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On behalf of CMS Collaboration

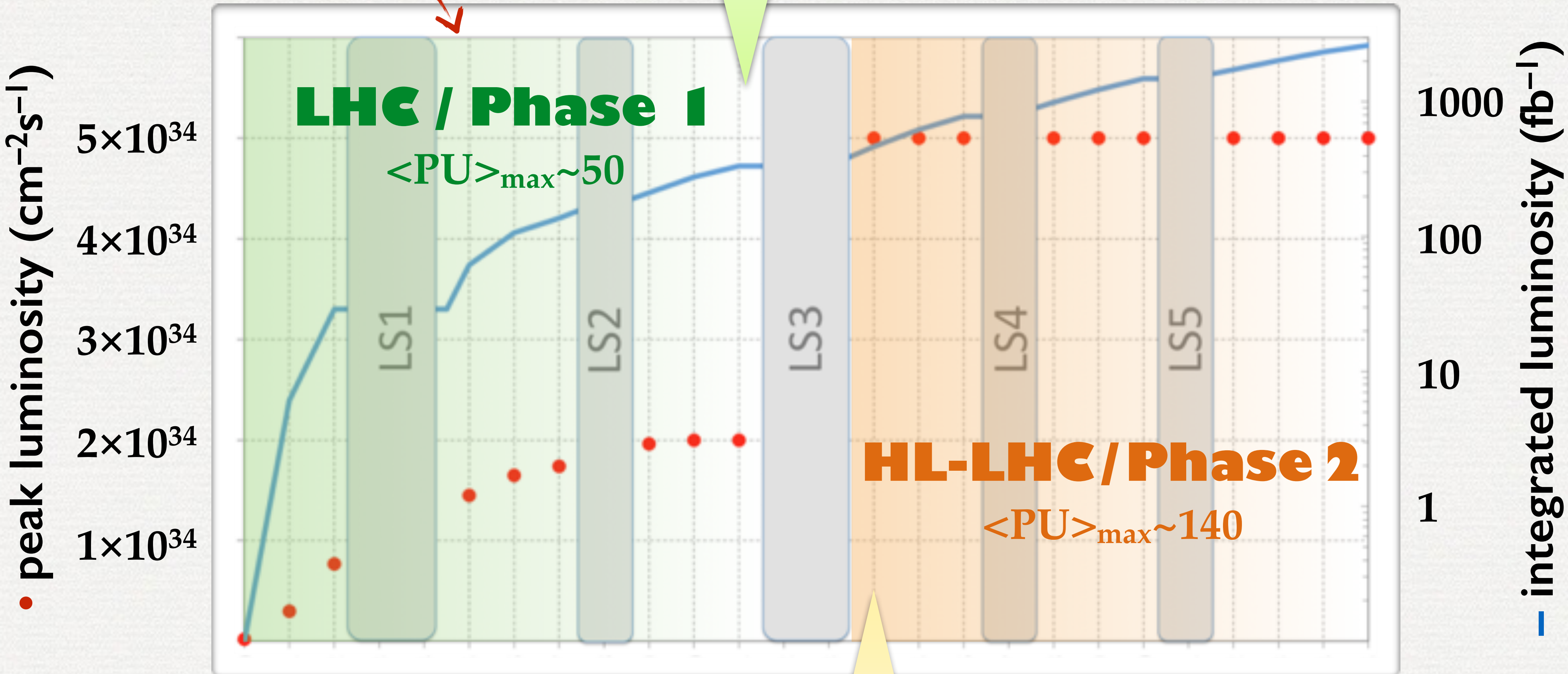
B PHYSICS AT CMS WITH LHC RUN-II AND BEYOND

FROM LHC TO HL-LHC

Here we are!

LHC operation up to LS3 (2023)

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



HL-LHC operation beyond LS3 (2025+)

New low-β triplets 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}.

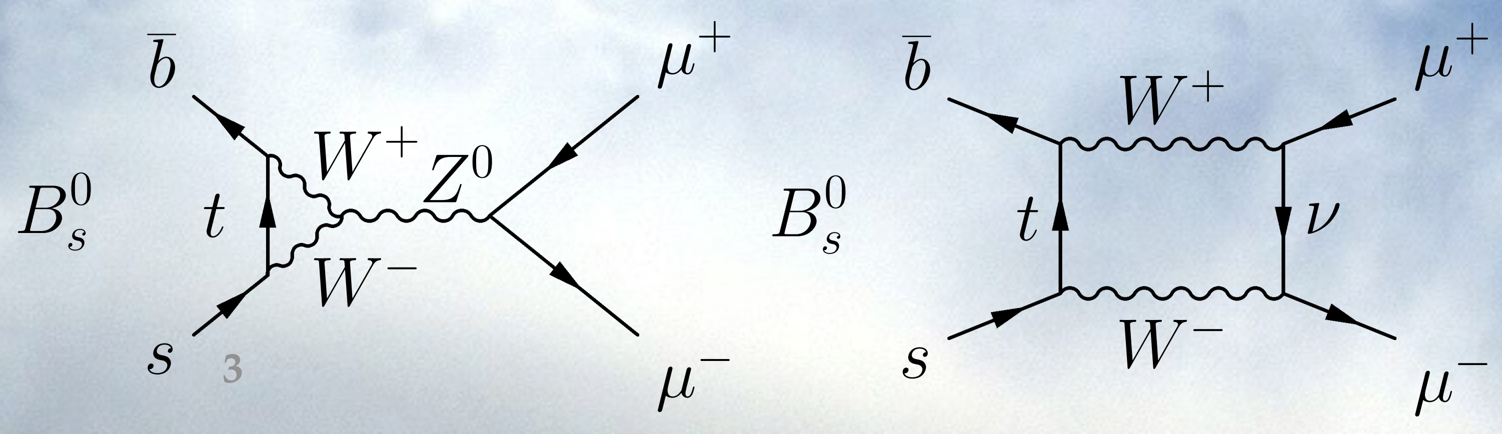
FLAVOUR PHYSICS @ FUTURE CMS

High luminosity × Large production cross section =
ONE OF THE BIGGEST B HADRON DATA SETS ON EARTH

- A unique test bench for flavour physics predictions.
- Measurements which require huge statistics will have a significant boost, such as CP phase in $B_s \to J/\psi\phi$, $B \to K^*\mu\mu$.
- Will allow to study (ultra) rare processes at a sensitivity level never attained, such as $B \to \mu\mu$, or lepton-flavor violating decays such as $B \to \mu\tau$, $\tau \to \mu\mu\mu$.

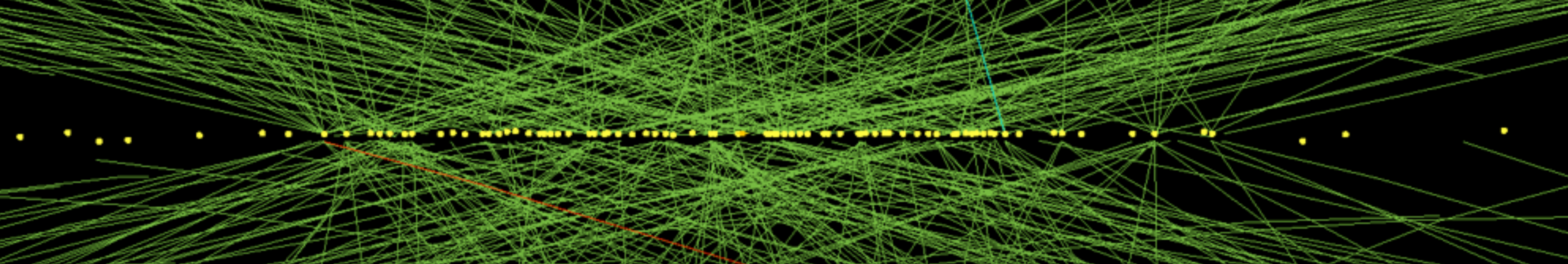
$B_{(s,d)} \to \mu^+\mu^-$

as a benchmark analysis today!



THE CHALLENGE TOWARD HL-LHC

An event with 78 reconstructed vertices — expected to exceed doubled pile-up events at the running condition of HL-LHC.

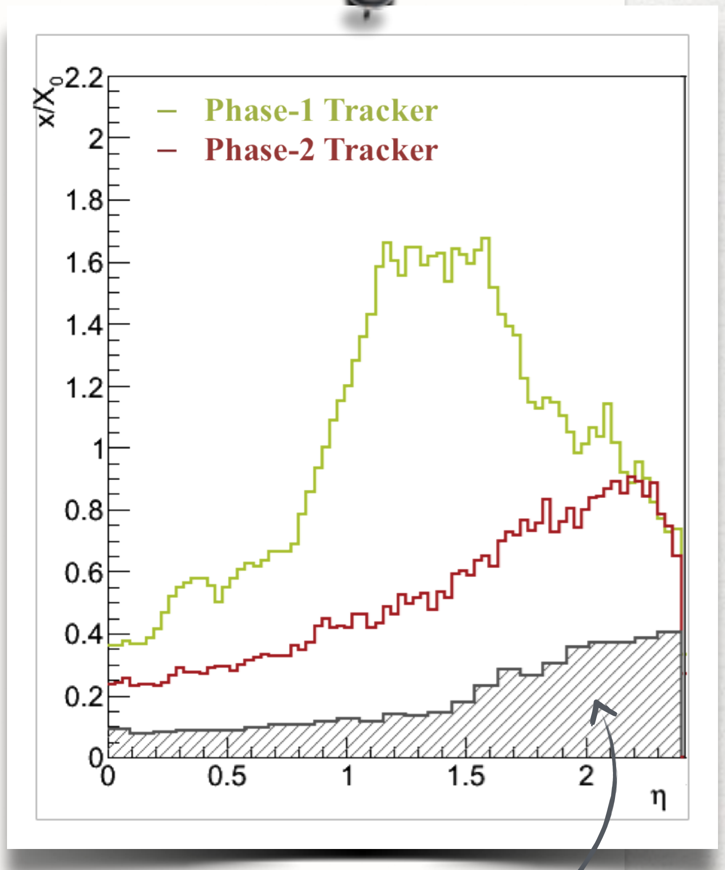


- Capability of operating at a very high pile-up of 140 interactions.
- The detector has to survive up to 3000 fb^{-1}, and to year 2035.
- Need to preserve a similar performance even at 140 PU, 3000 fb^{-1} as the current detector as in Run-I.
- Maintain current trigger acceptance for HL- LHC conditions, and preserve lowest possible trigger and analysis thresholds.

SCOPE OF CMS UPGRADE

- **New tracker system:**
  - Feature 4 pixel barrel layers and 5 disks on the endcaps with half of the material budget in the central region.
  - Combined with a smaller silicon sensors pitch, the momentum resolution will be improved, and help to **separate B^0 and B_s signals**.
- **Enhanced L1 trigger:**
  - Hardware track trigger at level-1 and maintaining low thresholds at HL-LHC luminosities.
  - Higher L1 trigger and software high-level trigger (HLT) accept rates [*5-10 times to the phase-I*].
  - Extended trigger capabilities for the muon system with improved coverage in the forward direction.

Material budget for ***Phase-I****/****Phase-II*** *tracker*



Phase-I pixel

THE PHYSICS TARGET

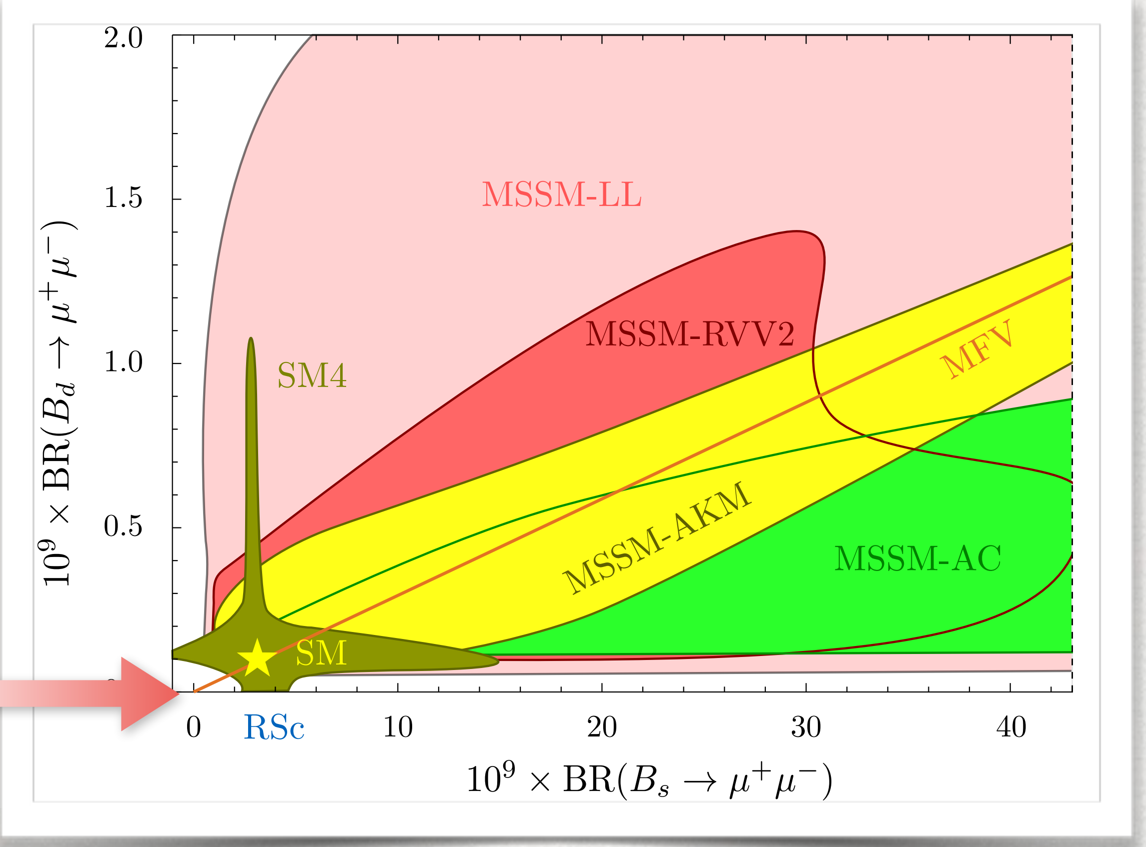
An obvious target for HL-LHc!

- $B_{s,d}\to\mu^+\mu^-$ decays are only proceed through FCNC processes and are highly suppressed in SM:
- Loop diagram + Suppressed SM + Theoretically clean = *An excellent place to look for new physics*.
- Some of the new physics scenarios may boost the $B\to\mu\mu$ decay rates by 10~20 times easily, for example:
  - **2HDM**: $\mathcal{B} \propto \tan^4\beta$ & $m(H^+)$
  - **MSSM**: $\mathcal{B} \propto \tan^6\beta$
- B_s/B_d ratio – a stringent test of minimal flavor violation hypothesis.

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

$$\mathcal{B}(B_s\to\mu^+\mu^-) = (3.65 \pm 0.23)\times10^{-9}$$
$$\mathcal{B}(B_d\to\mu^+\mu^-) = (1.06 \pm 0.09)\times10^{-10}$$

Ref: D. M. Straub, arXiv: 1012.3893



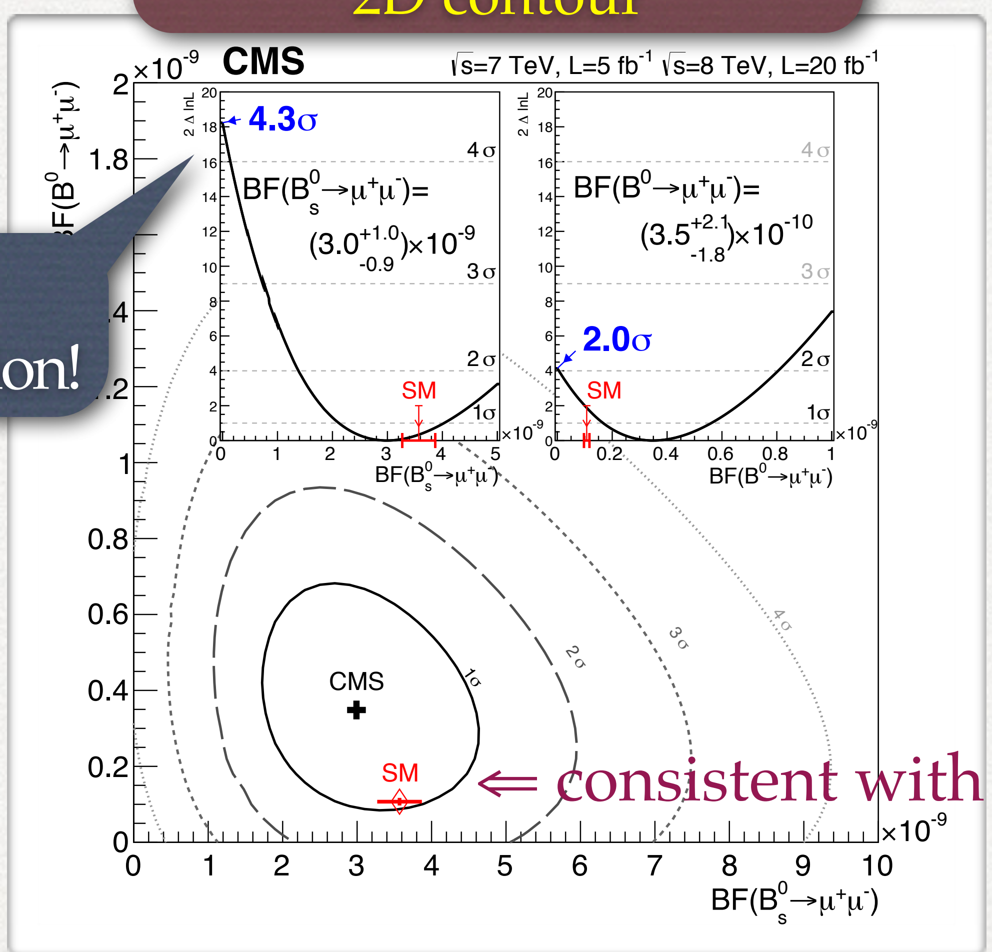
REFERENCE ANALYSIS

- Event classification is carried out by **Boosted Decision Tree (BDT)**.
- Branching fractions were extracted by unbined maximum likelihood fits in 12 categorized BDT bins.

Ref. CMS PRL 111 (2013) 101804

Channel	Branching fraction
$B_s \to \mu^+\mu^-$	$(3.0^{+1.0}_{-0.9})\text{x } 10^{-9}$
$B_d \to \mu^+\mu^-$	$<1.1\text{x}10^{-9}$ @ 95% CL

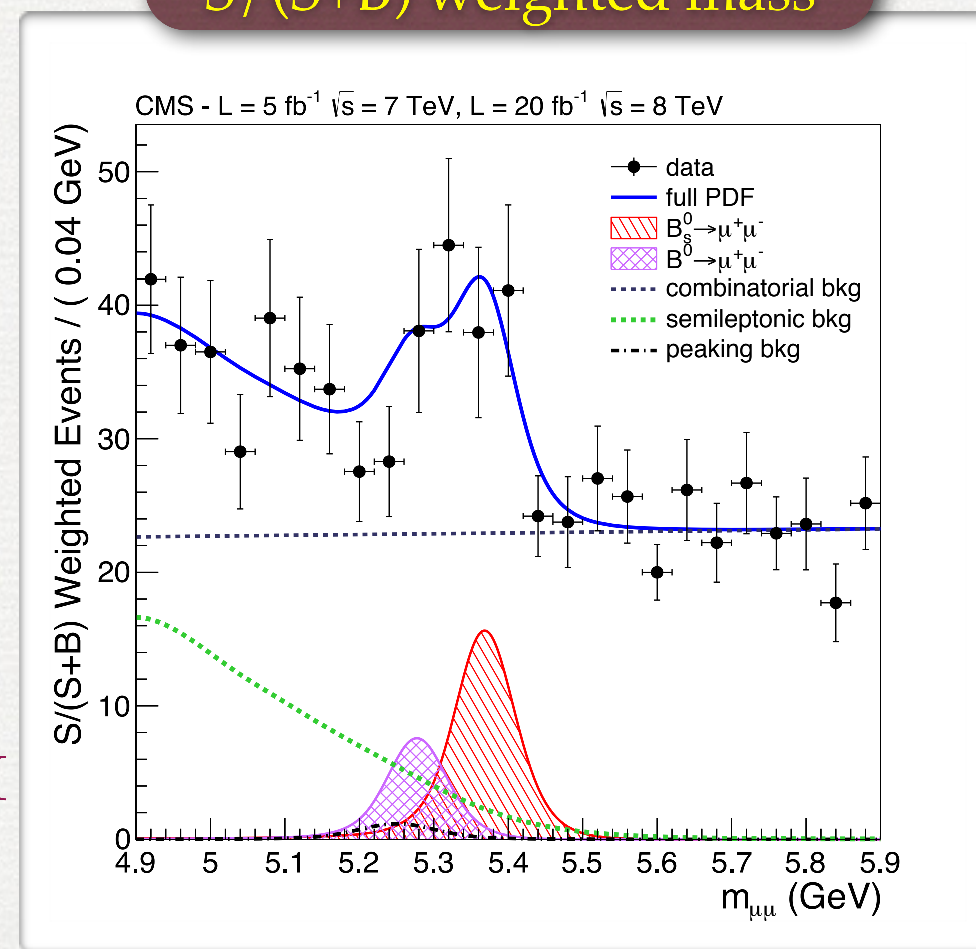
2D contour



4.3σ observation!

⇐ consistent with SM

S/(S+B) weighted mass



REFERENCE ANALYSIS

- Events are triggered by dimuon events at L1, and with mass/displaced vertex requirement at the HLT.
- MVA-based muon identification is introduced.
- Normalized to the reference channel **$B^+ \to J/\psi(\to\mu^+\mu^-)\, K^+$**.
- Updates on background decay model and physics parameters presented in the **CMS+LHCb combination Nature** are incorporated.

Ref. Nature 522 (2015) 68

$$\mathcal{B}(B_{s,d}\to\mu^+\mu^-) = \frac{N_S}{N(B^\pm\to J/\psi K^\pm)} \times \mathcal{B}(B^\pm\to J/\psi K^\pm) \times \frac{A(B^\pm)}{A(B_s)} \frac{\varepsilon^{ana}(B^\pm)}{\varepsilon^{ana}(B_s)} \frac{\varepsilon^{\mu}(B^\pm)}{\varepsilon^{\mu}(B_s)} \frac{\varepsilon^{trig}(B^\pm)}{\varepsilon^{trig}(B_s)} \frac{f_u}{f_s}$$

Acceptance

Selection efficiency

muon identification

Trigger efficiency

B-hadronization composition (B_s only)
(LHCb JHEP 04 (2013) 001: 0.256±0.020)

We do not introduce possible improvements on the analysis strategy itself.
An optimized analysis for $B^0\to\mu\mu$ will provide better results.

Then scale the analysis to LHC Run-2 and beyond!

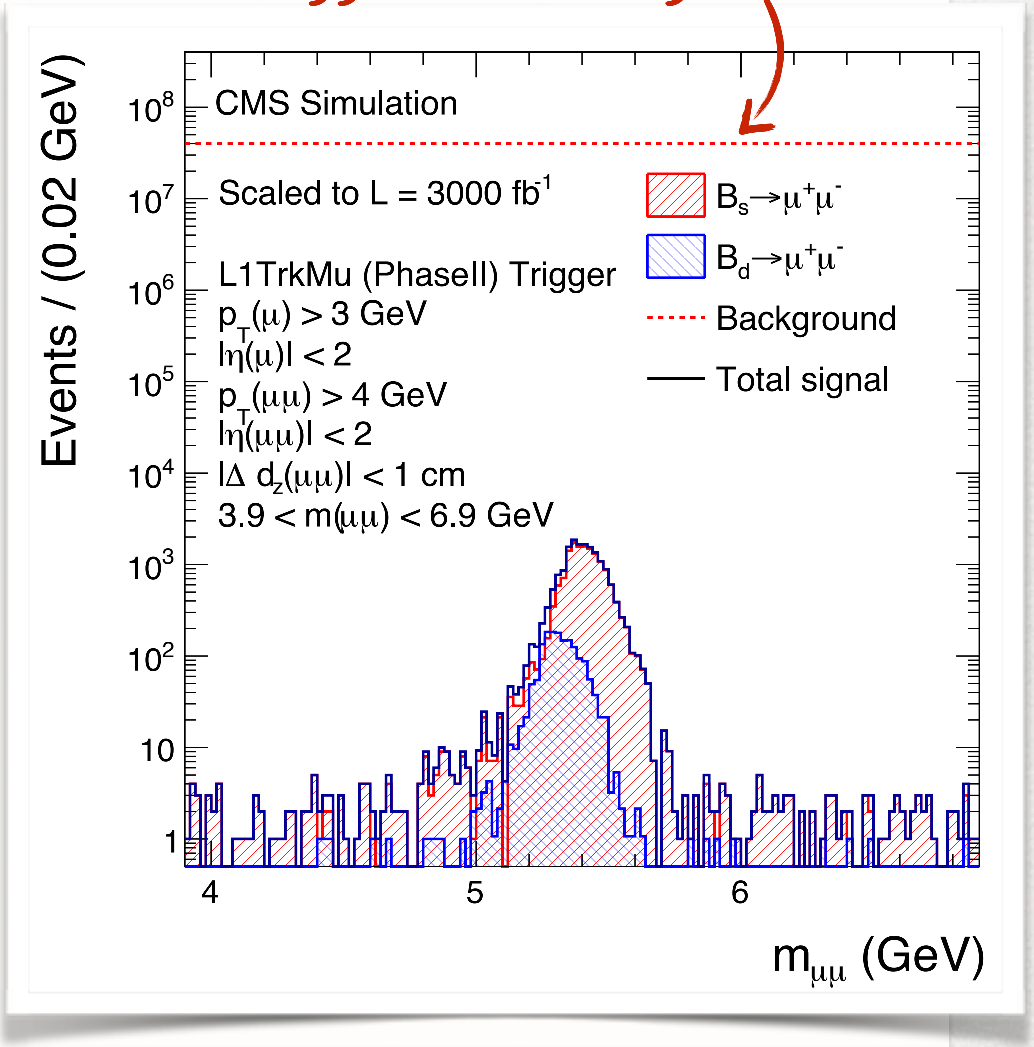
TOWARD THE FUTURE: ANALYSIS ASSUMPTIONS

- **Pseudo experiments** are used to estimate the expected CMS performance in two different scenarios:
  - **The Phase-1 scenario**: corresponding to the expected performance of the CMS detector including LHC Run-II and Run-III, to an integrated luminosity of **300 fb^{-1}** at 14 TeV.
  - **The Phase-2 upgrade scenario**: corresponding to the expected performance of the CMS detector after the full Phase-2 upgrades and to a luminosity of **3000 fb^{-1}** at 14 TeV.
- GEANT4-based simulated samples are used to estimated the performance of trigger, resolution, and pile-up effect at the phase-2 running condition.
- Muon efficiency and identification are assumed to be the same as Run-I.
- Standard Model branching fractions are assumed in the study.

TOWARD THE FUTURE:
L1 TRIGGER AT PHASE-2

- Low-p_T di-muon L1 trigger algorithm exploiting the triggering capabilities of the upgraded CMS tracker is studied with full simulation with the Phase-2 scenario.
- Invariant mass resolution for B→μμ at L1 is estimated to be **~70 MeV**.
- The rate of the L1 trigger is estimated from the minimum-bias simulation sample, and is equal to **a few hundred Hz**. This corresponds to a small fraction of the total available L1 bandwidth (~1 MHz).

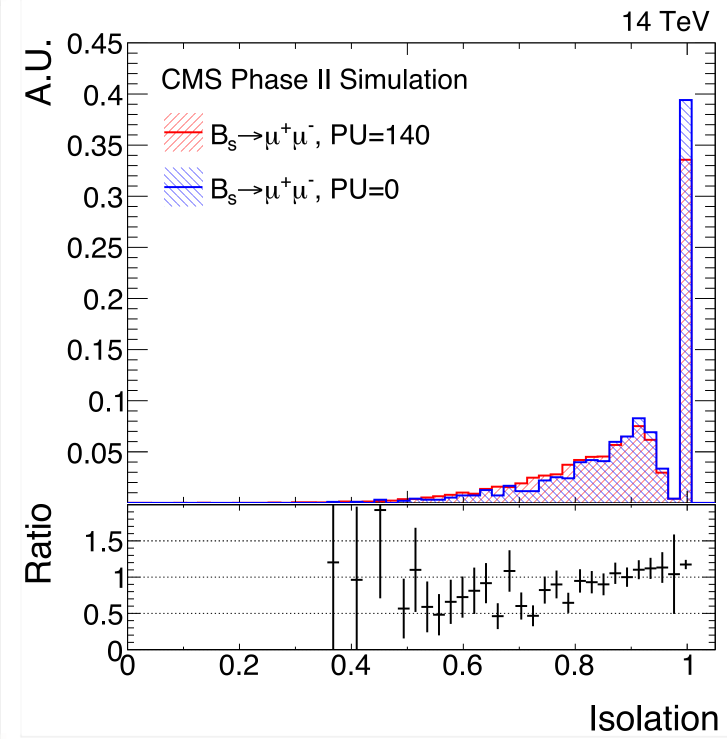
trigger at background level



Low-pT track-trigger-based algorithm as in Run-I is expected to be entirely feasible for Phase-2.

TOWARD THE FUTURE: PERFORMANCE INPUTS

- The offline invariant mass resolution is estimated from B→μμ simulated samples implementing the full detector simulation of the Phase-I and Phase-II scenarios.
- The effects of the high pile-up have studied based on simulated samples as well.



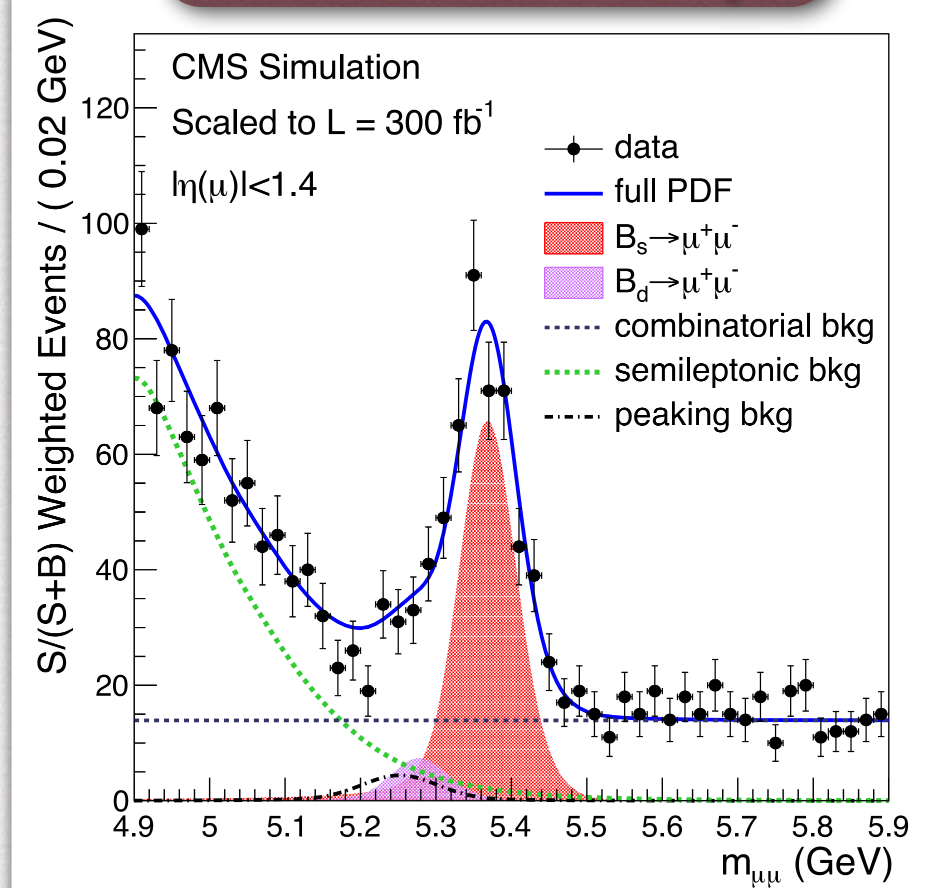
A comparison of isolation variable in ***PU=0*** *and* ***PU=140*** *environment.*

Inputs	Phase-1	Phase-2
Offline barrel mass resolution	42 MeV	28 MeV
Trigger & muon ID	as Run-I	as Run-I
Efficiency drop due to PU (sig./bkg.)	as Run-I	–30%/–35%
Uncertainty: B+ normalization	5%	3%
Uncertainty: peaking background	20%	10%
Uncertainty: semi-leptonic B decays	25%	20%
Uncertainty: fs/fu	5%	5%

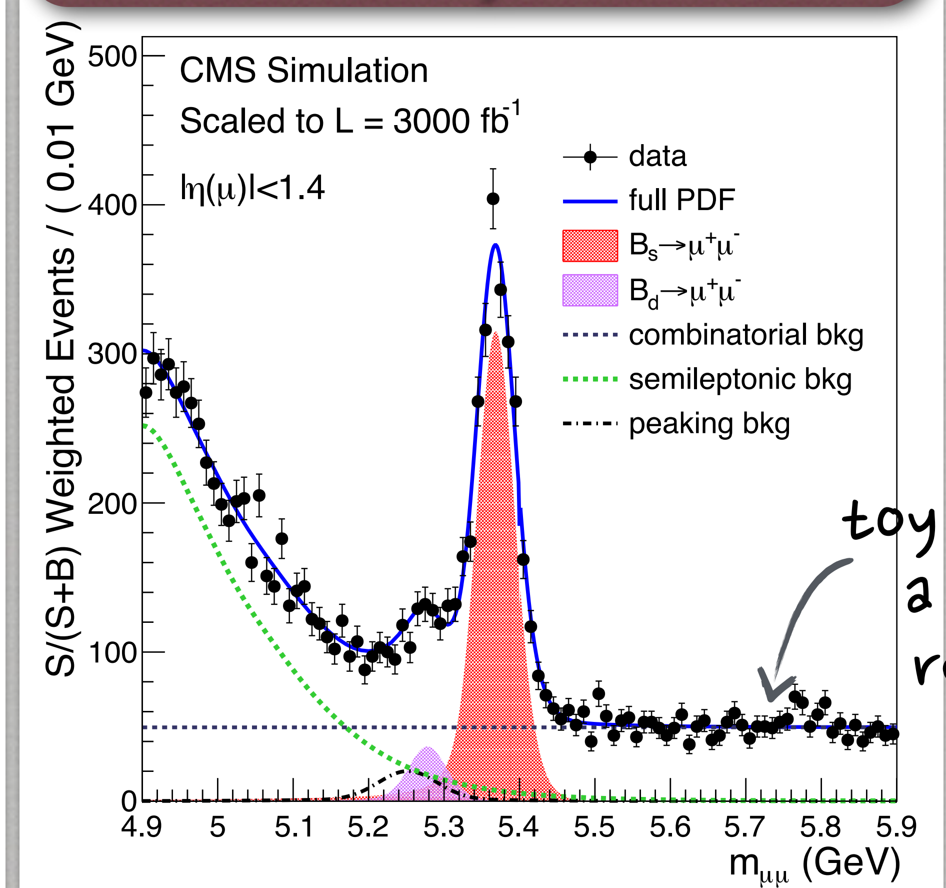
Inject into pseudo experiments for the sensitivity estimations.

TOWARD THE FUTURE: RESULTS

300 fb^{-1}, barrel only



3000 fb^{-1} w/ improved tracker



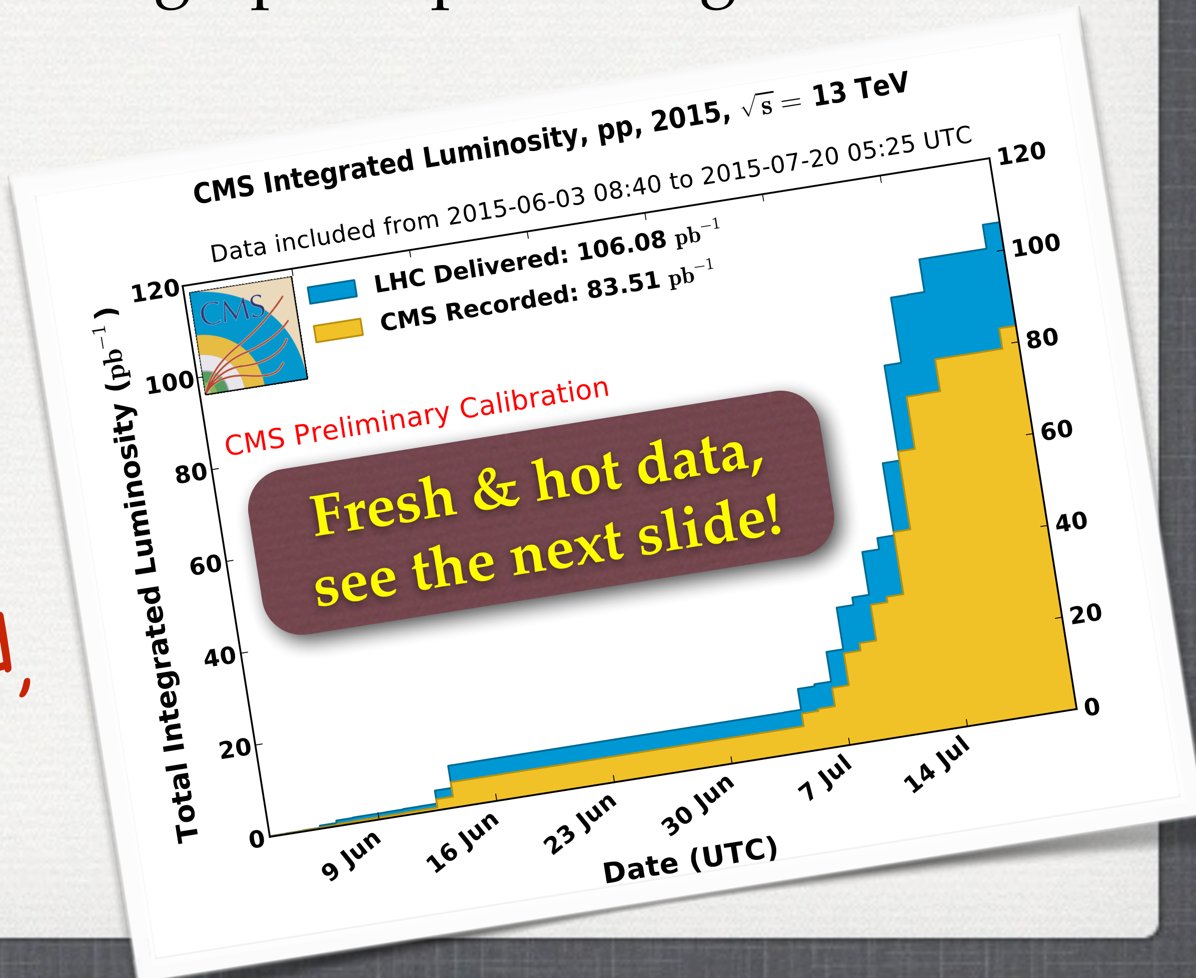
toy data assumed a strong BDT requirement

L (fb^{-1})	$\delta\mathcal{B}(B_s \to \mu^+\mu^-)$	$\delta\mathcal{B}(B_d \to \mu^+\mu^-)$	B_d sign.	$\delta[\mathcal{B}(B_d)/$
100	14%	63%	0.6–2.5σ	66%
300	12%	41%	1.5–3.5σ	43%
300 (barrel)	13%	48%	1.2–3.3σ	50%
3000 (barrel)	11%	18%	5.6–8.0σ	21%

Ref.
CMS PAS
FTR-14-015

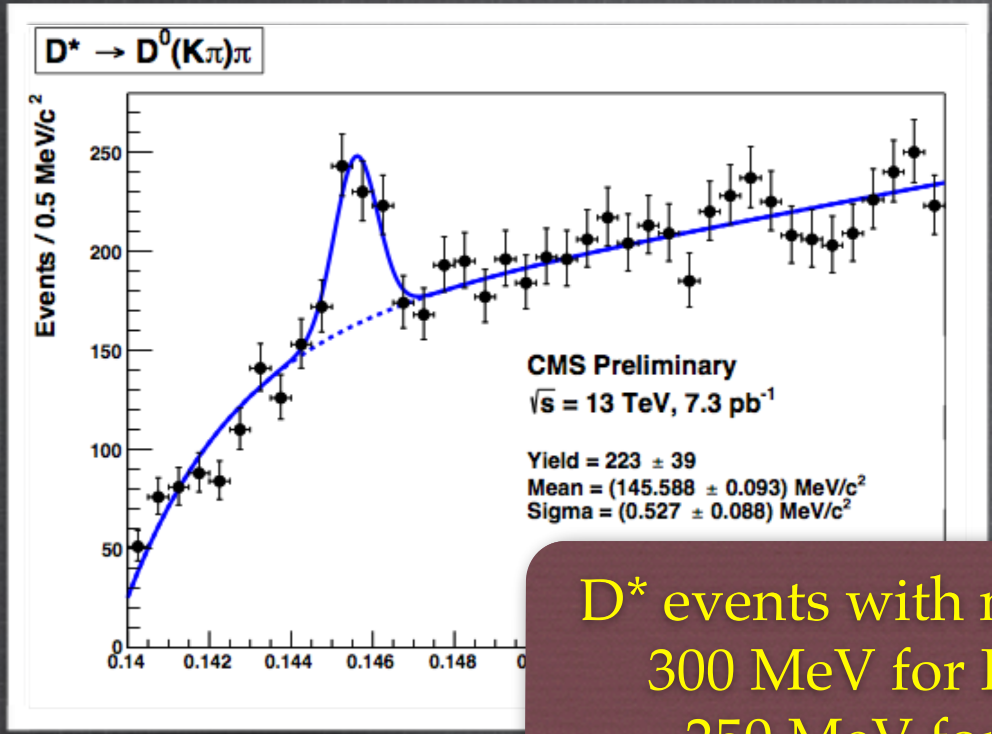
BEFORE MOVING AHEAD...

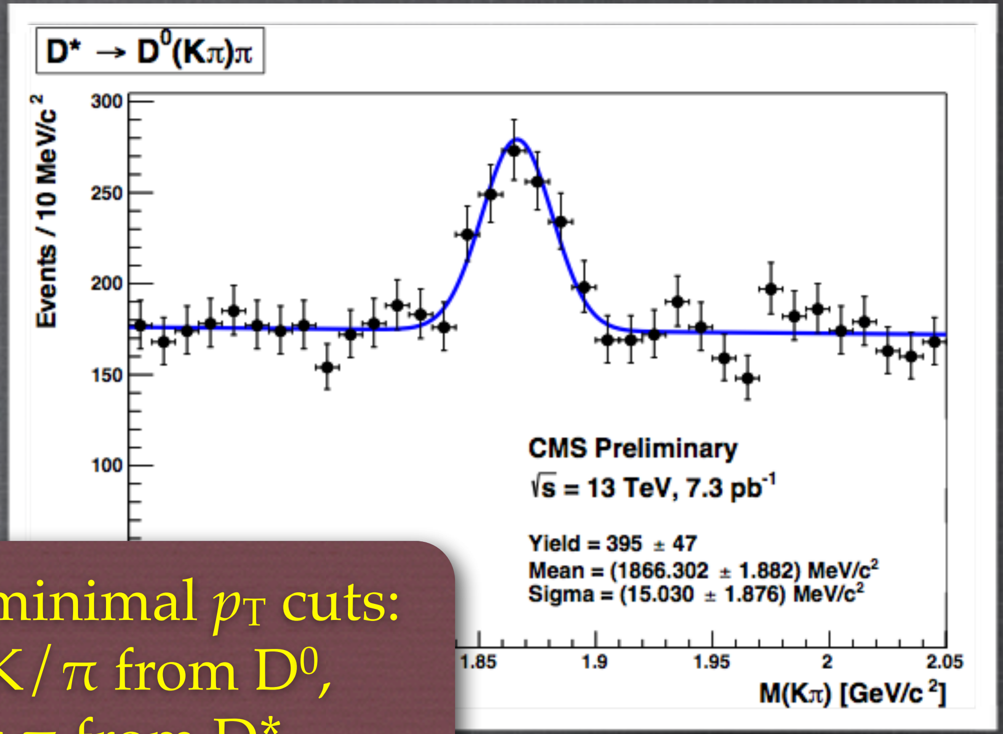
- The large data from LHC run-II and future operations will provide an excellent probe for the flavor physics.
- As a benchmark study, we estimate the CMS potential to trigger and reconstruct the $B_{s,d} \to \mu^+\mu^-$ processes at future LHC and HL-LHC runs.
- With the upgraded CMS detector, it will be possible to trigger and reconstruct the signal events even with the high pile-up running conditions at HL-LHC.
- The upcoming large data set will leads to high precision measurements and provide stringent tests of the Standard Model.



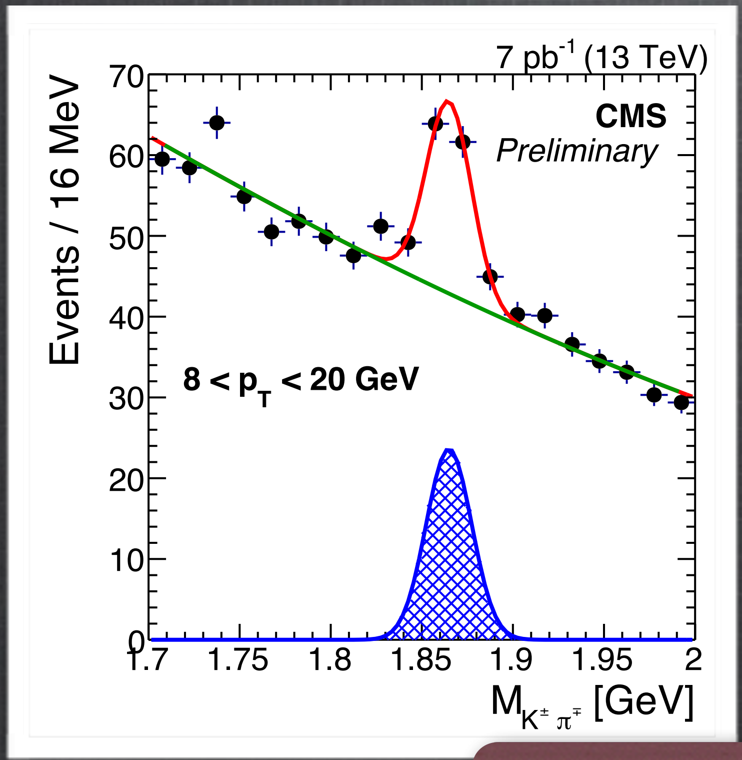
LHC run-II started as planned, CMS is back in business!

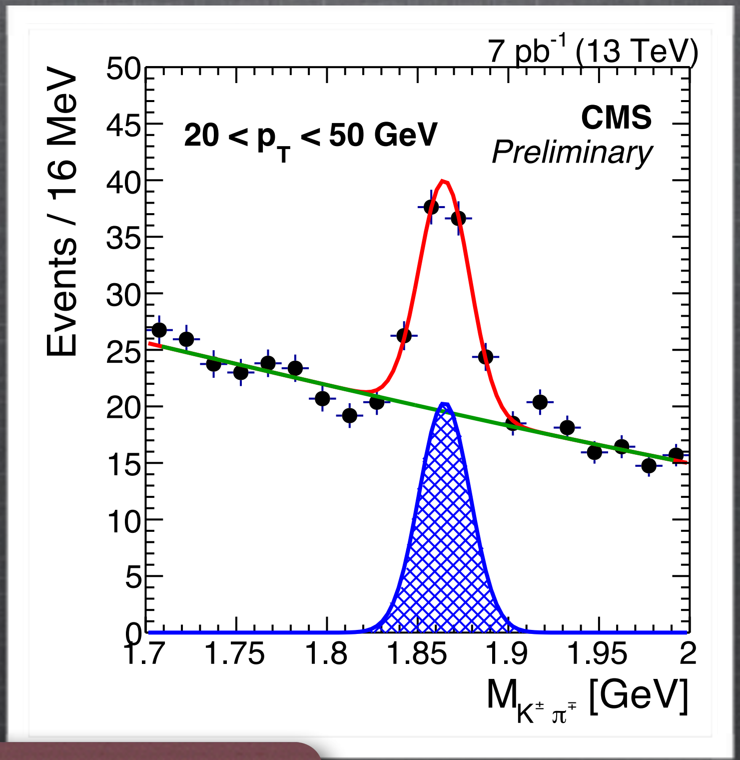
FRESH STUFF FROM RUN-II

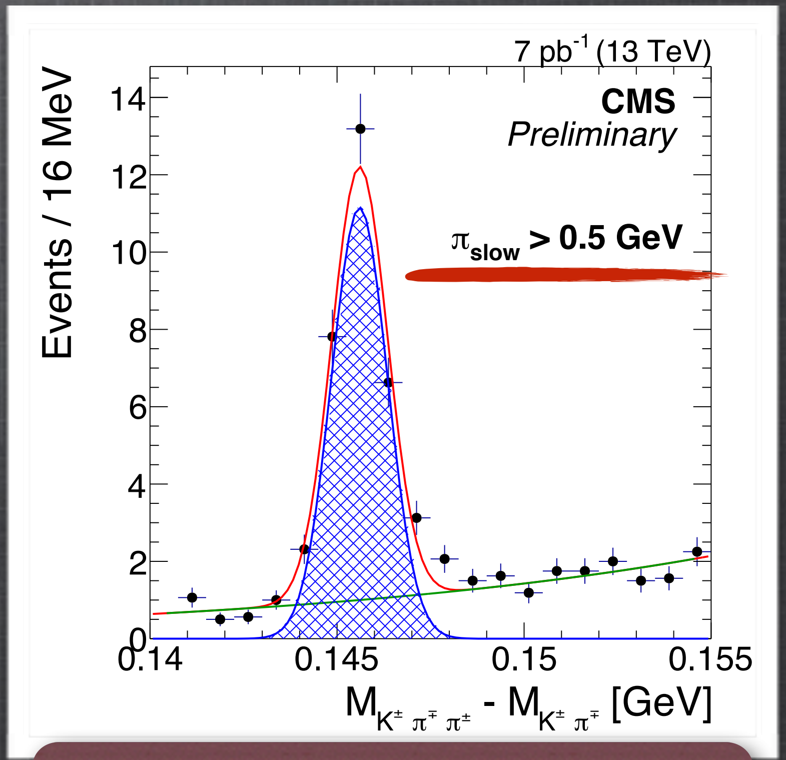




D* events with minimal p_T cuts:
300 MeV for K/π from D^0,
250 MeV for π from D*.



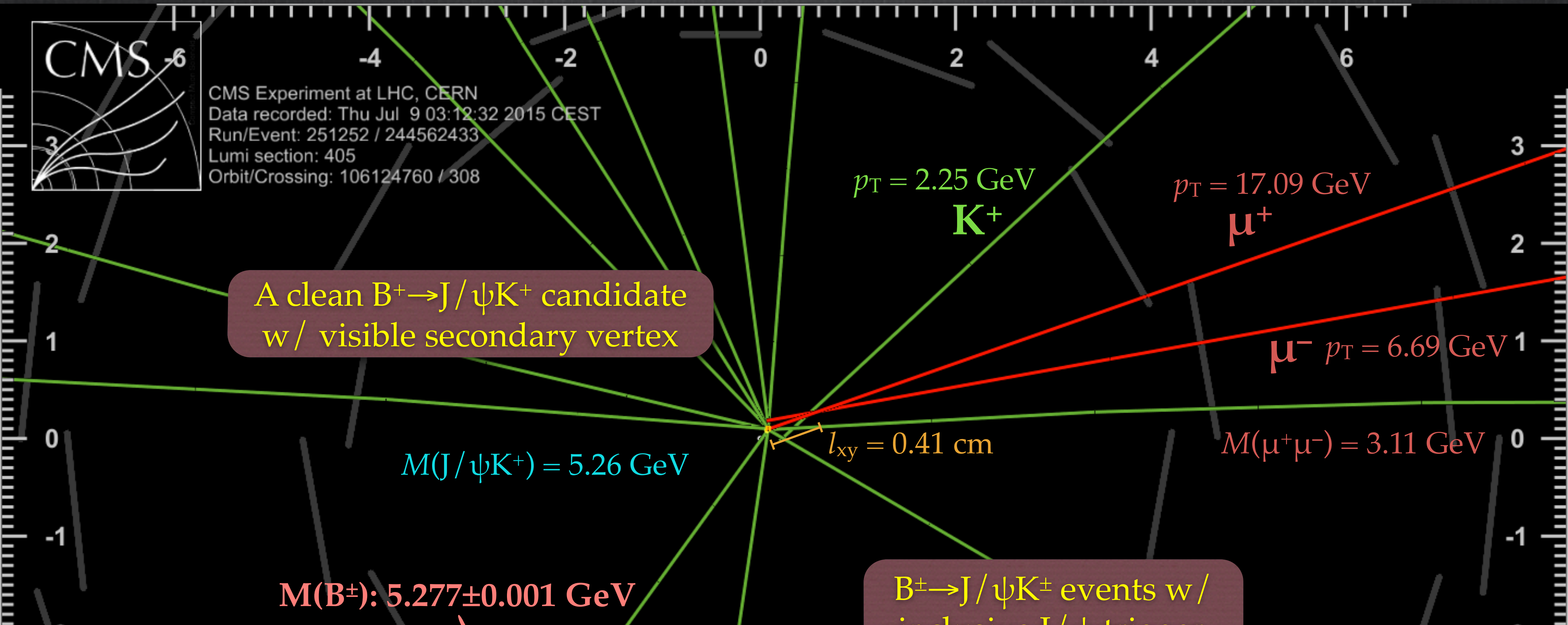




Inclusive D^0 events

D^* with tight requirement

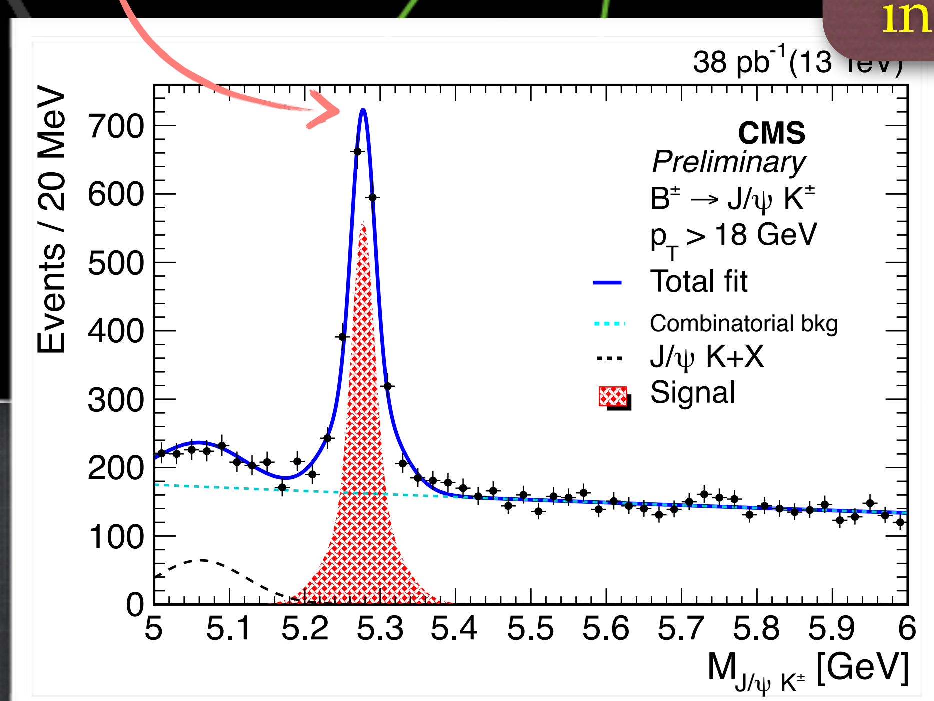
FRESH STUFF FROM RUN-II

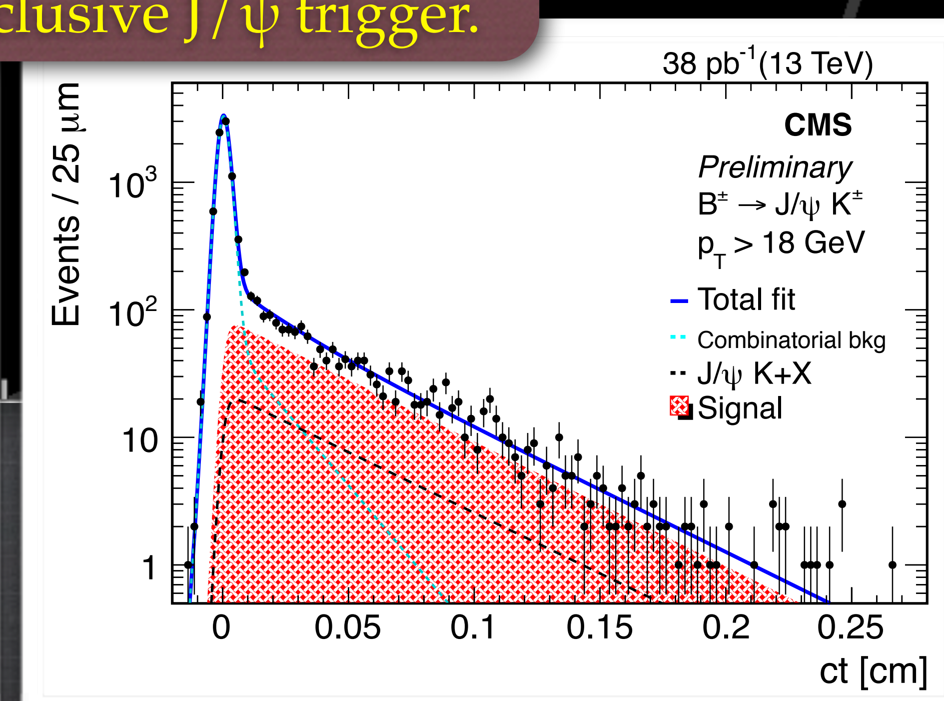


A clean $B^+ \to J/\psi K^+$ candidate w/ visible secondary vertex

M($B^\pm$): 5.277±0.001 GeV

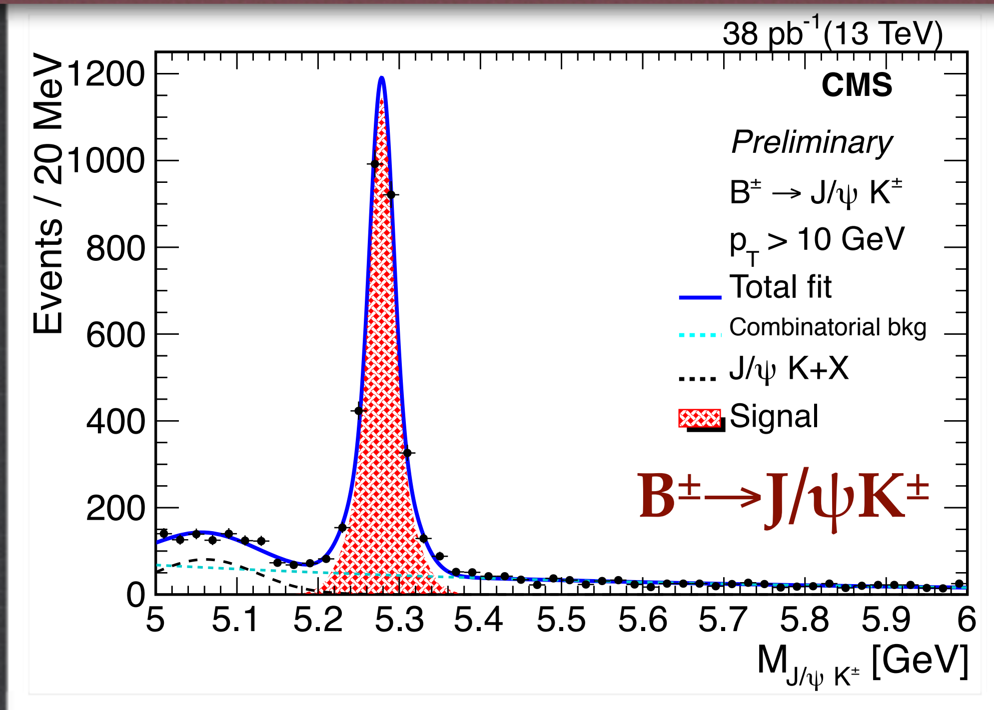
$B^\pm \to J/\psi K^\pm$ events w/ inclusive J/ψ trigger.

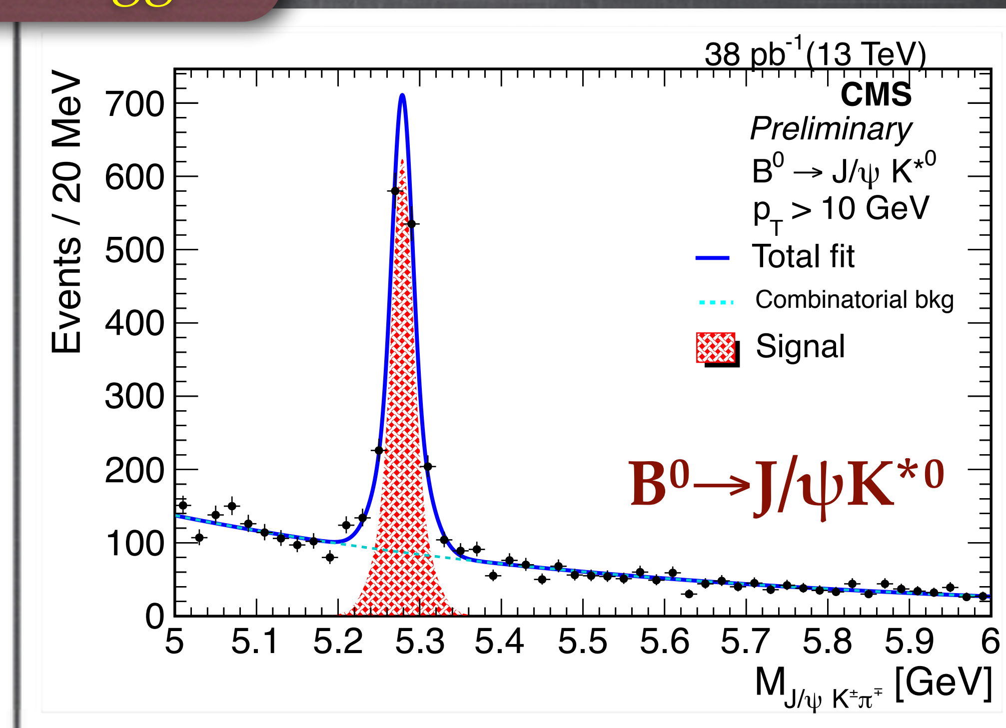


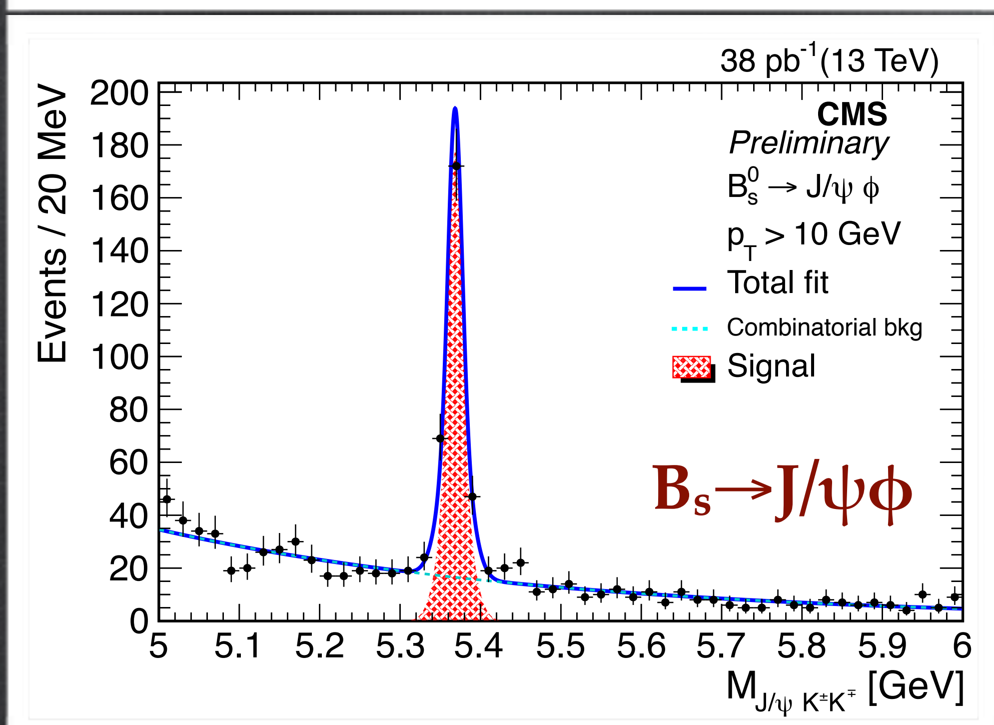


FRESH STUFF FROM RUN-II

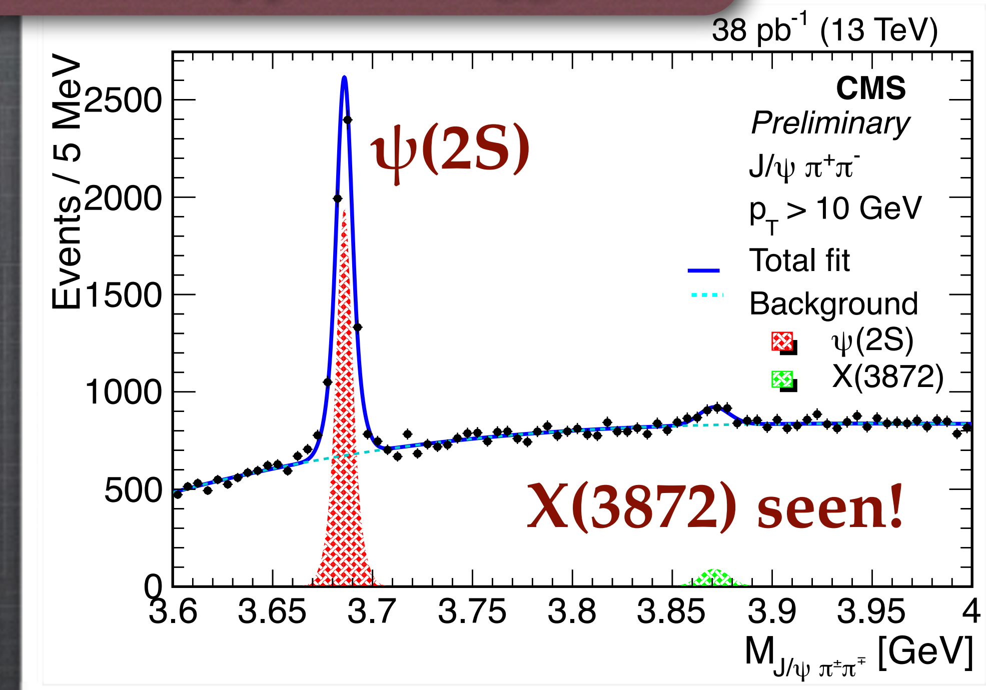
B hadron events w/ displaced J/ψ+track trigger.







Reconstructed J/ψπ+π− events
w/ both types of triggers



Stay tuned –
New results are coming soon!