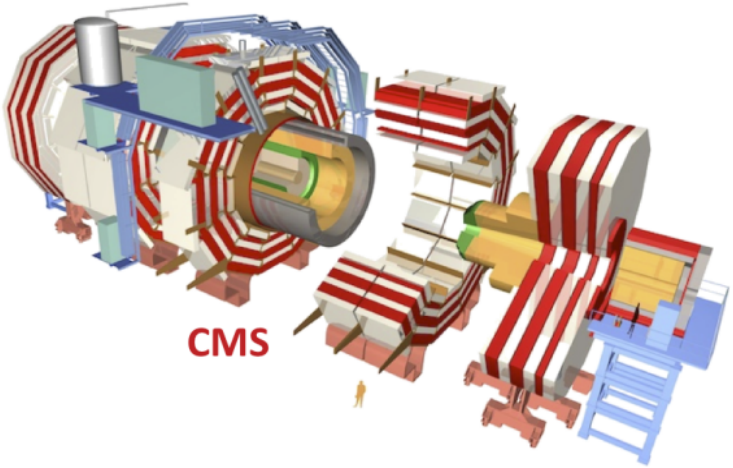

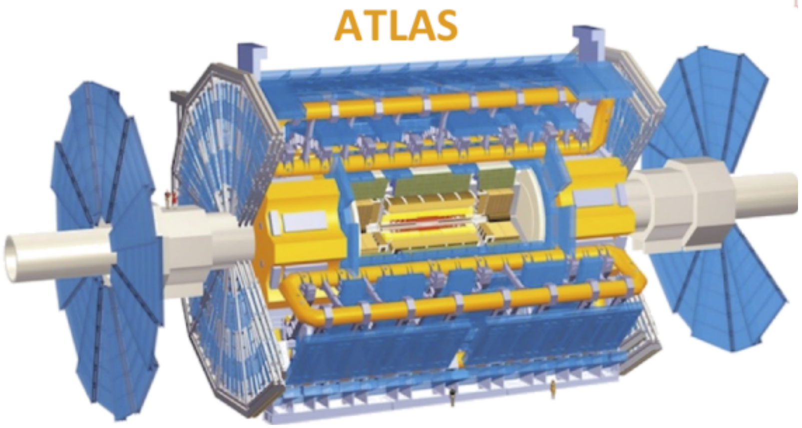

Heavy Flavor Physics from CMS & ATLAS

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NISER, India

March 13th, 2016

51st Rencontres de Moriond EW 2016
12-19 mars 2016
Europe/Paris timezone

Introduction

- **Flavor production and study of its properties is one of the most interesting areas among the particle physics community.**
- **There are many unsolved questions in this sector (listing only few):**

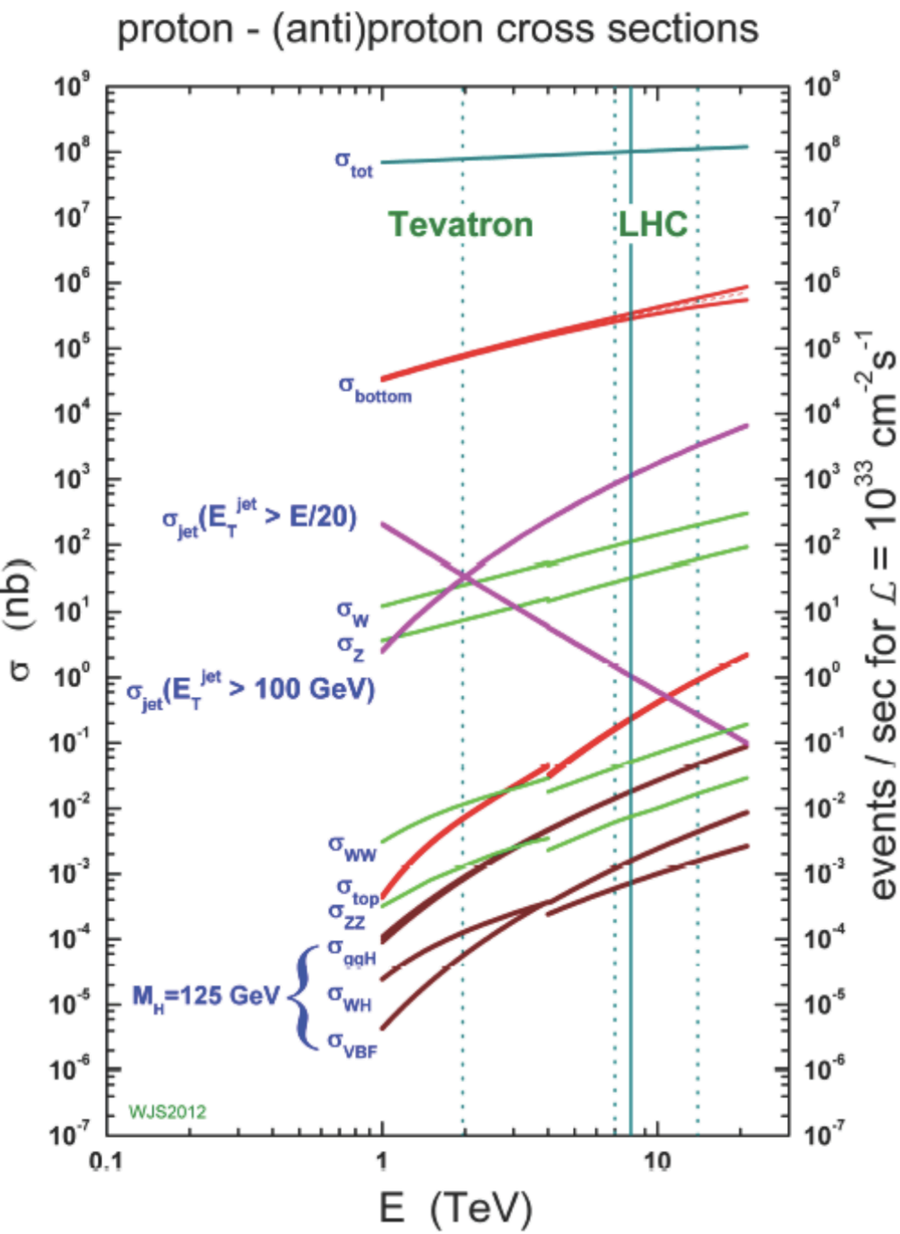
  -> What are the principles for the observed pattern of fermion mass and mixing angles ?
  -> Are there any new sources of flavor symmetry breaking apart from SM Yukawa couplings at TeV scale ?
  -> Are there new sources of CP violation to explain the observed matter-antimatter asymmetry of universe ?

- **LHC era is very important pin down some of the flavor questions.**

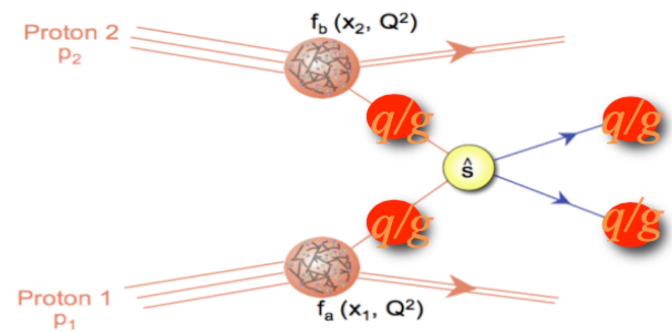
It allows us to search for NP : (two ways for NP search)

- **Produce heavy particles beyond SM. The production cross-section of those particles are usually small.**
- **Measure the observables/parameters of SM processes (specifically rare decay modes). Any significant deviation from SM prediction will be hint of NP.**

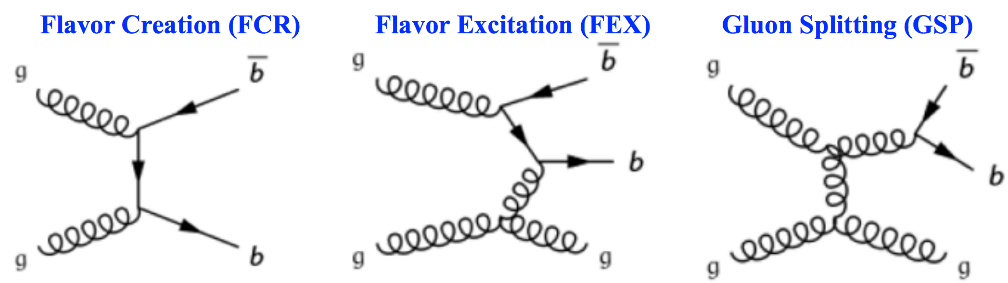
Why we can do better at higher energy ?



-> Because of large production rate



b-production cross-section goes up by almost order of magnitude higher compared to Tevatron [in LHC ~O(100μb)]

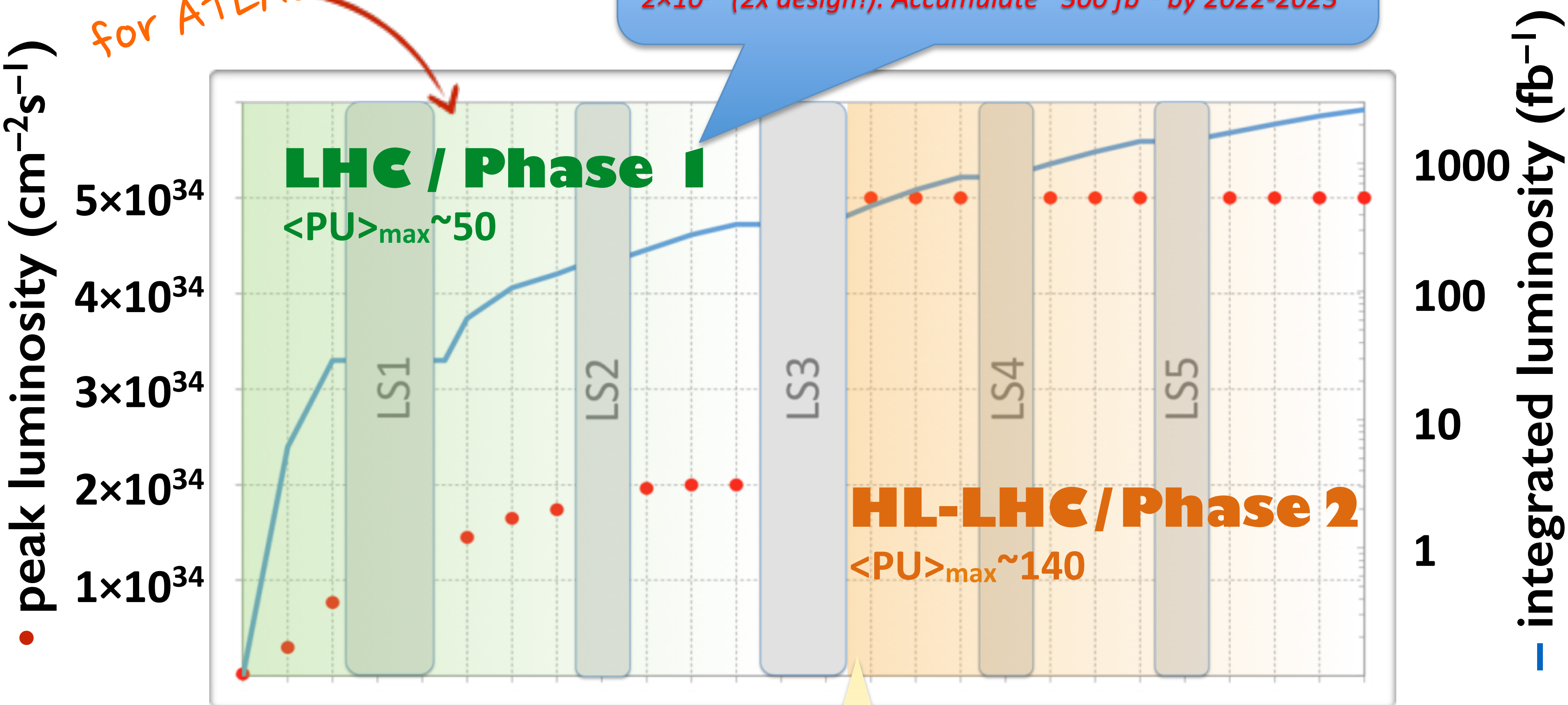


But its not the production only, the type of final state decay that is also important to observe those events

From 8TeV -> 13TeV and beyond (LHC to HL-LHC)

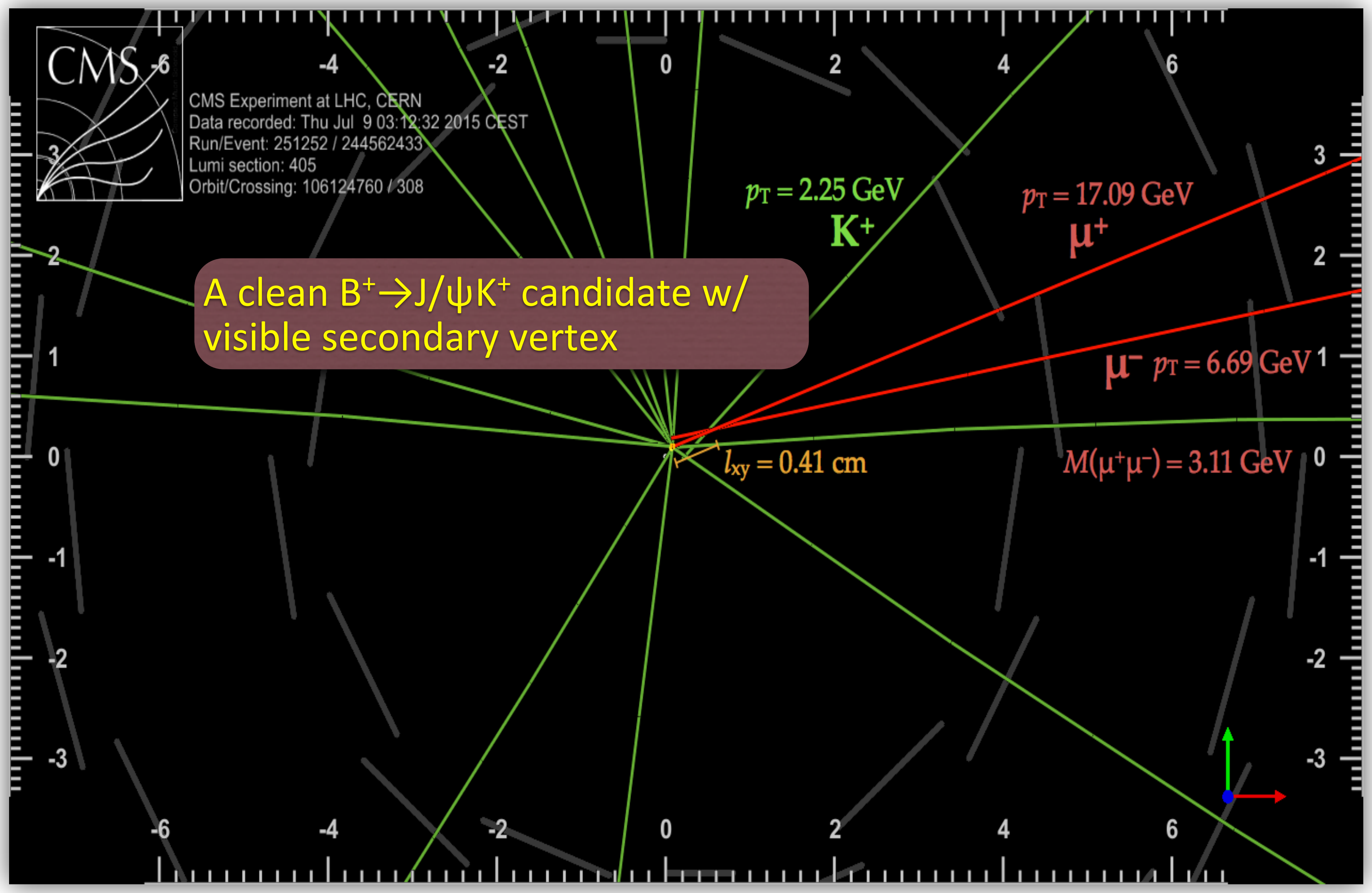
Results from here for ATLAS & CMS

LHC operation up to LS3 (2023):
25 ns bunch spacing, instantaneous luminosities up to 2×10^{34} (2x design!). Accumulate ~300 fb^{-1} by 2022-2023



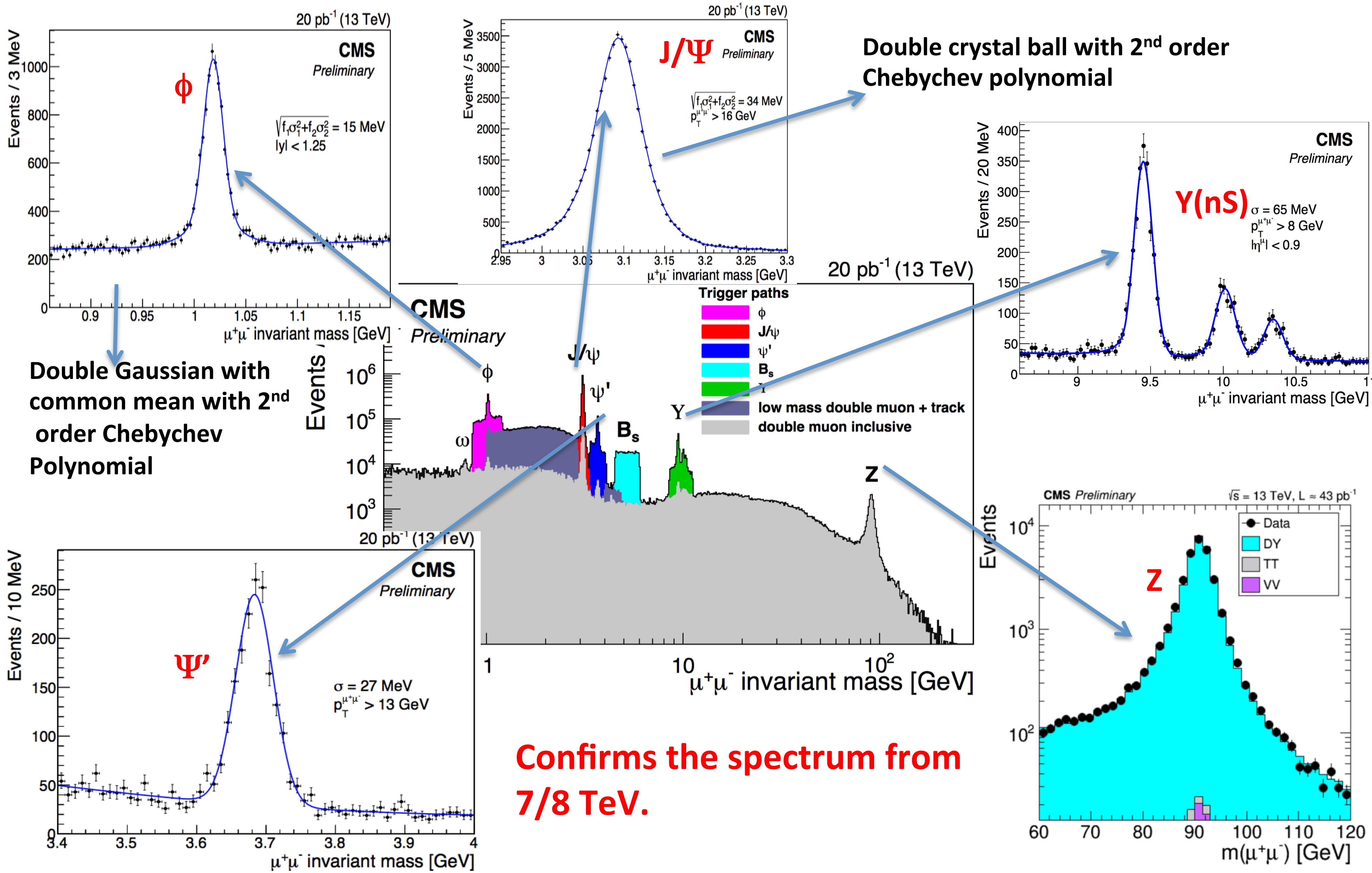
HL-LHC operation beyond LS3 (2025+)
New low-β beam configuration and crab-cavities to optimize the bunch overlap at the interaction region. Level the instantaneous luminosity at 5×10^{34} from a potential peak value of 2×10^{35}. Deliver ~250 fb^{-1} per year for 10 years of operation, accumulate up to 3000 fb^{-1}.

Event with di-muon from CMS @13TeV



CMS DP-2015/018

Physics with di-muons from CMS @13TeV



Double Gaussian with common mean with 2nd order Chebychev Polynomial

Double crystal ball with 2nd order Chebychev polynomial

Confirms the spectrum from 7/8 TeV.

CMS DP-2015/018

B^+ production cross section @13TeV from CMS

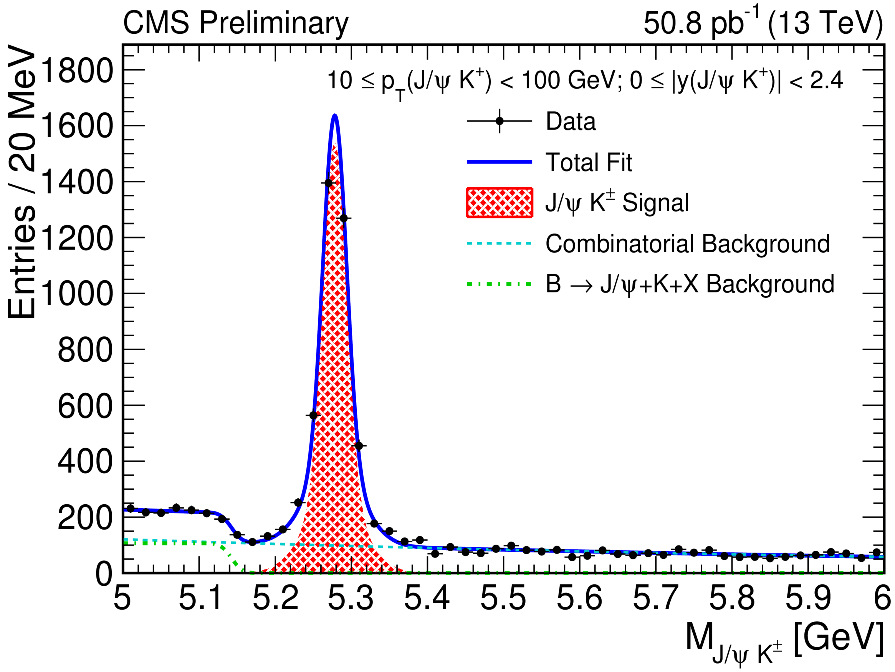
CMS DPAS-BPH-15-004

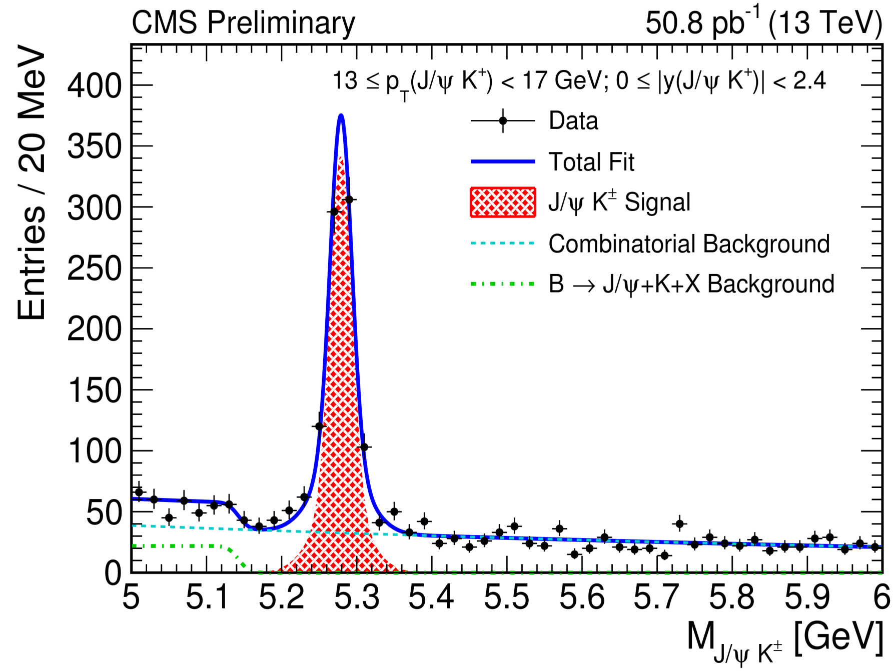
- Provides important information to understand particle interactions.
- B^+ differential production cross section as function of B transverse momentum and rapidity
- Uses exclusive decay mode $B^+ \to J/\Psi K^+$ ($J/\Psi \to \mu^+\mu^-$) [$pp \to B^+X \to J/\Psi K^+ X$]
- Both muons must be within $|\eta| < 1.6$ or one of the muons must have $P_T > 10$ GeV.
- J/Ψ candidates must have $P_T > 8$GeV and minimum χ^2 probability for vertex fit.
- Combined with charged track (considered to be kaon) with $P_T>1$GeV
- The cut in decay length significance in transverse plane (distance between secondary vertex and beam spot in transverse plane divided by its uncertainty)
- The signal is obtained by extended maximum likelihood fit to the B^+ invariant mass distribution in bins of B^+ P_T and $|\eta|$.
- The differential cross-section is calculated to be

$$\frac{\mathrm{d}\sigma(\mathrm{pp} \to \mathrm{B}^+\mathrm{X})}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{B}}} = \frac{n_{\mathrm{sig}}(p_{\mathrm{T}}^{\mathrm{B}})}{2\,A \cdot \epsilon(p_{\mathrm{T}}^{\mathrm{B}})\,\mathcal{B}\,\mathcal{L}\,\Delta p_{\mathrm{T}}^{\mathrm{B}}}, \quad \frac{\mathrm{d}\sigma(\mathrm{pp} \to \mathrm{B}^+\mathrm{X})}{\mathrm{d}y^{\mathrm{B}}} = \frac{n_{\mathrm{sig}}(|y^{\mathrm{B}}|)}{2\,A \cdot \epsilon(|y^{\mathrm{B}}|)\,\mathcal{B}\,\mathcal{L}\,\Delta y^{\mathrm{B}}}$$

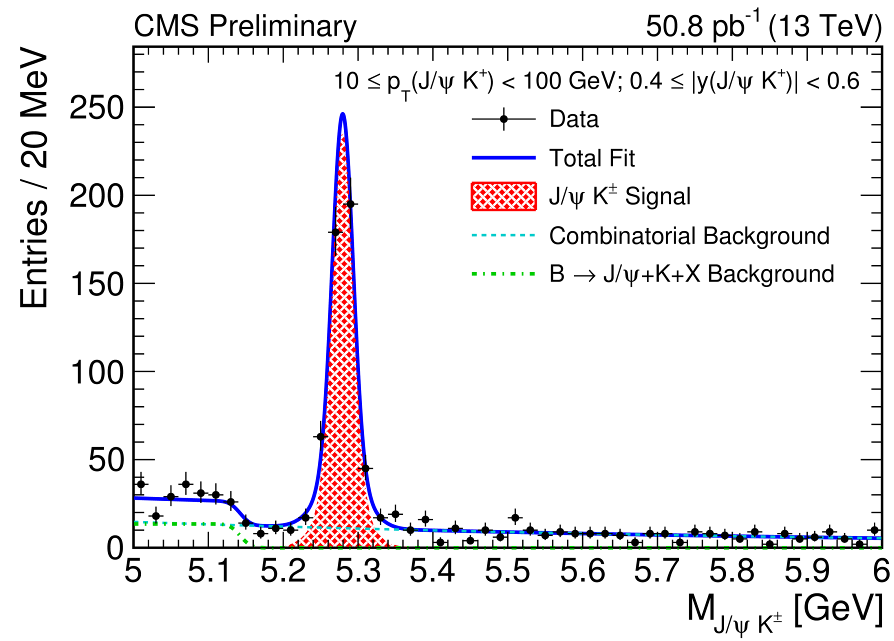
- Result shown is based on 50.8 pb^{-1} data collected at 13TeV

B^+ production cross section @13TeV from CMS



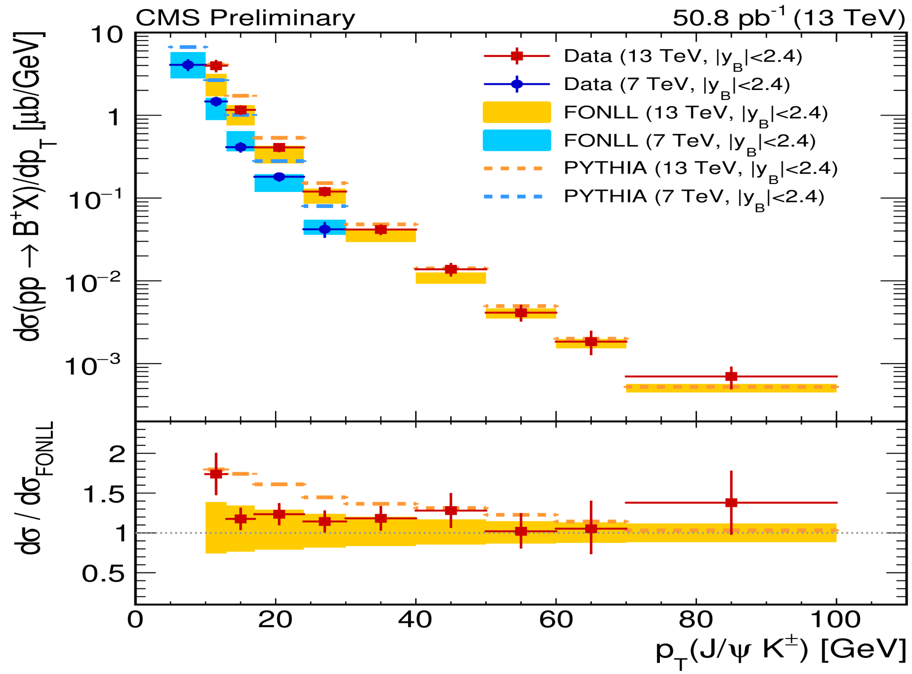


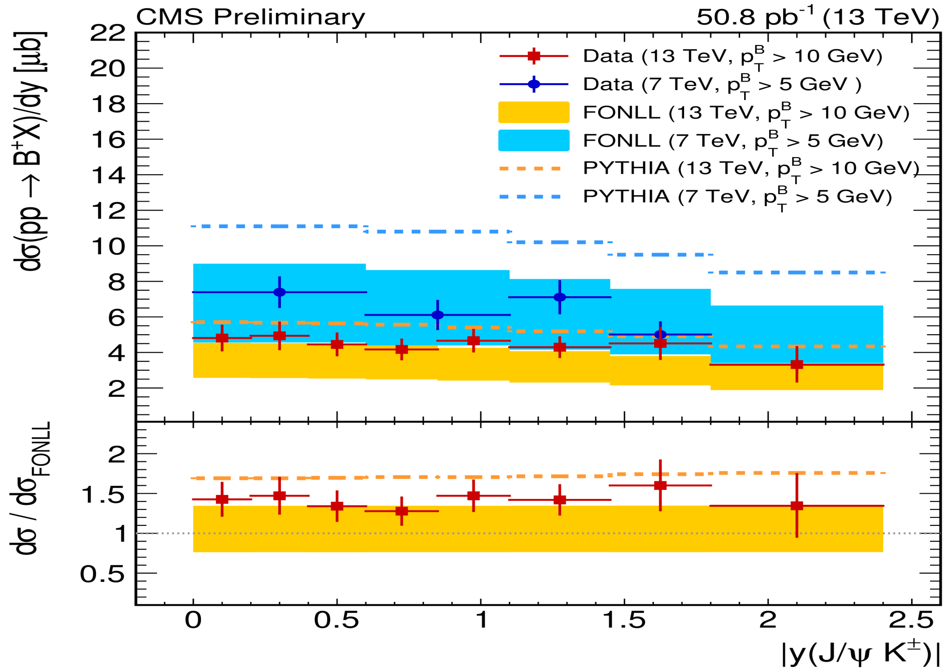
- **B Invariant mass distribution for different P_T and η regions.**
- **Signal -> Two Gaussian**
- **The normalization, mean and width of the tail Gaussian is fixed with respect to the core Gaussian.**

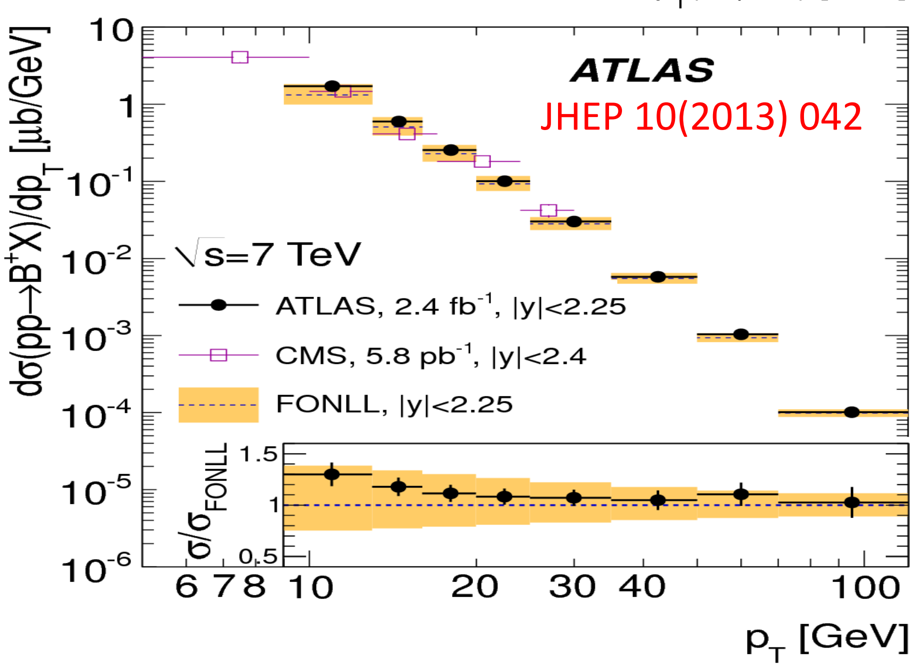


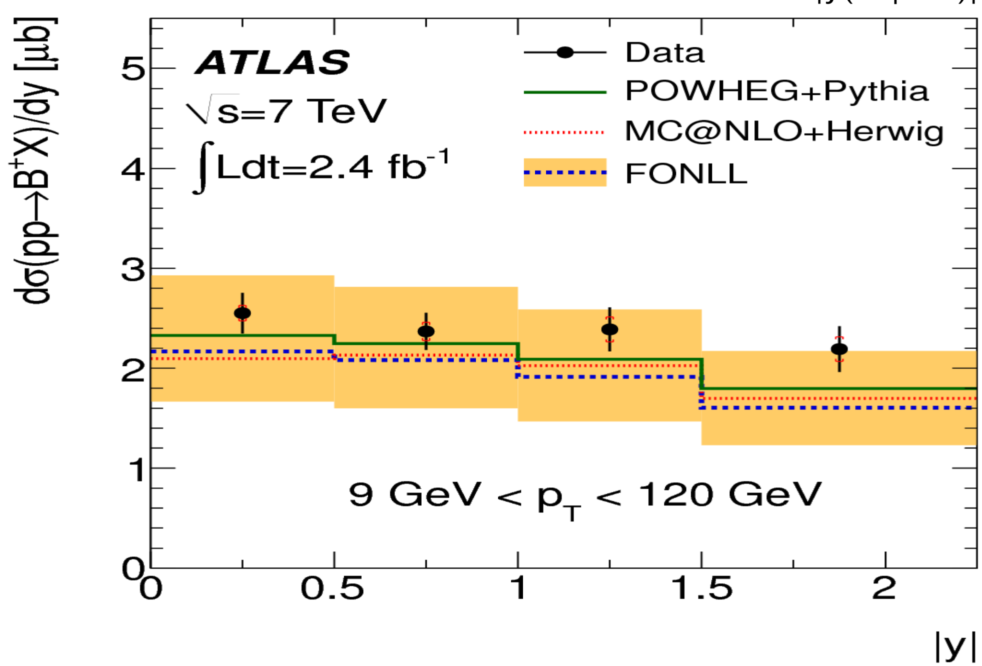
CMS PAS-BPH-15-004

B$^+$ production cross section from CMS & ATLAS



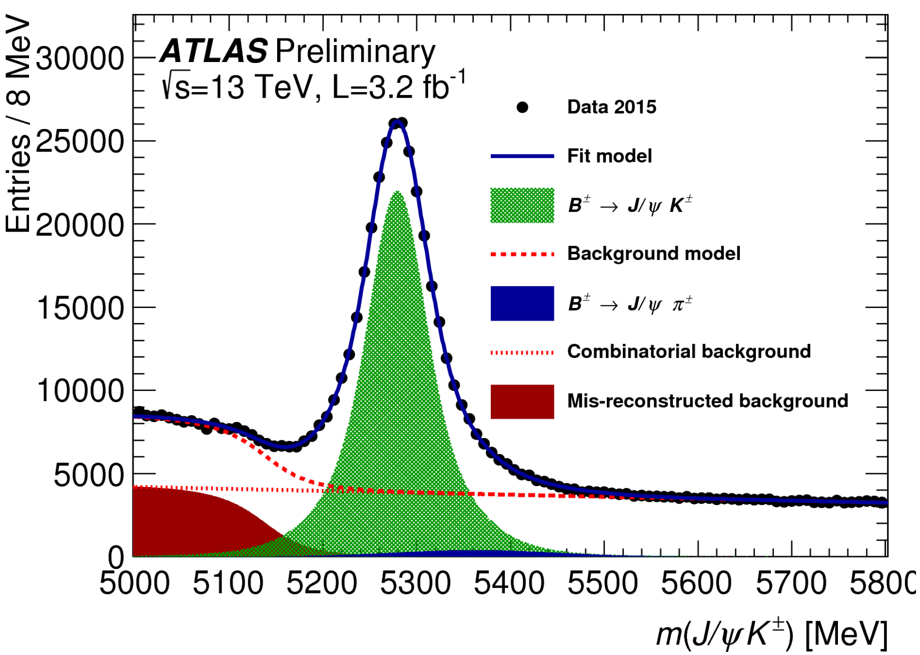


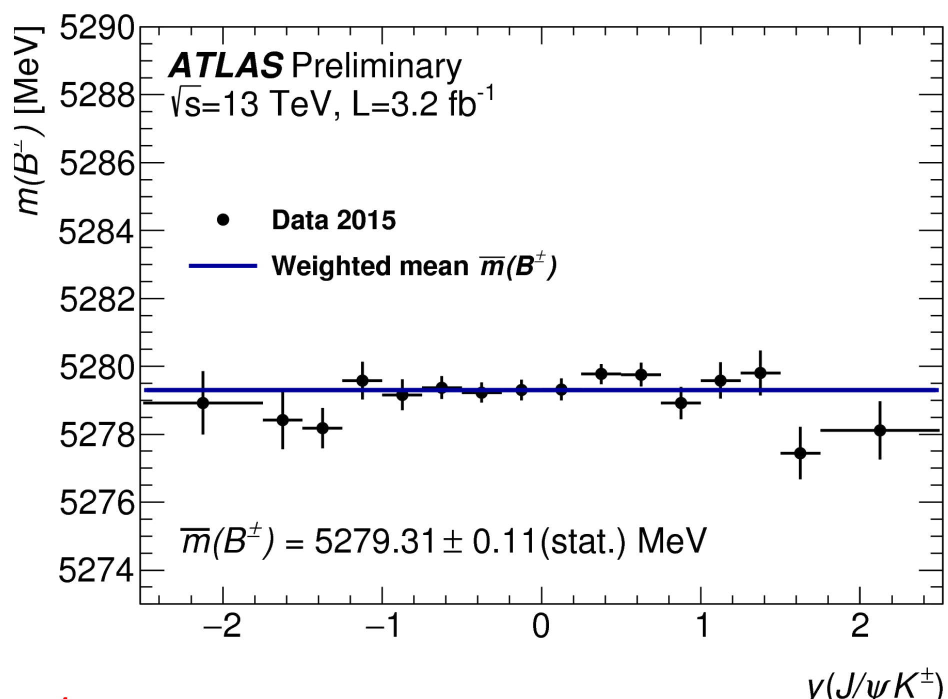




B$^+$ mass measurement @13TeV from ATLAS

- Tested the performance of the ATLAS detector by looking at B$^+$ mass in different |η|
- B$^+$ is reconstructed with J/Ψ ($\mu^+\mu^-$)K$^+$ mode
- Two muon with P_T>4GeV is choose for J/Ψ.
- Another track (a kaon candidate) chosen with P_T> 3GeV and |η| < 2.5
- An unbinned maximum likelihood fit on B-mass is done to get the signal.
- Uses 3.2 fb^{-1} data collected at 13TeV





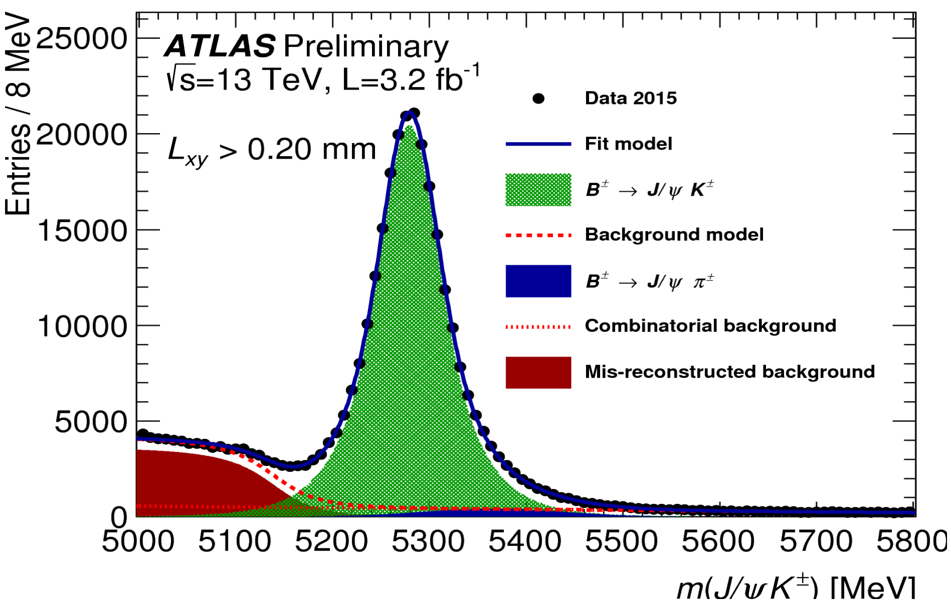
B$^+$ mass: 5279.31 +/- 0.11 MeV

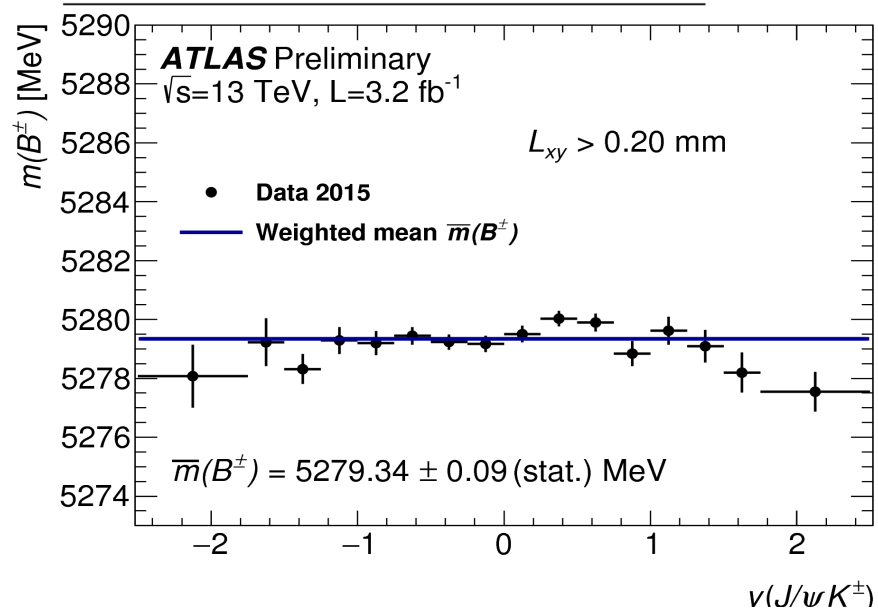
ATLAS-CONF-2015-064

B^+ mass measurement @13TeV from ATLAS

y			Fit Result [MeV]
-2.5	$\rightarrow$	-1.75	5279.93 ± 0.94
-1.75	$\rightarrow$	-1.5	5278.41 ± 0.86
-1.5	$\rightarrow$	-1.25	5278.18 ± 0.59
-1.25	$\rightarrow$	-1.0	5279.58 ± 0.55
-1.0	$\rightarrow$	-0.75	5279.16 ± 0.45
-0.75	$\rightarrow$	-0.5	5279.37 ± 0.34
-0.5	$\rightarrow$	-0.25	5279.23 ± 0.29
-0.25	$\rightarrow$	0.0	5279.30 ± 0.31

y			Fit Result [MeV]
0.0	$\rightarrow$	0.25	5279.32 ± 0.32
0.25	$\rightarrow$	0.5	5279.77 ± 0.30
0.5	$\rightarrow$	0.75	5279.76 ± 0.34
0.75	$\rightarrow$	1.0	5278.93 ± 0.48
1.0	$\rightarrow$	1.25	5279.59 ± 0.54
1.25	$\rightarrow$	1.5	5279.81 ± 0.66
1.5	$\rightarrow$	1.75	5277.45 ± 0.78
1.75	$\rightarrow$	2.5	5278.11 ± 0.86





Fit	$B^{\pm}$ mass [MeV]	Fit error [MeV]
Default Fit	5279.31	0.11 (stat.)
$L_{xy} > 0.2$ mm	5279.34	0.09 (stat.)
World Average fit	5279.29	0.15
LHCb	5279.38	0.11 (stat.) $\pm$ 0.33 (syst.)

J/ψ production @13TeV from ATLAS

- Heavy quarkonium states are good testing ground for perturbative and non-pertubative regime of QCD
- First stage is short distance production of heavy quark pair (described perturbatively)
- Second stage is non-perturbative hadronization of heavy quark pair into quarkonium state, such as J/Ψ

$$pp \xrightarrow[\text{Perturbative QCD}]{\text{Production}} Q\bar{Q} \xrightarrow[\text{Non-pertubative QCD}]{\text{Hadronisation}} J/\psi$$

- J/Ψ can be produced directly from hard collisions of partons in proton-proton machine (prompt J/Ψ) or via decay of b-flavor hadrons (non-prompt J/Ψ)

Here the fraction of non-prompt J/Ψ is obtained by:

$$f_b^{J/\psi} \equiv \frac{pp \to b + X \to J/\psi + X'}{pp \xrightarrow{\text{Inclusive}} J/\psi + X'} = \frac{N_{J/\psi}^{\text{NP}}}{N_{J/\psi}^{\text{NP}} + N_{J/\psi}^{\text{P}}}$$

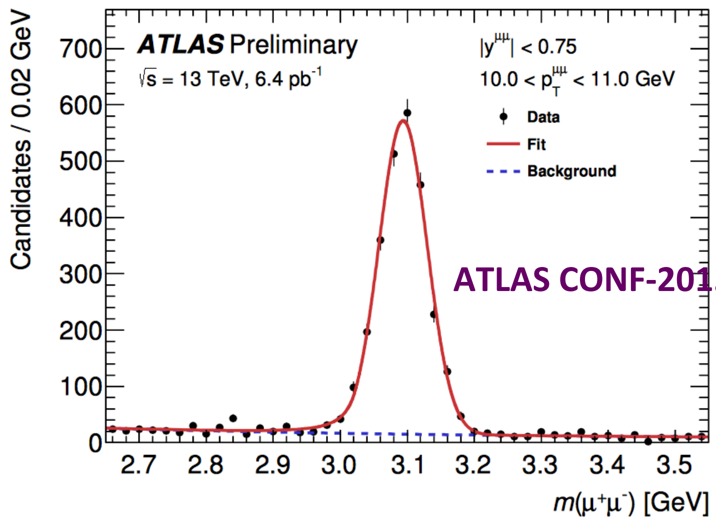
- The two can be differentiated by different decay times of reconstructed J/Ψ
- The yield is obtained by unbinned maximum likelihood fit to dimuon mass and decay time

Pseudo-lifetime: $\tau = L_{xy} m_{J/\psi}^{\text{PDG}} / p_{\text{T}}$ $\quad L_{xy} \equiv \vec{L} \cdot \vec{p}_{\text{T}} / p_{\text{T}}$

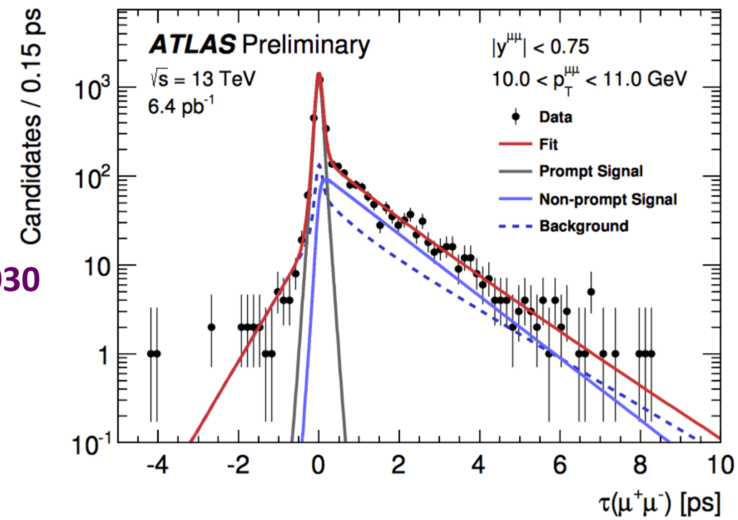
- J/ψ is particular interesting for detector calibration due to large BF

ATLAS CONF-2015-030

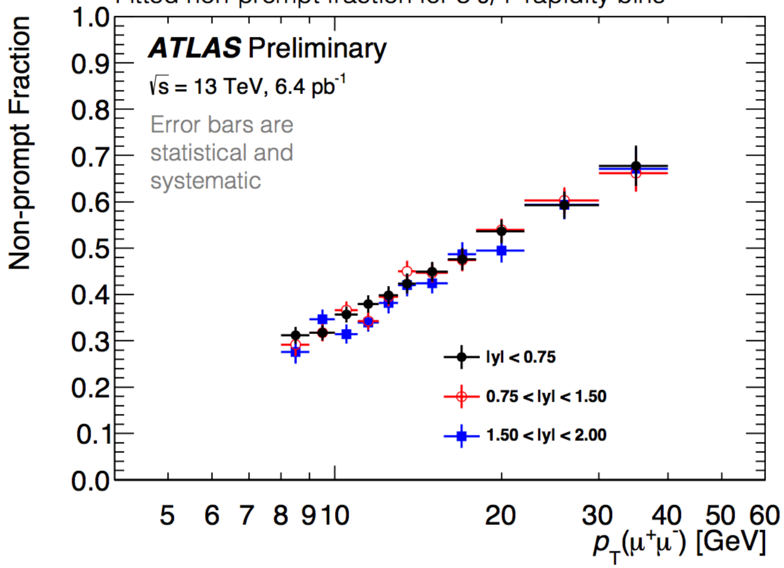
J/ψ production @13TeV from ATLAS (cont.)



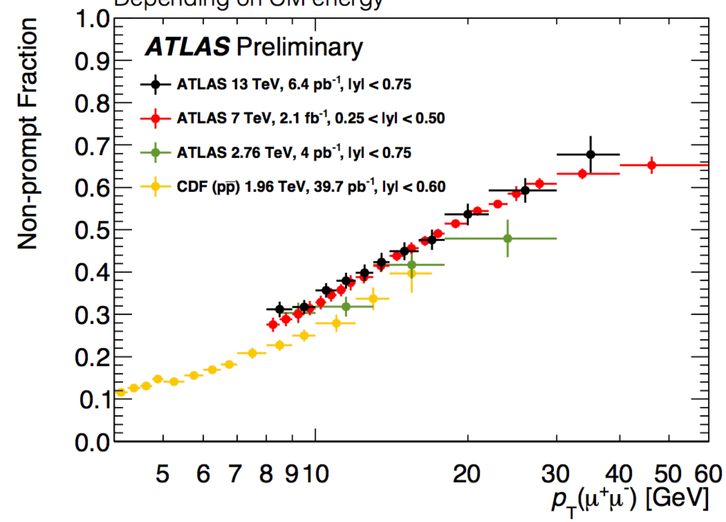
ATLAS CONF-2015-030



Fitted non-prompt fraction for 3 J/Ψ rapidity bins



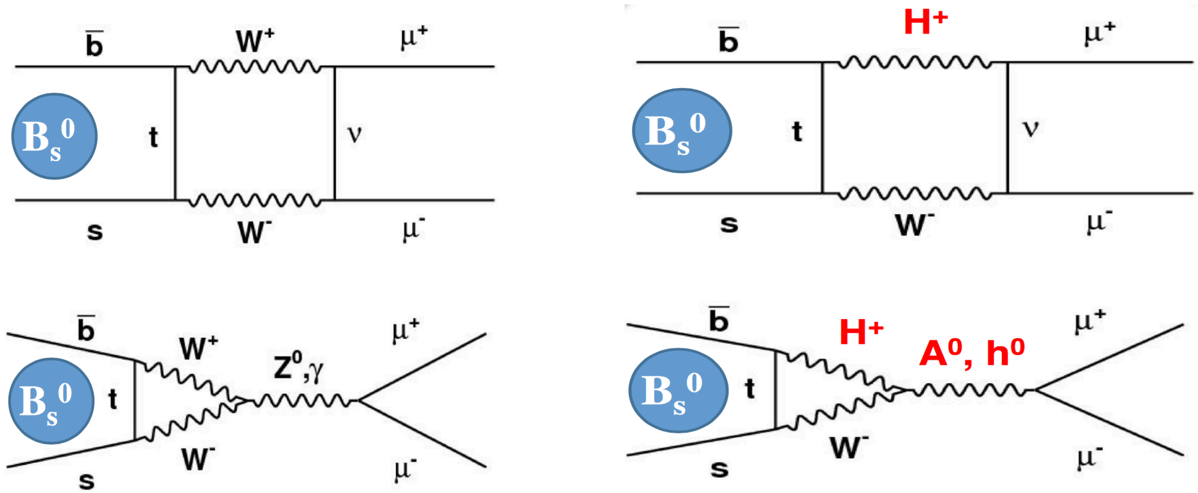
Depending on CM energy



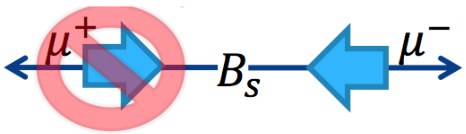
- **The non-prompt fraction increases from 0.25 at 8GeV J/Ψ P_T to 0.65 at 40 GeV**
- **Consistent with previous results**
- **No variation in different pseudo-rapidity regions.**

Facts about $B_s \to \mu^+\mu^-$

- It's a flavor changing neutral current (FCNC) process. Tree level contribution is forbidden in Standard Model.
- Only occurs via loop diagram as shown below.



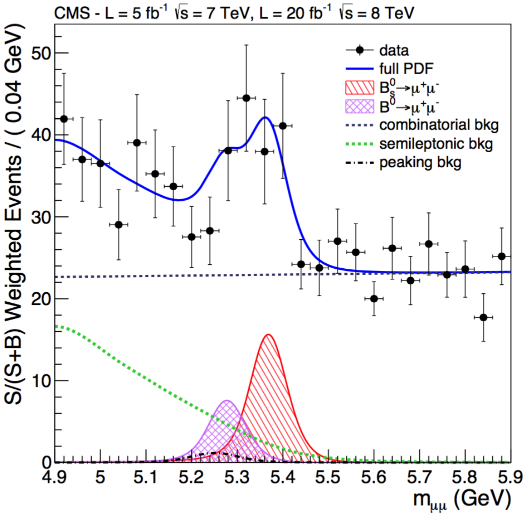
- The process is helicity suppressed by factor $(m_\mu/m_B)^2$ (forces one of the muons to have wrong helicity direction)

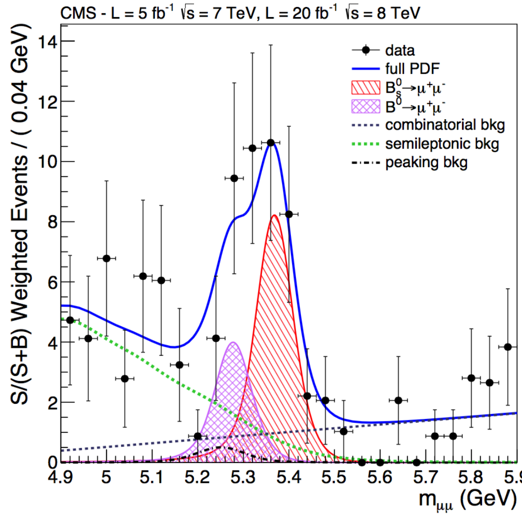


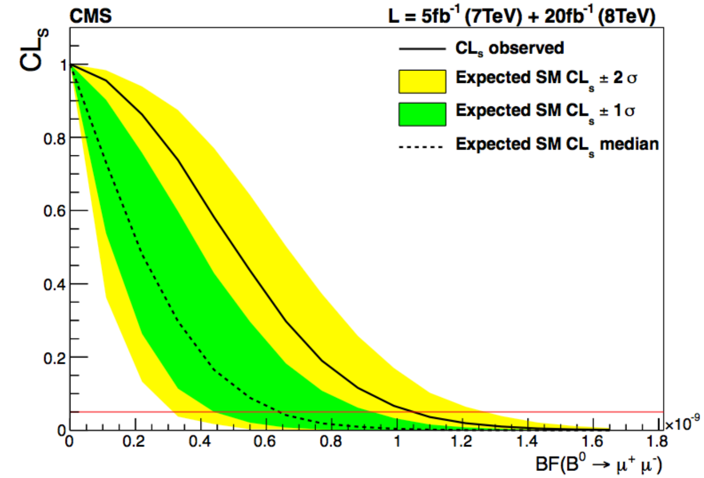
- $B_d \to \mu^+\mu^-$ is further suppressed compared to $B_s \to \mu^+\mu^-$ as $|V_{td}| < |V_{ts}|$
- Sensitive to pseudo-scalar and scalar couplings
- Any New Physics could change the branching fraction (extra amplitudes will contribute to the decay process).
- Probably the cleanest rare decay both experimentally and theoretically.

CMS results for $B \to \mu^+\mu^-$

PRL 111 (2013) 101804







		$\varepsilon_{tot}[10^{-2}]$	N^{exp}_{signal}	N^{exp}_{total}	N_{obs}
7 TeV	B^0 Barrel	(0.33 ± 0.03)	0.27 ± 0.03	1.3 ± 0.8	3
	B^0_s Barrel	(0.30 ± 0.04)	2.97 ± 0.44	3.6 ± 0.6	4
	B^0 Endcap	(0.20 ± 0.02)	0.11 ± 0.01	1.5 ± 0.6	1
	B^0_s Endcap	(0.20 ± 0.02)	1.28 ± 0.19	2.6 ± 0.5	4
8 TeV	B^0 Barrel	(0.24 ± 0.02)	1.00 ± 0.10	7.9 ± 3.0	11
	B^0_s Barrel	(0.23 ± 0.03)	11.46 ± 1.72	17.9 ± 2.8	16
	B^0 Endcap	(0.10 ± 0.01)	0.30 ± 0.03	2.2 ± 0.8	3
	B^0_s Endcap	(0.09 ± 0.01)	3.56 ± 0.53	5.1 ± 0.7	4

$B_s \to \mu\mu$ significance: 4.3 σ

$$BR(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\text{stat})^{+0.6}_{-0.4}\ (\text{syst})\right)\times 10^{-9}$$

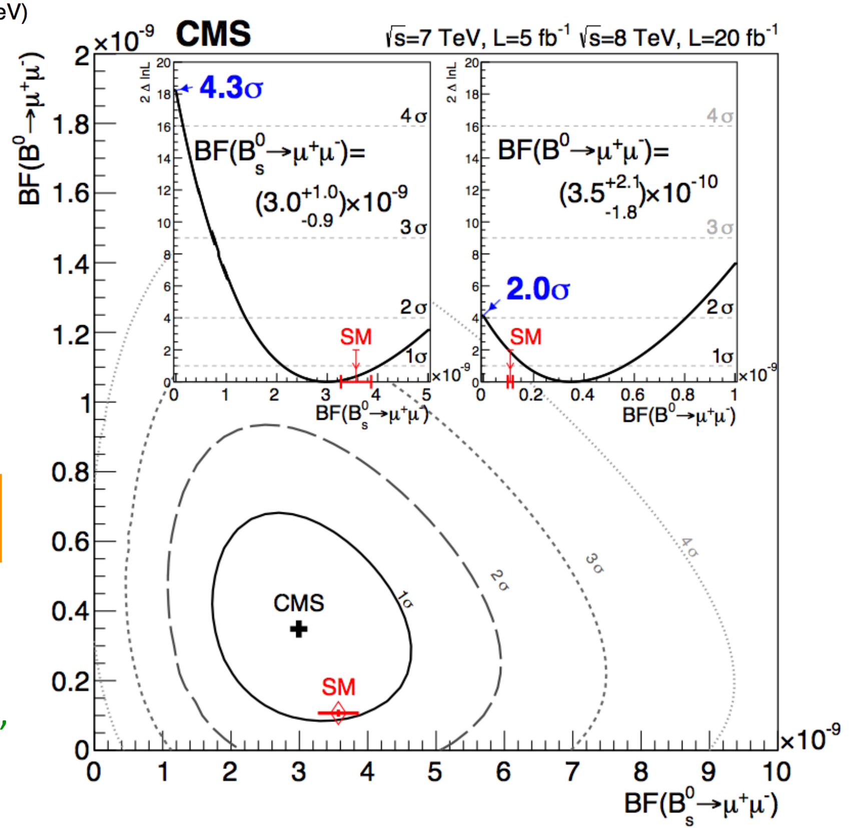
$B_d \to \mu\mu$ significance: 2.0 σ

$$BR(B_d \to \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (\text{stat+syst})\right)\times 10^{-10}$$

$\mathcal{B}(B_s\to\mu^+\mu^-) = (3.65 \pm 0.23)\times 10^{-9}$

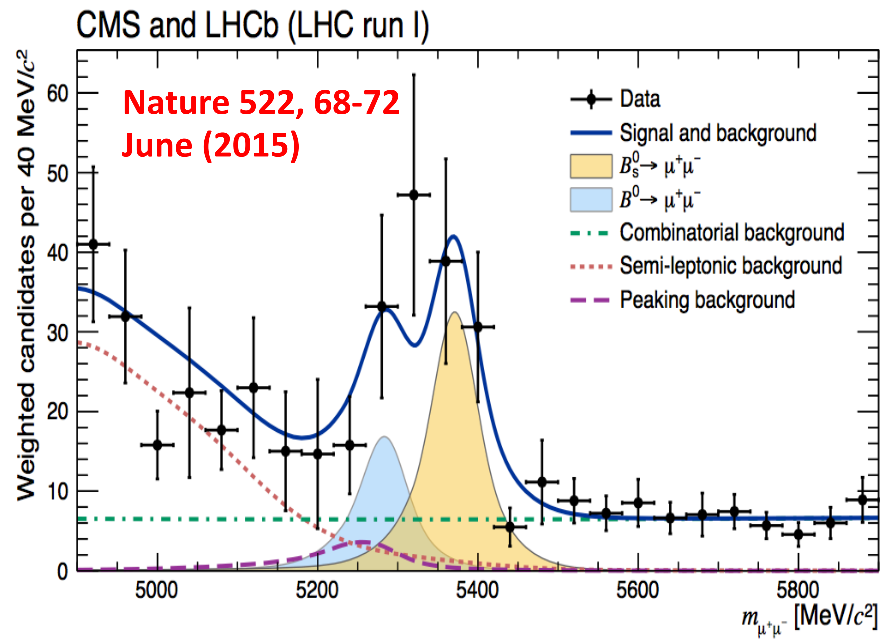
$\mathcal{B}(B_d\to\mu^+\mu^-) = (1.06 \pm 0.09)\times 10^{-10}$

Ref: Bobeth et al, PRL 112, 101801 (2014)



CMS & LHCb combination for $B \to \mu^+\mu^-$

- Both CMS & LHCb data are simultaneously fitted with BFs as common free parameters
- An un-binned maximum likelihood fit to the di-muon invariant mass is done over all BDT bins (12 bins for CMS and 8 bins for LHCb)

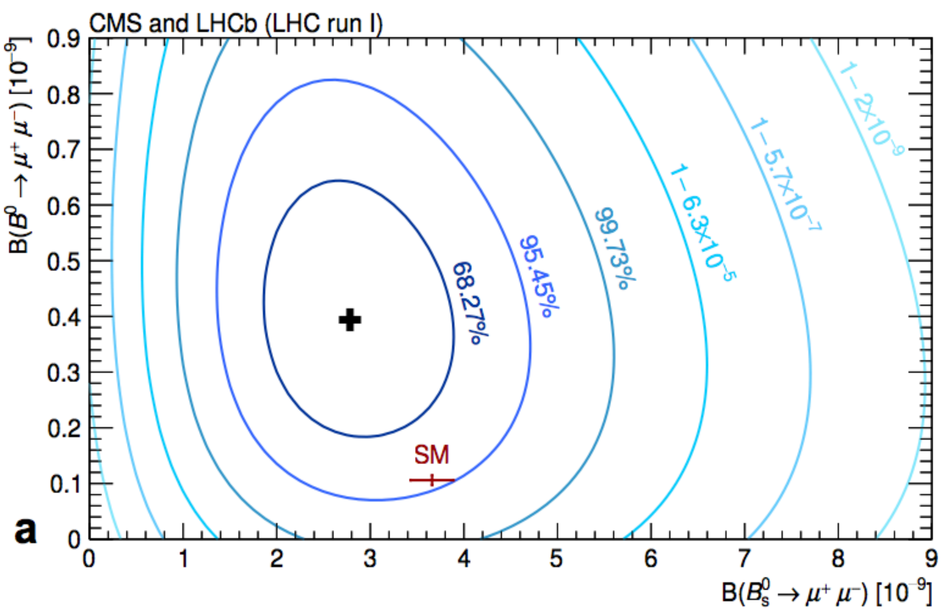


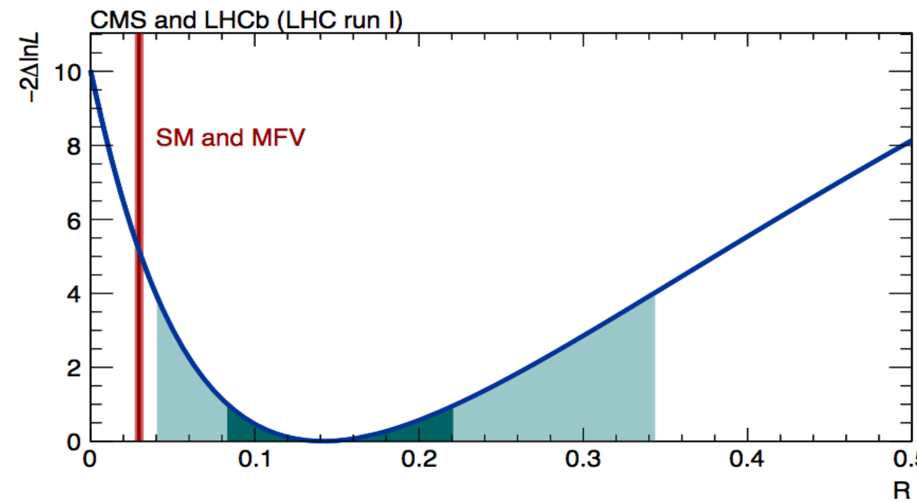
Observed branching fraction:

$BR(B^0_s) = (2.8^{+0.7}_{-0.60}) \times 10^{-9}$ (35% syst) 6.2σ observed

$BR(B^0) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ (18% syst) 3.0σ evidence

SM compatibility: 1.2σ for B_s and 2.2σ for B^0

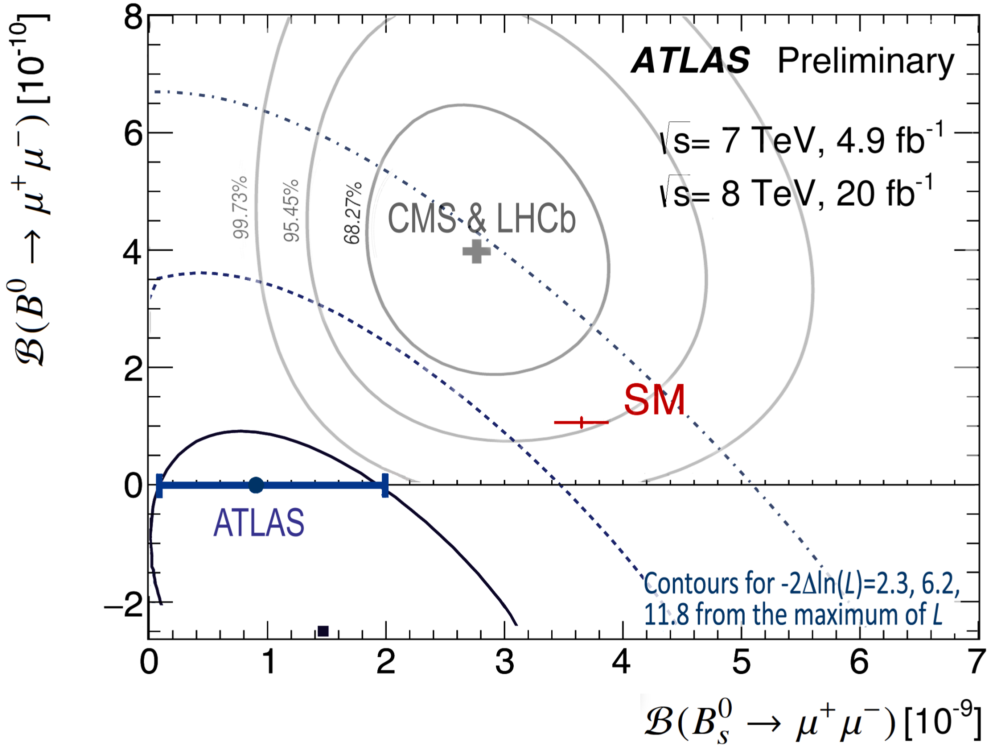




$$\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)_{SM}/\mathcal{B}(B^0_s \to \mu^+\mu^-)_{SM} = 0.0295^{+0.0028}_{-0.0025}$$

Experiment $\mathcal{R} = 0.14^{+0.08}_{-0.06}$ **(2.3σ away from SM)**

ATLAS result on $B_s \to \mu^+\mu^-$



Using the data collected in Run-1, ATLAS today showed preliminary results on the rare decays of B^0_s and B^0 into muon pairs.

For B^0_s:

- BR($B^0_s \to \mu^+\mu^-$) = $0.9^{+1.1}_{-0.8} \times 10^{-9}$
- $< 3.0 \times 10^{-9}$ at 95% CL (from CL_s)

For B^0:

- BR($B^0 \to \mu^+\mu^-$) $< 4.2 \times 10^{-9}$ at 95% CL (from CL_s)
- The limit is above the SM prediction
- and reaches the central value of the CMS & LHCb combination $BR(B^0)_{CMS\&LHCB} = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$.

The compatibility with the SM, for the simultaneous fit, is 2.0 σ .

NP constraints with $B \to \mu^+\mu^-$

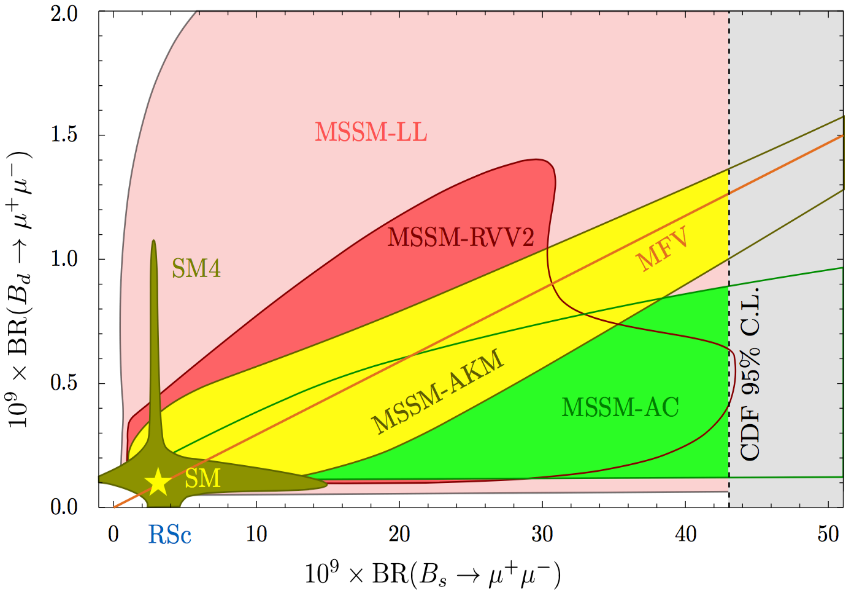
- NP can enter through the Wilson coefficient (C_i's) of operator in effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

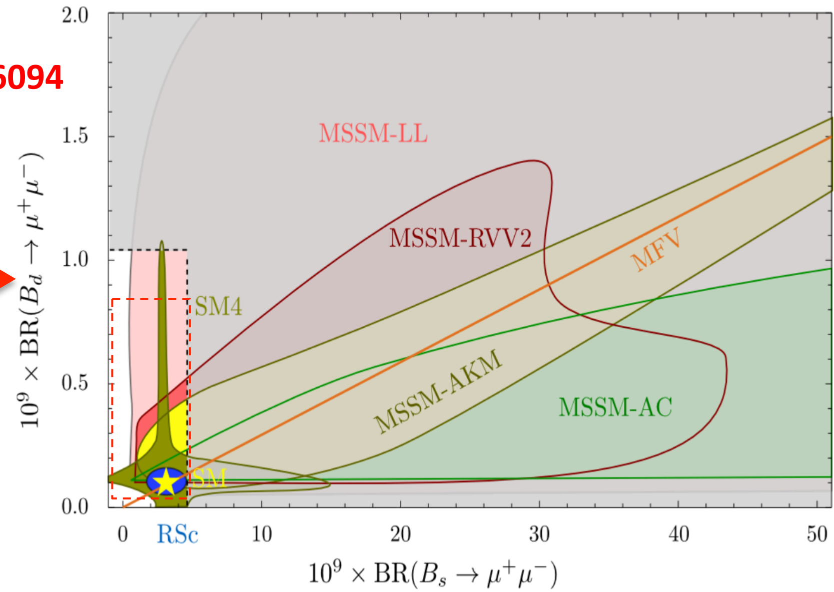
$$O_S^{(\prime)} = \frac{m_b}{m_{B_s}} (\bar{s} P_{R(L)} b)(\bar{\ell}\ell)$$

$$O_P^{(\prime)} = \frac{m_b}{m_{B_s}} (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

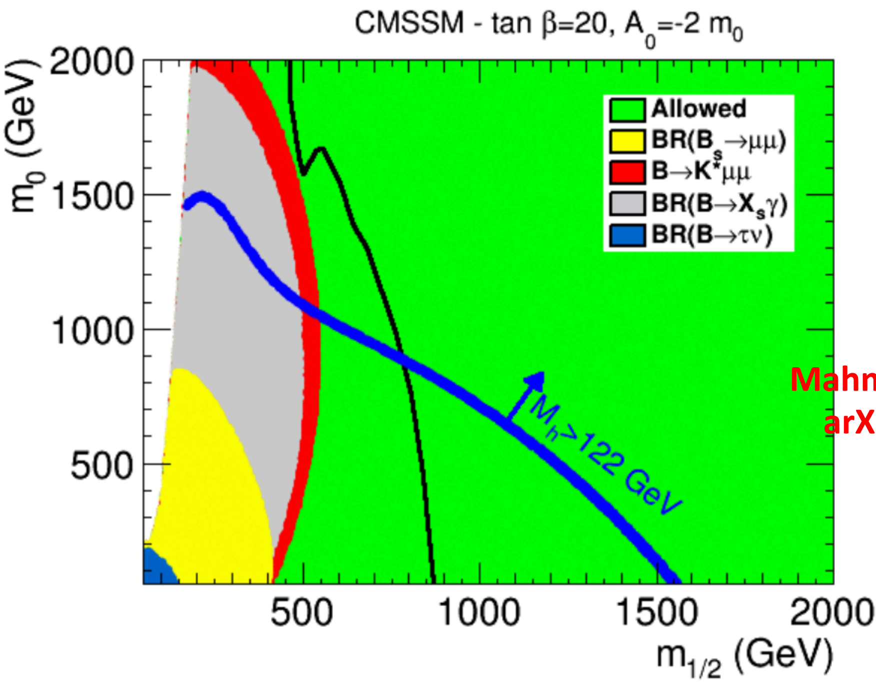
- The BF for $B \to \mu^+\mu^-$ can be enhanced in the presence of NP in the scalar or pseudoscalar operators, which can lift the helicity suppression.
- Can create some correlation among different decay modes such as $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$
- A large part of parameter space of SUSY models with large tanβ are ruled out.
- However, SM4 or RSc or SUSY models with low tanβ is to be probed now.
- For example, SM4 is ruled out if enhancement in both $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ is observed.

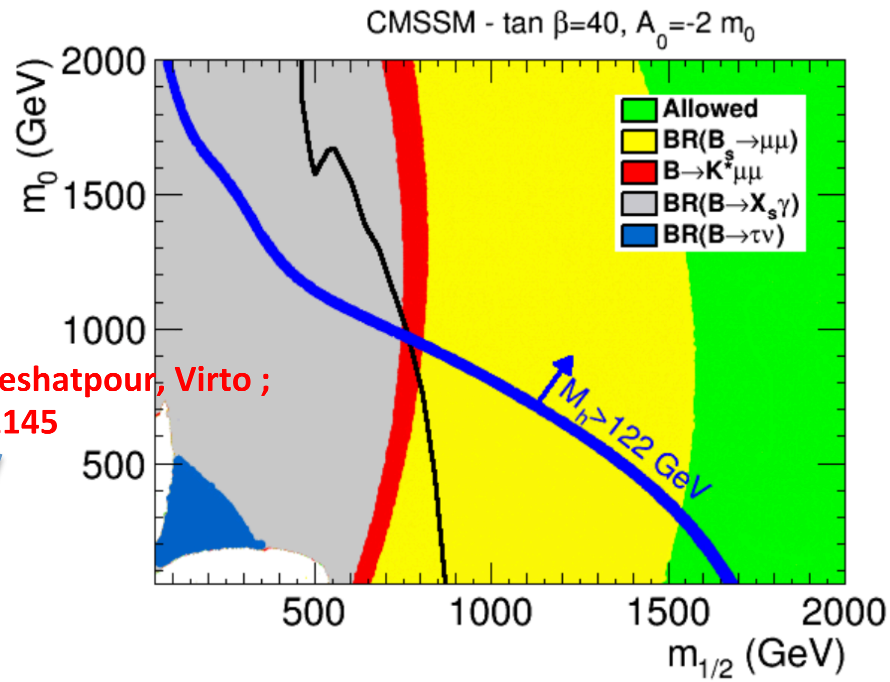


D Straub
arXiv: 1205.6094



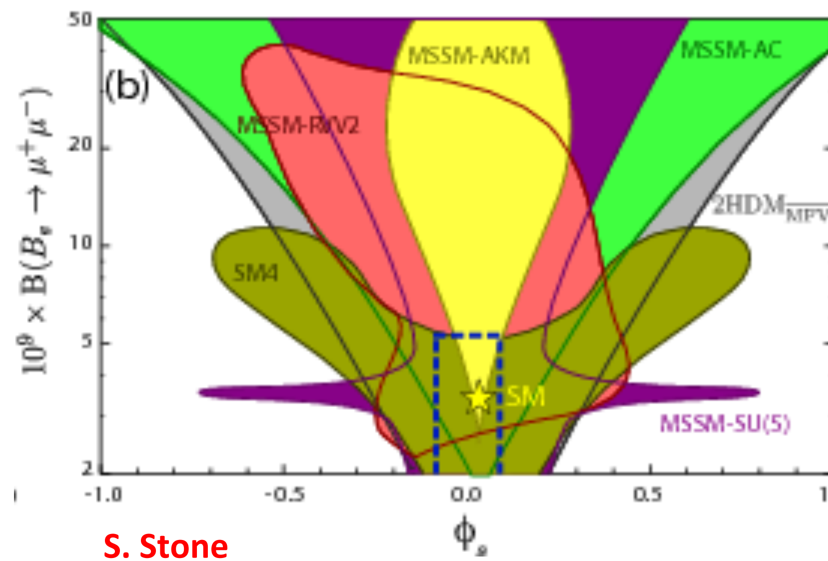
NP constraints with $B \rightarrow \mu^+\mu^-$





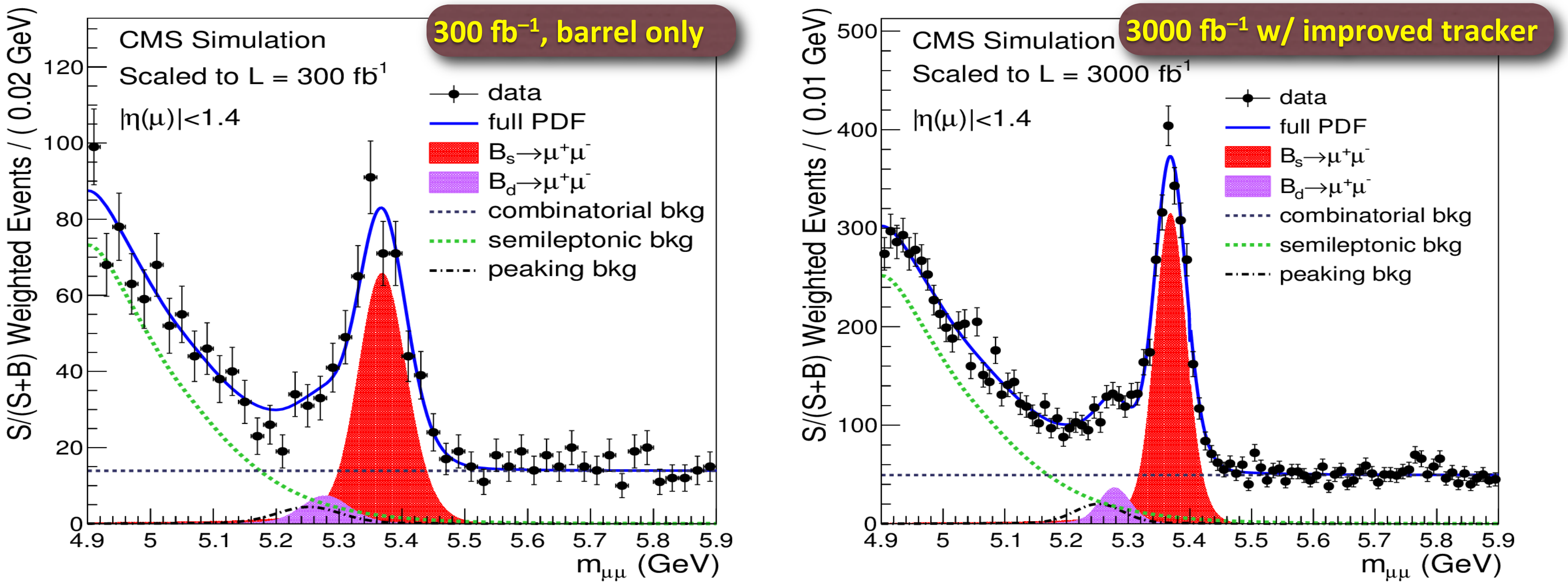
Mahmoudi, Neshatpour, Virto ;
arXiv1401.2145

- Takes different experimental measurements
- Constrains $m_{1/2}$ and m_0 SUSY parameter space
- Trilinear soft breaking parameter $A_0 = -2m_0$ is chosen to keep consistency with observed Higgs mass
- Constraints from $B_s \to \mu^+\mu^-$ at large tanβ are stronger than lower tanβ (also to direct search)
- Plot on the right shows the allowed region by $B_s \to \mu^+\mu^-$ BF measurement and the mixing induced CP asymmetry (ϕ_S)



S. Stone
arxiv: 1212.6374

CMS future prediction

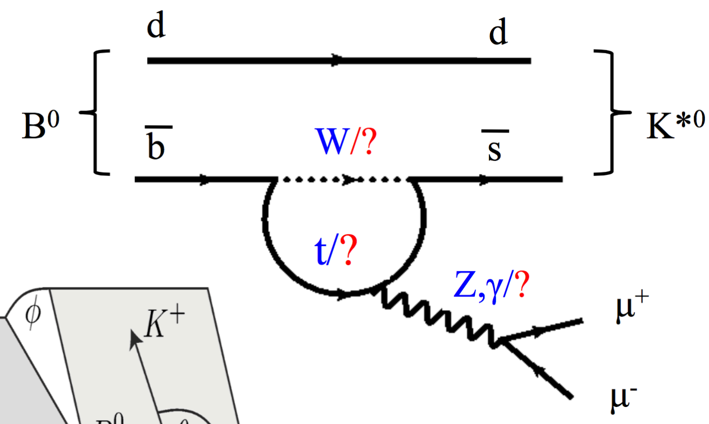


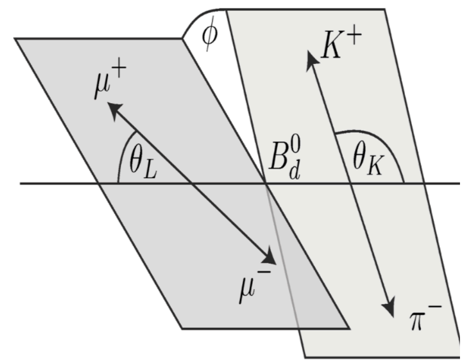
$\mathcal{L}(fb^{-1})$	$N(\mathrm{B_s})$	$N(\mathrm{B^0})$	$\delta\mathcal{B}(\mathrm{B_s} \to \mu\mu)$	$\delta\mathcal{B}(\mathrm{B^0} \to \mu\mu)$	$\mathrm{B^0}$ sign.	$\delta\frac{\mathcal{B}(\mathrm{B^0} \to \mu\mu)}{\mathcal{B}(\mathrm{B_s} \to \mu\mu)}$
20	18.2	2.2	35%	>100%	0.0-1.5 σ	>100%
100	159	19	14%	63%	0.6-2.5 σ	66%
300	478	57	12%	41%	1.5-3.5 σ	43%
300 (barrel)	346	42	13%	48%	1.2-3.3 σ	50%
3000 (barrel)	2250	271	11%	18%	5.6-8.0 σ	21%

- **Expectation assuming SM branching fraction and planned detector upgrade.**
- **Large pile up will affect detection efficiency, tightening selection criteria, reduce background, better determination of peaking background.**

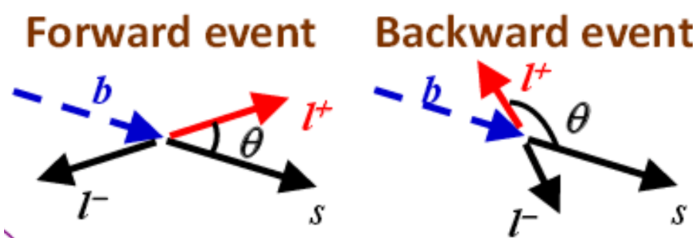
Measurement of B->$K^{*0}\mu^+\mu^-$ at CMS

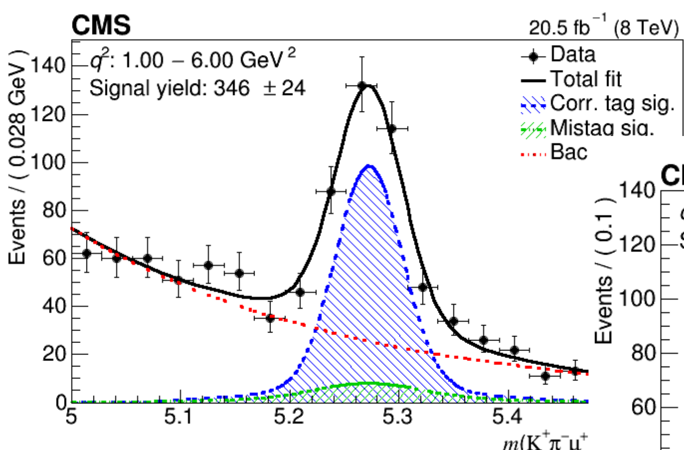
- Forbidden at tree level, but allowed via loop
- Diagrams (as shown on right)
- Sensitive to NP through BSM particles in the loop
- Small branching fraction (10^{-6}) .
- Observables to compare with SM predictions: differential BF, A_{FB}, A_{CP}, P_5', Isospin asymmetry…



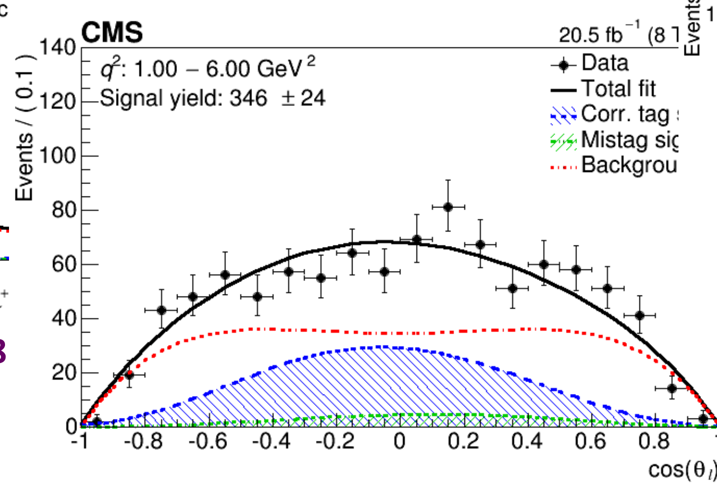


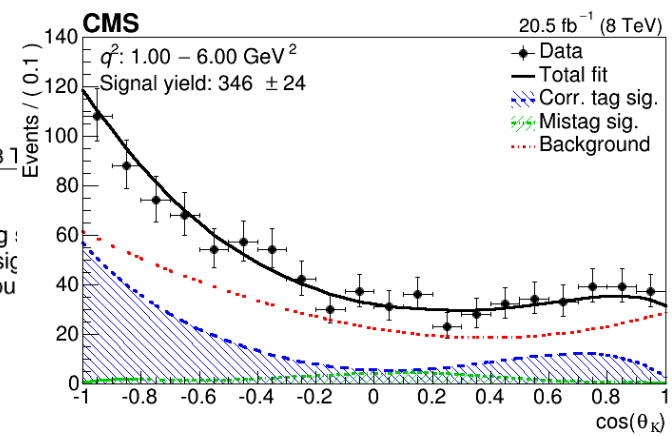
e.g A_{FB}



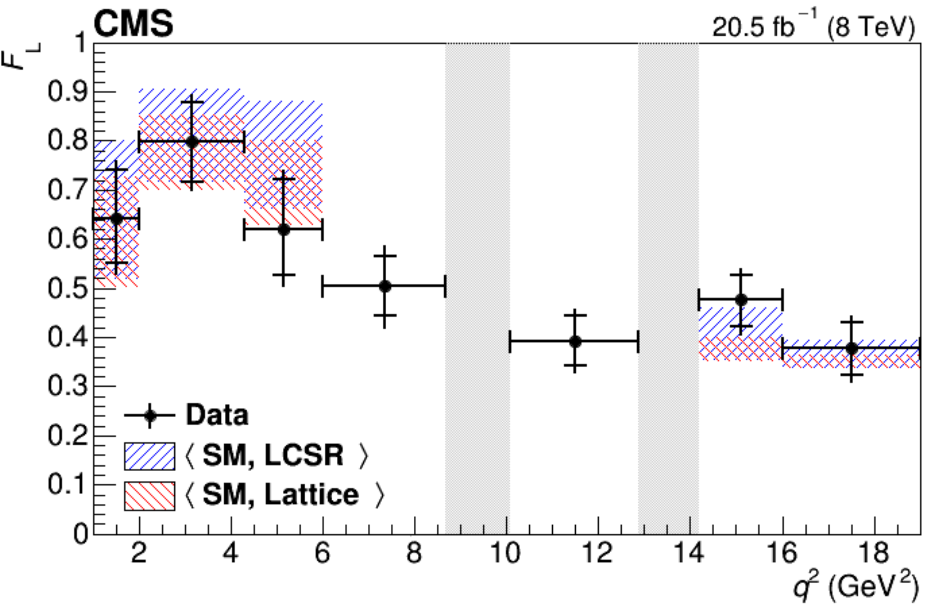


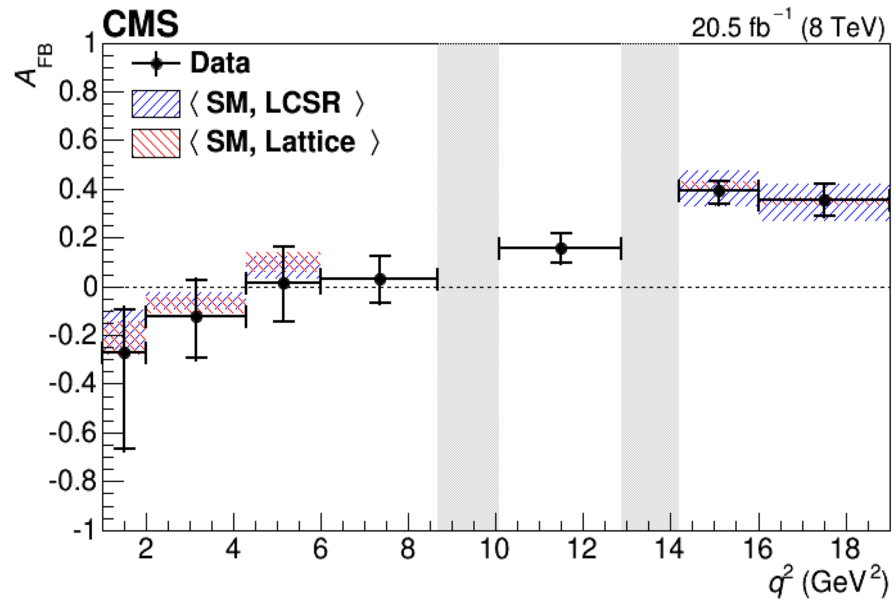
PLB 753 (2016) 424 (arXiv: 1507.08



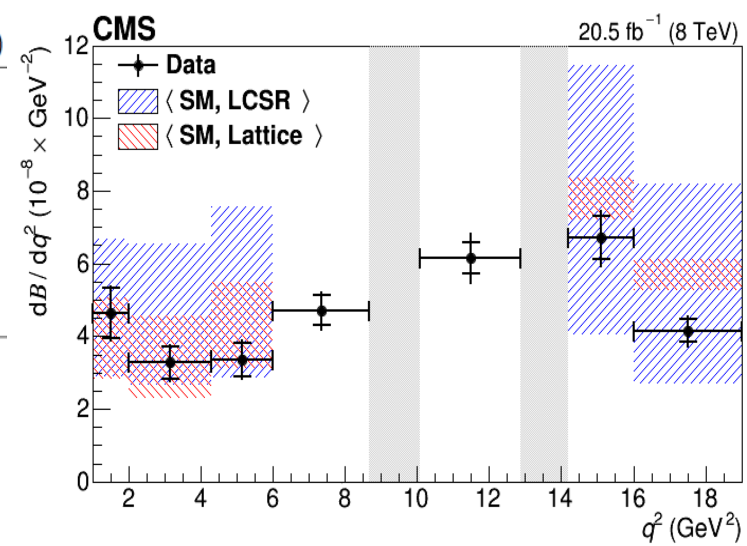


$B\to K^{*0}\mu^+\mu^-$ at CMS (cont.)





Experiment	F_L	A_{FB}	$d\mathcal{B}/dq^2$ $(10^{-8}\,\mathrm{GeV}^{-2})$
CMS (7 TeV)	$0.68 \pm 0.10 \pm 0.02$	$-0.07 \pm 0.12 \pm 0.01$	$4.4 \pm 0.6 \pm 0.4$
CMS (8 TeV, this analysis)	$0.73 \pm 0.05 \pm 0.04$	$-0.16^{+0.10}_{-0.09} \pm 0.05$	$3.6 \pm 0.3 \pm 0.2$
CMS (7 TeV + 8 TeV)	0.72 ± 0.06	-0.12 ± 0.08	3.8 ± 0.4
LHCb	$0.65^{+0.08}_{-0.07} \pm 0.03$	$-0.17 \pm 0.06 \pm 0.01$	$3.4 \pm 0.3^{+0.4}_{-0.5}$
BaBar	—	—	$4.1^{+1.1}_{-1.0} \pm 0.1$
CDF	$0.69^{+0.19}_{-0.21} \pm 0.08$	$0.29^{+0.20}_{-0.23} \pm 0.07$	$3.2 \pm 1.1 \pm 0.3$
Belle	$0.67 \pm 0.23 \pm 0.05$	$0.26^{+0.27}_{-0.32} \pm 0.07$	$3.0^{+0.9}_{-0.8} \pm 0.2$
SM (LCSR)	$0.79^{+0.09}_{-0.12}$	$-0.02^{+0.03}_{-0.02}$	$4.6^{+2.3}_{-1.7}$
SM (Lattice)	$0.73^{+0.08}_{-0.10}$	$-0.03^{+0.04}_{-0.03}$	$3.8^{+1.2}_{-1.0}$

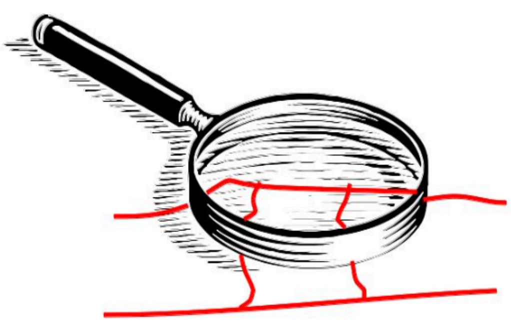


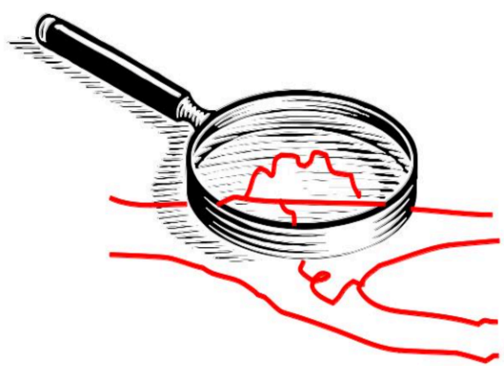
CMS results consistent with theory prediction as well as other experimental results.

PLB 753 (2016) 424 (arXiv: 1507.08126)

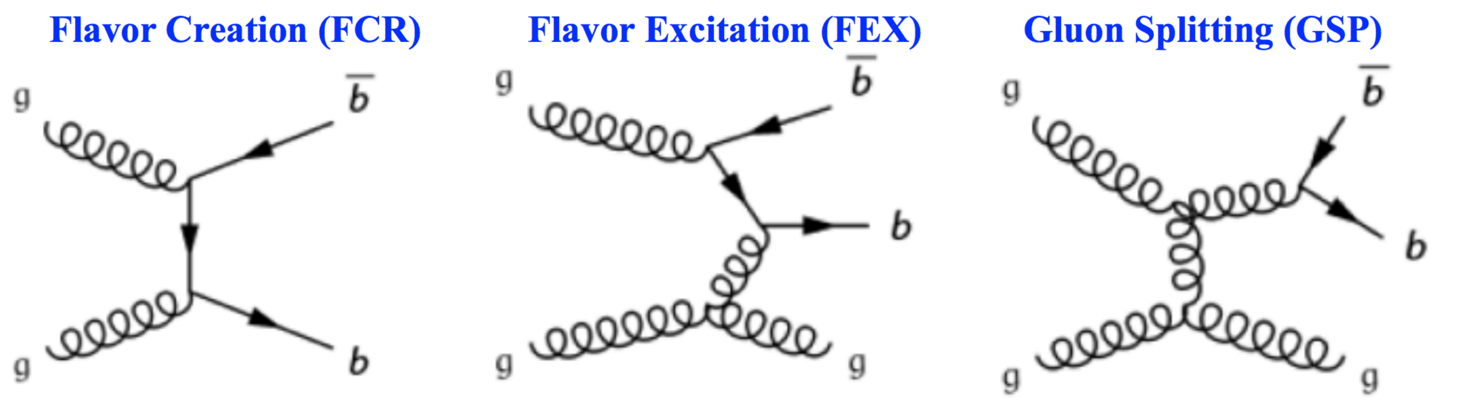
Summary

- The 13TeV results from CMS and ATLAS are consistent with theory prediction.
- CMS and LHCb reported a first observation of $B_s \rightarrow \mu^+\mu^-$ (6.2σ from combined data). The measured BF is compatible with SM prediction (within 1.2σ)
- Combined result reported first evidence of $B^0 \rightarrow \mu^+\mu^-$. The measurement is compatible with SM within 2.2σ
- The result started to constrain the NP parameter spaces.
- However, we look forward for new (13 TeV & 14 TeV) datasets to give us $B^0 \rightarrow \mu^+\mu^-$ observation soon.
- B->$K^{*0}\mu^+\mu^-$ results are consistent with theory prediction as well as other experiments.
- The next few years would be very crucial for LHC to look for something beyond SM.





B-physics results from CMS & ATLAS



$$\sigma\left(b\bar{b}\right)^{14\ \mathrm{TeV}} = 2\times\sigma\left(b\bar{b}\right)^{7\ \mathrm{TeV}}$$

	LHC era		HL-LHC era		
	2010-2012	2015-2017	2019-2021	2024-2026	2028-2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II	-	0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-