Flavor physics with CMS: Status and Perspectives

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(PSI)

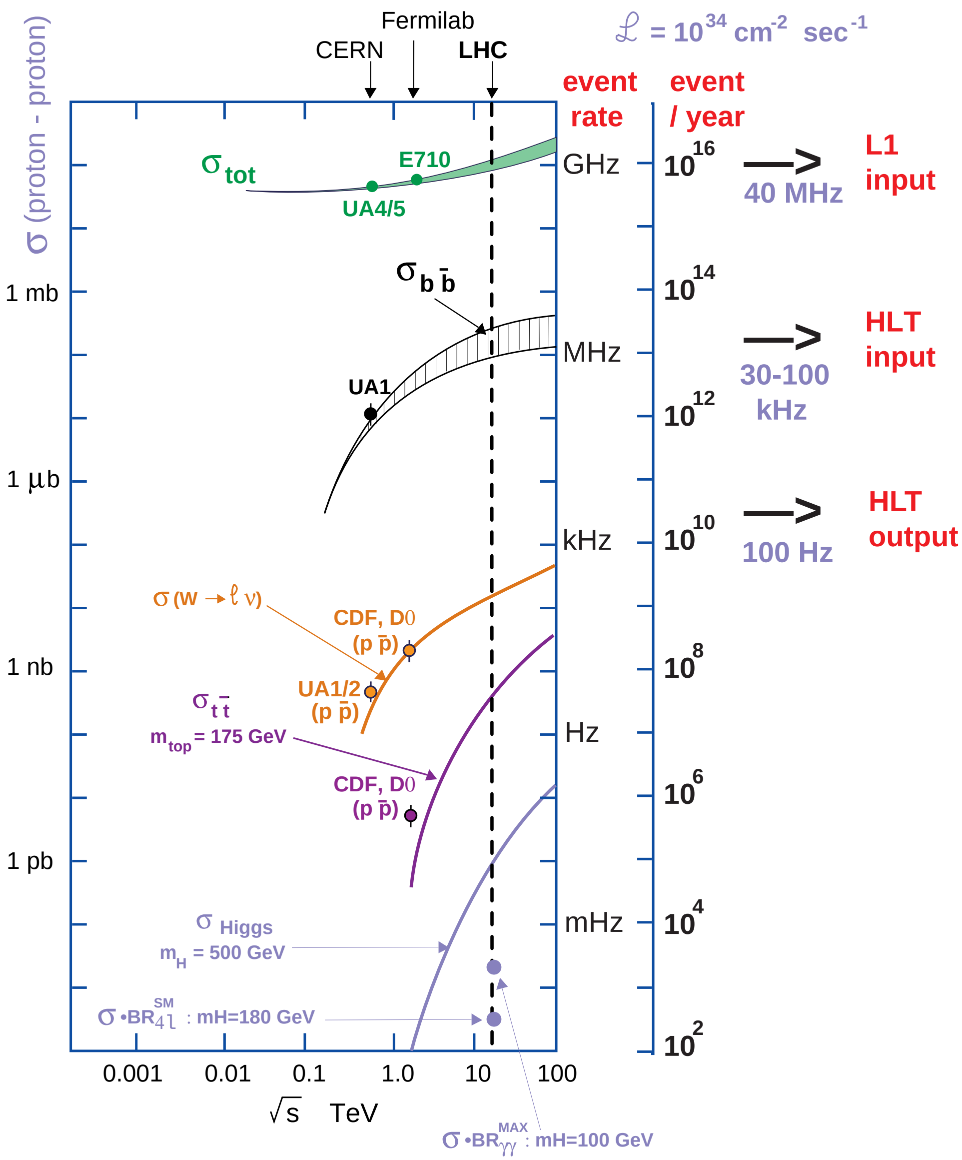
Flavor Physics and CP Violation 2010
2010/05/25

- Introduction
- Data results at $\sqrt{s} = 7\,\text{TeV}$
  - ▷ tracks and muons
- Example Perspectives
  - ▷ $B_s^0 \to \mu^+\mu^-$
  - ▷ top

Heavy Flavor Physics in CMS

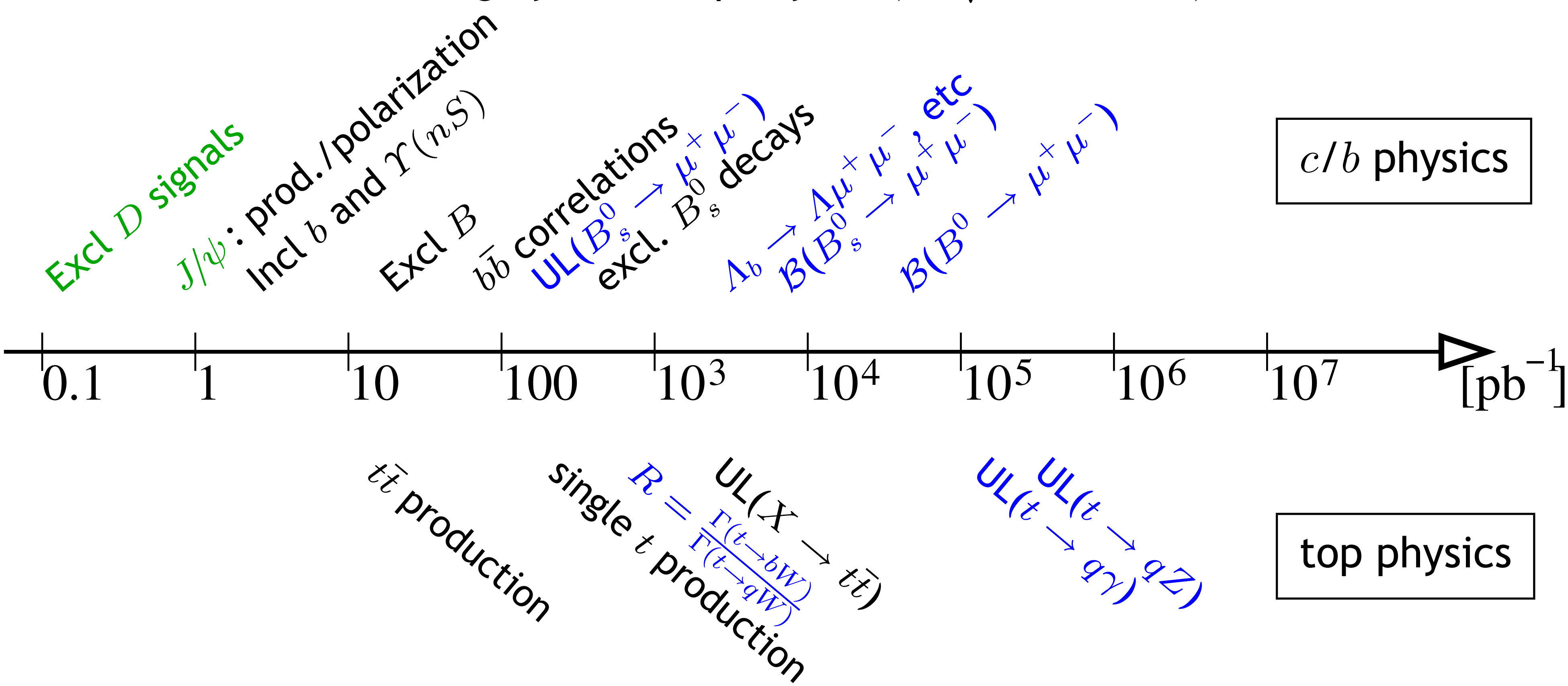
- Beauty and top quark physics
  - ▷ production: QCD (and EW)
  - ▷ decays: FP(CP)
  - ▷ Search for 'New Physics'
    - ▷ indirectly: b, t decays
    - ▷ directly: t production

- Motivations
  - ▷ interesting physics:
    SM rediscovery and measurements
    BSM searches
  - ▷ abundant signals from the start
  - ▷ commissioning
    detector
    trigger
    data management
  - ▷ essential background determination for many other searches



Continuous Evolving Program

- Reminder:
  - ▷ 2010: roughly 100 pb^{-1} of *delivered* integrated luminosity at $\sqrt{s} = 7$ TeV
  - ▷ 2011: roughly 1 fb^{-1} at $\sqrt{s} = 7$ TeV
  - ▷ 10^{34} cm^{-2}s^{-1}: roughly 30 fb^{-1} per year (at $\sqrt{s} = 14$ TeV)



with many intermediate and/or improved results

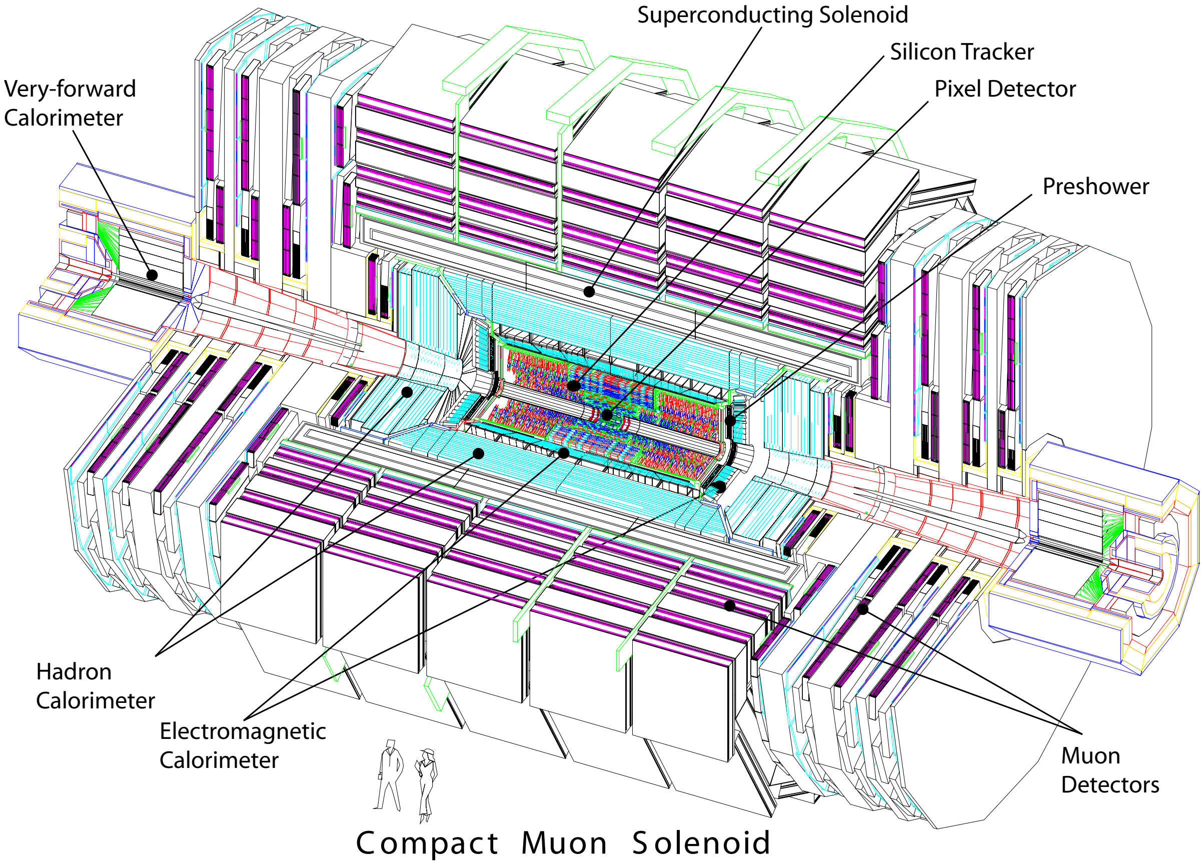
JINST 3, S08004 (2008)

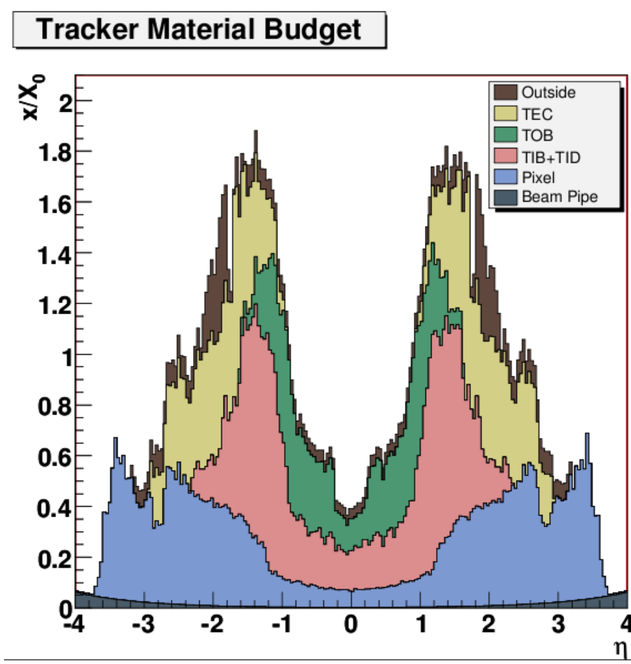
The CMS Detector

- Requirements
  - ▷ lepton ID
  - ▷ b/τ tagging
  - ▷ jets and $\not{E}_T$

(and affordable)

Weight	12'500 t
Length	21.6 m
Diameter	15 m
Magnetic field	4 T
Cost	'500' MCHF

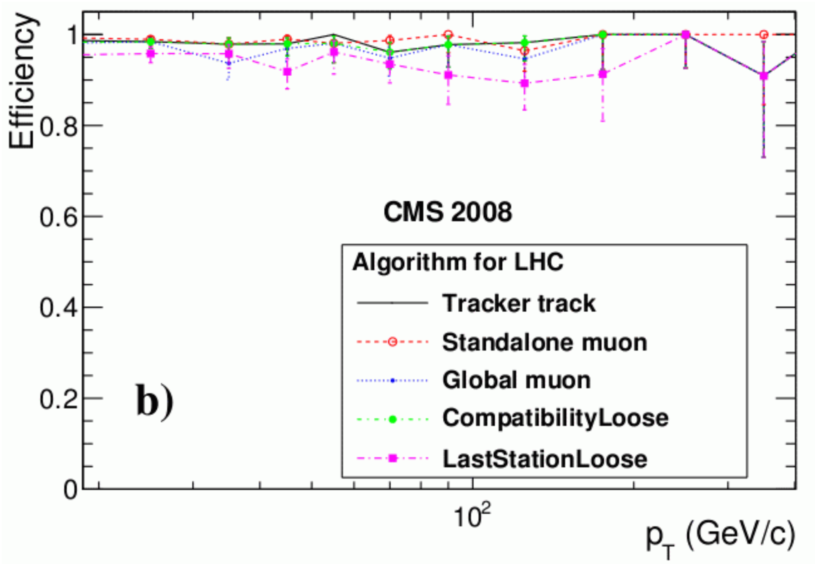


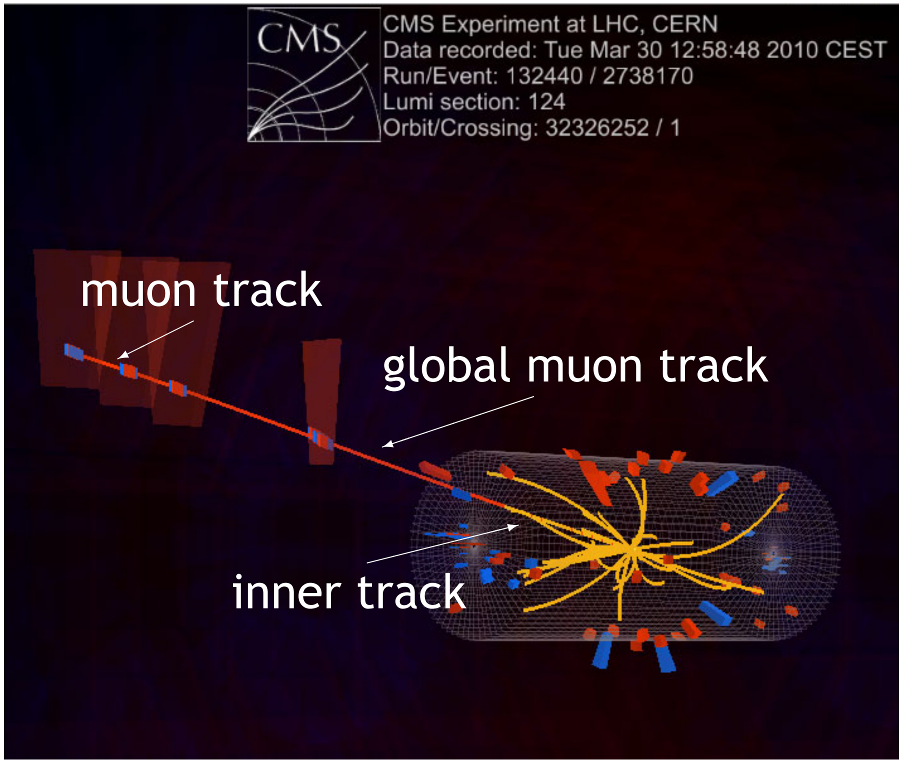


Component	Characteristics	resolutions
Pixel	3/2 Si layers	$\delta_z \approx 20\ \mu$m, $\delta_\phi \approx 10\ \mu$m
Tracker	10/12 Si strips	$\delta(p_\perp)/p_\perp \approx 1\%$
ECAL	$PbWO_4$	$\delta E/E \approx 3\%/\sqrt{E} \oplus 0.5\%$
HCAL (B)	Brass/Sc, $> 7.2\lambda$	$\delta E/E \approx 100\sqrt{E}\%$
HCAL (F)	Fe/Quartz	$\delta(\not{E}_T) \approx 0.98\sqrt{\sum E_T}$
Magnet	4 T solenoid	
Muons	DT/CSC + RPC	$\delta(p_\perp)/p_\perp \approx 10\%$ (STA)

Muon Reconstruction

- Redundant precise muon trajectory measurement
  - barrel: drift tubes (tracking) plus RPC (timing)
  - endcap: cathode strip chambers (tracking) plus RPC (timing)
  - inner tracker: silicon pixel and strip detectors
- Muons
  - standalone muon: reconstructed in muon system only
  - global muon ('GM'): outside-in standalone muon $\longrightarrow$ to inner track
  - tracker muon ('TM'): inside-out inner track $\longrightarrow$ muon detector

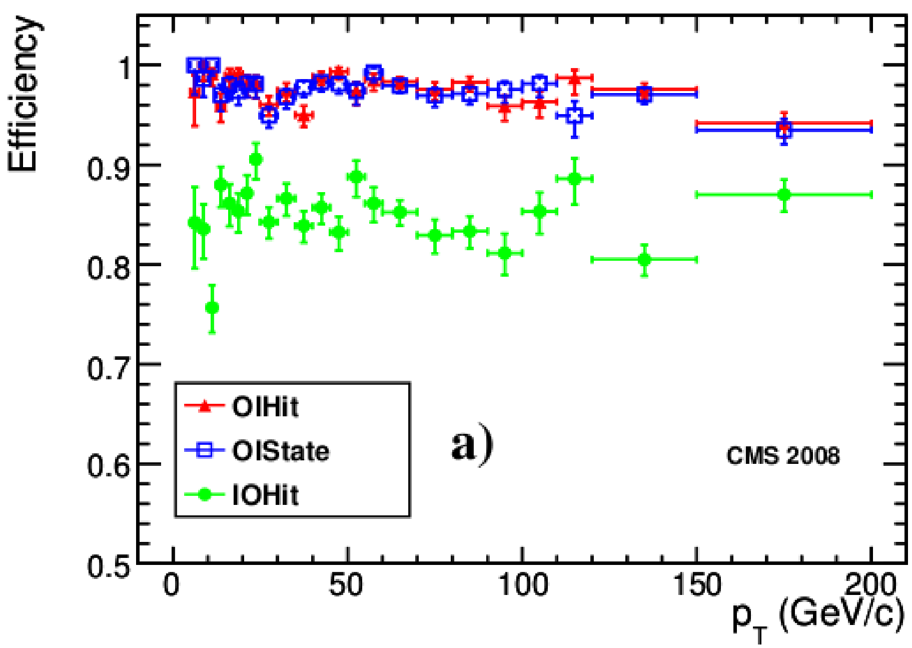


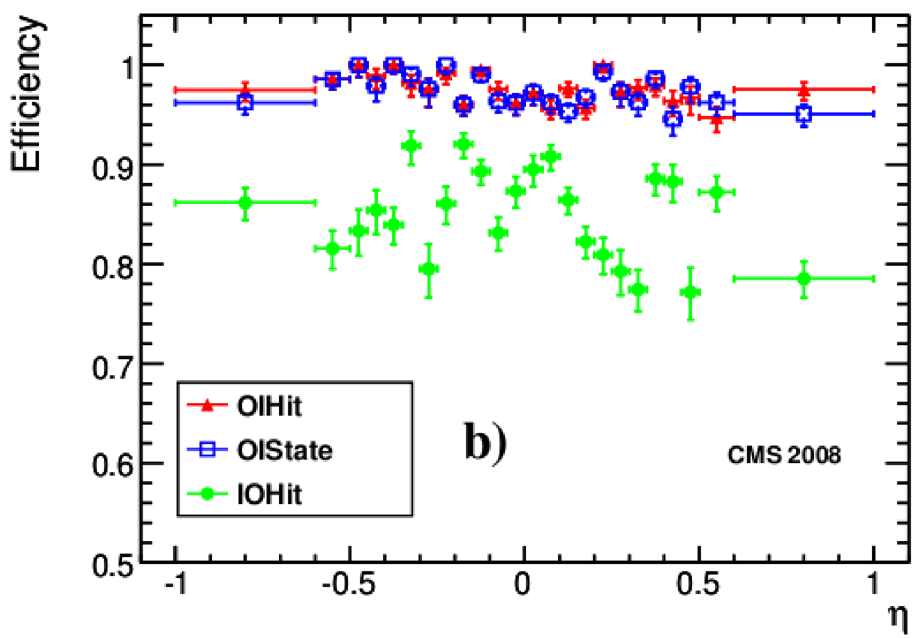


JINST 5, T03022 (2010)

Muon Trigger (at 'high' luminosity)

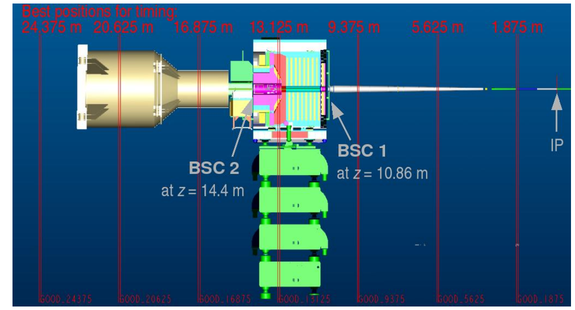
- Muon trigger
  - ▷ L1 trigger: DT/CSC/RPC
  - ▷ High-level trigger:
    L2: improve L1 measurement
    L3: combine with inner tracker (in r.o.i.)
- HLT thresholds:
  - ▷ double muon: 3 GeV
- L3 efficiency measured in 2008 cosmic muon data taking
  - ▷ OIHit: outside-in with tracker seeds
  - ▷ OIState: outside-in with L2 seeds
  - ▷ IOHit: inside-out (low efficiency b/c pixel r/o only 1bc; cosmics asynchronous)



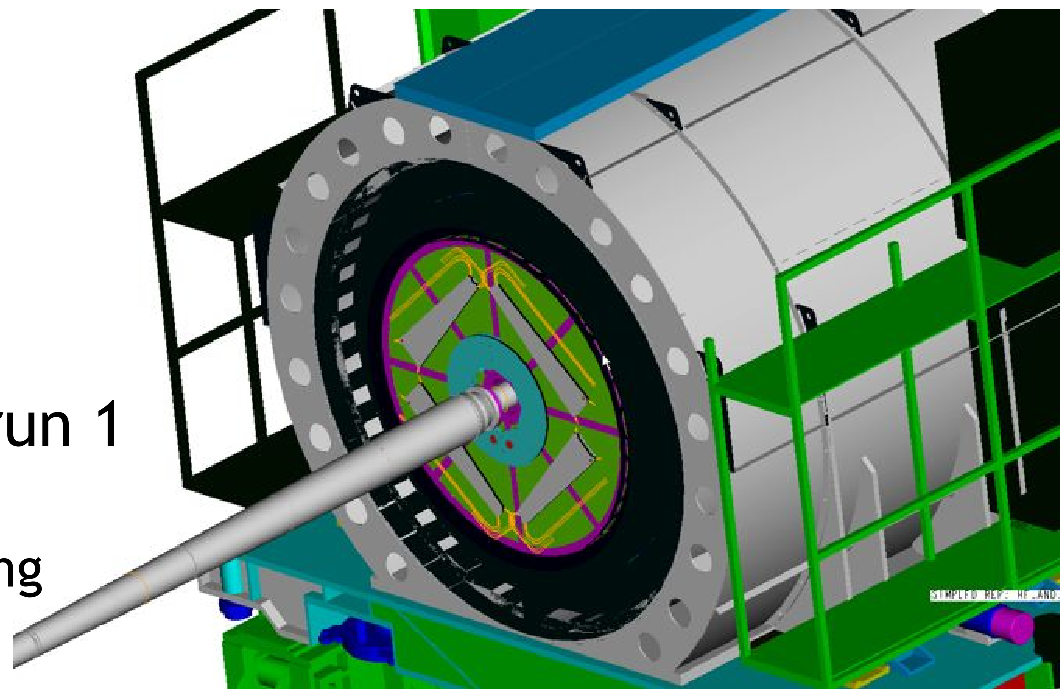


Low-luminosity triggering

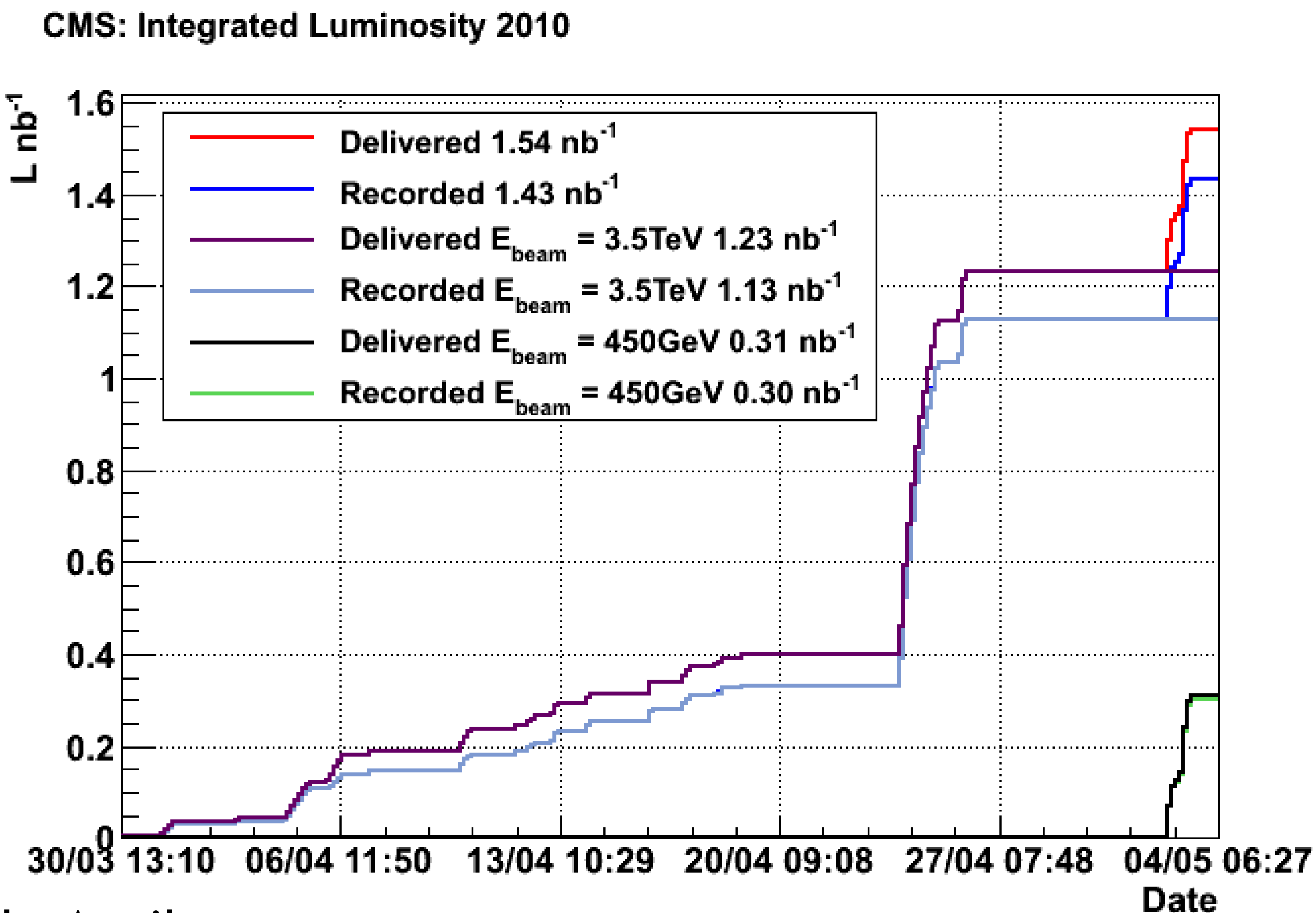
- Beam monitoring detectors used for triggering at low luminosity
  - ▷ beam scintillator counters
    - BSC1: located at ± 10.9 m inner radius 20 cm
    - BSC2: located at ± 14.4 m inner radius 4 cm
    - NIM electronics
  - ▷ beam pickup timing detectors
    - measure mirror charges of passing beam (bunches)



- Other applications:
  - ▷ beam halo triggers
  - ▷ beam gas triggers
  - ▷ zero-bias triggers
  - ▷ minimum-bias triggers
- BSC to be replaced after run 1
  - ▷ radiation damage
  - ▷ essential for HI MB triggering



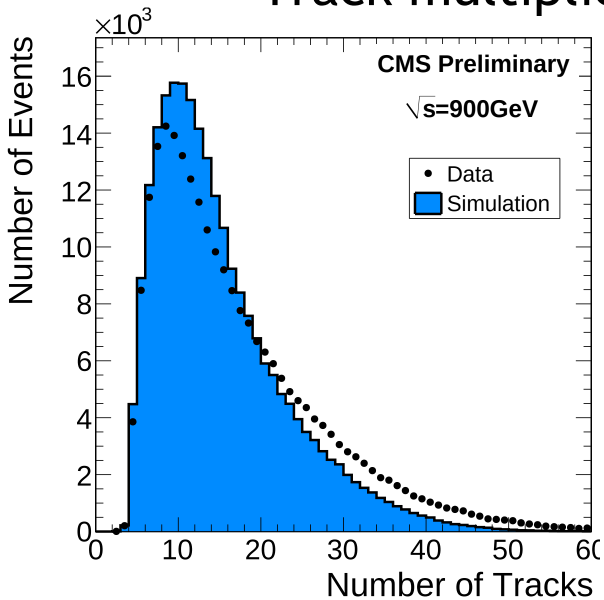
Data Taking

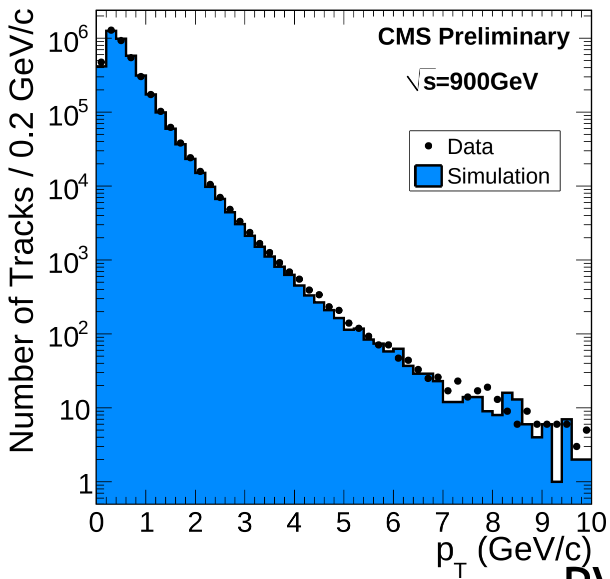


- Early April:
  - ▷ delay scans for many subdetectors
- Except for detector studies: data taking efficiency $> 90\%$

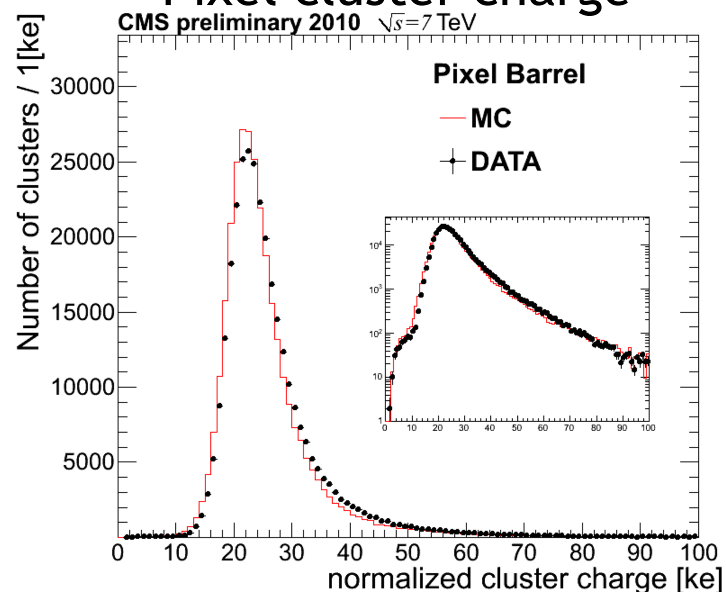
Detector Performance Impressions

Track multiplicity and $p_\perp$ spectrum

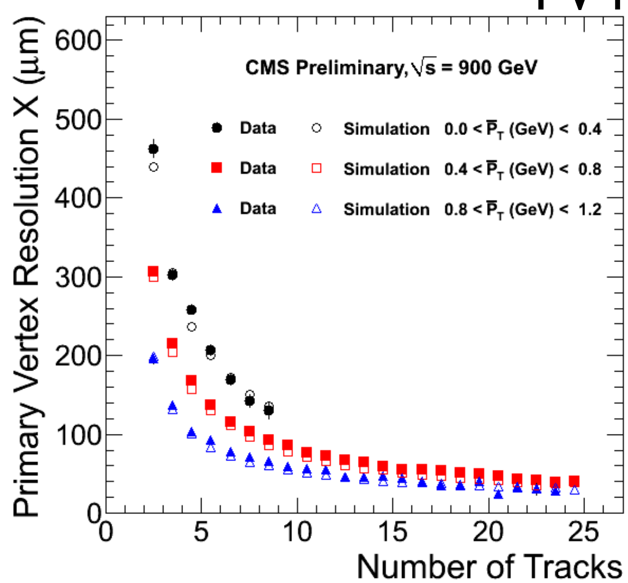


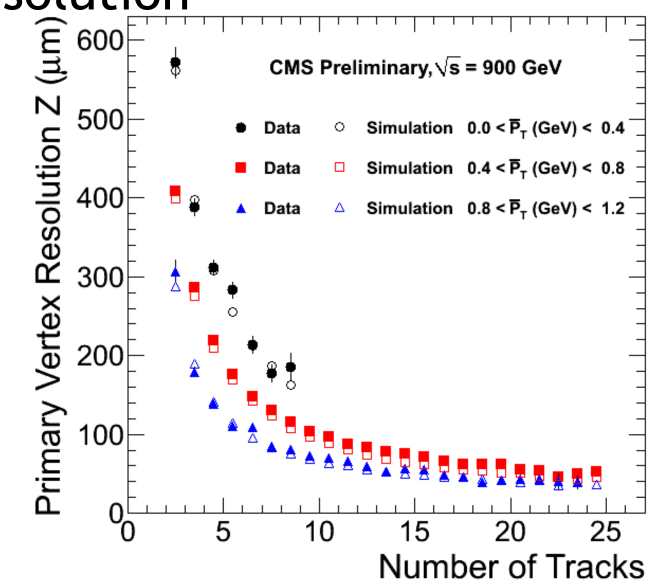


Pixel cluster charge



PV resolution



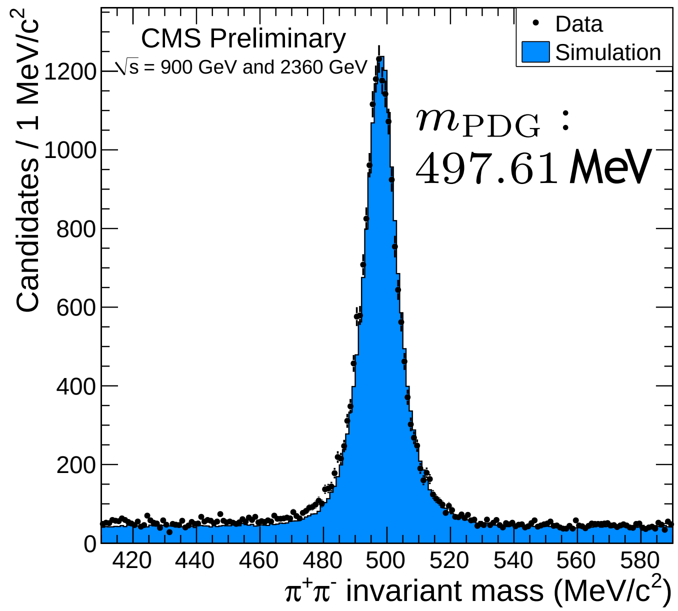


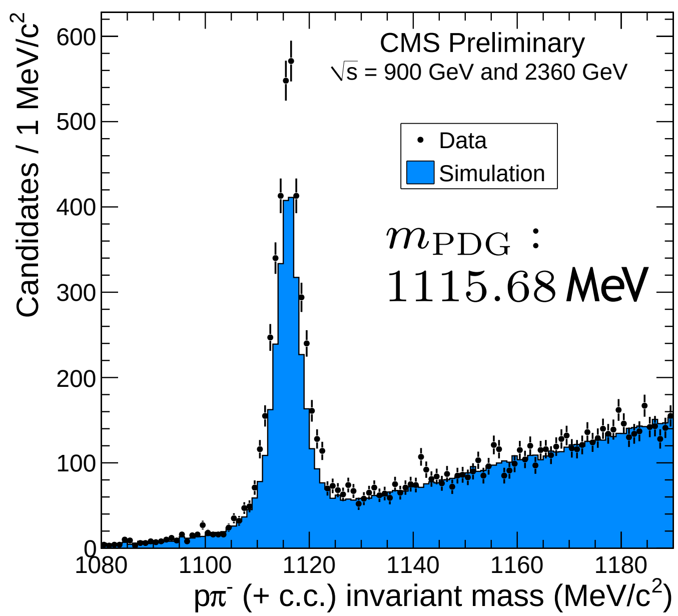
- MC simulation
  - detector well described
  - need for some physics tuning

V0 reconstruction

- Long-lived particles ($c\tau > 1\,$cm)
  - oppositely-charged tracks
  - detached from primary vertex
  - forming a good secondary vertex
  - Λ: high-momentum track = p
- Track requirements
  - $N_{\mathrm{hits}} > 5$
  - $\chi^2/\mathrm{dof} < 5$
  - $d_{xy}/\sigma(d_{xy}) > 0.5$
- Vertex requirements
  - $\chi^2/\mathrm{dof} < 7$ and $d_{xy}/\sigma(d_{xy}) > 15$
- Both lifetimes consistent with PDG

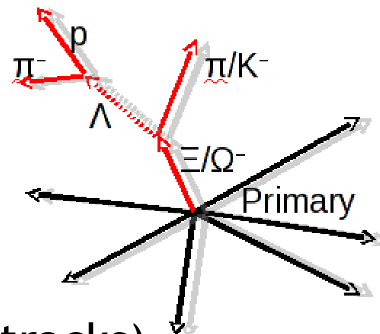
V0	Data [MeV]	MC [MeV]
K_S peak	497.68 ± 0.06	498.11 ± 0.01
K_S width	7.99 ± 0.14	7.63 ± 0.03
Λ peak	1115.97 ± 0.06	1115.93 ± 0.02
Λ width	3.01 ± 0.08	2.99 ± 0.03

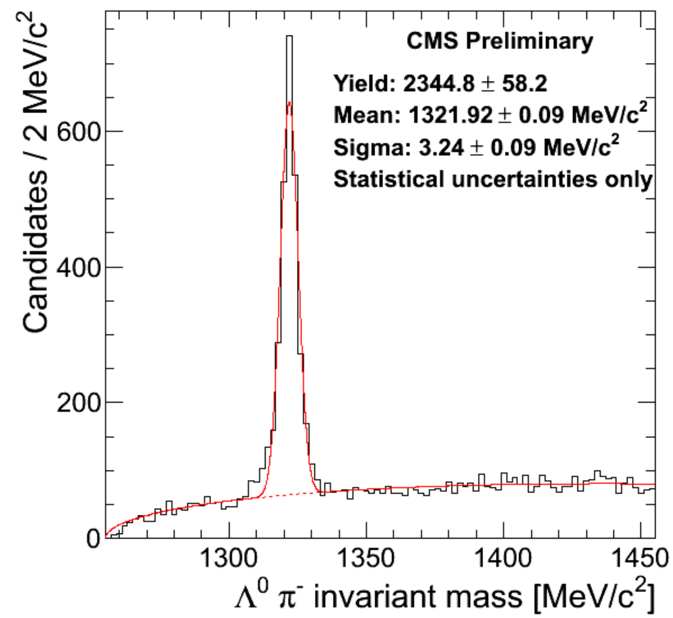


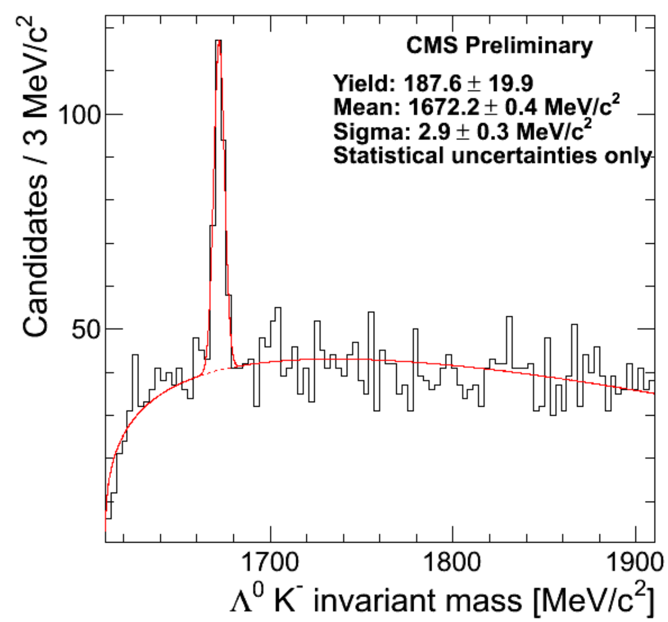


More Baryons: $\Xi^- \to \Lambda\pi^-$, $\Omega^- \to \Lambda K^-$

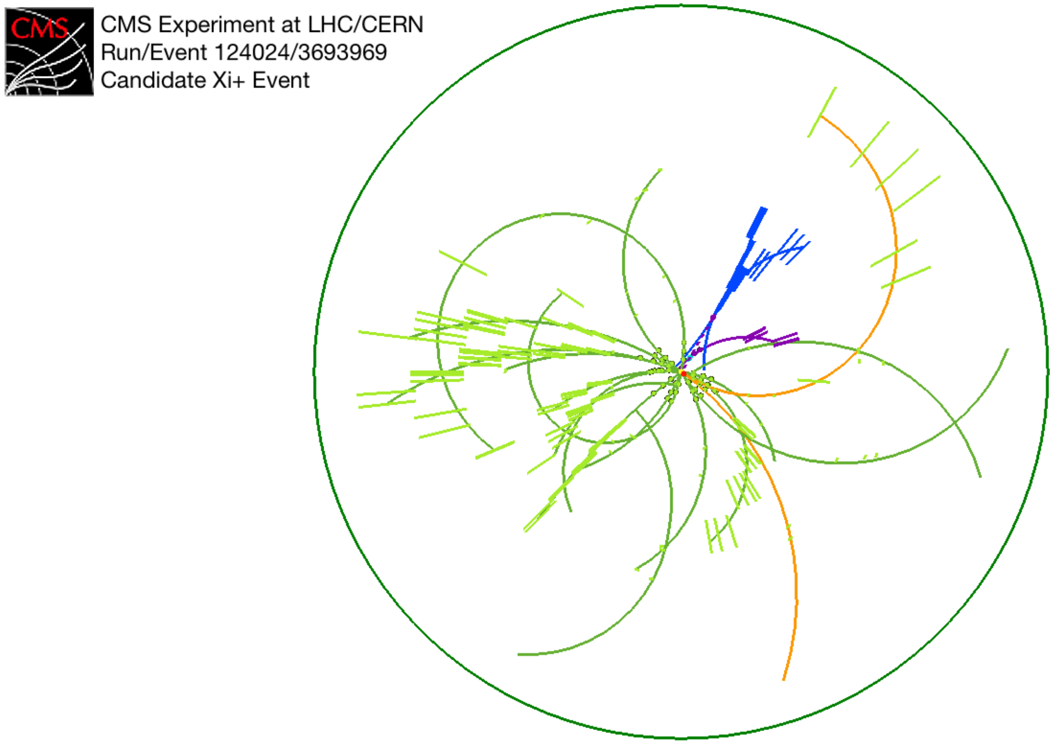
- Reconstruction of $\Lambda(\pi, K)$
  - ▷ loose Λ selection
    - vertex $d_{xy} > 10\sigma$
    - track $d_0 > 0.5\sigma$
    - $|m_\Lambda - m_\Lambda^{\mathrm{PDG}}| < 8$ MeV
  - ▷ track selection
    - $d_0^{3d} > 3\sigma$ wrt PV (w/o signal tracks)
    - kaon $p_\perp > 600$ MeV
    - charge correlation of meson tracks
  - ▷ vertexing
    - $P(\chi^2) > 1\%$
    - $d_{\mathrm{Vtx}} > 4\sigma$
  - ▷ events with single candidates only
- Masses and widths
  - ▷ consistent with PDG and MC

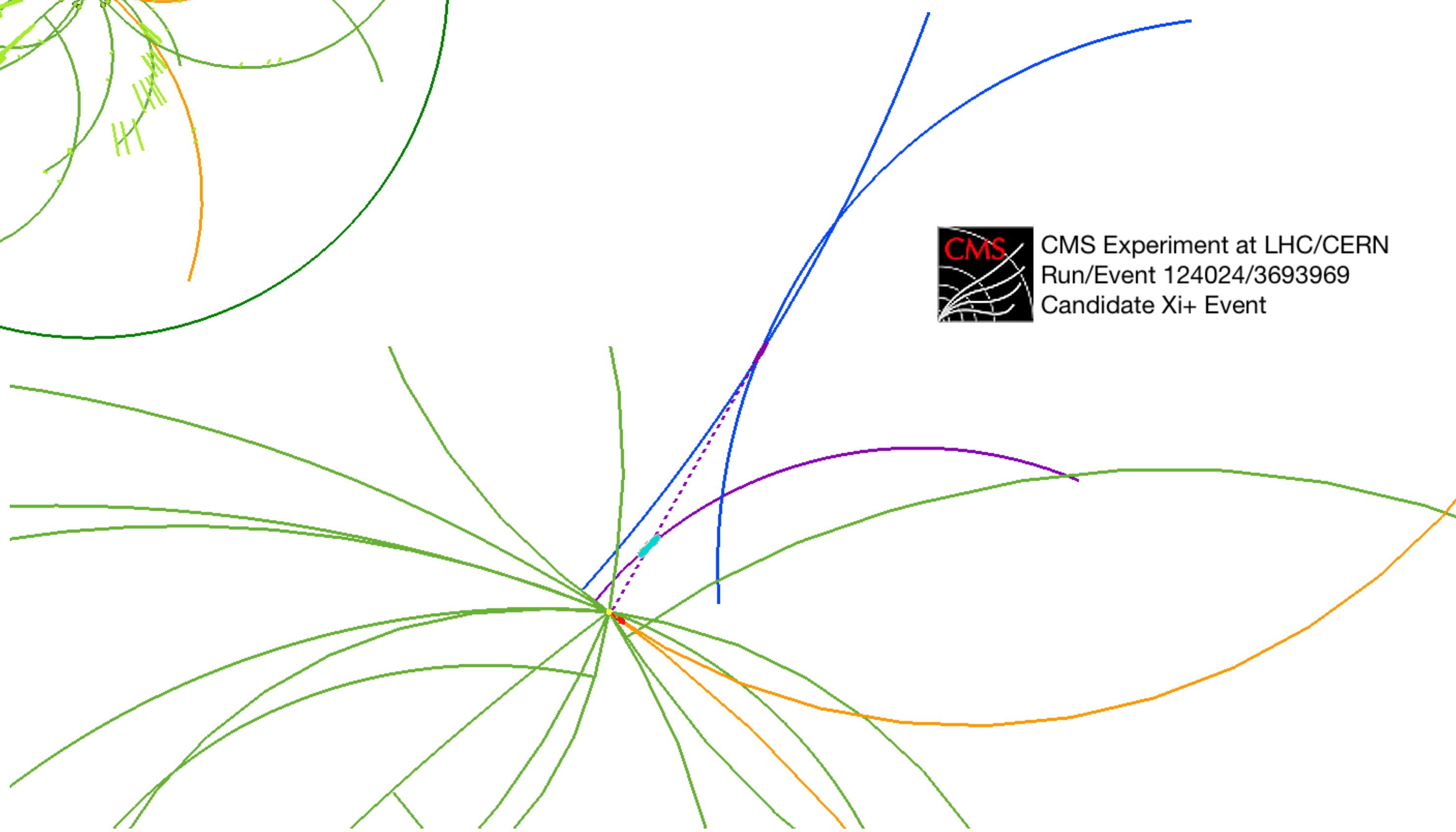






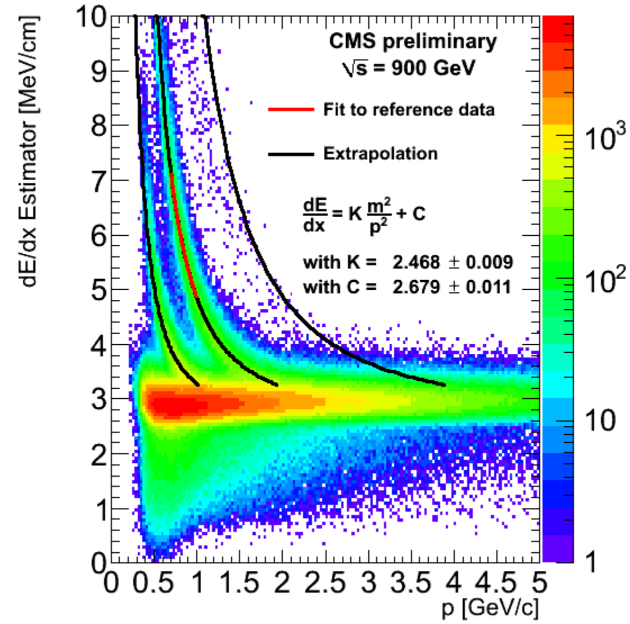
Candidate decay $\Xi^+ \rightarrow \bar{\Lambda}(\rightarrow \bar{p}\pi^+)\pi^+$



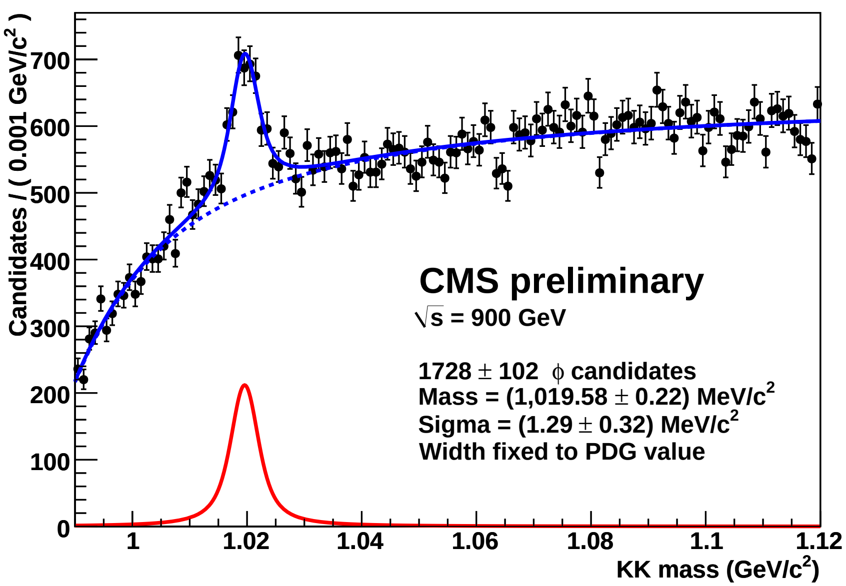


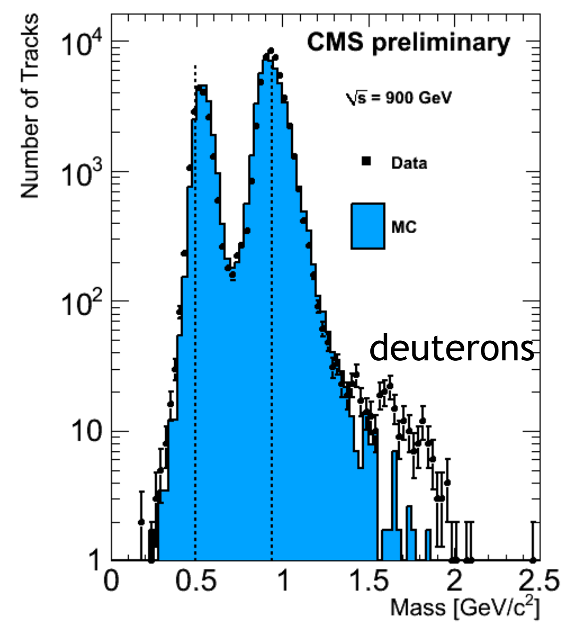
Particle identification: tracker dE/dx

- Measure specific ionization energy loss
  - ▹ analog readout of silicon strip detector
  - ▹ high purity tracks, $N_{\mathrm{hits}} > 9$
  - ▹ robust dE/dx estimator
    $I_h = \left(\frac{1}{N}\sum_i c_i^k\right)^{1/k}, k = -2$



- Inclusive reconstruction of $\phi \to K^+K^-$
  - ▹ Tracks: $p > 1$ GeV or $|m - m_K| < 200$ MeV





Inclusive Reconstruction of D^0

- Dataset: 27 million minimum bias events
- Decay mode reconstruction

$$D^0 \rightarrow K^-\pi^+$$

- Selection criteria
  - ▷ transverse momentum cuts

$$p_\perp(K) > 1.25\,\text{GeV}$$
$$p_\perp(\pi) > 1.0\,\text{GeV}$$
$$p_\perp(D^0) > 3.0\,\text{GeV}$$

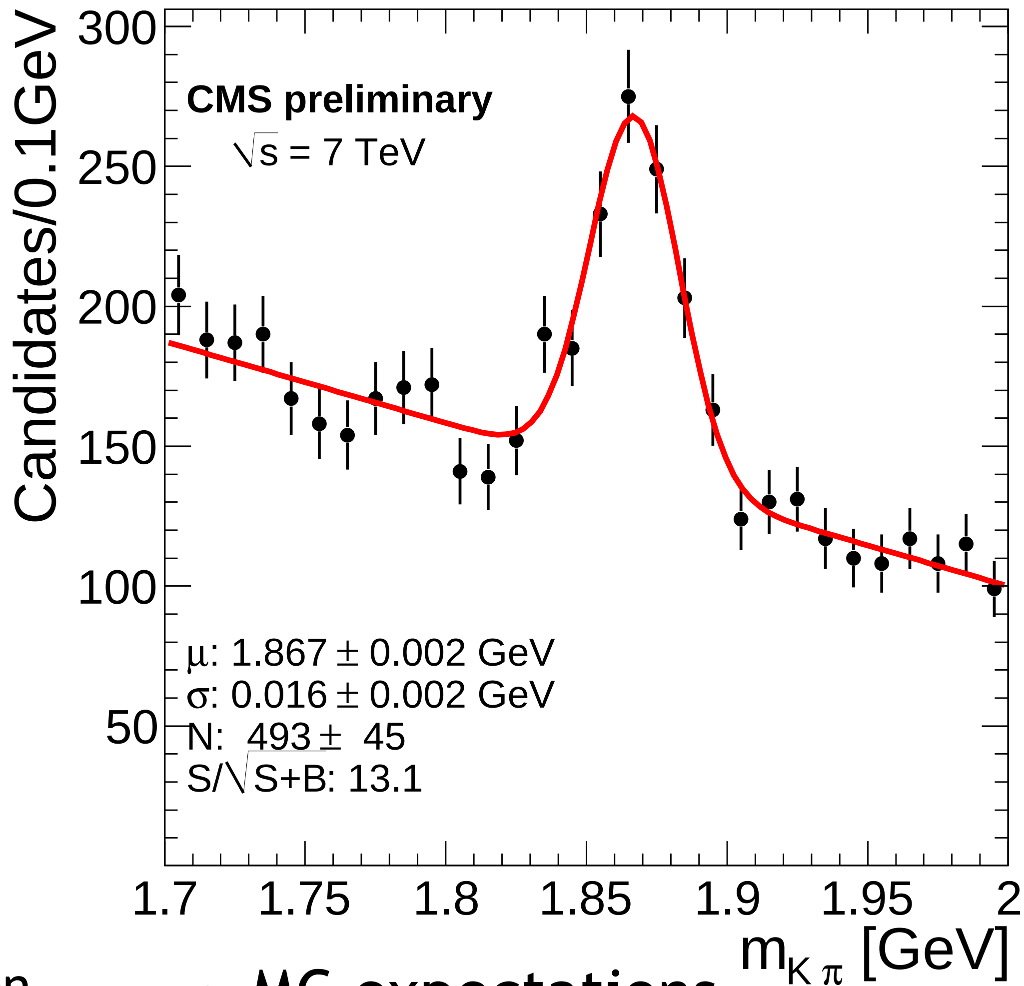
  - ▷ Vertexing cuts

$$d(K,\pi) < 0.025\,\text{cm}$$
$$\chi^2 < 4.5$$
$$3 < l_{xy}/\sigma(l_{xy}) < 20$$
$$\sigma(l_{xy}) < 0.03\,\text{cm}$$

  - ▷ D^0 momentum vs. PV-SV direction

$$\angle(\vec{p}_{D^0}, \overline{PV:SV}) < 0.1$$

  - ▷ allow for multiple candidates



- MC expectations
  - ▷ Peak: 1.863 ± 0.002 GeV
  - ▷ Width: 0.014 ± 0.002 GeV

More Open Charm: D^{*+}

- Data set: 37 million minimum bias events
- Decay mode reconstruction

$$D^{*+} \quad \rightarrow \quad D^0\pi_s^+ \rightarrow K^-\pi^+\pi_s^+$$

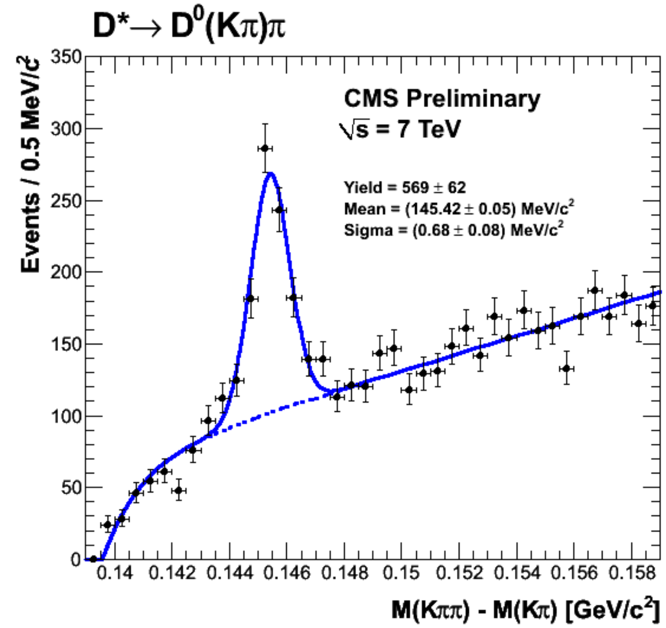
- Kinematic selection

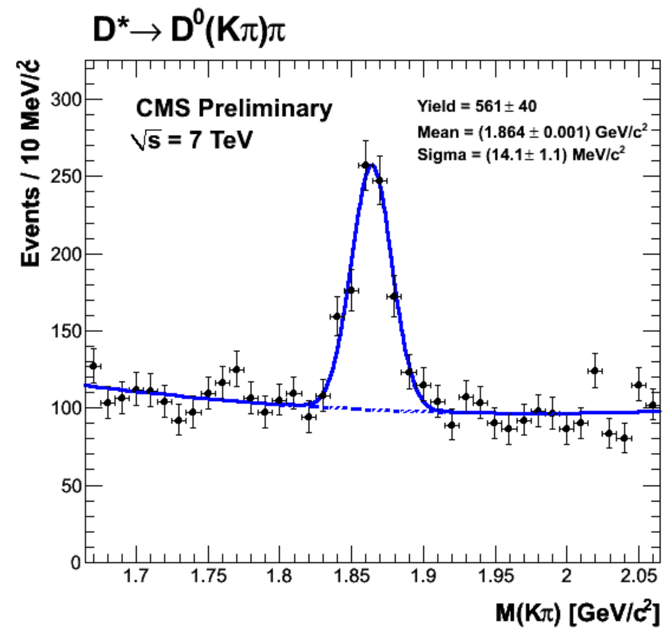
$$\begin{aligned} p_\perp{}^{\text{track}} &> 0.6\,\text{GeV} \\ p_\perp{}^{\pi_s} &> 0.25\,\text{GeV} \\ p_\perp{}^{D^{*+}} &> 5\,\text{GeV} \end{aligned}$$

choose single D^{*+} candidate
(with highest transverse momentum)

- Mass windows (for other projections)

$$\begin{aligned} |m_{K\pi} - m_{\text{PDG}}^{D^0}| &< 25\,\text{MeV} \\ |m_{K\pi\pi_s} - m_{K\pi} - \delta m_{\text{PDG}}| &< 1.2\,\text{MeV} \end{aligned}$$

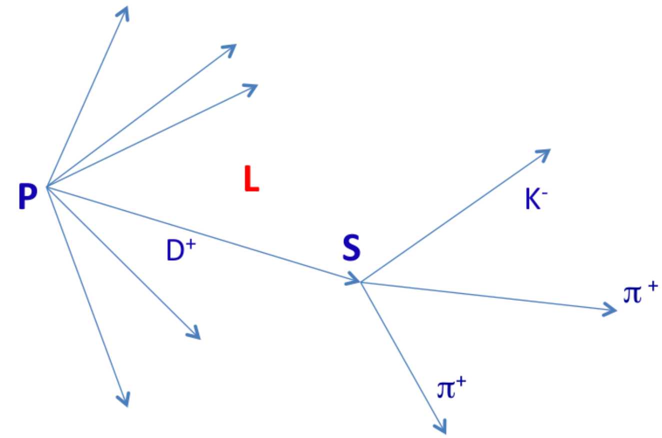




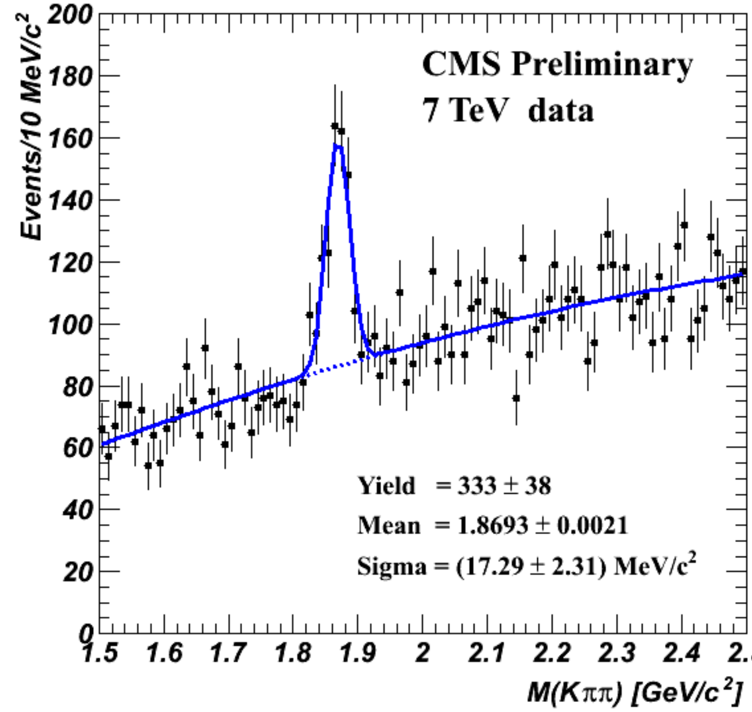
. . . and D^+

- Data set: ≈ 11 million minimum bias events
- Decay mode:

$$D^+ \quad \rightarrow \quad K^-\pi^+\pi^+$$



- Kinematic selection
  - ▷ $p_\perp > 0.1$ GeV
  - ▷ $p > 1$ GeV
- Vertexing selection
  - ▷ $\vec{p}_{D^+}$ should point to PV (5σ)
  - ▷ PV: $P(\chi^2) > 0.01$
  - ▷ SV: $P(\chi^2) > 0.02$
  - ▷ $L/\delta(L) > 7$



- Note: D^0 vs. D^{*+} vs. D^+
  - ▷ three independent analyses
  - ▷ unified selection was not a goal

see poster by M. Musich!

Charmonium

- This is not really flavor physics
  - ▷ but important ingredient and milestone
- Dataset: $\approx 1\,\text{nb}^{-1}$, single muon trigger
  - ▷ $p_\perp > 3\,\text{GeV}$ (rate limited at some point)
- Reconstruction of $J/\psi \to \mu^+\mu^-$
  - ▷ track selection

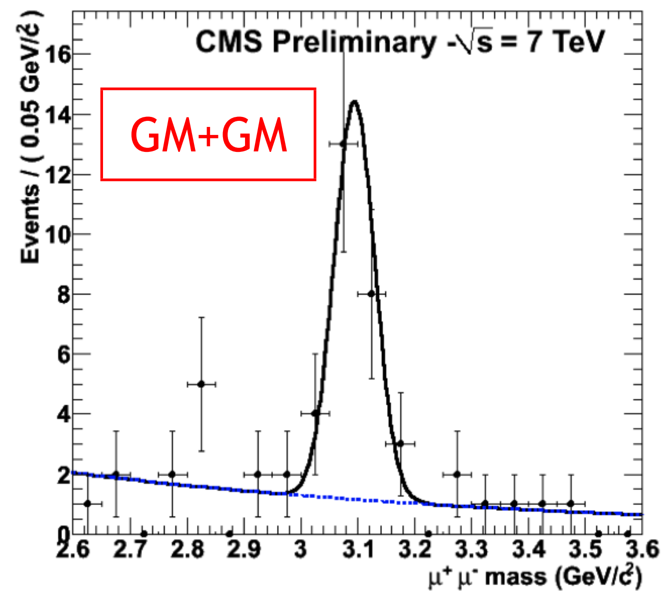
    $N_{\text{hit}} > 10$

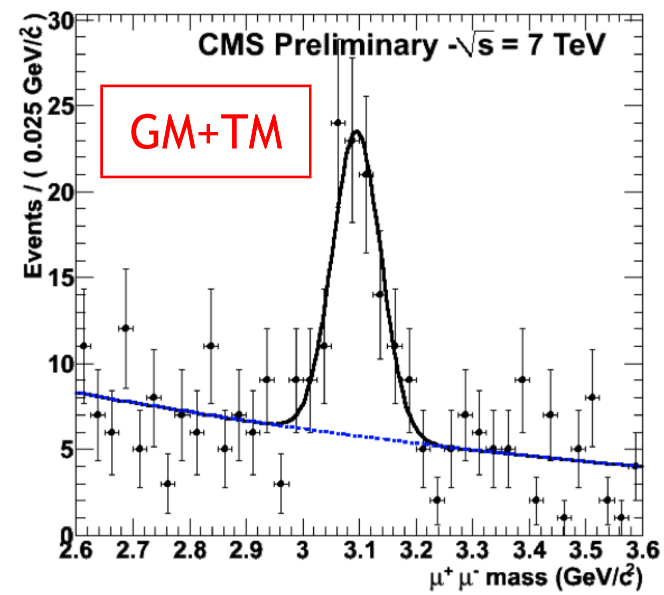
    $d_0 < 5\,\text{cm}$, $d_z < 20\,\text{cm}$
  - ▷ vertex selection

    $P(\chi^2) > 0.1\%$
- Yields

Category	Yield	Mass [MeV]	Width [MeV]
GM+GM	24 ± 5	3094 ± 9	35.5 ± 6.8
GM+TM	76 ± 12	3095 ± 7	42.5 ± 6.3

- Mass resolution
  - ▷ strongly pseudorapidity dependent
  - ▷ average $\approx 30\,\text{MeV}$ with '100 pb^{-1} alignment'



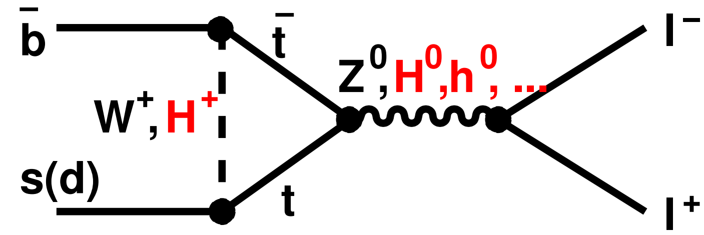


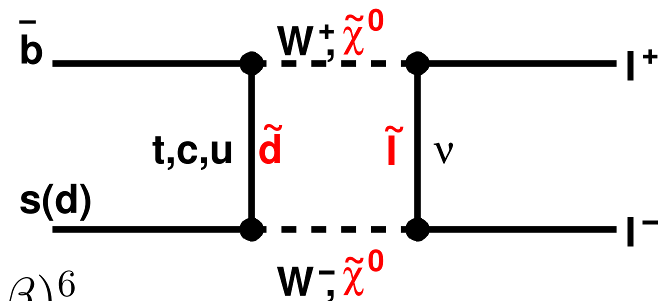
$B_s^0 \to \mu^+\mu^-$: Search for New Physics

- Decays highly suppressed in Standard Model (Artuso et al, 2008)
  - ▷ effective FCNC, helicity suppression
  - ▷ SM expectation:

$$\boxed{\begin{aligned} \mathcal{B}(B_s^0 \to \mu^+\mu^-) &= (3.86 \pm 0.15) \times 10^{-9} \\ \mathcal{B}(B^0 \to \mu^+\mu^-) &= (1.06 \pm 0.04) \times 10^{-10} \end{aligned}}$$

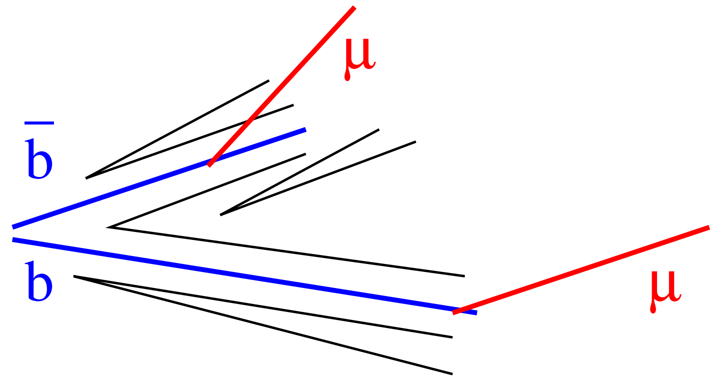
  - ▷ Cabibbo-enhancement $(|V_{ts}| > |V_{td}|)$ of $B_s^0 \to \mu^+\mu^-$ over $B^0 \to \mu^+\mu^-$ only in MFV models





- Sensitivity to new physics
  - ▷ 2HDM: $\mathcal{B} \propto (\tan\beta)^4, m_{H^+}$; MSSM: $\mathcal{B} \propto (\tan\beta)^6$
  - $\longrightarrow$ Constraints on parameter regions
  - $\longrightarrow$ 'Measurement' of $\tan\beta$ (Kane, *et al.* ph/0310042)
- Plus: 'time-dependent' physics program
  - ▷ very early data: π, K muon misid rates with $b \to \mu D^0(K^-\pi^+)X$
  - ▷ early data: $B^+ \to J/\psi K^+$, $B_s^0 \to J/\psi\,\phi$ normalization/control sample
  - ▷ some more data: $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ upper limit
  - ▷ even more data: $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ measurement

$B_s^0 \to \mu^+\mu^-$: Analysis Overview



- b-hadrons produced in
  - ▷ gluon splitting (close together)
  - ▷ flavor excitation
  - ▷ gluon-gluon fusion (back-to-back)
- Signal signature
  - ▷ two muons from one decay vertex and not much else in vicinity
  - ▷ dimuon mass around $m_{B_s^0}$
- Background composition
  - ▷ two independent semileptonic B decays (mostly from gluon splitting)
  - ▷ one semileptonic (B) decay and one misidentified hadron
  - ▷ rare single B decays (peaking and non-peaking)

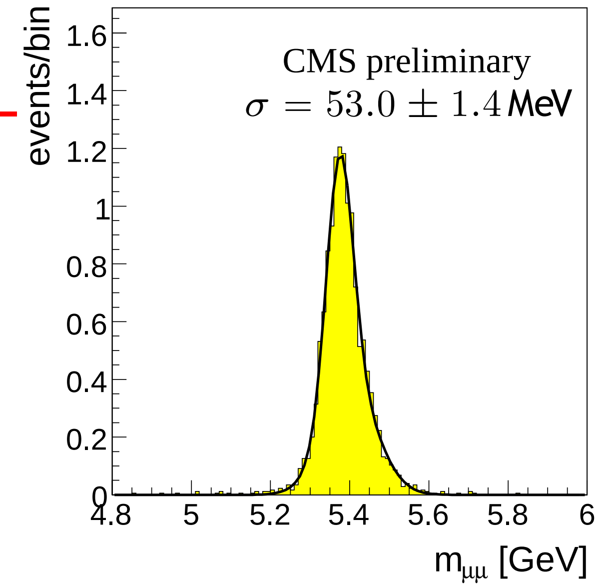
  $\longrightarrow$ roughly similarly important

  no prompt+cascade muons from one single B decay (within current BG MC statistics)

$\Rightarrow$ High signal efficiency and high background reduction
  - ▷ one decay vertex and large/significant flight length
  - ▷ isolation of dimuon system
  - ▷ mass window, sidebands for non-peaking background estimation

MC simulations: $B_s^0 \to \mu^+\mu^-$

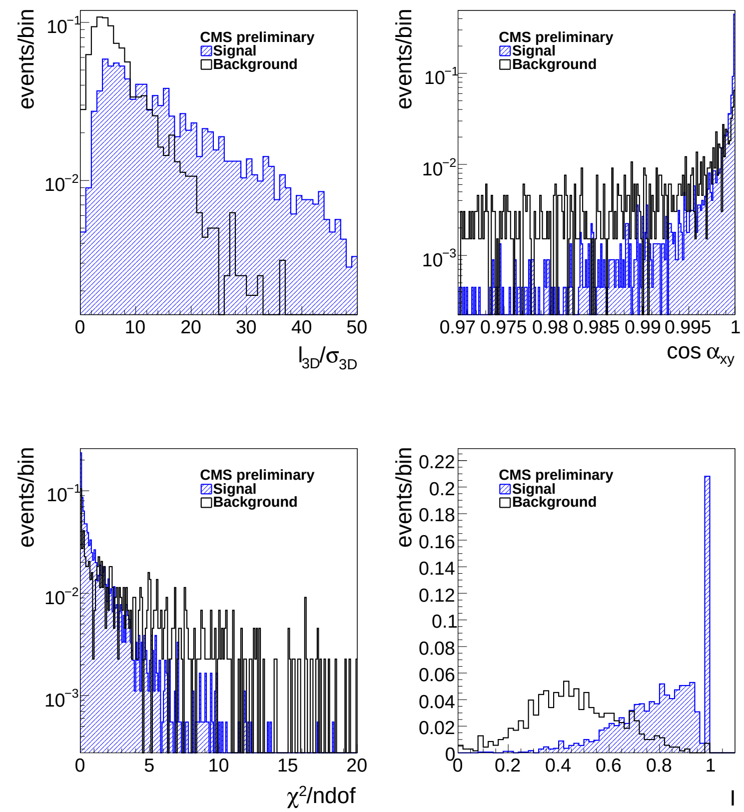
CMS-PAS-BPH-07-001



- Muon selection
  - 2 global muons (GM)
  - $p_\perp > 4$ GeV, $|\eta| < 2.4$
- B_s^0 candidate
  - $p_\perp > 5$ GeV, $|\eta| < 2.4$
  - $4.8 < m_{\mu^+\mu^-} < 6.0$ GeV
  - Secondary vertex fit
    - $\cos(\alpha) > 0.9985$ (i.e. 3.1°)
    - $l_{3D}/\sigma_{3D} > 17.0$
    - $\chi^2 < 5.0$
  - Isolation

$$I = \frac{p_\perp(B_s^0)}{p_\perp(B_s^0) + \sum_{trk} |p_\perp|} > 0.850$$

using tracks with
$p_\perp > 0.9$ GeV and $\Delta R(t, B_s^0) < 1$



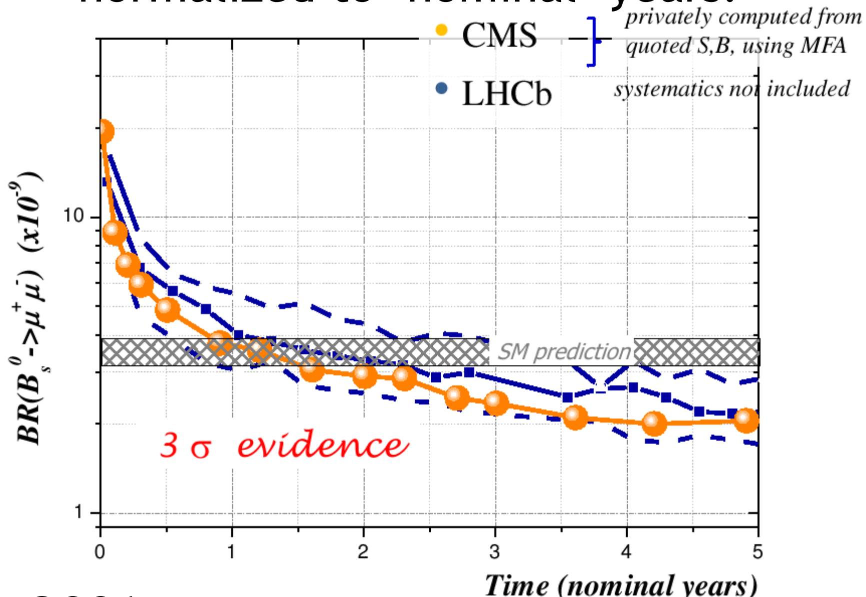
$B_s^0 \to \mu^+\mu^-$: Expected Performance

- With $1.0\ \text{fb}^{-1}$ at $\sqrt{s} = 14\,\text{TeV}$, expect to obtain at 90% C.L.

Signal yield	$n_{\rm S}$	$= 2.36^{+0.076}_{-0.074}(\text{stat})$
Signal efficiency	$\varepsilon_{\rm S}$	$= 0.023 \pm 0.001(\text{stat})$
BG rejection	$\varepsilon_{\rm B}$	$= (7.82 \pm 0.369) \times 10^{-9}(\text{stat})$
BG: dimuons	$n_{\rm B}^{\mu\mu}$	$= 2.54^{+0.719}_{-0.560}(\text{stat})$
BG: muon+fake	$n_{\rm B}^{\mu h}$	$= 2.54^{+0.719}_{-0.560}(\text{stat})$
	$n_{\rm B}^{\rm non-rare} = n_{\rm B}^{\mu\mu} + n_{\rm B}^{\mu h}$	$= 5.07^{+1.44}_{-1.12}(\text{stat})$
BG: rare	$n_B^{\rm rare}$	$= 1.45^{+0.276}_{-0.276}(\text{total})$
	$n_{\rm B} = n_B^{\rm non-rare} + n_{\rm B}^{\rm rare}$	$= 6.53^{+2.43}_{-2.43}(\text{total})$

$$\boxed{\mathcal{B}(B_s^0 \to \mu^+\mu^-) \quad \leq \quad 1.6 \times 10^{-8}}$$

normalized to ‘nominal’ years:



▷ Substantial improvement with respect to 2006

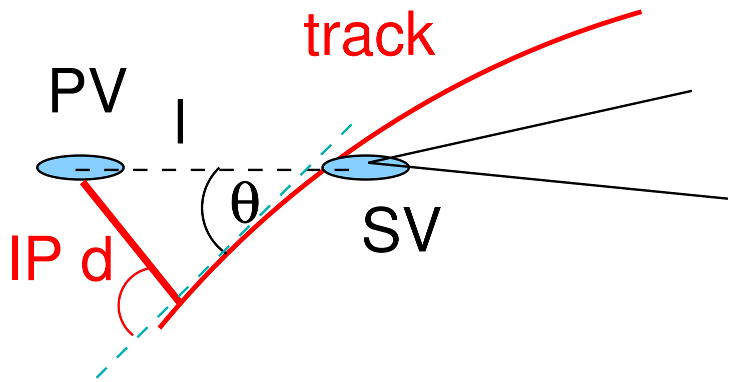
– no pile-up, $\sqrt{s} = 14\,\text{TeV}$

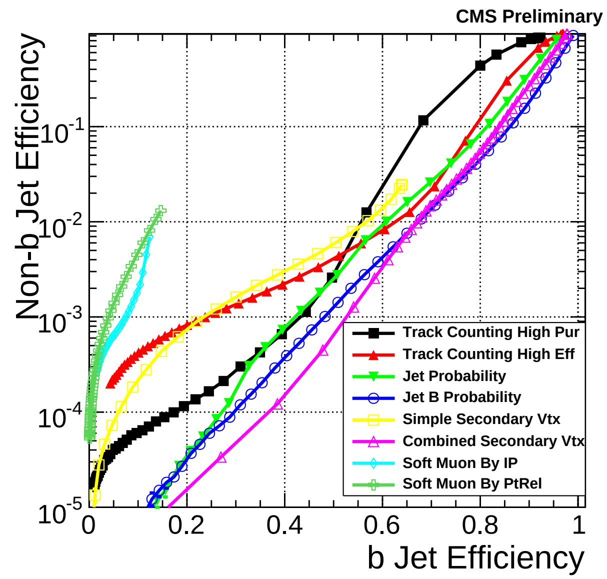
+ high-luminosity trigger, no tracker muons, cut-n-count analysis

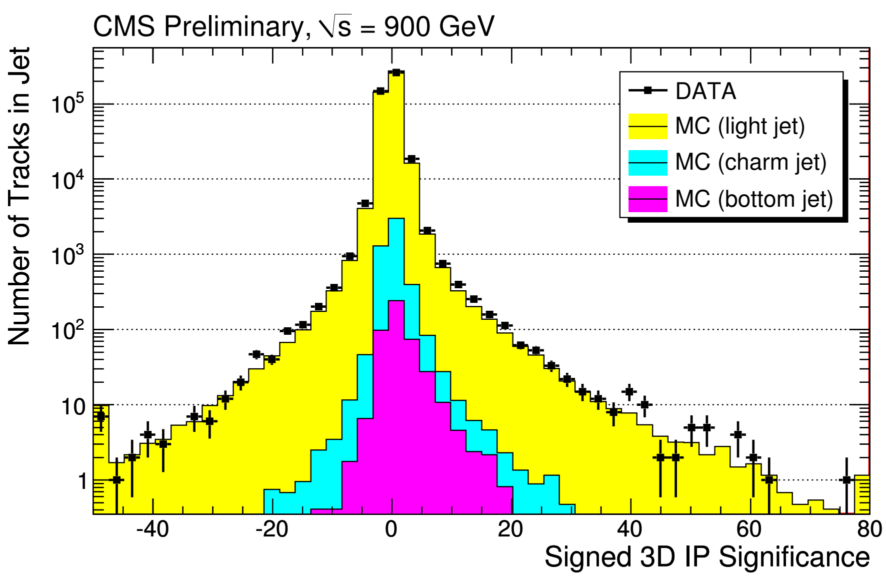
CMS-PAS-TRK-10-001

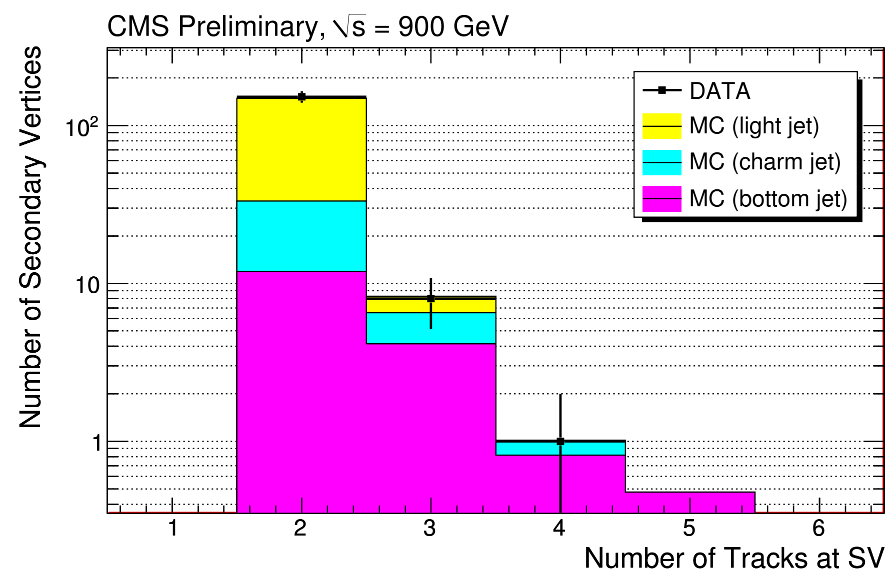
b-tagging of a different kind

- Not B-flavor tagging, but determination of b vs. $udsg$ jet-origin
  - ▷ impact parameter (wrt primary vertex)
  - ▷ secondary vertex reconstruction
  - ▷ leptons







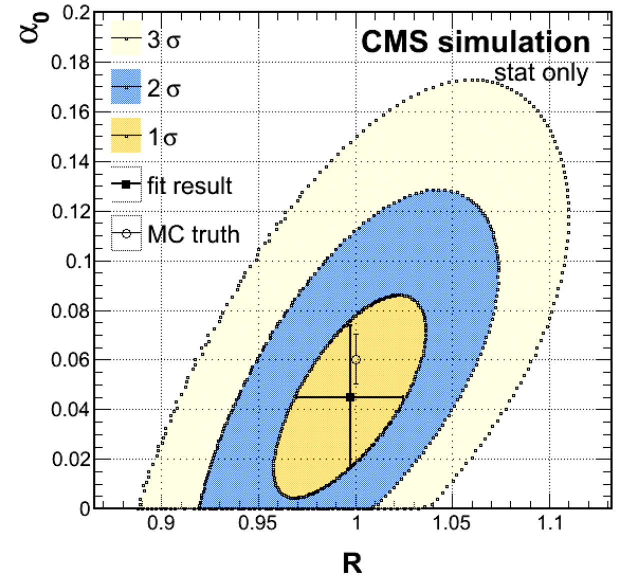


Top Flavor Physics: R

- Top decays to b vs all quarks

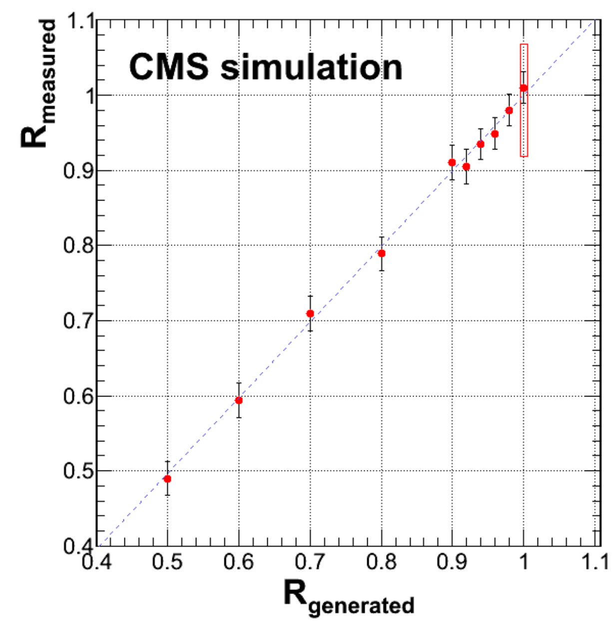
$$R = \frac{\Gamma(t \to bW)}{\Gamma(t \to qW)}$$
$$= \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \quad \text{(in SM)}$$

  - ▷ $|V_{tb}|$ measurement (in SM with 3 generations)
  - ▷ constraints on $|V_{tb}|$ (in BSM)



- P_i: Probability to find i b-tagged jets

$$\begin{aligned} A_i(R; \varepsilon_b, \varepsilon_q) &= R^2 P_i(t\bar{t} \to WWb\bar{b}) \\ &+2R(1-R)P_i(t\bar{t} \to WWbq) \\ &+(1-R)^2 P_i(t\bar{t} \to WWqq) \end{aligned}$$



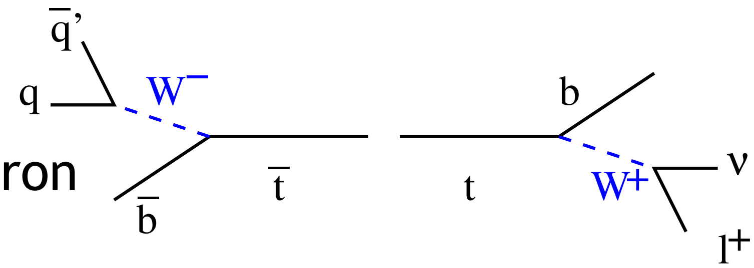
- In 250 pb^{-1} with dilepton $e\mu + 2$ jets sample

$$\begin{aligned} \delta R &= 0.02_{\text{stat}} \oplus 0.09_{\varepsilon_b} \oplus 0.03_{\text{syst}} \\ \delta\varepsilon_b &= 0.02_{\text{stat}} \oplus 0.04_{\text{syst}} \end{aligned}$$

LHC as a Top Factory

- The LHC at $\sqrt{s} = 14\,$TeV is a top 'factory'

$$\boxed{\sigma_{\rm tot}(pp \to t\bar{t}) \quad \approx \quad 830\,\text{pb}}$$

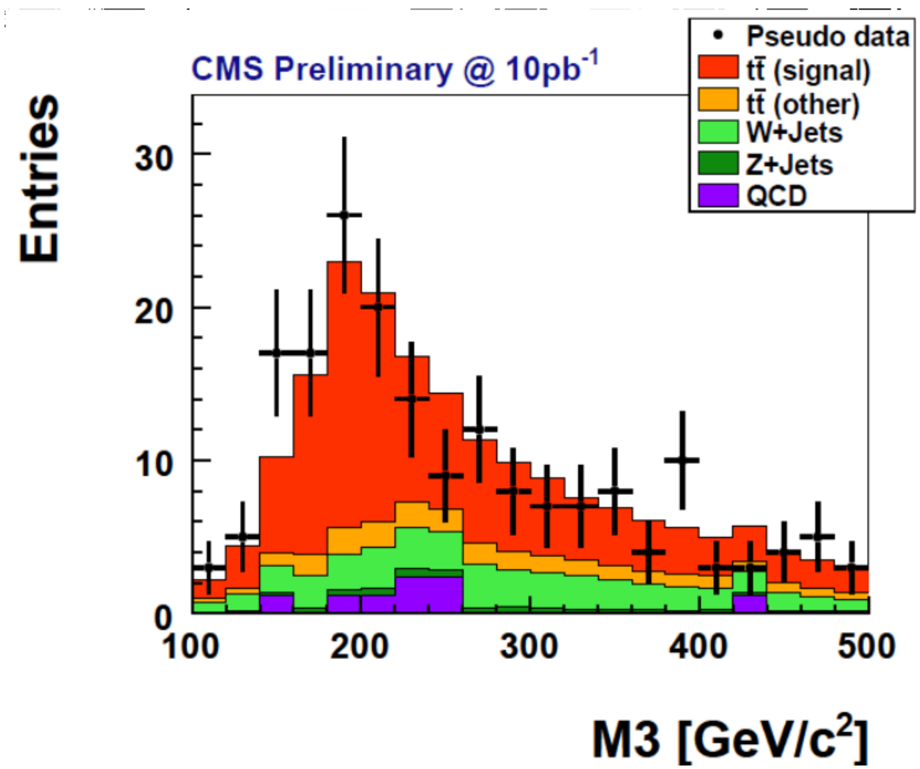


  - ▷ 100-fold increase of cross section wrt Tevatron (LHC at $10/7\,$TeV $\approx 50/20\times$ Tevatron)
  - ▷ 100-fold increase of (design) luminosity

($\mu+$ jets: 15%)

- Decays
  - ▷ $2/3$: $t \to q\bar{q}'$
  - ▷ 11%: $t \to \ell^+\nu, \ell = e, \mu$
- Example analysis at $\sqrt{s} = 14\,$TeV
  - ▷ isolated muon $p_\perp > 30\,$GeV
  - ▷ jets with $E_T > 65, 40, 40, 40\,$GeV
  - ▷ observable: hadronic top 3-jet mass

  $\rightarrow$ In $10\,\text{pb}^{-1}$
  128 signal events
  90 background events



$\Rightarrow$ or: 'recoil' physics . . .

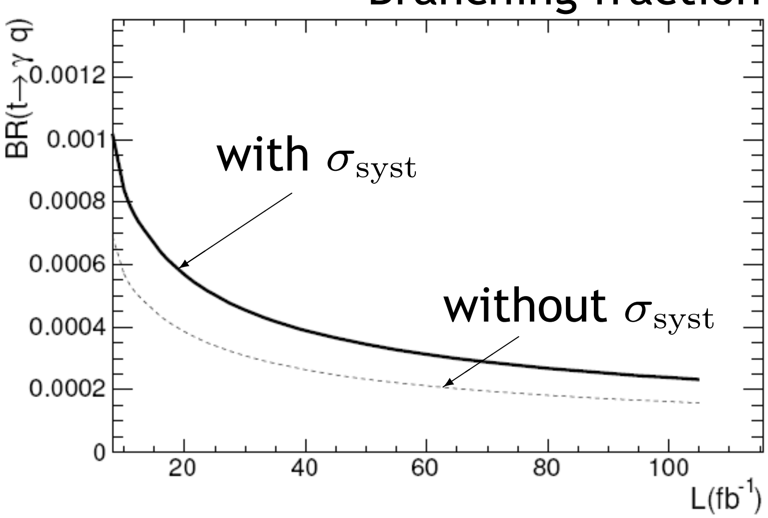
Top Flavor Physics: Rare Decays

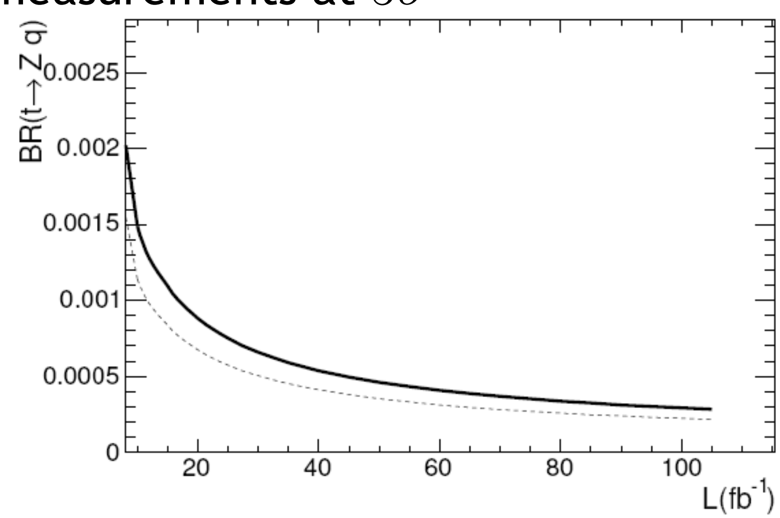
- FCNC top decays are an excellent area for BSM searches

Decay	SM	two-Higgs	SUSY with $R\!\!\!/$	Exotic Quarks	Exper. Limits(95% CL)
$t \to gq$	5×10^{-11}	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 5 \times 10^{-4}$	< 0.29 (CDF+TH)
$t \to \gamma q$	5×10^{-13}	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-5}$	< 0.0059 (HERA)
$t \to Zq$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-4}$	$\sim 10^{-2}$	< 0.14 (LEP-2)

- Event selection
  - ▷ 1 isolated high-$p_\perp$ lepton ($p_\perp > 20$ GeV) + 1 high-E_T photon ($E_T > 50$ GeV)
  - ▷ exactly 1 b jet ($E_T > 40$ GeV) + 1 non-b jet ($E_T > 50$ GeV)
  - ▷ $150 < m_{\gamma q} < 200$ GeV, $\cos(t_{\gamma q}, t_{SM}) < -0.95$
  - $\rightarrow$ efficiency $\varepsilon \approx 2\%$

Branching fraction measurements at 5σ





Conclusions and Outlook

- CMS has started successfully with data taking at $7\,$TeV
  - multitude of light and heavy particles reconstructed as expected
  - muon triggers running wide open (compared to 'high-lumi' trigger scenarios)
- Heavy flavor physics expectations
  - for this summer: production (QCD)
    - quarkonia ($c\bar{c}$ and $b\bar{b}$)
    - inclusive b production cross section
    - exclusive b production cross section
    - $b\bar{b}$ correlations
    - $t\bar{t}$ production cross section
  - for next year: flavor physics in B (and top) sector
    - $B_s^0 \to \mu^+\mu^-$
    - $B_s^0 \to J/\psi\,\phi$
- Ultimately:
  - measurement of very rare (leptonic) B_s^0 and B_d^0 decays
  - top flavor 'recoil' physics