B Physics: Status & Perspectives @ CMS

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- Past: Recent Results
- Future: Next Years Strategy
  - Analyses Prioritization
  - Trigger & Data Parking

This presentation has been developed together with Mario Galanti, BPH co-convener

BPH Organization: Italian Involvement

Conveners: M. Galanti, M. Margoni

- Production (S. Argiro`, A. Sanchez-Hernandez, I. Kratschmer → A. Sanchez-Hernandez, I. Kratschmer)
  Test of perturbative & non-perturbative QCD models of hadron production and fragmentation.
  Possible cross PAG analyses with SMP, FSQ, HIN.

- Spectroscopy & Properties (A. Pompili, E. A. Yetkin → R. Chistov, G. Fedi)
  Study of heavy flavor decays and BRs, mixing and CPV. Study of new resonances.
  Possible cross PAG analyses with TOP.

- Rare Decays (S. Lacaprara, U. Langenegger → S. Lacaprara, S. Fiorendi)
  Precision SM measurements (angular analyses, leptonic B decays, LFV)
  Possible cross PAG analyses with SMP

- Contacts:
  - Trigger (A. Boletti, S. Polikarpov)
  - MC (O. Ozcelik)
  - Muon POG (L. Cristella)
  - PPD & Tools (P. Ronchese)
  - Tracking POG (S. Fiorendi)
  - EGM (P. Behera)

Publication Status

- BPH PAG Produced 37 Publications (1 on Run2):
  - 3 Papers with > 100 citations
  - 7 Papers with > 50 citations
- 3 Submitted results (1 on Run2)
- Ongoing Analyses:
  - 3 on 2011 dataset, 12 on 2012, 3 on 2016, 2 on 2017, 1 Run1+Run2
  - 6 “Mature” results Preapproved or Approved
  - 15 at the AWG discussion stage or just started

Papers Published/Subm. during 2017

- Measurement of B^+ production cross section at 13 TeV
  BPH-15-004, PLB 771, 435
- Observation of $\Upsilon(1S)$ pair production at CMS
  BPH-14-008, JHEP 05, 013
- Observation of $B^+ \rightarrow \Psi(2S)\phi K^+$
  BPH-13-009, PLB 764, 66
- Measurement of the P5' angular observable of the decay
  $B^0 \rightarrow K^*\mu\mu$ from pp collisions at $\sqrt{s}$=8 TeV
  BPH-15-008, Subm. to PLB 
- Quarkonium production cross sections in pp collisions at $\sqrt{s}$=13 TeV
  BPH-15-005, Subm. to PLB 
- Precision lifetime measurement of B hadrons reconstructed in final states with a J/Ψ meson
  BPH-13-008, Subm. To EPJC 

47 Talks given at International Conferences
13 Italian Speakers (11 from Italian Institutions)

Next Years Strategy

Analyses Prioritisation

- Run2 confronts us with different opportunities and challenges depending on the specific analysis (statistical vs systematic errors, competitiveness wrt other collaborations results, manpower limitation)
  - Prioritised list of topics defined according to physics impact, competitors results, time scale, trigger rate consumption
  - Results extrapolated to the full Run2 statistics assuming:
    - $L(R2)_{CMS}$~150 fb^{-1} (7 X R1)
    - $L(R2)_{LHCb}$ ~4-5 fb^{-1} (1.5 X R1)
  - Exercise useful towards the definition of the future trigger paths and rate allocation:
    - Some paths, developed for measurements already limited by systematic uncertainties or not sensitive to CM energy, could be limited to save trigger rate.
    - Other measurements could be pursued parasitically using trigger paths developed for other ones (or other PAGs: SMP, TOP).

Trigger & Data Parking

- Different classes of measurements according to:

  A) Need (or not) all the integrated L

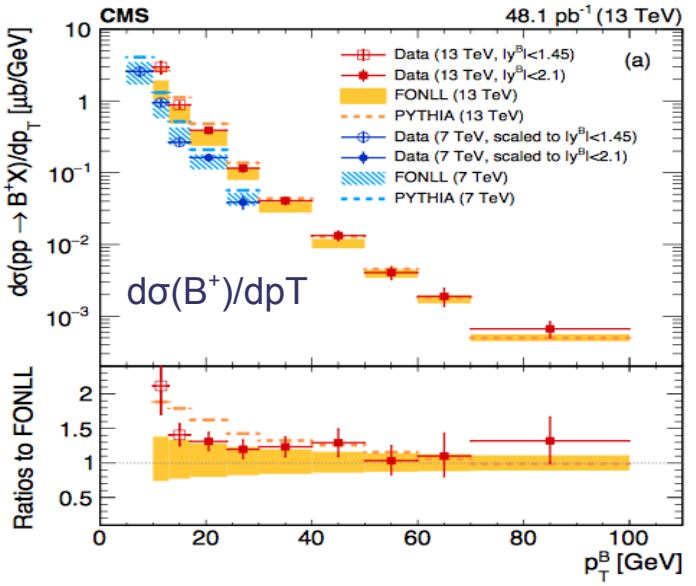
  B) Need (or not) to analyze data asap

A1) Rare Decays, CPV: limited by statistical error, need all the available luminosity (B→μμ, τ→3μ, B→K*μμ, B_s → J/ψΦ,...)

A2) Production: often already limited by systematics or already pursued in a given phase space region (σ, polarization: B, quarkonium, double quarkonium: J/ψJ/ψ)

- Prescale / increase thresholds / turn off at high L
- Define L1/HLT paths with different thresholds according to the instantaneous L scenario:
  - Low-threshold paths: active at low L
  - High-threshold paths: always active
- Use low thresholds only for a limited period of data taking to allow comparison / junction with already accomplished measurements (e.g. Differential σ in the lower pT range)

PLB 771, 453 (2017)



Trigger & Data Parking

- Different classes of measurements according to:

  A) Need (or not) all the integrated L

  B) Need (or not) to analyze data asap

B1) Groups pursuing “fast” or very hot analyses need data as soon as they are collected (search for new states, ϒμμ, B→μμ)

B2) Groups still analyzing previous data taking periods or pursuing long-term measurements limited by statistics (CPV in B_s ?) could opt for Data Parking to:

- Favor other paths while waiting for additional statistics
- Benefit from a possible larger bandwidth reducing thresholds.

- Implementing prescaled & unprescaled streams for the same HLT path will allow to start looking at the data while waiting for the full parked dataset

- Cross PAGs (SMP or TOP) analyses (Z/W → ψ (ϒ) X, BPH in t → b decays) will benefit from trigger paths developed for other measurements

- Strategy for next years is going to be discussed at the next CMS Week & Trigger Workshop, Belgrade, December 11-14: https://indico.cern.ch/event/674023/

High Priority Analyses

- ## Production:

  Quarkonium cross sections and ratios, Polarization measurements (Quarkonium, φ, Λ_b), $\chi_b \rightarrow \Upsilon(nS)\gamma$

- ## Spectroscopy & Properties:

  Double quarkonia (including ϒJ/ψ): cross sections and resonance searches, ϒμμ, Φ_s & $\Delta\Gamma_s$ with $B_s \rightarrow J/\psi\varphi$, BPH measurements using t→ b decays

- ## Rare Decays:

  $B \rightarrow \mu\mu$, Z/W → J/Ψ(ϒ)+X (cross PAG with SMP), $\tau \rightarrow 3\mu$, $B \rightarrow K^* \mu\mu$

- ## Cross Subgroups:

  BΛ resonances (Production & Spectroscopy), B → τX (Rare & Properties)

Production

Quarkonium x-sections and ratios

- CMS: long history of state-of-art measurements on 7, 8, and 13 TeV
  - Differential prompt and non-prompt x-sections and ratios for J/ψ, ψ(2S), Υ(nS) (n=1, 2, 3), $X_{c1,2}$, $X_{b1,2}$
- Main competitor: ATLAS, due to the different phase space wrt LHCb
- Physics implications:
  - Test QCD models underlying heavy flavor production
  - Prepare for double-quarkonium production (DPS effective x-section) and quarkonium polarization measurements (see next slides)
- Analysis ongoing on 2012 dataset: Measurement of J/ψ pair production (Tennessee)
  - Two CADI lines: BPH-17-001 (thesis endorsement) & BPH-17-002
  - Free for Run2 dataset

Quarkonium polarization

- One of the main probes to the processes governing prompt quarkonium production
  - CMS has a leading history in this field (BPH-11-023, BPH-13-003)

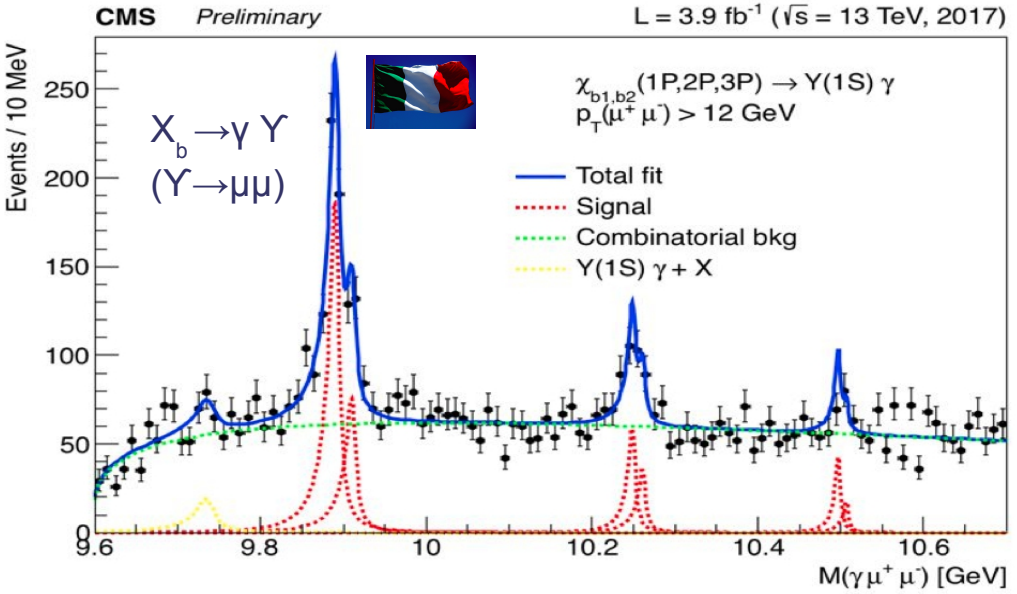
- No polarization found for any of the S-wave $c\bar{c}$ and $b\bar{b}$ states in the y and pT ranges probed on 2010 and 2011 datasets
- Analysis ongoing on Run1 + Run2 (BPH-13-001)

- Open questions:
  - Are P-wave states (χ_c, χ_b) behaving in the same way?
  - Models predict that non-null polarization may appear at higher pT:
    - To be tested with more luminosity

- Main Issue:
  - Spurious polarization measured in 2012 and 2016 data vs 2011
  - Origin still unclear despite several efforts

Quarkonium x-section & polarization

- Needs:
  - Good mass and time resolution to discriminate peaks and prompt/non-prompt components
  - Good γ conversion reconstruction for P-wave states



- HLT paths:
  - Select the two muons from the quarkonium decay
  - Low pT part of the spectrum already systematics-limited
  - Current HLT paths: Dimuon Barrel Φ (6.7 Hz), J/ψ (6.9 Hz), ψ' (4.7 Hz), Υ(7.3Hz)
  - Need data in the high pT region: good candidates to increase the trigger thresholds

- Goal: publish on full Run2 dataset

- Manpower: somehow limited (Vienna)

Spectroscopy & Properties

Φ_s & $\Delta\Gamma_s$ from $B_s \rightarrow J/\psi\Phi$

- Golden channel for CPV measurement in the B_s sector. Probe of possible new sources of CPV.

- BPH-13-012 published result (PLB 757, 97) limited by angular efficiency, DT/MC agreement and fit bias
- Analysis already started on 2016+2017 data

- Sensitivity will be improved by:
  - Muon identification: dedicated MVA (similarly to $B \rightarrow \mu\mu$, working to turn it into a common BPH tool)
  - New flavor tagging: OS lepton + Jet charge + SS kaon
  - Possible byproducts: Double gluon splitting, mixing, f_d & f_s, $\sigma(pp \rightarrow bbX)$ on the recoil of $B^+ \rightarrow J/\psi K^+$
  - Hopefully pixel detector (?): $\sigma(t)$ from 70 fs to 60/45 fs (2018 ?)

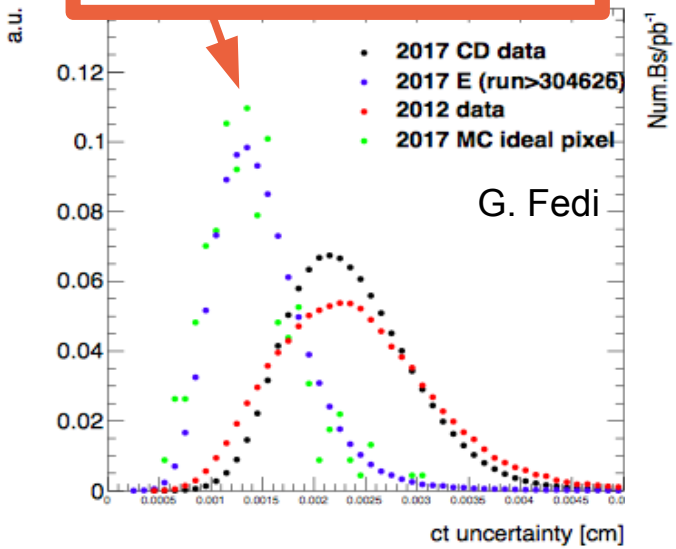
- Complementary dedicated HLT paths (since 2017 v2 (Era C)):
  - J/ψ displaced + 2 trks (invariant mass cut to select Φ candidates) 10.9 Hz
  - $J/\psi + \mu$ (No L/σ cut, muon tag strong enhancement) 13.8 Hz
  - Yield of tagging muons roughly doubled by including the $J/\psi + \mu$ path

- L1 seed (2017) with dimuon DR range allows lowering of pT cuts

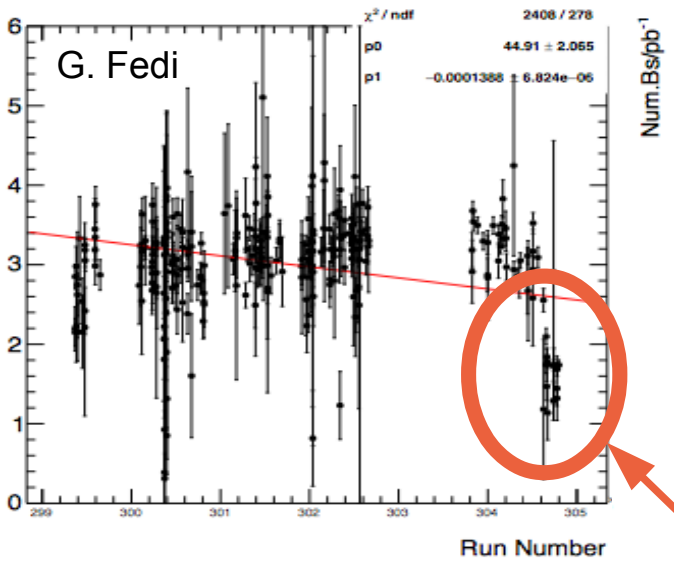
Φ_s & $\Delta\Gamma_s$ from $B_s \rightarrow J/\psi\Phi$

- Goal: publish on full Run2 dataset
- Manpower: well covered (Padova, Pisa)

New APEs from Era E. Will improve in rereco in other Eras

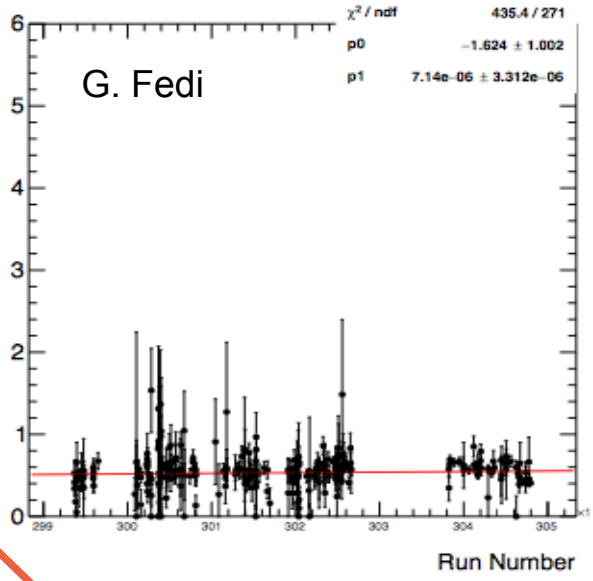


J/ψ displ. + 2 trks



$N_{sig}(Run2)/N_{sig}(Run1) \sim 1.2$ per fb^{-1}

J/ψ + μ



2017 ≥ E dataset pixel issue

- Extrapolation to full Run2 statistics:
  - CMS: σ_{stat} ~22/32 mrad (assuming $\varepsilon_{trigger}$ ~60% Run1)
  - LHCb: σ_{stat} ~30 mrad
- Run2 results will be still probably dominated by statistical error: could benefit from data parking: to be discussed

BPH meas. using t → b decays

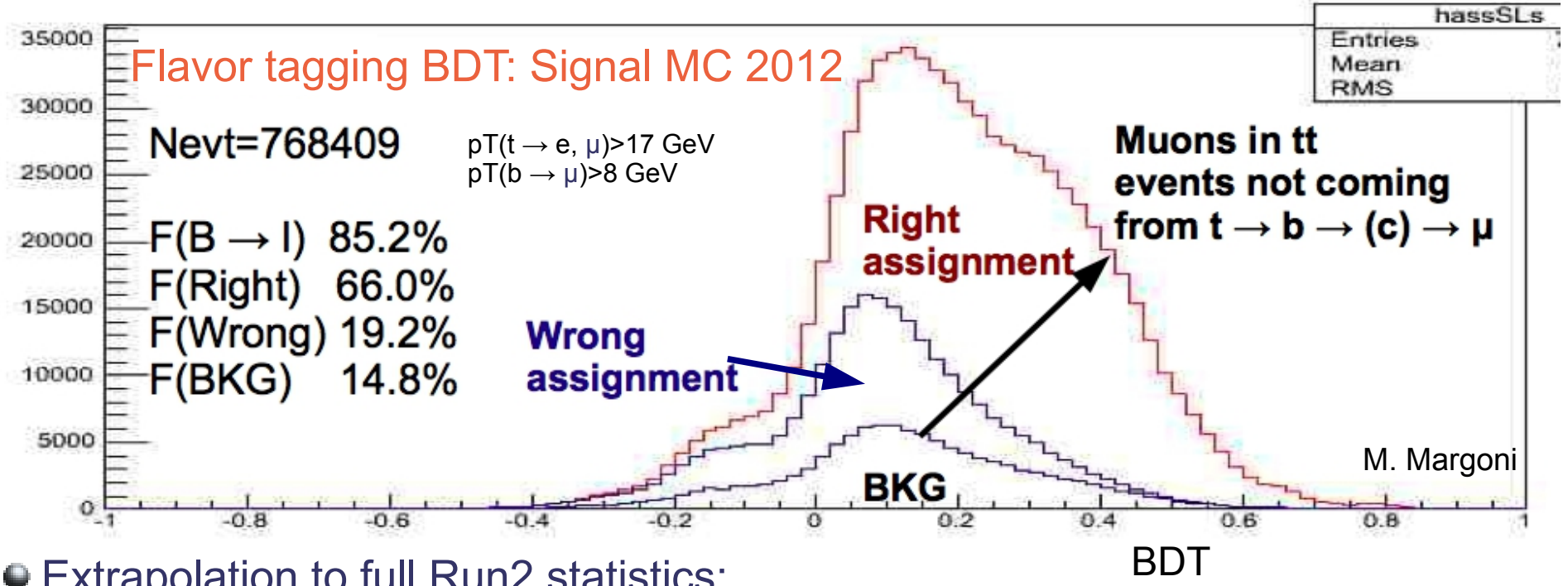
- pp → t $\bar{t}$ X events: source of b quarks with flavor tagging from the parent-t charge (arXiv:1212.4611)
- For a given b → X process to be reconstructed:
  - Comparison of effective efficiencies for tt vs bb:

$$R = \boldsymbol{\sigma}_{tt}/\boldsymbol{\sigma}_{bb} \times (1-2w_t)^2/(1-2w_b)^2 \times 2 \times 2 \times (\varepsilon^*Acc)_t/(\varepsilon^*Acc)_b$$
$$\sim 5 \times \boldsymbol{\sigma}_{tt}/\boldsymbol{\sigma}_{bb} \times (\varepsilon^*Acc)_t/(\varepsilon^*Acc)_b$$

- Pros:
  - Mistagging prob $w_t < 20\%$ vs $w_b > 30\%$
  - Factor of 2 from tagging lepton: BR(t → e, μ) vs BR(b → μ)
  - Factor of 2 from opposite side and same side tagging lepton
  - $\varepsilon_t > \varepsilon_b$ due to harder pT tagging lepton spectrum
  - Cross PAG with Top: Possibly parasitic use of trigger for SL top decays
- **Cons: limited by $\sigma_{tt} << \sigma_{bb}$**

BPH meas. using t → b decays

- With the Run2 statistics interesting for inclusive final states (e.g. b→ μ)
- Measurement of integrated mixing started on Run1 to be used as a baseline for Run2 (BPH-14-007, now inactive for lack of manpower)
- Goal: Publish mixing and CPV in mixing on full Run2 dataset
- Manpower: strongly inadequate (Padova)



- Extrapolation to full Run2 statistics:
  - $\delta_{mixing}(stat) \sim 0.4 \cdot 10^{-3}$; $\delta_{SL\ Asymmetry} \sim (stat) \sim 0.4 \cdot 10^{-2}$
  - Not (yet) competitive with LHCb, but a measurement with a novel technique

Search for ϒϒ* → 4μ resonance

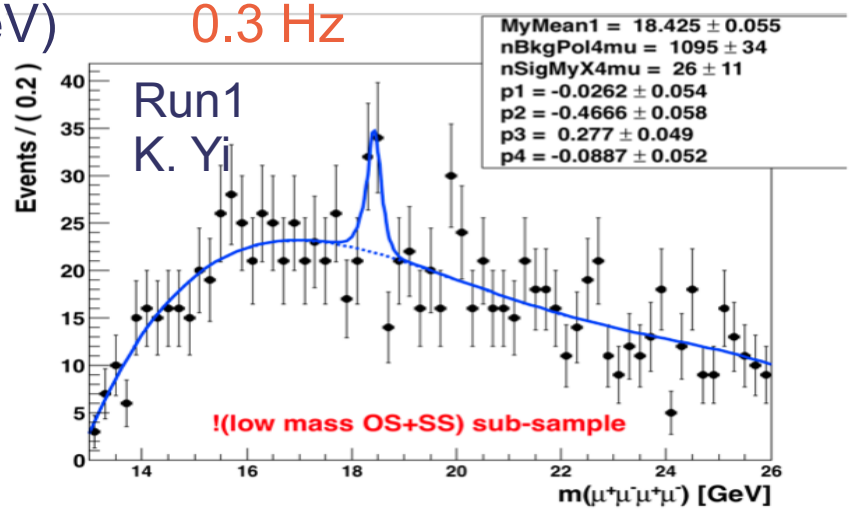
- Very hot analysis ongoing since a while. Theory paper on possible tetraquark discovery @LHC in ϒϒ* available: https://arxiv.org/abs/1709.09605

- After a quite long review in the BPAG (trigger matching and BKG issues) now the analysis (BPH-14-006) is near to be finalized on Run1 Dataset, going to start on Run2

- Sensitivity will be improved by new additional HLT dedicated trigger paths included in 2017 HLT v4.1:
  - (ϒ → 2μ) + μ with pT>5, 3.5, 2 GeV (previous one) 9.9 Hz
  - NEW (ϒ → 2μ) + μ with open muons pT>5, 3.5, 2 GeV 5.1 Hz
  - NEW (ϒ → 2μ) + 2e (pT(μ)>5 GeV, pT(e)> 3 GeV) 0.05 Hz
  - NEW (ϒ → 2e) + 2μ (pT(μ)>3 GeV, pT(e)>7.5 GeV) 0.3 Hz

- Goal: publish Run1 Data asap (after some preliminary checks on Run2)

- Manpower issues solved:
  - Two new groups going to join Iowa to analyze & publish Run2 Dataset with High Priority



Rare Decays

$B \rightarrow \mu\mu$

- Flagship CMS analysis
  - Three iterations on Run1, ended with joint CMS+LHCb observation of $B_s \rightarrow \mu\mu$ and stringent limit to $B^0 \rightarrow \mu\mu$

- Fourth iteration ongoing (Run1+2016 dataset):
  - Goals: improve limit on BF($B^0 \rightarrow \mu\mu$) & precision on BF($B_s \rightarrow \mu\mu$), measure $B_s \rightarrow \mu\mu$ effective lifetime
  - Sensitivity improved by: new μ ID BDT, in-situ measurement of f_s/f_u, optimization for B^0, data driven μ fake-rate determination
  - Issues with data (strips HIP problems) and with MC still delaying release
  - Limited manpower: would strongly benefit from additional qualified people/groups joining the effort

- Trigger rates under control with current setup:
  - L1: Double muon, η<1.5, opposite-charge, single quality, DR<1.4 3.3 kHz
  - HLT: Double muon (pT> 4 GeV and pT> 3 GeV) @ B_s (9.6 Hz) or J/ψ (4.9 Hz with prescale 8)

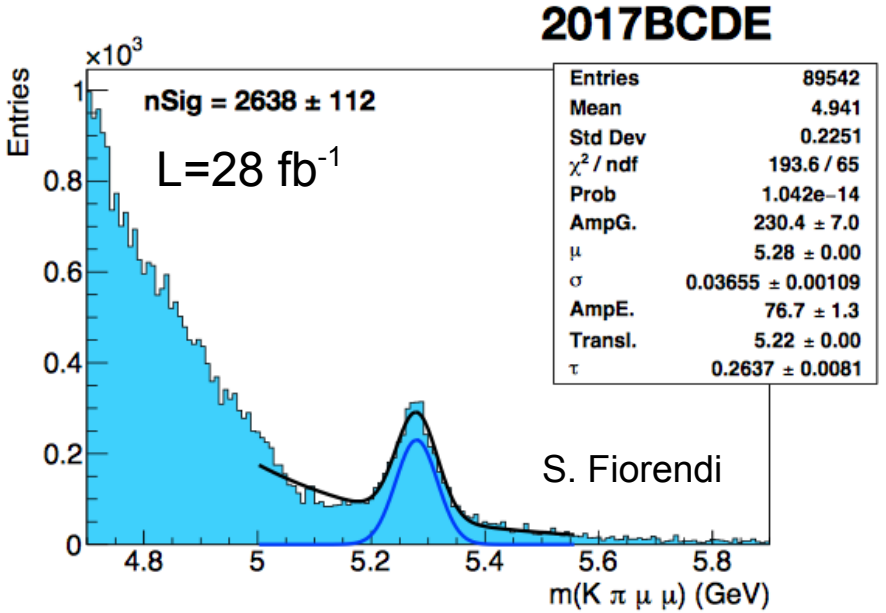
- Goal: publish 2016 data and 5th iteration on full Run2 dataset

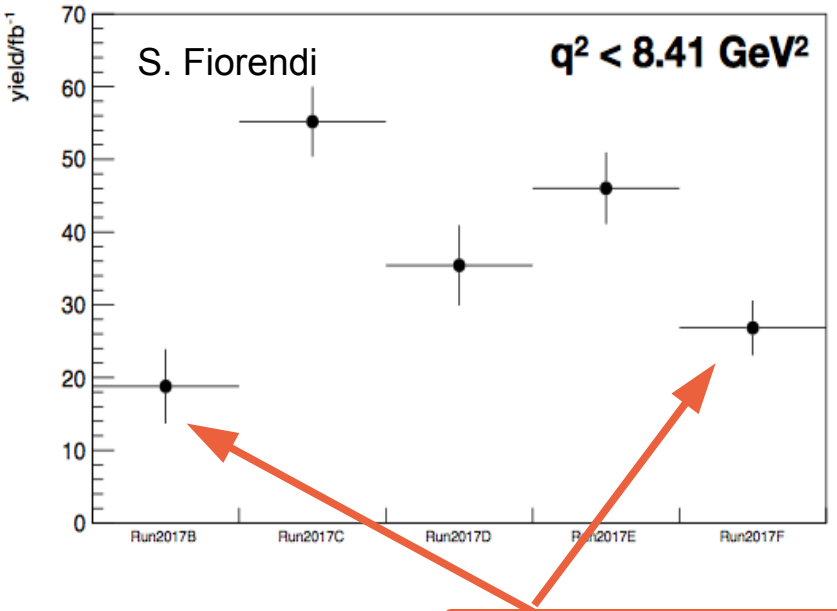
$B^0 \rightarrow K^*\mu\mu$

- Flagship CMS analysis. Indirect search for New Physics.
- Submitted P5' result BPH-15-008 (arXiv:1604.04042) limited by statistical error and fixed parameters from previous measurement
- Analysis just started on 2016+2017 data
- Sensitivity will be improved by:
  - Statistics
  - Global fit with all parameters free to float
  - Hopefully pixel detector (?)
- HLT paths since v1.1 (Era B):
  - Low-mass non-resonant dimuons + 1 trk displaced 22.1 Hz
  - J/ψ(ψ) + 1 trk displaced for control/normalization channels 15.1(1.2) Hz
- L1 seed with dimuon DR range allows reduction of pT cuts
- Run2 results will be still dominated by statistical error

$B^0 \rightarrow K^*\mu\mu$

- Goal: publish on 2016+2017 or full Run2 (TBD)
- Manpower: well covered (Milano, Padova)





- Signal yield 95 evts/fb^{-1} to be compared with 70 evts/fb^{-1} in 2012

Pixel commissioning & Era ≥ E issue

- Extrapolation to full Run2 statistics:
  - CMS: ~ 11000 evts (assuming $\varepsilon_{trigger}$ ~60% Run1)
  - LHCb: ~7500 evts (assuming stable performaces as during Run1) ...but with better S/N ratio and PID

$\tau \rightarrow 3\mu$

- Golden channel for LFV
  - Best limit by BELLE: BR<2.1 x 10^{-8} (@90% CL) will be sharply improved by BELLE2
  - Window of opportunity not long: publish fast !

- Two Analyses ongoing on Run2 (2016 dataset) using different production channels:
  - $W \rightarrow \tau\nu$ (Milano, more advanced)
  - $D_s \rightarrow \tau X$ (Florida, FNAL, MIT)

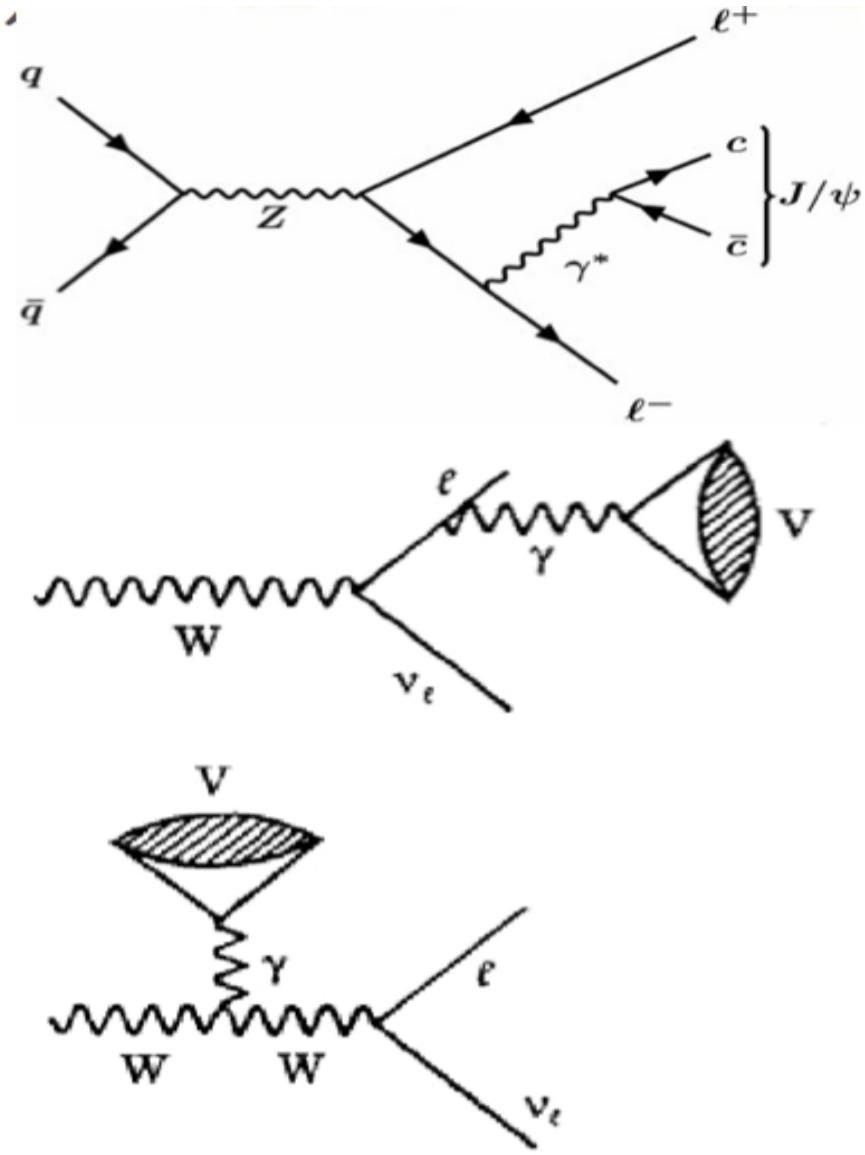
- HLT dedicated paths:
  - 2μ + 1trk +good 3-object displaced vertex (developed for $D_s \rightarrow \tau X$) 18.6 Hz
  - Improved since 2017 v2.2:
    - 2μ + 1 tracker μ, loose requirements on pT and dZ, isolation on the 3μ object 4.8 Hz

- Goal: publish 2016 result asap then move to full Run2 dataset. Milano analysis aiming at Moriond 2018 with final result
- Manpower: well covered

- Expected limit on the 10^{-7} level with 2016 data
  - Improved trigger paths in 2017+2018: limit will scale better than L

Z/W → V+X

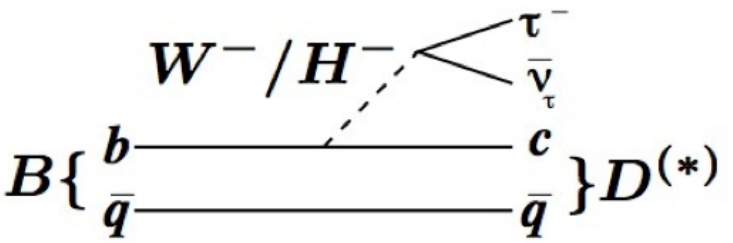
- High integrated luminosity allows search for Z/W rare decays
  - Cross-PAG analyses with SMP
- One Analysis ongoing on 2012 data being approved (BPH-16-001): first observation of Z→ J/ψll (l=e, μ)
- Other similar measurements within our reach:
  - With Run2 data: Z → φll, ψ(2S)ll,W → J/ψlν
  - With more statistics: Z → Υ(1S)ll
  - They can prepare for H decay in the same final states
- Trigger Strategy:
  - Current analysis: high pT non-resonant leptons (no BPH path needed)
  - Where needed (e.g. for the W) can use ψ/Υ→μμ
- Manpower: just one (Colorado) group: room for more contributions

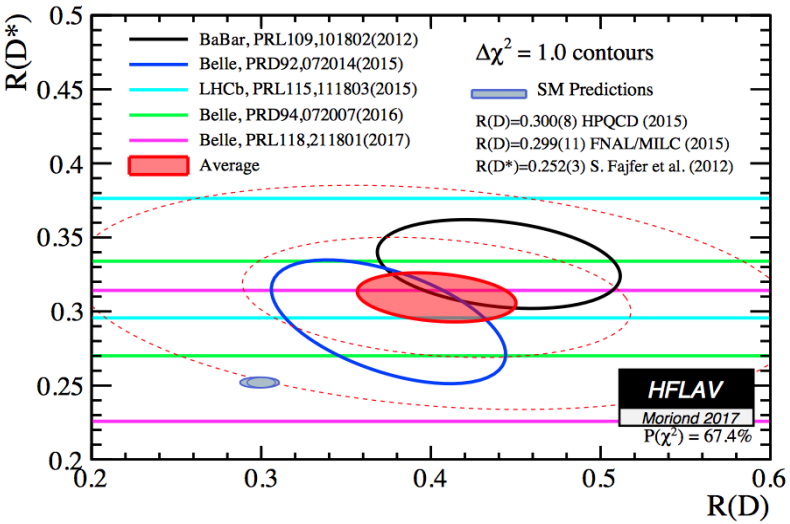


Cross Supgroups

$B \rightarrow \tau + X$

- Probe of New Physics (e.g. 2-Higgs Doublet Model) due to large H^+-fermion coupling.
- Two classes of possible measurements:
  - X=e, μ, τ: search for LFV / non-universality
  - X=π, ρ, $D^{(*)}$, J/ψ: measurement of CKM matrix elements. Some tensions present wrt Standard Model expectations ($R(D^*)=B\rightarrow D^{(*)}\tau\nu/B\rightarrow D^{(*)}l\nu$)





- Difficult τ reconstruction, BKG reduction and normalization:
  - "New" possible strategy to be studied: analysis on the recoil of another reconstructed B decay to reduce the amount of useful tracks
  - "Untriggered" measurement
- Very challenging measurements not started yet
  - Room for new groups with different expertise
  - Possible increase of importance in the near future

Conclusions

- Important relative weight of Italian Institutions in the PAG (analysts and conveners / subconveners)
- Still several analyses ongoing on Run1 dataset, however almost 50% (8) are going to be finalized in the next months.
- Prioritization effort finalized: High-Priority and Medium-Priority Analyses selected
- Trigger experts at work with analysts to define the next years data taking strategy:
  - Production paths for x-section & polarization measurements might be good candidates for threshold increase (at least at high instantaneous L)
  - A few measurements can be pursued using trigger paths developed by other PAGs (SMP, TOP)
  - Some measurements limited by statistics are good candidates for Data Parking
- BPH Group is small, several analyses are ongoing or will start soon.
- Some flagship measurements have manpower issues:
  - Help is needed and very welcome!

Backup

L1 seeds vs analysis (2017 v4.1)

L1 menu	Unprescaled rate [1.5e34]	Prescale value [column 1]	Quarkonium cross sections and polarization	Chi_b->Y(nS) gamma	Double quarkonia (including J/Psi Y)	Ymumu	CPV with Bs -> J/Psi Phi	Bmm	Z -> J/Psi X	tau->3Mu search	P5' angular analysis	B Lambda resonance search
L1_DoubleMu0er1p5_SQ_OS_dR_Max1p4	3,286	1	x	x			x	x		x	x	x
L1_DoubleMu4p5er2p0_SQ_OS_Mass7to18	1,752	1	x	x								
L1_DoubleMu5_SQ_OS_Mass7to18	1,275	1	x	x								
L1_DoubleMu8_SQ	1,080	1	x	x								
L1_DoubleMu4_SQ_OS_dR_Max1p2	3,506	1		x			x			x	x	x
L1_TripleMu_5_3p5_2p5_DoubleMu_5_2p5_OS_Mass_5to17	1,313	1			x	x						
L1_TripleMu_5SQ_3SQ_0OQ_DoubleMu_5_3_SQ_OS_Mass_Max9	1,488	1			x		x			x		
L1_DoubleMu5Upsilon_OS_DoubleEG3	543	1				x						
L1_DoubleMu3_OS_DoubleEG7p5Upsilon	432	1				x						
L1_TripleMu_5OQ_3p5OQ_2p5OQ_DoubleMu_5_2p5_OQ_OS_Mass_8to14	954	1				x						
L1_TripleMu_5OQ_3p5OQ_2p5OQ_DoubleMu_5_2p5_OQ_OS_Mass_5to17	1,627	only for L<1.45				x						
SMP High pT triggers									x			

HLT paths vs analysis (2017 v4.1)

HLT menu	Prescaled rate [@ 1.5e34]	average prescale	Quarkonium cross sections and polarization	Chi_b->Y(nS) gamma	Double quarkonia (including J/Psi Y)	Ymumu	CPV with Bs -> J/Psi Phi	Bmm	Z -> J/Psi X	tau->3Mu search	P5' angular analysis	B Lambda resonance search
HLT_Dimuon10_PsiPrime_Barrel_Seagulls	4.7	1	x									
HLT_Dimuon20_Jpsi_Barrel_Seagulls	6.9	1	x									
HLT_Dimuon10_Upsilon_Barrel_Seagulls	7.3	1	x	x								
HLT_Dimuon14_Phi_Barrel_Seagulls	6.7	1	x									
HLT_Dimuon12_Upsilon_eta1p5	8.6	1		x								
HLT_Dimuon0_Jpsi3p5_Muon2	13.8	1			x		x					
HLT_Trimuon5_3p5_2_Upsilon_Muon	9.9	1			x	x						
HLT_TrimuonOpen_5_3p5_2_Upsilon_Muon	v4 5.1	1				x						
HLT_DoubleMu5_Upsilon_DoubleEle3_CaloIdL_TrackIdL	v4 0.05	1				x						
HLT_DoubleMu3_DoubleEle7p5_CaloIdL_TrackIdL_Upsilon	v4 0.3	1				x						
HLT_DoubleMu4_JpsiTrkTrk_Displaced	10.9	1					x					
HLT_DoubleMu4_3_Bs	9.6	1						x				
HLT_DoubleMu4_3_Jpsi_Displaced	4.9	8						x				
SMP High pT triggers									x			
HLT_DoubleMu3_Trk_Tau3mu	18.6	1								x		
HLT_Tau3Mu_Mu7_Mu1_TkMu1_IsoTau15_Charge1	4.7	1								x		
HLT_Tau3Mu_Mu7_Mu1_TkMu1_IsoTau15	4.8	1								x		
HLT_Tau3Mu_Mu7_Mu1_TkMu1_Tau15_Charge1	0.7	20								x		
HLT_Tau3Mu_Mu7_Mu1_TkMu1_Tau15	0.7	20								x		
HLT_DoubleMu4_LowMassNonResonantTrk_Displaced	22.1	1									x	
HLT_DoubleMu4_JpsiTrk_Displaced	15.1	1									x	x
HLT_DoubleMu4_PsiPrimeTrk_Displaced	1.2	1									x	

Medium-Priority Analyses

- Production:

  f_d, f_s fragmentation functions, B and B_c cross sections

- Spectroscopy & Properties:

  Y(4140) in $B^+ \rightarrow J/\psi\varphi K$, $J/\psi\varphi$ resonances, X_b, $B_s \rightarrow J/\psi\varphi$ byproducts from flavor tagging studies: χ, g splitting, σ_{bb}

- Rare Decays:

  Associated production of $ZJ/\psi(\Upsilon)$, $WJ/\psi(\Upsilon)$ (cross PAG with SMP)