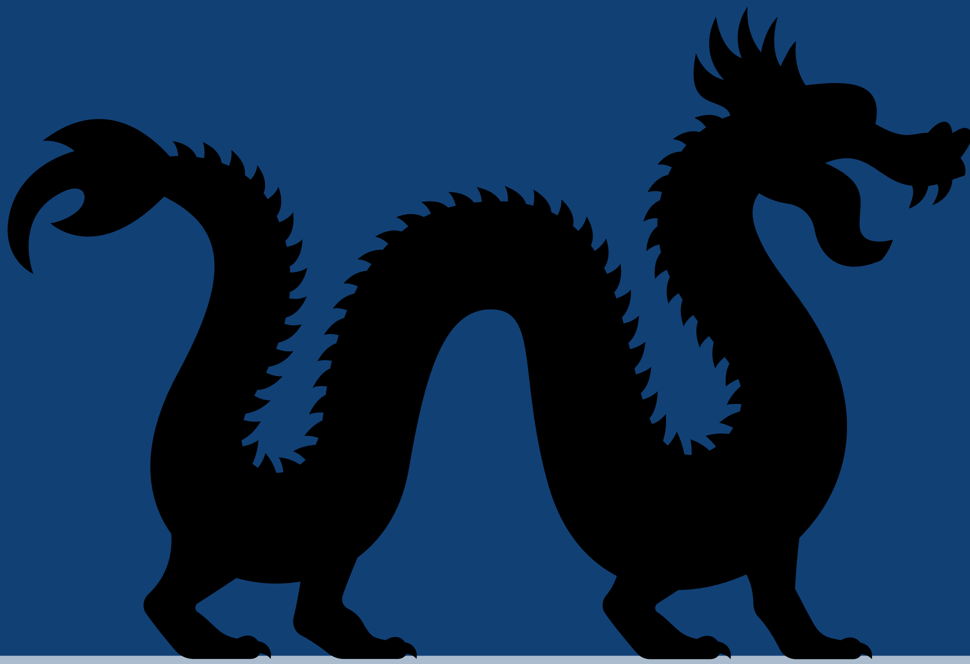
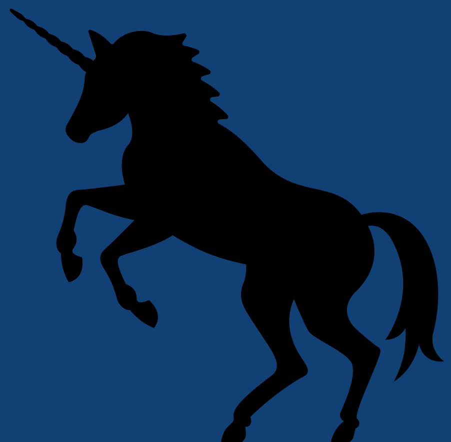


Semi-tauonic B-meson decays at Belle and Belle II



Florian Bernlochner

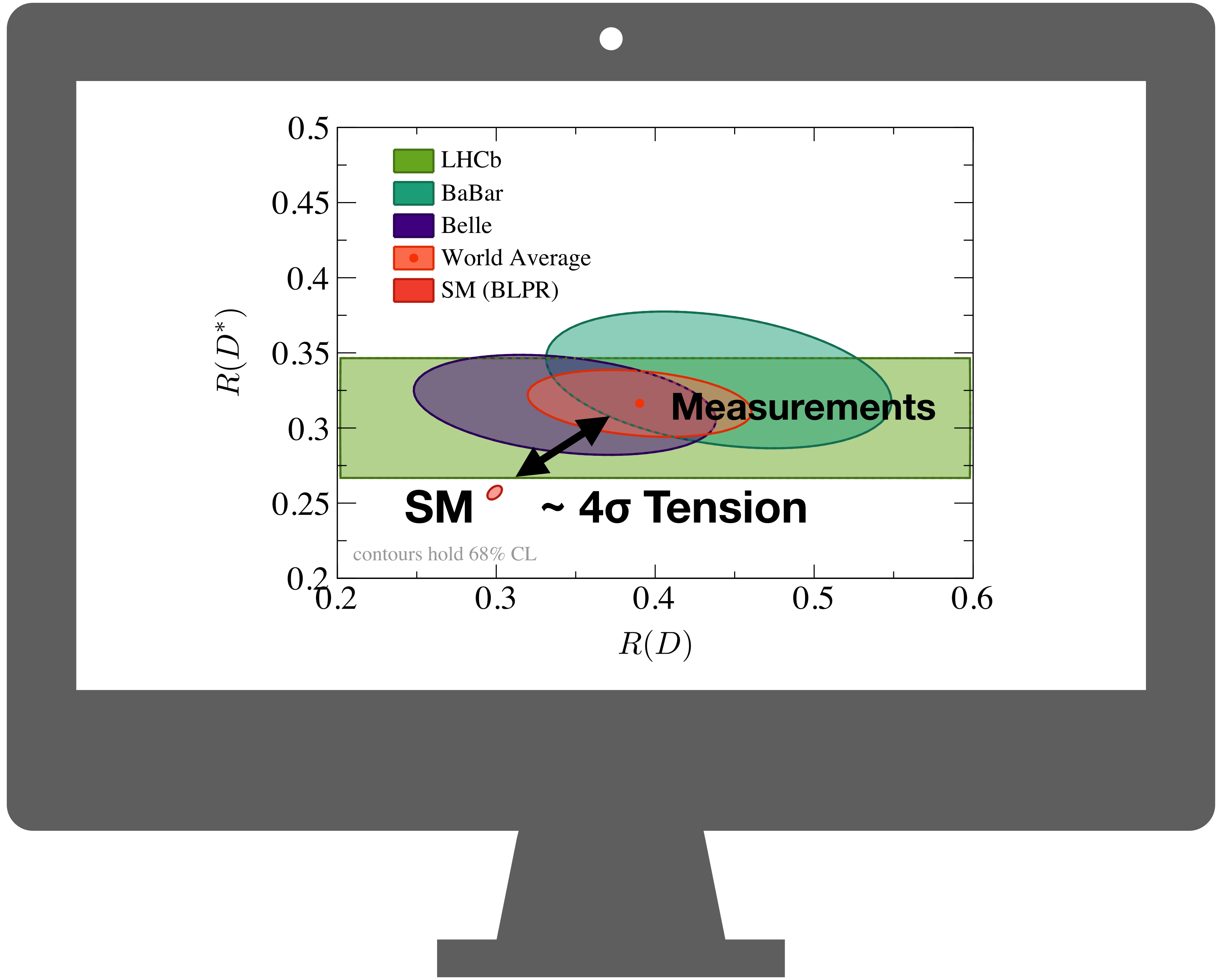
KEK-FF, February 2019

$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

$\ell = e, \mu$

$\downarrow$

$$R(D^{(*)}, \pi, J/\psi)$$



1. How do we measure these ratios at Belle?

2. Potential at Belle II

Belle

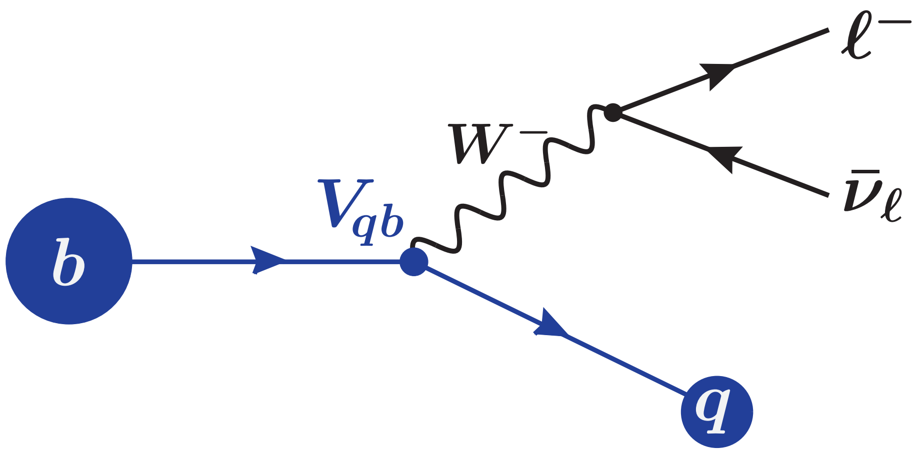
Overview

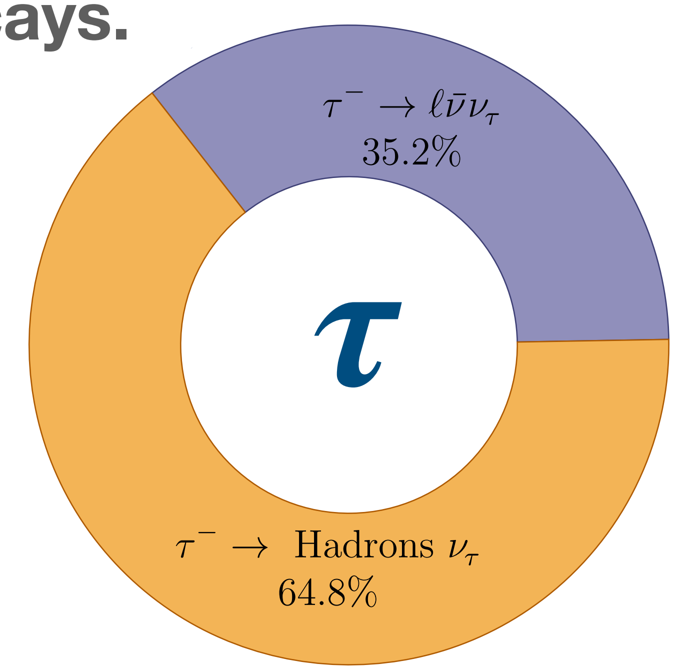
$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

$\ell = e, \mu$

1. **Leptonic or Hadronic τ decays?**

Some properties (e.g. τ **polarisation**) **only accessible** in **hadronic decays.**





2. **Albeit not necessarily a rare decay of O(%) in BF, TRICKY to separate from normalisation and backgrounds**

LHCb: **Isolation** criteria, **displacement** of τ, **kinematics**

B-Factories: Full reconstruction of event (**Tagging**), **matching topology, kinematics**

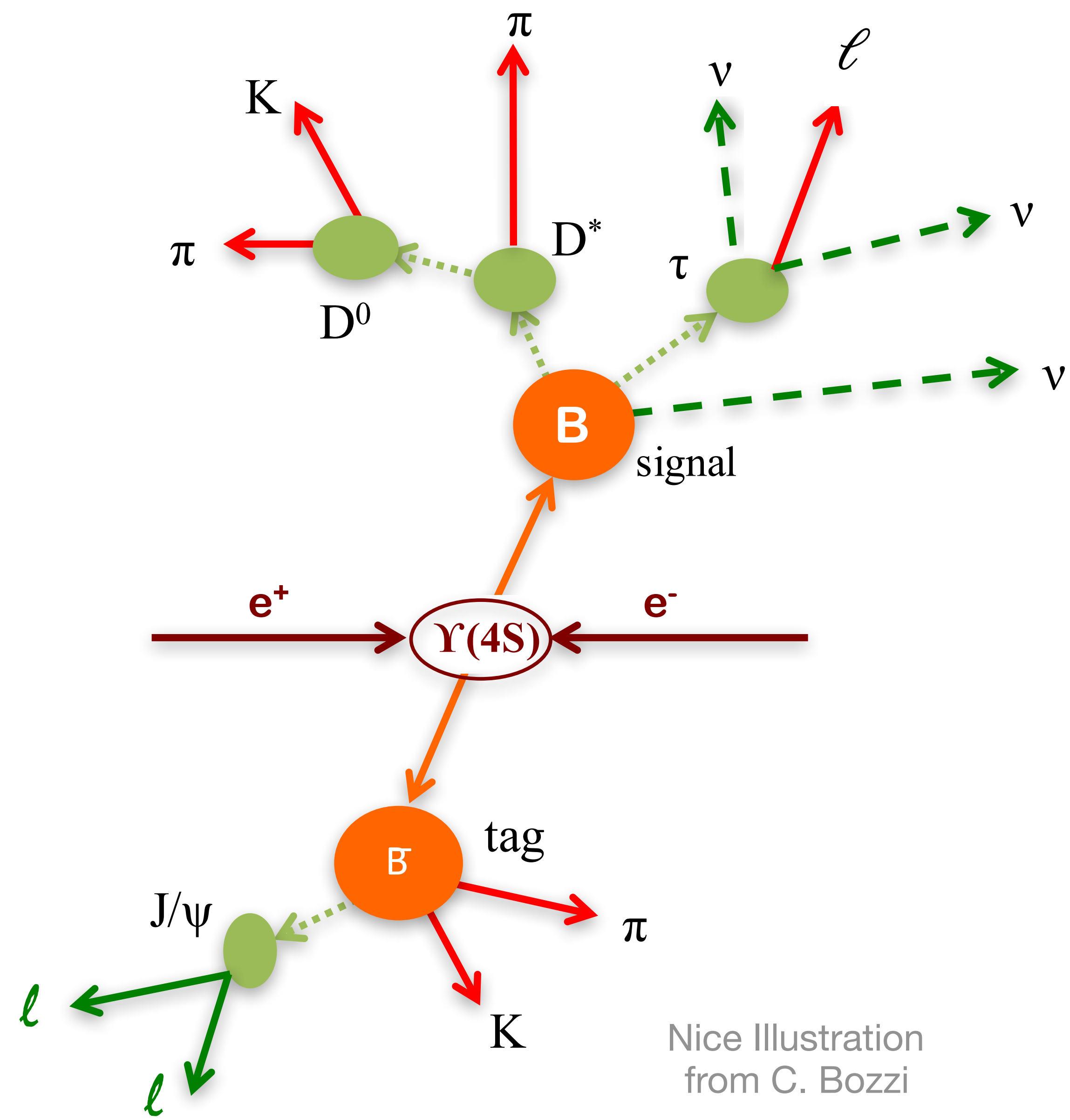
Hadronic Tagging

Tagging approach in a nut-shell:

- e+/e- collision produces ***Y(4S) → BB̄***
- Fully reconstruct one of the two B-mesons ('tag') → **possible** to measure **momentum** of signal B
- **Missing four-momentum** (**neutrinos**) can be reconstructed with high precision

$$p_{\rm miss} = (p_{\rm beam} - p_{B{\rm tag}} - p_{D^{(*)}} - p_{\ell})$$

✓ **Small efficiency (~0.2-0.4%) compensated by large integrated luminosity**



Nice Illustration from C. Bozzi

Hadronic Tagging

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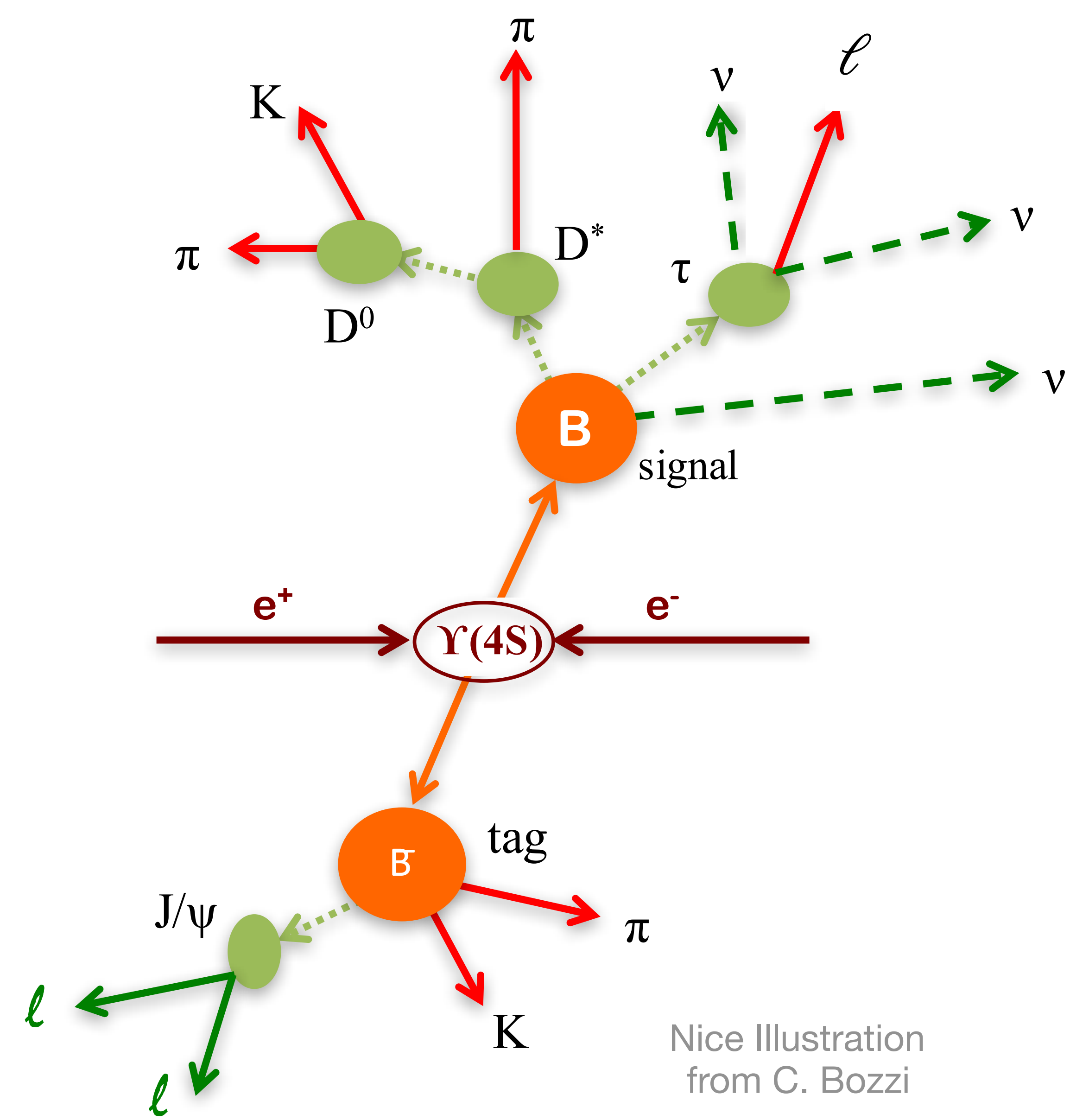

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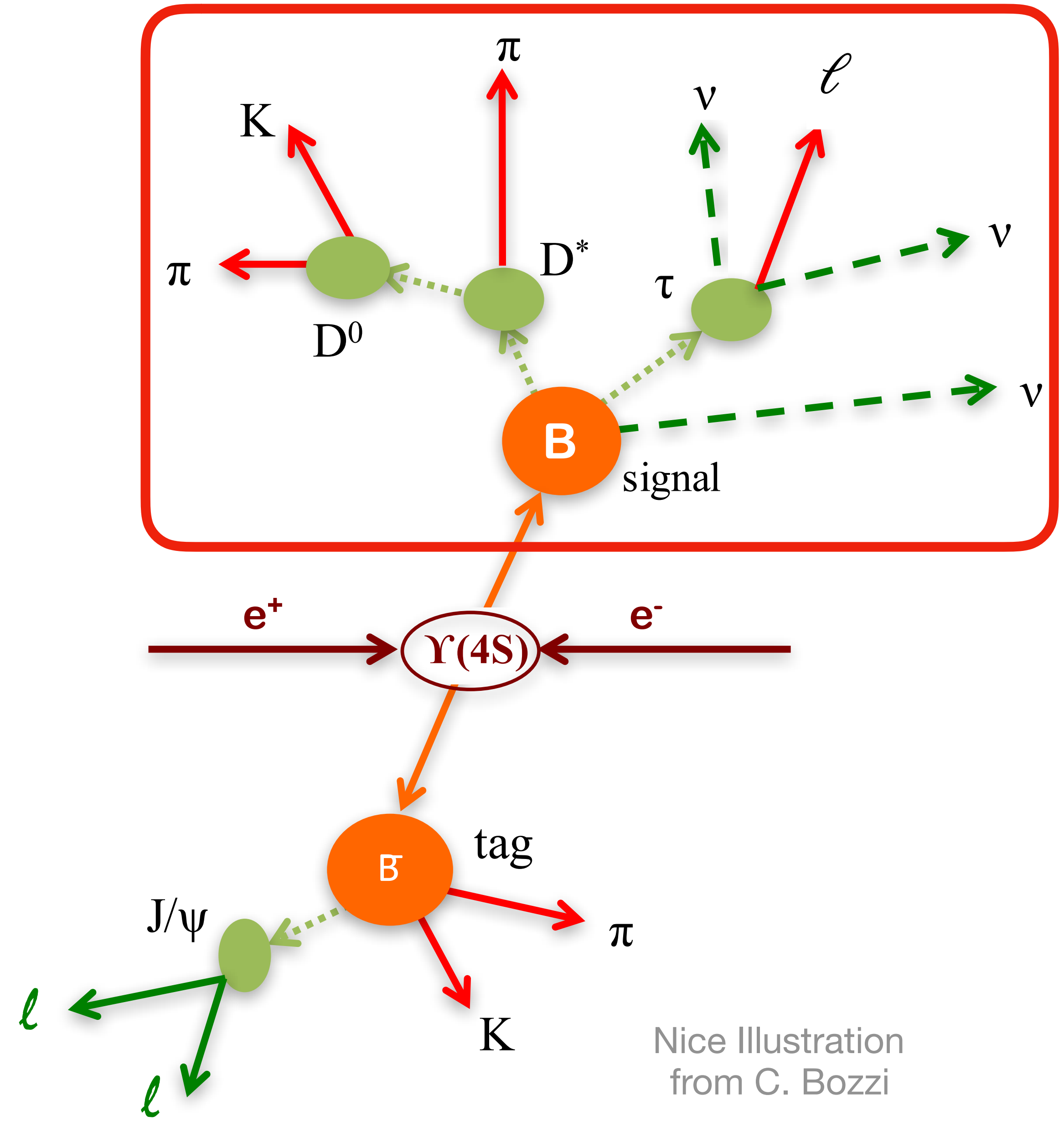
$$p_{\text{miss}} = (p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_{\ell})$$

✓ **Small efficiency (~0.2-0.4%) compensated by large integrated luminosity**

✓ **Demand matching topology**



Nice Illustration from C. Bozzi

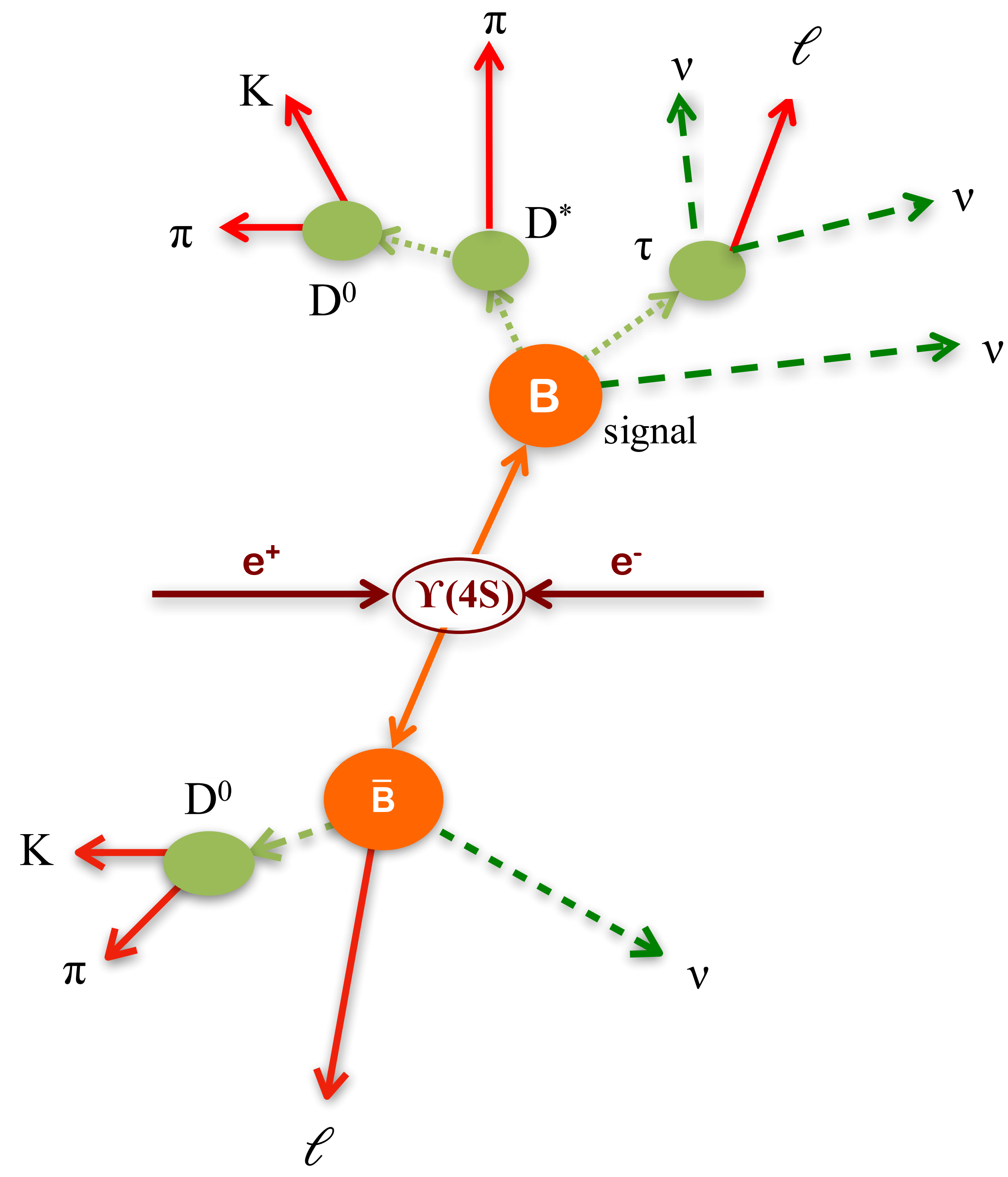
Semi-leptonic Tagging

Tagging approach in a nut-shell:

- e^+/e^- collision produces ***Y(4S) → BB***
- Fully reconstruct one of the two B-mesons ('tag') → **possible** to **assign all particles** to either signal or tagging B
- **Matching topology & Extra-energy from unassigned neutrals** powerful discriminator: E_{extra} or E_{ECL}

$$E_{\text{extra}} = E_{\text{ECL}} = \sum_i E_i^\gamma$$

✓ **Higher efficiency (~0.5-2%) but additional impurities and challenges**



Semi-leptonic Tagging

Tagging approach in a nut-shell:

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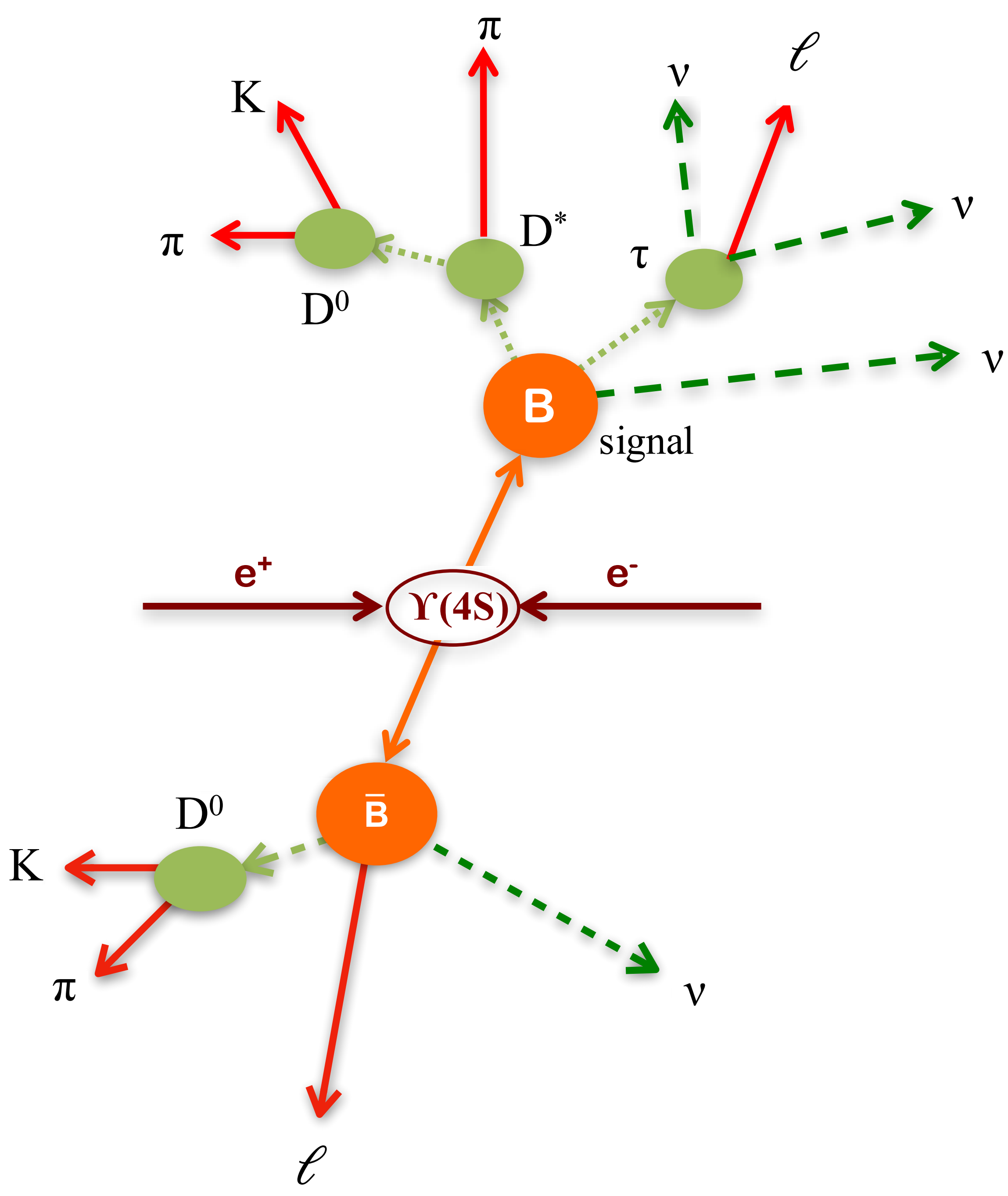
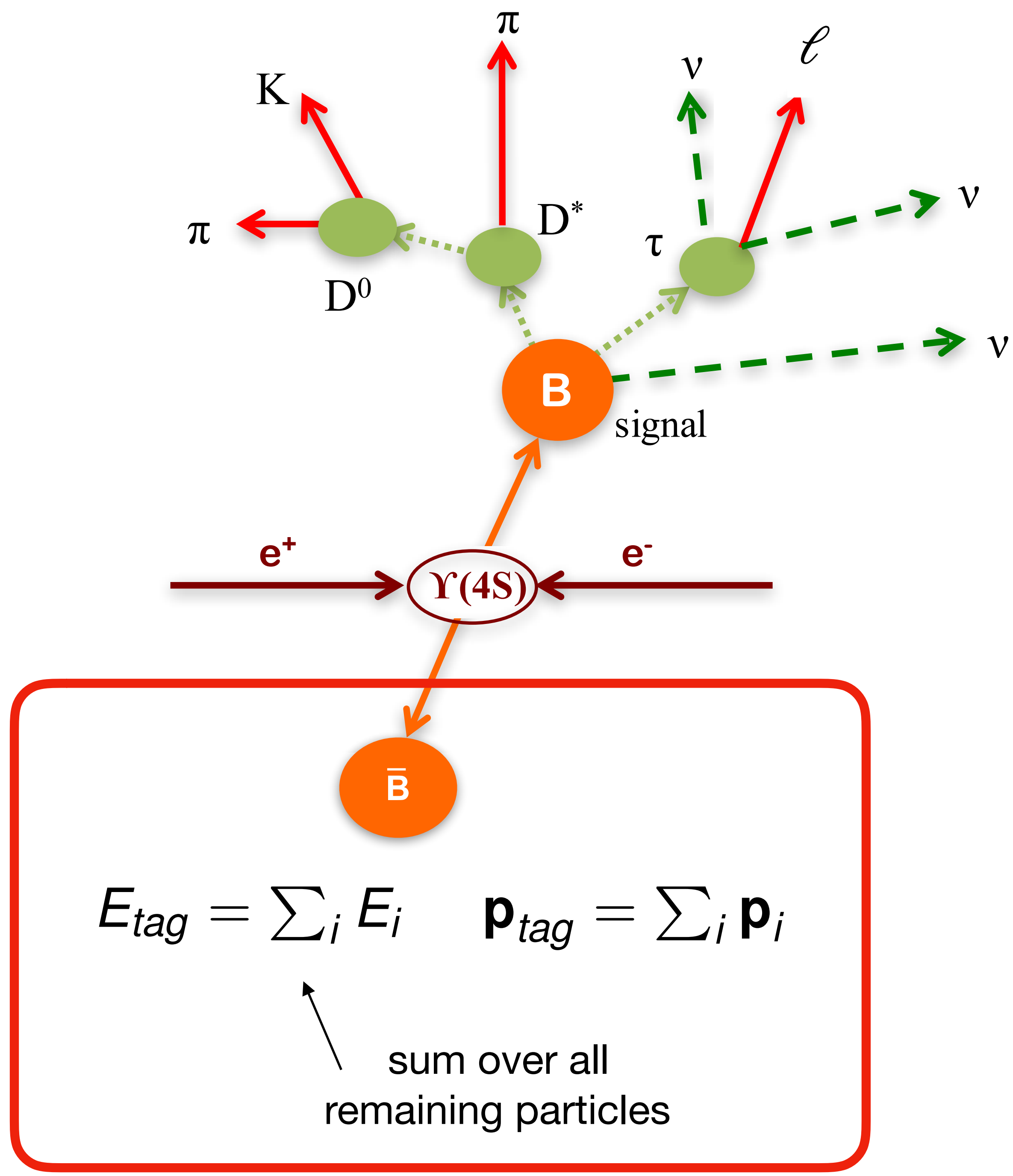


Inclusive Tagging

Tagging approach in a nut-shell:

- e^+/e^- collision produces ***Y(4S) → BB***
- Fully reconstruct one of the two B-mesons ('tag')
- **First** reconstruct **signal** side**; then** construct **tag** from **all** remaining **charged particles** and **calorimeter depositions**
- **Veto events with leptons** on tag side to maximize hadronic modes

✓ **Highest efficiency but also lowest purity**



Meet the "Measurement Matrix"

	Hadronic or inclusive tagging	SL tagging
Leptonic τ	✓	✓
Hadronic τ	✓	✗

⊗ Polarisation

Belle:
Phys.Rev.Lett.118,211801 (2017)
Phys. Rev. D 97, 012004 (2018)
(D* had tag)

⊗

$q^2 = (p_B - p_{D^{(*)}})^2$	p_{D^*} p_ℓ

⊗

D	D^*	π

Polarisation

LHCb:
Phys.Rev.Lett.115,111803 (2015)
(D*, Leptonic τ)
Phys.Rev.D 97, 072013 (2018)
Phys.Rev.Lett.120,171802 (2018)
(D*, Hadronic τ)

Belle:
Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)
Phys.Rev. D94,072007 (2016)
(D*, SL tag, p_{D^*}, p_l)

Belle:
Phys. Rev. D 93, 032007 (2016)
(π had tag)

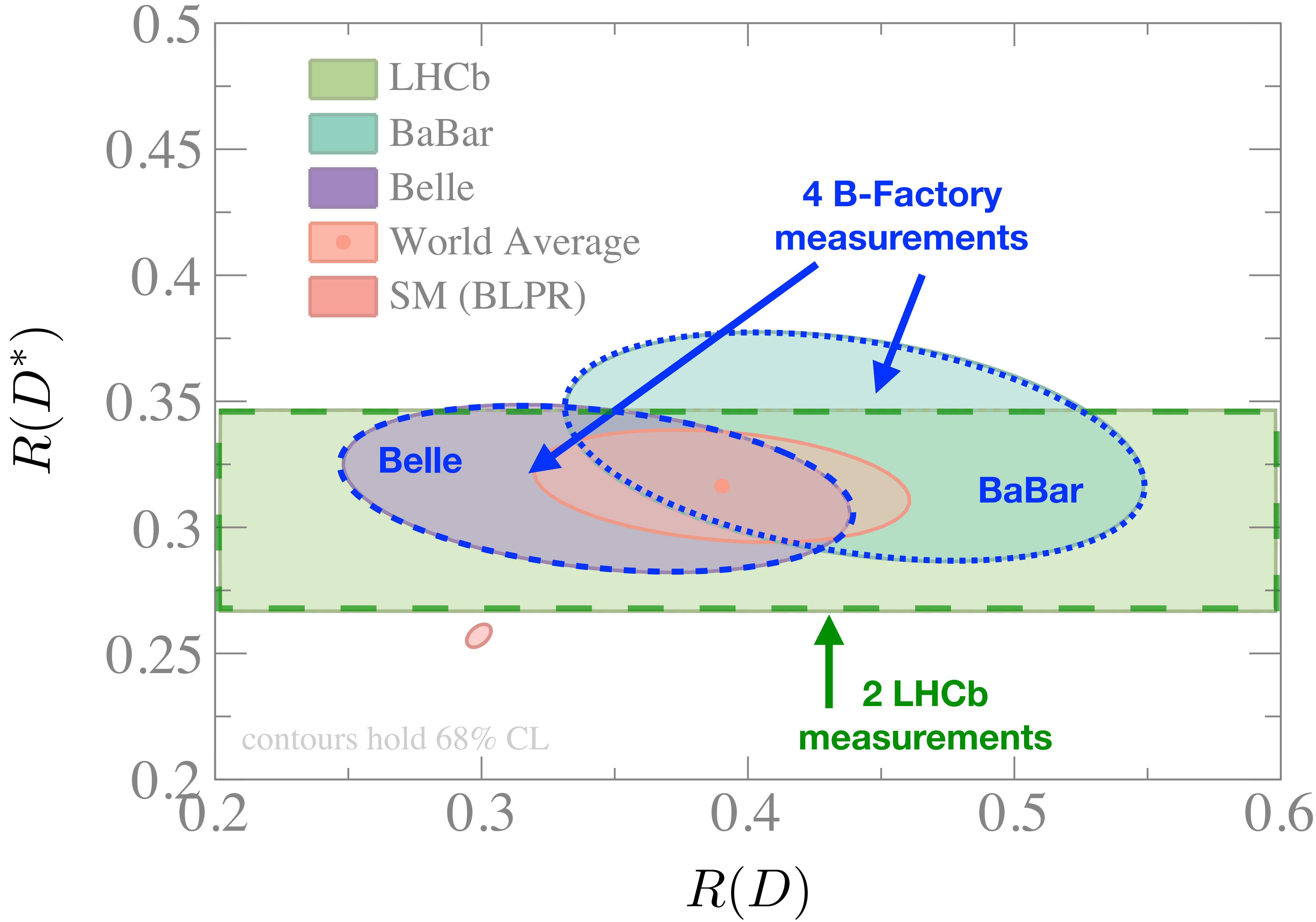
BaBar:
Phys.Rev.Lett. 109,101802 (2012)
Phys.Rev.D 88, 072012 (2013)
(D/D* had tag, q^2)

New!

Prel. Belle: https://arxiv.org/pdf/1901.06380.pdf (D*, incl. tagging)

& older work, e.g.

Belle:
Phys.Rev. D82 (2010) 072005
(D/D* incl. tag)



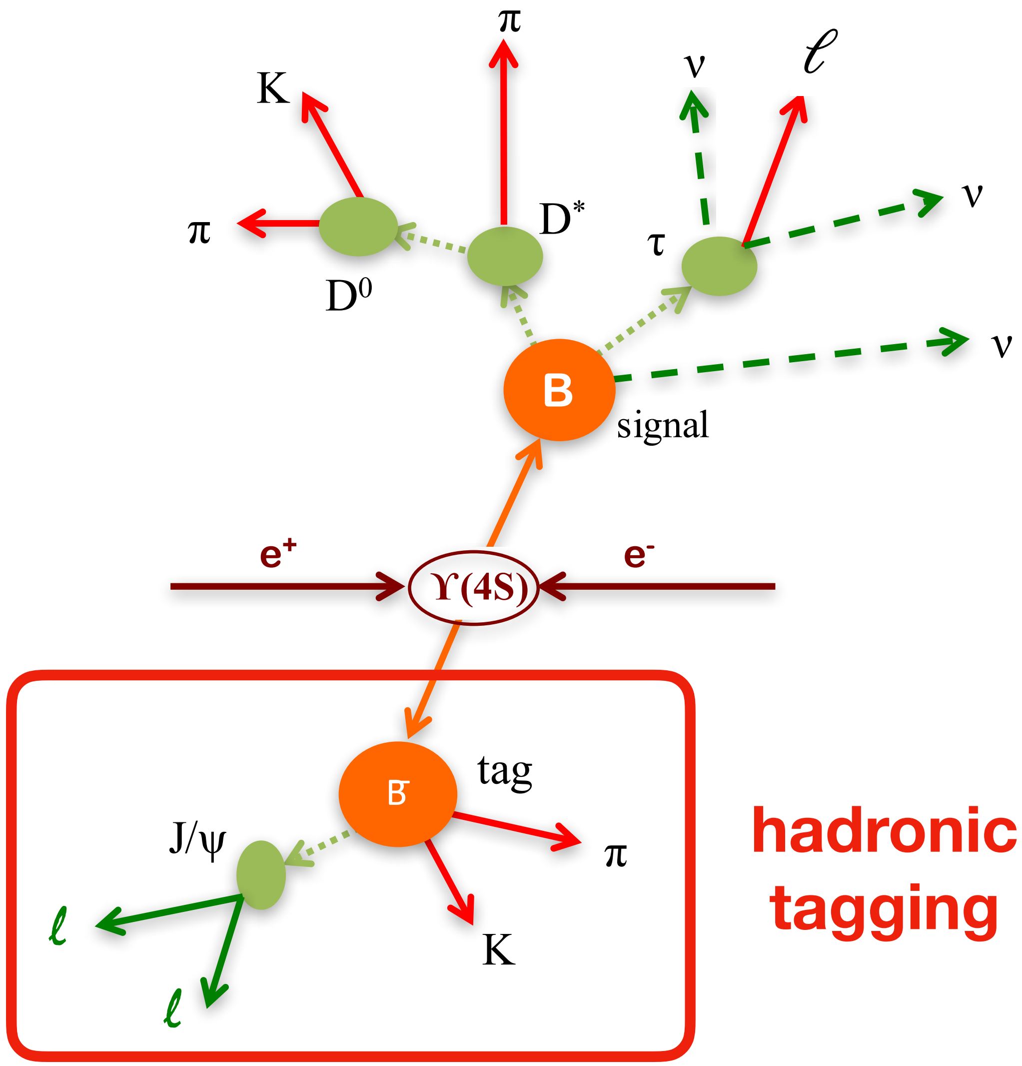
+ 1 B-Factory measurement of $R(\pi)$

1 LHCb measurement of $R(J/\psi)$

R(D) and *R(D*)* with had. tagging

Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)

- Use of $\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu$ to reconstruct **τ-lepton**
- Simultaneous analysis of *R(D)* vs. *R(D*)* using $B^0 \to D^{*-}\tau\nu$, $B^- \to D^{*0}\tau\nu$, $B^0 \to D^-\tau\nu$, $B^- \to D^0\tau\nu$

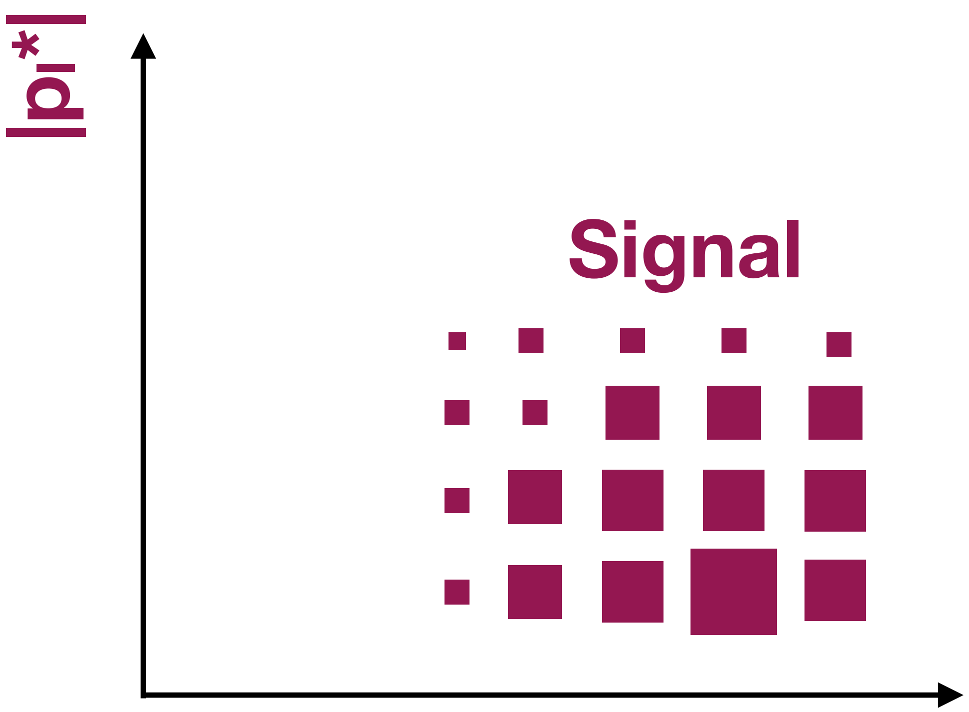


hadronic tagging

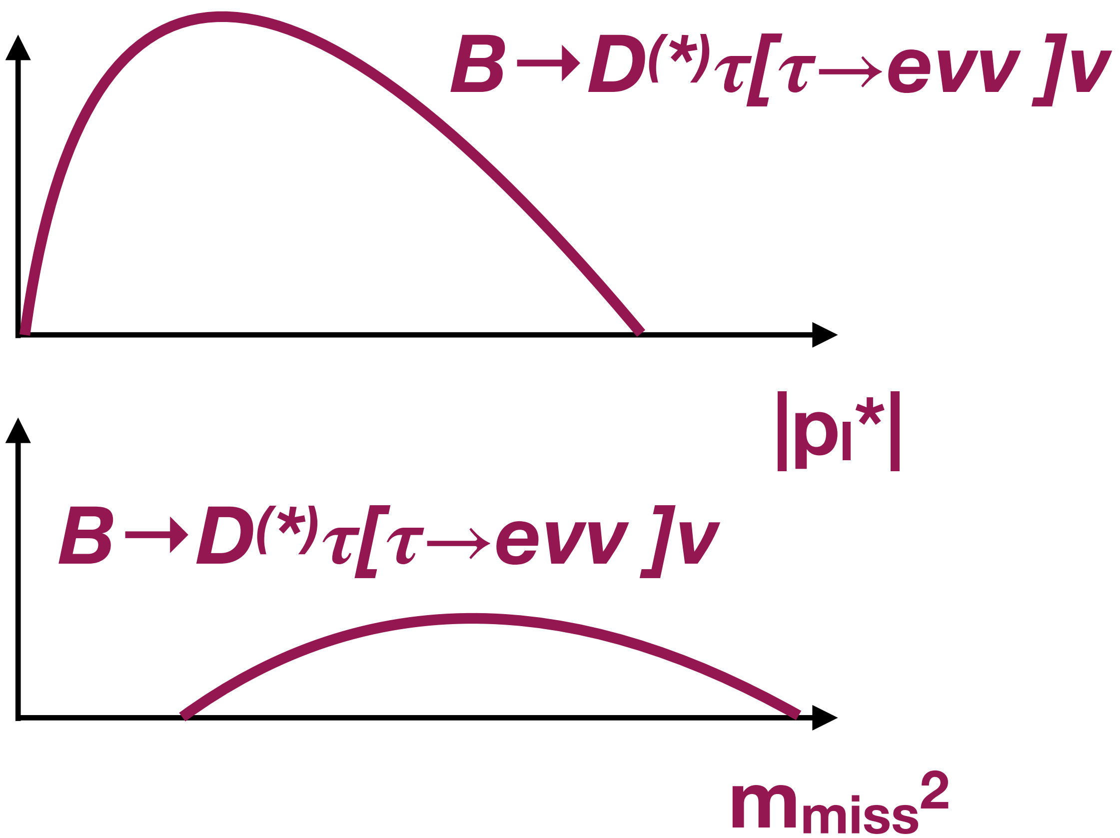
R(D) and *R(D*)* with had. tagging

Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)

- Next step after tag & signal reconstruction: **suppress backgrounds**
- Very powerful variables: $|p_l^*|$, m_{miss}^2



$(p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_\ell)^2 =$ m_{miss}^2



R(D) and *R(D*)* with had. tagging

Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)

- Next step after tag & signal reconstruction: **suppress backgrounds**
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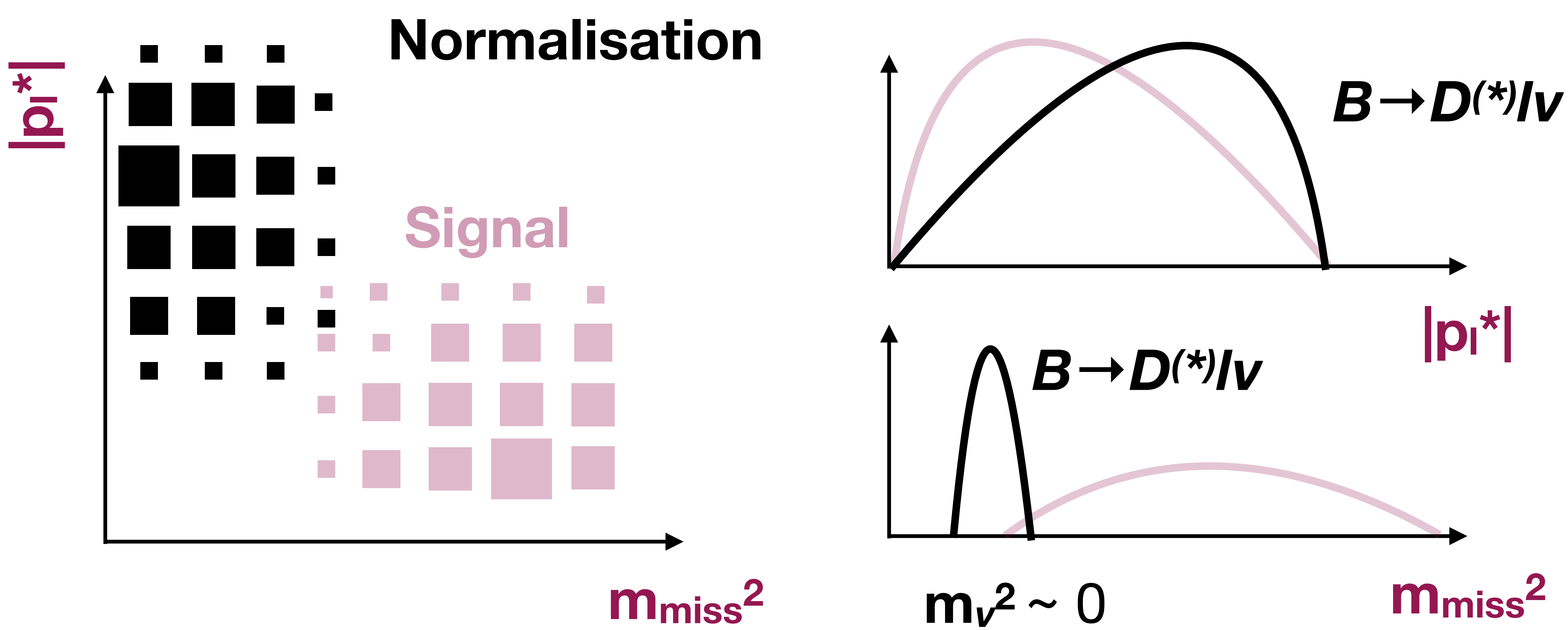

R(D) and *R(D*)* with had. tagging

Phys.Rev.D 92, 072014 (2015)
(D/D^* had tag, q^2)

- Next step after tag & signal reconstruction: **suppress backgrounds**
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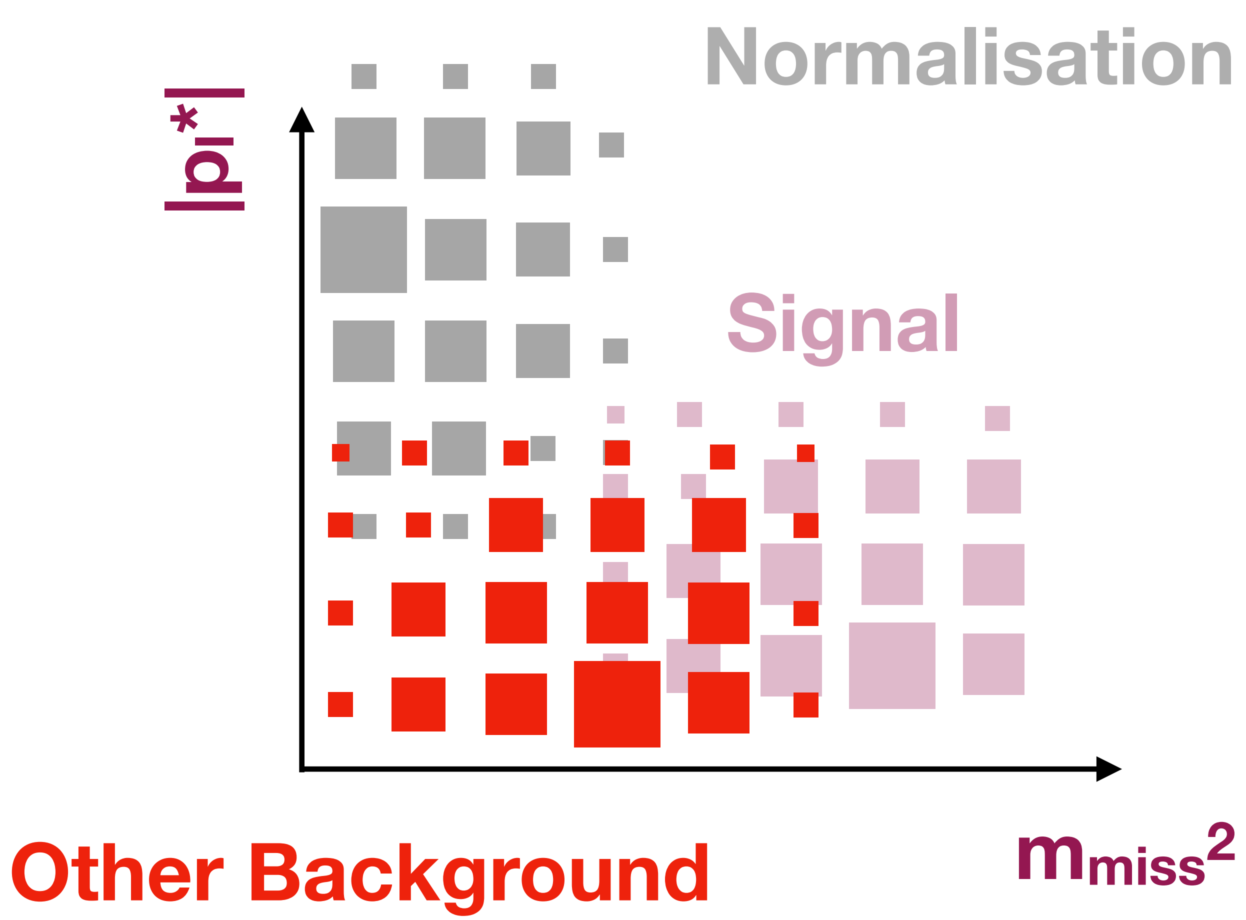
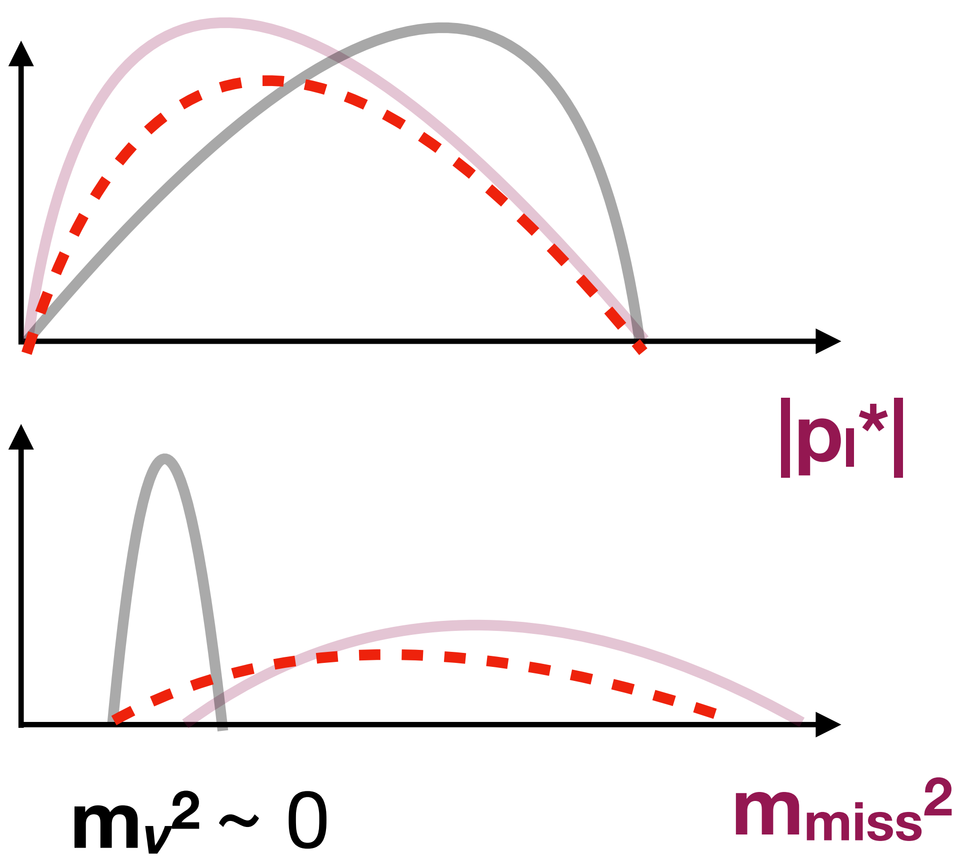


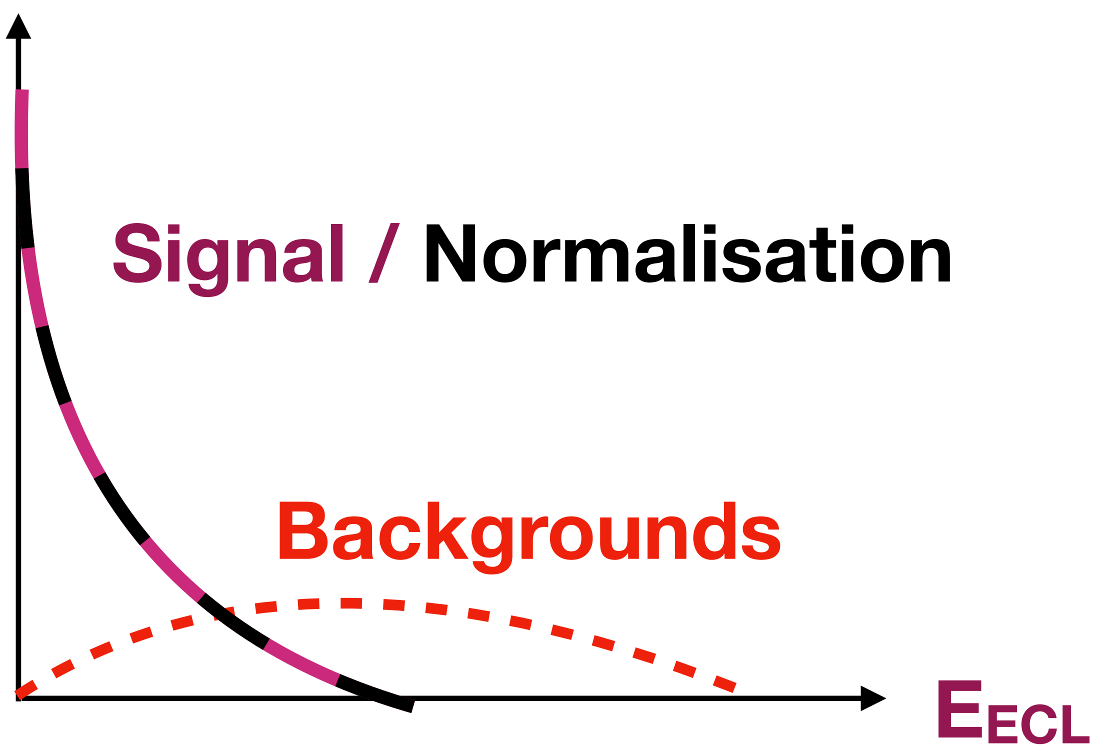


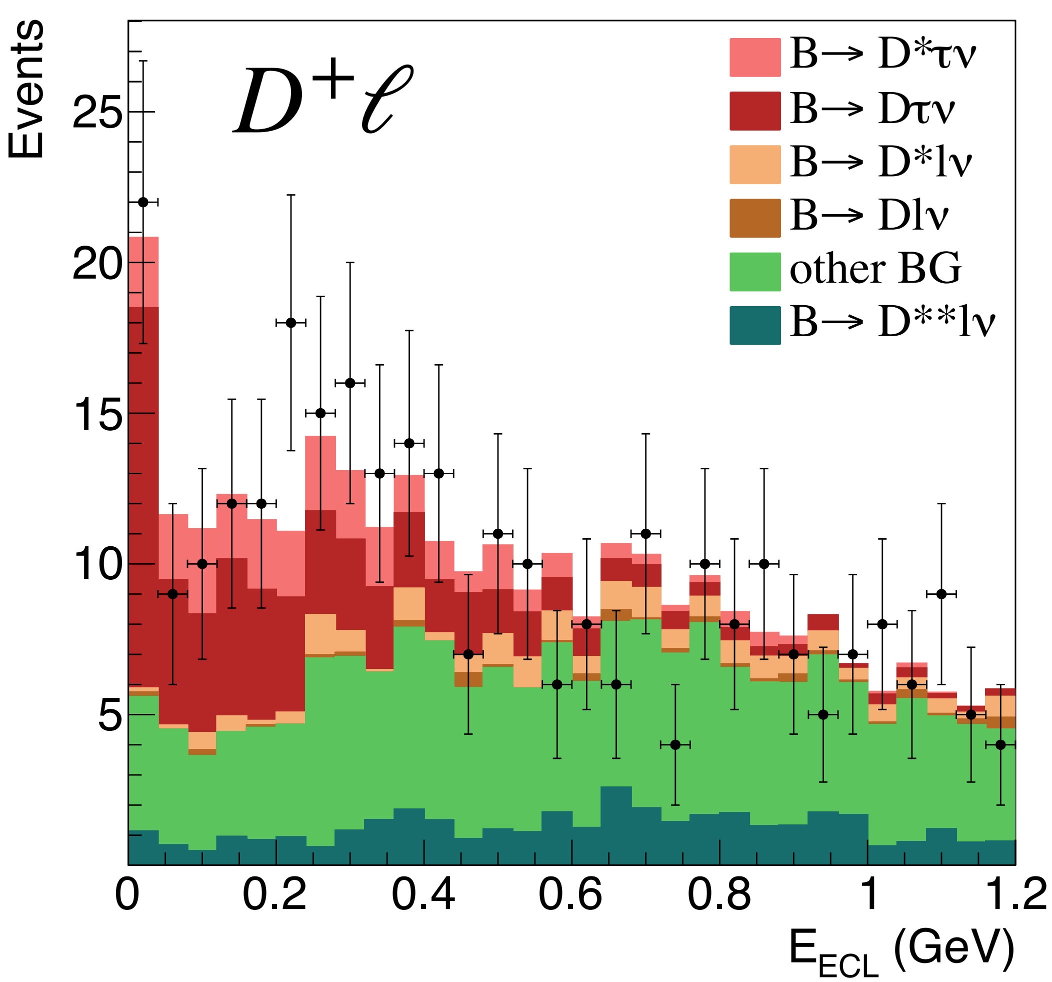
R(D) and *R(D*)* with had. tagging

Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)

- Next step after tag & signal reconstruction: **suppress backgrounds**
- Very powerful variables: **$|p_l^*|$, m_{miss}^2,**

E_{ECL} = unassigned neutral energy in the calorimeter





R(D) and *R(D*)* with had. tagging

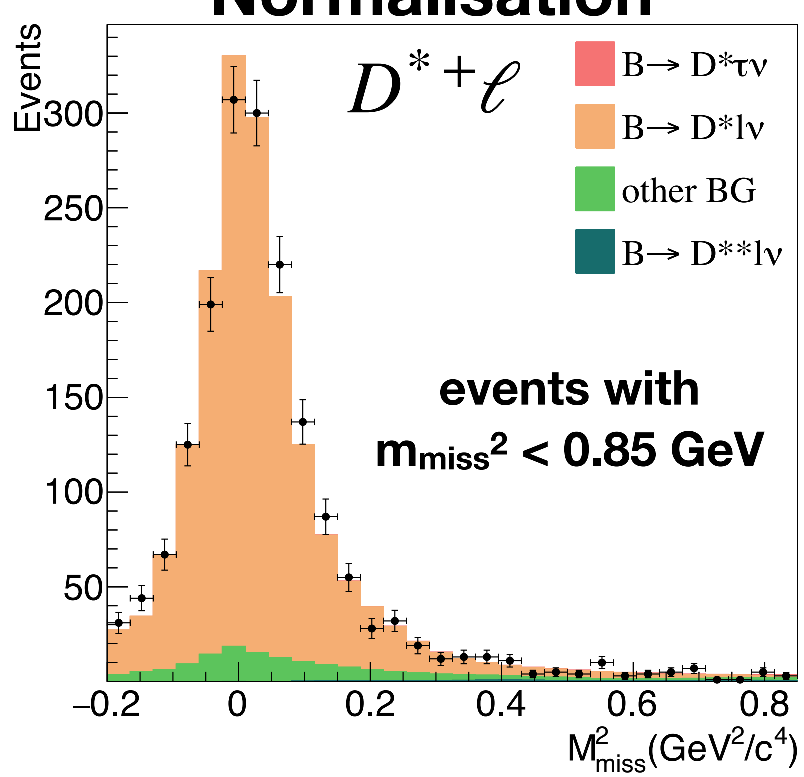
Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)

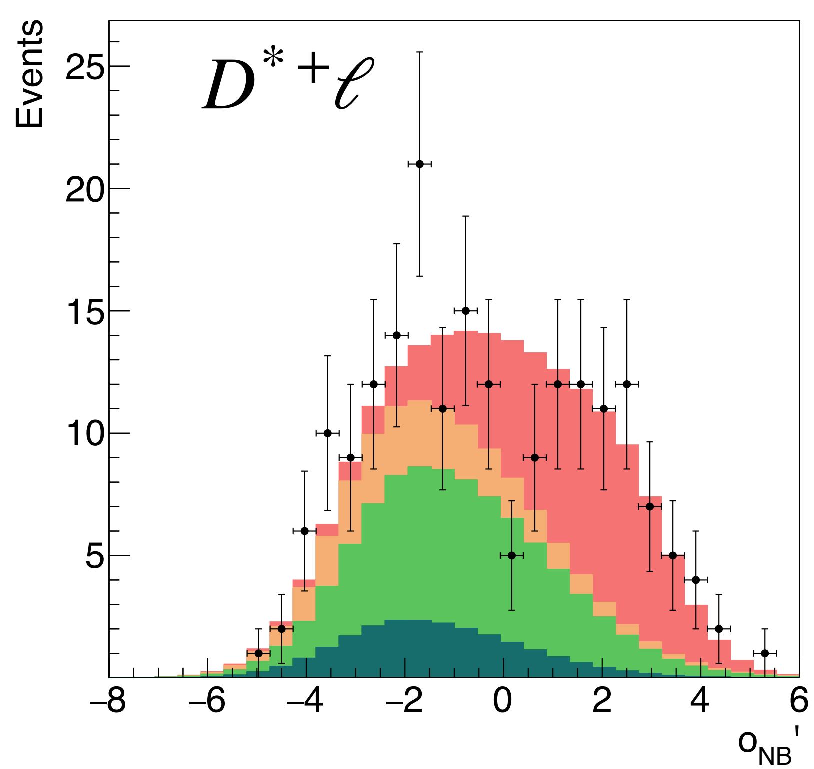
- Next step after tag & signal reconstruction: **suppress backgrounds**
- Very powerful variables: $|p_l^*|$, m_{miss}^2, E_{ECL} = unassigned neutral energy in the calorimeter + q^2 + 3 other variables

Multivariate Classifier

all events with m_{miss}^2 > 0.85 GeV

Normalisation





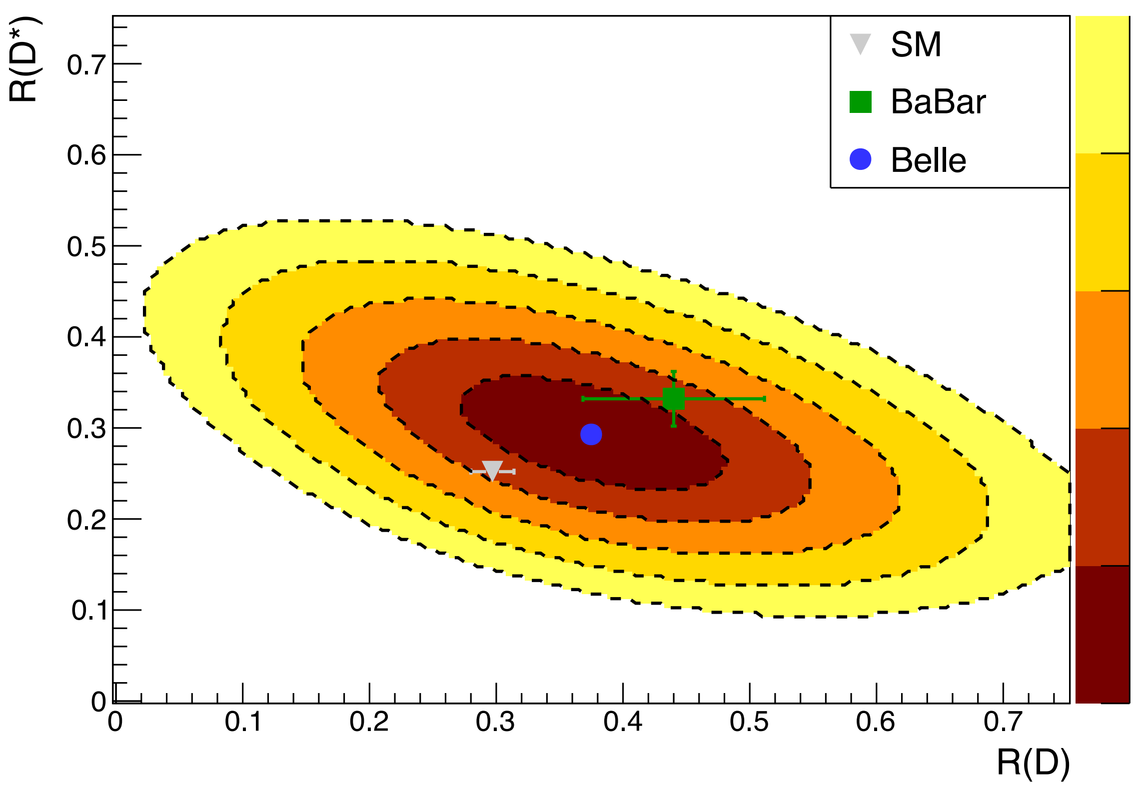
simultaneous unbinned ML fit of all Channels

$D^+\ell$
$D^0\ell$
$D^{*+}\ell$
$D^{*0}\ell$

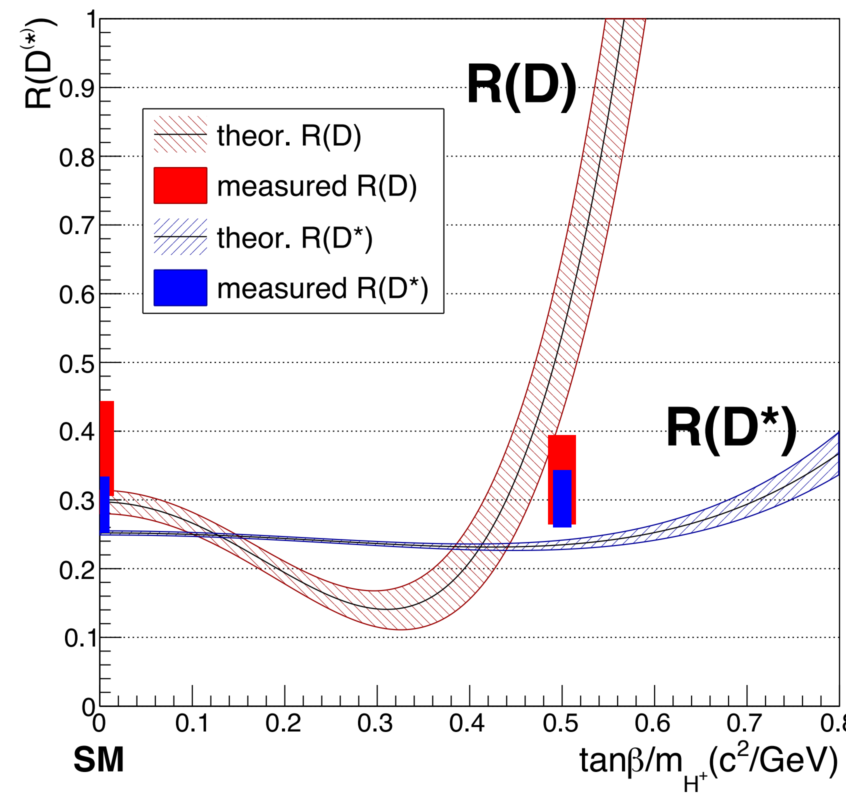
R(D) and *R(D*)* with had. tagging

Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)

SM



2HDM Type II



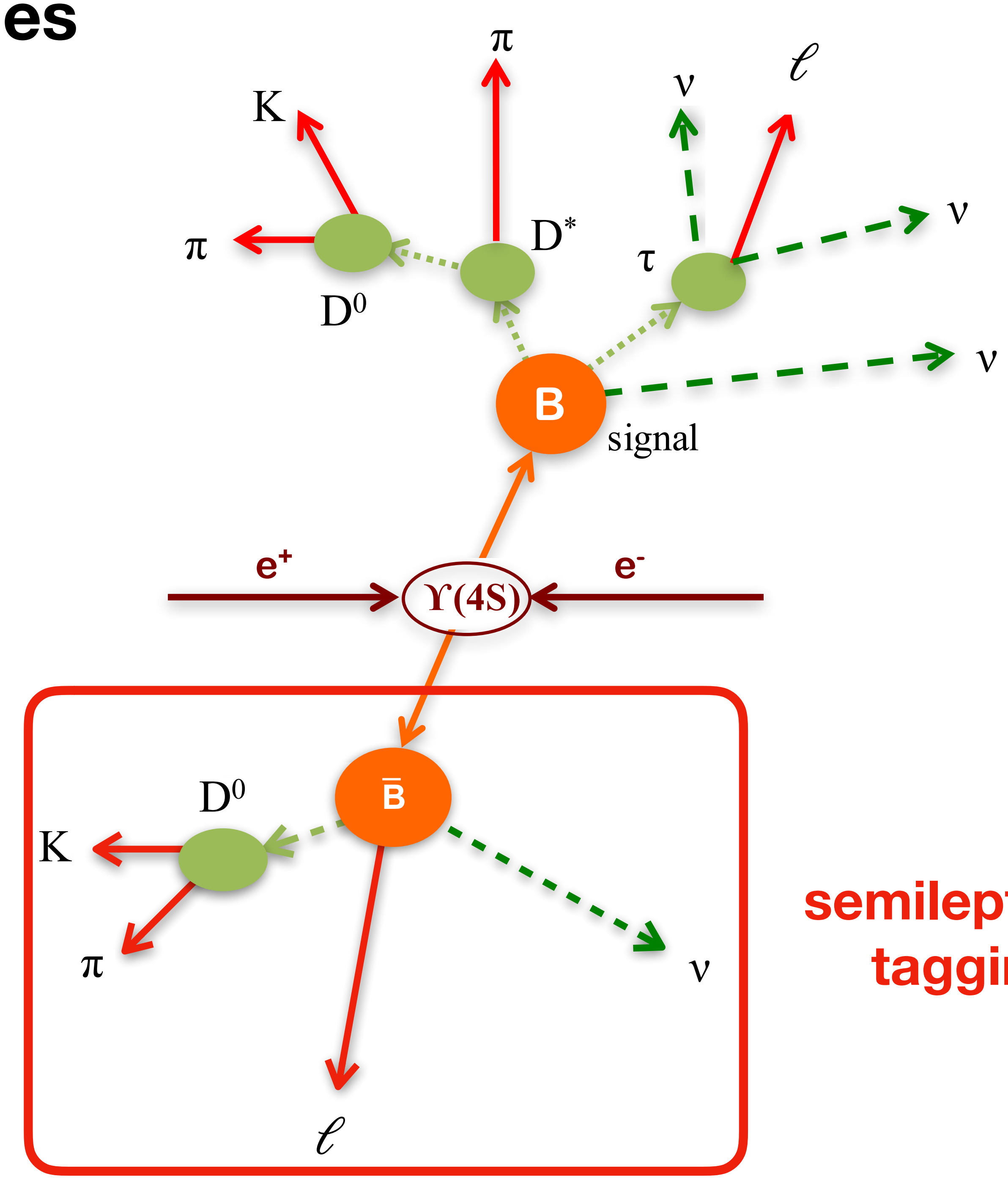
R(D) = 0.375 ± 0.064 (stat) ± 0.026 (syst)
R(D*) = 0.293 ± 0.038 (stat) ± 0.015 (syst)

✓ **Combination is 1.8σ from SM**

R(D)* with SL tagging

Phys.Rev. D94,072007 (2016)
(D*, SL tag, p_{D^*}, p_l)

- Use of ***τ→evv*** and ***τ→μvv*** to reconstruct ***τ*-lepton** and set of **D* modes**



semileptonic tagging

$R(D^*)$ with SL tagging

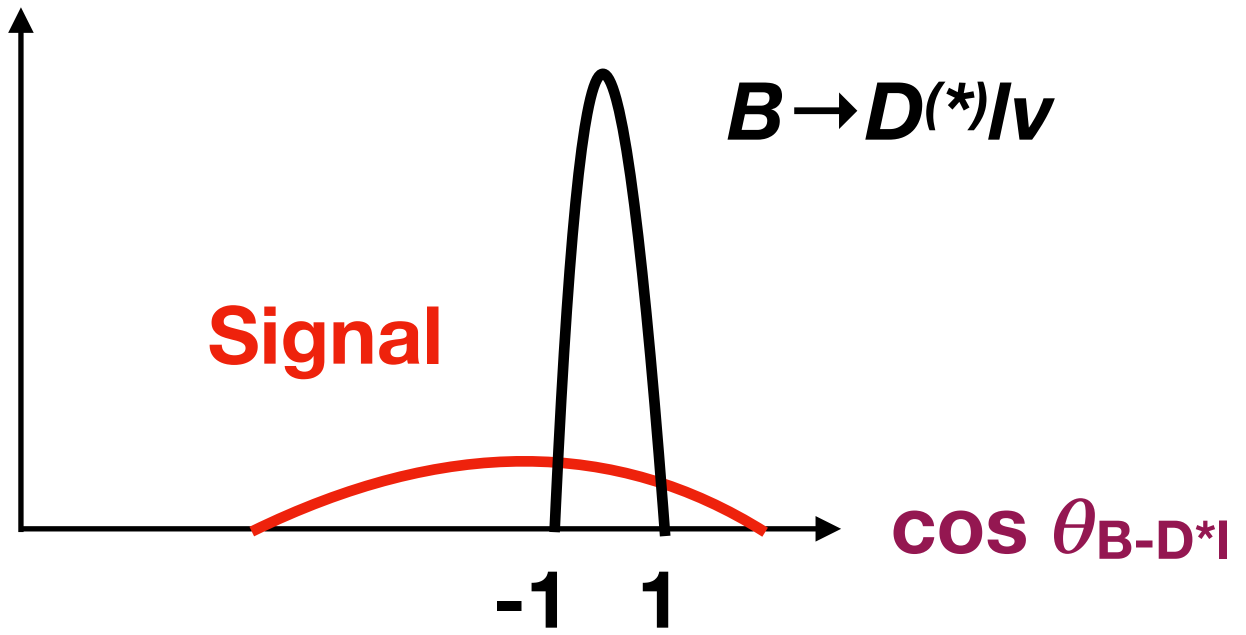
Phys.Rev. D94,072007 (2016)
(D^*, SL tag, p_{D^*}, p_l)

- Another powerful variables: **$\cos\theta_{B\text{-}D^*l}$**

$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\mathrm{beam}}E_{D^*\ell} - m_B^2c^4 - M_{D^*\ell}^2c^4}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|c^2},$$

visible particles

beam or Y(4S) properties



$R(D^*)$ with SL tagging

Phys.Rev. D94,072007 (2016)
(D^*, SL tag, p_{D^*}, p_l)

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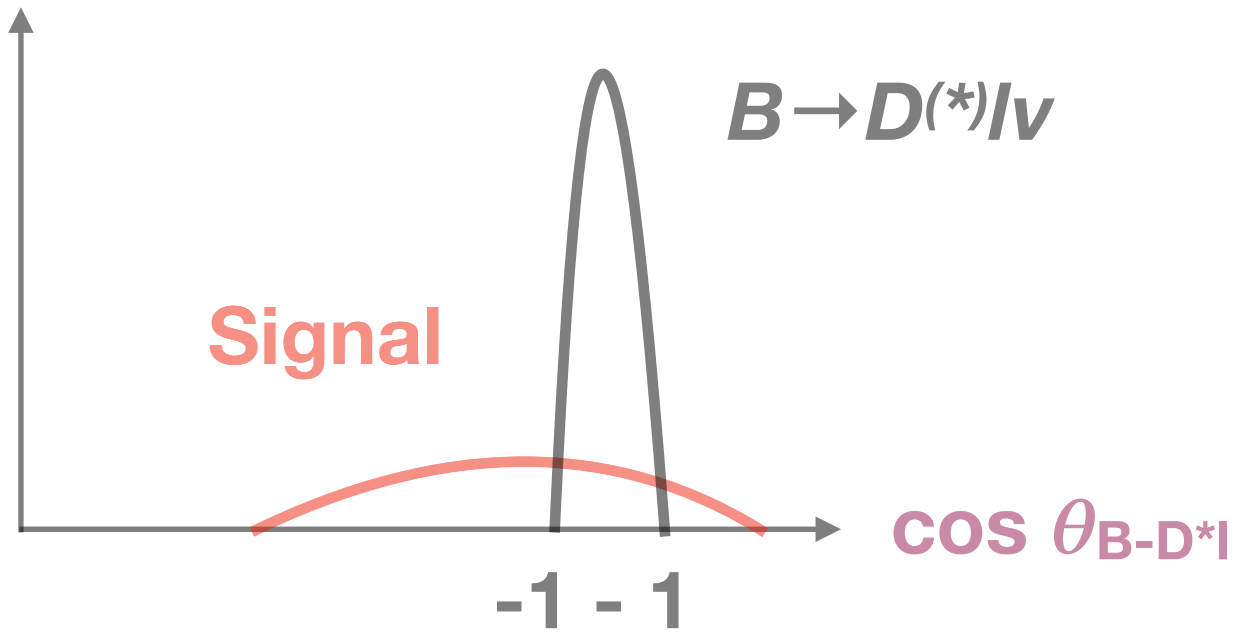
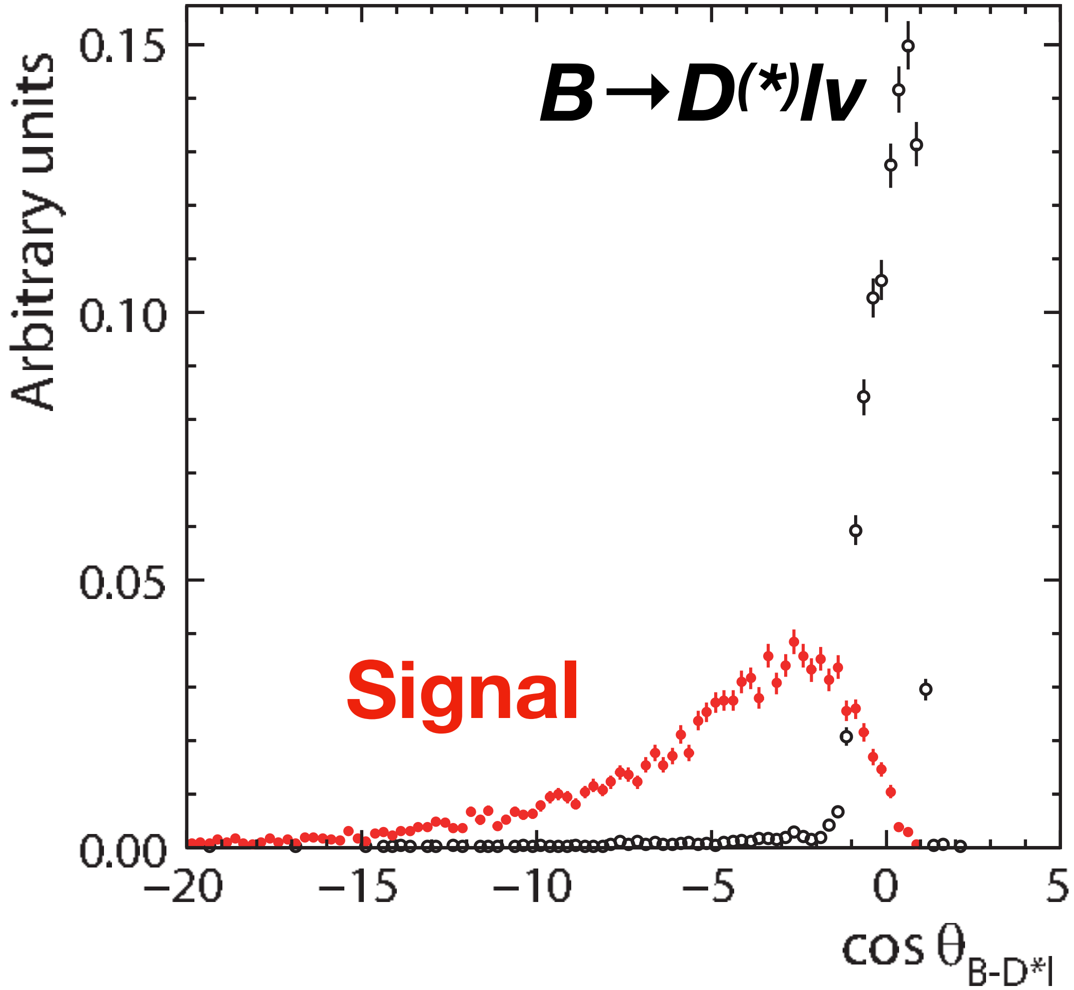




$R(D^*)$ with SL tagging

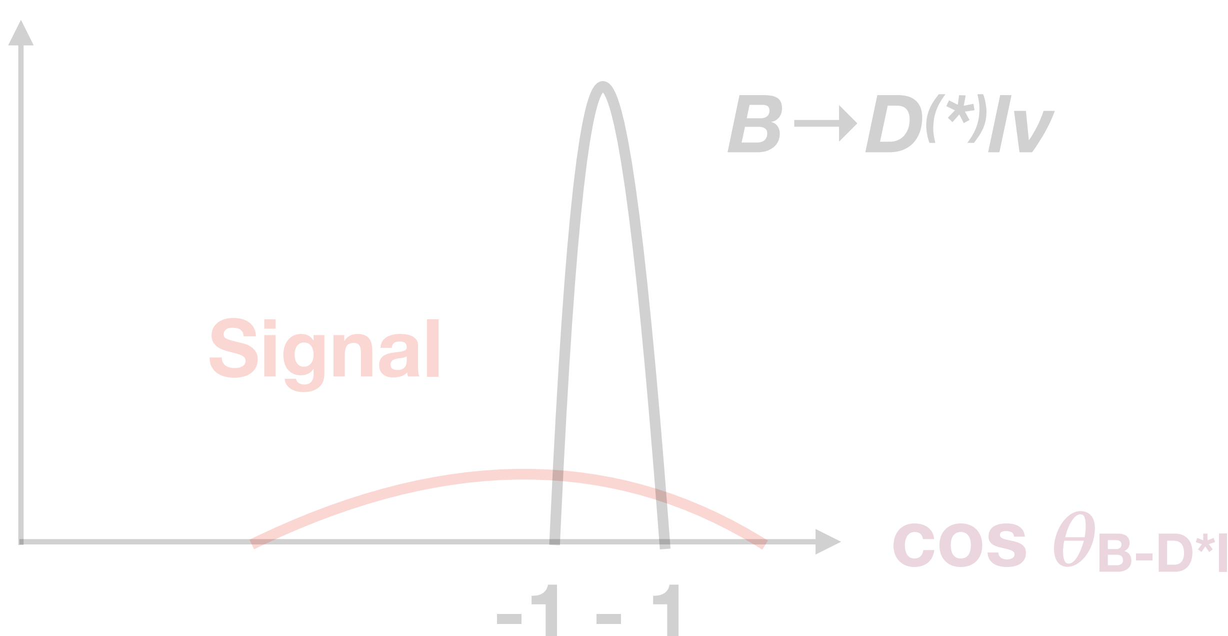
Phys.Rev. D94,072007 (2016)
(D^*, SL tag, p_{D^*}, p_l)

- Another powerful variables: $\cos\theta_{B\text{-}D^*l}$, m_{miss}^2 + total visible Energy → 2D ML fit $\mathcal{O}_{NB} \oplus E_{\mathrm{ECL}}$

$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\mathrm{beam}}E_{D^*\ell} - m_B^2c^4 - M_{D^*\ell}^2c^4}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|c^2},$$

visible particles

beam or Y(4S) properties



$R(D^*)$ with SL tagging

Phys.Rev. D94,072007 (2016)
(D^*, SL tag, p_{D^*}, p_l)

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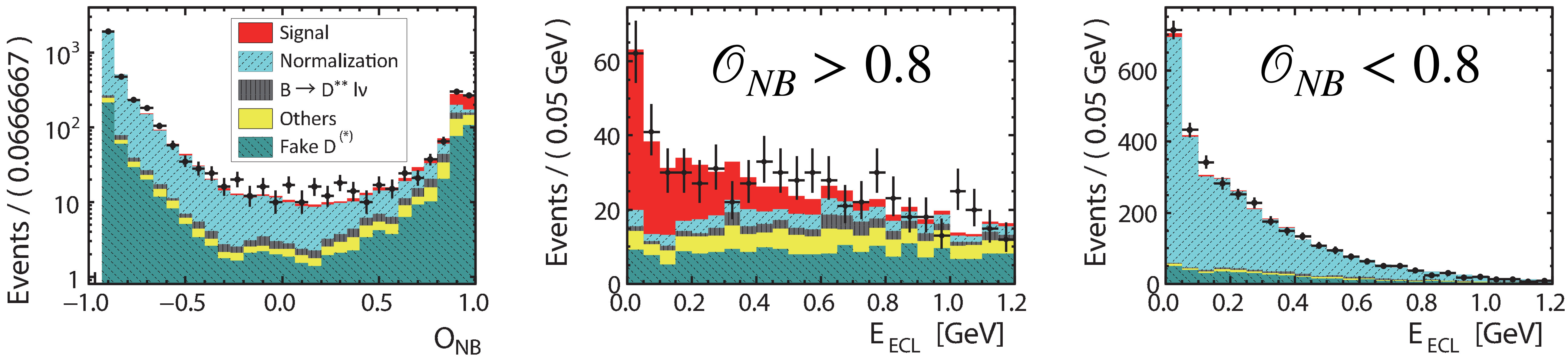


$$\mathcal{R}(D^*) = \frac{1}{2\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)} \cdot \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \cdot \frac{N_{\rm sig}}{N_{\rm norm}},$$

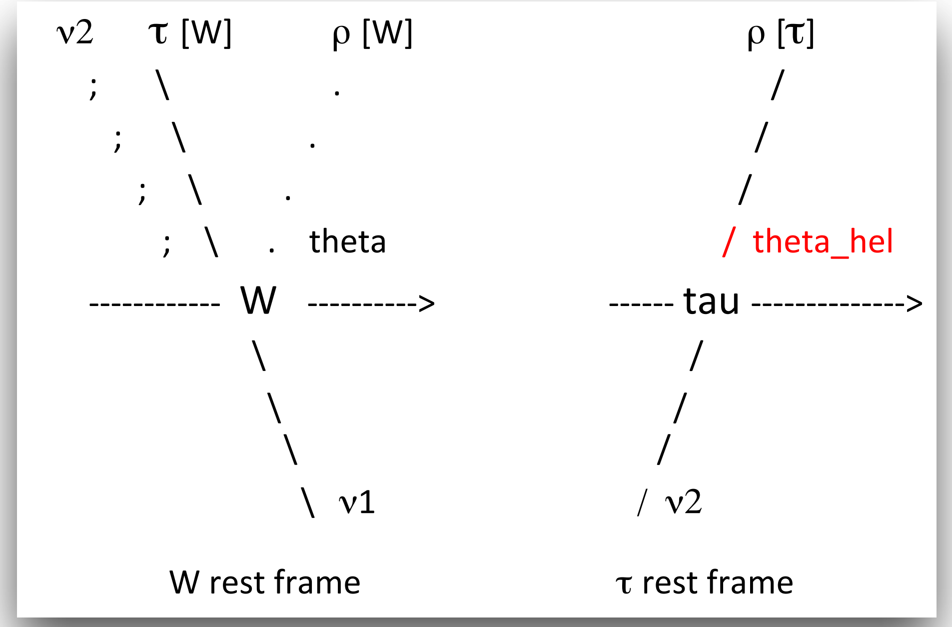
$R(D^*) = 0.302 \pm 0.030$ (stat) ± 0.011 (syst)

✓ **1.6σ above SM**

$R(D^*)$ and τ Polarisation

Phys.Rev.Lett.118,211801 (2017)
Phys. Rev. D 97, 012004 (2018)
(D* had tag)

- Decay angles of $\tau \to \pi \nu$ and $\tau \to \rho \nu$ encode ***τ-polarisation***, sensitive to NP!
  - ✓ **Need to reconstruct helicity angle, but a-priorio τ-restframe not accessible**
  - ✓ **Luckily there is a relation between *<(τh) in $\tau \nu$-frame and this angle***



Nice Illustration from V. Luth

$R(D^*)$ and τ Polarisation

Phys.Rev.Lett.118,211801 (2017)
Phys. Rev. D 97, 012004 (2018)
(D* had tag)

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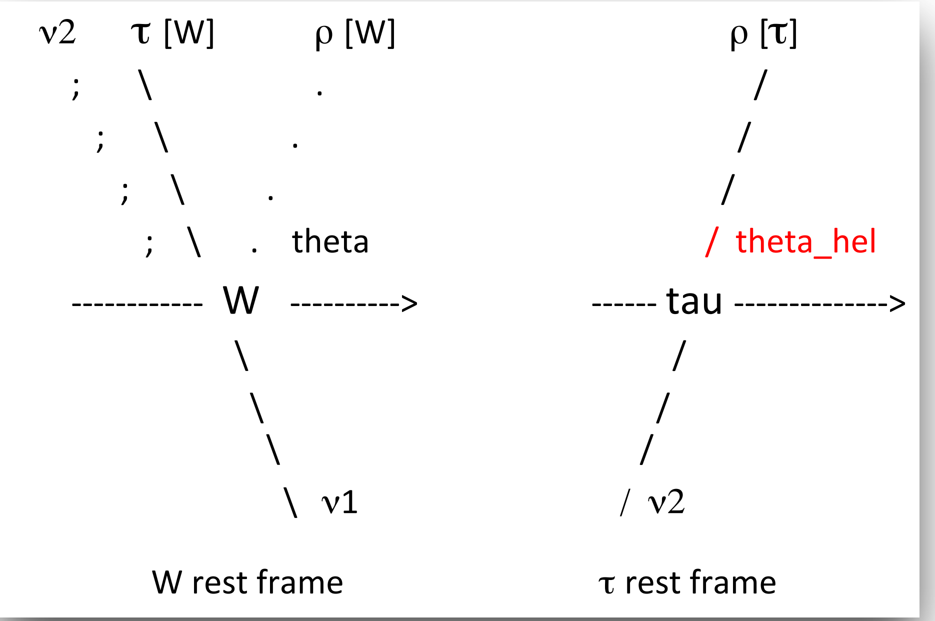
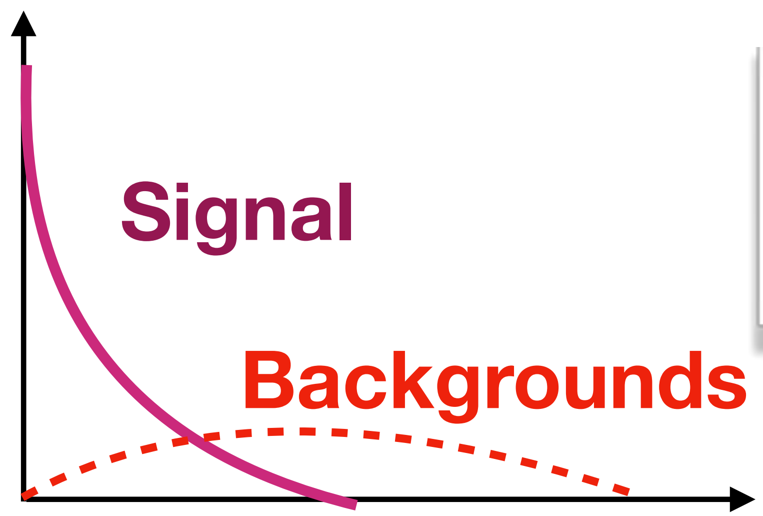


Nice Illustration from V. Luth

- Signal extraction via **E_{ECL} (unassigned energy in the calorimeter)** and in two bins of helicity angle **$\cos\Theta_{hel}$** with binned likelihood fit



$E_{ECL} = E_{Extra}$

$$R(D^*) = \frac{\epsilon^j_{\rm norm} N^{ij}_{\rm sig}}{\mathcal{B}^i_\tau \epsilon^{ij}_{\rm sig} N^j_{\rm norm}},$$

$$P_\tau(D^*) = \frac{2}{\alpha_i} \frac{N^{Fij}_{\rm sig} - N^{Bij}_{\rm sig}}{N^{Fij}_{\rm sig} + N^{Bij}_{\rm sig}},$$

Normalisation: ***$B \to D^* \ell \nu$***

$R(D^*)$ and τ Polarisation

Phys.Rev.Lett.118,211801 (2017)
Phys. Rev. D 97, 012004 (2018)
(D* had tag)

- Decay angles of $\tau \to \pi\nu$ and $\tau \to \rho\nu$ encode ***τ-polarisation***, sensitive to NP!
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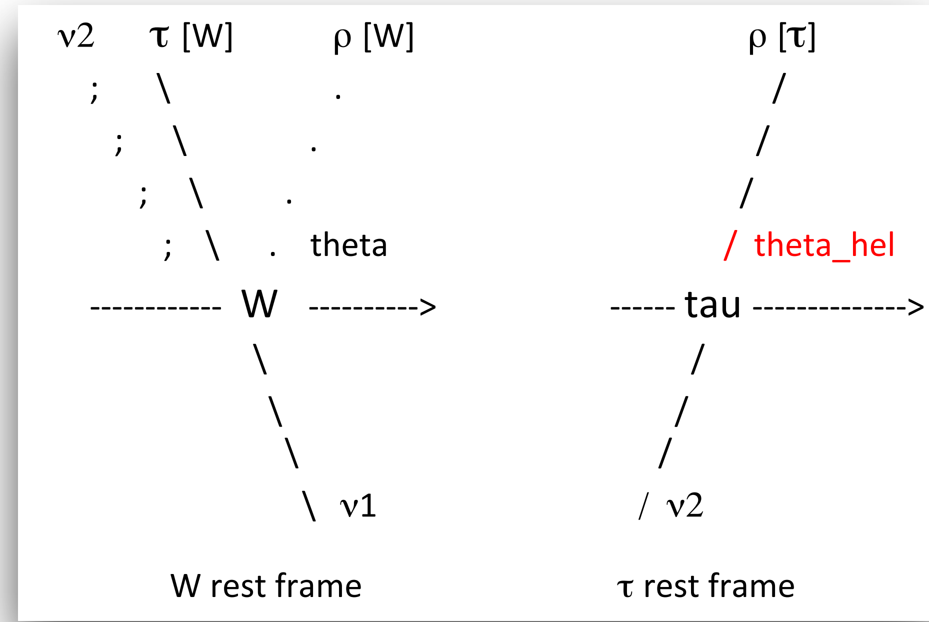
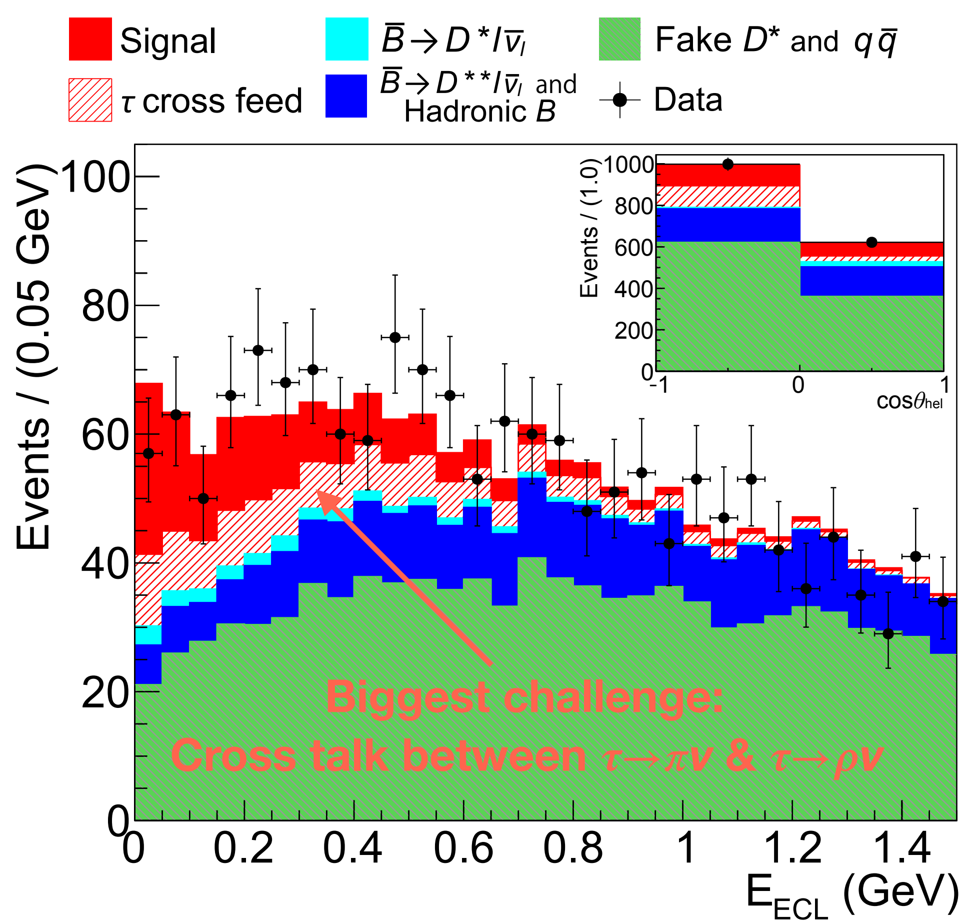
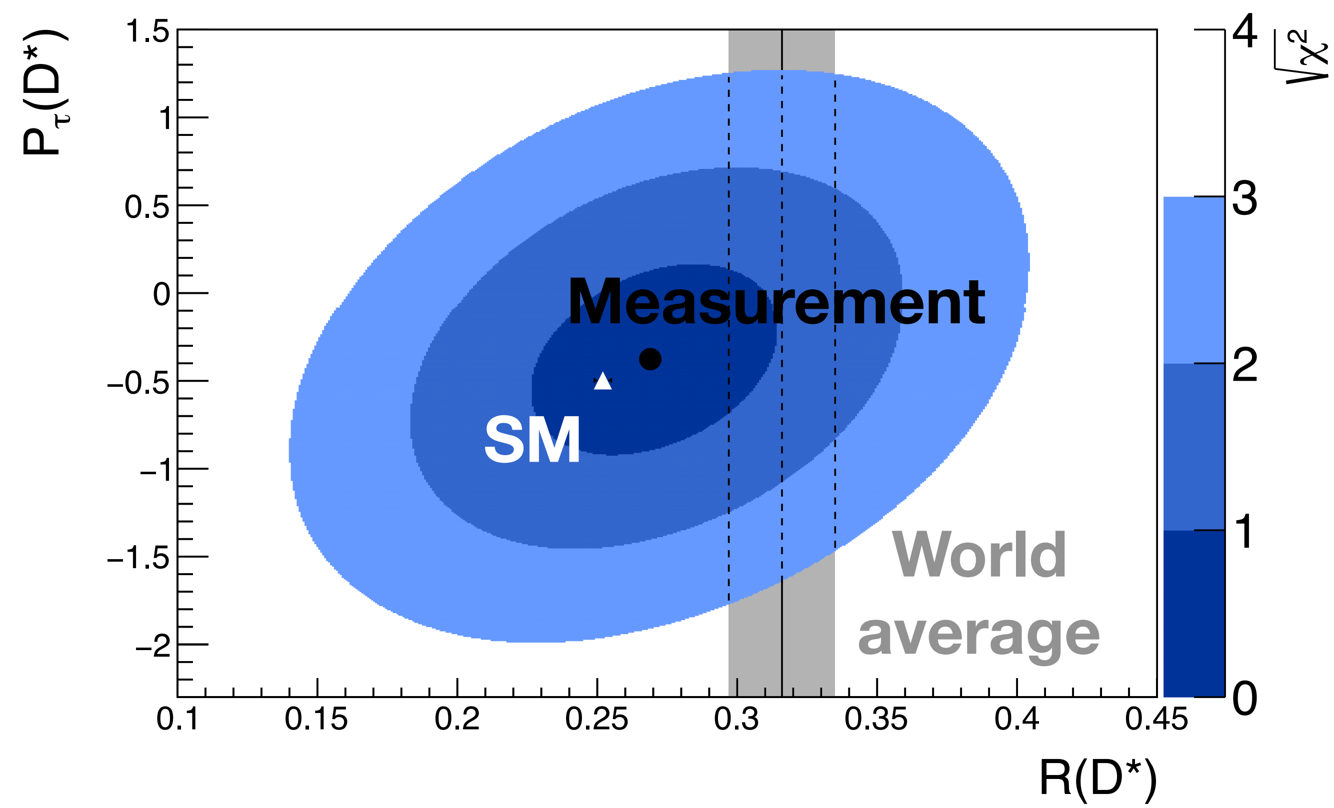


Nice Illustration





$R(\pi)$ with hadronic tagging

Phys. Rev. D 93, 032007 (2016)
(π had tag)

- Reconstruct $\tau\to\ell\nu\nu$, $\tau\to\pi\nu\nu$, $\tau\to\rho\nu\nu$, $\tau\to a_1\nu\nu$ and charged pion

$$R(\pi) = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to \pi\ell\bar{\nu}_\ell)}$$

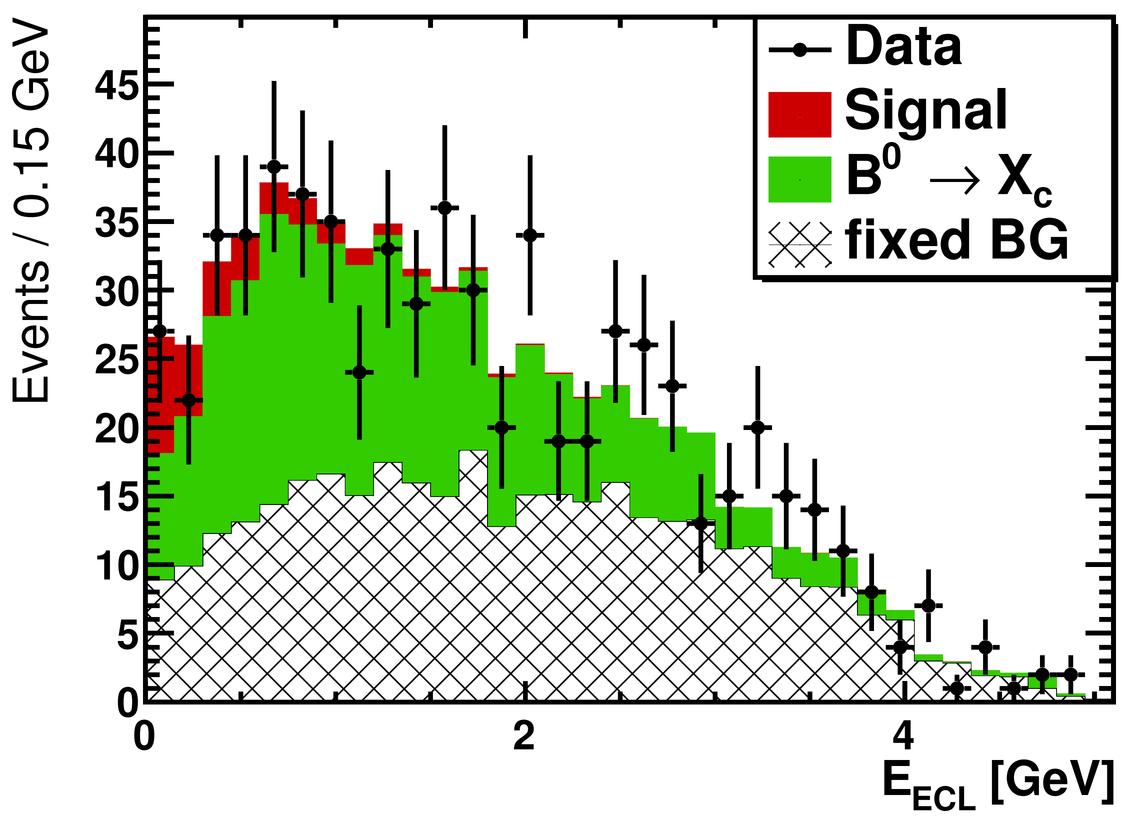
1D fit in E_{ECL} determines

$R(\pi)$ = 1.05 ± 0.51

$R(\pi)_{SM} = 0.641 \pm 0.016$
Phys. Rev. D 92, 115019 (2015)

2.4 σ significance over background-only hypothesis

$\tau \to \pi\nu$

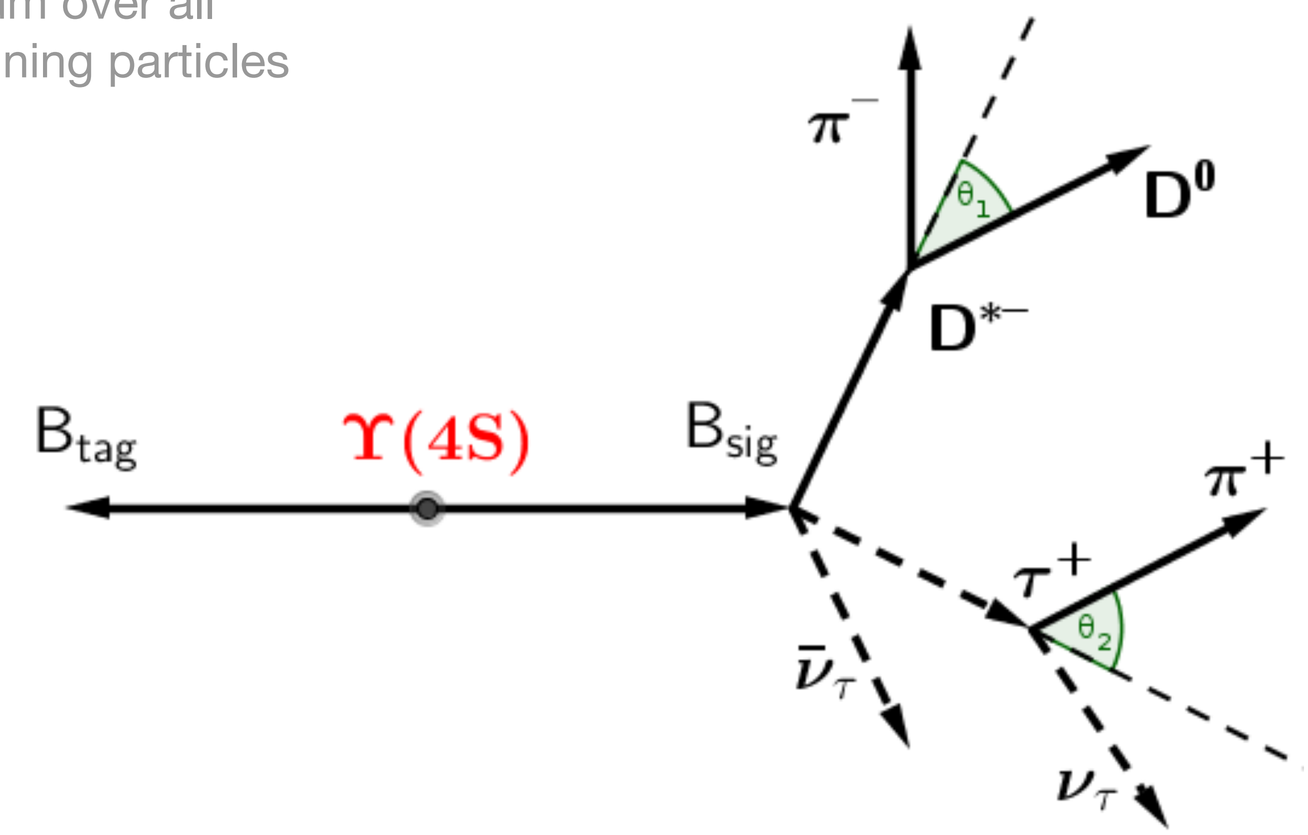


$F_L^{D^*}$ with inclusive tagging

Prel. Belle: https://arxiv.org/pdf/1901.06380.pdf (D*, incl. tagging)

- **First:** reconstruct signal side: $\tau \to \ell \nu\nu$ and $\tau \to \pi \nu$ plus $D^{*-} \to D^0 \pi^-$ with pure D^0 modes
- **Inclusive Tag:** $E_{tag} = \sum_i E_i$ $\quad \mathbf{p}_{tag} = \sum_i \mathbf{p}_i$

sum over all remaining particles



$F_L^{D^*}$ with inclusive tagging

Prel. Belle: https://arxiv.org/pdf/1901.06380.pdf (D*, incl. tagging)

- **First:** reconstruct signal side: $\tau \to \ell \nu \nu$ and $\tau \to \pi \nu$ plus $D^{*-} \to D^0 \pi^-$ with pure D^0 modes
- **Inclusive Tag:** $E_{tag} = \sum_i E_i$ $\quad \mathbf{p}_{tag} = \sum_i \mathbf{p}_i$ $\longrightarrow$

$$\Delta E_{tag} = E_{beam} - E_{tag}$$

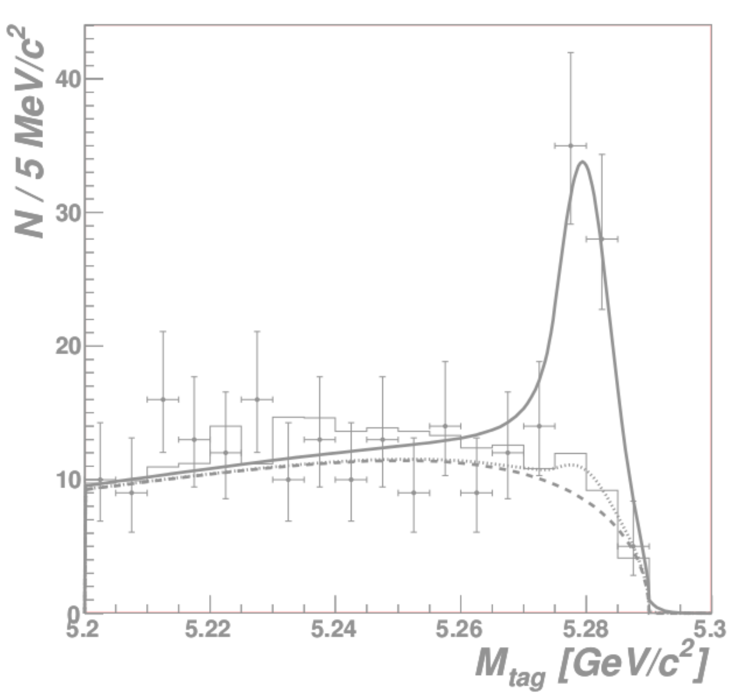
$$M_{tag} = \sqrt{E_{beam}^2 - \mathbf{p}_{tag}^2},$$

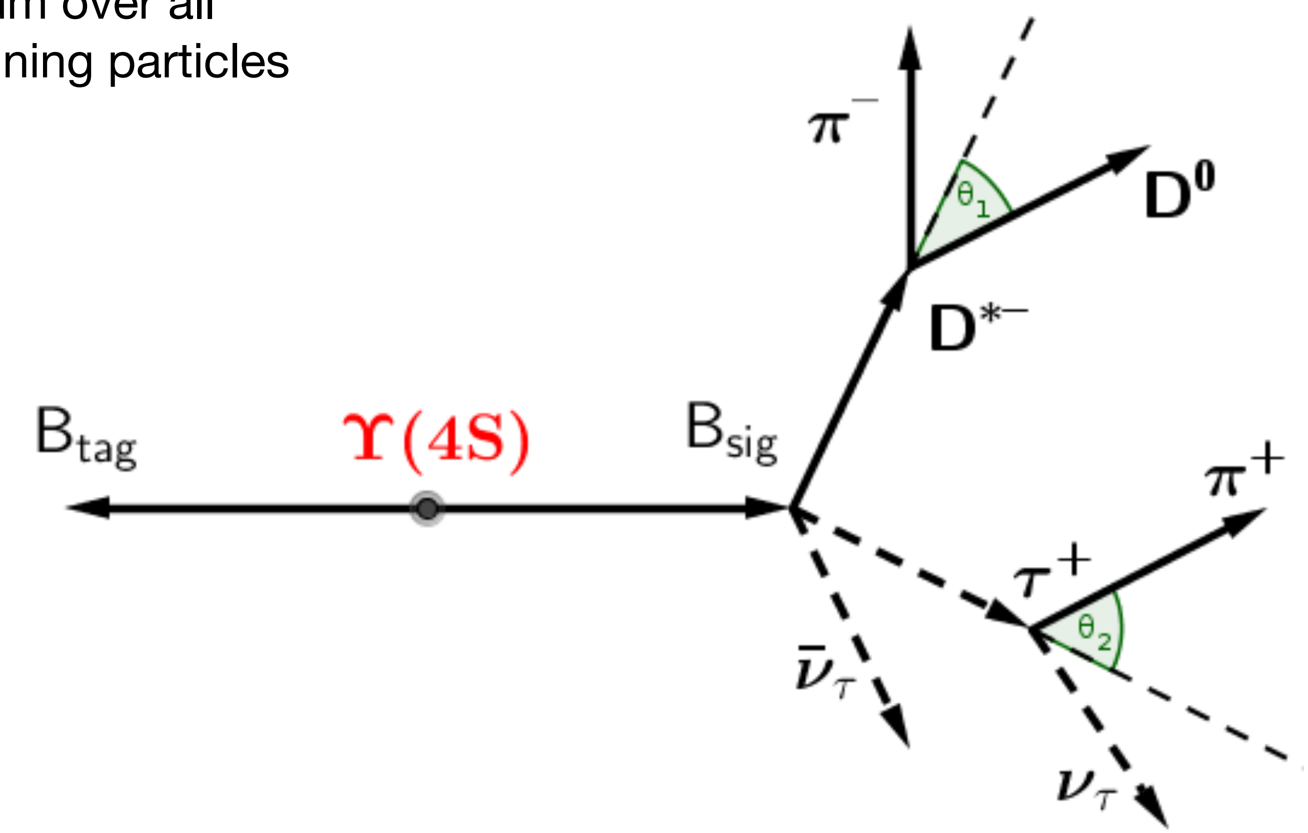
sum over all remaining particles

Check validity of tag:

$$\Delta E_{tag} \in [-0.3, 0.05]\,\mathrm{GeV}$$

PRL **99**, 191807





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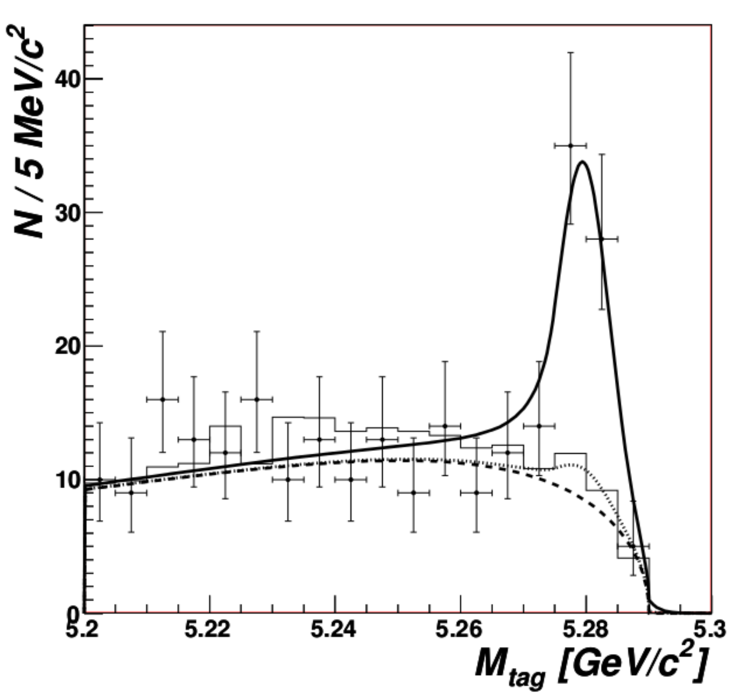

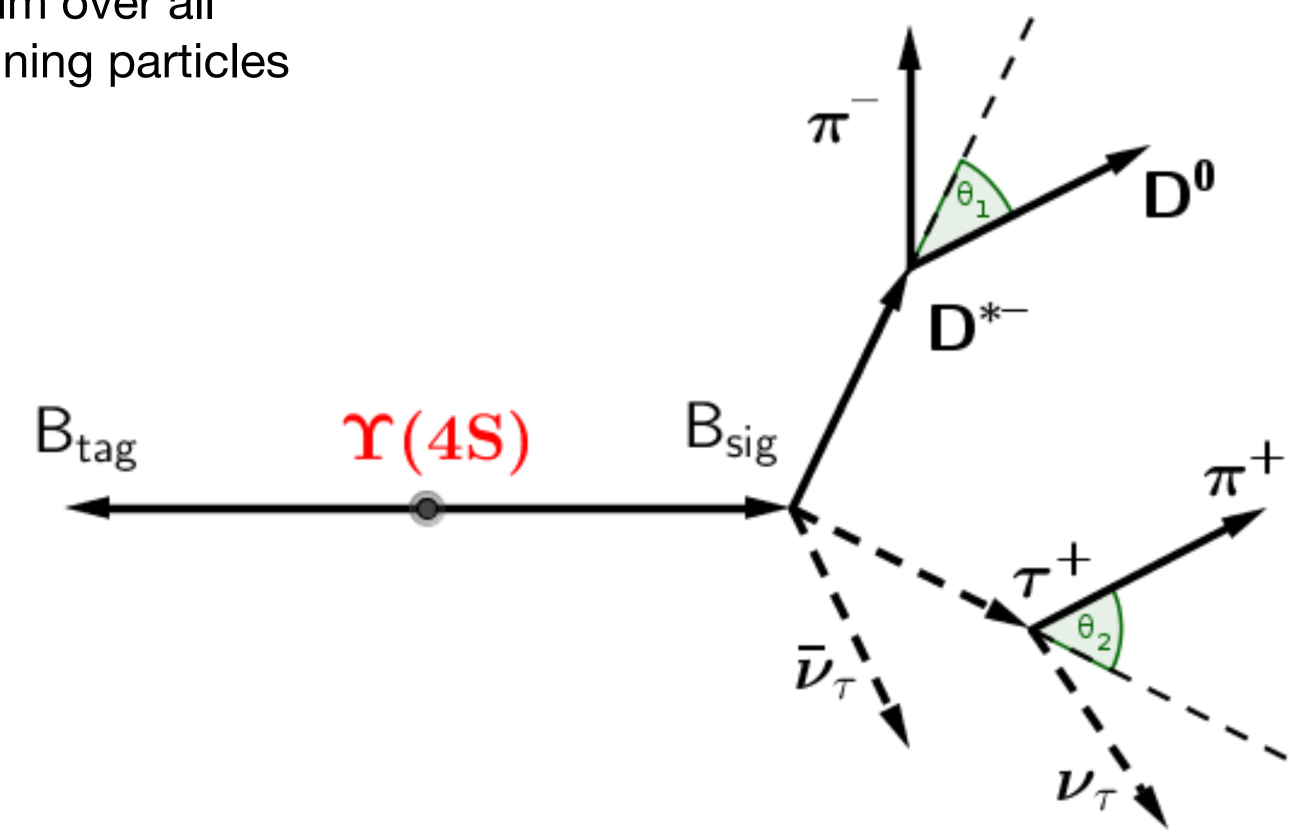

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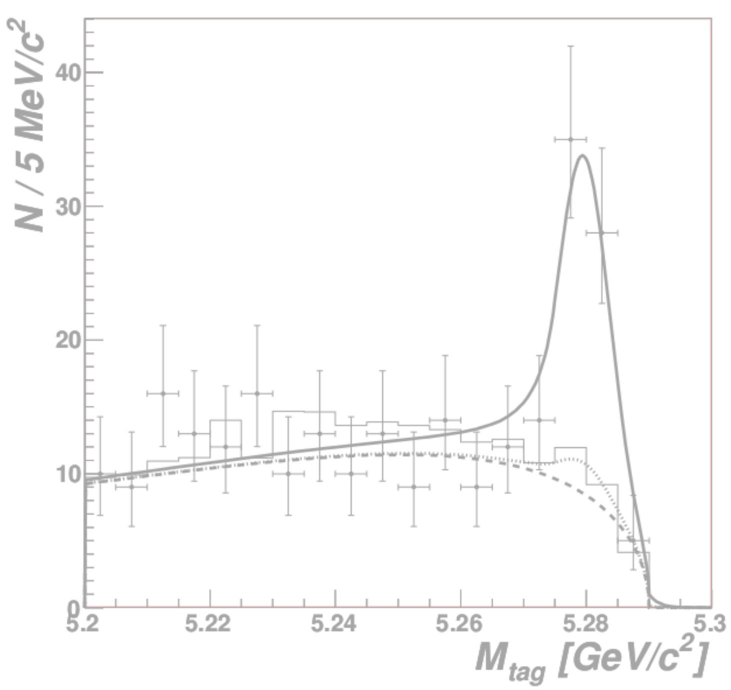
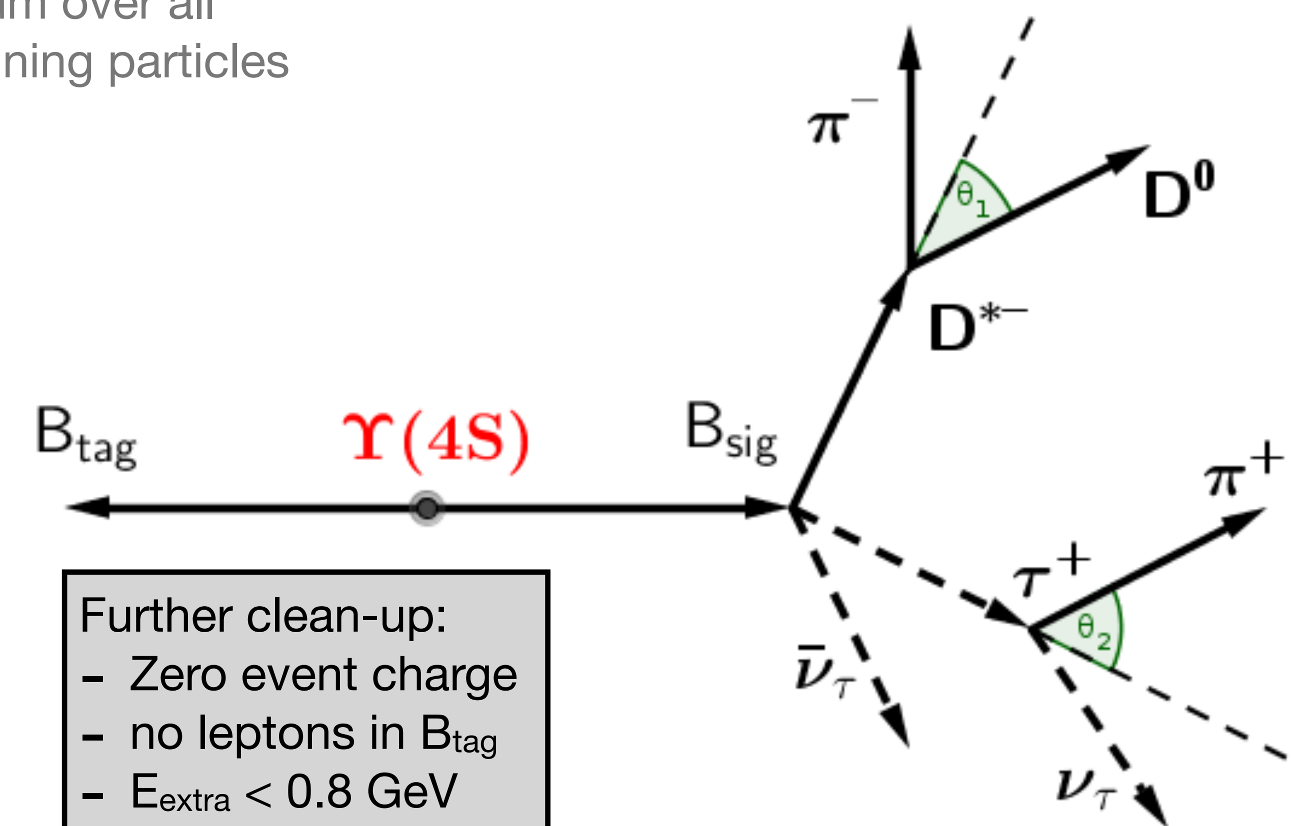


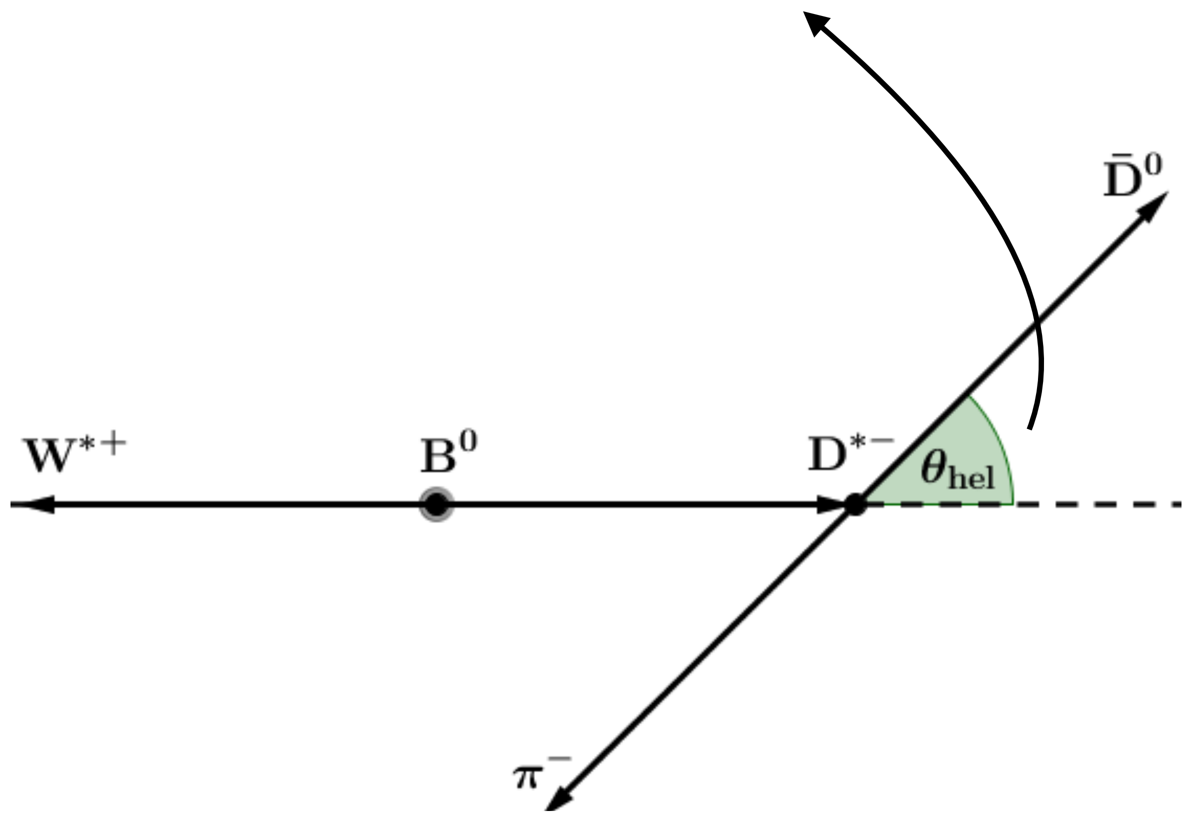


Further clean-up:
- Zero event charge
- no leptons in B_{tag}
- $E_{extra} < 0.8$ GeV
- $q^2 > 4$ GeV

$F_L^{D^*}$ with inclusive tagging

Prel. Belle: https://arxiv.org/pdf/1901.06380.pdf (D*, incl. tagging)

- **Unbinned ML** fit in **categories of**
  τ & D-Decay mode and **bins** of $\cos\theta_{\rm hel}(D^*)$



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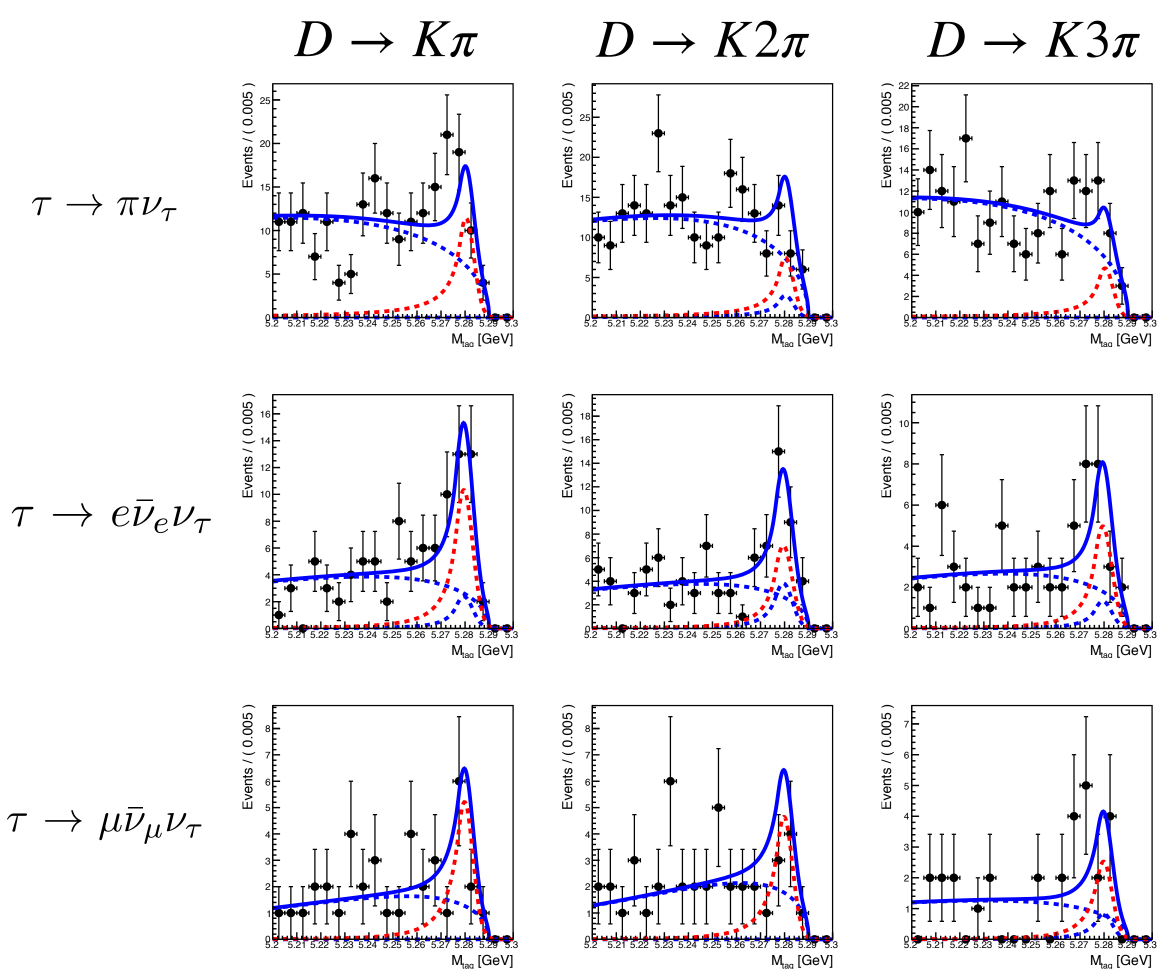

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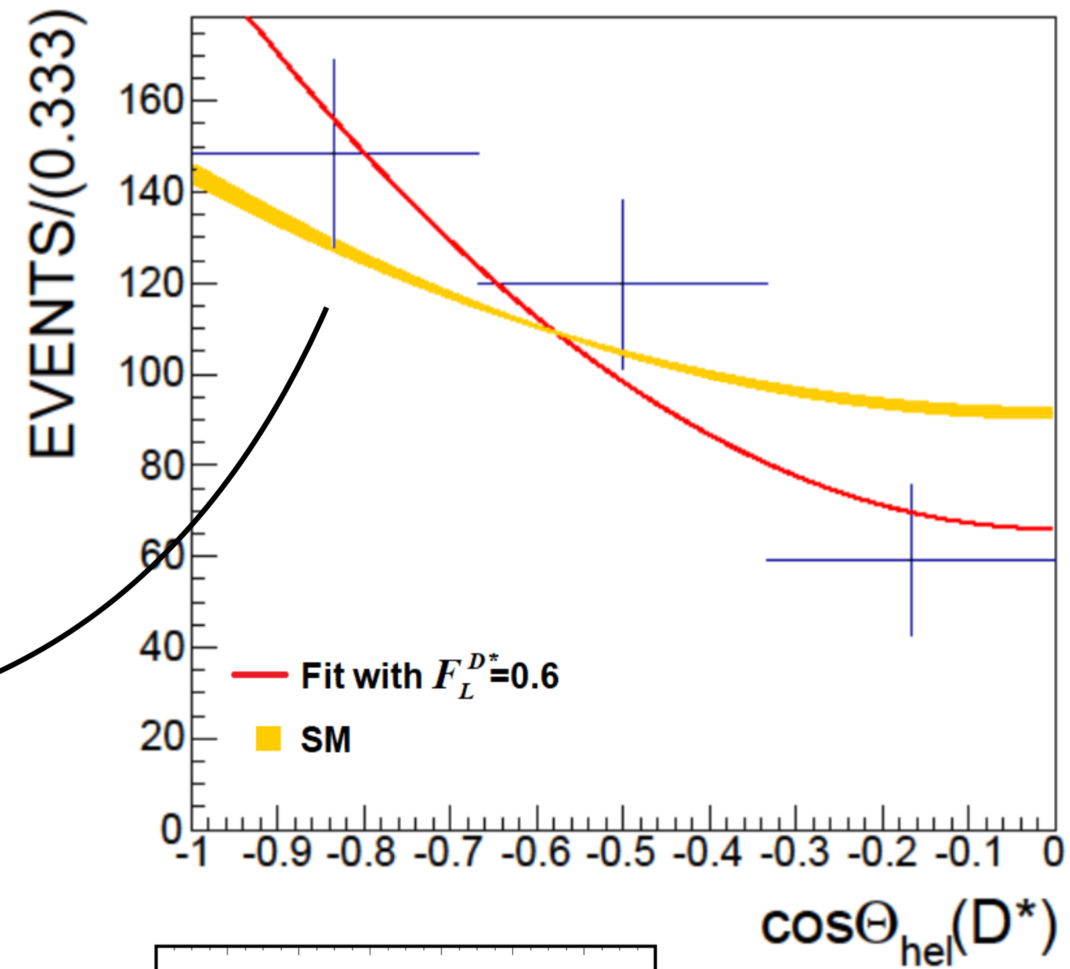
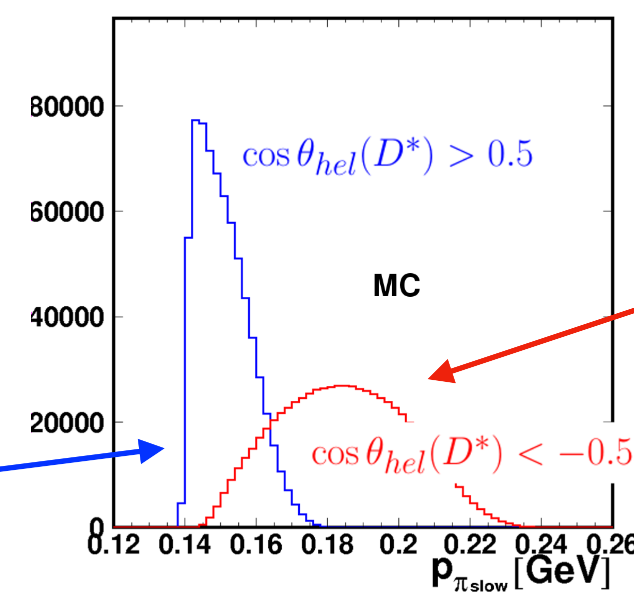




slow pions in [-1,0]

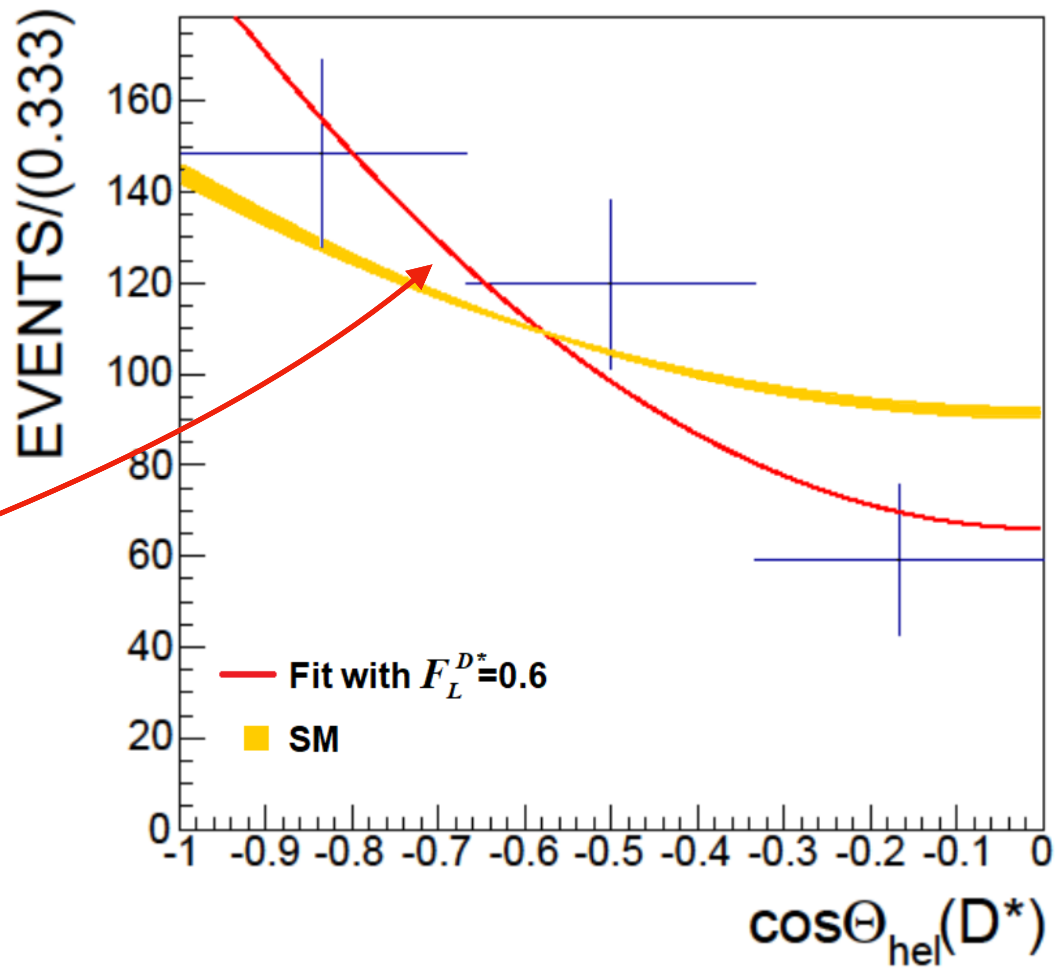
- **Restrict measurement to [-1,0] due to low efficiency for slow pions in [0,1]**

$F_L^{D^*}$ with inclusive tagging

Prel. Belle: https://arxiv.org/pdf/1901.06380.pdf (D*, incl. tagging)

- **Fit longitudinal polarisation fraction: $F_L^{D^*}$**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{\rm hel}(D^*)) + (1 - F_L^{D^*})\sin^2(\theta_{\rm hel}(D^*))]$$



$$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$$

- **SM Expectation**

SM: $F_L^{D^*} = 0.46 \pm 0.03$ (Phys. Rev. D **95**, 115038 (2017), A.K. Alok, et al) (1.5 σ)

SM: $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al) (1.8 σ)

Summary of Belle R(D/D*) measurements

Phys. Rev. D 95, 115008 (2017)

$R(D)_{SM} = 0.299 \pm 0.003$
$R(D^*)_{SM} = 0.257 \pm 0.003$

Several results using different techniques:

- **$\tau \to e\nu\nu$** and **$\tau \to \mu\nu\nu$**, *hadronic tag*

  $R(D) = 0.375 \pm 0.064$ (stat) ± 0.026 (syst)
  $R(D^*) = 0.293 \pm 0.038$ (stat) ± 0.015 (syst)

  Analysis very similar to BaBar

- **$\tau \to e\nu\nu$** and **$\tau \to \mu\nu\nu$**, *semi-leptonic tag*

  $R(D^*) = 0.302 \pm 0.030$ (stat) ± 0.011 (syst)

- **$\tau \to \pi\nu$** and **$\tau \to \rho\nu$**, *hadronic tag*

  $R(D^*) = 0.270 \pm 0.035$ (stat) ± 0.027(syst)
  $P_\tau(D^*) = -0.38 \pm 0.51$ (stat) ± 0.18 (syst)

  First measurement of τ polarisation

- **$\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$** and **$\tau \to \pi\nu$**, *inclusive tag*

  $F_L(D^*) = 0.60 \pm 0.08$ (stat) ± 0.04 (syst) First measurement of *D** polarisation

Summary of Belle measurements

Phys. Rev. D 95, 115008 (2017)

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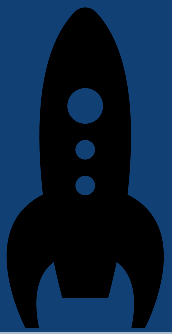
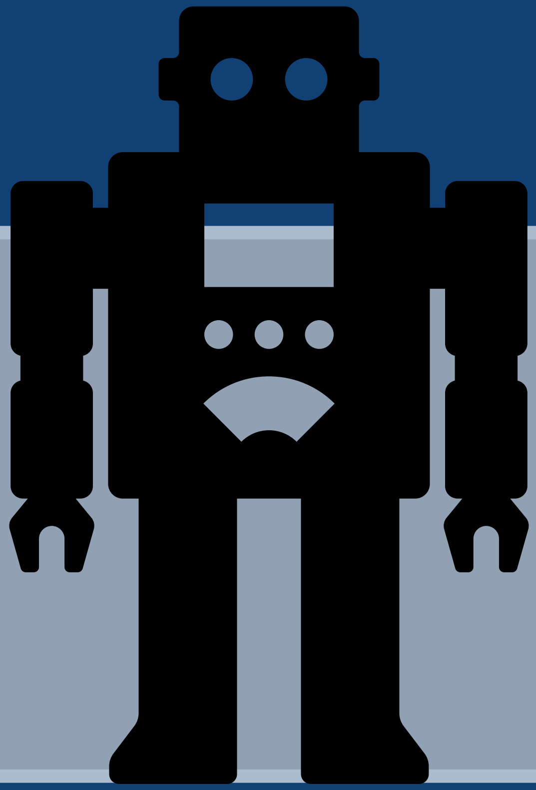
✓ **All $R(D^{(*)})$ measurements consistent but above SM**



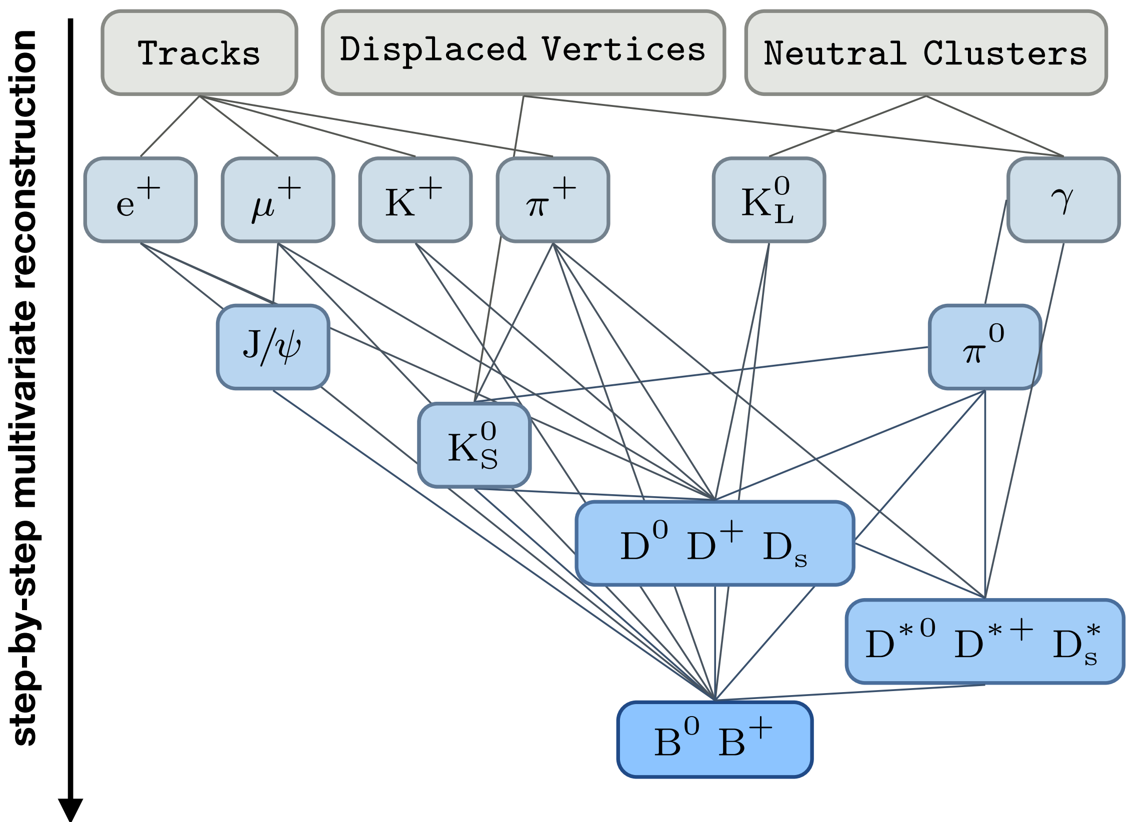
Belle II

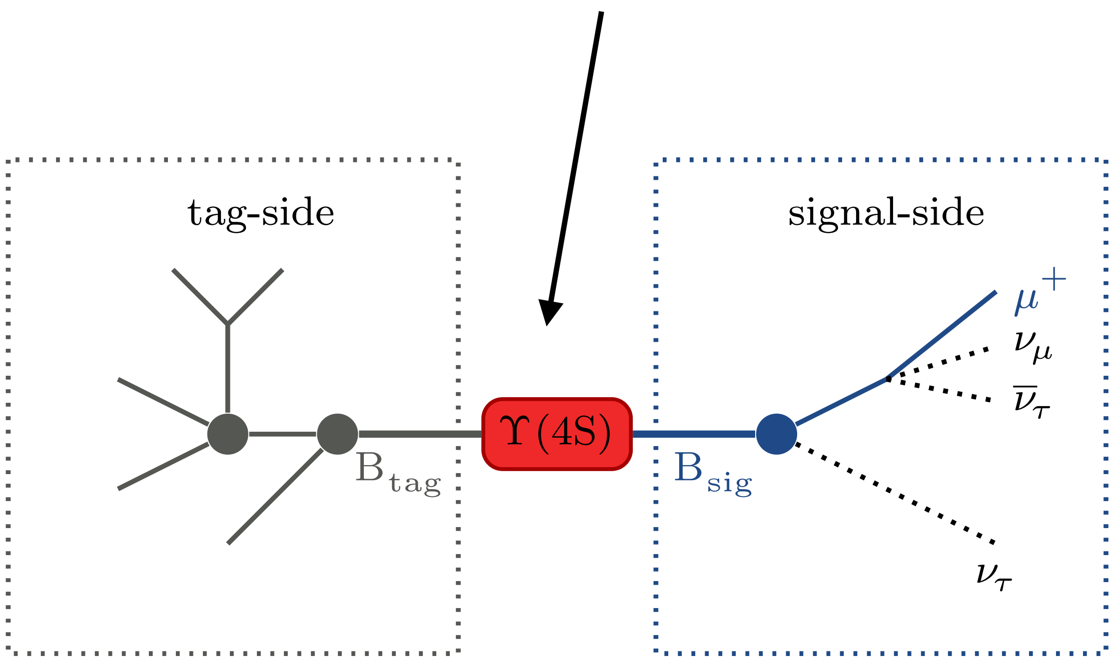


"I am here to help"

Tagging in Belle II: Meet the FEI

T. Keck et al, arXiv:1807.08680, accepted by Computing and Software for Big Science





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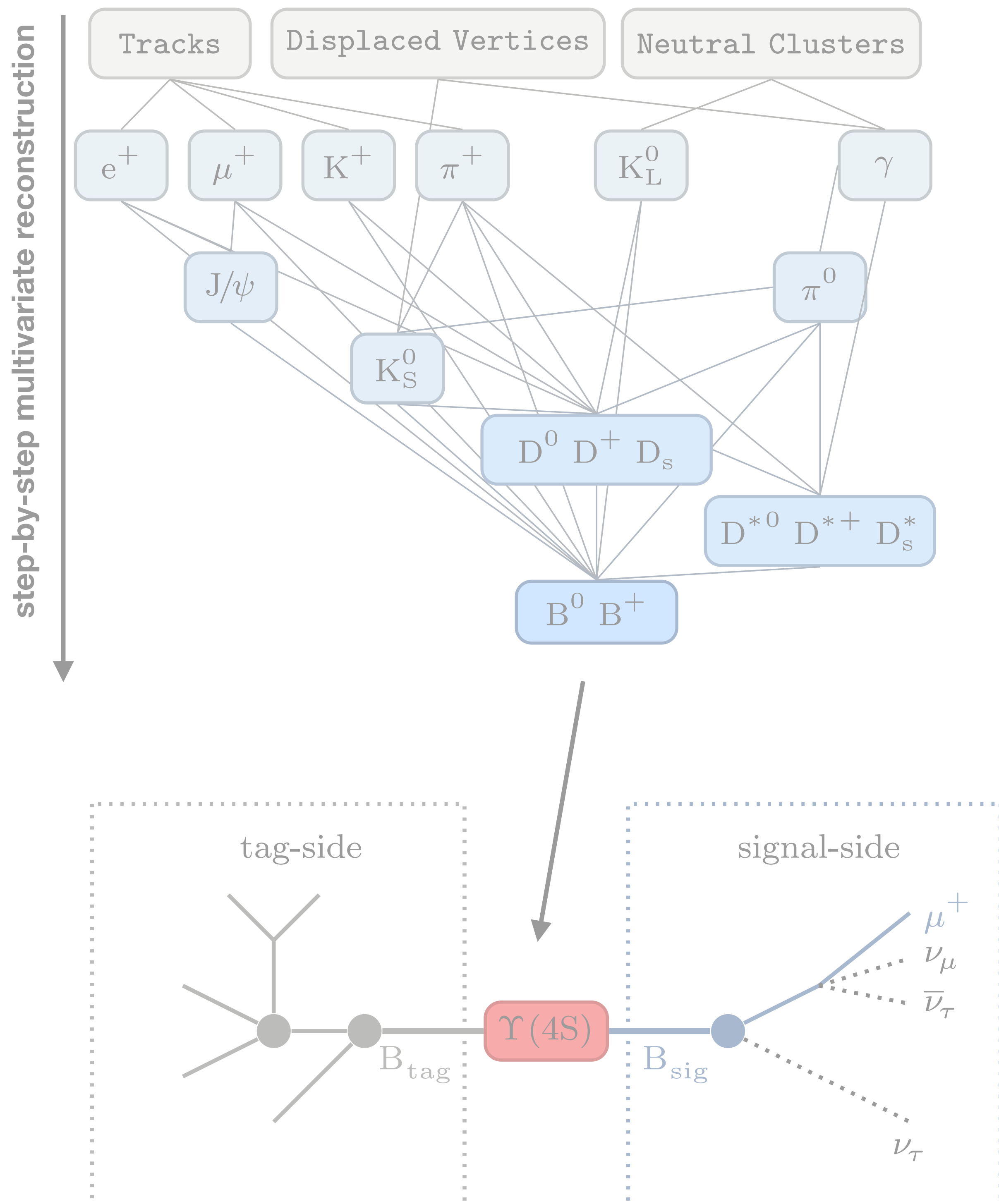
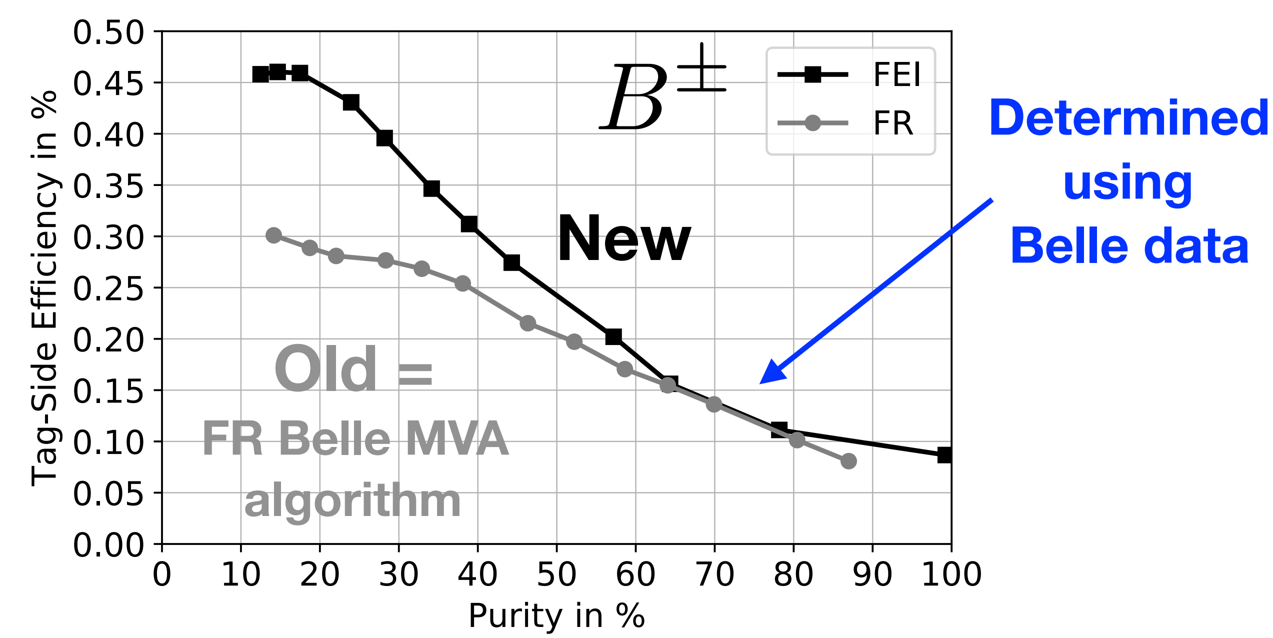


Full Event Interpretation (FEI) Performance:

	FEI		other algorithms		
	$B^\pm$	B^0		$B^\pm$	B^0
Hadronic			Hadronic		
FEI with FR channels	0.53 %	0.33 %	FR	0.28 %	0.18 %
FEI	0.76 %	0.46 %	SER	0.4 %	0.2 %
Semileptonic			Semileptonic		
FEI	1.80 %	2.04 %	FR	0.31 %	0.34 %
			SER	0.3 %	0.6 %

- **Significant improvement of performance**



Tagging in Belle II: Meet the FEI

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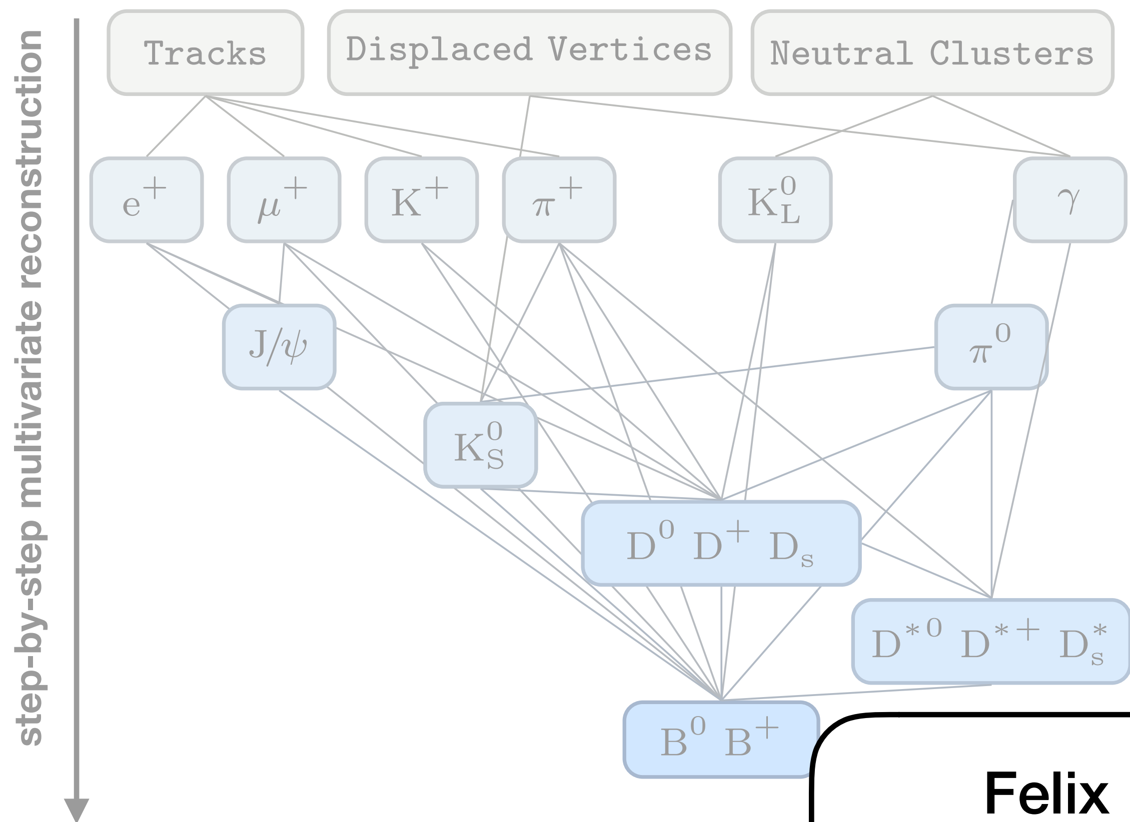

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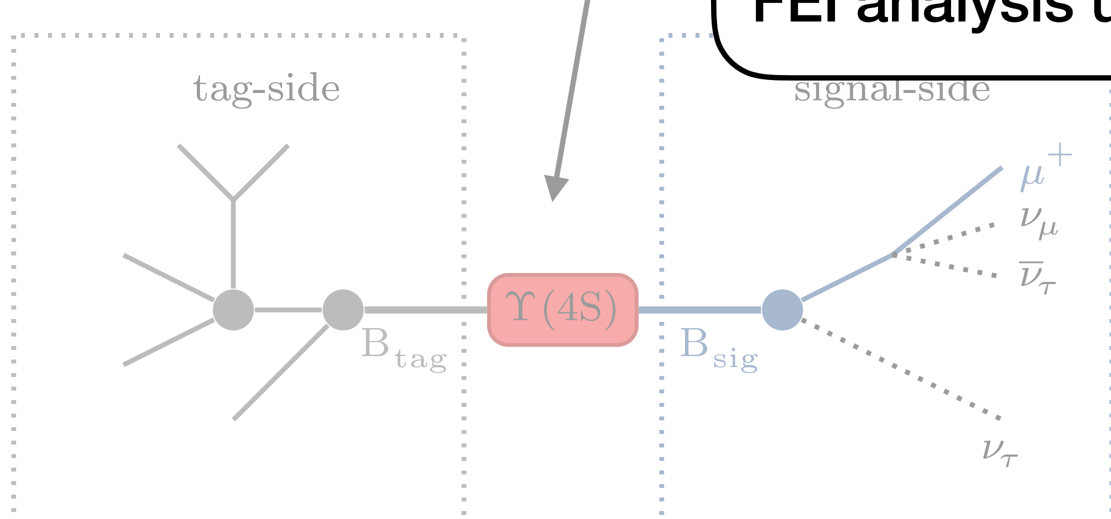
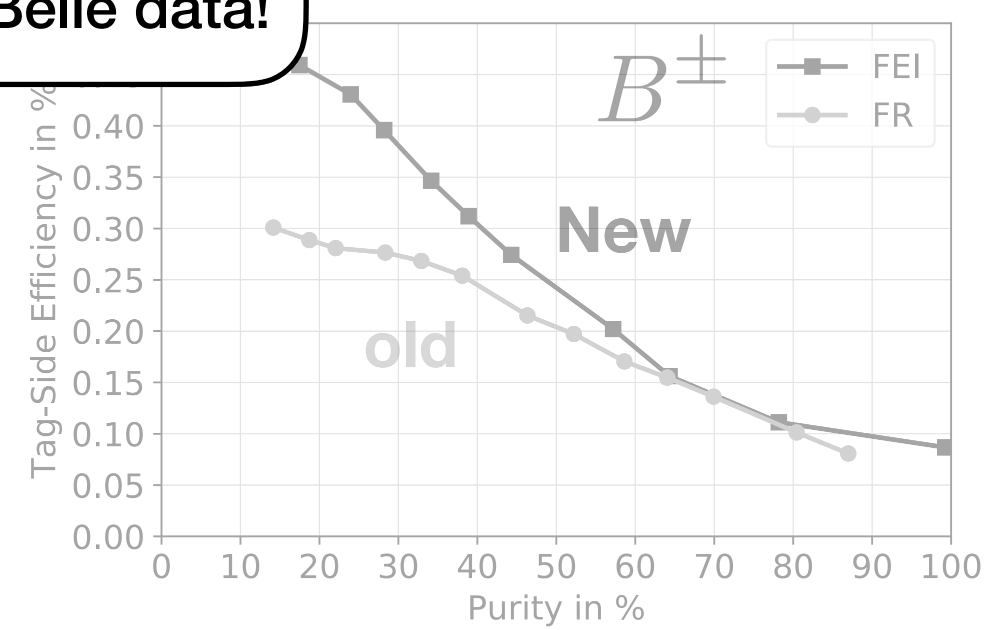
Felix Metzner's talk will show details of the first FEI analysis using Belle data!

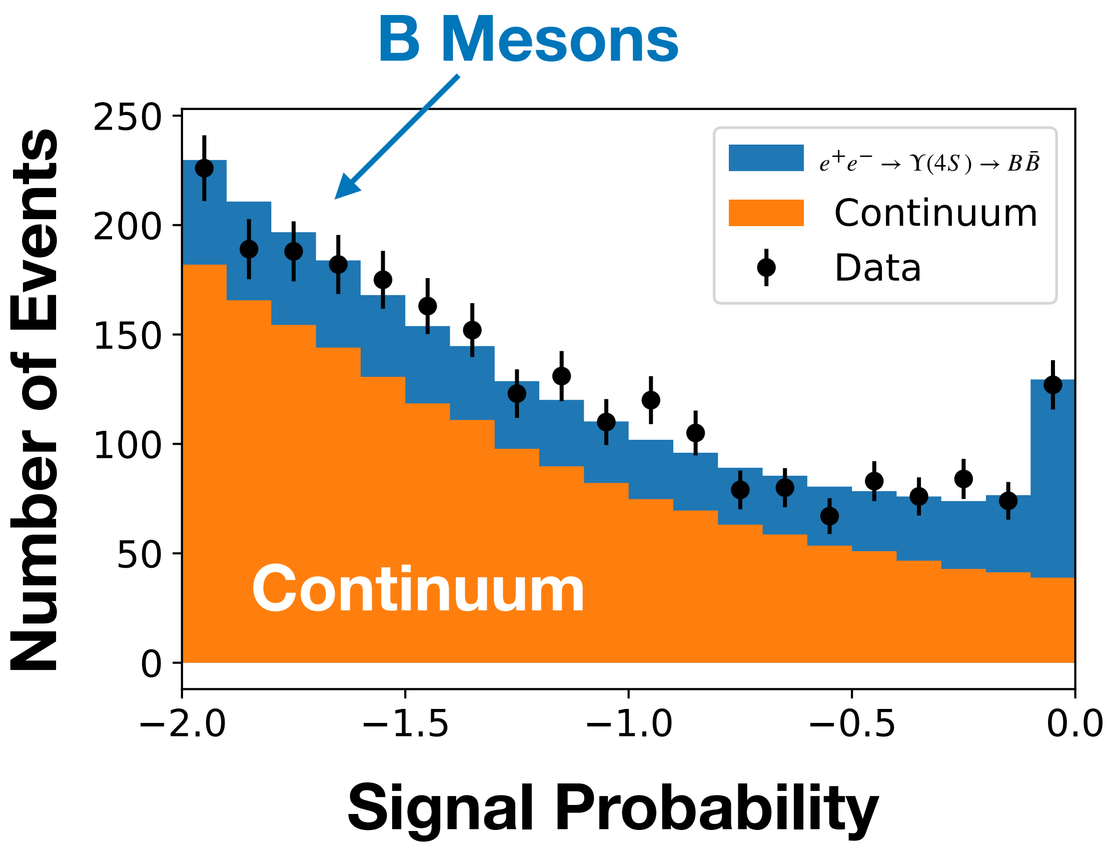
…t improvement of performance





FEI validation with first Belle II data

- Validated FEI functionality in first Belle II data
- **Classifier output** of **0.5/fb** Phase II **data**
  - After applying a shape fit to normalise B-Meson and continuum contributions properly



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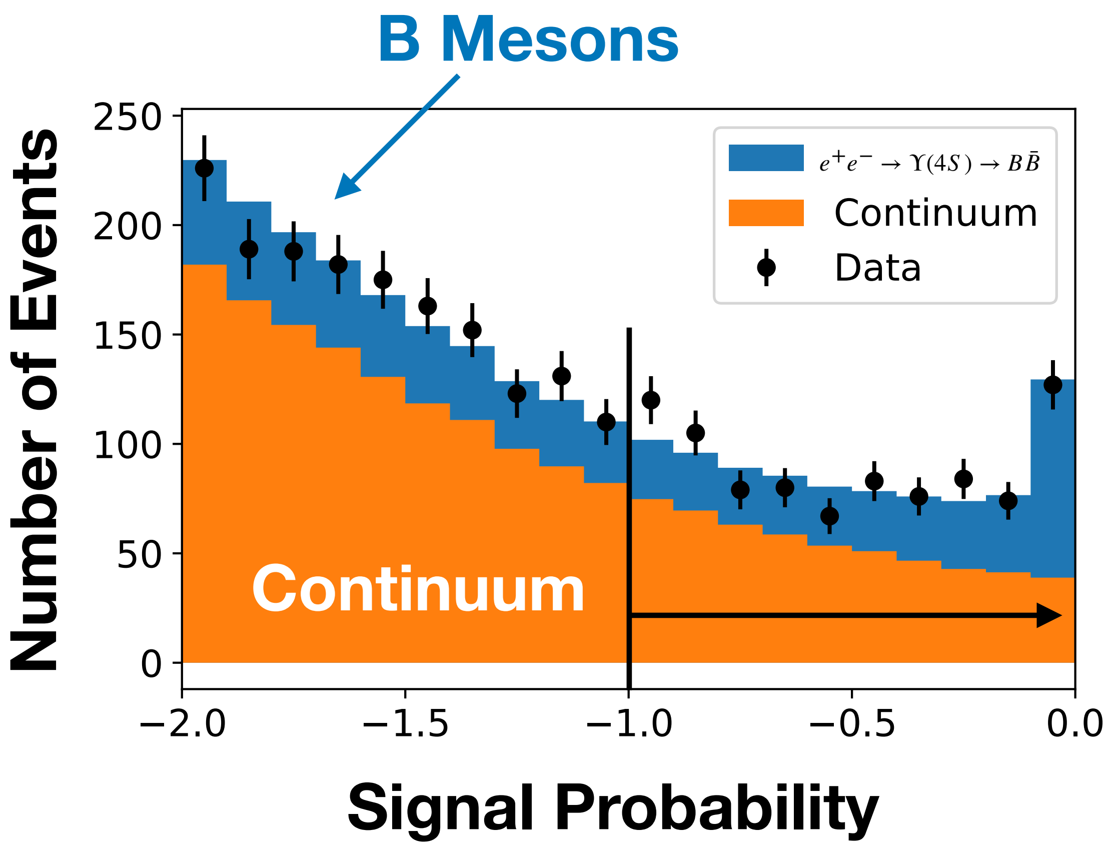
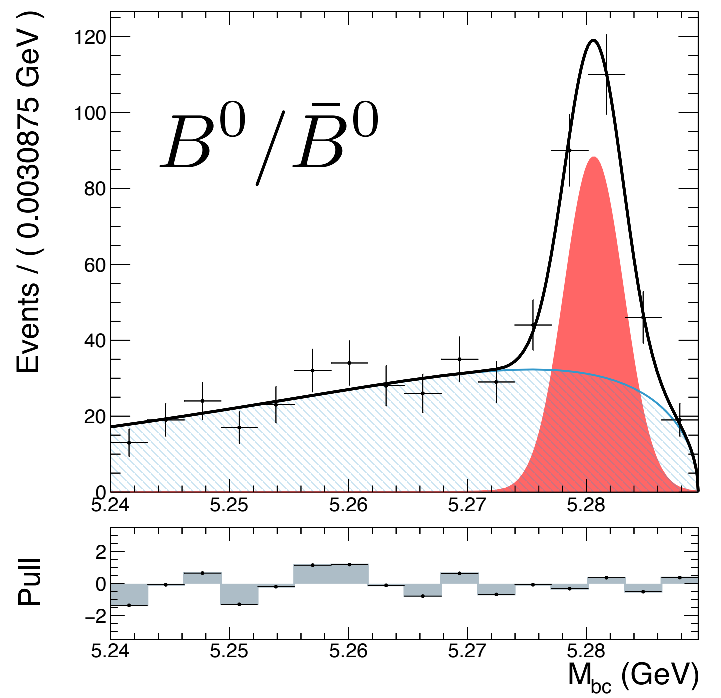
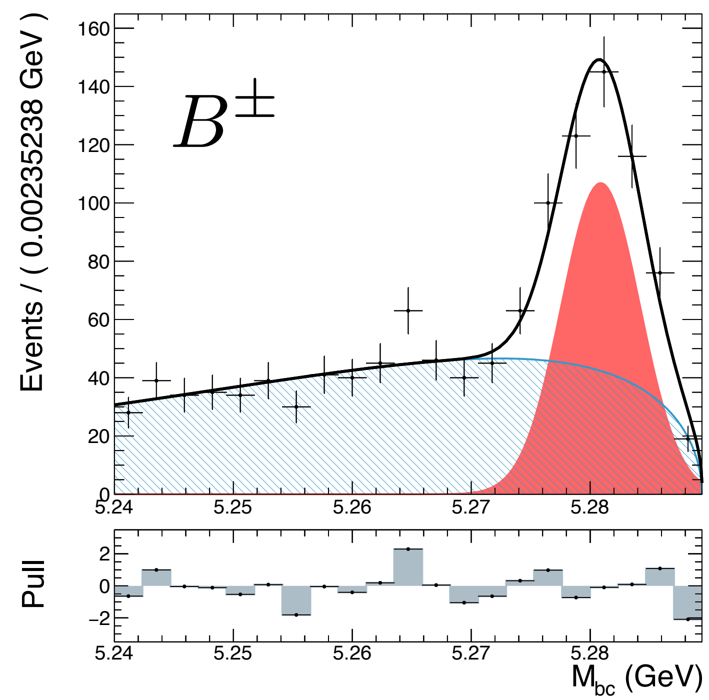




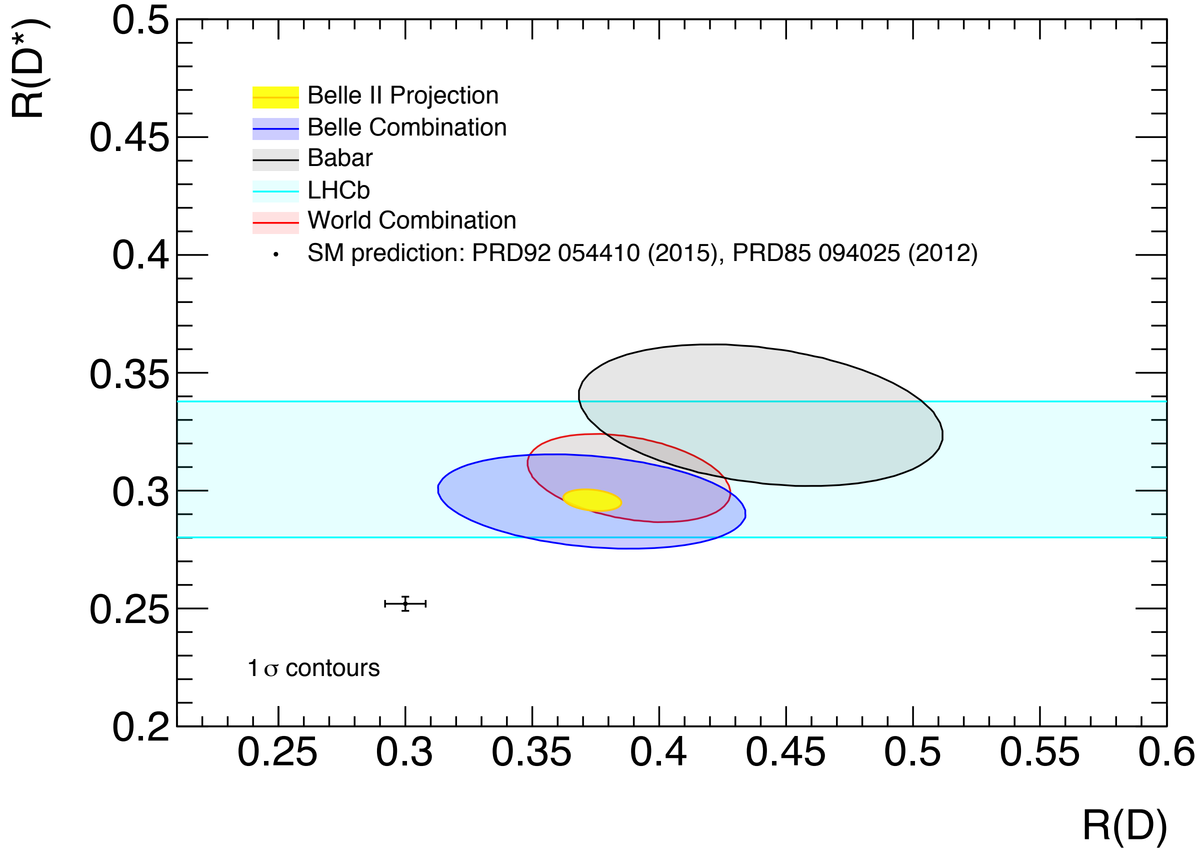
beam constrained B Meson mass

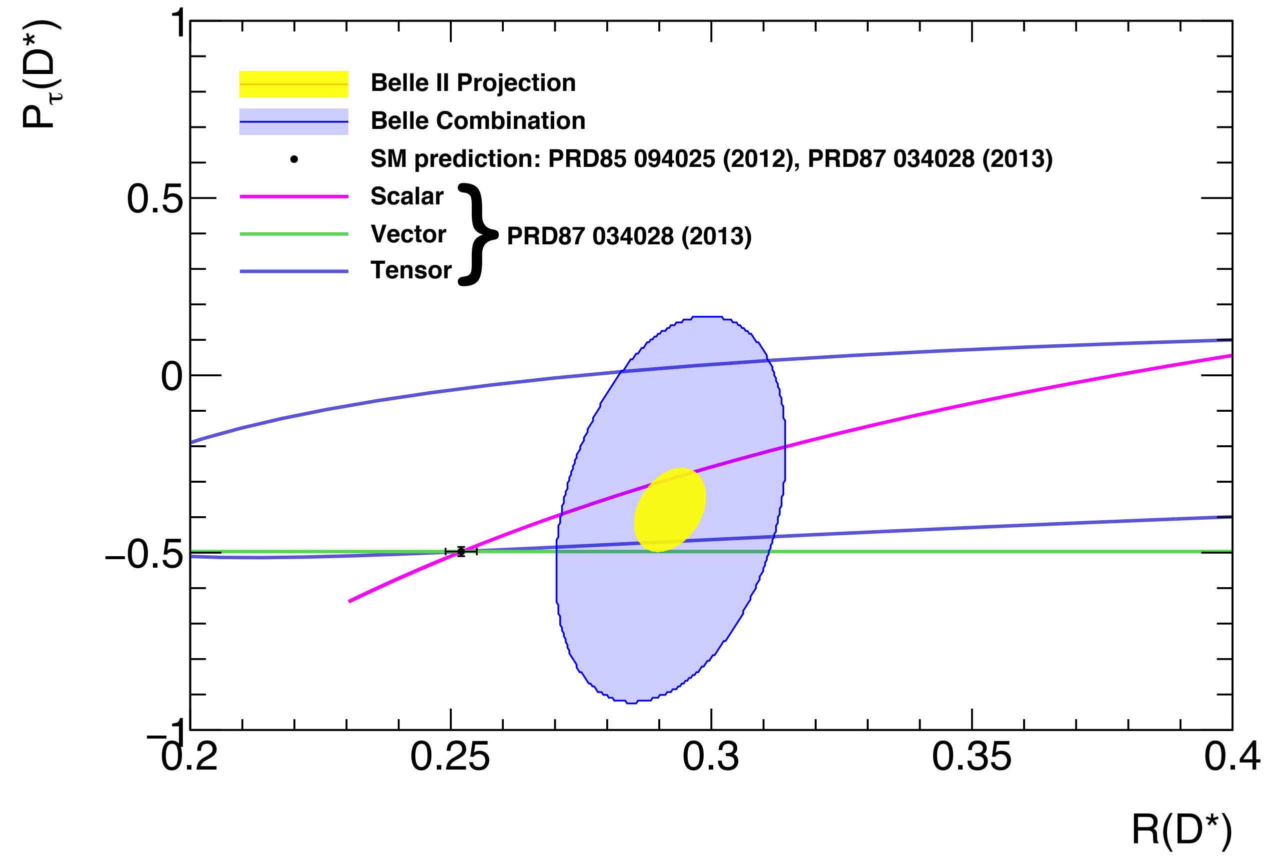


beam constrained B Meson mass

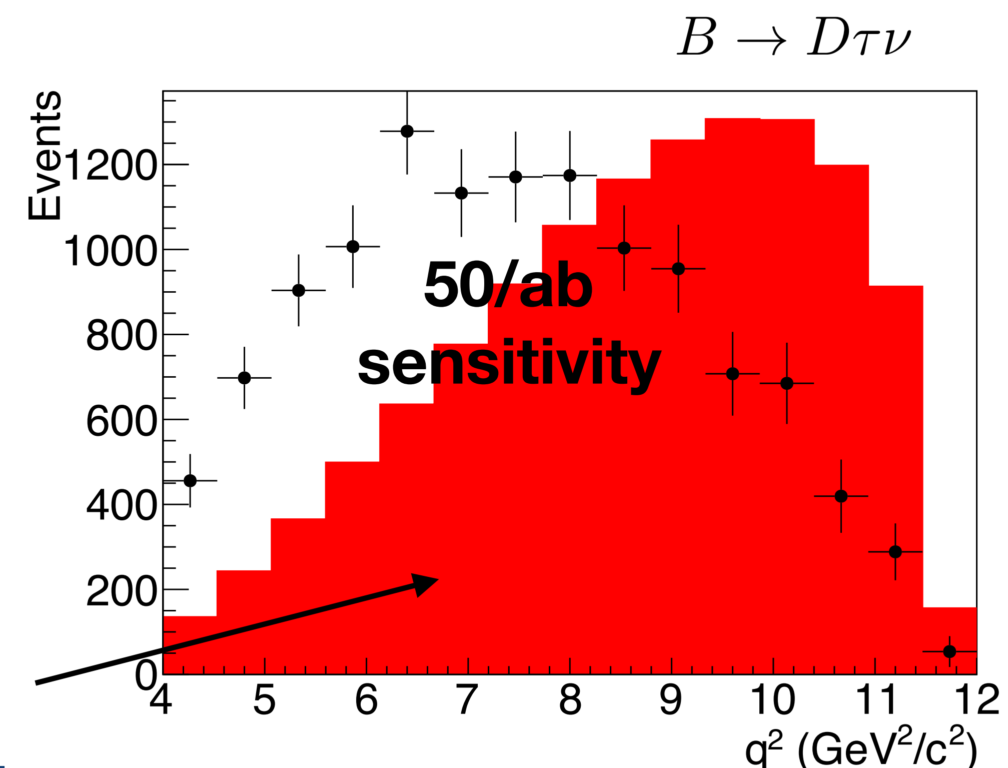
- Found **374 ± 40** charged and **176 ± 23** neutral B meson candidates from fitting $M_{\rm bc} = \sqrt{s/4 - |\vec{p}_B|^2}$

R(D) and R(D*) in the Belle II era





	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$



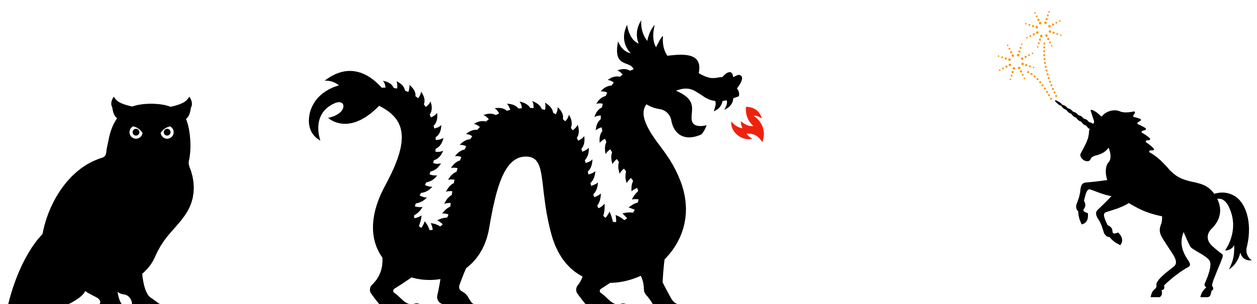
2HDM of type II at $\tan\beta/m_{H^\pm} = 0.5\ (\mathrm{GeV}/c^2)^{-1}$.

Summary :

Belle II will be highly competitive **measuring semi-tauonic decays**

Belle data still very useful to **prototype** or **develop** new analysis strategies

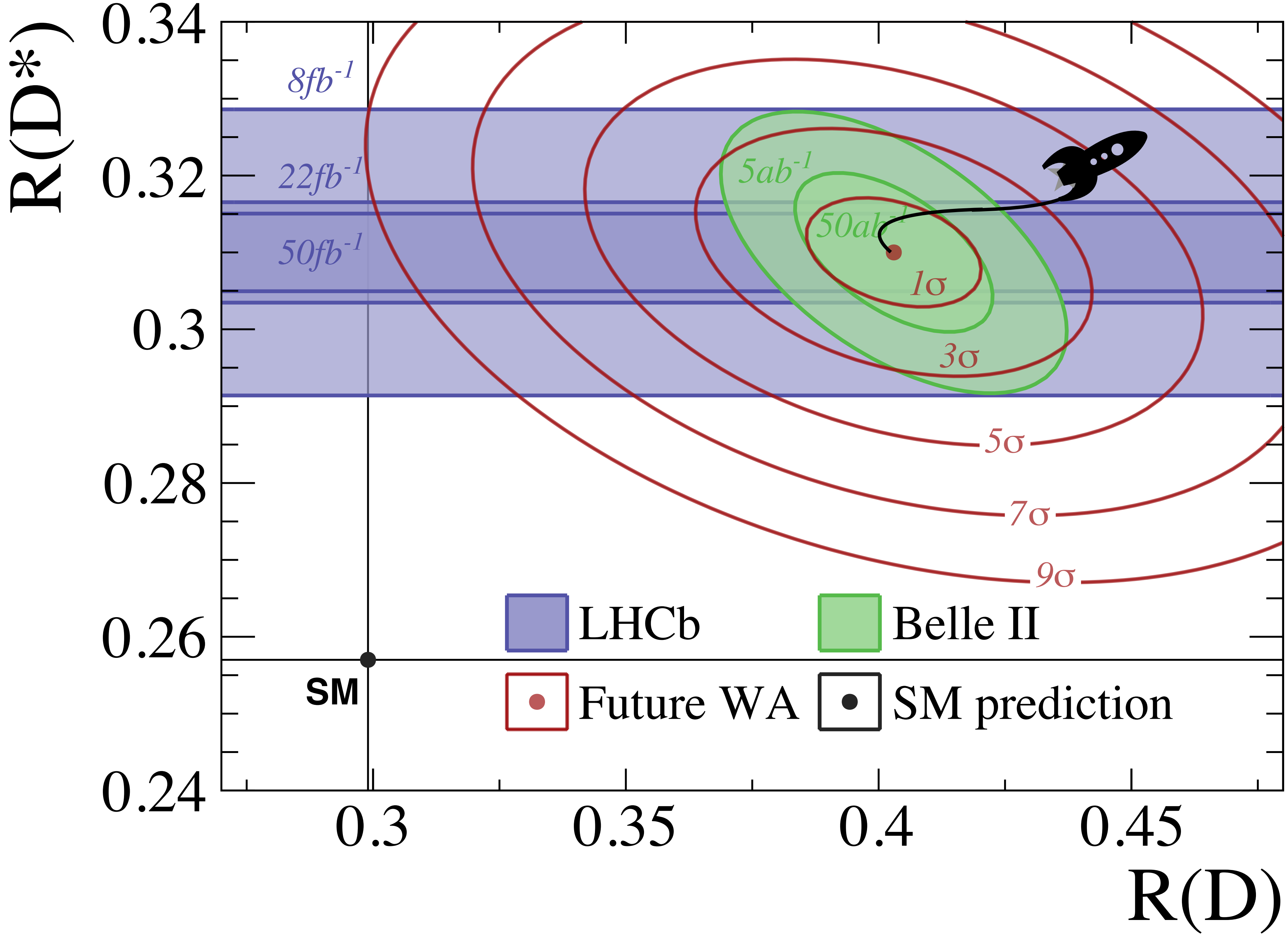
The years to come will be exciting!



Backup

And including the competition (older numbers for Belle II)

J. Albrecht, FB, S. Reicher,
M. Kenzie, D. Straub, A. Tully
arXiv:1709.10308



LHCb
10/fb & 22/fb
4% & 2%

Belle II
5/ab & 50/ab
R(D): 5.6% & 3.2%
R(D*): 3.9% & 2.2%

Impact of **τ-polarisation in**

$\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ decays :

- **-** **secondary lepton** emitted preferentially **in** the **direction** of the τ
    - **Carries more momentum of the τ-lepton**
- **+** **secondary lepton** emitted preferentially **against** the **direction** of the τ
    - **Carries less momentum of the τ-lepton**