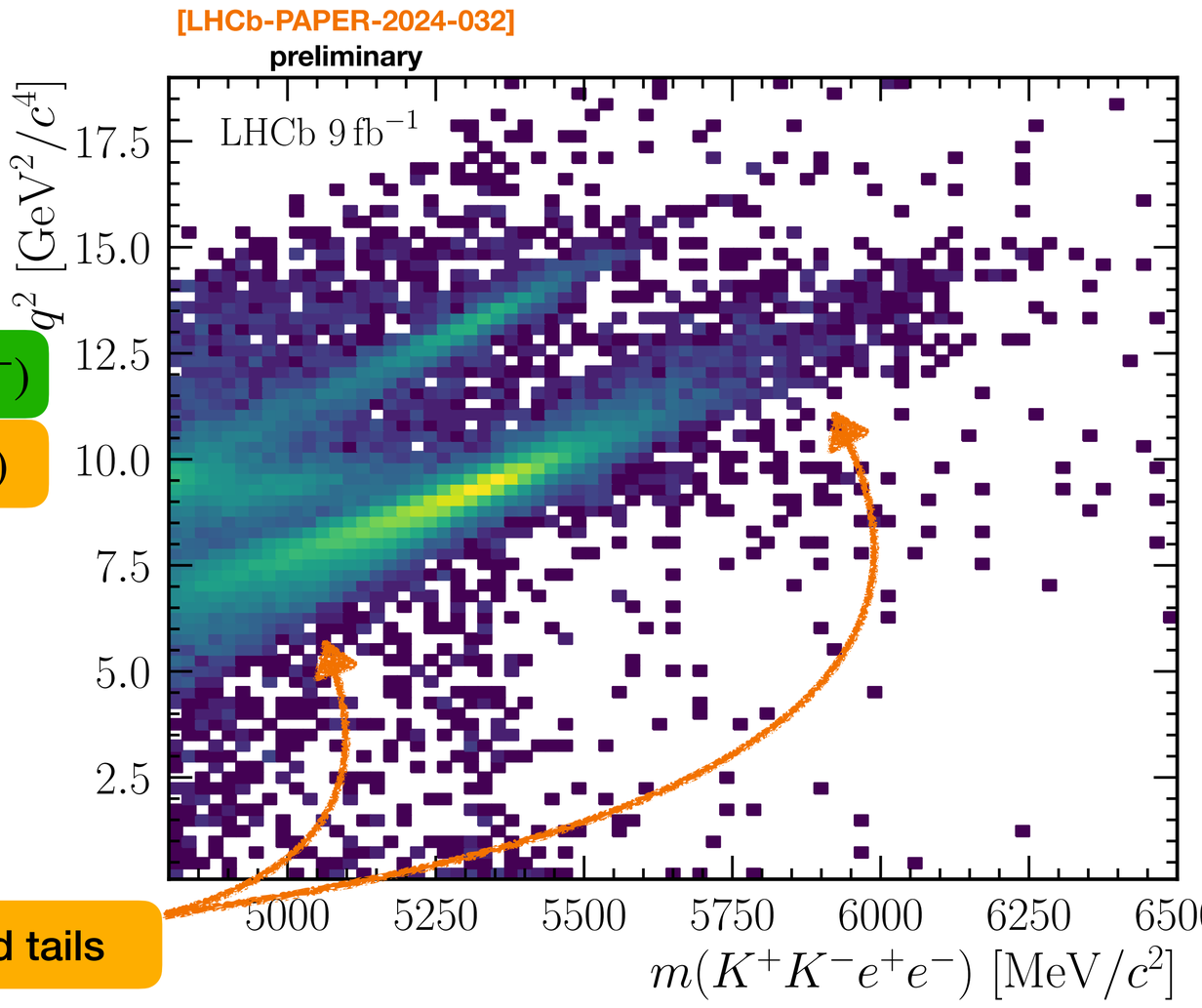
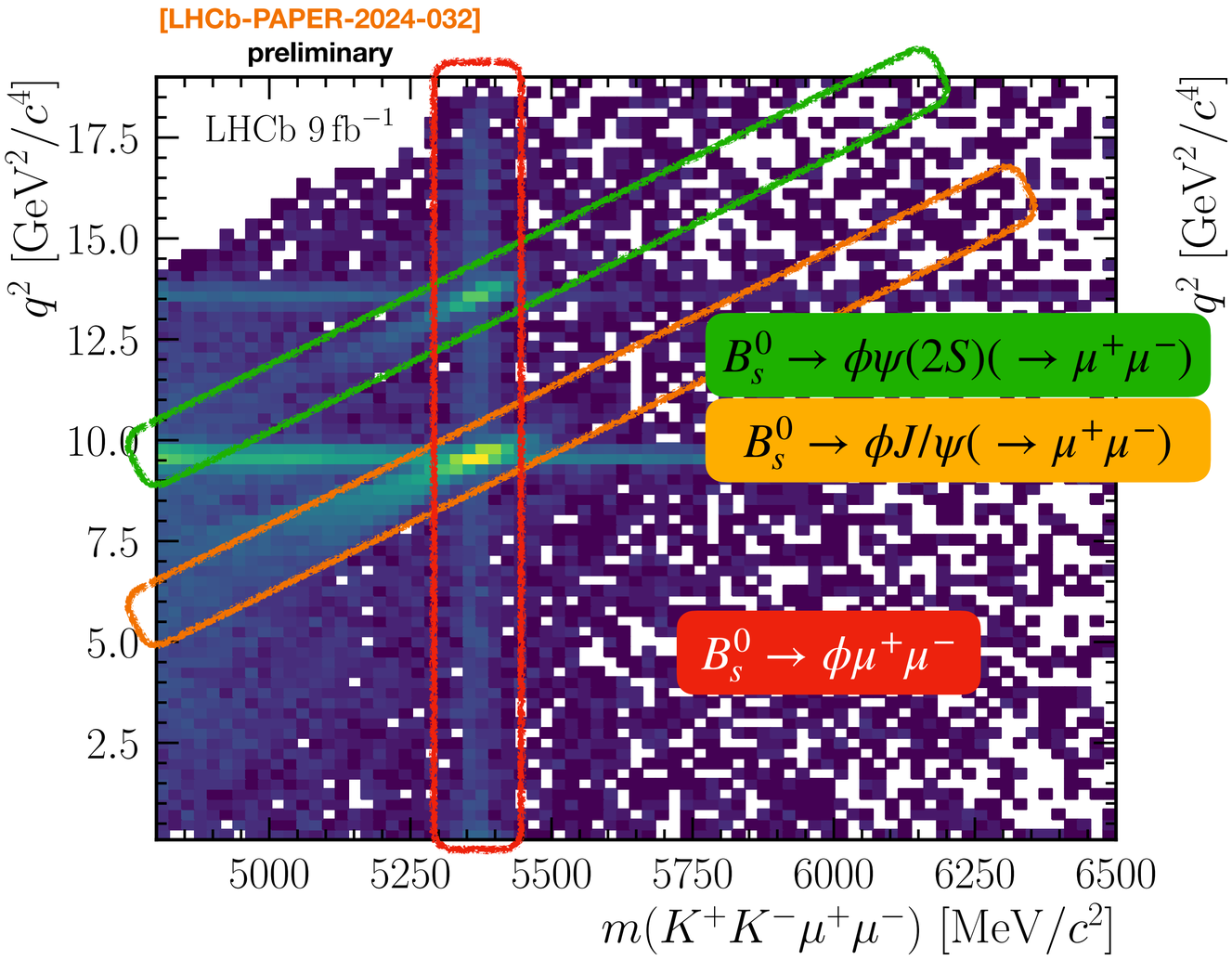




More pronounced tails

Effects of Bremsstrahlung



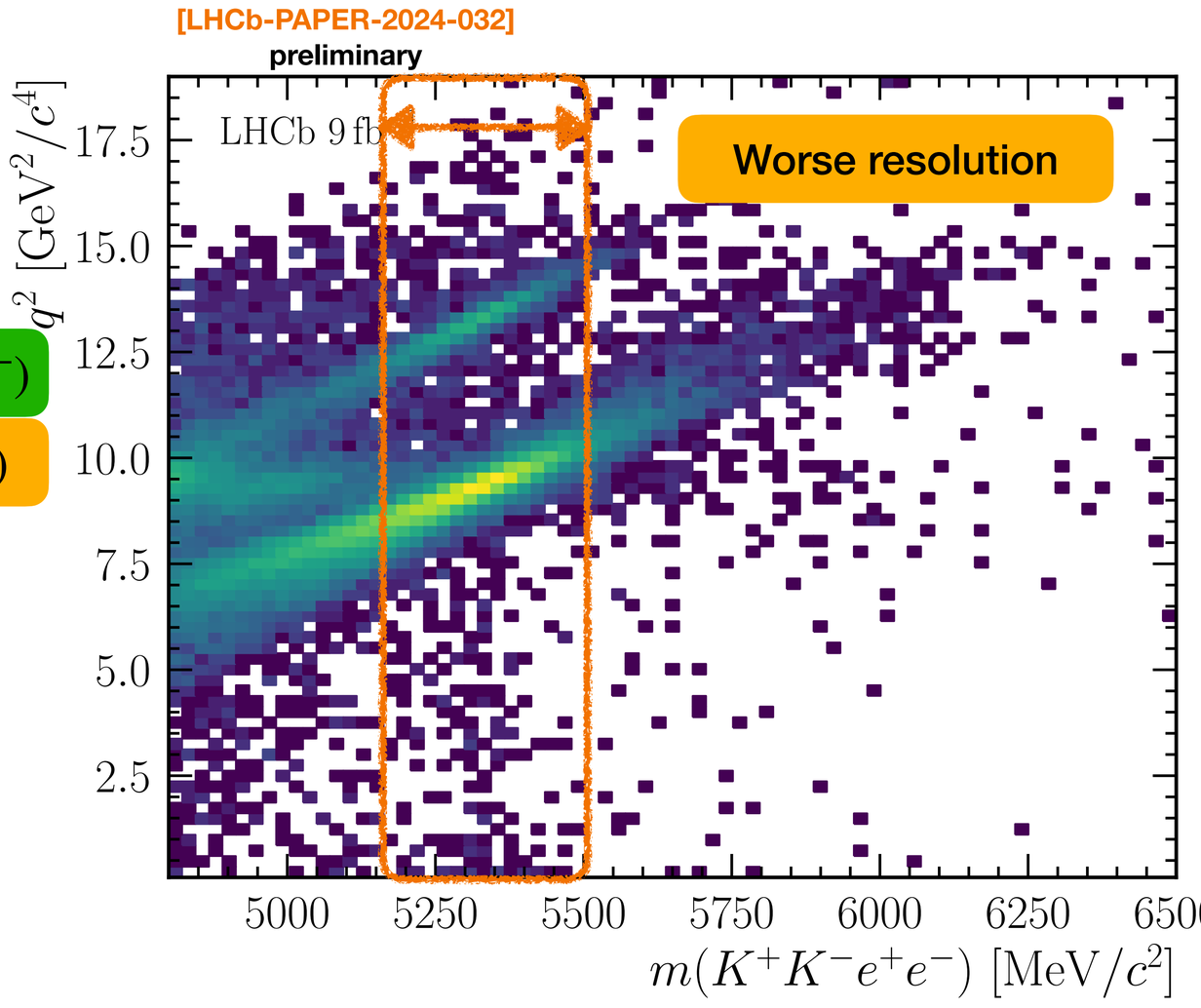
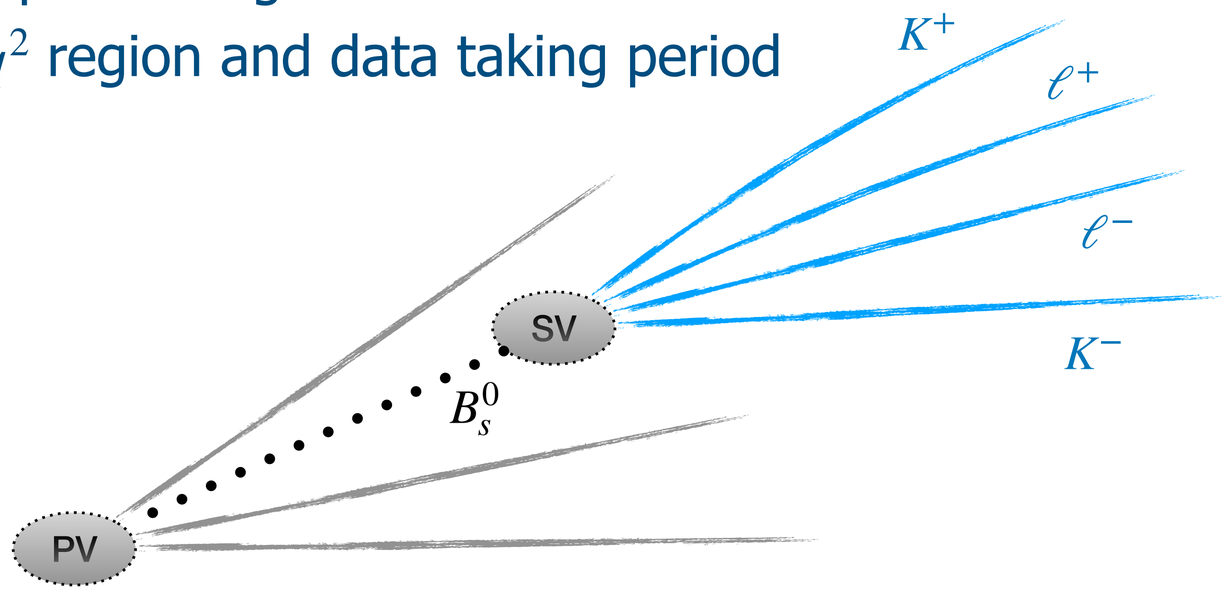


Photo: S. Schmitt

SELECTION

- Leverage **narrow ϕ resonance** and excellent K^+K^- mass resolution
- Require displaced secondary decay vertices
- **Multivariate classifiers** to suppress combinatorial background
  - Using vertex quality and kinematics
  - Optimise significance for each q^2 region and data taking period



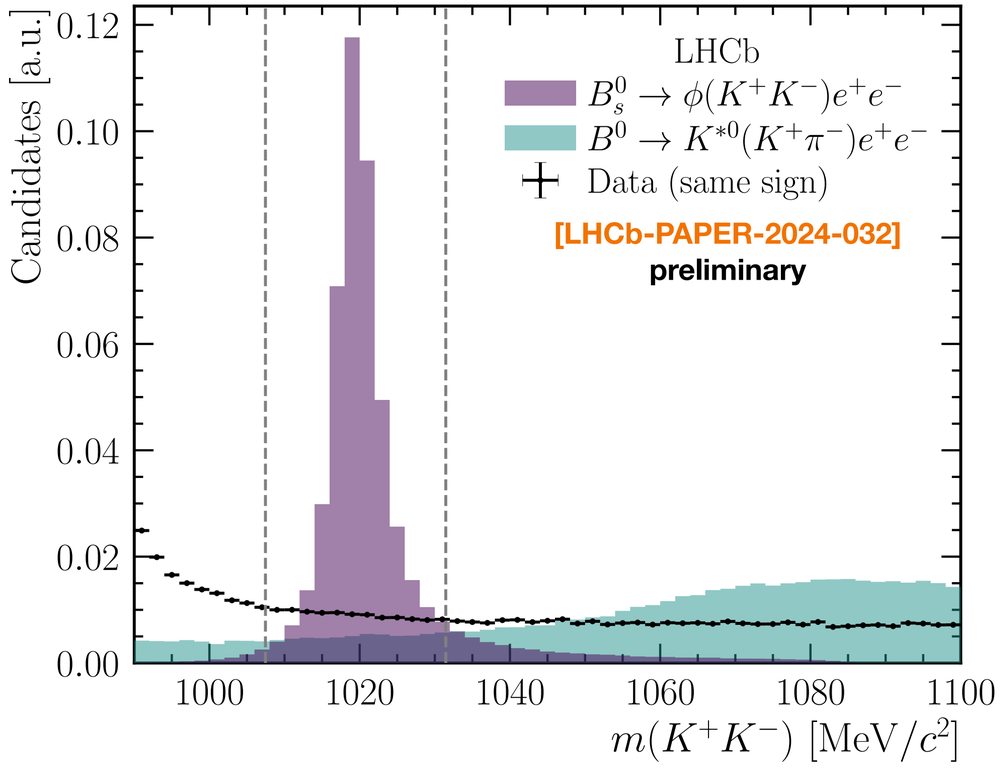


Photo: S. Schmitt

Efficiencies and Corrections

- Data driven, staged **simulation correction chain**, similar to [PRD 108 (2023) 3, 032002]
- "**Prior corrections**" to ensure kinematics corrections universally applicable

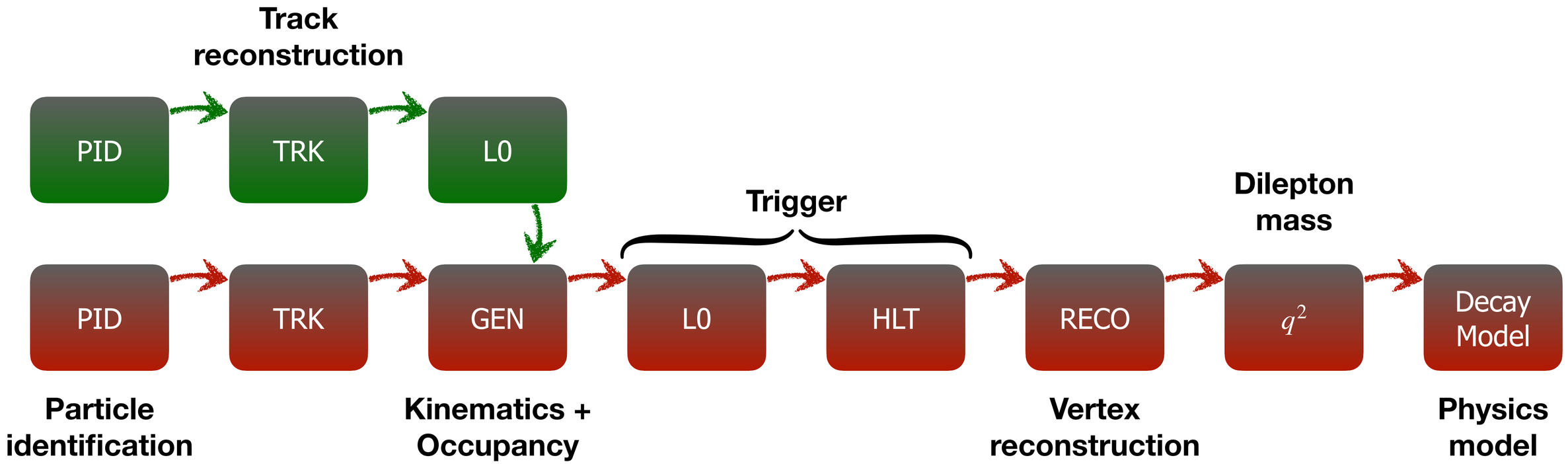


Photo: S. Schmitt

CROSSCHECKS $r_{J/\psi}$

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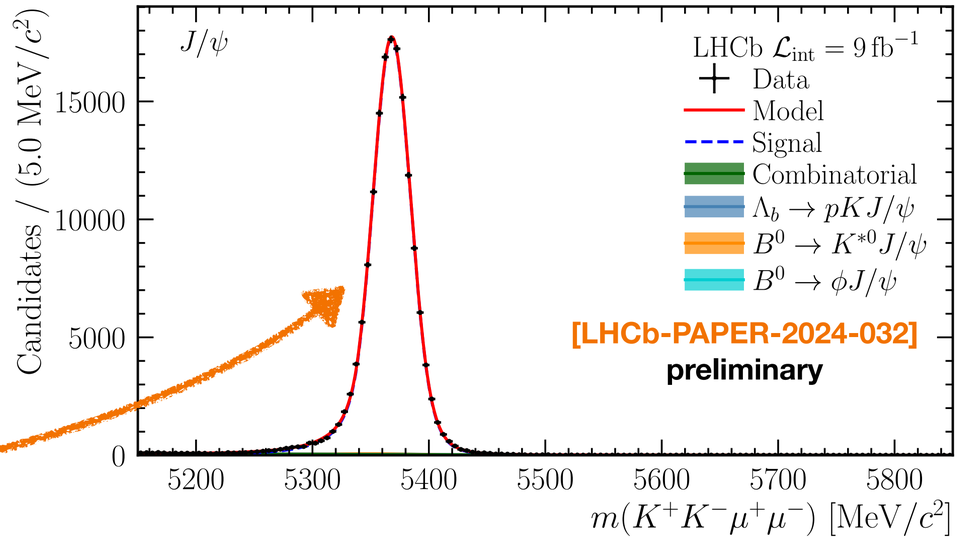

Very clean signal peak!
Negligible background levels!

Worse mass resolution
⇒ wider fit range

Higher background levels

Photo: S. Schmitt

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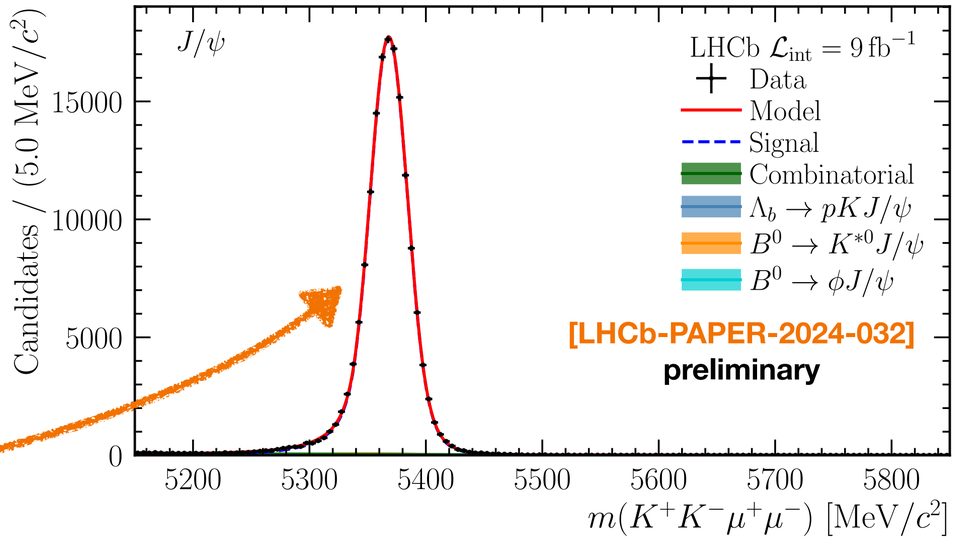

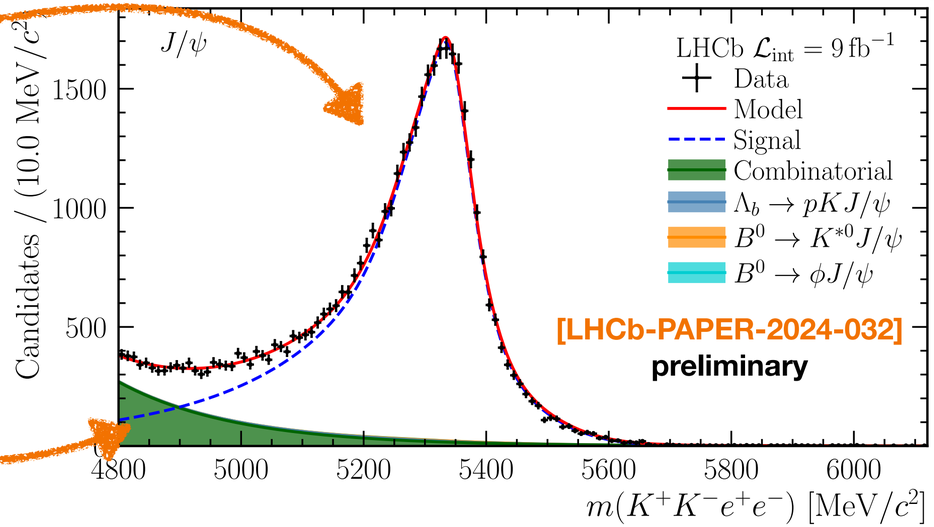

Photo: S. Schmitt

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- $r_{J/\psi} = \dfrac{\mathcal{B}(B_s^0 \to \phi J/\psi(\mu^+\mu^-))}{\mathcal{B}(B_s^0 \to \phi J/\psi(e^+e^-))} = 0.997 \pm 0.013$
  - σ includes systematics from calibration sample size

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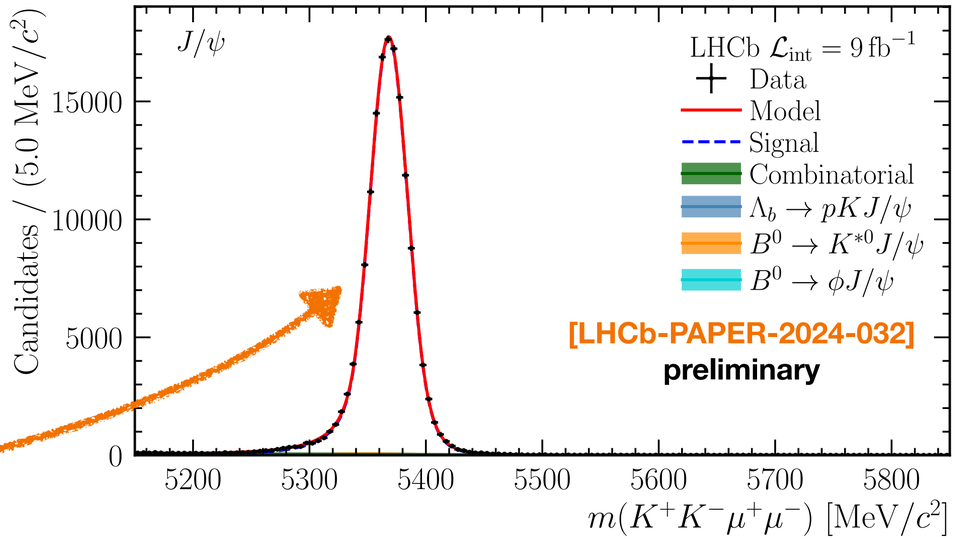

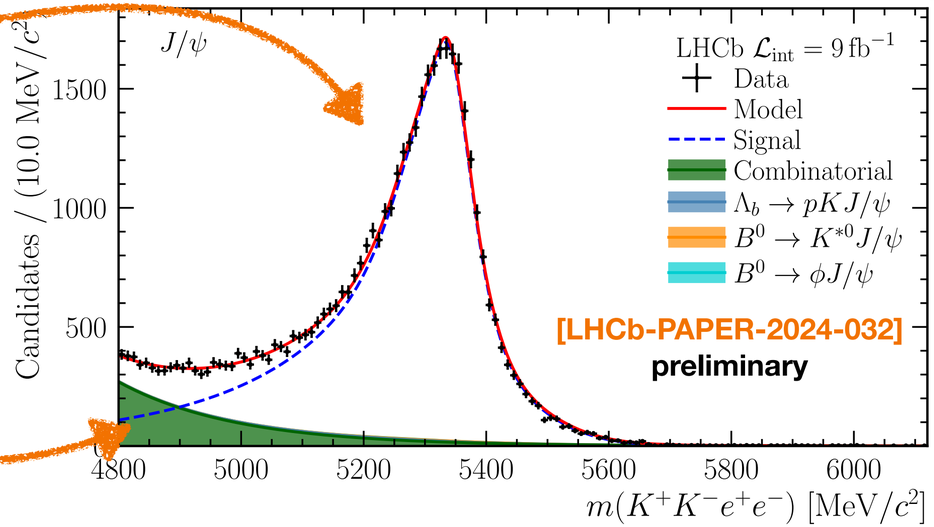

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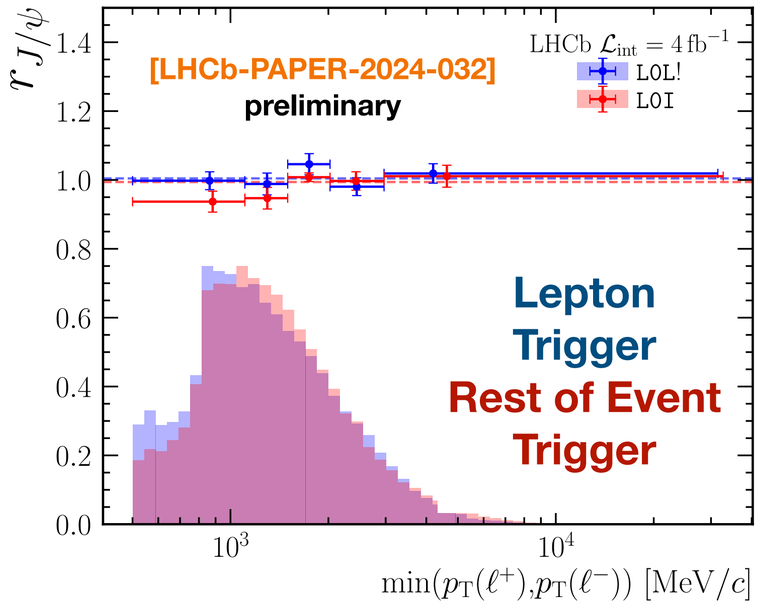
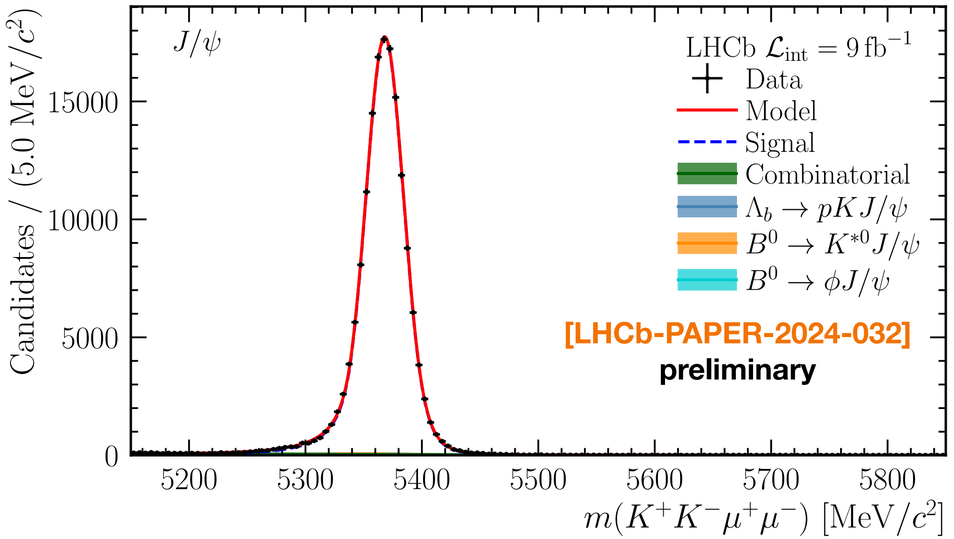
  - σ includes systematics from calibration sample size
- $r_{J/\psi}$ **independent of kinematics**

Demonstrates control of electron and muon efficiency scales!





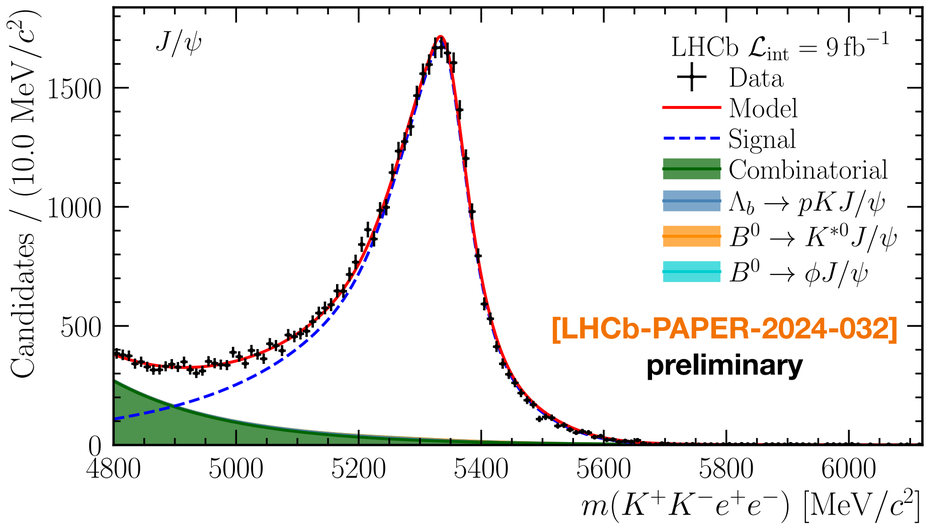
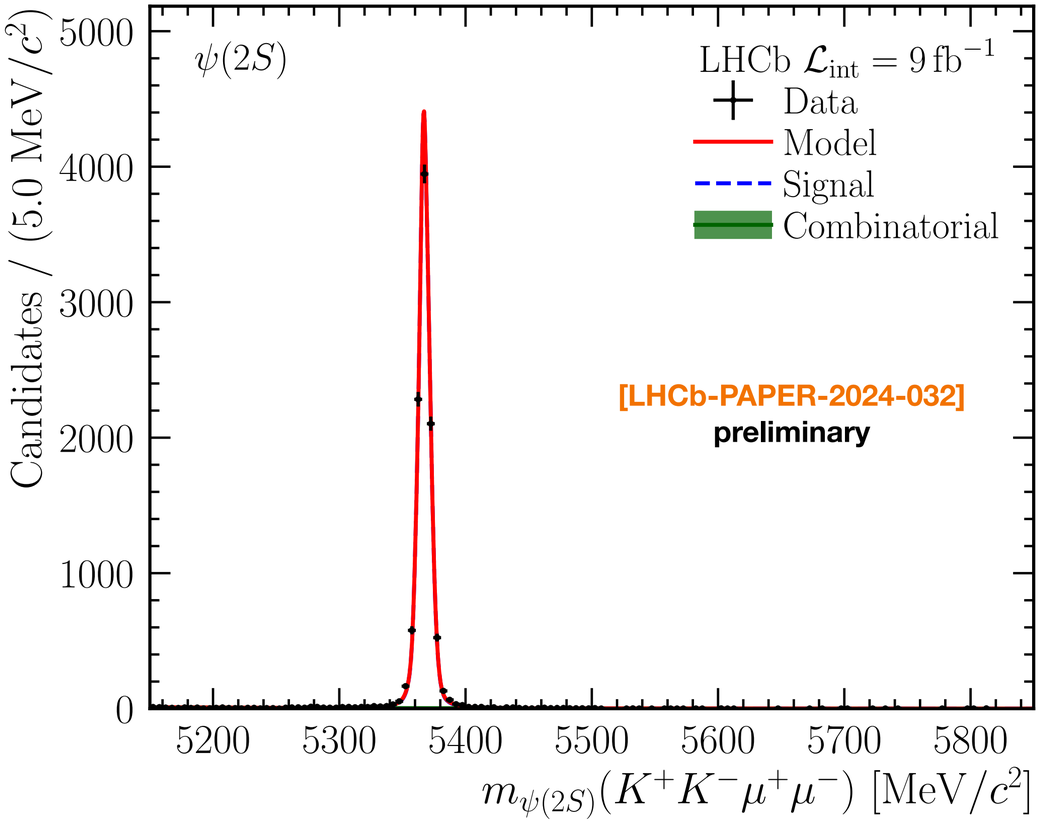


Photo: S. Schmitt

CROSSCHECKS $R_{\psi(2S)}$

- $R_{\psi(2S)} = \dfrac{\mathcal{B}(B_s^0 \to \phi\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B_s^0 \to \phi\psi(2S)(e^+e^-))} \times r_{J/\psi}^{-1}$

Constrained dilepton mass to $\psi(2S)$ mass ⇒ Improved resolution



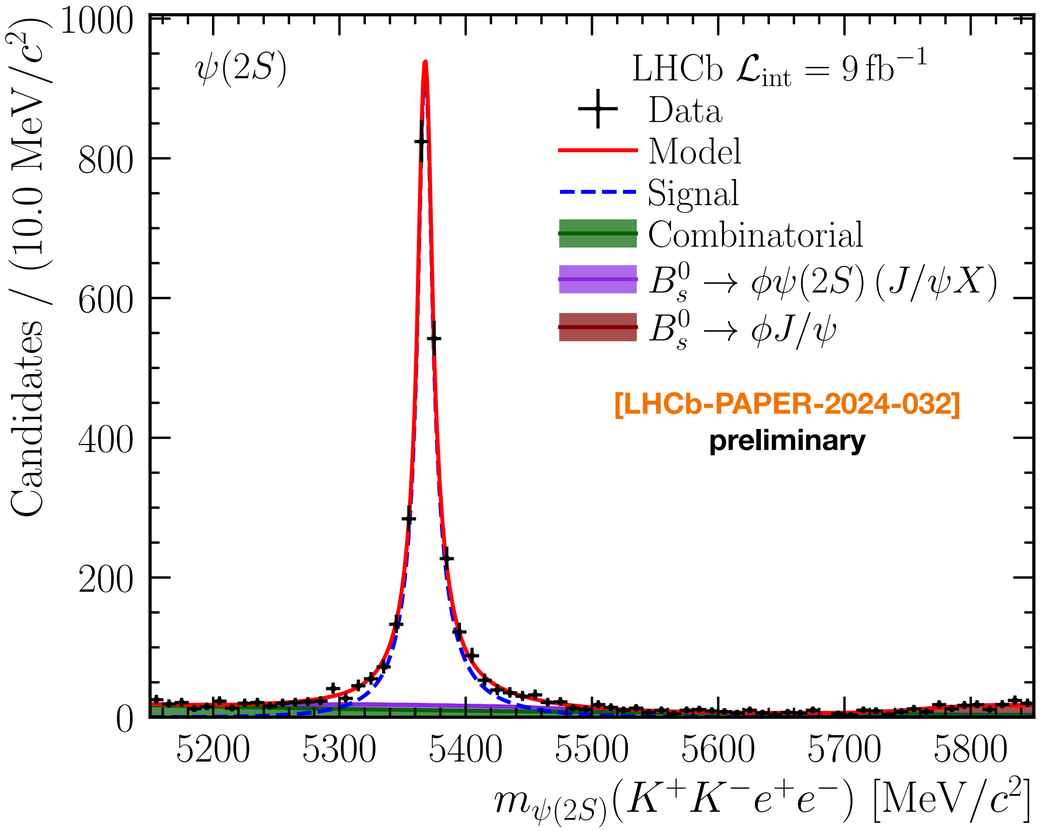


Photo: S. Schmitt

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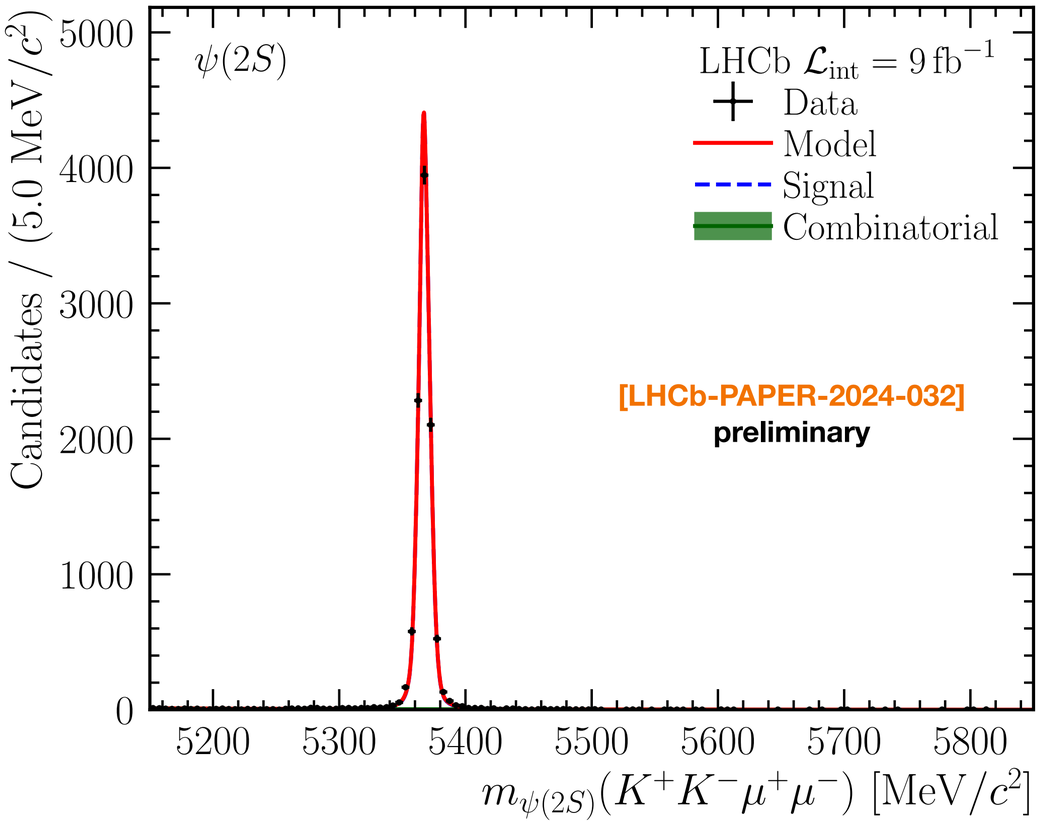
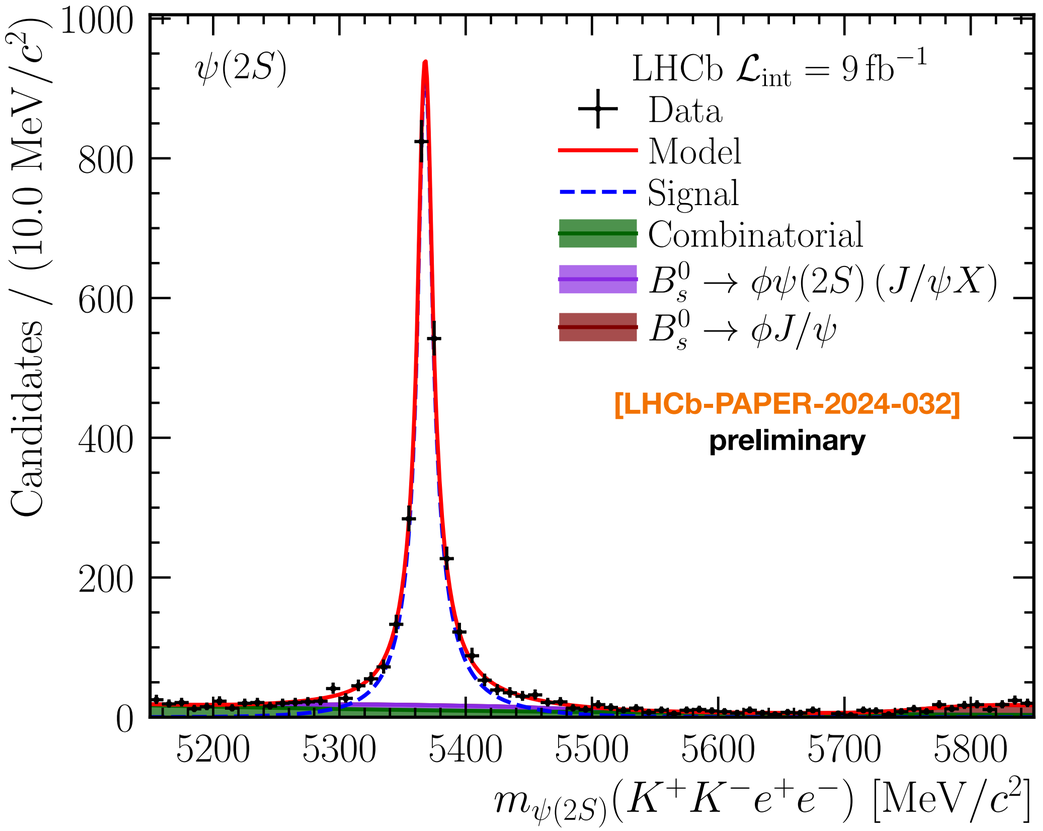
σ includes systematics from calibration sample size





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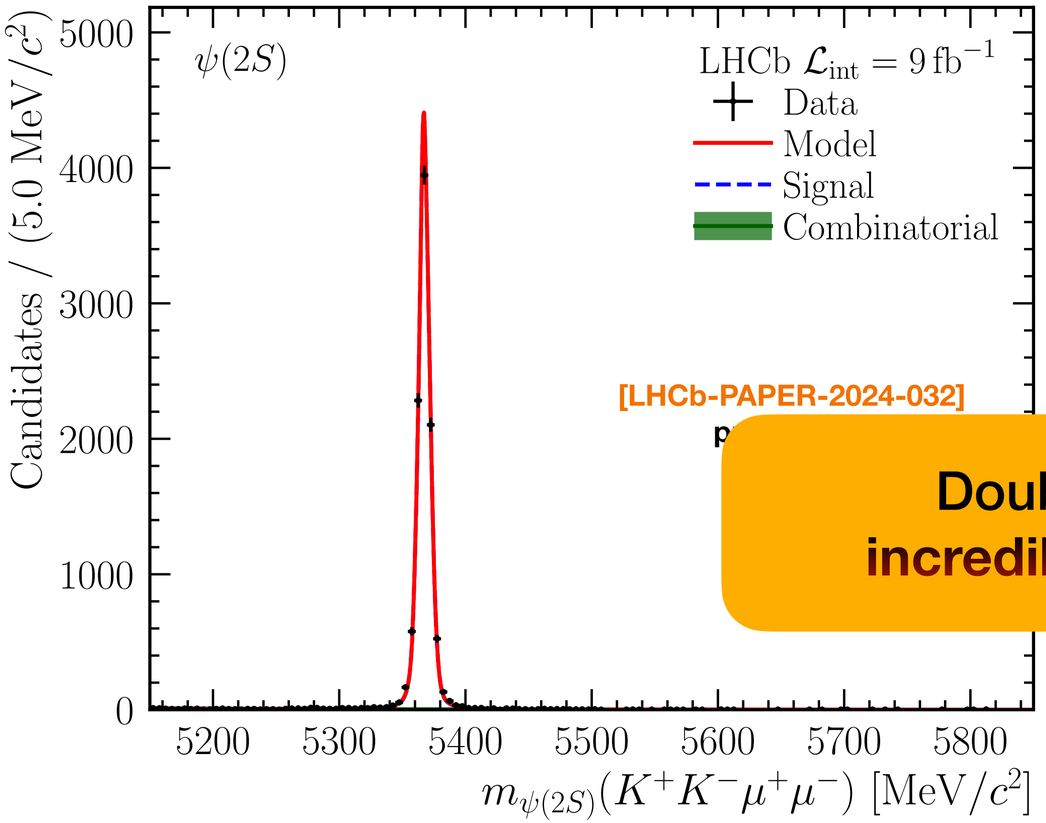

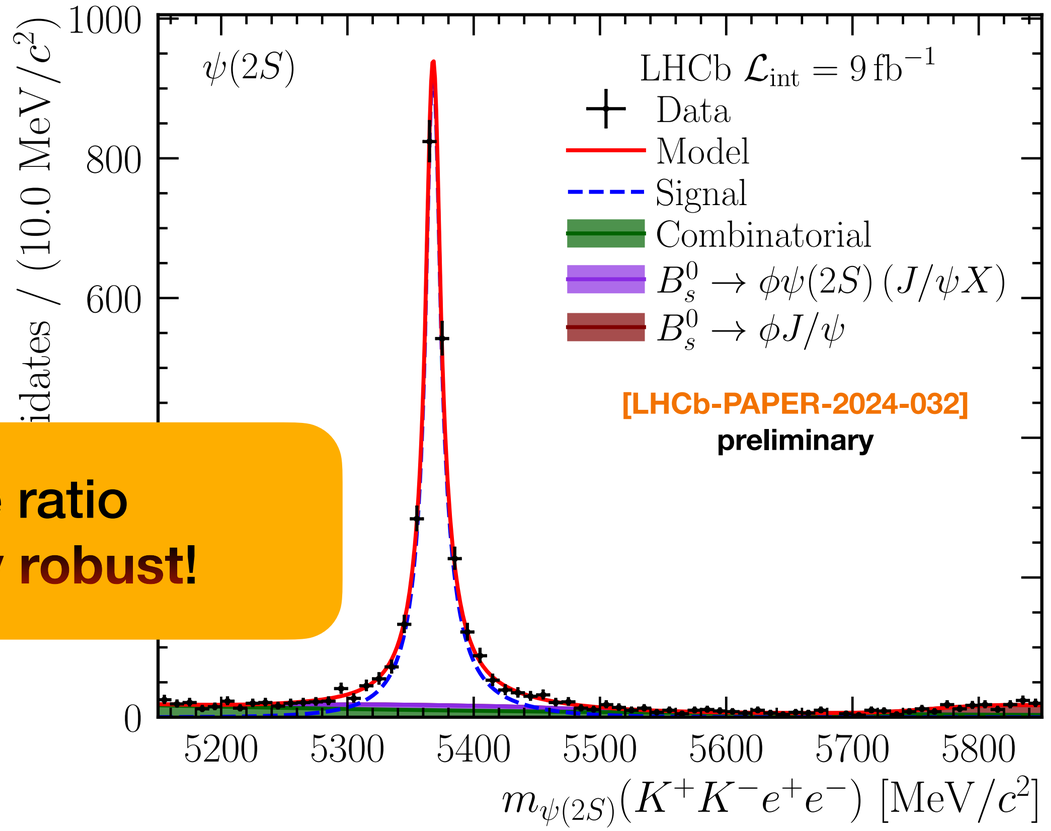

Double ratio incredibly robust!

Photo: S. Schmitt

Robustness of the Double Ratio

- Single ratio $r_{J/\psi}$ changes about $25\,\%$ after all simulation corrections applied

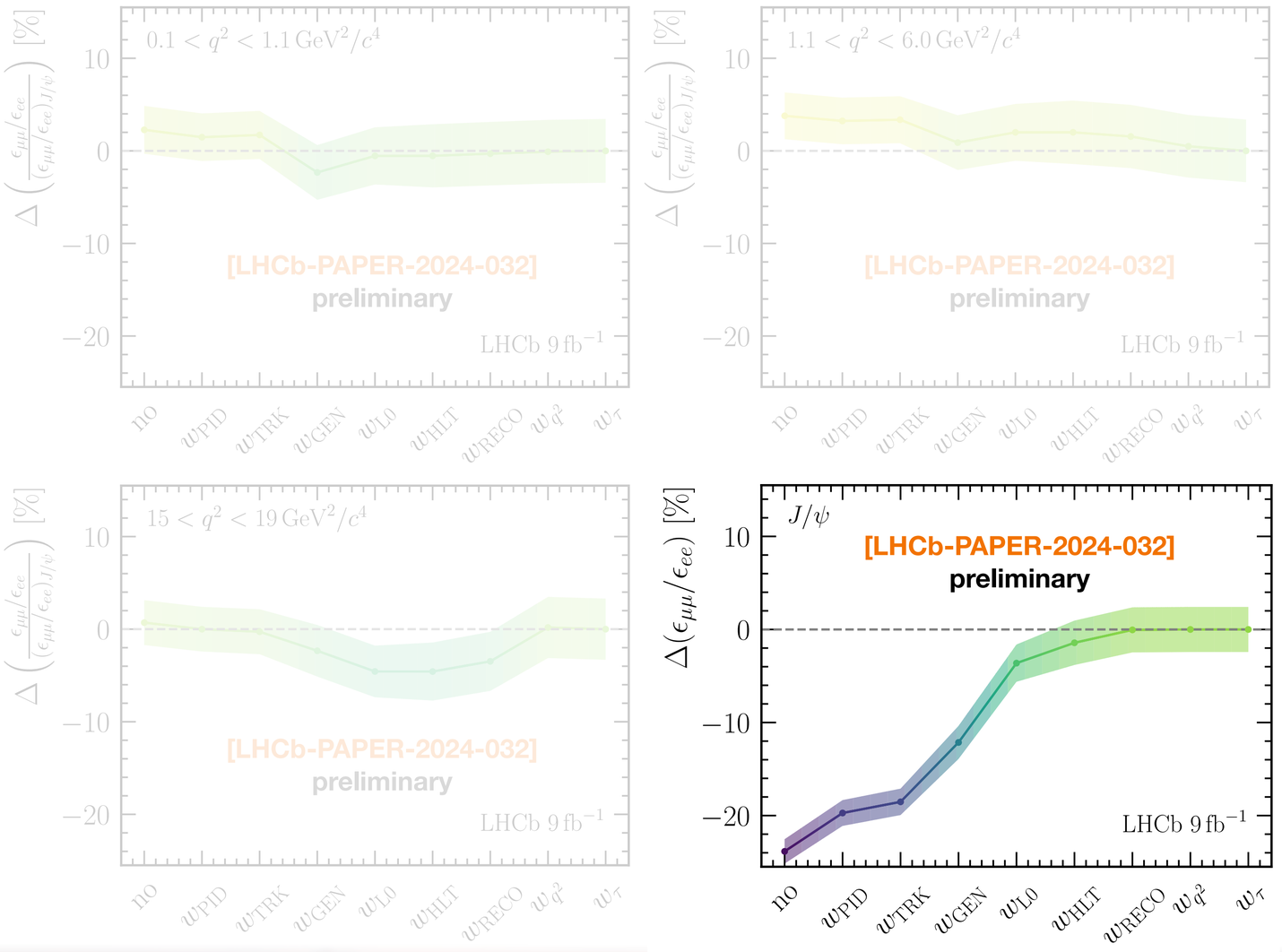

Photo: S. Schmitt

Robustness of the Double Ratio

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- Double ratio R_ϕ and $R_{\psi(2S)}$ move only about $\mathcal{O}(1\,\%)$

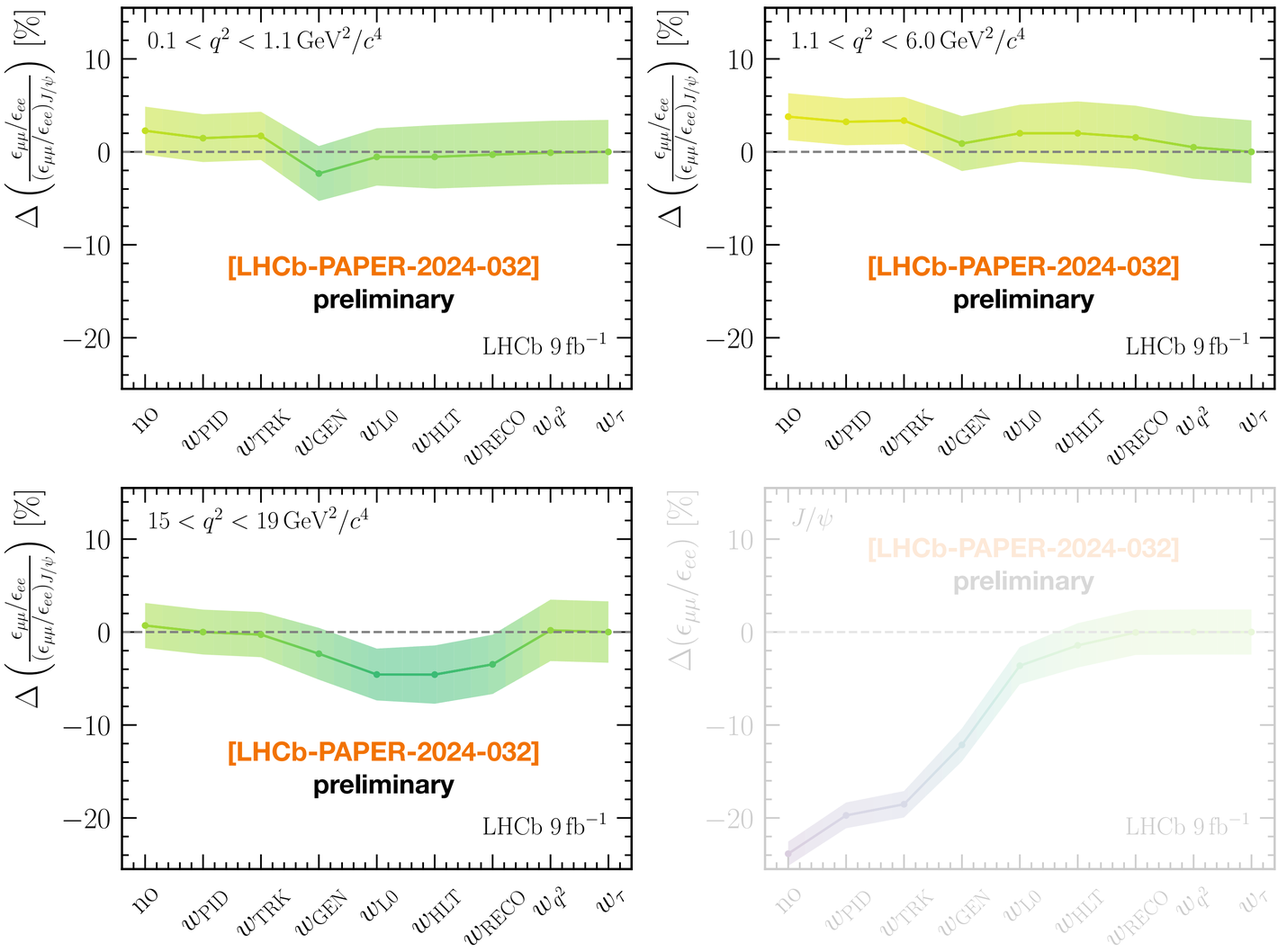


Photo: S. Schmitt

Robustness of the Double Ratio

- Single ratio $r_{J/\psi}$ changes about $25\,\%$ after all simulation corrections applied
- Double ratio R_ϕ and $R_{\psi(2S)}$ move only about $\mathcal{O}(1\,\%)$
- Reinforces **robustness** of the **double ratio approach**
- Highlights control of systematic uncertainties

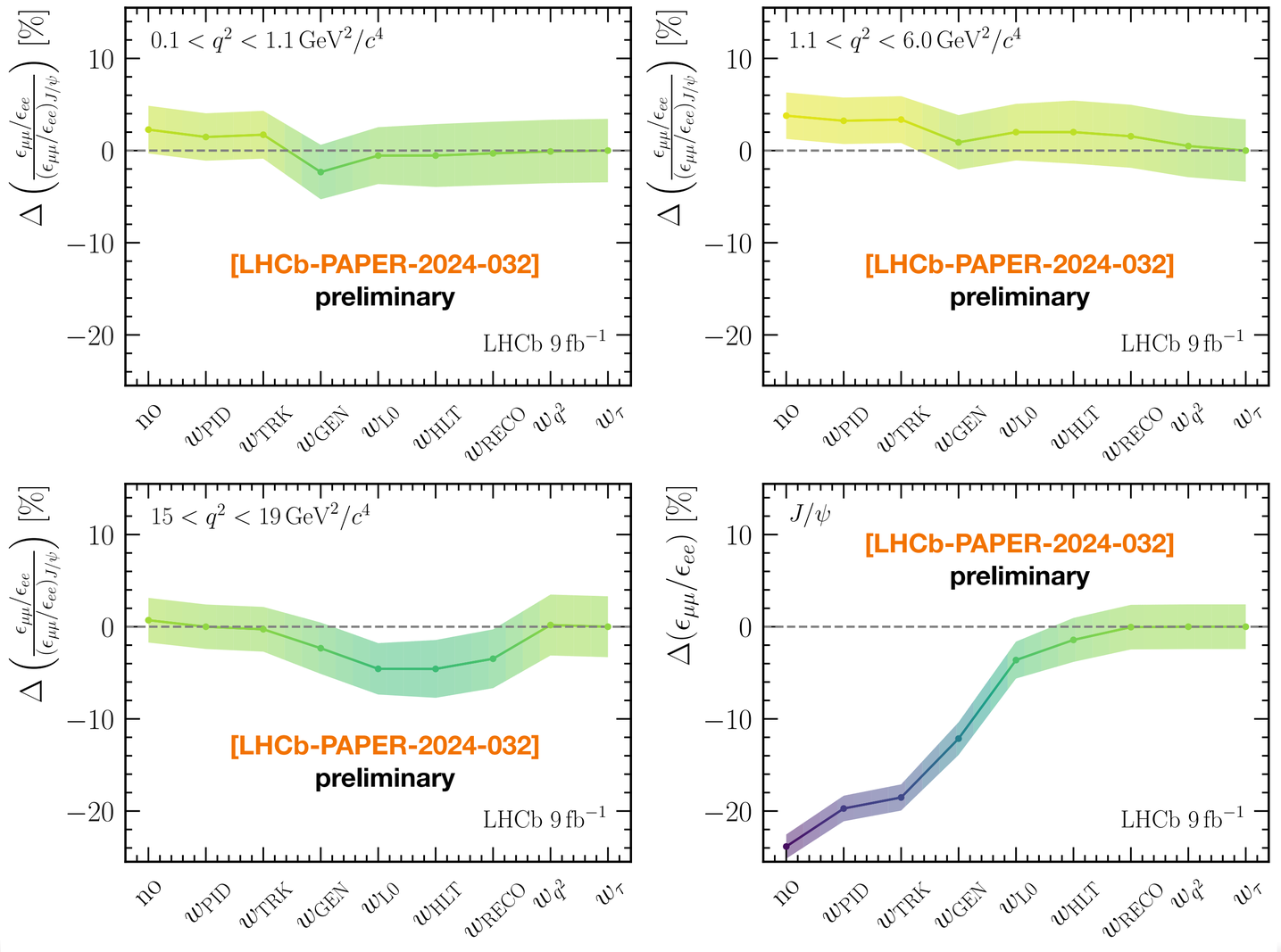
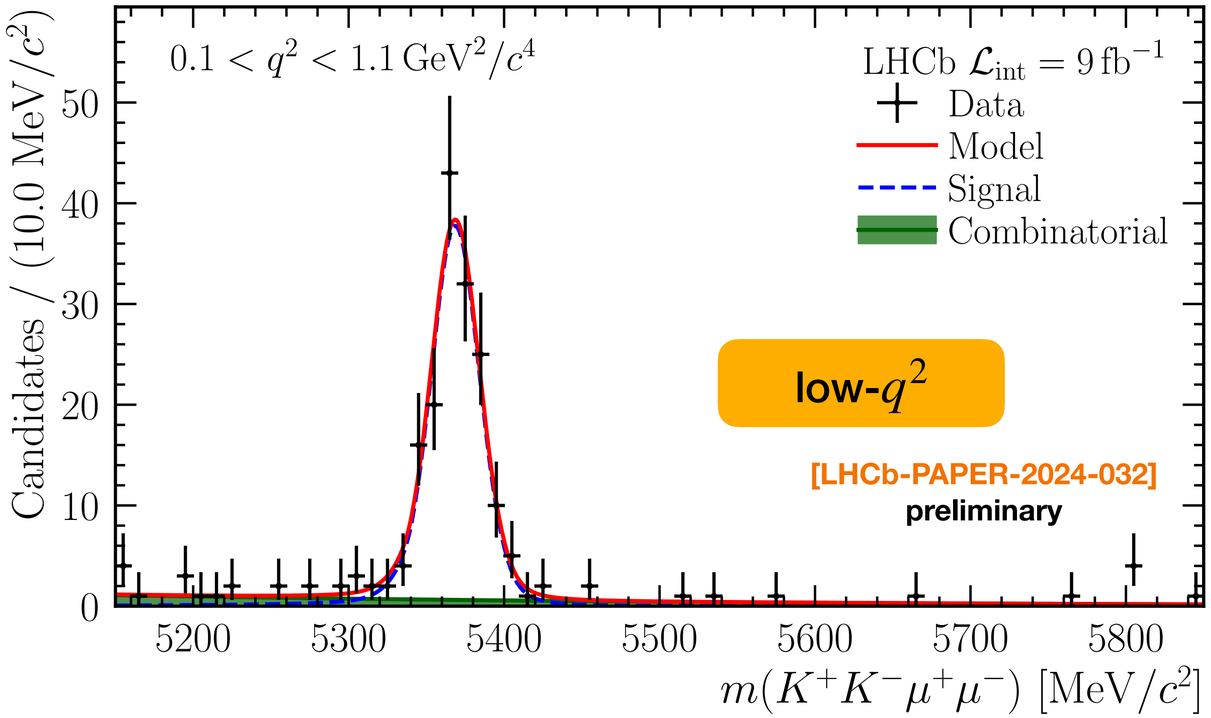


Photo: S. Schmitt

Mass Fit To Low and Central q^2 - Muons

- Clean signal peak
- Almost **negligible** background levels
- Simultaneous fit: **mean shift** and **width scale** shared and constrained from J/ψ



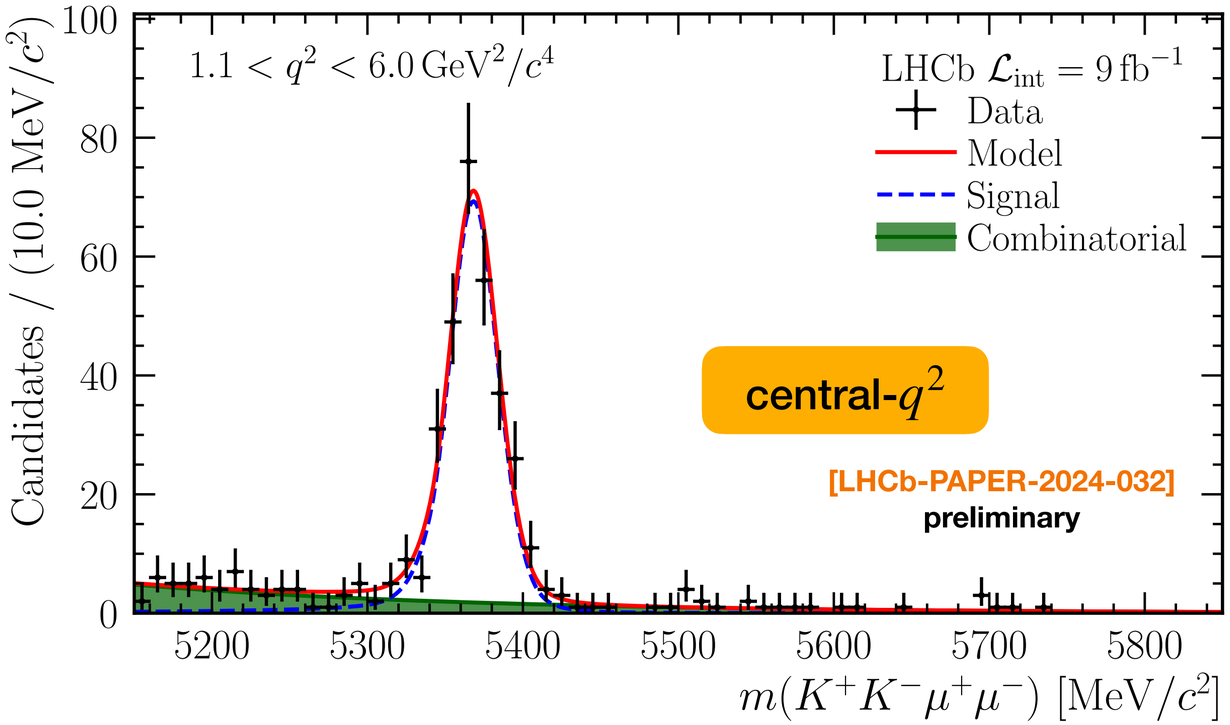
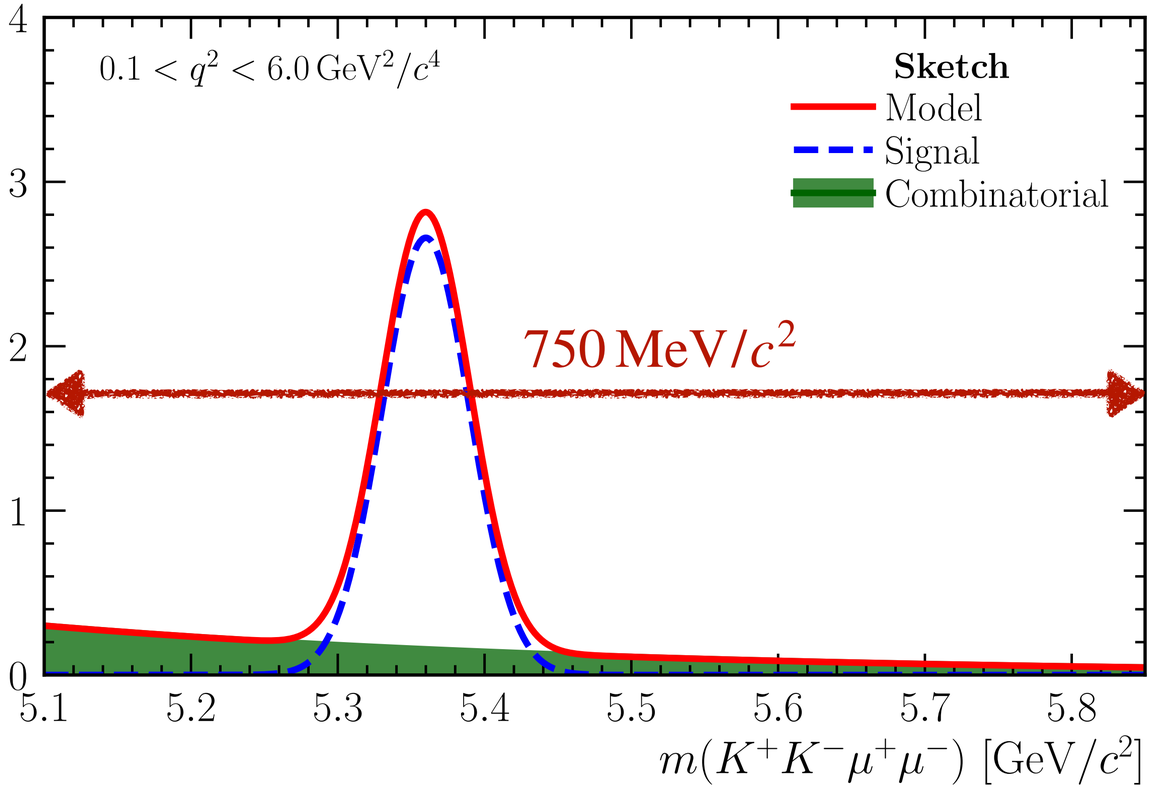


Photo: S. Schmitt

From Muon Fits to Electron Fits

- **Wider mass range** due to compromised resolution, pronounced tails



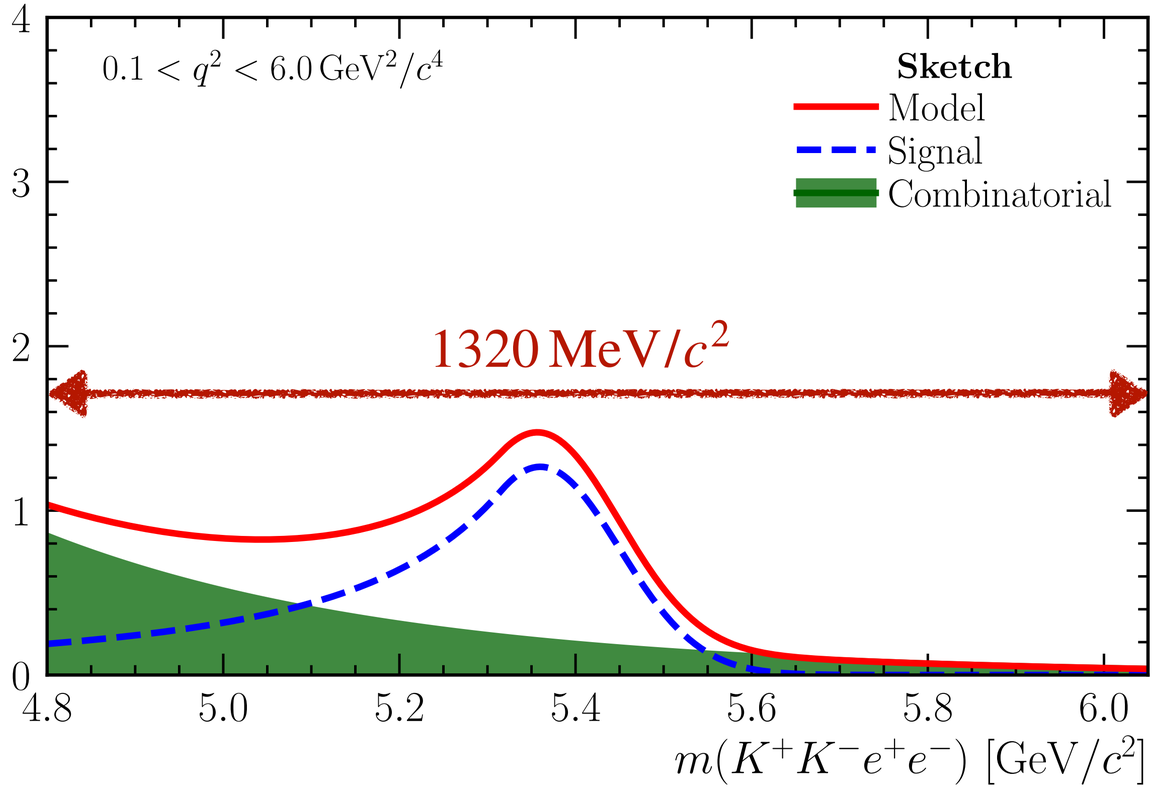
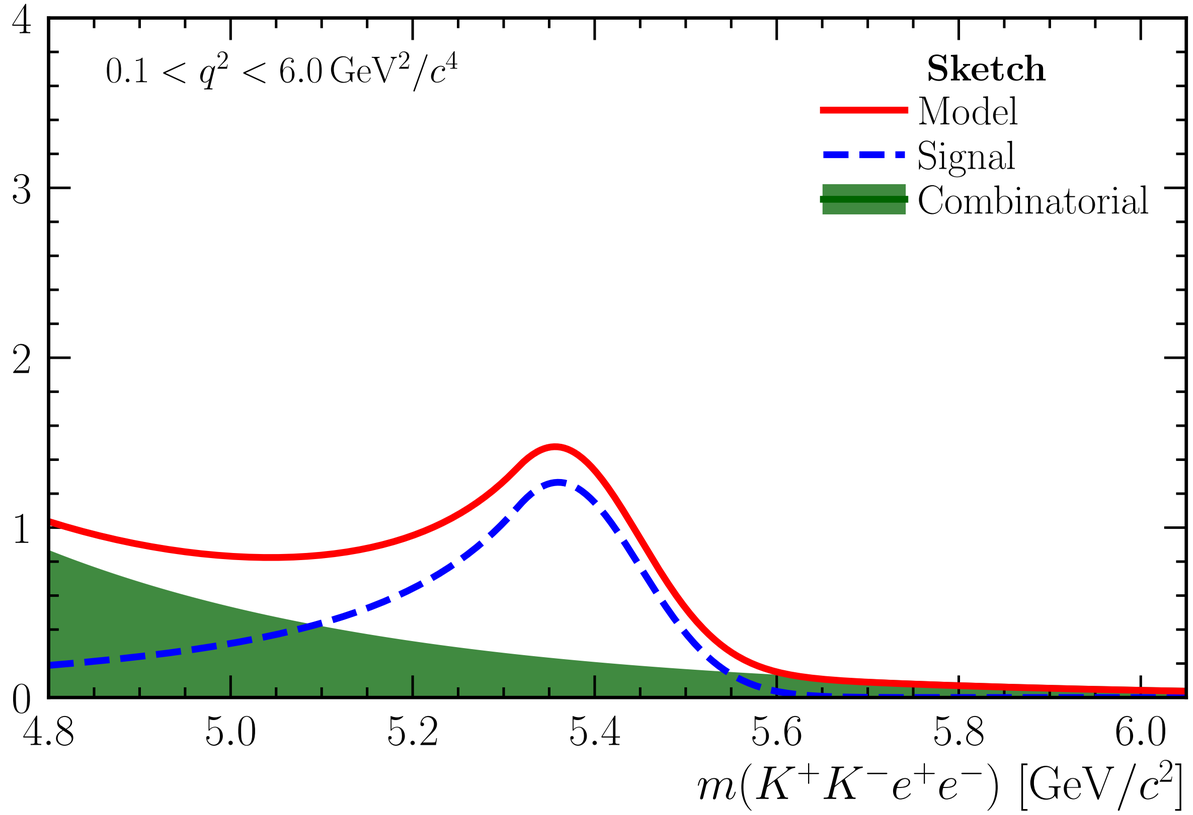
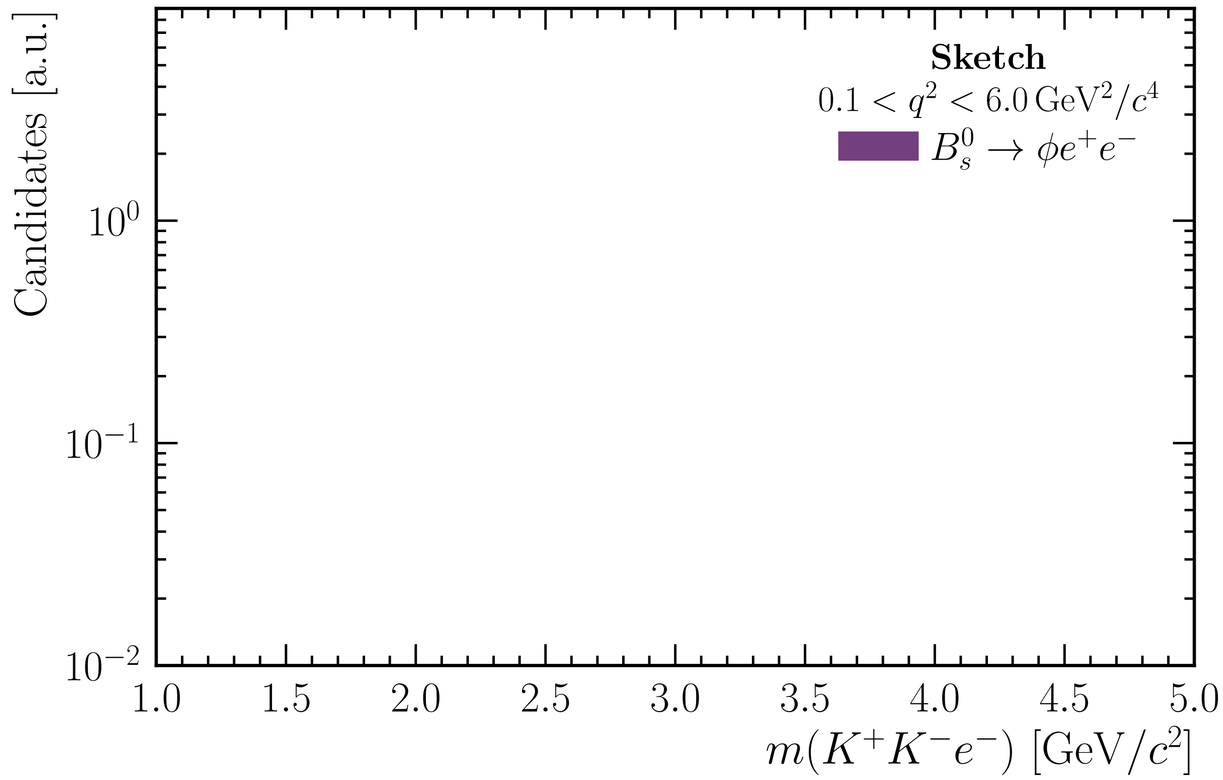


Photo: S. Schmitt

Electron Fits: Tree Level Background

- **Wider mass range** due to compromised resolution, pronounced tails
  - Tree-level $B_s^0 \to D_s^- e^+ \nu_e$ become relevant





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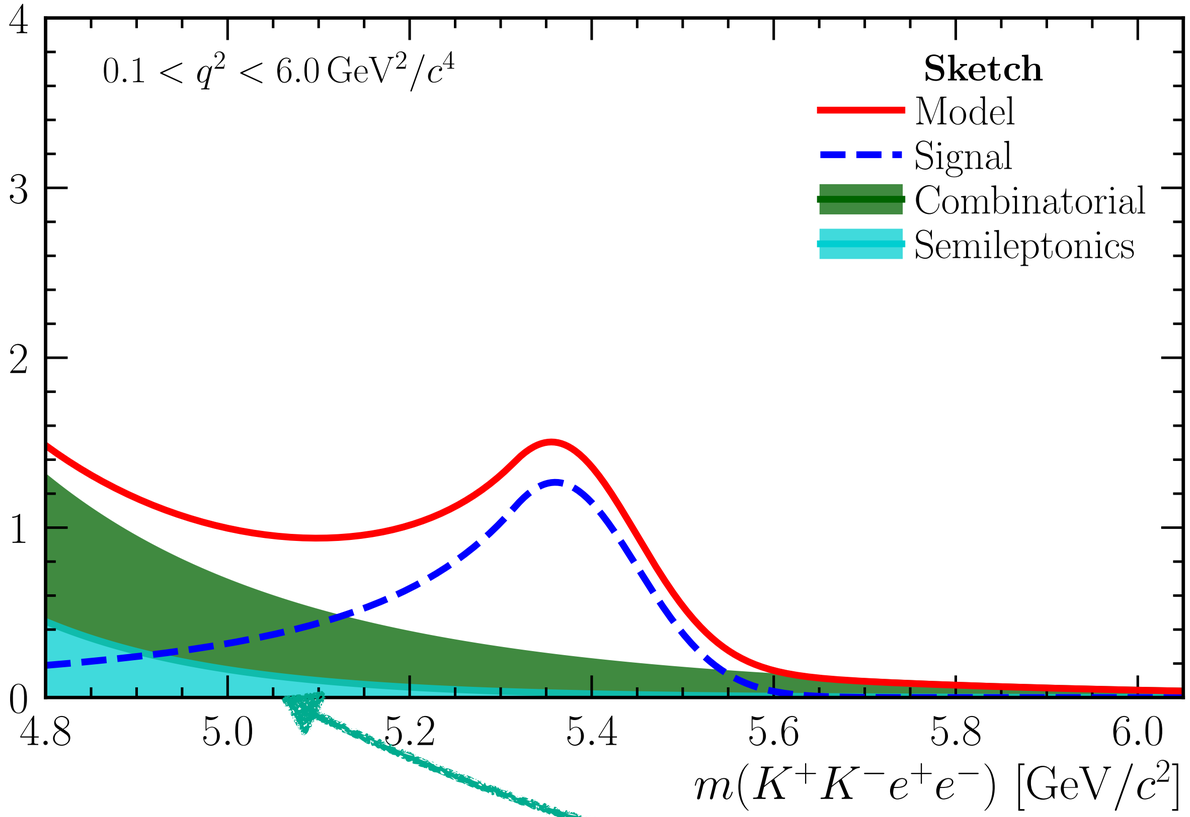

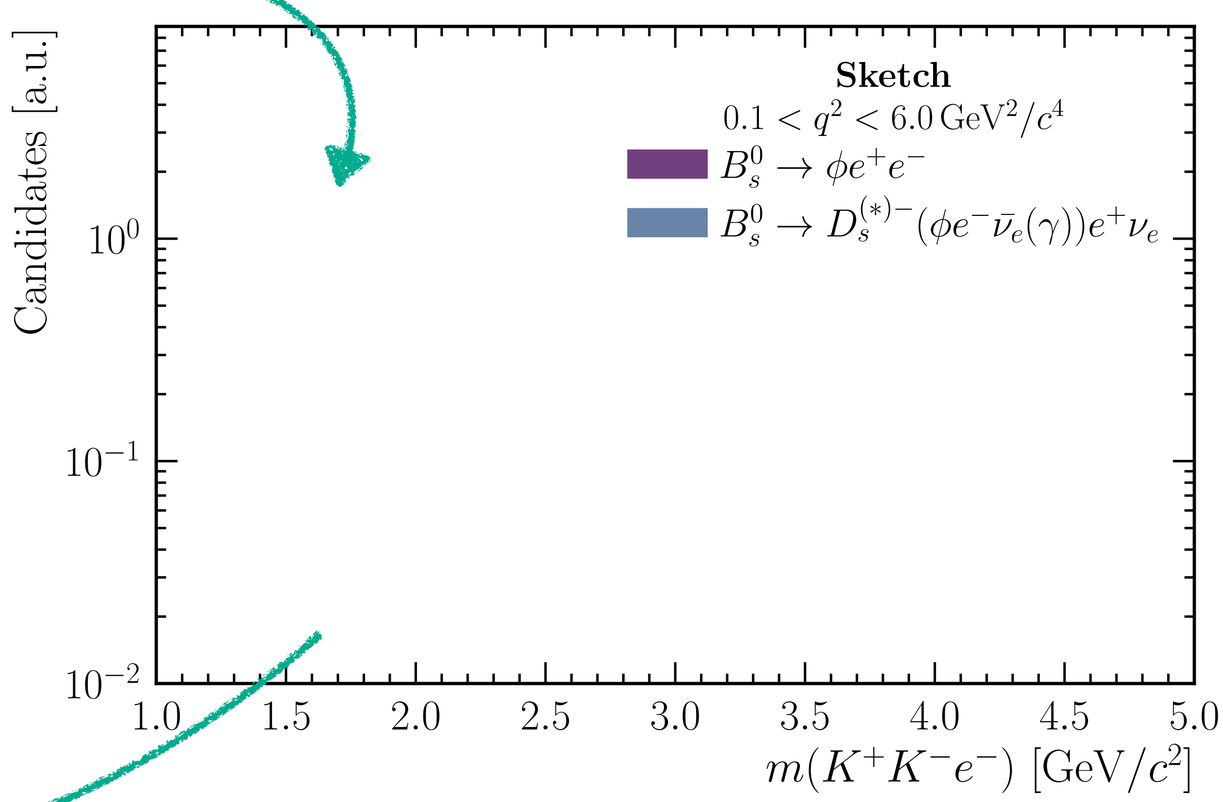

Photo: S. Schmitt

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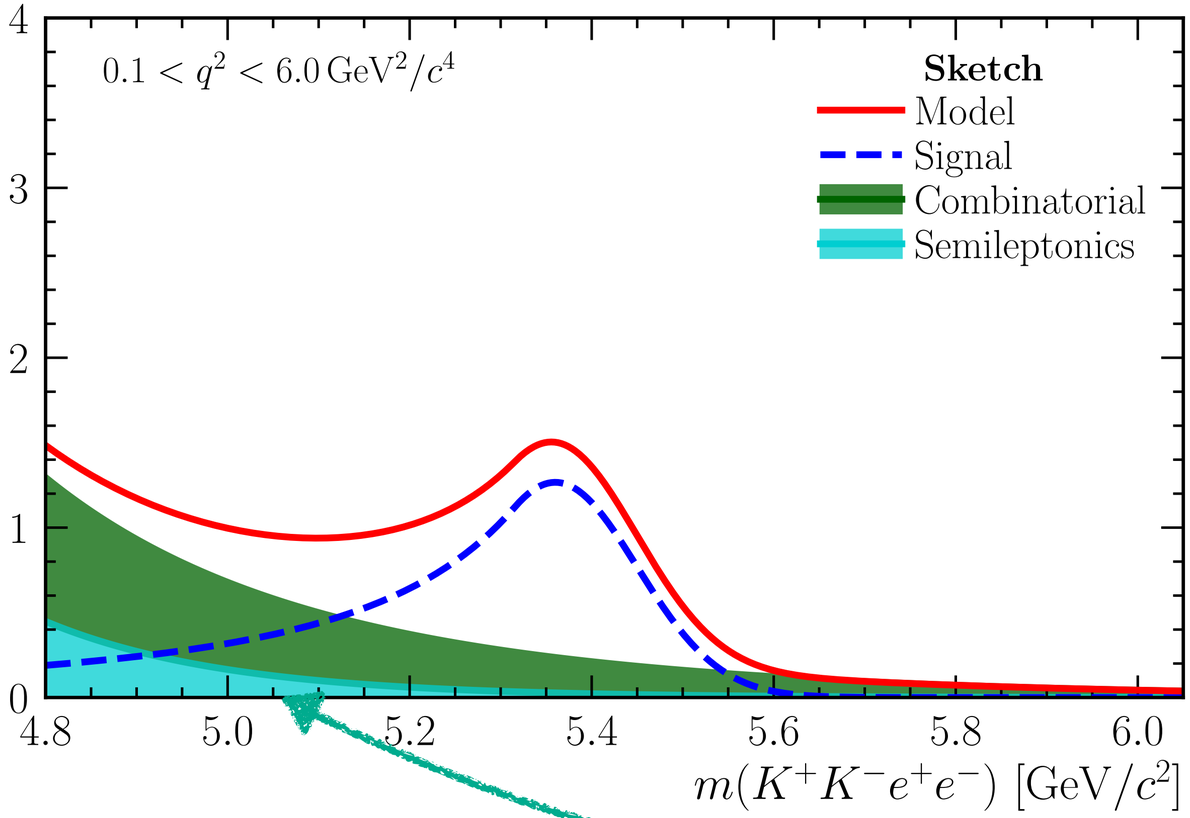

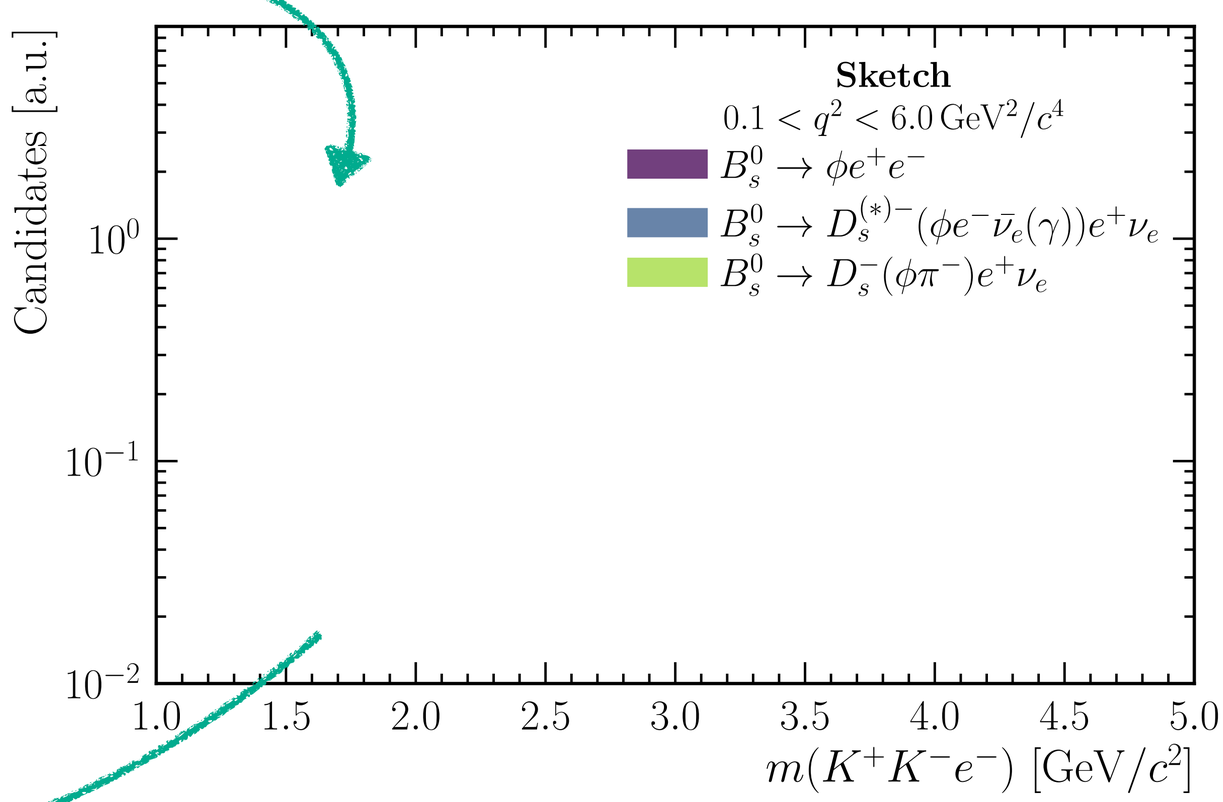

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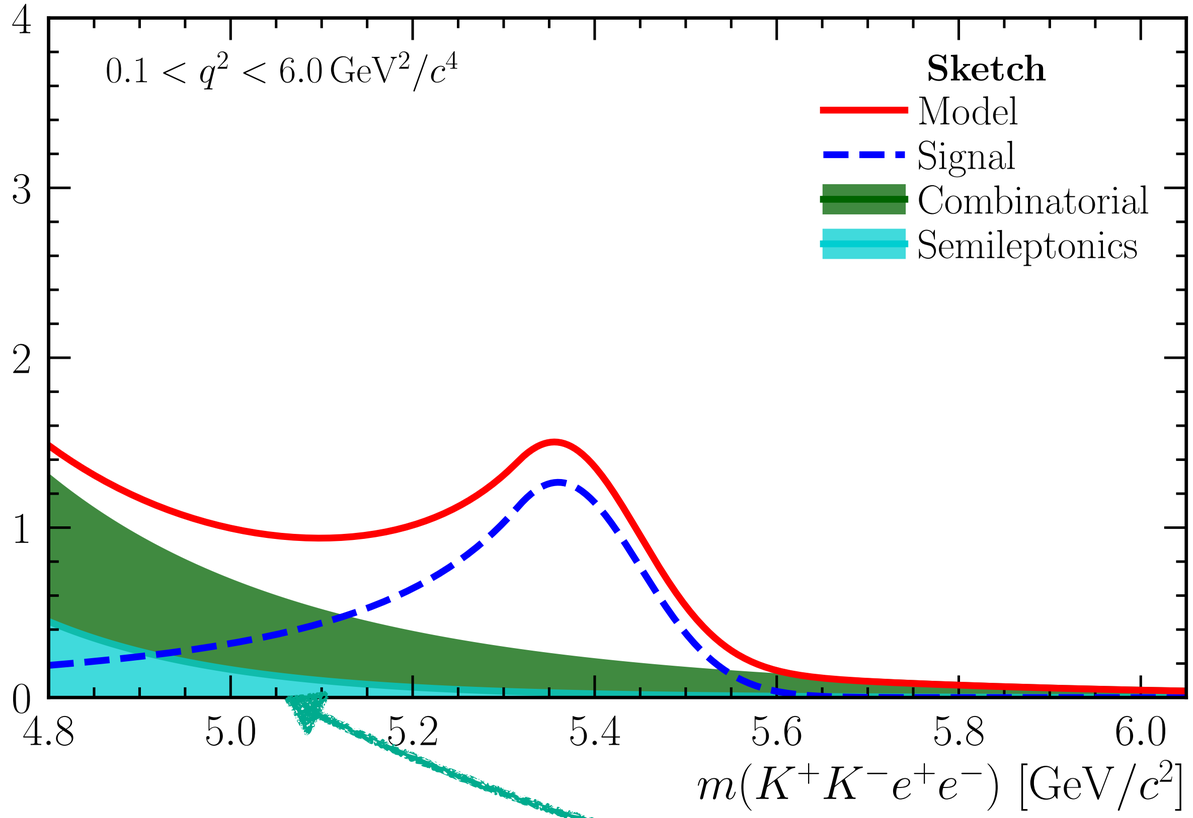


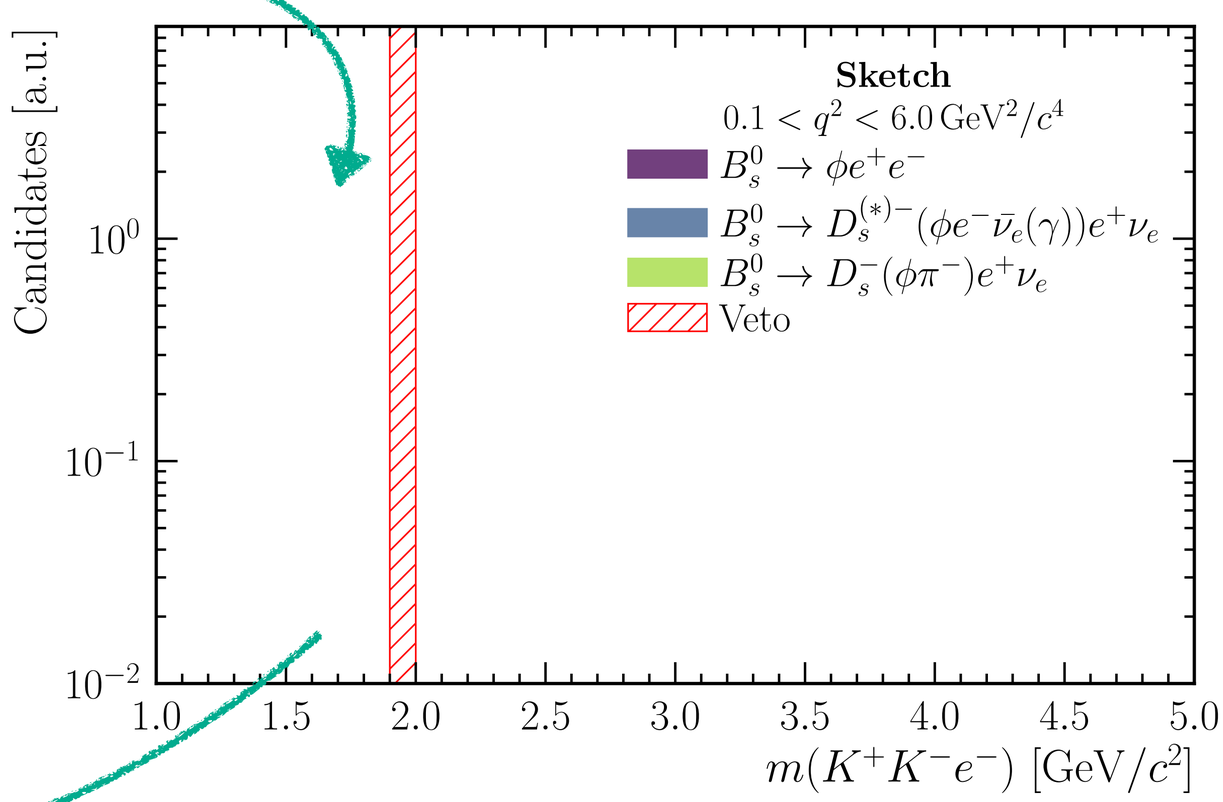
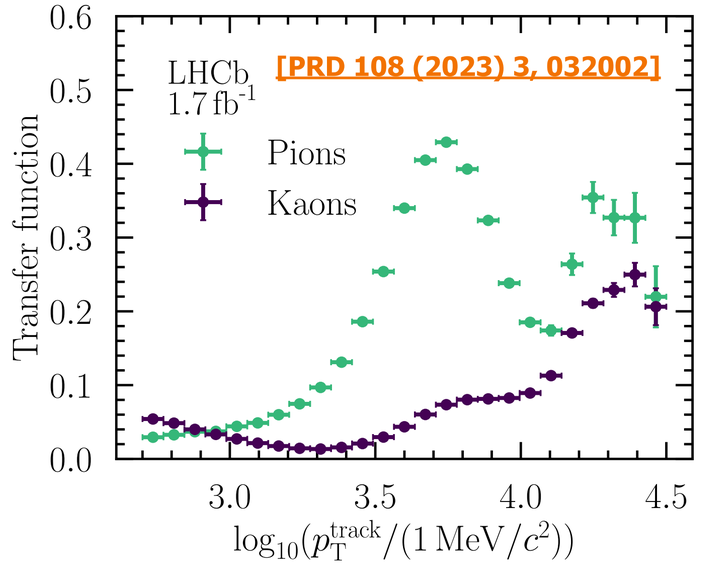
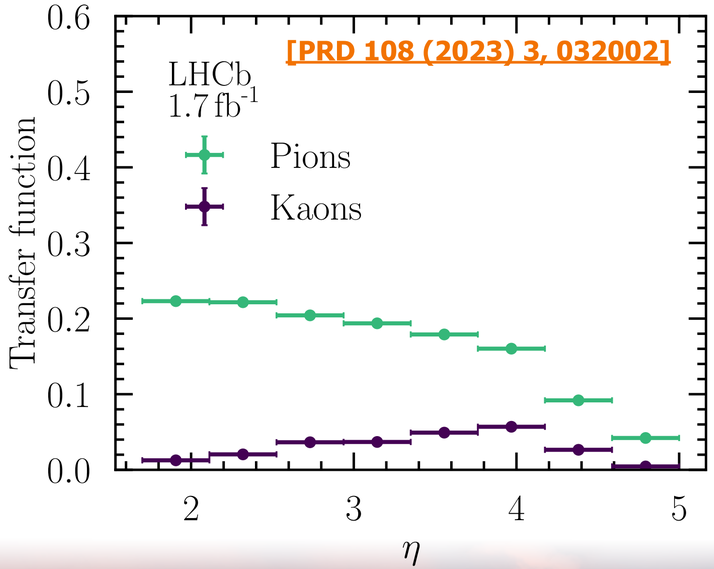


Photo: S. Schmitt

Residual Background Sources

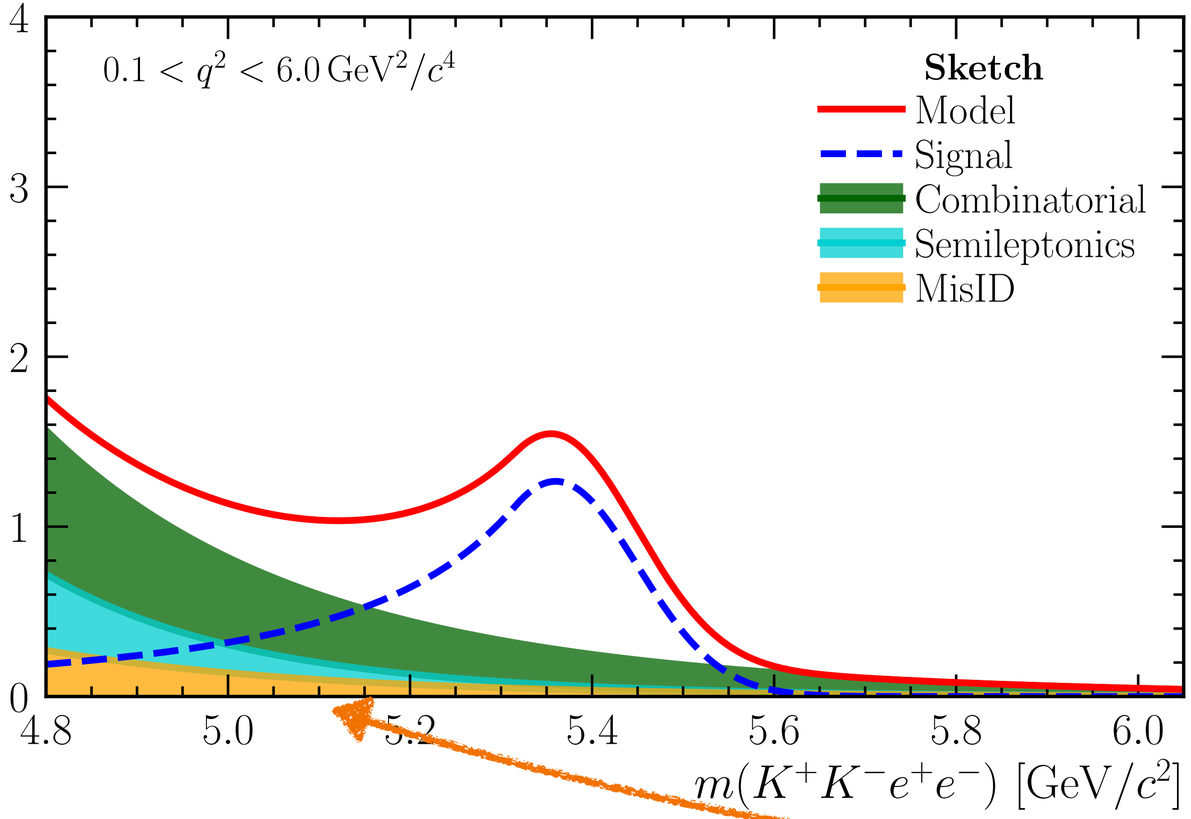
- **Data driven** estimate of residual $h \to e$ mis-ID similar to [PRD 108 (2023) 3, 032002]
  - Extrapolate from background enriched control region which inverts the PID requirements
  - 3 regions: $e^+_{\text{fail}}e^-_{\text{pass}}$, $e^+_{\text{pass}}e^-_{\text{fail}}$, and $e^+_{\text{fail}}e^-_{\text{fail}}$
- Build **transfer functions** $T_h(p_{\text{T}}, \eta, \text{L0}_{\text{e}})$ from calibration samples
  - Encode **probability** for candidate in background region to be reconstructed in signal region
- Obtain prediction for **shape** and **amount** of residual backgrounds!
- Validated using $D \to K\pi$ decays in $B^0_s \to \phi e^+ e^-$ data





Electron Fits: MisID Background

- **Wider mass range** due to compromised resolution, pronounced tails
  - Hadron to electron mis-identification plays a role



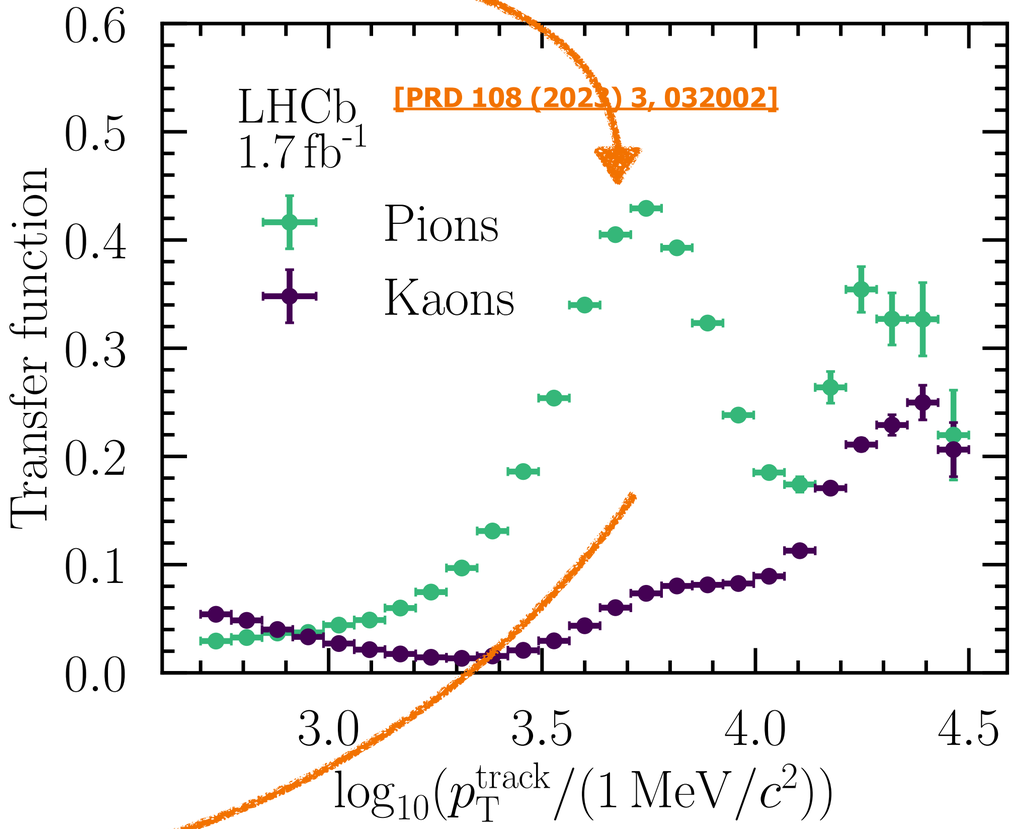


Photo: S. Schmitt

Electron Fits: Leakage Background

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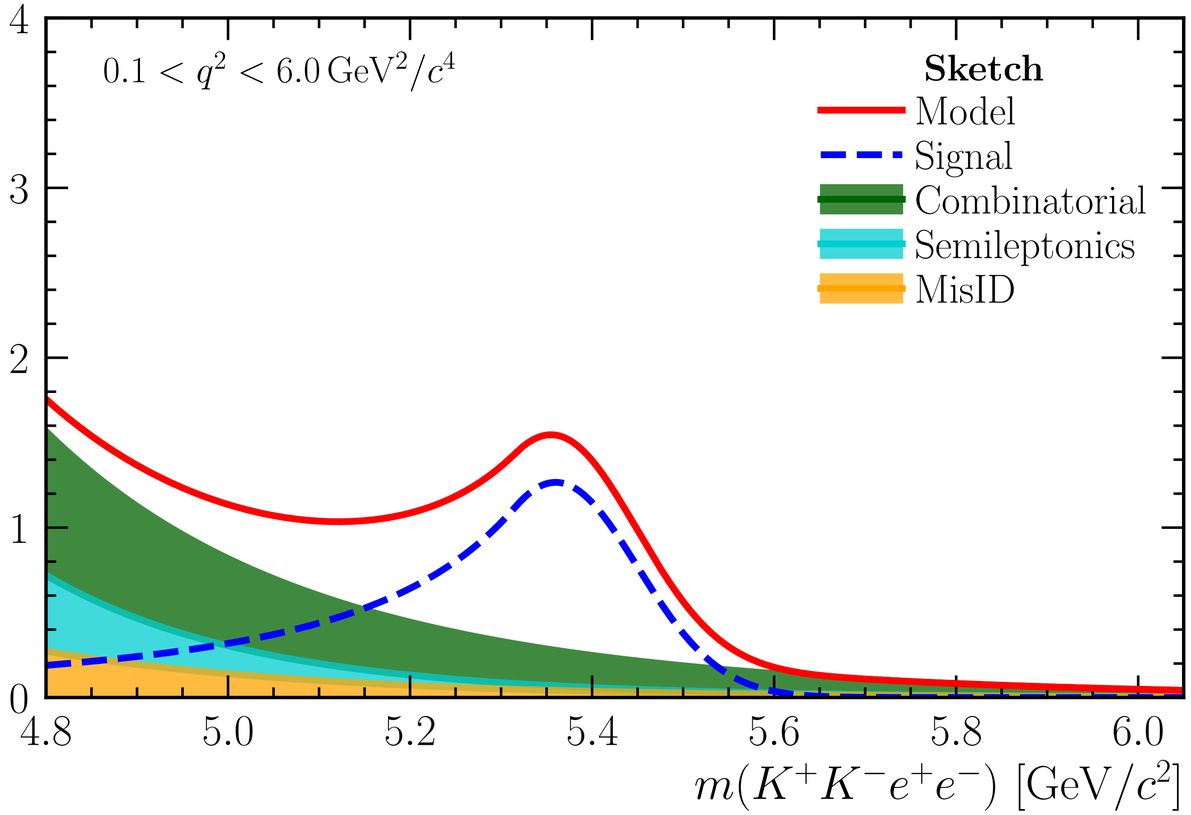
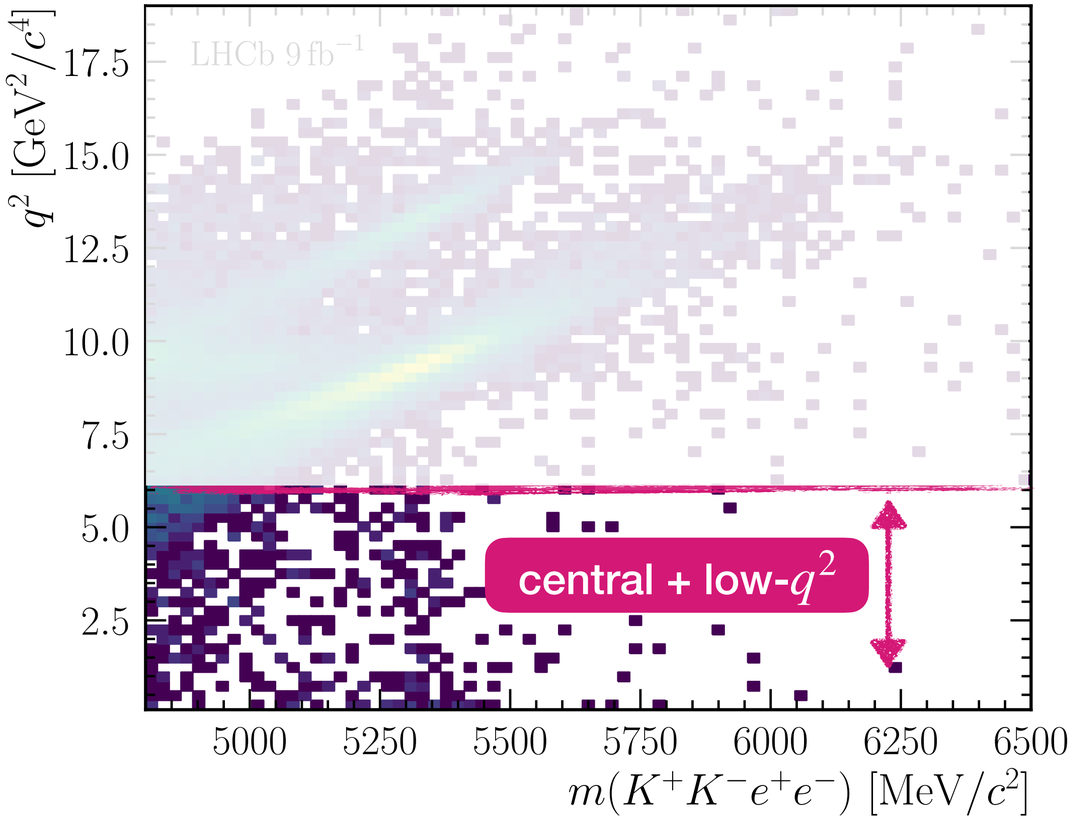
  - Leakage from $B_s^0 \to \phi J/\psi(\to e^+e^-)$ with missed bremsstrahlung γ

[LHCb-PAPER-2024-032]
preliminary





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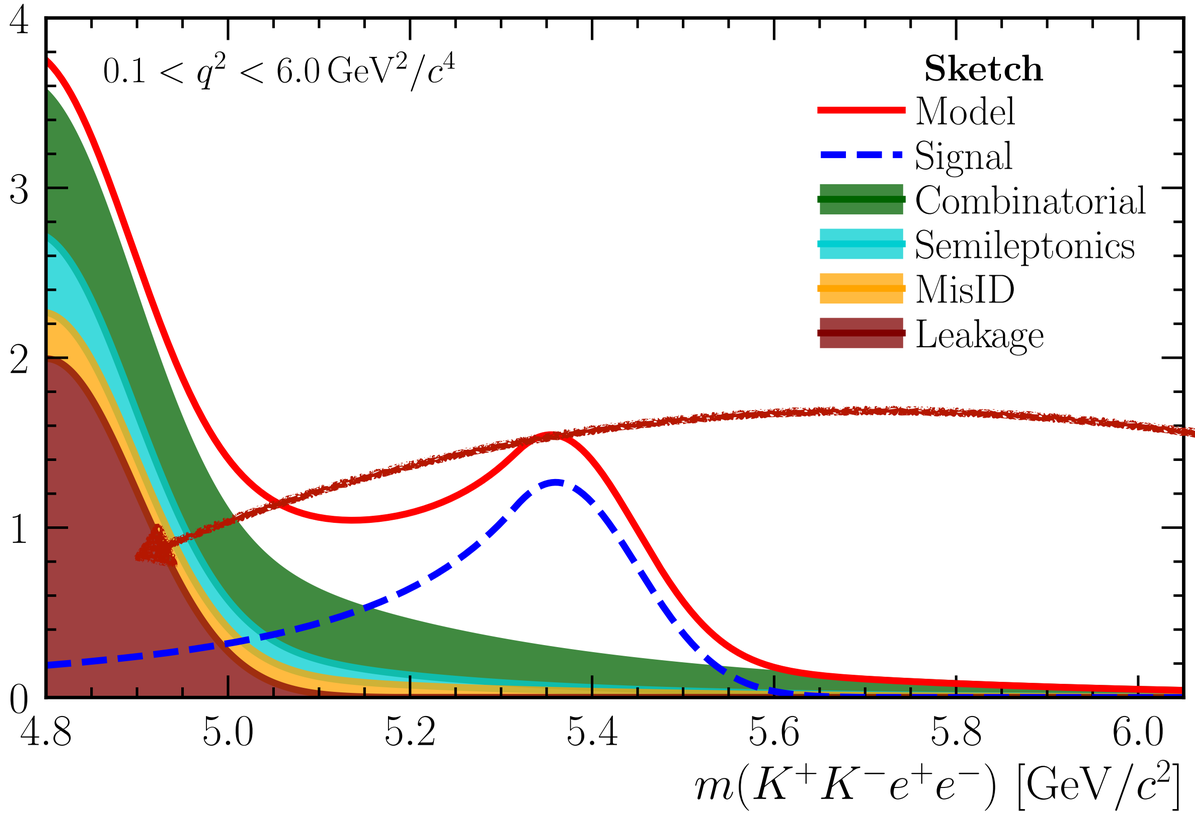


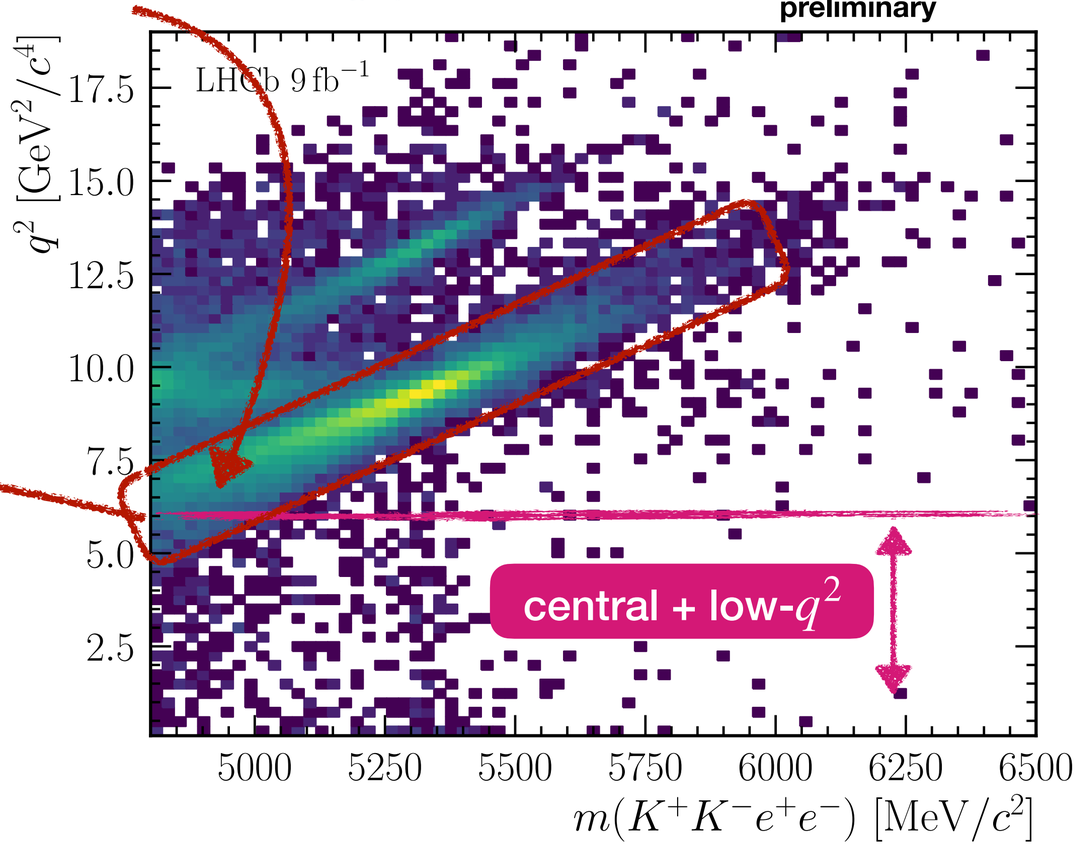
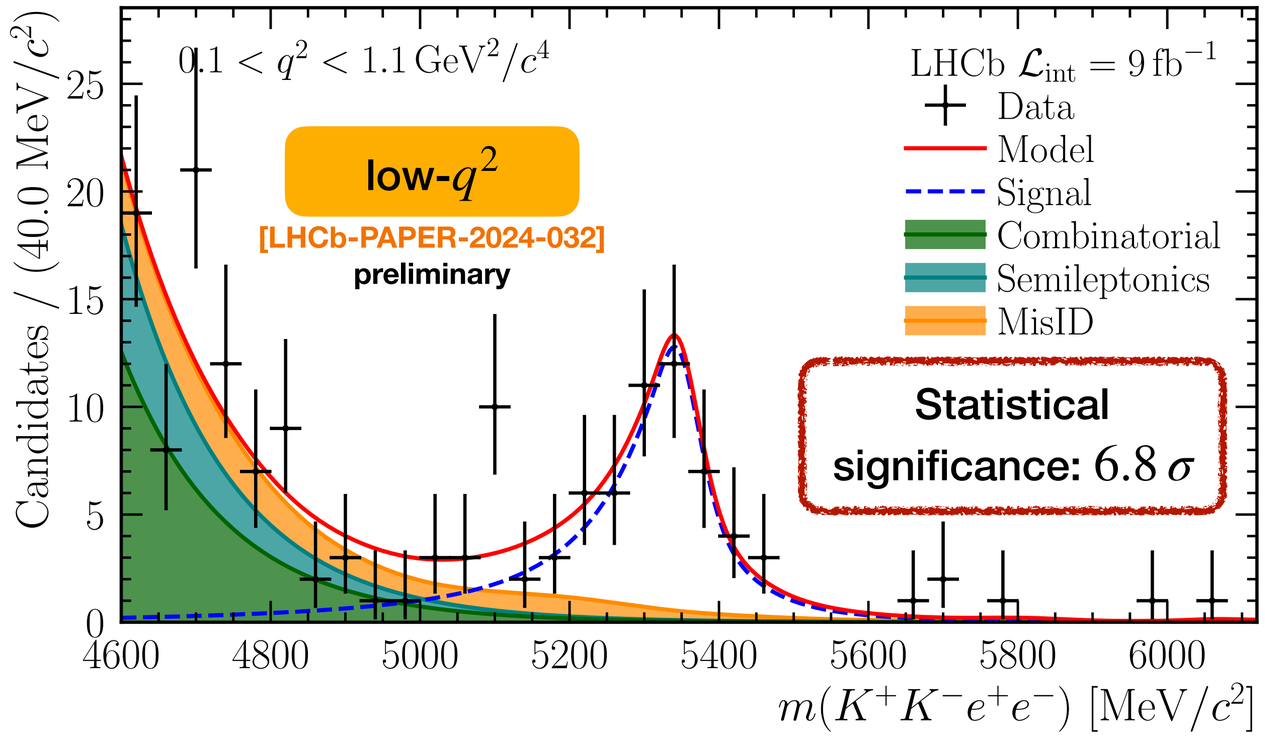


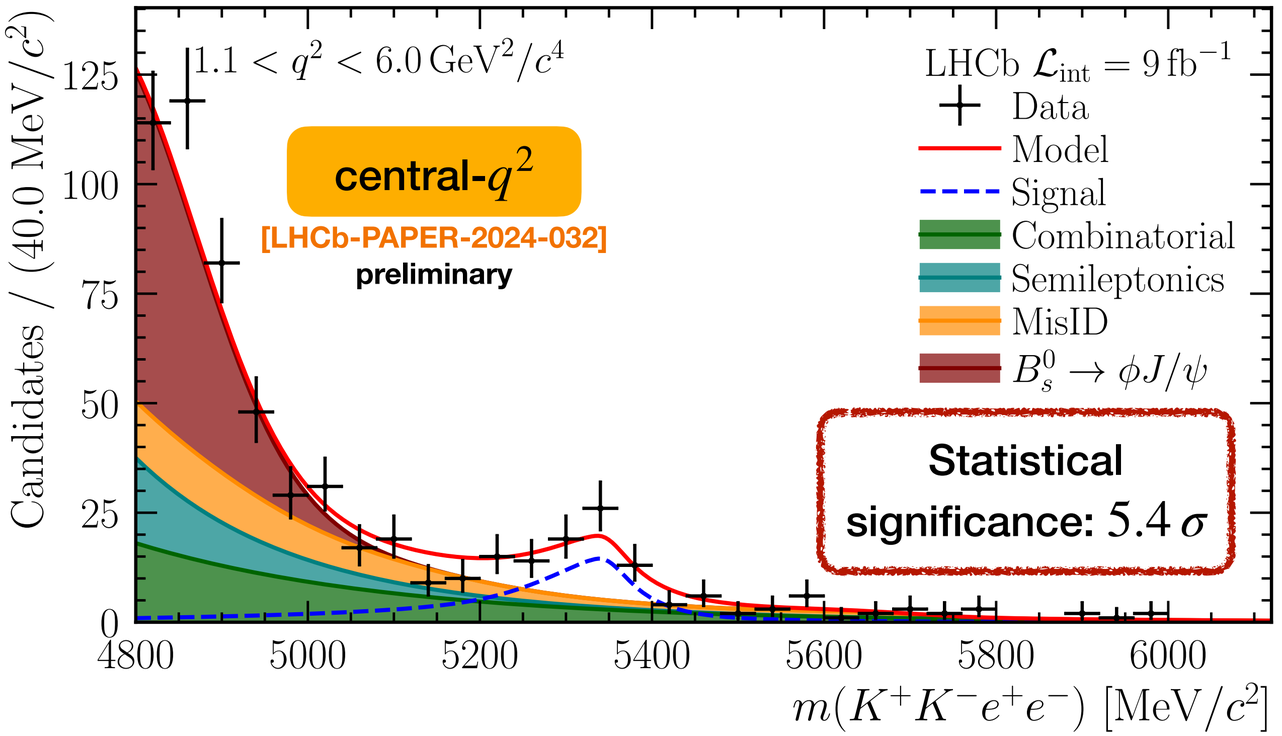
Photo: S. Schmitt

Mass Fits To Low and Central q^2: Electrons

- Relatively clean signal inspite of challenges
- $B_s^0 \to \phi J/\psi$ only relevant for central-q^2 (right)

First observation of $B_s^0 \to \phi e^+ e^-$!
Together with [LHCb-PAPER-2024-030]
(in preparation)





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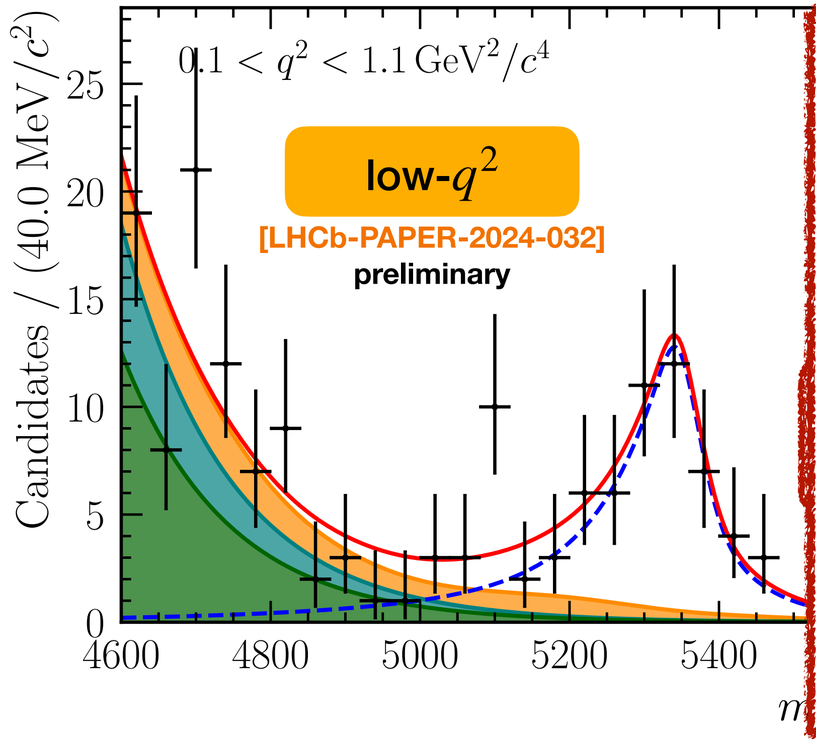
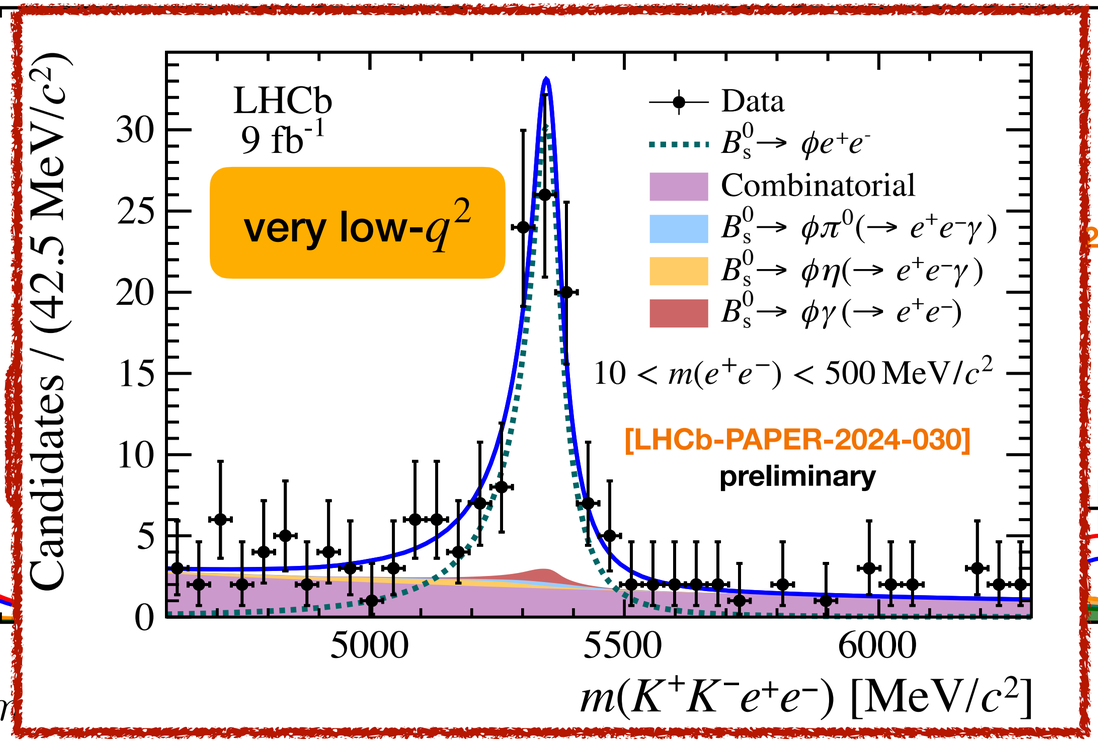




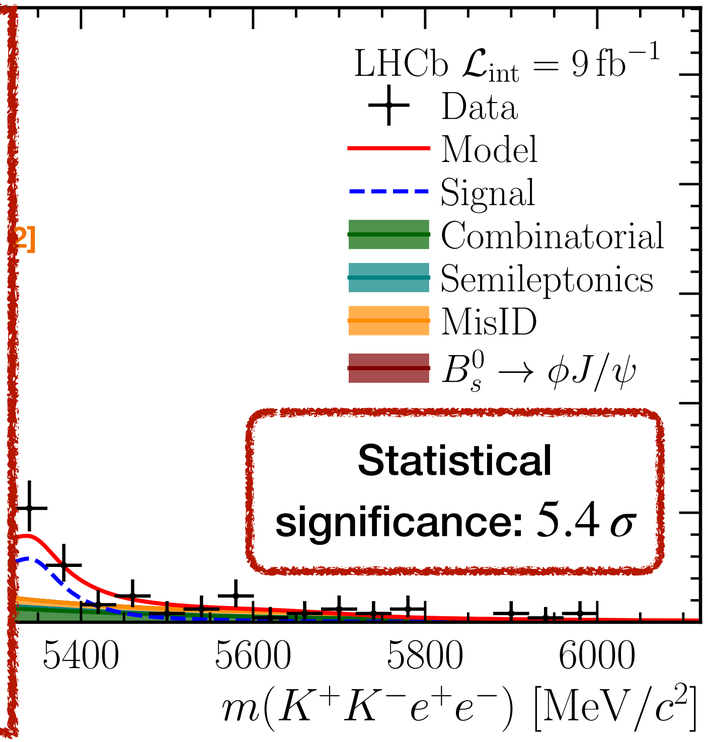
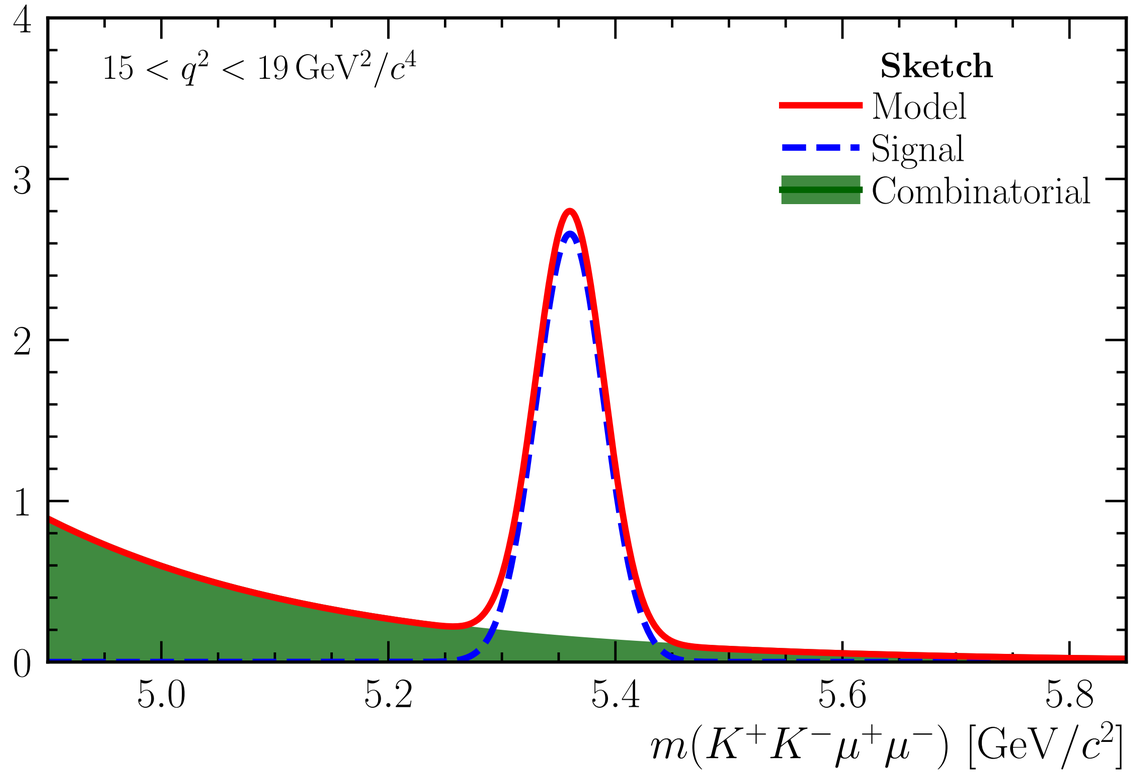


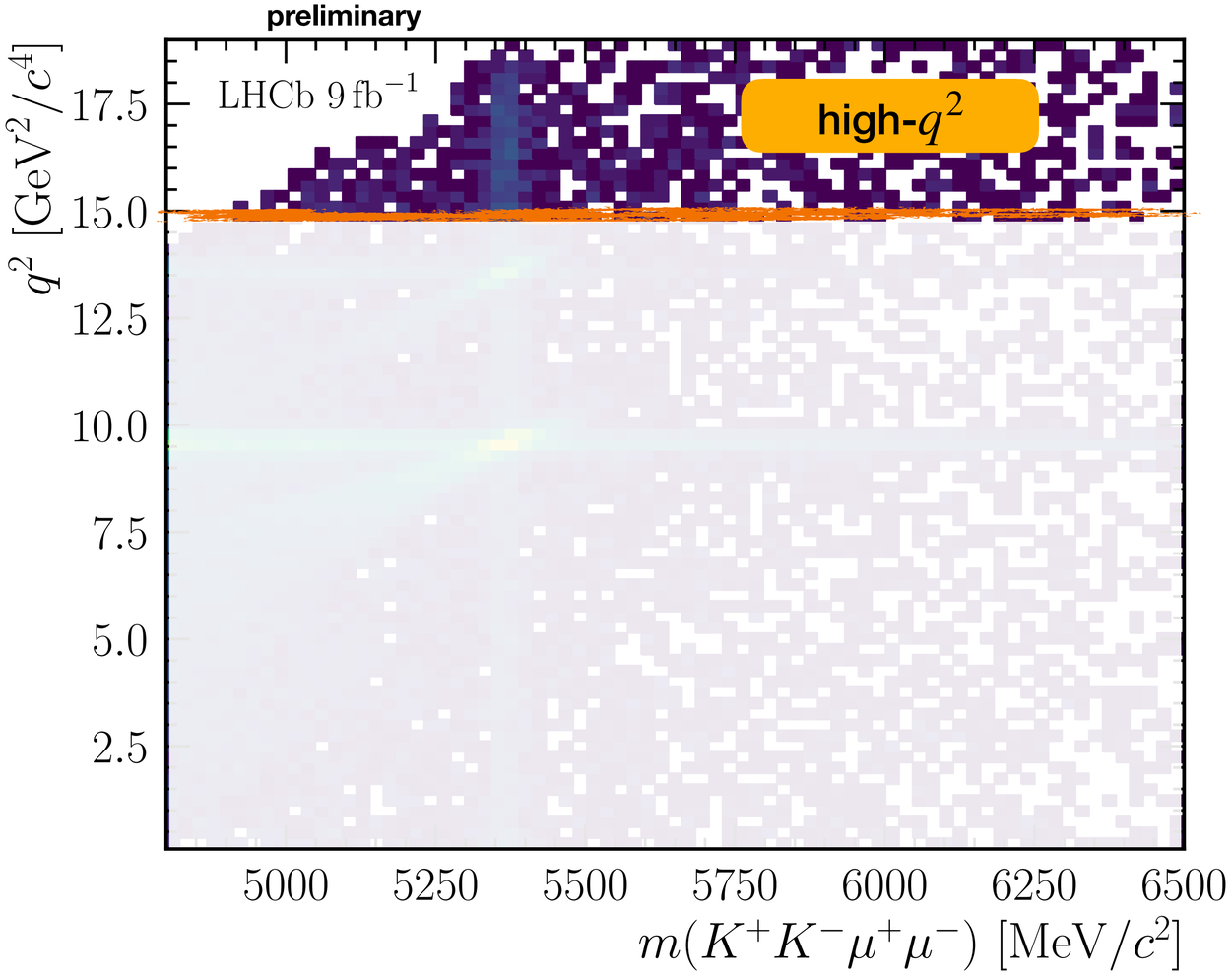
Photo: S. Schmitt

Challenges at High-q^2: Combinatorial

- Phase-space **limited** due to selection
- Morphs distributions at high-q^2



[LHCb-PAPER-2024-032]



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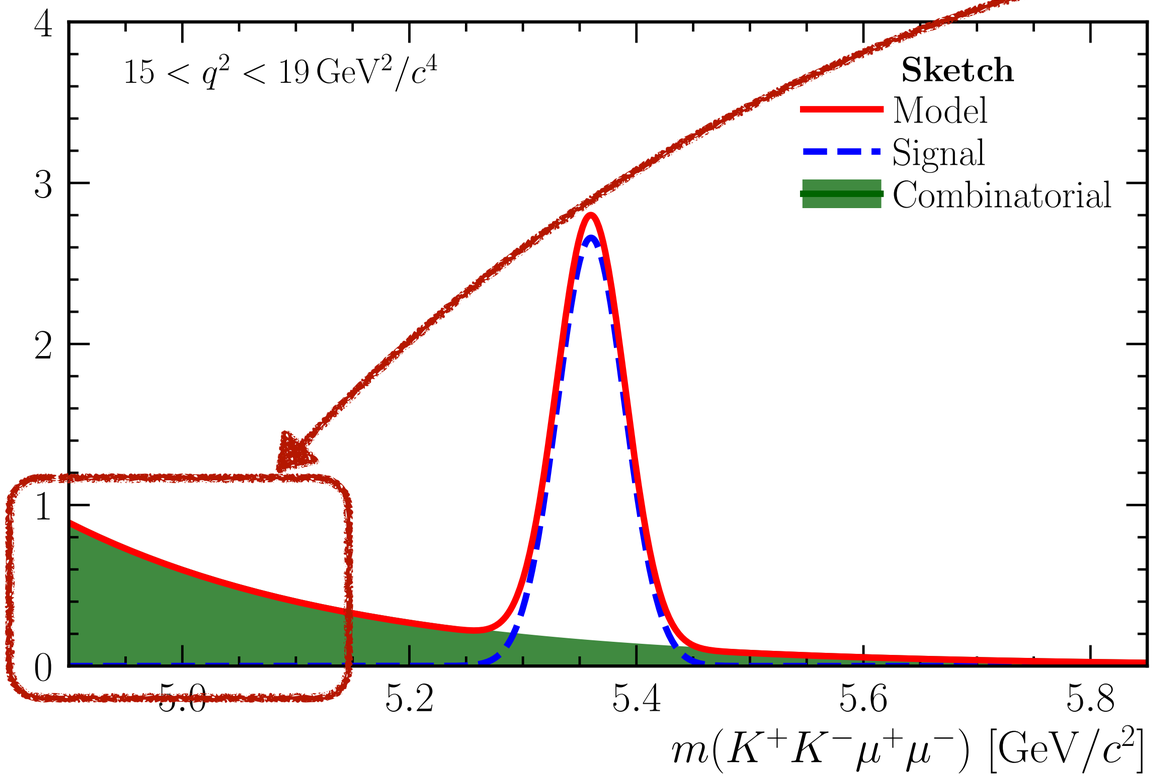
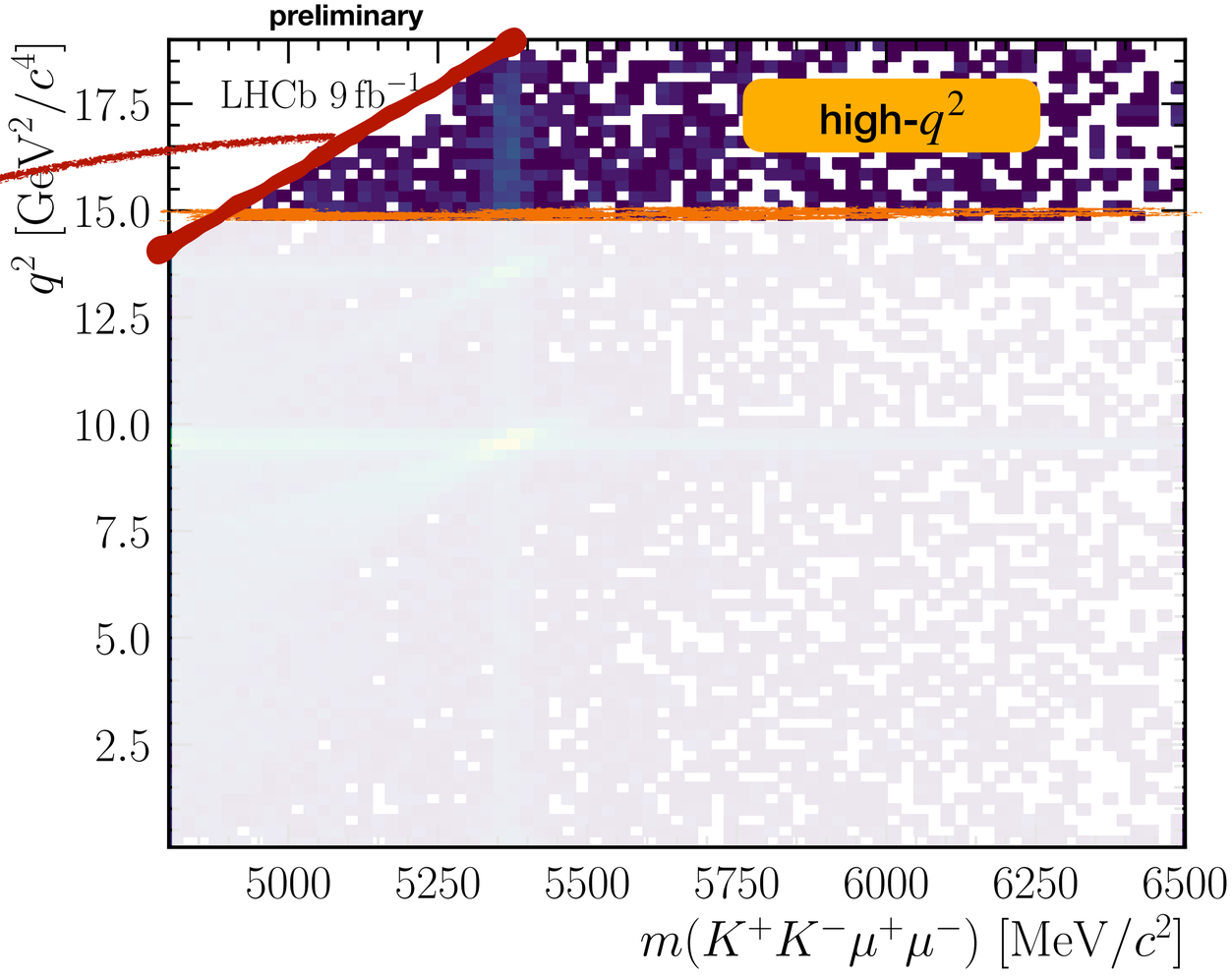


[LHCb-PAPER-2024-032]



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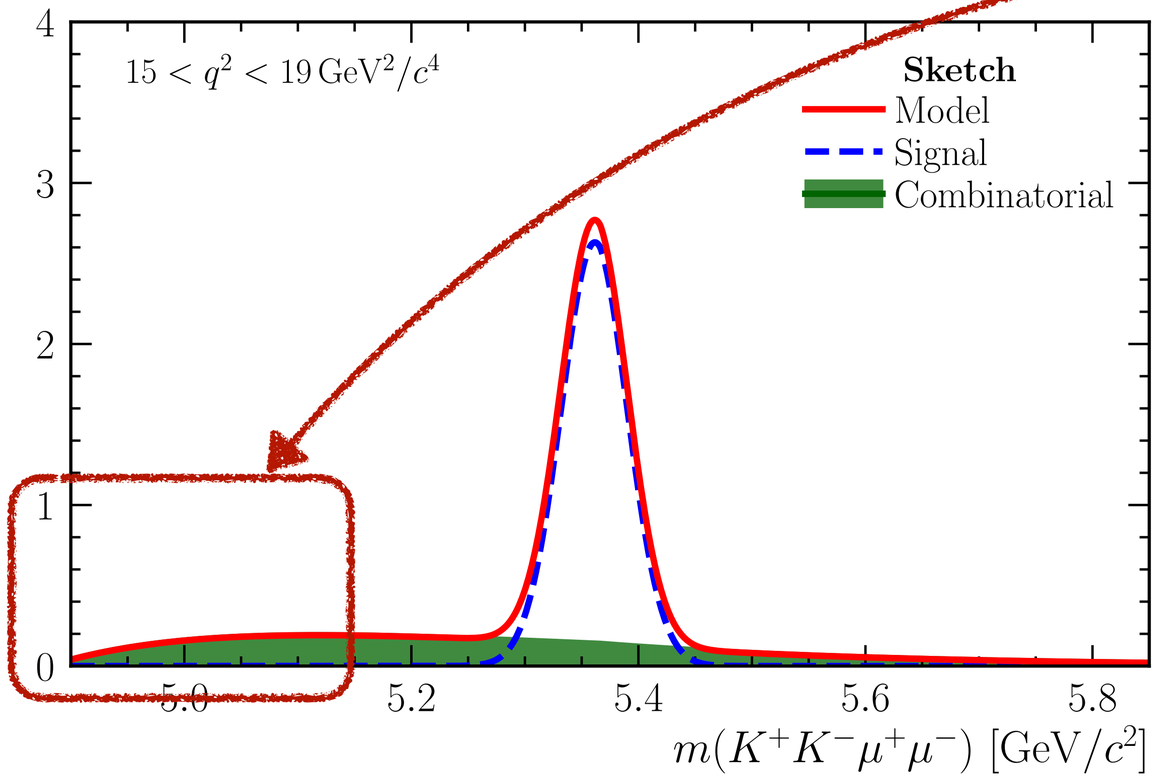


[LHCb-PAPER-2024-032]

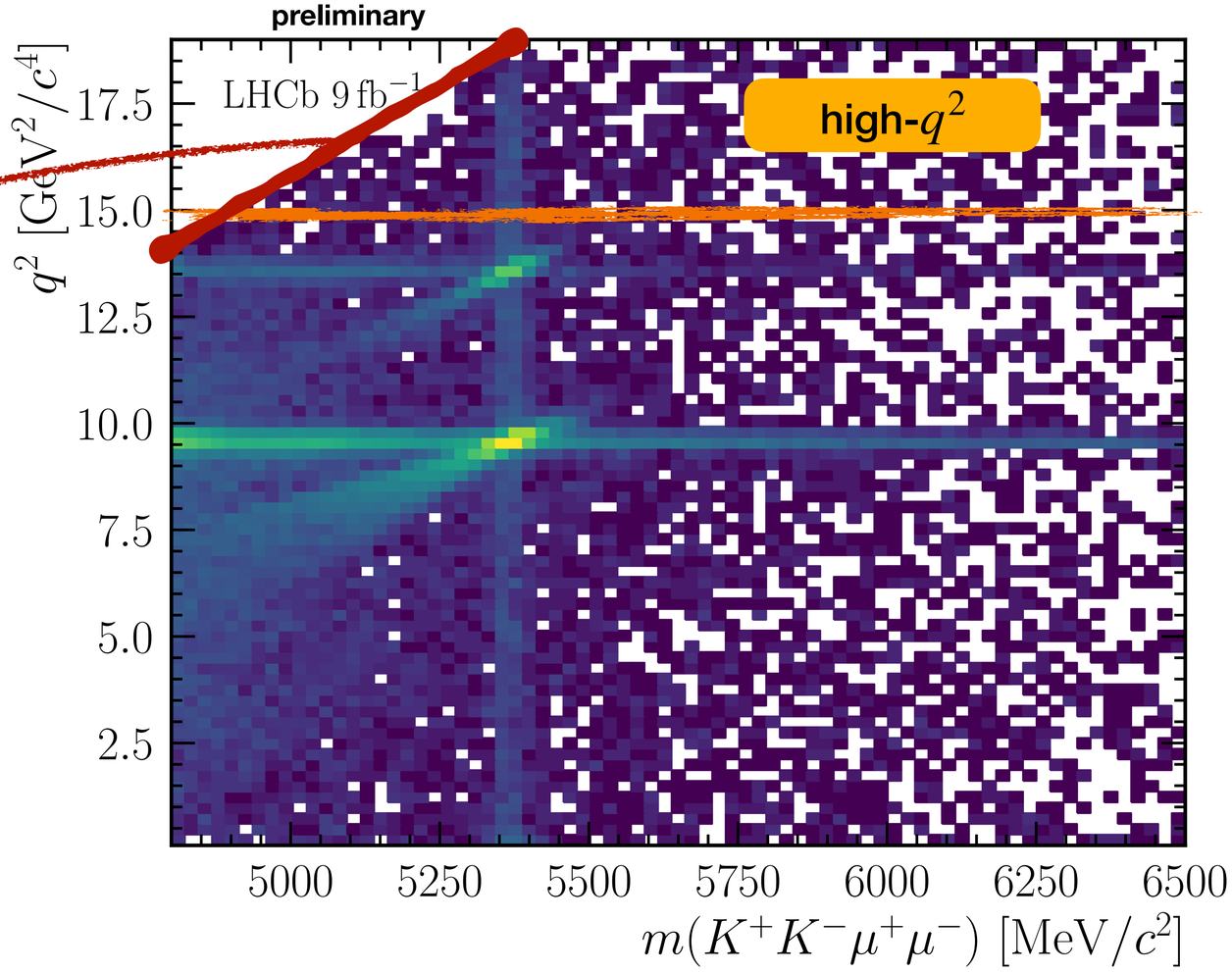


Photo: S. Schmitt

Challenges at High-q^2: Combinatorial

- Phase-space **limited** due to selection
- Morphs distributions at high-q^2
- Missing part of phase space modelled using "**acceptance**" function
  - **Data driven** estimation of missing phase space at high-q^2
- **Validated** using same-sign data
- Extensive **systematic variations** explored

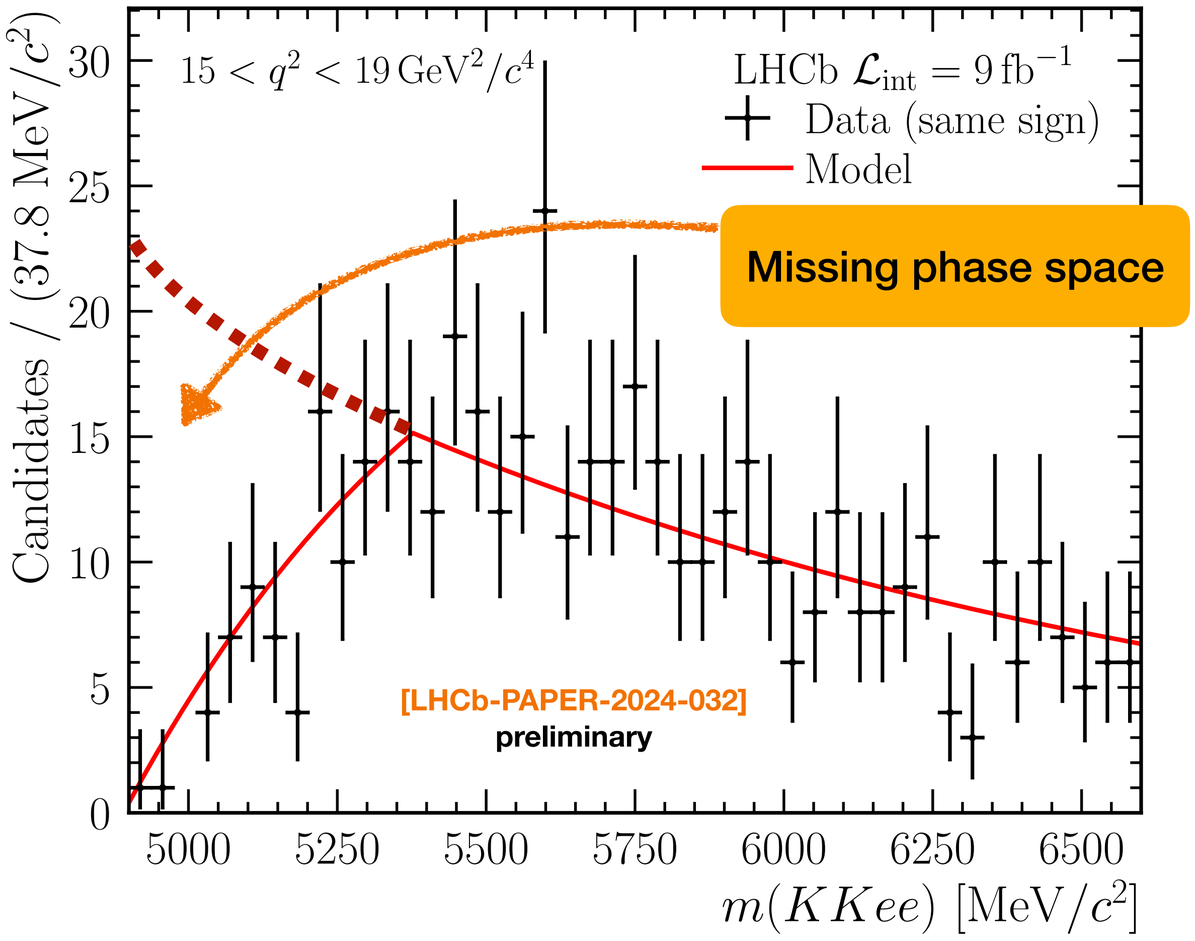


Photo: S. Schmitt

Mass Fit to High q^2: Muons

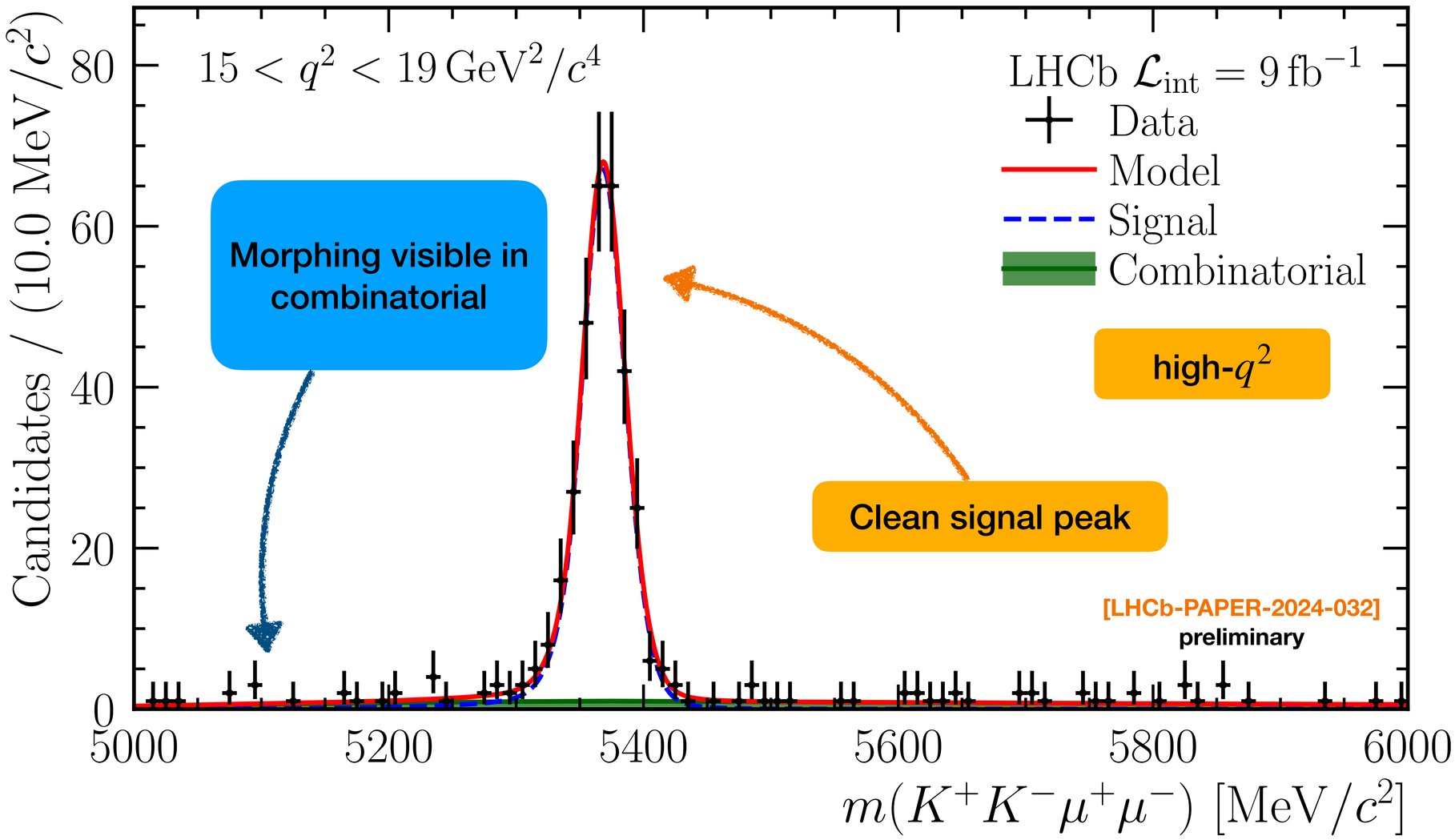
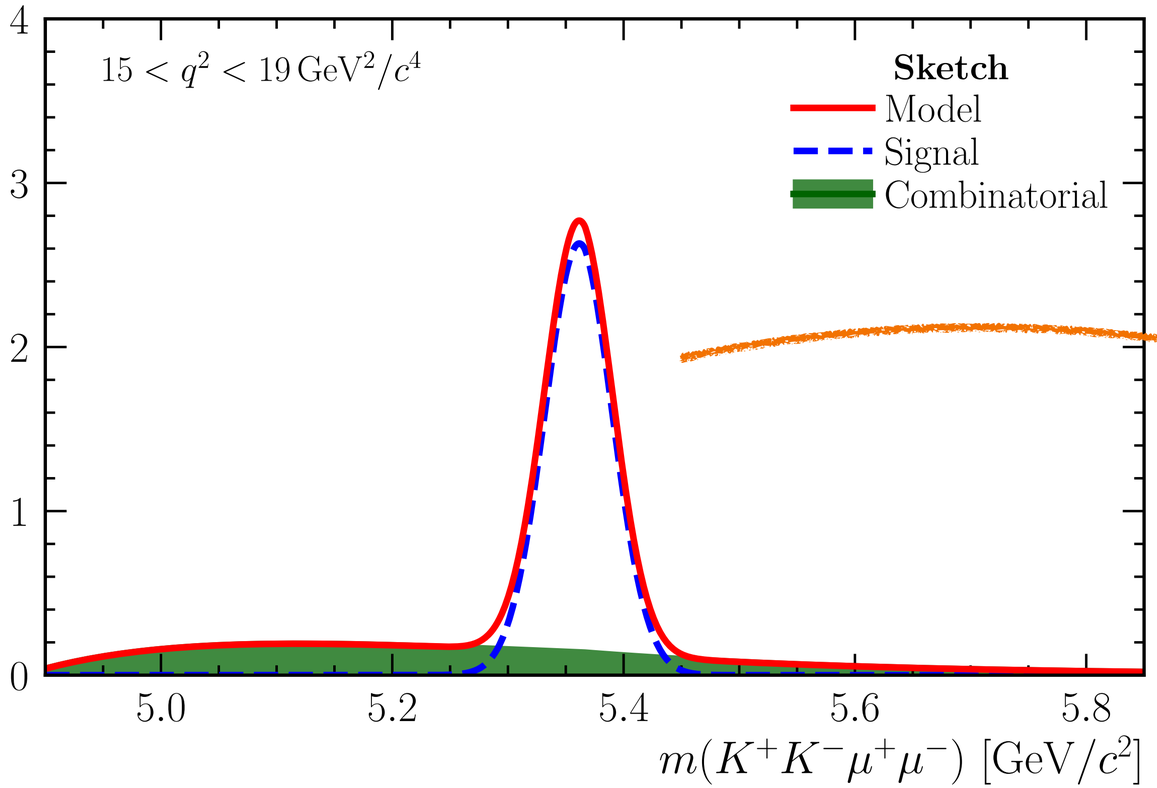


Photo: S. Schmitt

From Muon Fits to Electron Fits

- Deteriorated mass resolution and roll-over combinatorial

Two broad peaking structures overlayed



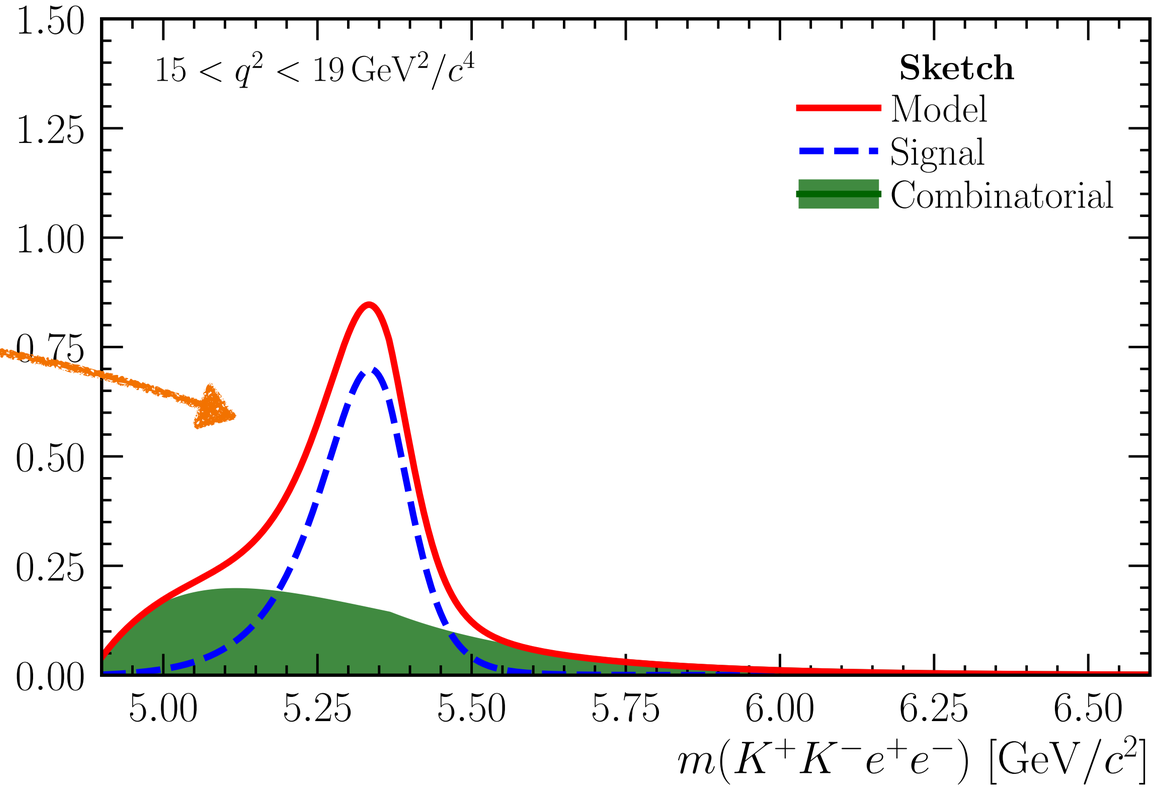
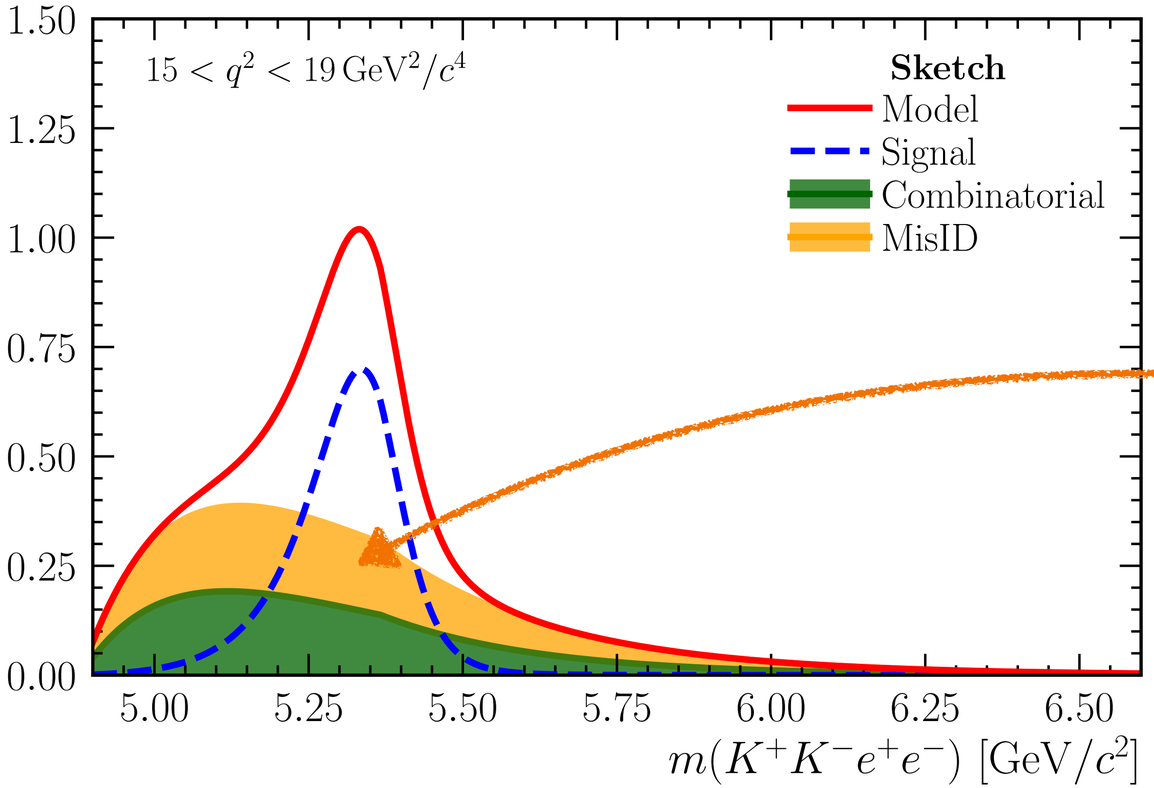


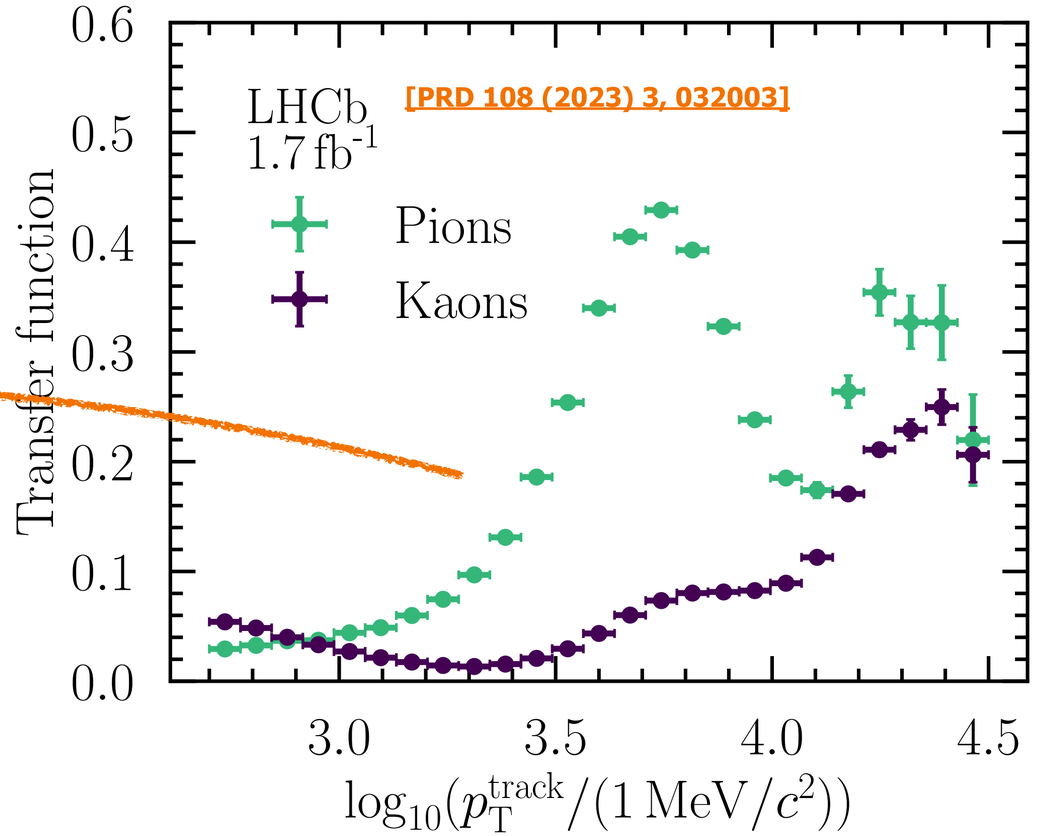
Photo: S. Schmitt

From Muon Fits to Electron Fits

- Deteriorated mass resolution and roll-over combinatorial
- Additional background from hadron to electron mis-identification

Three broad peaking structures overlayed





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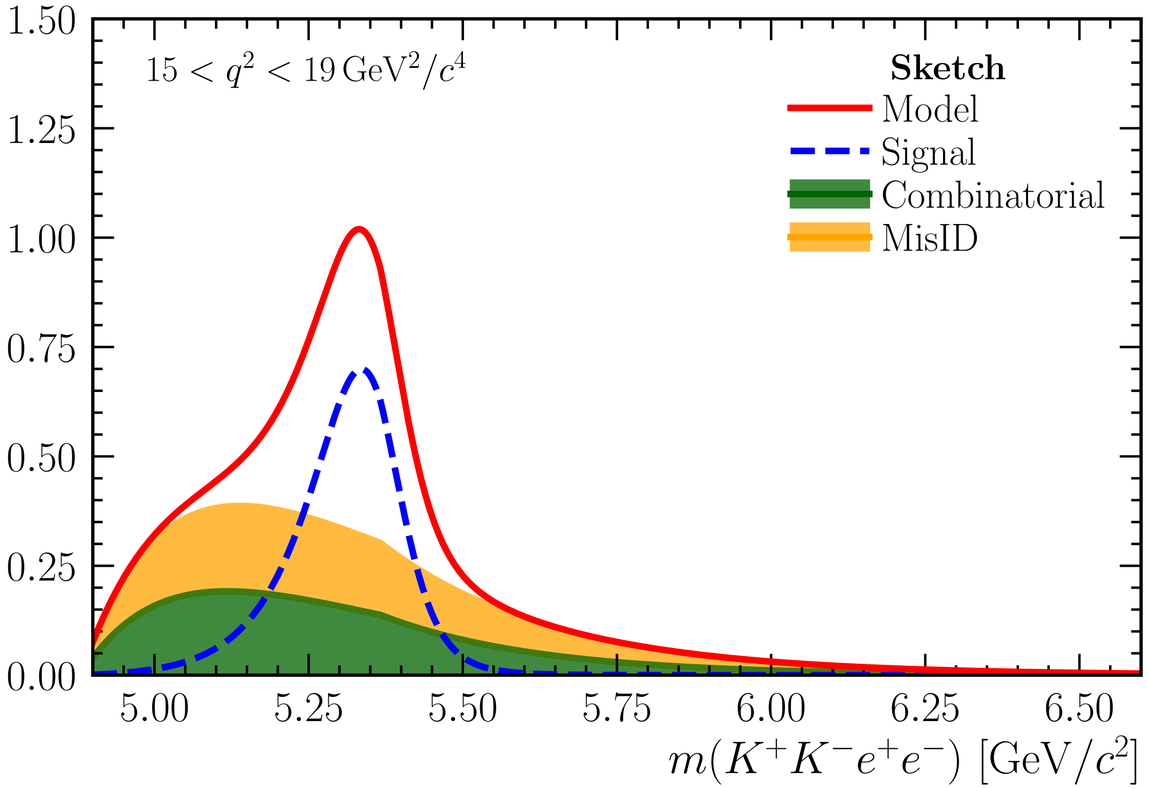
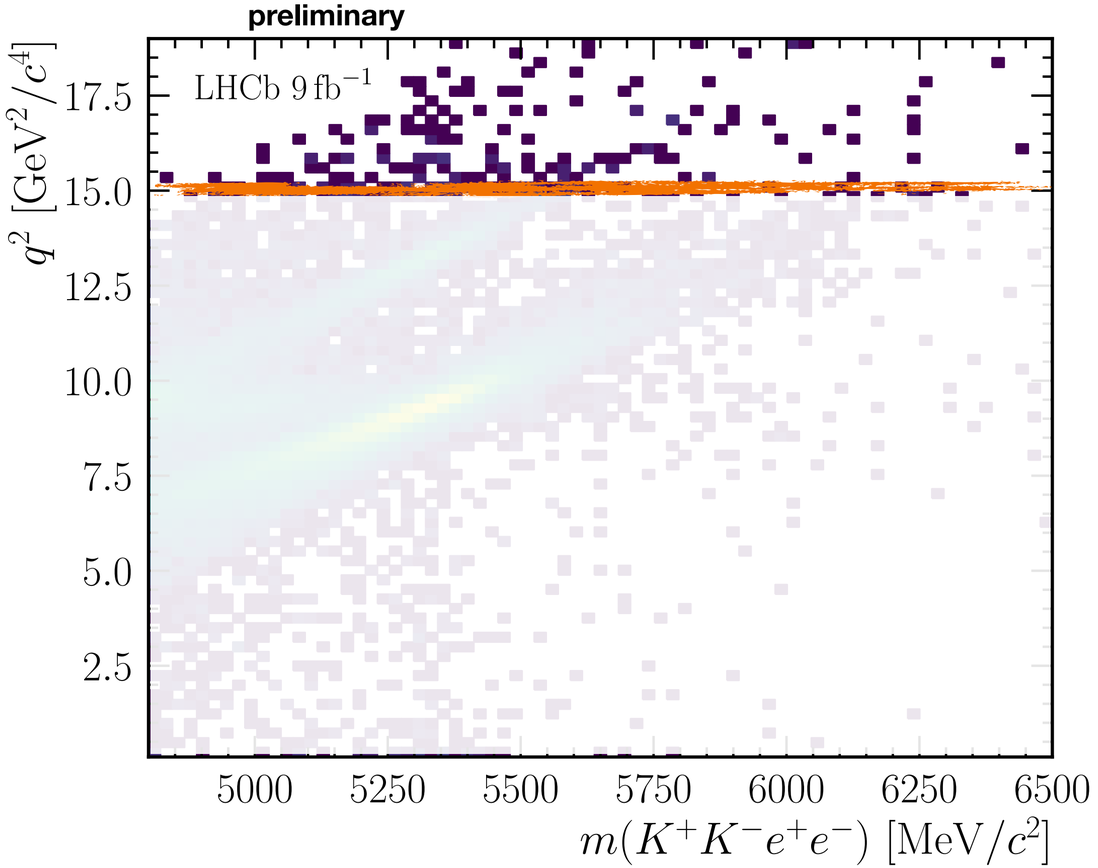
From Muon Fits to Electron Fits

- Deteriorated mass resolution and roll-over combinatorial
- Leakage from $B_s^0 \to \phi\psi(2S)$ decays

Three broad peaking structures overlayed



[LHCb-PAPER-2024-032]



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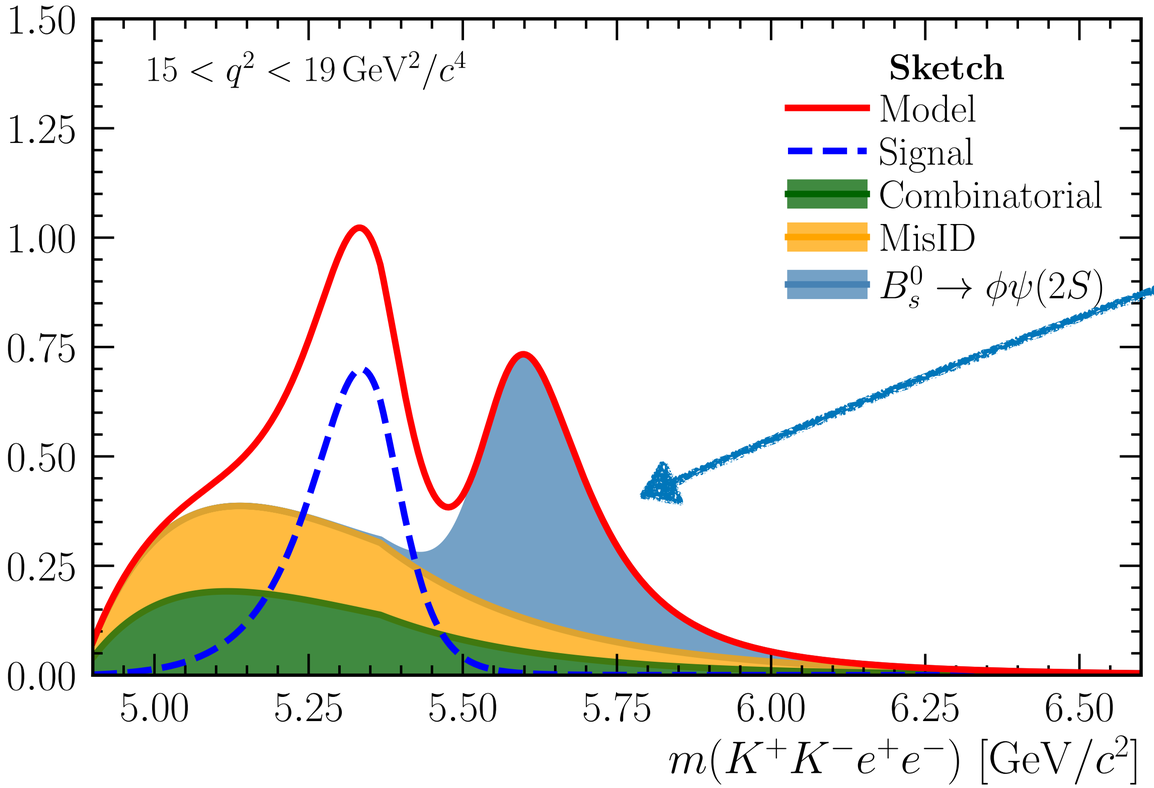
Four broad peaking structures overlayed



[LHCb-PAPER-2024-032]

preliminary

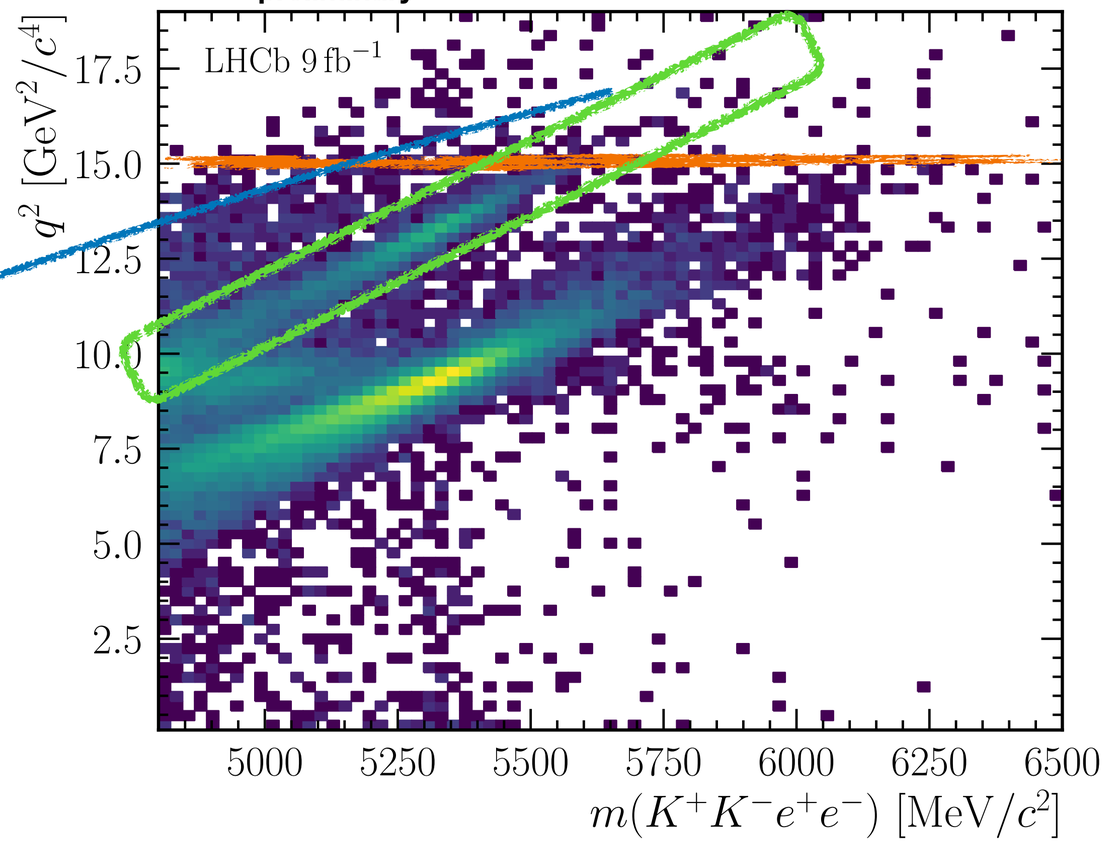
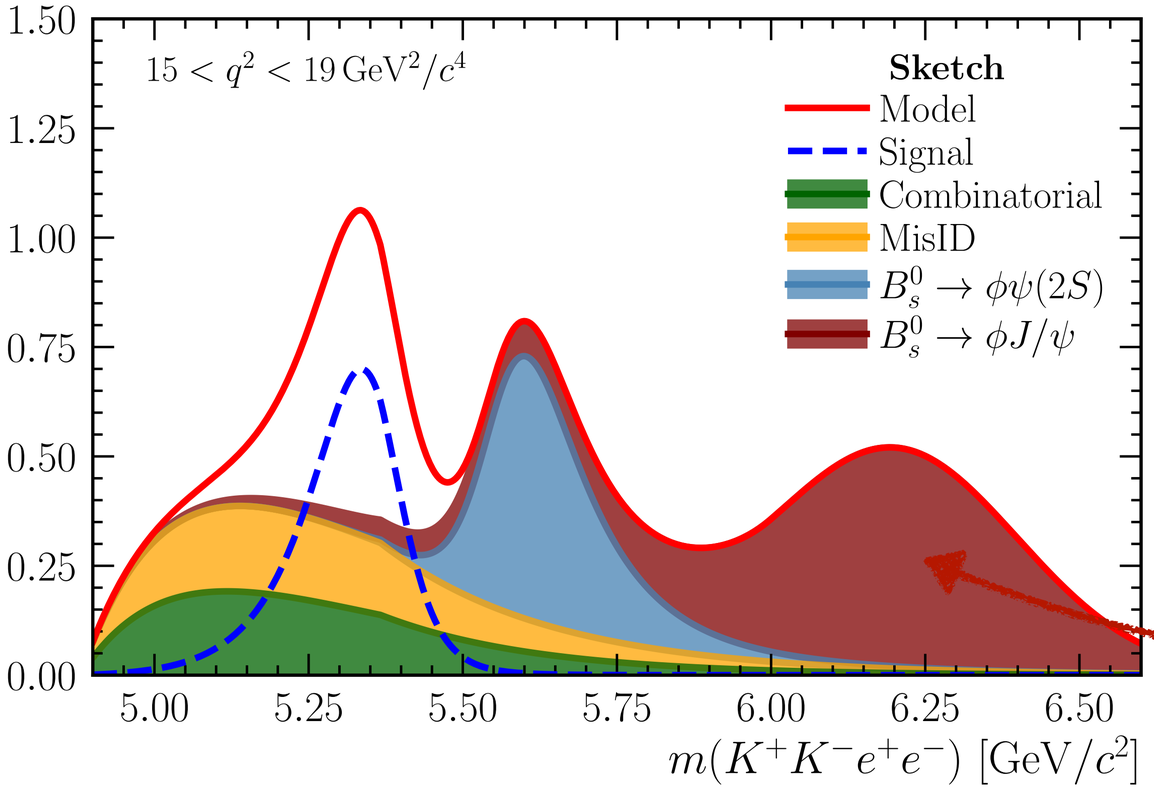


Photo: S. Schmitt

From Muon Fits to Electron Fits

- Deteriorated mass resolution and roll-over combinatorial
- Leakage from $B_s^0 \to \phi J/\psi$ decays, with wrong bremsstrahlung γ

Five broad peaking structures overlayed



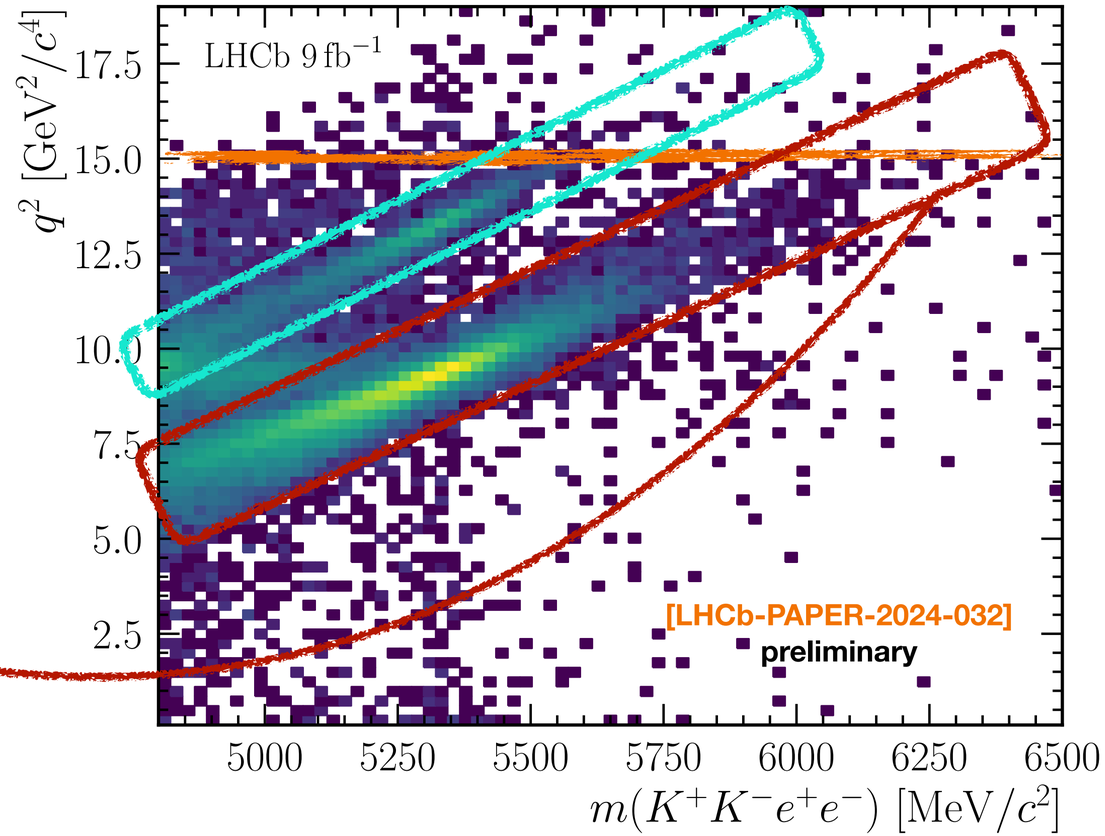
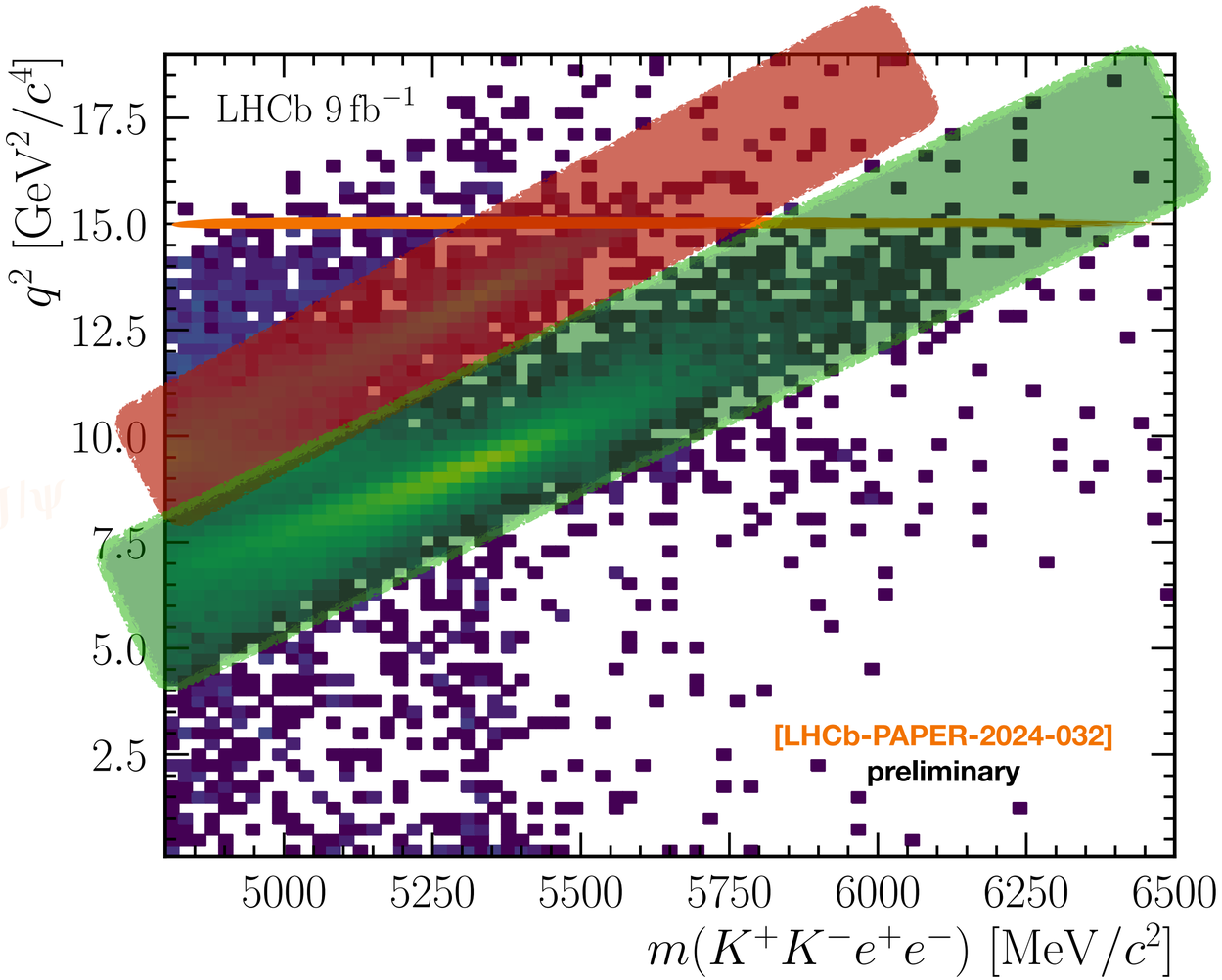


Photo: S. Schmitt

Challenges at High-q^2: Leakage

- Leakage from $B_s^0 \to \phi\psi(2S)$ and $B_s^0 \to \phi J/\psi$
- But not limited to only these!



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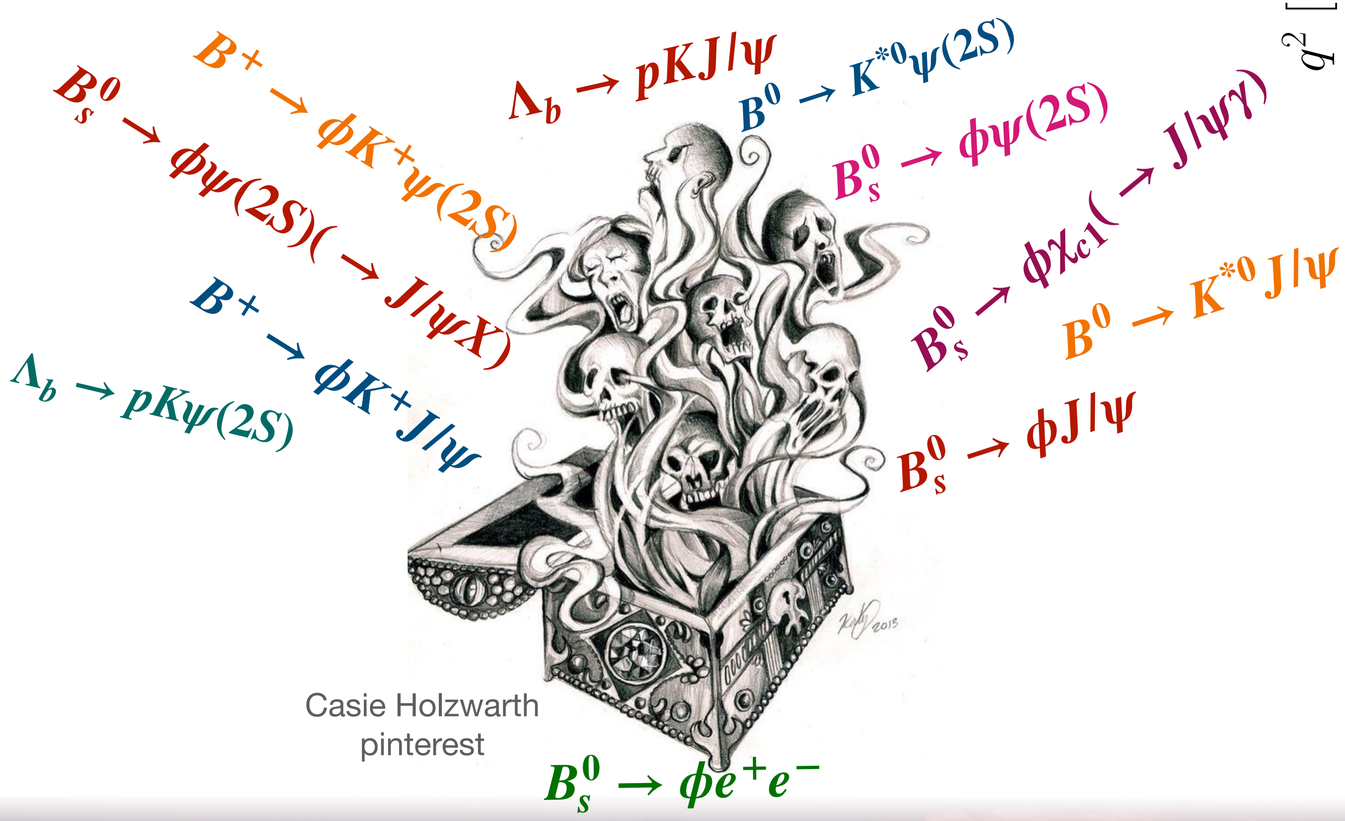
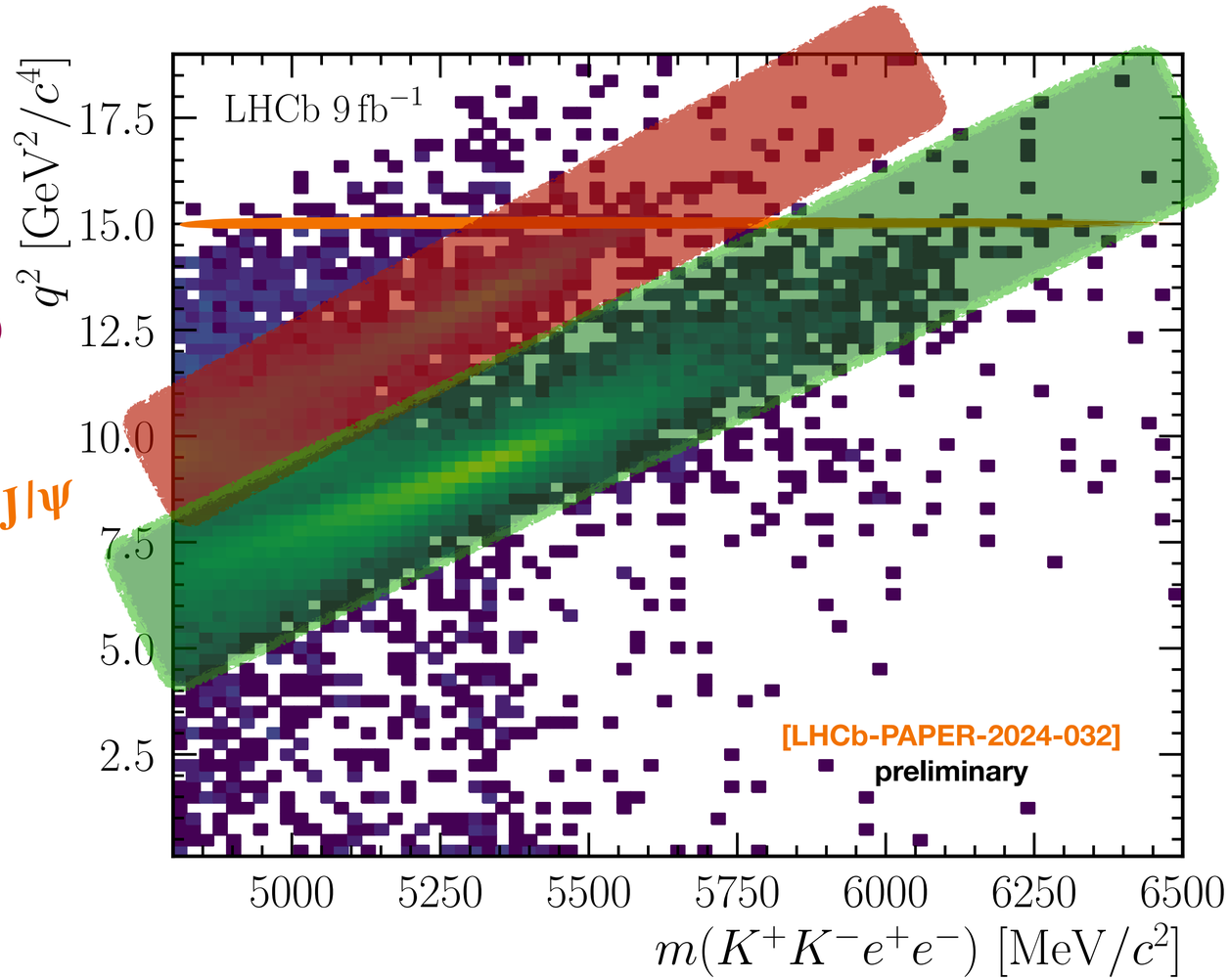


Casie Holzwarth
pinterest



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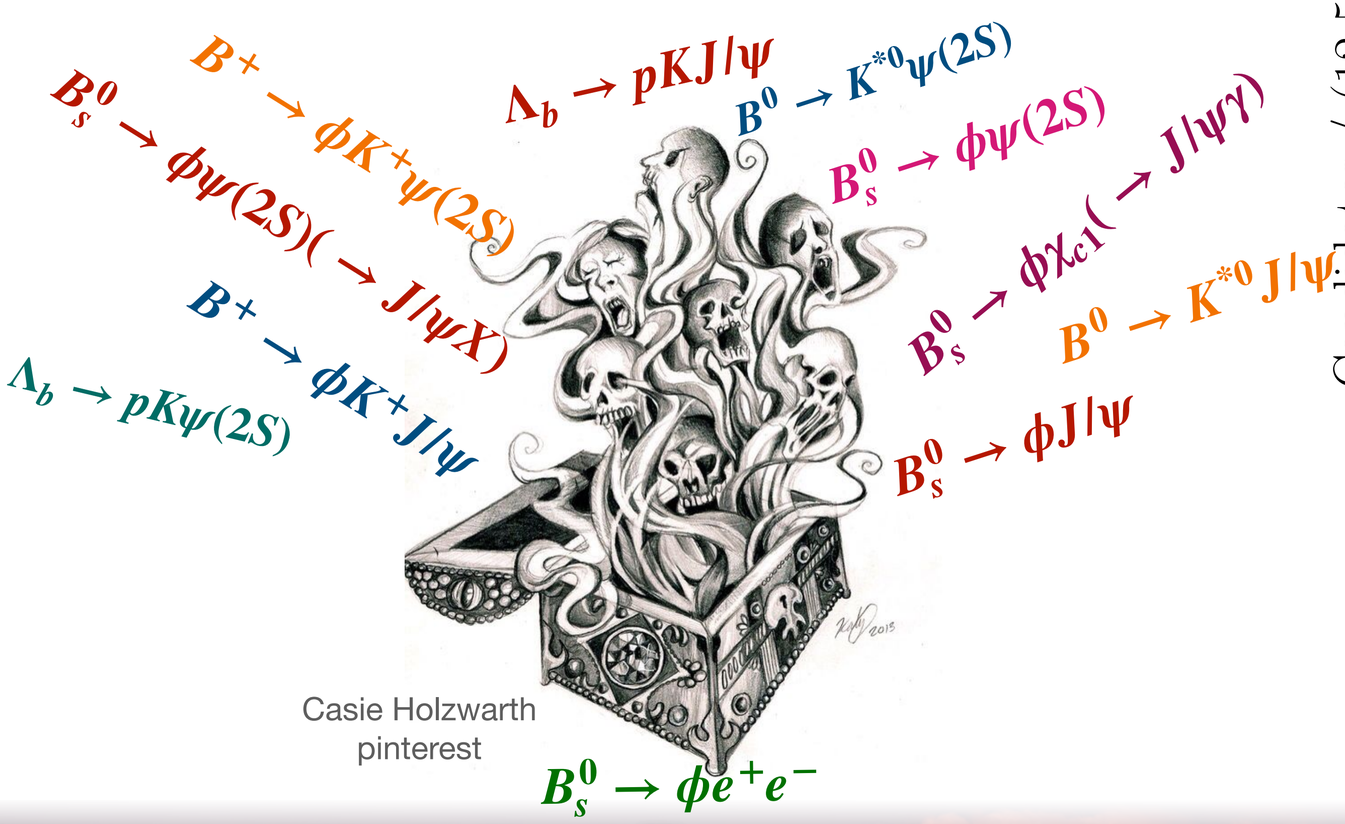

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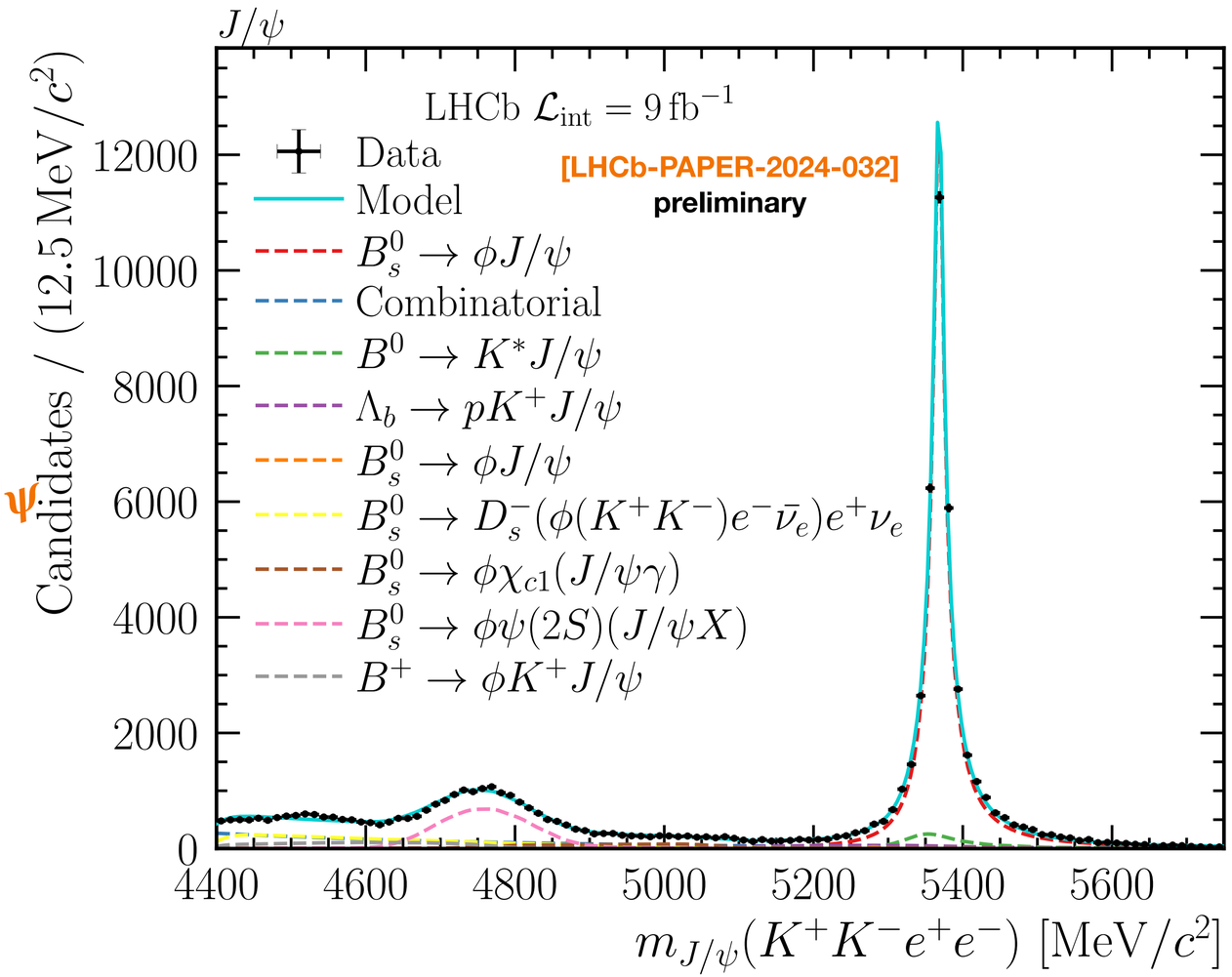

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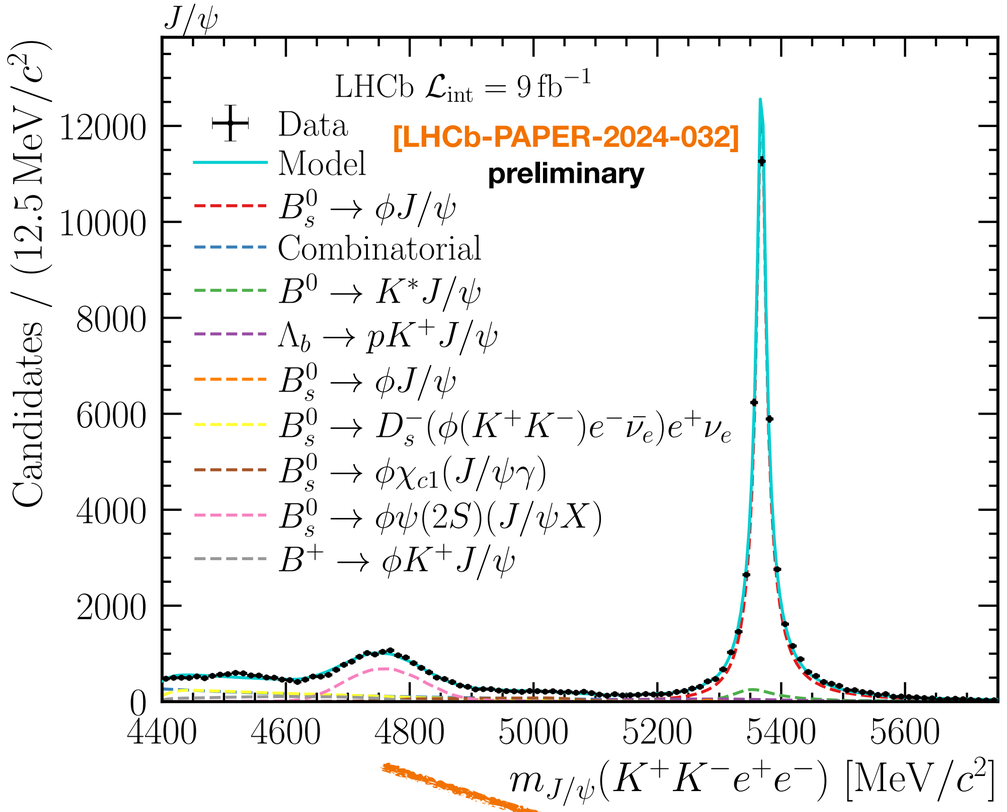

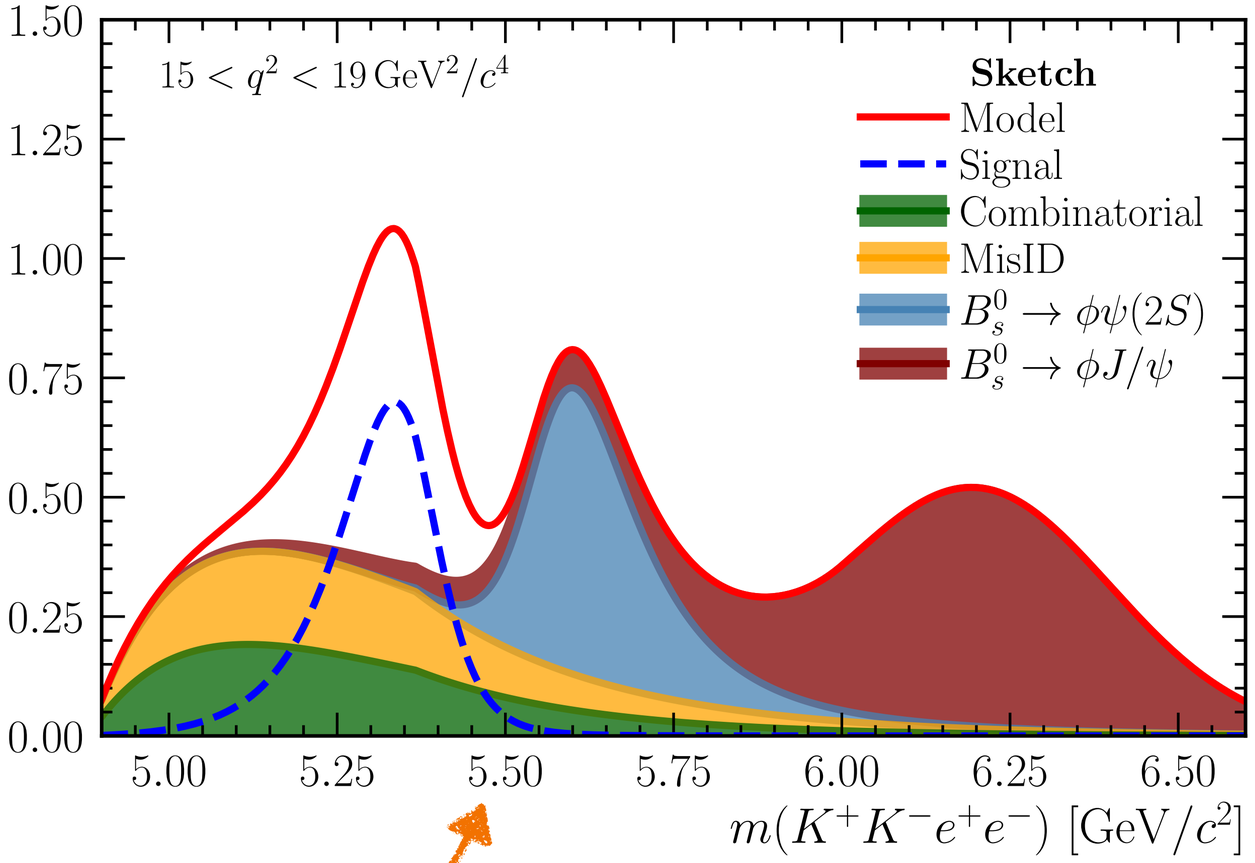

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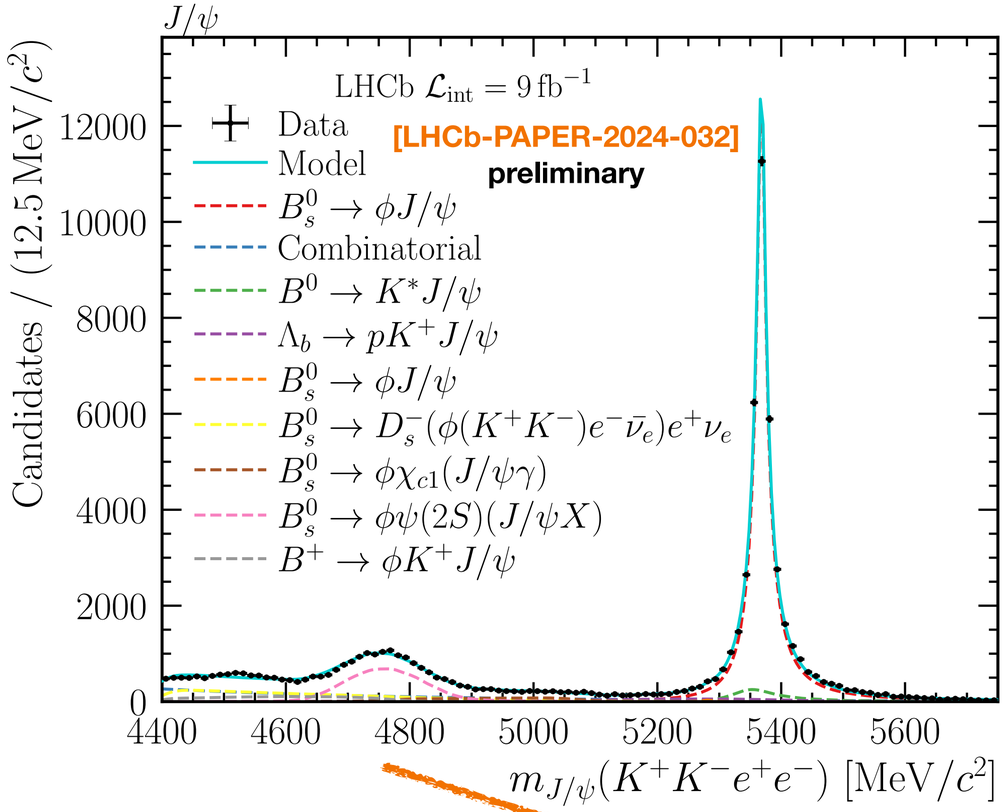
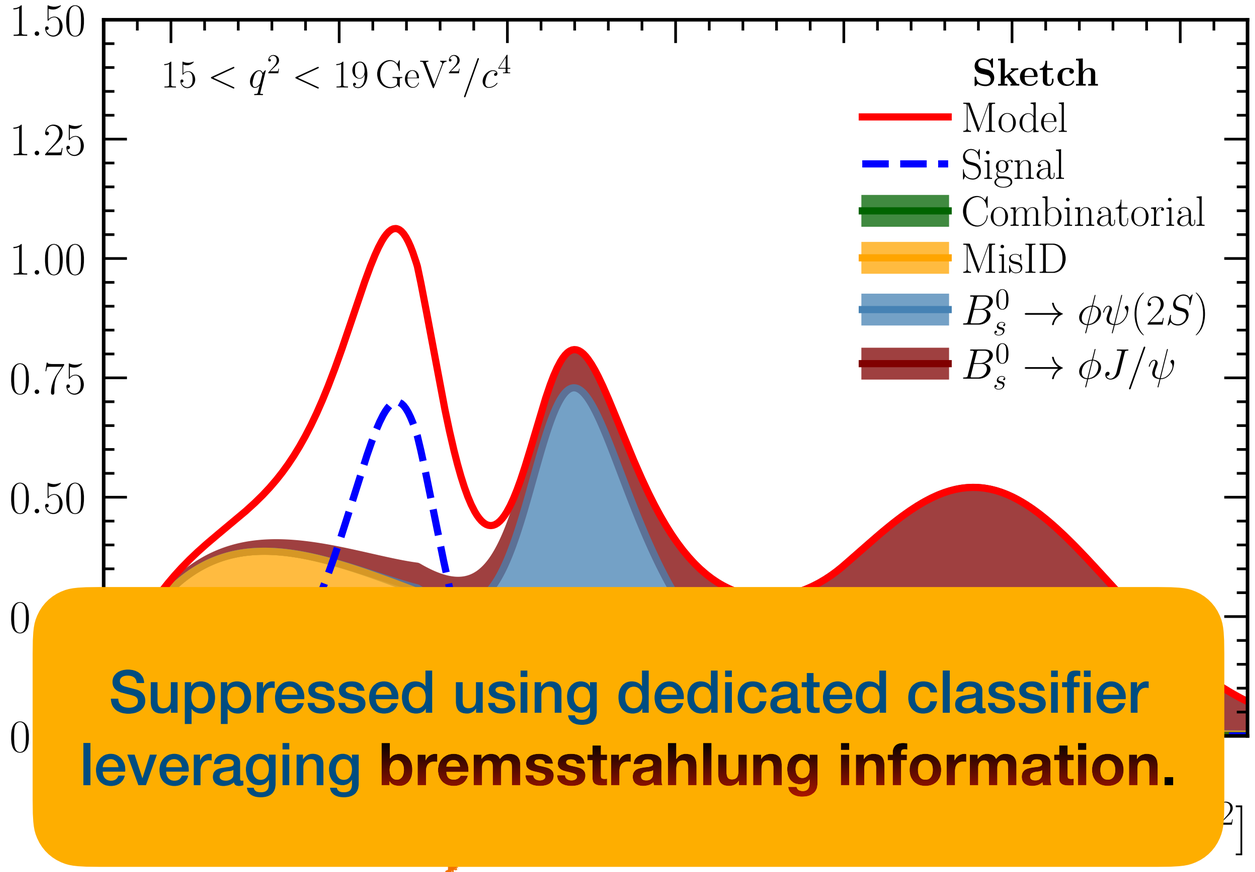
- Leakage from $B_s^0 \to \phi\psi(2S)$ and $B_s^0 \to \phi J/\psi$
- But not limited to only these!

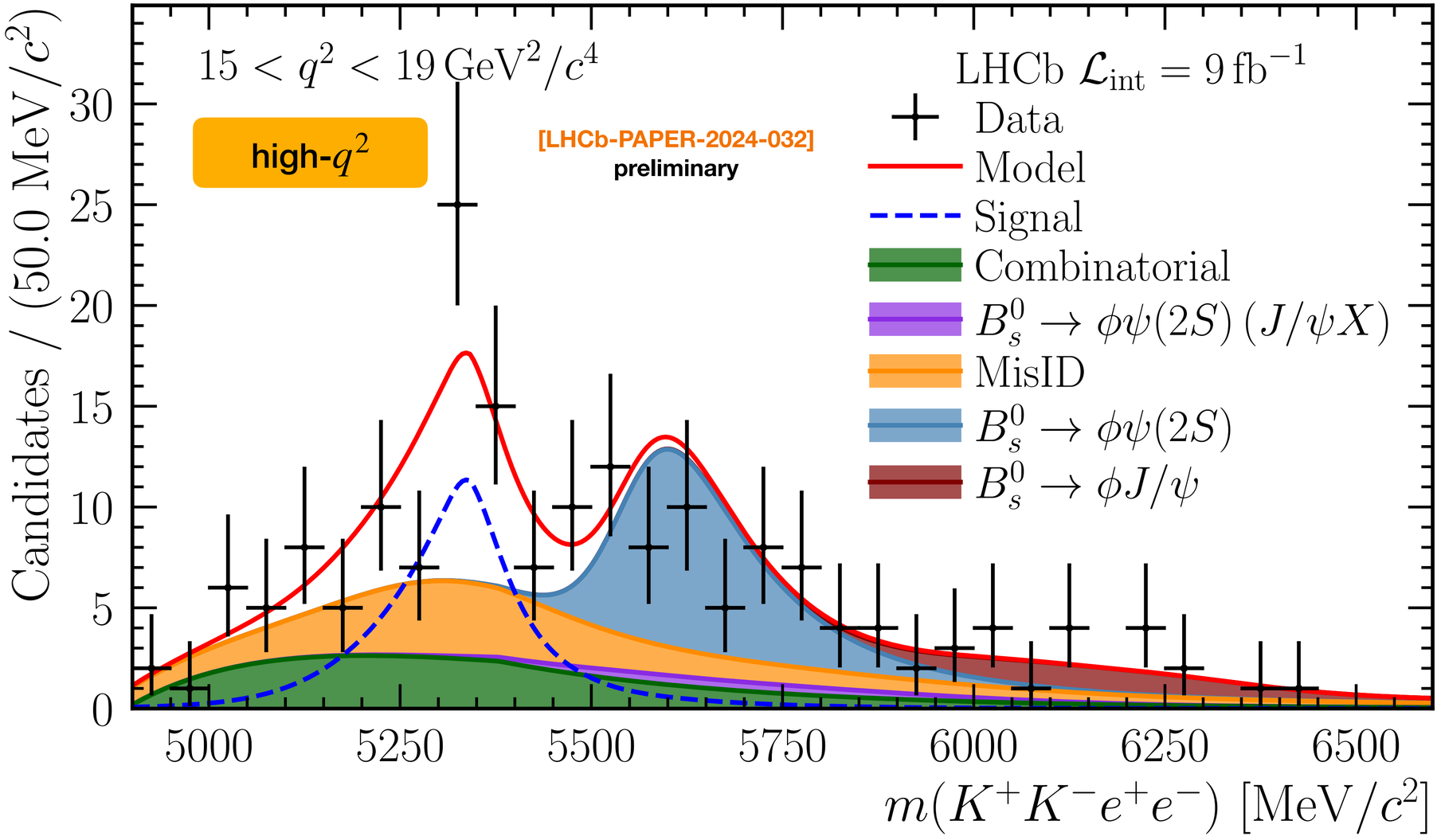




Suppressed using dedicated classifier leveraging **bremsstrahlung information.**

Photo: S. Schmitt

Mass Fit to High-q^2: Electrons



Statistical significance: $3.6\,\sigma$

Photo: S. Schmitt

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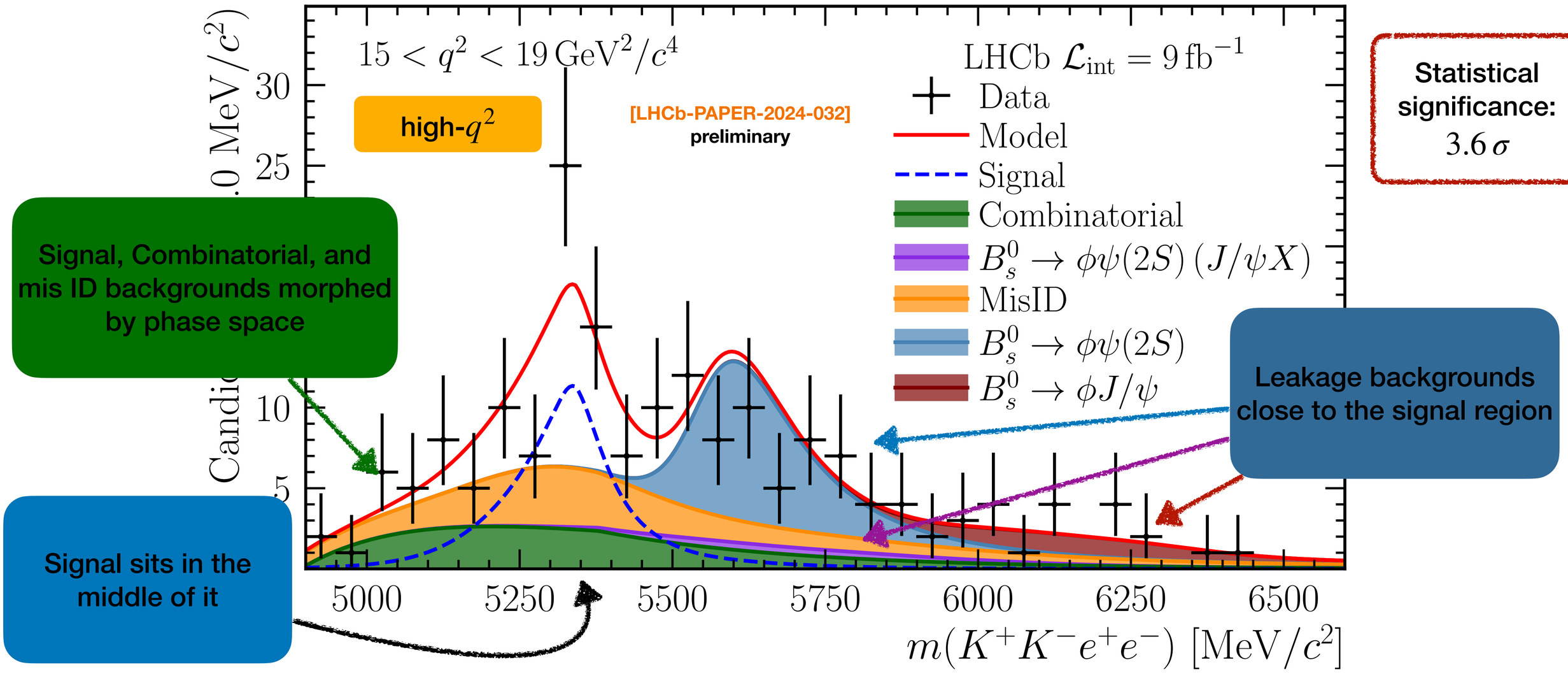

Statistical significance: $3.6\,\sigma$

Signal, Combinatorial, and mis ID backgrounds morphed by phase space

Leakage backgrounds close to the signal region

Signal sits in the middle of it

Photo: S. Schmitt

Systematic Uncertainties

[LHCb-PAPER-2024-032]
preliminary

- Uncertainty dominated by **statistical component**
- Many systematics will **shrink with bigger sample** size

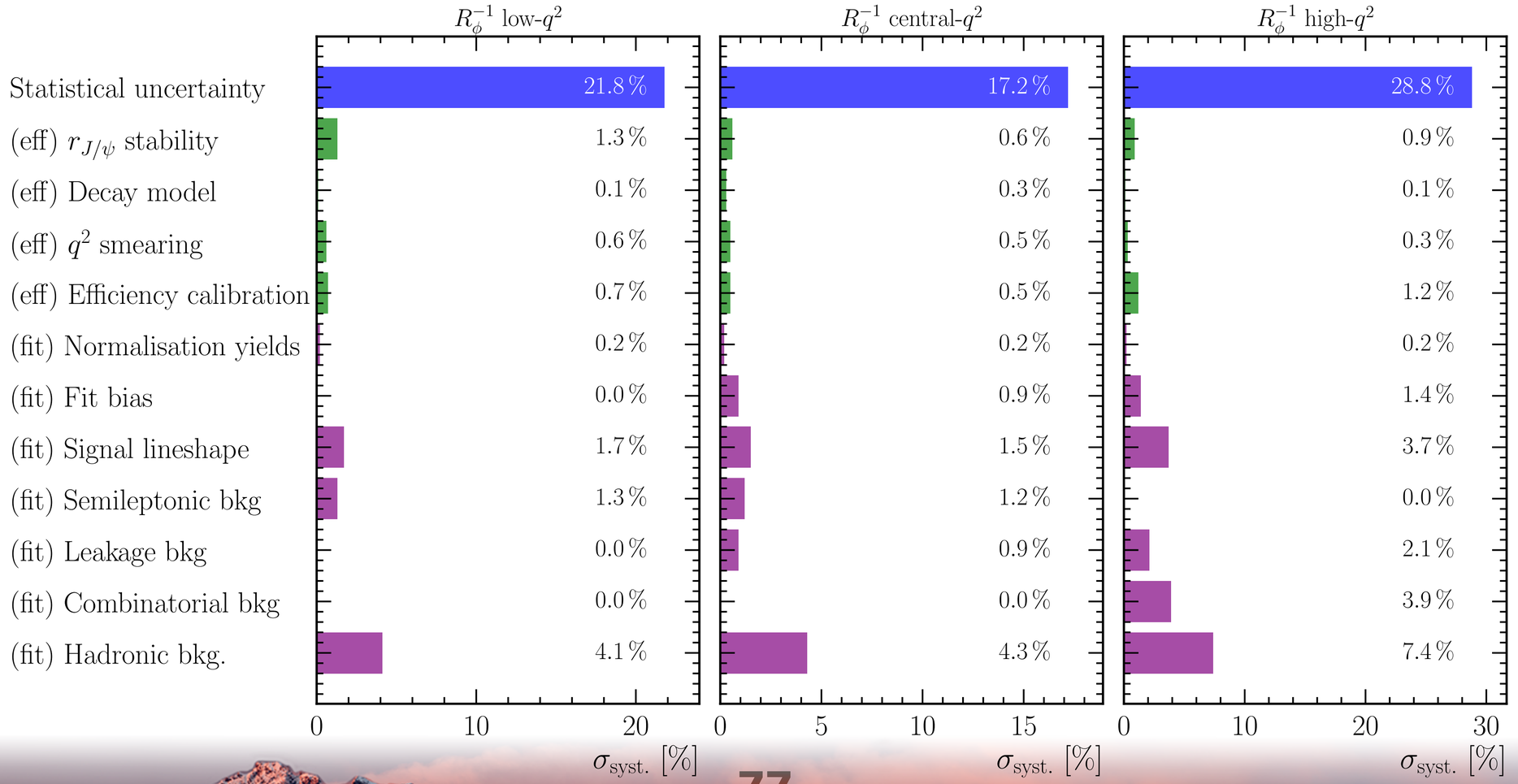

Photo: S. Schmitt

RESULTS

- Measurement is in **agreement with the SM predictions**

$$R_\phi^{-1}(\text{low} - q^2) = 1.57\,^{+0.28}_{-0.25} \pm 0.05$$

$$R_\phi^{-1}(\text{central} - q^2) = 0.91\,^{+0.20}_{-0.19} \pm 0.05$$

$$R_\phi^{-1}(\text{high} - q^2) = 0.85\,^{+0.24}_{-0.23} \pm 0.09$$

- Presence of local minimum at low-q^2
  - Fully visible in more dimensions

⇒ Likelihood is non-Gaussian

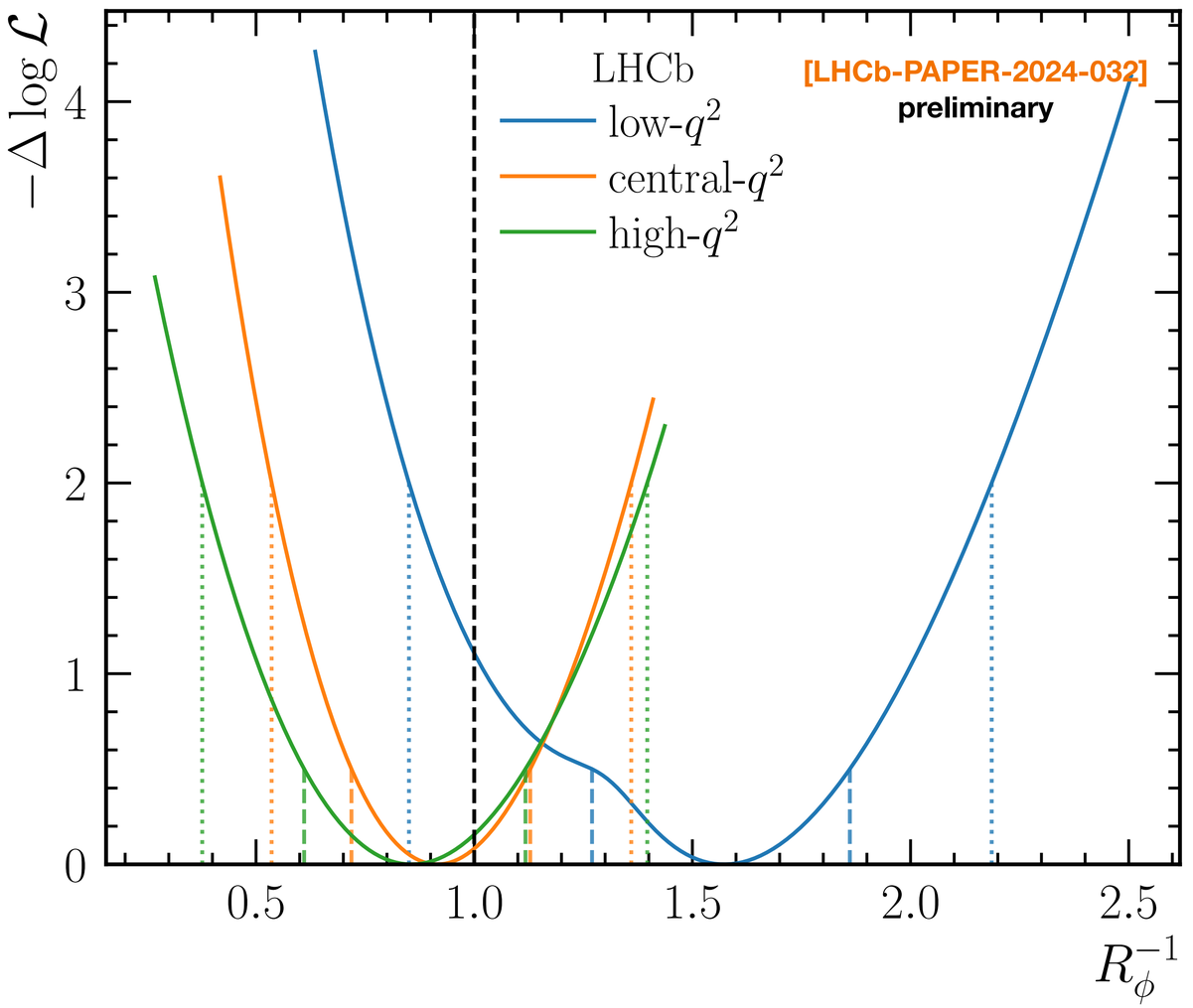

Photo: S. Schmitt

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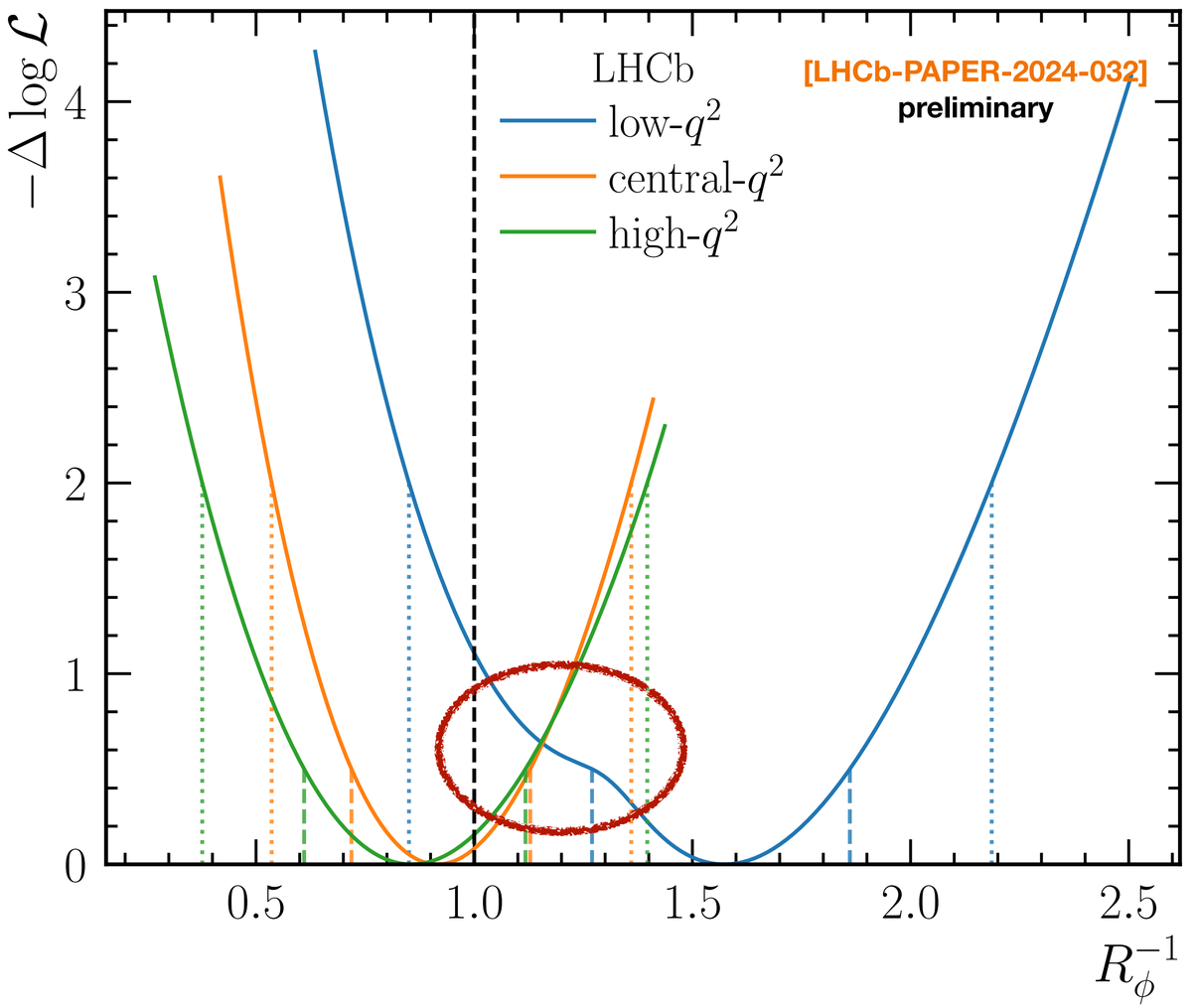
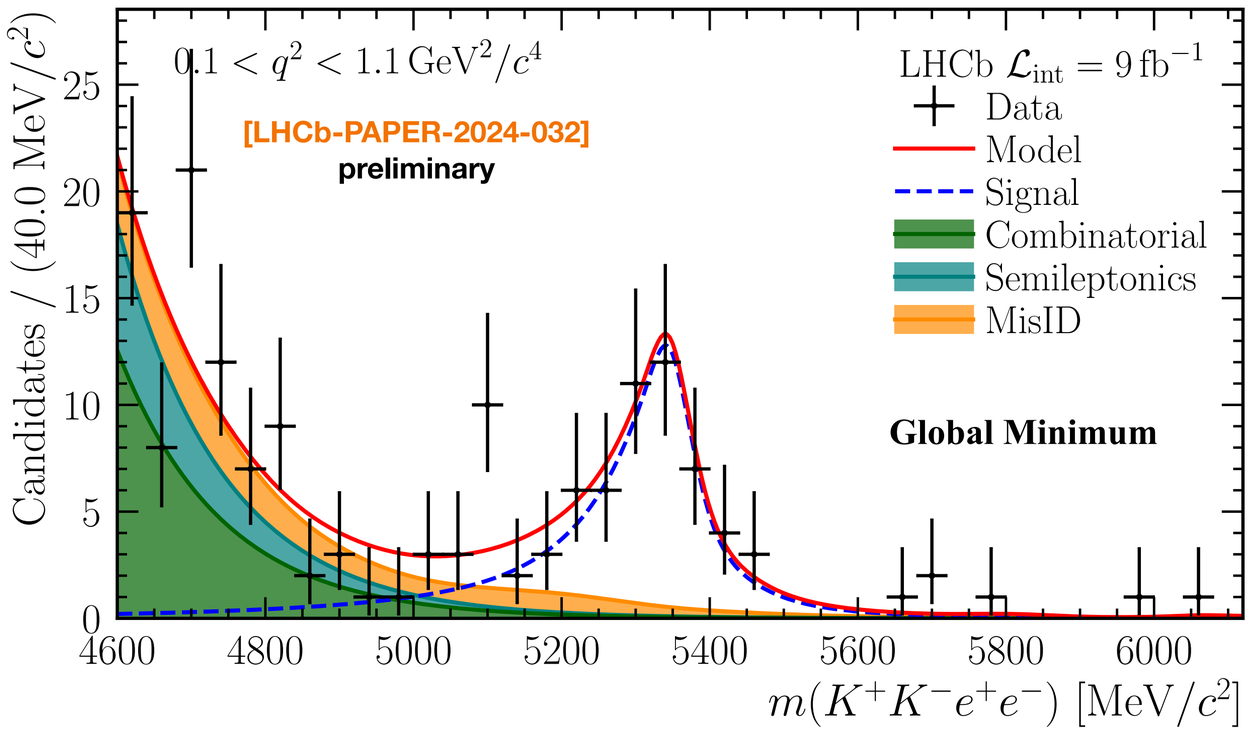


Photo: S. Schmitt

Secondary Minimum at low-q^2

- Local minimum characterised by **flatter combinatorial**



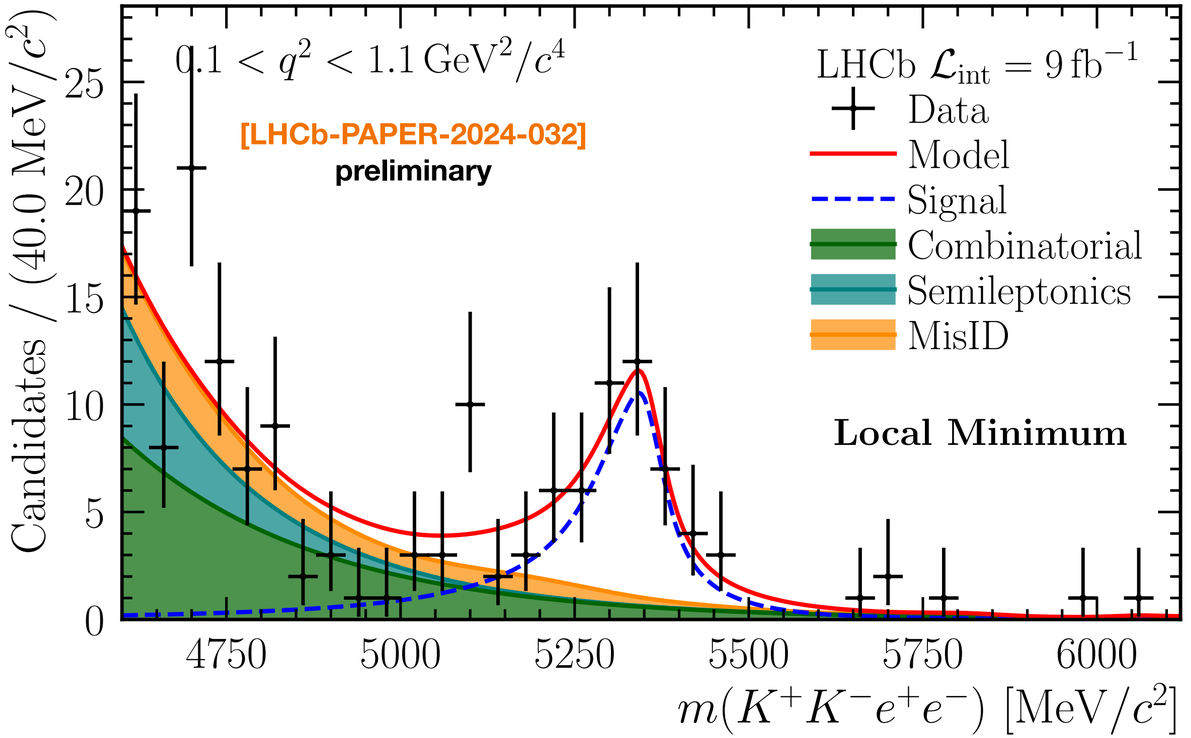
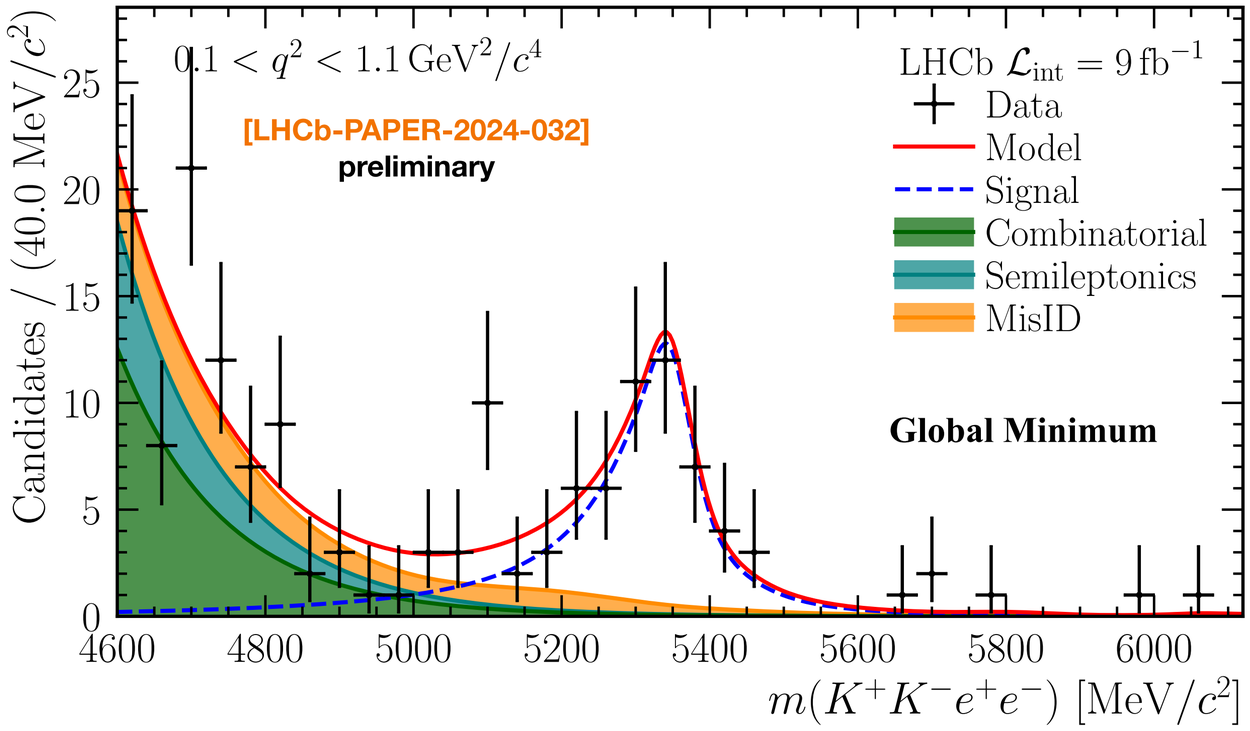


Photo: S. Schmitt

Secondary Minimum at low-q^2

- Local minimum characterised by **flatter combinatorial**
- Variations of analysis choices affect which minimum is global



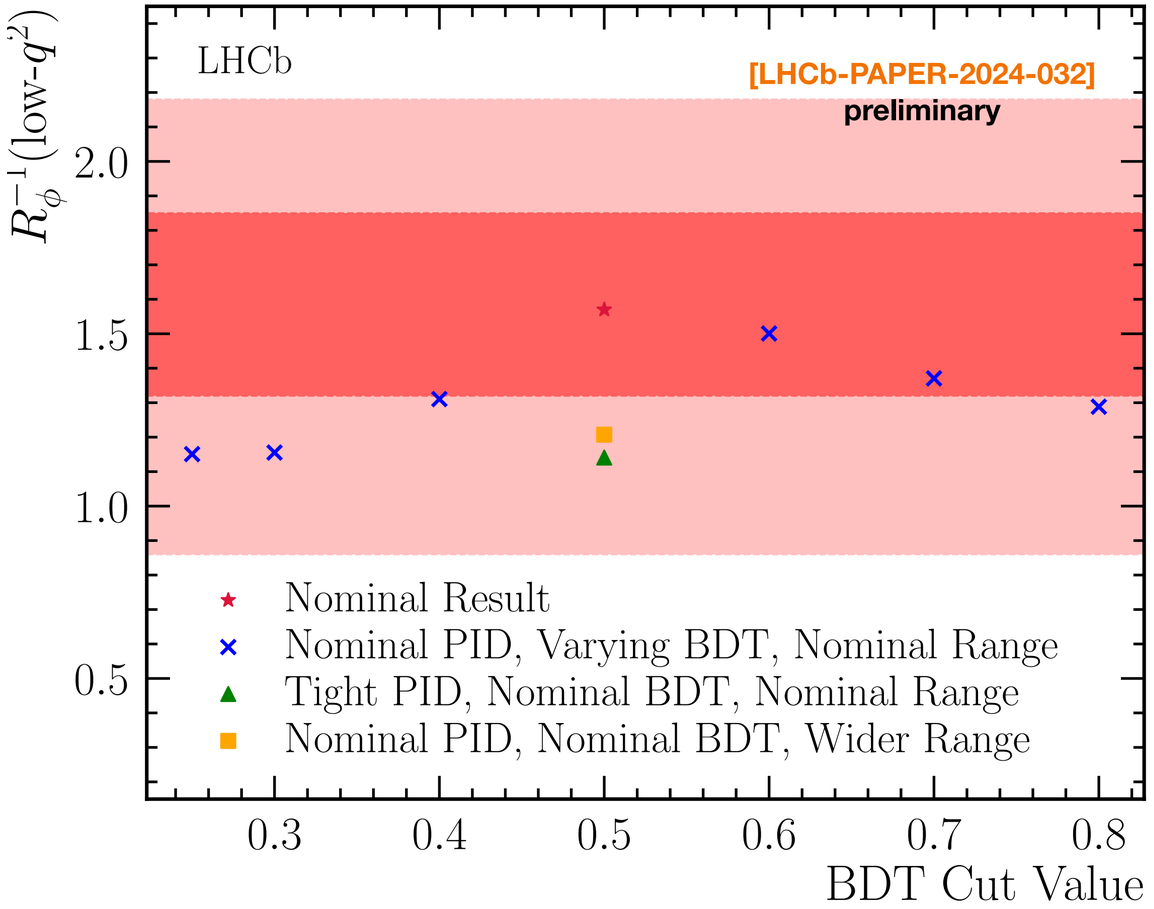


Photo: S. Schmitt

Branching Fractions

- Branching fraction extracted from R_ϕ^{-1} measurement
- $\mathcal{B}(B_s^0 \to \phi e^+ e^-)$ agrees with the SM and the measured $\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)$
- Low-q^2 slightly above the $\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)$ measurement
- Deviation in central-q^2 similar for both modes

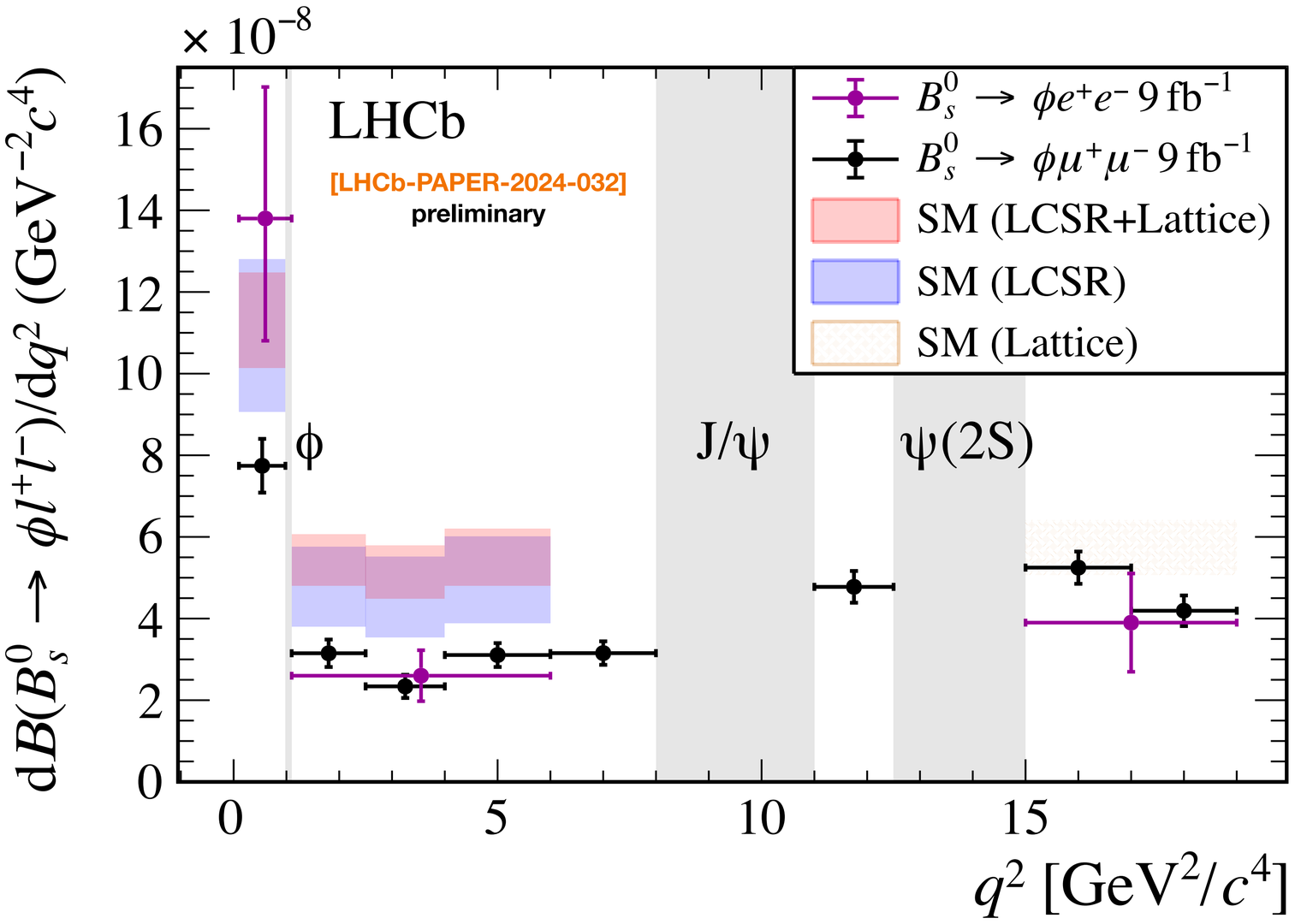


Photo: S. Schmitt

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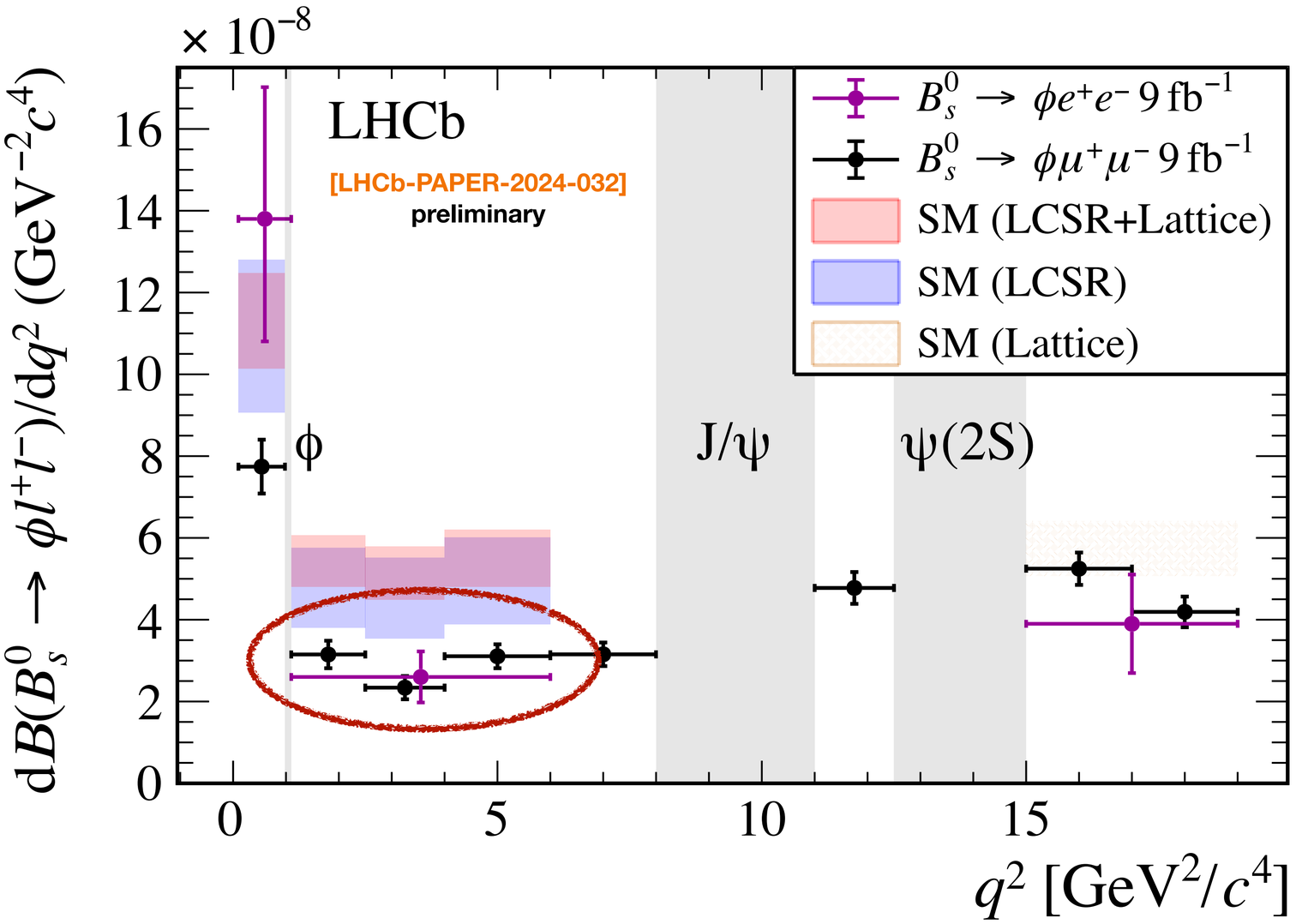


Photo: S. Schmitt

Conclusion

- A lot of **firsts**!
  - **First LFU test at high-q^2 for LHCb**
  - **First LFU test in B_s^0 decays**
  - **First observation of $B_s^0 \to \phi e^+ e^-$**
- **Most precise LFU test at high-q^2**
- Results are in **good agreement** with the SM

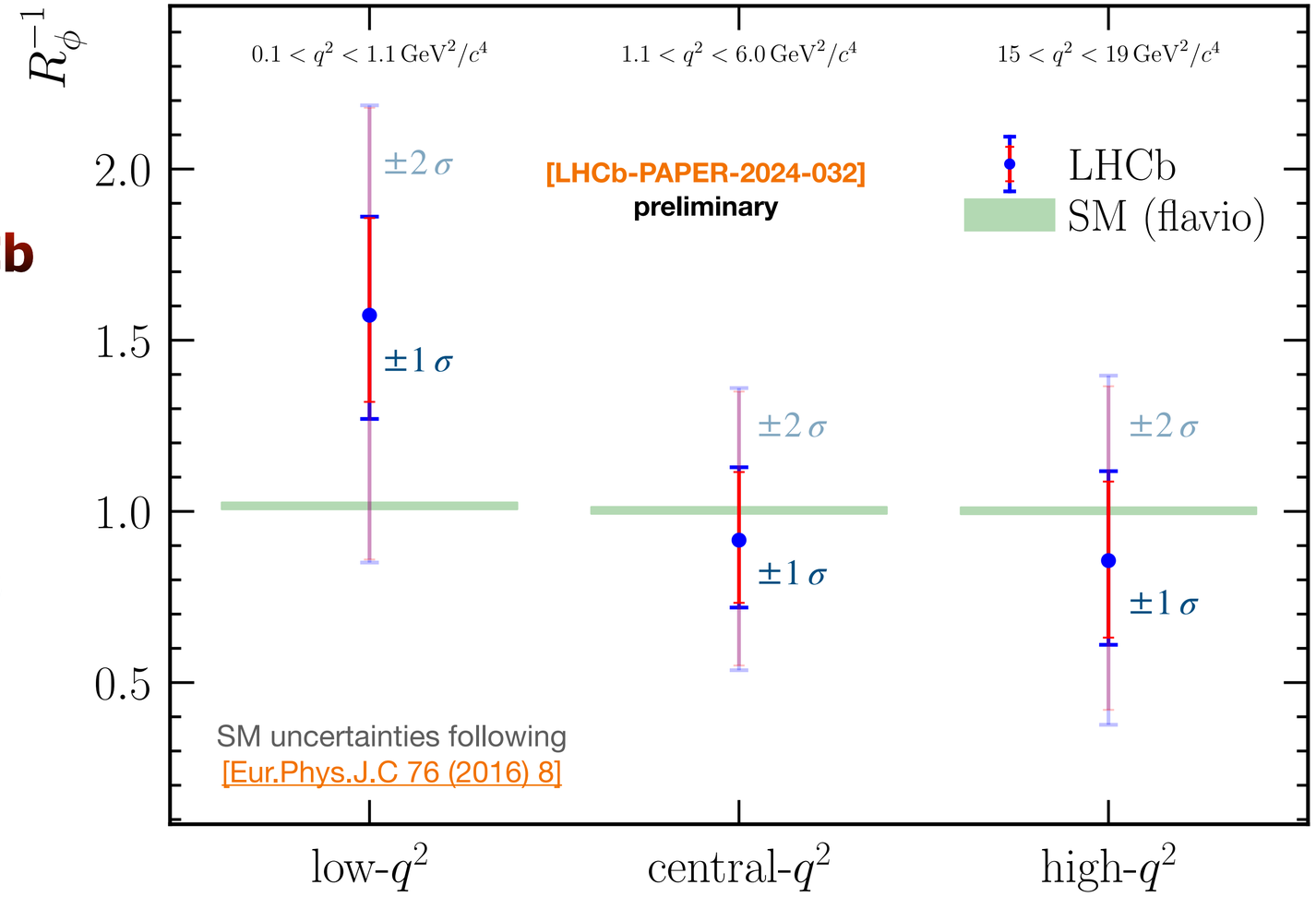


Photo: S. Schmitt

Outlook

- $b \to s\ell\ell$ transitions are **powerful probes** of the SM
- LFU tests are the most **precisely predictable** observables
- Data favour flavour universality in B^+, B^0, and B_s^0 decays
- With Run 3 and 4 LHCb will increase the number of recorded B_s^0 decays by a **factor of about 5**
  - **Removal of L0**-trigger drastic **improvement** for electrons!
  - **Unprecedented precision** for flavour observables
  - Systematic uncertainties for R_ϕ will **reduce with data sample size**
- Upgrade II aims to collect $\mathscr{L}_{\text{int}} \approx 300\,\text{fb}^{-1} \Rightarrow$ increase of factor ~ 6 compared to Run 3 and 4!
- **Tensions** in the branching fractions and angular observables **remain** but seem to be lepton flavour universal

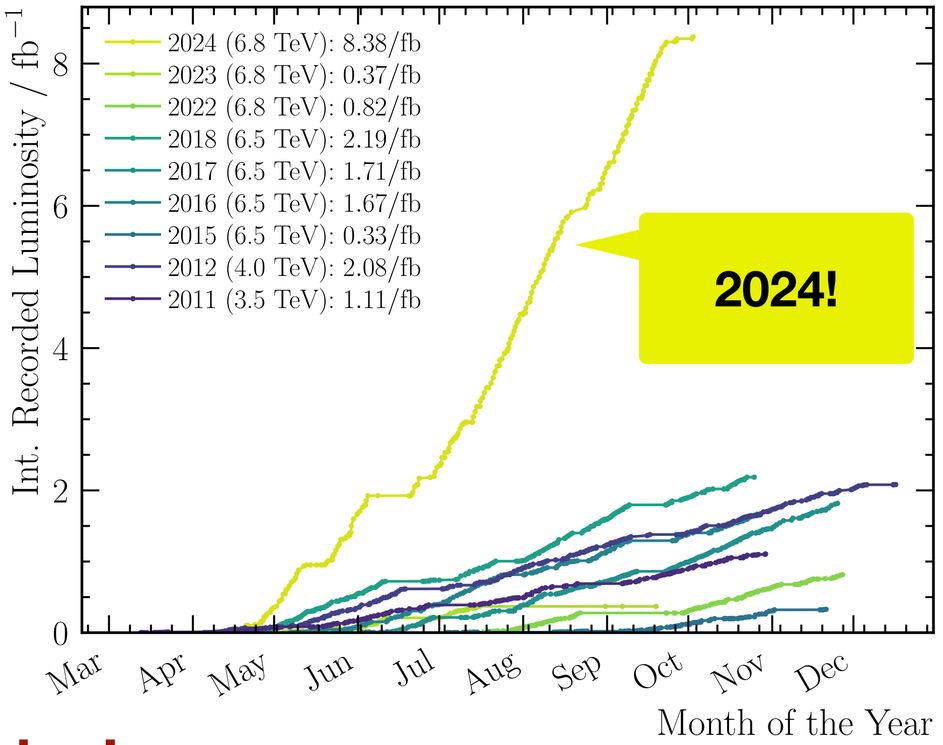


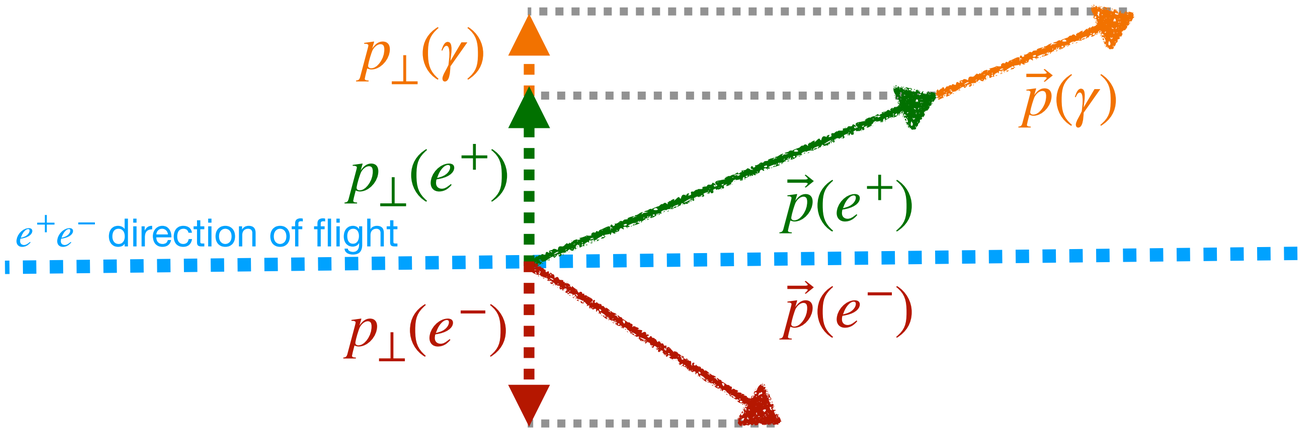
Photo: S. Schmitt

Thank you for Listening!

Photo: Sebastian Schmitt

Over Reconstructed Bremsstrahlung

- Inclusively suppress over reconstructed γ using multivariate classifier
- Leverage ratio of bremsstrahlung momentum to electron momentum
- Momentum asymmetries and isolation of the tracks



Missing energy evaluated from ratio of momenta

$$\alpha = \frac{p_\perp(e^+) + \sum p_{\perp,i}(\gamma_{e^+})}{p_\perp(e^-) + \sum p_{\perp,i}(\gamma_{e^-})}$$

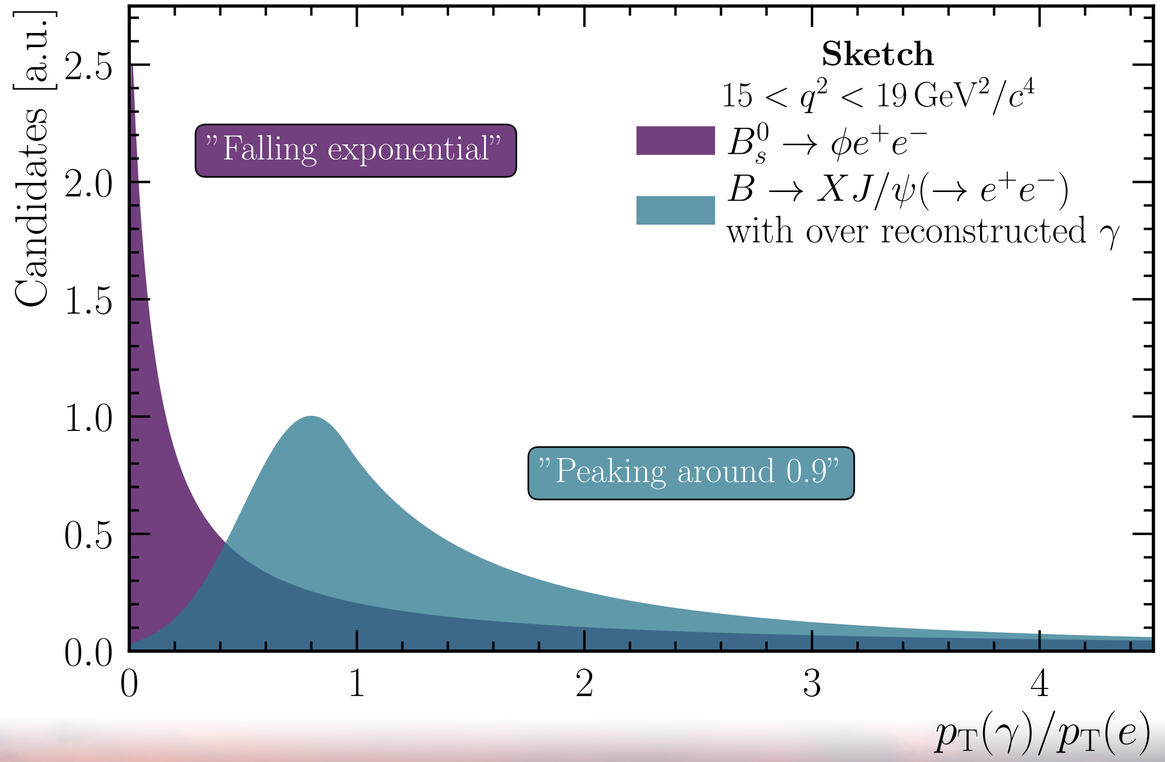
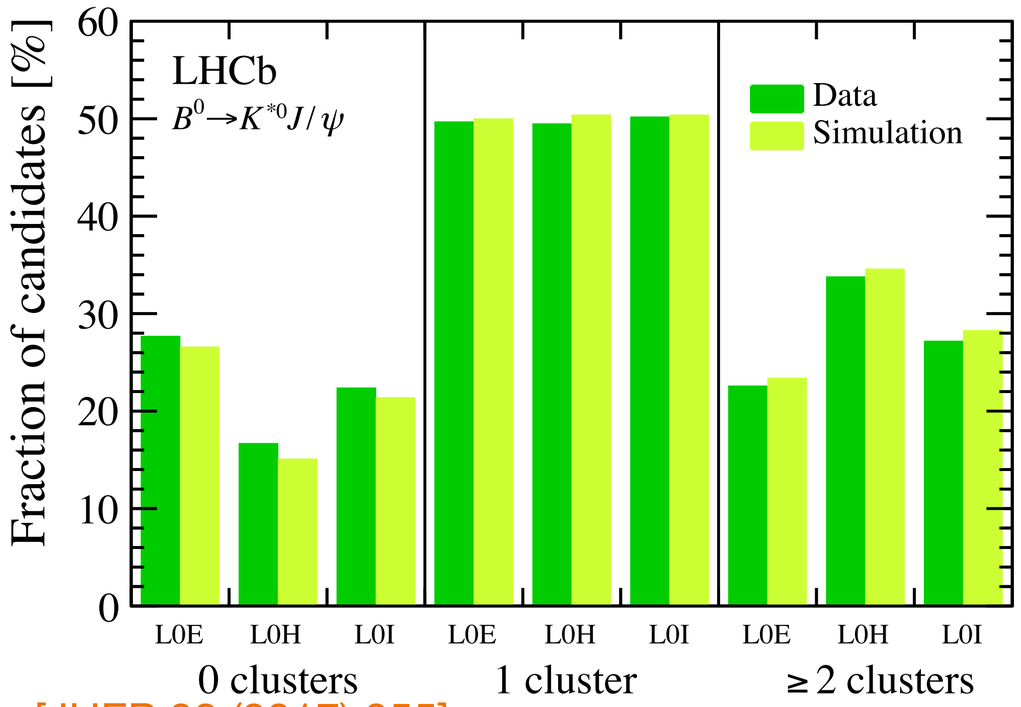


Photo: S. Schmitt

Bremsstrahlung and Shapes

- Different bremsstrahlung categories:
  - Brem-0: 0 clusters added
  - Brem-1: 1 cluster added
  - Brem-2: 2 or more clusters added



[JHEP 08 (2017) 055]

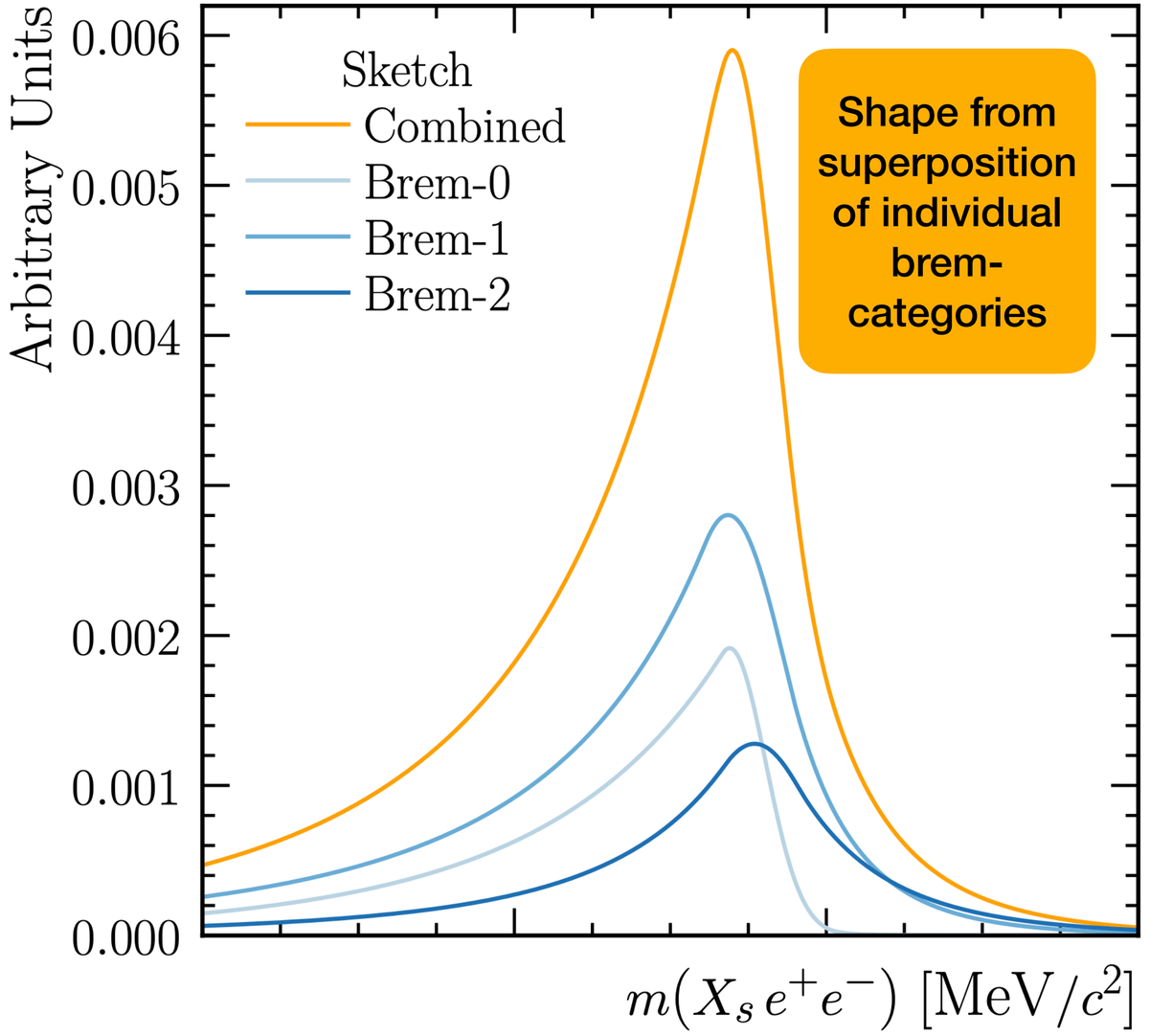


Photo: S. Schmitt

Extended Mass Range Fit

- Demonstrate knowledge of full spectrum down to low $K^+K^-\ell^+\ell^-$ masses
- Considered all contributions when asserting leakage for high-q^2

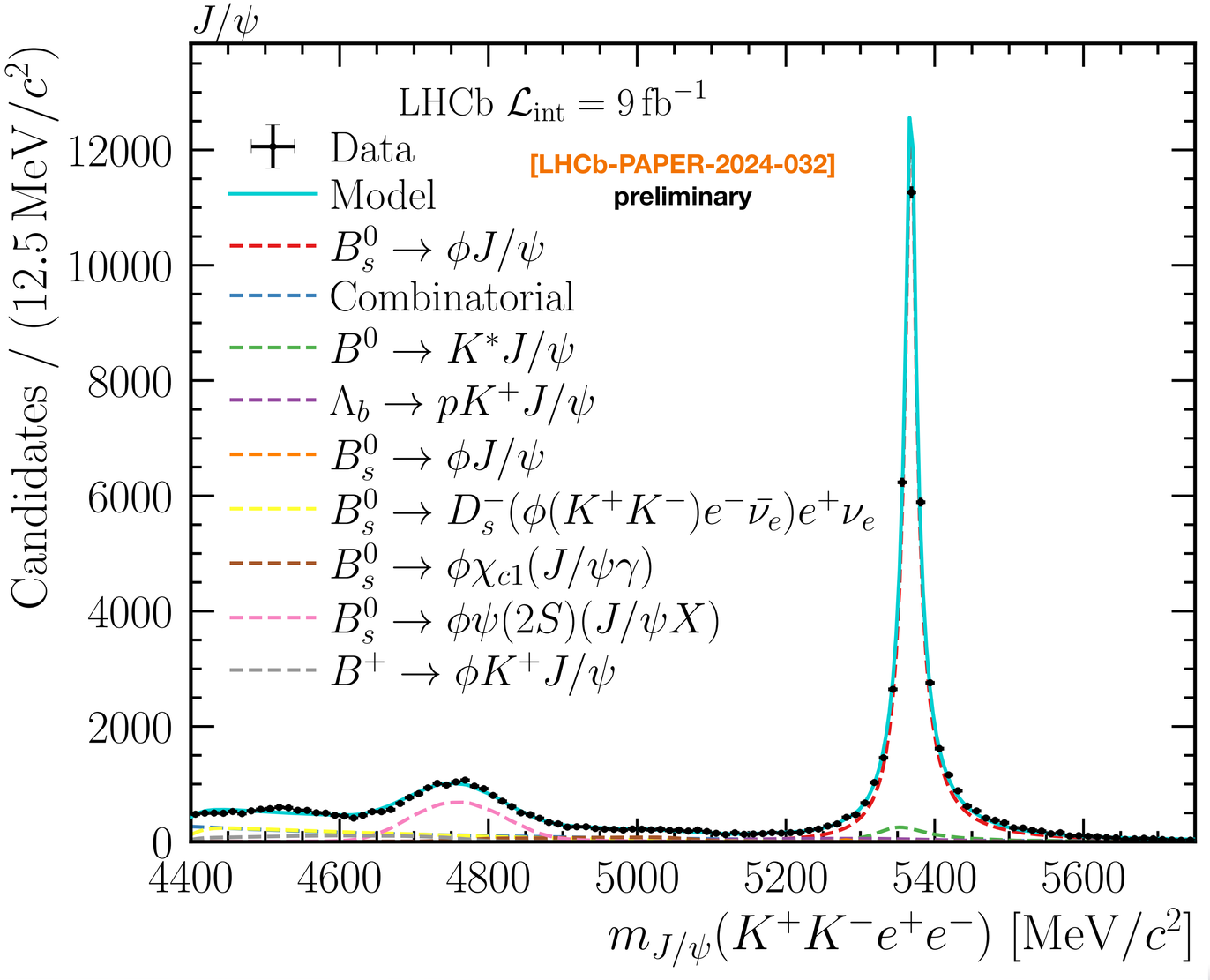
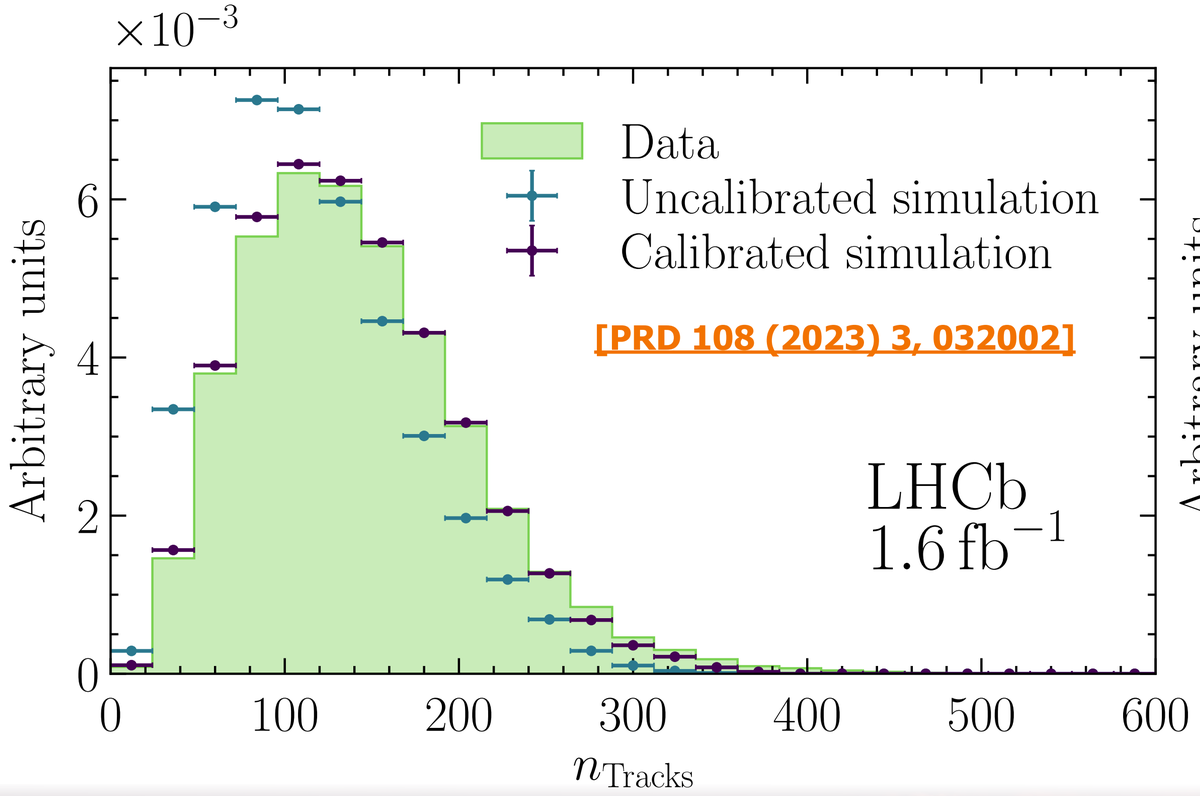


Photo: S. Schmitt

Simulation Calibration Gen + Reco

- Calibrated using $B_s^0 \to \phi J/\psi$ decays, similar procedure as [PRD 108 (2023) 3, 032002]
- Calibrated with BDT reweighter, background subtraction performed using ${}_sW$eighting



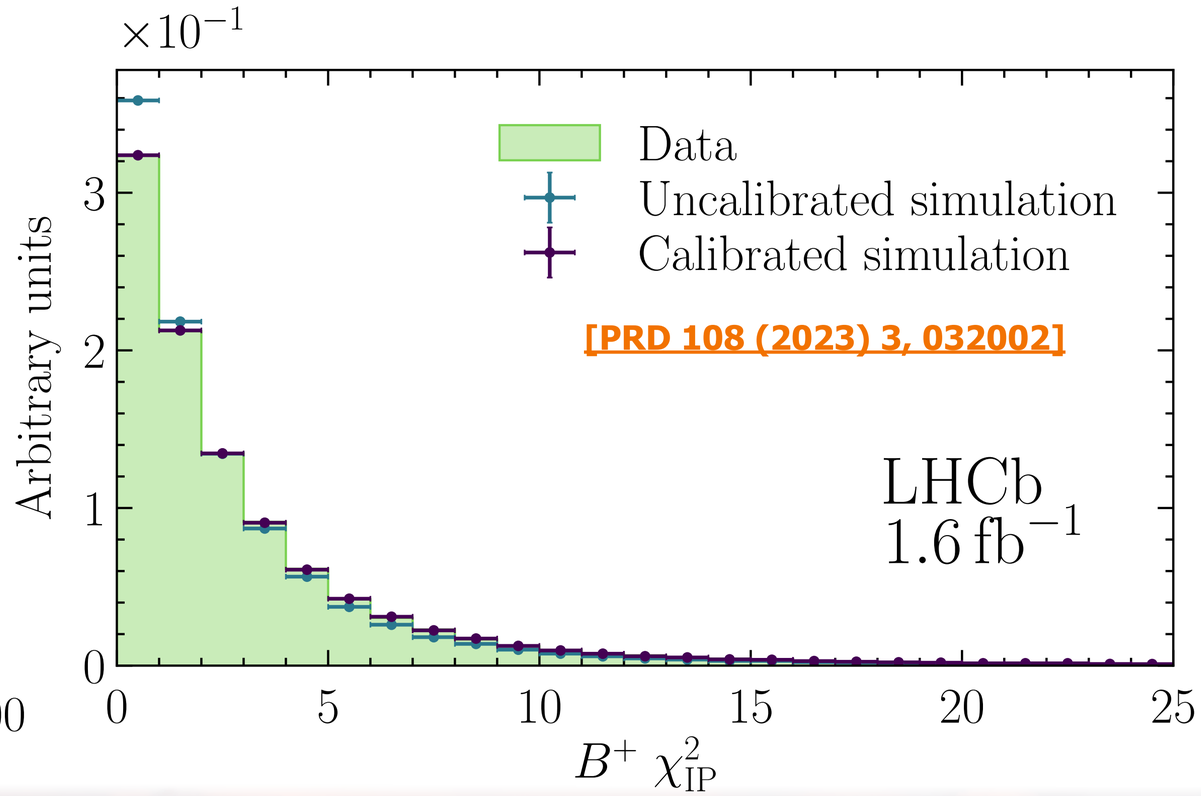
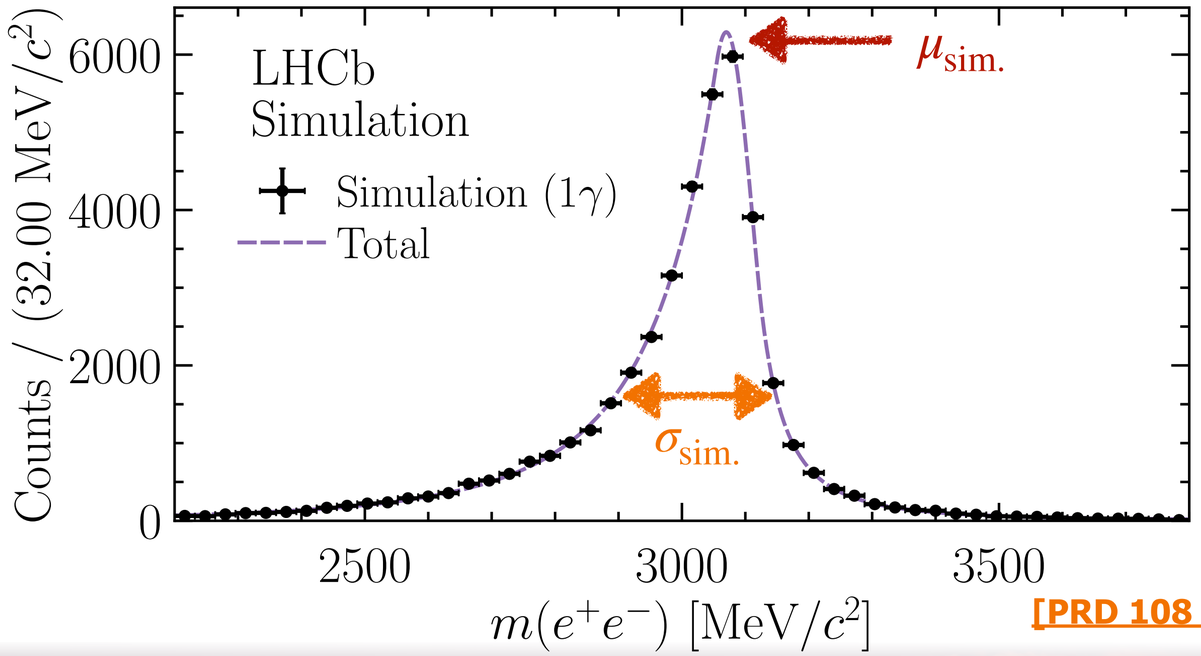


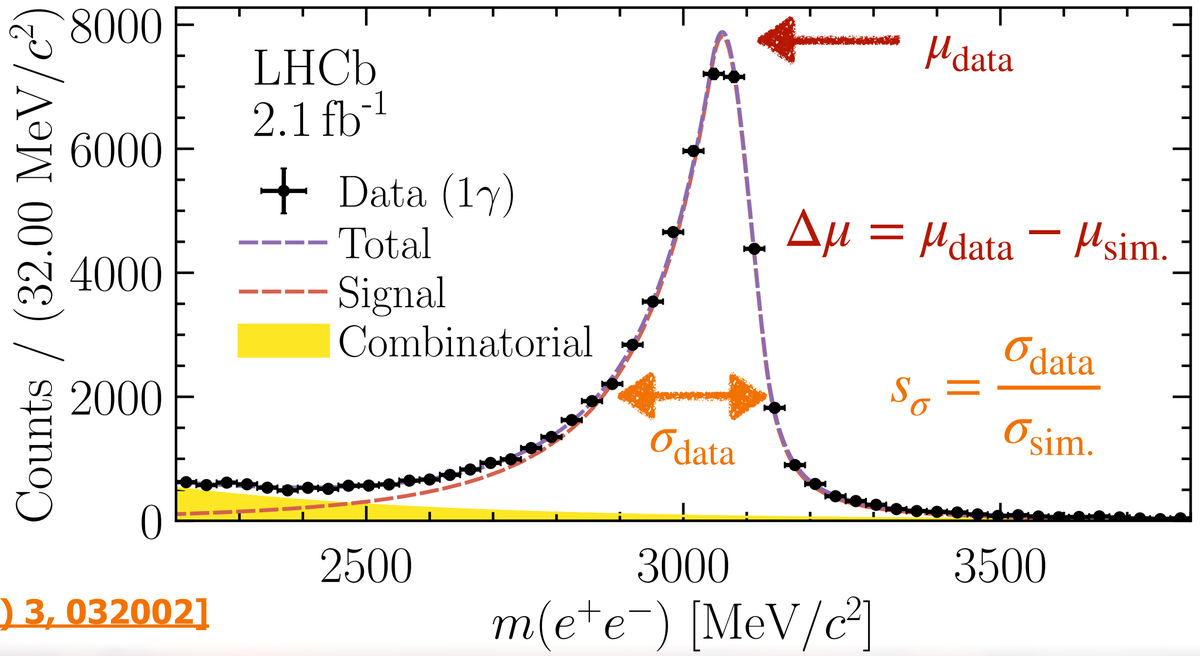
Photo: S. Schmitt

Dilepton Mass Calibration

- Extracted from fits to $B_s^0 \to \phi J/\psi(\to e^+e^-)$ data and simulation
- Determine width scale s_σ and mean shift $\Delta\mu$ to compute corrected mass
- $m^{\text{corr.}} = m^{\text{true}}_{\text{pre FSR}} + s_\sigma(m^{\text{sim.}} - m^{\text{true}}_{\text{pre FSR}}) + \Delta\mu + (1-s_\sigma)(\mu^{\text{sim.}} - m^{\text{pdg}}_{J/\psi})$

Depending on number of bremsstrahlung γ associated with candidate





[PRD 108 (2023) 3, 032002]

Photo: S. Schmitt

Misidentified Electron Backgrounds

- Strategy follows [PRD 108 (2023) 3, 032002]
- **Calibration sample** with $D^{*-} \to \overline{D}^0(\to K^+\pi^-)\pi^-$ decays
  - High purity and sample size
- **Transfer function:** $\frac{\text{Pass}}{\text{Fail}}$ in bins of p_T, η, L0-trigger decision
- **Validated** using $D \to K\pi$ decays in $B^0_s \to \phi e^+e^-$ data
  - Can be isolated when removing selection requirements

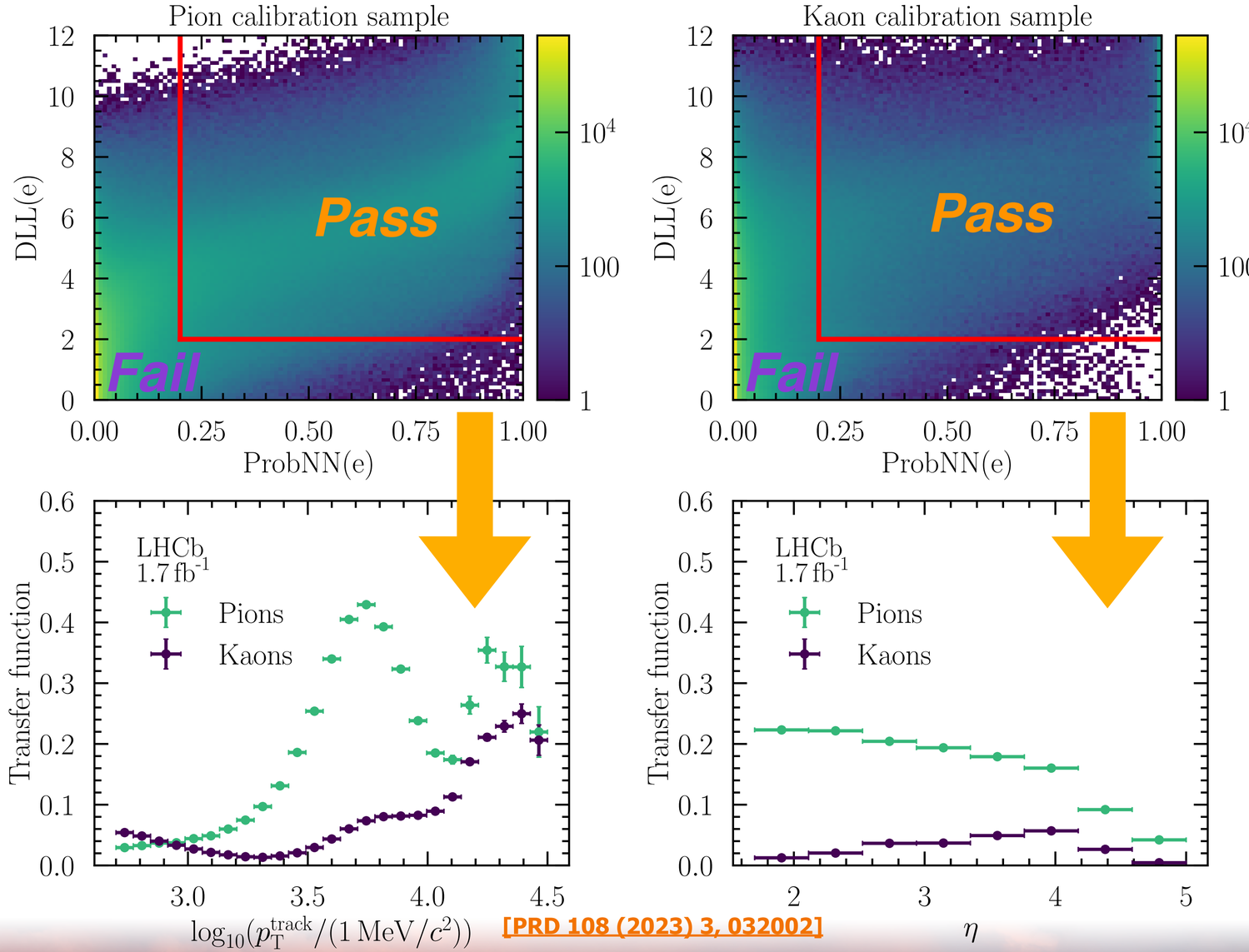


Photo: S. Schmitt