



中国科学院大学
University of Chinese Academy of Sciences



底强子半轻衰变中的 轻子普适性检验

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提纲

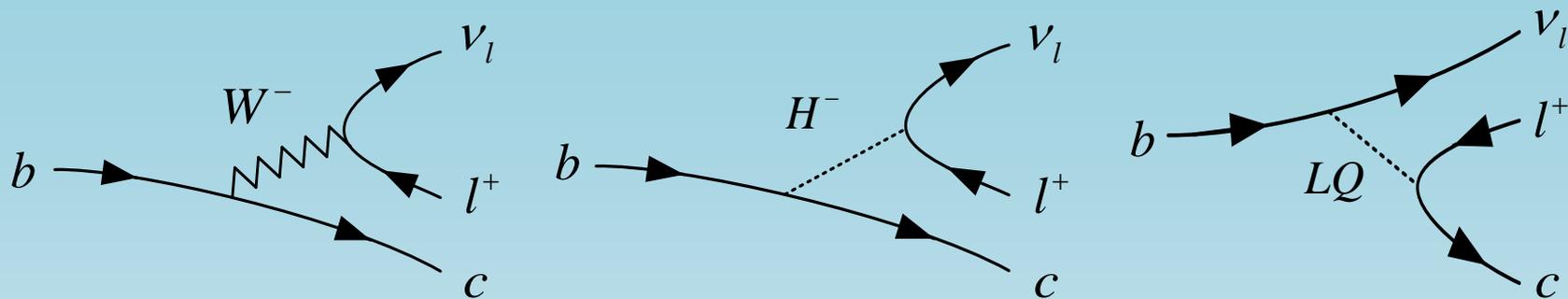
1. 轻子普适性介绍

2. LHCb上的轻子普适性测量

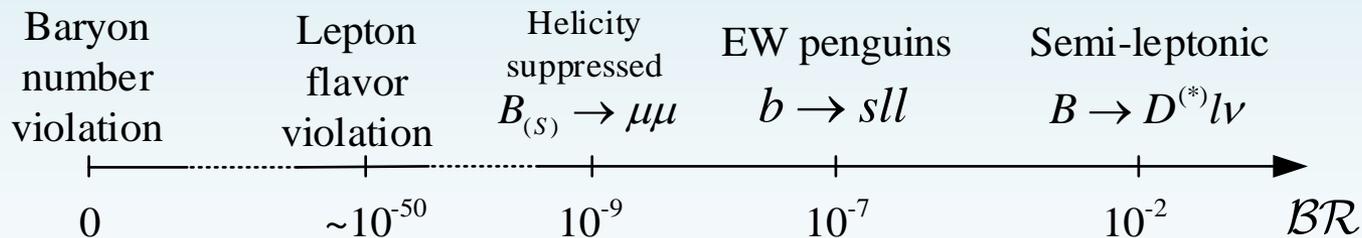
- $\mathcal{R}(D^*) \tau \rightarrow \mu$ 衰变测量
- $\mathcal{R}(D^*) \tau \rightarrow \pi^+ \pi^- \pi^+$ 衰变测量
- $\mathcal{R}(J/\psi) \tau \rightarrow \mu$ 衰变测量

3. 结论与展望

轻子普适性



- 标准模型假设，三代轻子与规范波色子有相同的耦合强度，称为轻子普适性。
- 轻子间差异仅仅体现在质量不同。
- 新物理：假设有过程，与更重的轻子有更强的耦合。
- $\mathcal{B}(b \rightarrow ct\nu)/\mathcal{B}(b \rightarrow cl\nu)$ 相对衰变分支比将在 $\mathcal{O}(10^{-2})$ 上检验标准模型。



轻子普适性

轻子普适性在其他系统中的检验

- 较轻粒子的全轻/半轻衰变中没有发现显著偏离：

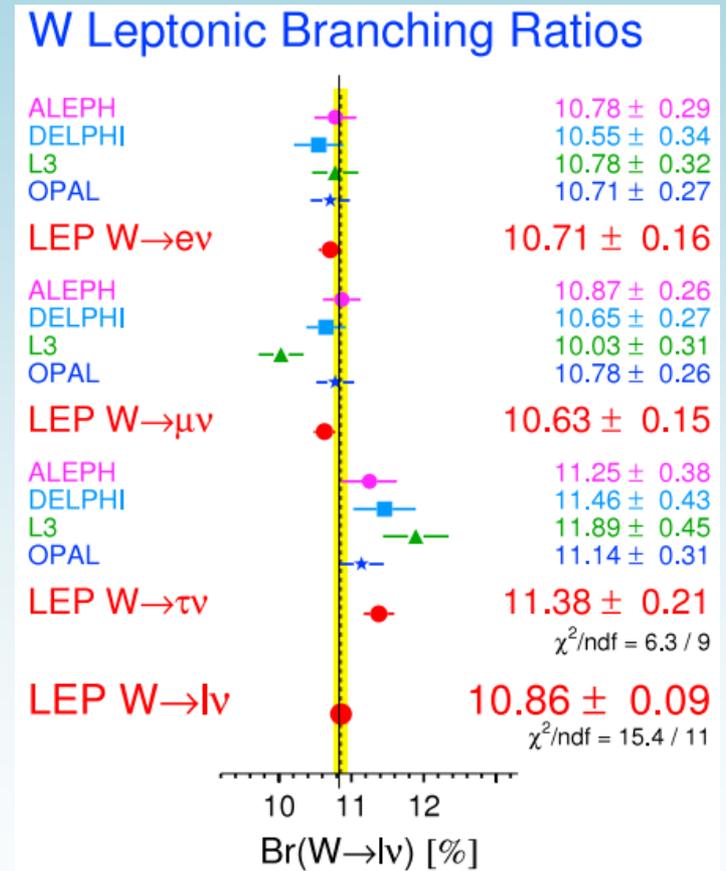
$$J/\psi \rightarrow ll, \tau \rightarrow l\nu\bar{\nu}, \pi \rightarrow l\nu, K \rightarrow \pi l\nu, \dots$$

- $Z \rightarrow ll$ 没有发现偏离。
- $W \rightarrow l\nu$ 中 τ 过程相对有 2σ 偏离：

$$\frac{\mathcal{B}(W \rightarrow \mu\bar{\nu}_\mu)}{\mathcal{B}(W \rightarrow e\bar{\nu}_e)} = 0.993 \pm 0.019$$

$$\left. \begin{aligned} \frac{\mathcal{B}(W \rightarrow \tau\bar{\nu}_\tau)}{\mathcal{B}(W \rightarrow e\bar{\nu}_e)} &= 1.063 \pm 0.027 \\ \frac{\mathcal{B}(W \rightarrow \tau\bar{\nu}_\tau)}{\mathcal{B}(W \rightarrow \mu\bar{\nu}_\mu)} &= 1.070 \pm 0.026 \end{aligned} \right\} 2\sigma$$

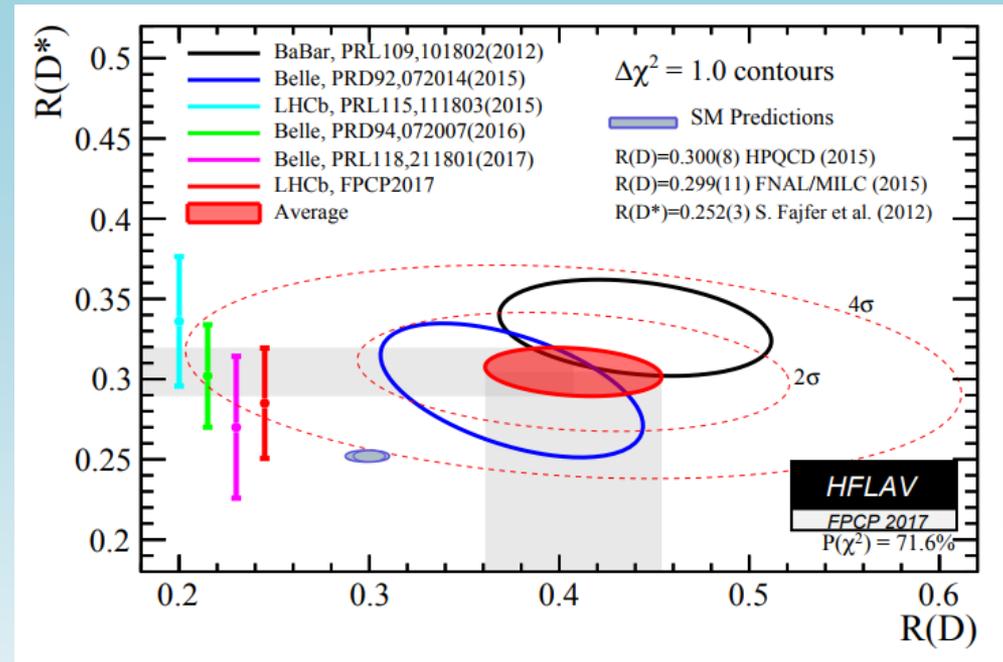
- B 介子 FCNC 过程 $\mathcal{R}(K^{(*)})$ 有 $>2\sigma$ 偏离。



使用B半轻衰变检验轻子普适性: $\mathcal{R}(D^{(*)})$

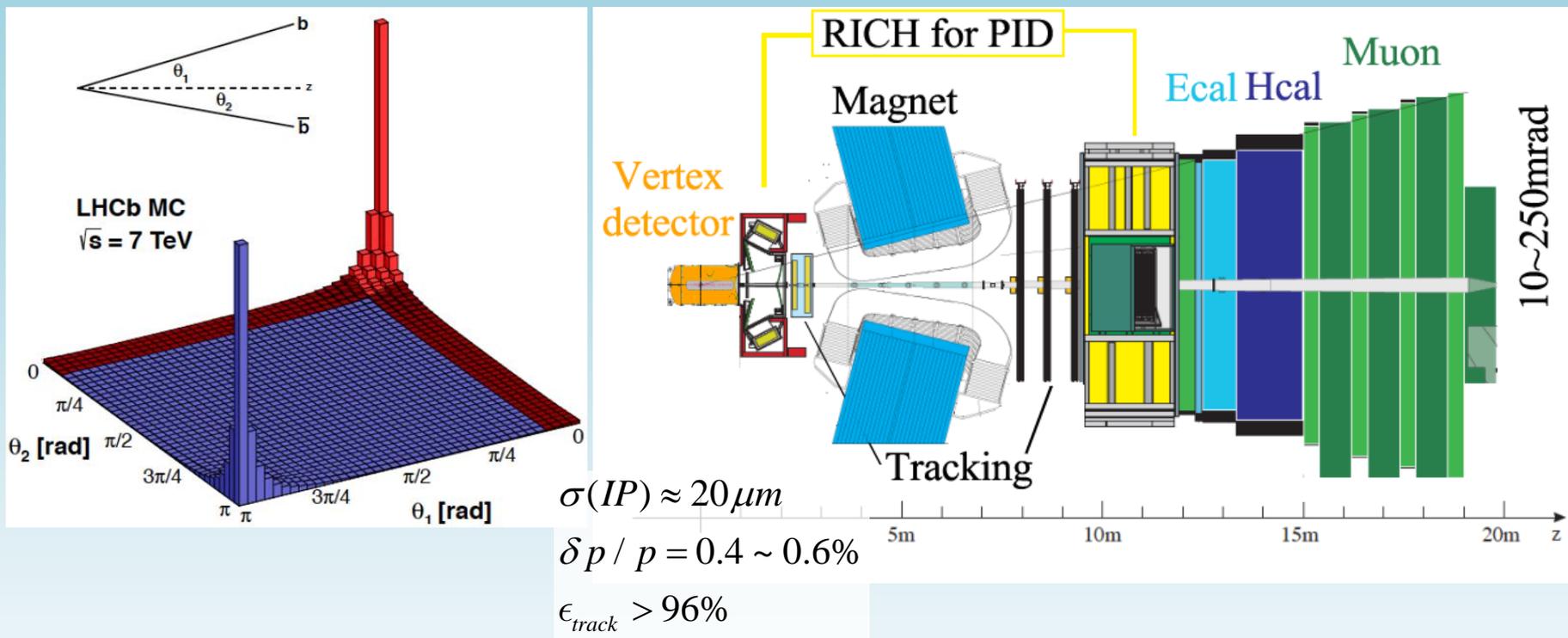
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu}_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} l \bar{\nu}_l)}$$

$$l = e, \mu$$



实验	使用衰变道	τ reconstruction	偏离SM预期
BaBar 2012	$\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D^{(*)} l \bar{\nu}_l)$	$\tau \rightarrow l \nu \bar{\nu}$	+3.4 σ
Belle 2015	$\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D^{(*)} l \bar{\nu}_l)$	$\tau \rightarrow l \nu \bar{\nu}$	+1.8 σ
LHCb 2015	$\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$	$\tau \rightarrow \mu \nu \bar{\nu}$	+2.1 σ
Belle 2016	$\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} l^- \bar{\nu}_l)$	$\tau \rightarrow l \nu \bar{\nu}$	+1.6 σ
Belle 2017	$\mathcal{B}(\bar{B} \rightarrow D^* \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D^* l^- \bar{\nu}_l)$	$\tau^- \rightarrow \pi^- \nu_\tau, \rho^- \nu_\tau$	<1 σ
LHCb 2017	$\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$	$\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu$	+1.0 σ

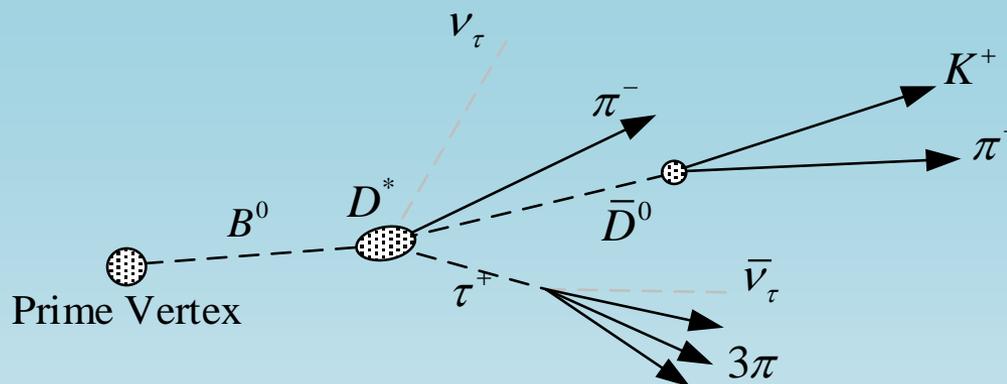
LHCb对轻子普适性检验



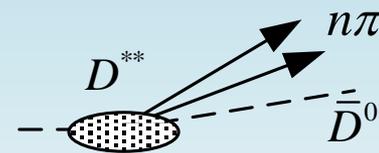
优势：海量事例。径迹重建，初级与次级顶点区分， μ 与D事例高触发效率。

困难：没有质心能量约束、missing energy，使信号没有特征峰。

分析方法



- 精确的次级顶点重建：
Soft π for D^* 顶点, 3π for τ 衰变顶点。
- Charge & neutron isolation 方法, 筛选掉大部分物理本底。
- 部分重建方法, 近似重建出粒子信息。



$$\frac{(p_B)_z}{m_B} \simeq \frac{(p_{visible})_z}{m_{visible}} \rightarrow |p_B| = (p_B)_z \sqrt{1 + \tan^2 \alpha}$$

$$\left. \begin{array}{l} p_\tau^\mu = p_{3\pi}^\mu + p_\nu^\mu \\ (p_\nu^\mu)^2 = 0 \end{array} \right\} \rightarrow p_\tau^\mu; \quad \left. \begin{array}{l} p_B^\mu = p_{D^*}^\mu + p_\tau^\mu + p_\nu^\mu \\ (p_\nu^\mu)^2 = 0 \end{array} \right\} \rightarrow p_B^\mu$$

$\mathcal{R}(D^*)(\tau \rightarrow \mu)$ 测量

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}, \begin{cases} \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu \\ D^{*+} \rightarrow D^0 \pi^+ \\ D^0 \rightarrow K^- \pi^+ \end{cases}$$

- 形状因子的误差可以部分抵消，理论计算准确。
- $\mathcal{B}(\tau^+ \rightarrow \mu^+ \bar{\nu}_\tau \nu_\mu) = (17.41 \pm 0.04)\%$
- 使用B质心系中的运动学变量进行三维拟合：

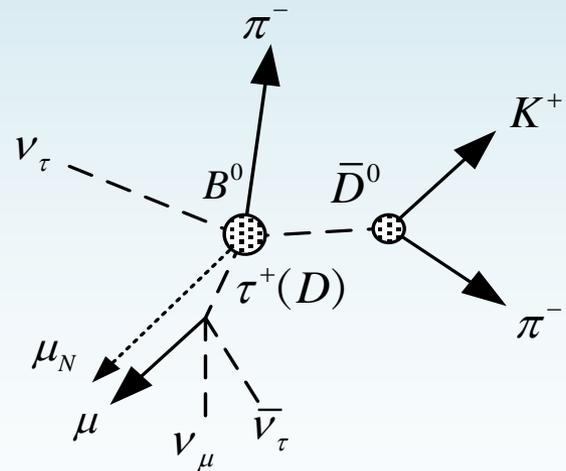
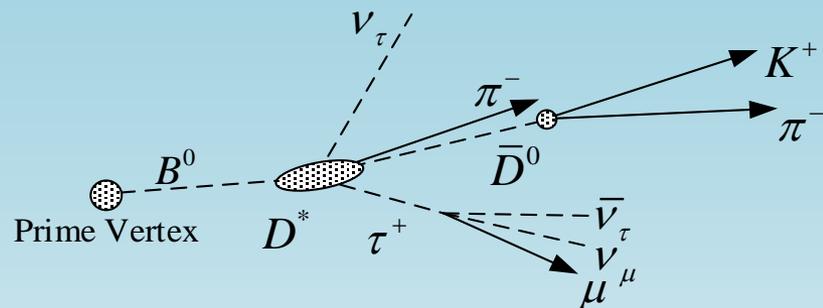
- μ 能量 E_μ^* .

- 丢失质量：

$$m_{miss}^2 = (p_B^\mu - p_{D^*}^\mu - p_l^\mu)^2$$

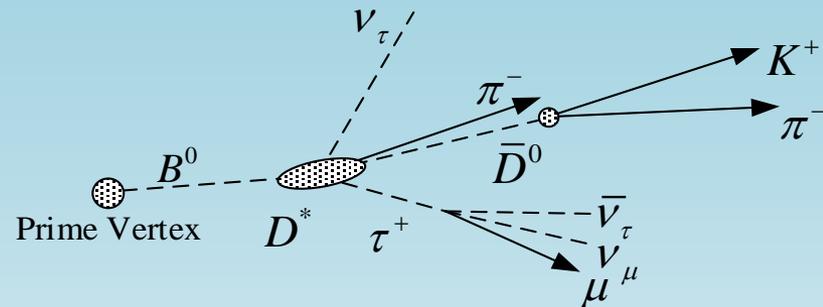
- 转移4-动量

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



$\mathcal{R}(D^*)(\tau \rightarrow \mu)$ 测量

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- 转移4-动量

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

信号与 D^*D 事例

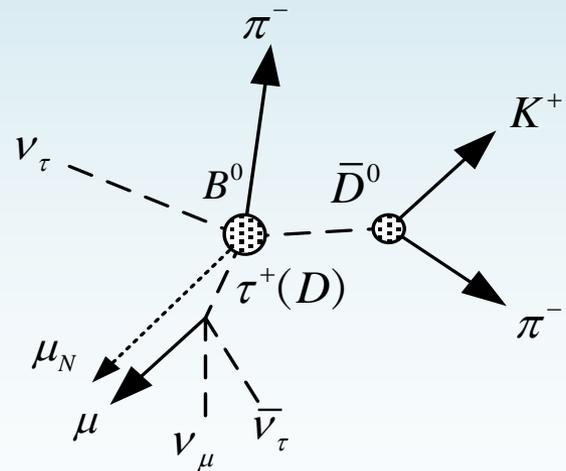
小 E_μ^* , 大 q^2

$$m_{miss}^2 > 0$$

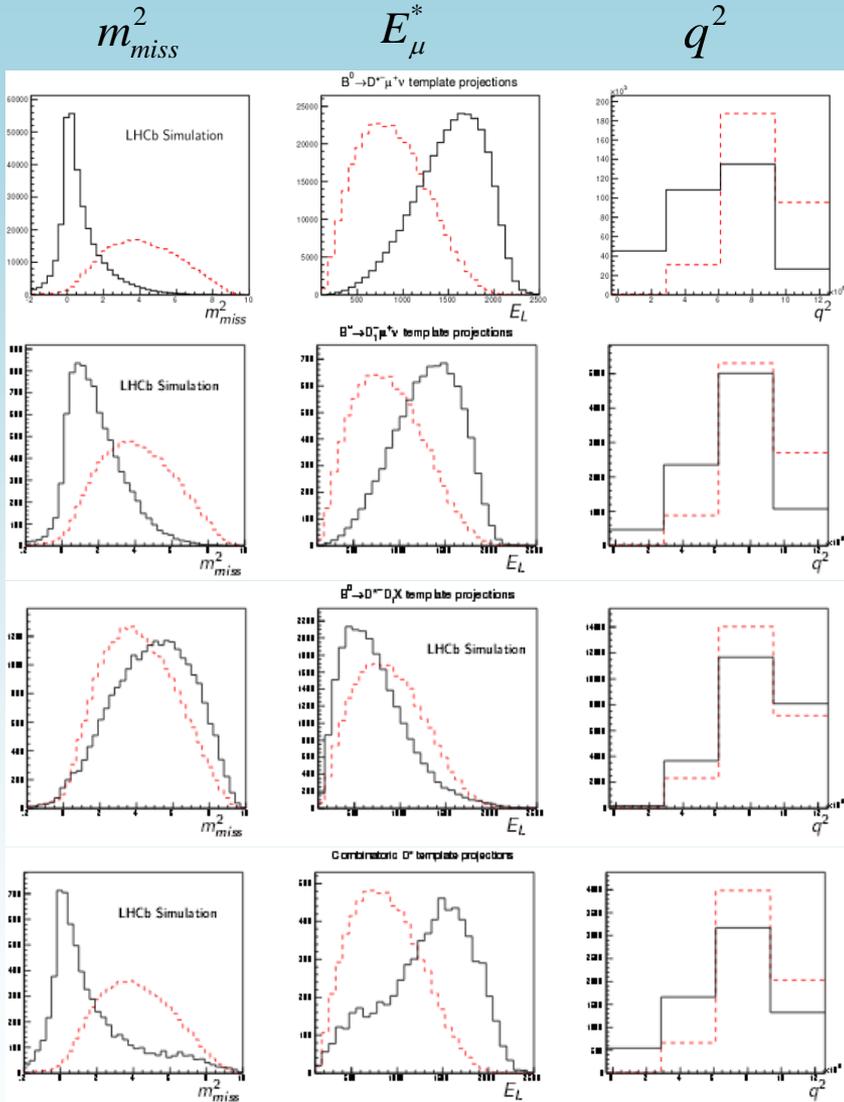
归一化道

大 E_μ^* , 平均的 q^2

$$m_{miss}^2 \approx 0$$



$\mathcal{R}(D^*)(\tau \rightarrow \mu)$ 测量



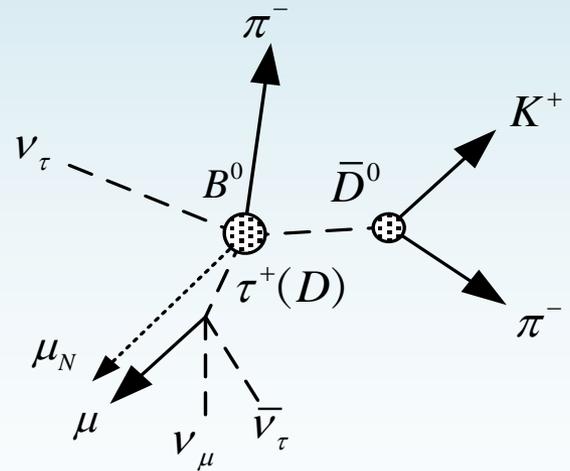
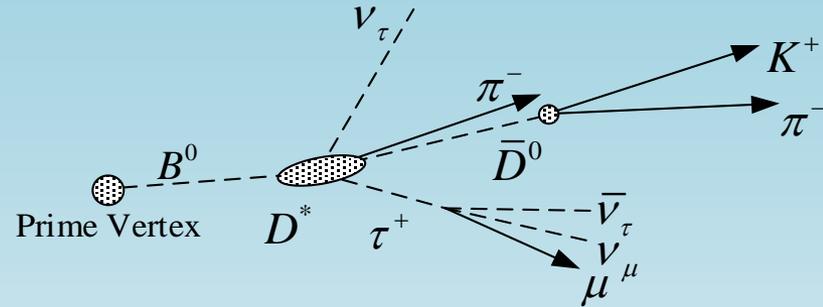
$D^* \tau \nu$

$D^{*+} \mu \nu$

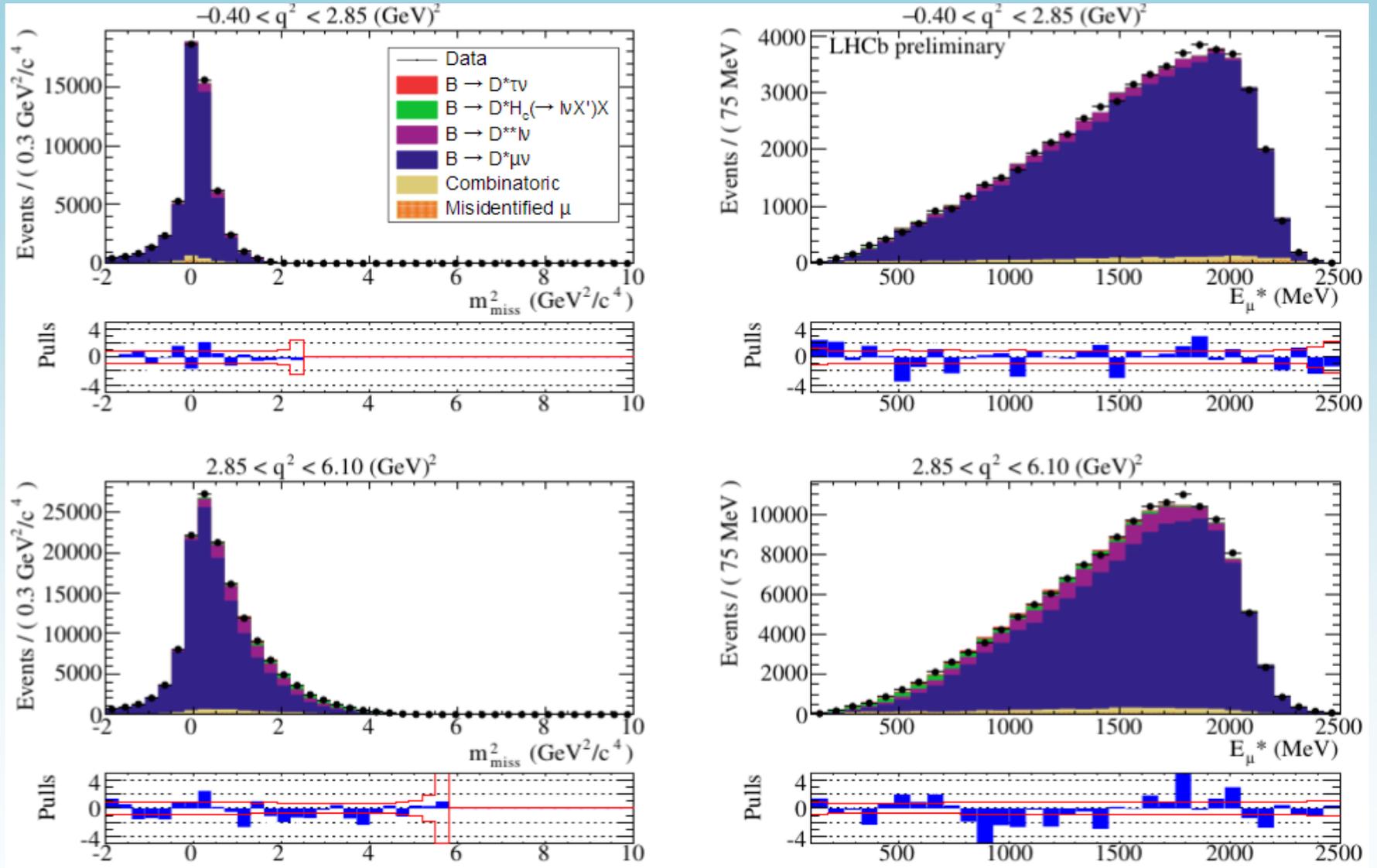
$D^{**} l \nu$

$D^* D$

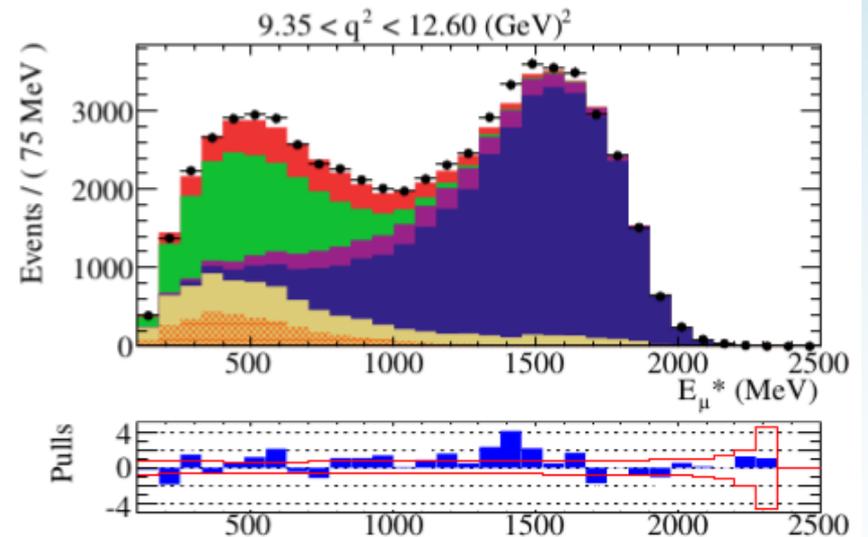
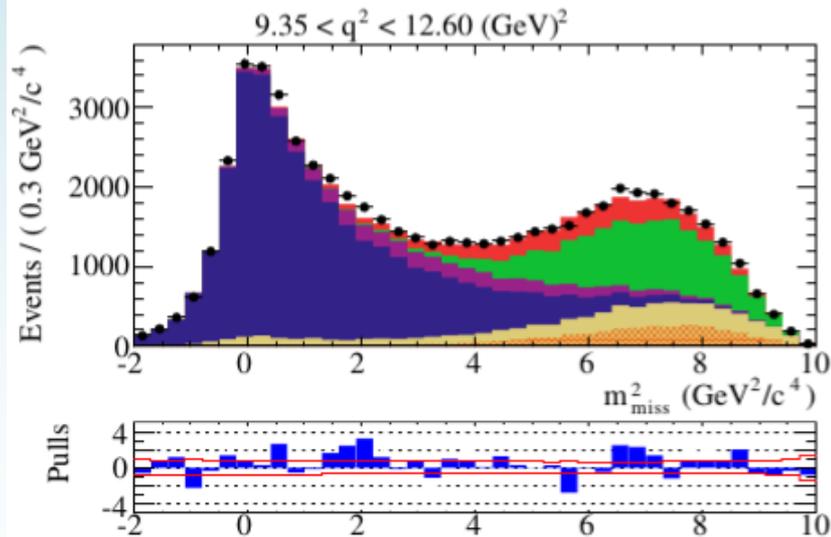
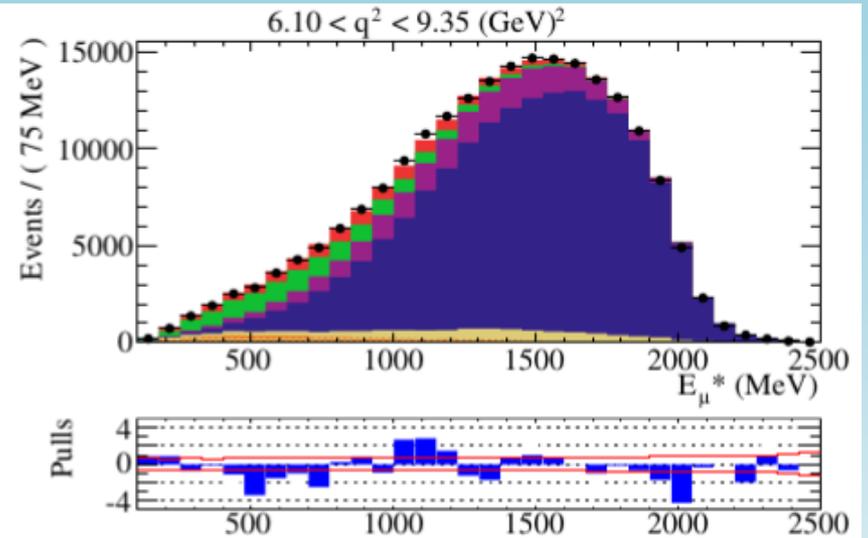
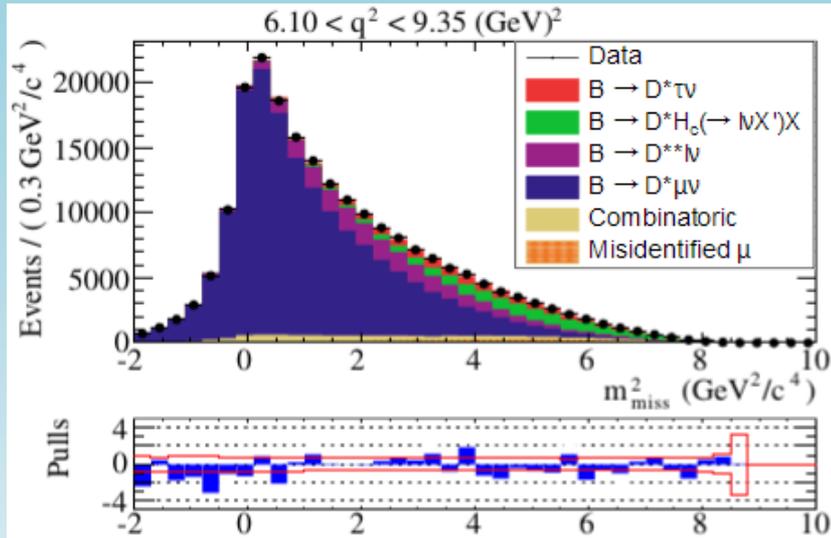
组合本底



$\mathcal{R}(D^*)(\tau \rightarrow \mu)$ 分析拟合结果(小 q^2)

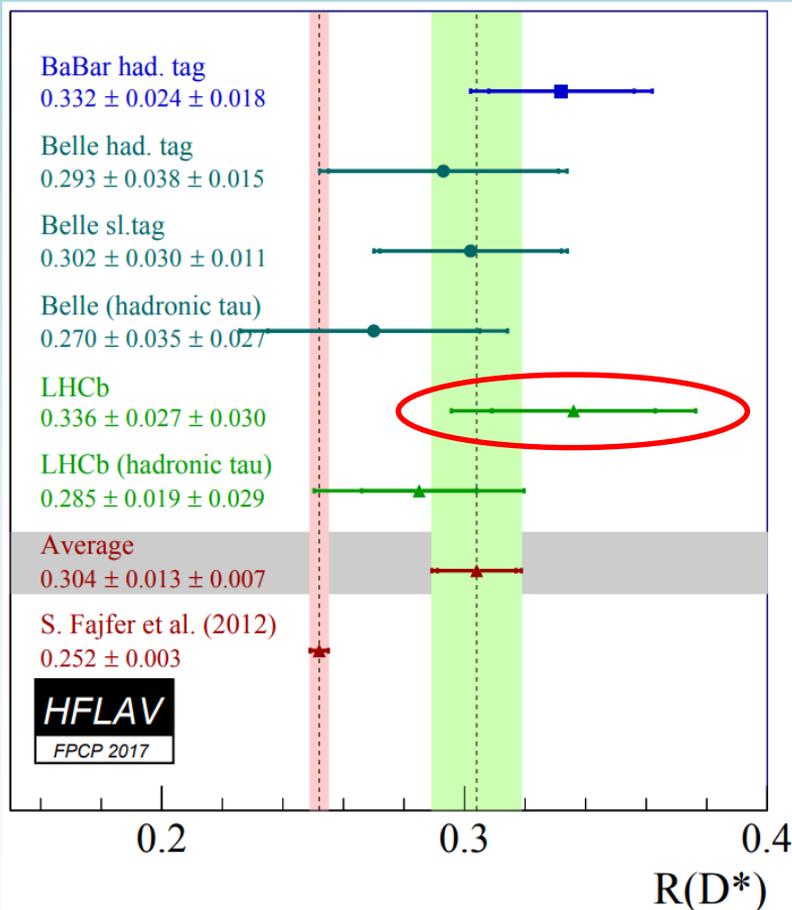


$\mathcal{R}(D^*)(\tau \rightarrow \mu)$ 分析拟合结果 (大 q^2)



$\mathcal{R}(D^*)(\tau \rightarrow \mu)$ 结果

- 使用 LHC 3.0fb⁻¹ 2011 & 2012 @ 7TeV & 8TeV 数据。
- $\mathcal{R}(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$, 偏离理论预期 2.1 σ 。



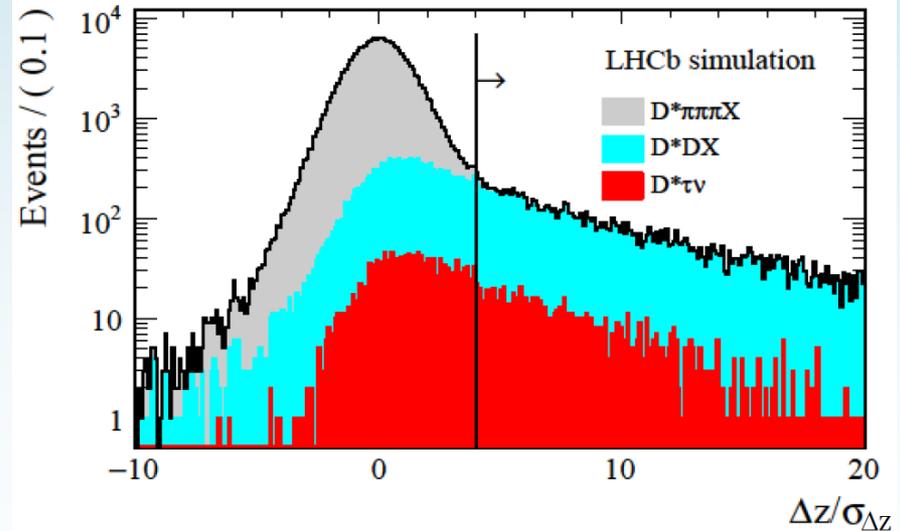
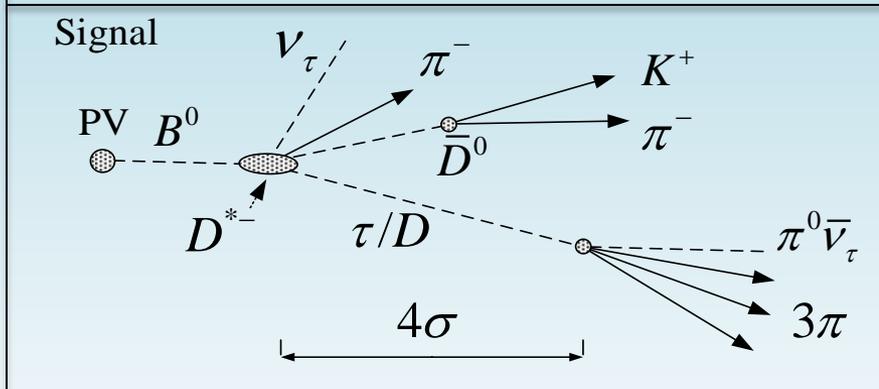
Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \rightarrow D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \rightarrow D^{*+}H_c(\rightarrow \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \rightarrow D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \rightarrow D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \rightarrow D^{**}(\rightarrow D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \rightarrow D^{**}(\rightarrow D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \rightarrow D^{*+}(D_s \rightarrow \tau\nu)X$ fraction	0.1
Total model uncertainty	2.8
Normalization uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	0.9
Total systematic uncertainty	3.0

$\mathcal{R}(D^*)(\tau \rightarrow 3\pi)$ 测量

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)} \begin{cases} \tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau \\ D^{*+} \rightarrow D^0 \pi^+ \\ D^0 \rightarrow K^- \pi^+ \end{cases}$$

$$= \frac{\overbrace{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}^{\text{Signal}}}{\underbrace{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)}_{\text{Normalization}}} \times \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}$$

- 使用 $B \rightarrow D^* 3\pi$ 作为归一化道。
- 3π 重建 τ 衰变顶点，对 τ 飞行距离进行选择：
 - $D^* 3\pi$ 极大压低 (10^3),
 - 35% 信号效率,
 - 剩余 $D^* D$ 事例。



$\mathcal{R}(D^*)(\tau \rightarrow 3\pi)$ 测量-双粲事例筛除与确定

$X_b \rightarrow D^{*-}D_s^+X$: 10倍信号

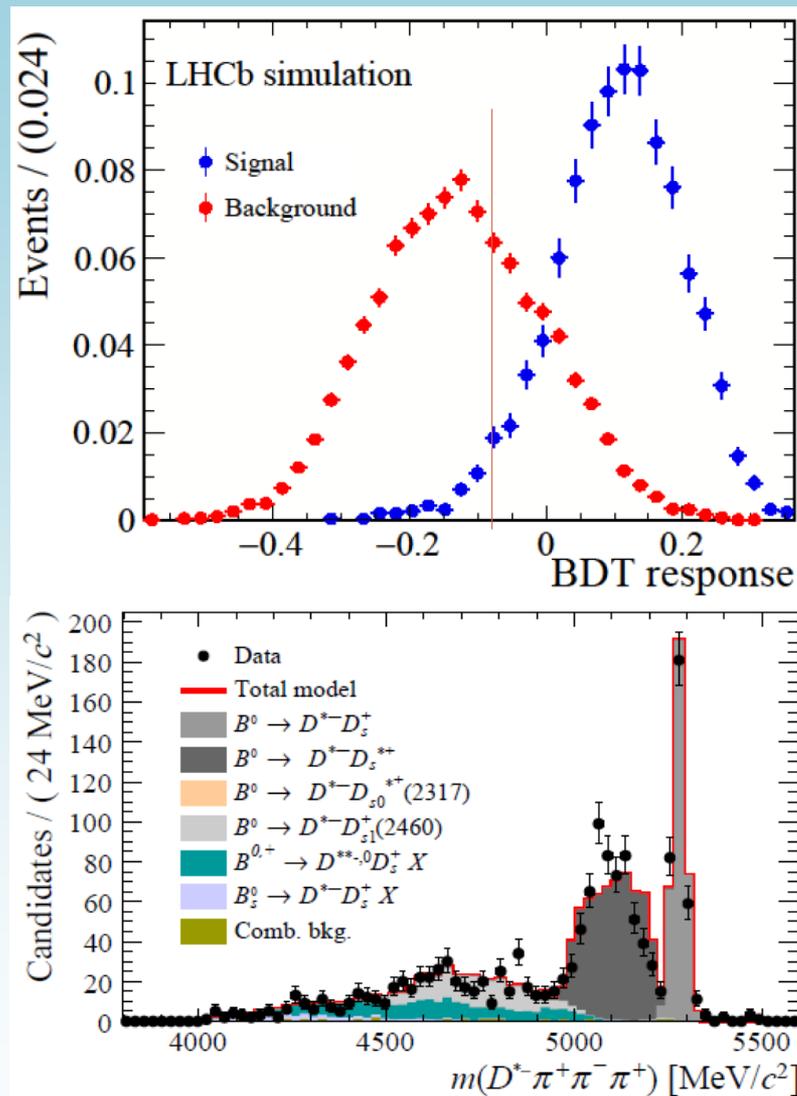
$X_b \rightarrow D^{*-}D^+X$: 1倍信号

$X_b \rightarrow D^{*-}D^0X$: 0.2倍信号

- 使用包括isolation方法在内的变量训练

BDT:

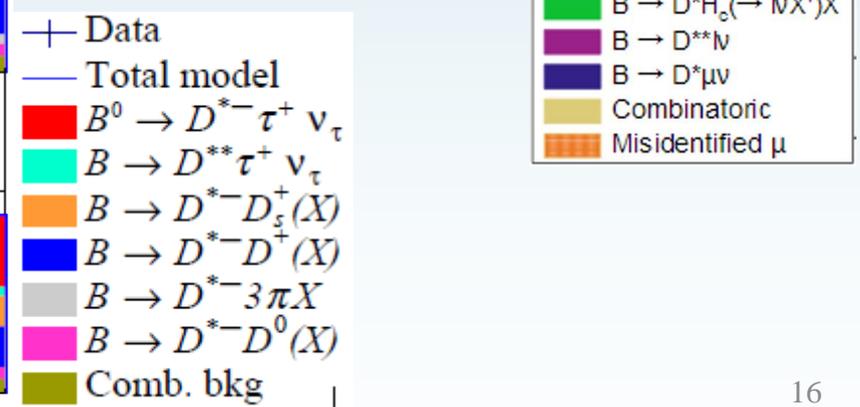
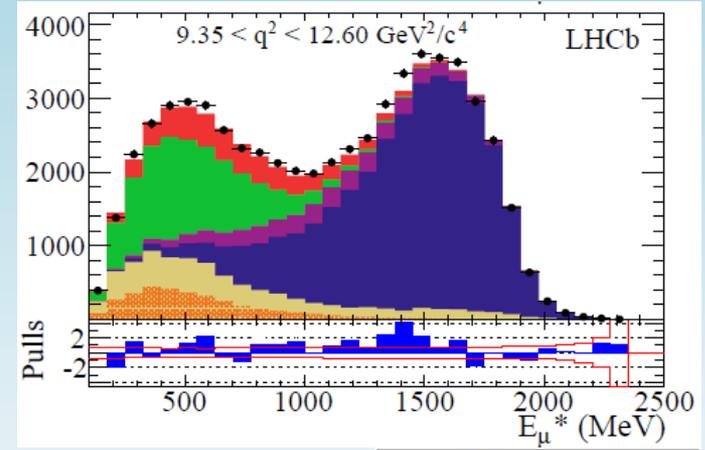
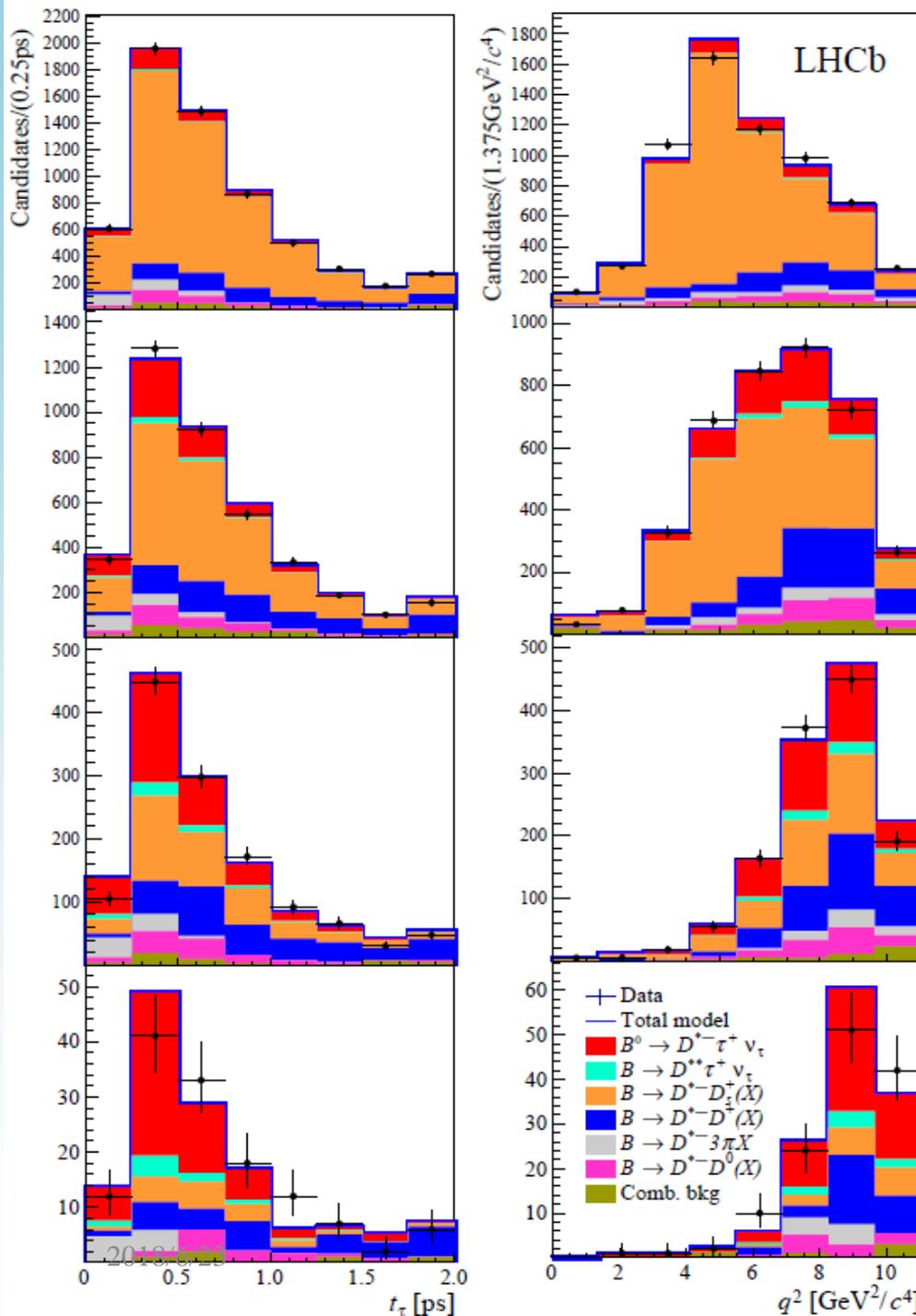
- 低端研究双粲本底各成分组分。
- 高端拟合信号。
- D^*D 事例质量峰: 归一化 D_s 事例。
- $2\pi/3\pi$ 质量谱的共振结构:
 - $\tau \rightarrow a_1 \rightarrow \rho\pi$



$\mathcal{R}(D^*)(\tau \rightarrow 3\pi)$ 分析

BDT分bin拟合结果(左图)

对比 $\tau \rightarrow \mu$ 重建方法, $\tau \rightarrow 3\pi$ 可以更好地区分信号与本底。

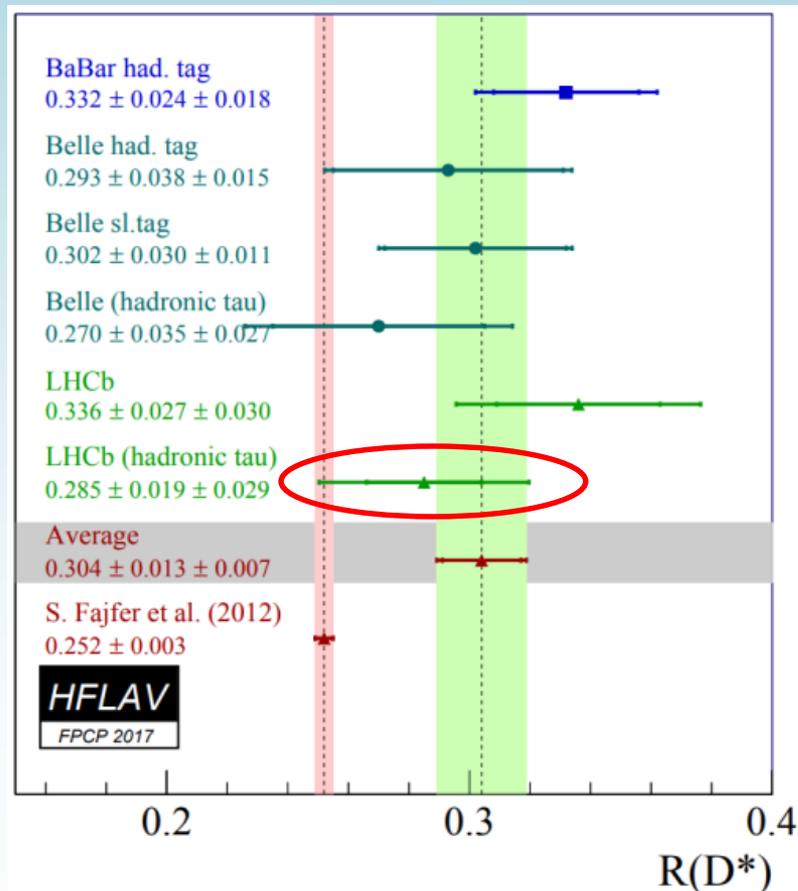


$\mathcal{R}(D^*)(\tau \rightarrow 3\pi)$ 分析结果

使用 LHC 3.0fb⁻¹ 2011 & 2012 @ 7TeV & 8TeV 数据。

$$\frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)} = 1.93 \pm 0.13_{stat} \pm 0.17_{syst}$$

$R(D^{*-}) = 0.285 \pm 0.019_{stat} \pm 0.025_{syst} \pm 0.13_{ext}$, 超出标准模型 1.0σ 。



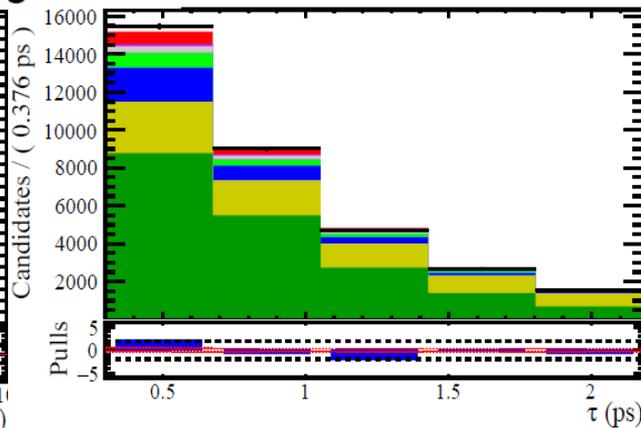
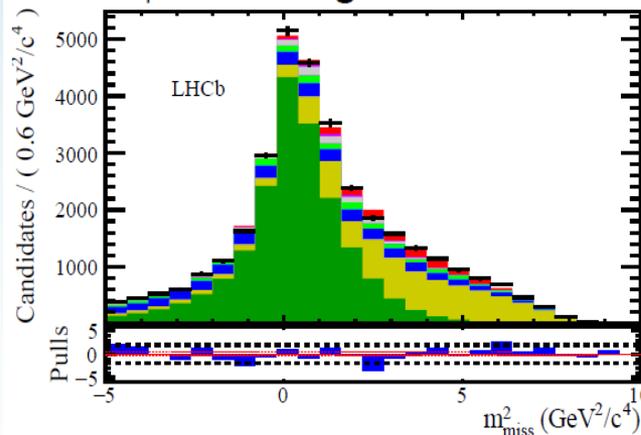
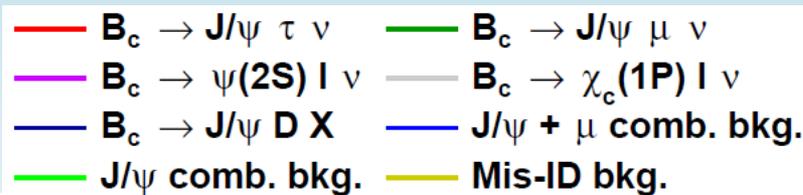
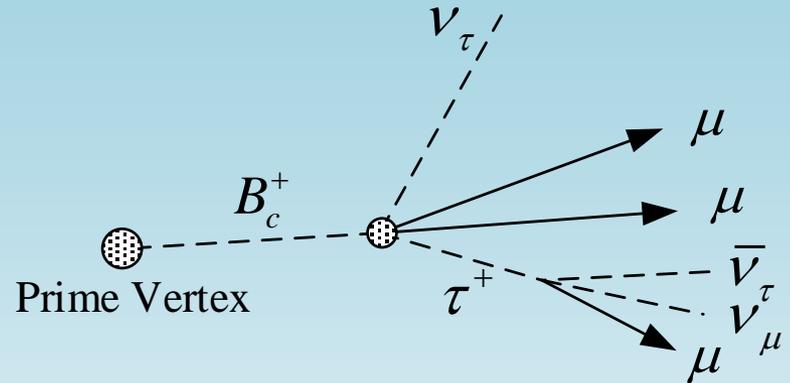
$\mathcal{R}(D^*)(\tau \rightarrow 3\pi)$ 误差

Contribution	Value %
Fit bias	< 0.1
Form factors (template shape)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$3\pi\pi^0/3\pi$	0.7
Signal efficiencies (Monte Carlo statistics)	1.7
Normalization channel efficiency (Monte Carlo statistics)	1.6
$D^{*\pm}\tau\nu$ contribution	2.3
B_s^0 feed-down	1.5
D^* 3π X from B decays yield	2.1
D^* 3π X from B decays Dalitz	1.9
$D_s^+ \rightarrow 3\pi X$ decay model	2.5
D_s^+ , D^0 and D^+ templates shape	2.9
$B \rightarrow D^{*-}D_s^+X$ and $B \rightarrow D^{*-}D^0X$ decay model	2.6
Combinatorial background	0.7
Trigger acceptance shape	1.2
L0Hadron trigger efficiency	1.0
Stripping	2.0
Selection	2.0
Charged Isolation criterium	1
Normalization channel	1.0
PIDCalib weight	1.3
MC statistics	4.1
Bias due to empty bins in templates	1.3
Total internal error	8.9
External BR $D^* 3\pi$	4.3
External error BR $D^*\mu\nu$	2.1
Total External error	4.8

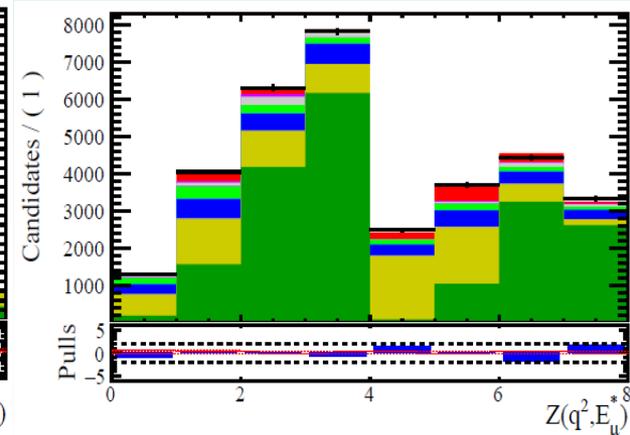
$\mathcal{R}(J/\psi)(\tau \rightarrow \mu)$ 测量

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \begin{cases} \tau^+ \rightarrow \mu^+ \bar{\nu}_\tau \nu_\mu \\ J/\psi \rightarrow \mu\mu \end{cases}$$

- 与 $R(D^*)$ 方法一致。
- B_c 衰变时间 $\tau(B_c) < \tau(B_{u,d,s})$ 。

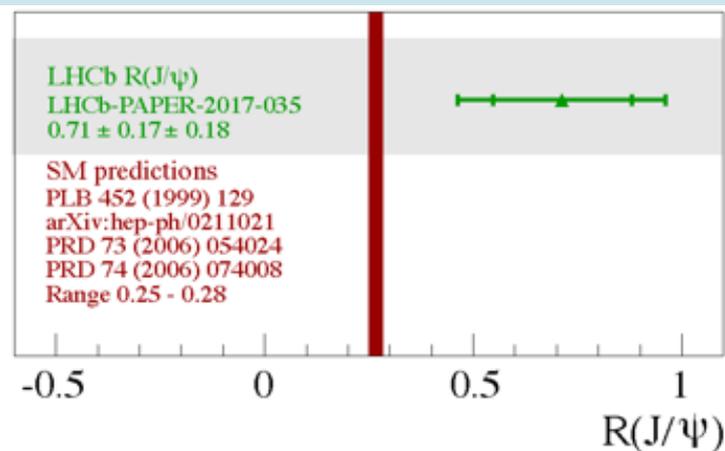


Z: the bin number of (q^2, E_μ^*)



$\mathcal{R}(J/\psi)(\tau \rightarrow \mu)$ 测量结果

- 使用 LHC 3.0fb⁻¹ in 2011 & 2012 @ 7TeV & 8TeV 数据。
- $B_c^+ \rightarrow J/\psi\tau^+\nu_\tau$ 信号显著性为 3σ 。
- $\mathcal{R}(J/\psi) = 0.71 \pm 0.17(stat) \pm 0.18(syst)$, 超出理论 2σ 。



Model uncertainties	Size (eff. corrected) ($\times 10^{-2}$)
MC stat. uncertainty	8.0
$B_c^+ \rightarrow J/\psi$ form factors	12.1
$B_c^+ \rightarrow \psi(2S)$ form factors	3.2
Bias correction	5.4
$B_c^+ \rightarrow J/\psi DX$ cocktail composition	3.6
Z binning strategy	5.6
Misidentification background strategy	5.4
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
Empirical reweighting	1.6
Semitauconic $\psi(2S)$ and χ_c feed-down	0.9
Fixing $A_2(q^2)$ slope to zero	0.3
Efficiency ratio	0.6
$\mathcal{B}(\tau \rightarrow \mu\nu\nu)_w$	0.2
B_c^+ lifetime	included in stat.
Total systematic uncertainty	0.177
Stat. uncertainty	0.173

结论与展望

- 使用B强子半轻衰变检验轻子普适性，可以用来探测新物理。
 - SM理论精度高，统计量大，对新物理敏感。
- LHCb探测器优秀性能，使用轻子与强子重建测量了 $\mathcal{R}(D^*)$ 与 $\mathcal{R}(J/\psi)$ 。
 - $\mathcal{R}(D^*)$ 超出标准模型预言 3.4σ ， $\mathcal{R}(J/\psi)$ 超出标准模型 2σ 。
- $R(J/\psi)$, $R(D)$, $R(\Lambda_c^{(*)})$, $R(D_s)$ 等分析正在进行。
- LHCb第二轮取数即将结束，有更多统计量以提高测量精度。
- 正在开发快速模拟方法，提高MC统计量。



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谢谢!

● Systematic uncertainties

	$B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$	$B^+ \rightarrow K^+\mu^+\mu^-$	$B^+ \rightarrow J/\psi(e^+e^-)K^+$	$B^+ \rightarrow K^+e^+e^-$
sig models	-	-	-1.0%	-1.0%
bkg models	-	-	+0.0%	+0.5%
bin migration	-	-	-	1.6%
trigger efficiency	-	3%	-	3%
Kaon PID	+0.2%	-0.1%	-2.0%	-1.9%
Electron PID	-	-	+3.0%	+3.0%
Muon PID	-0.1%	+0.1%	-	-
K-e veto	-	-	+0.1%	+0.3%

● $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$, compatible with SM within 2.6σ

